Response to Reviewer 1:

I am very grateful to your comments for the manuscript. Thank you for your advice. All your suggestions are very important. They have important guiding significance for our paper and our research work. We have revised the manuscript according to your comments. The response to each revision is listed as following:

General Comment

Since the M6.9 Menyuan earthquake occurred close to the Menyuan station, I would like to ask: why do the authors interpret the signals recorded at this borehole strain gauge station as precursors to the Maduo (Mado) earthquake, which occurred more than 400 km away? Unless the authors can clearly explain how this signal can be attributed to the Maduo earthquake rather than to unrelated phenomena or local seismic events, I find the current conclusions unconvincing.

Response:

Thanks for your suggestion.

Borehole strain data studies have focused on short-term as well as proseismic anomalies (3 months before the earthquake) (Chi et al., 2023; Yi, 2005; Li et al., 2024b). The anomalies of the Maduo earthquake extracted from the Mengyuan station in our study were about 3 months before the earthquake (mid-February 2021) and 2 months before the earthquake (end-March 2021), which are short-term as well as proseismic anomalies. On the other hand, the Menyuan earthquake occurred on January 08, 2022, which is about 11 months different from the time when the Maduo seismic anomaly was extracted from the Menyuan station, and it does not belong to short-term as well as proseismic anomaly. Therefore, we believe that the anomaly extracted from the Mengyuan station is a pre-seismic precursor of the Maduo earthquake, not of the Mengyuan earthquake. I will answer the details below.

Specific Comments:

Comment 1

Introduction: The section cites too many references, each describing different precursor phenomena from strain gauges, making the narrative overly verbose and lacking synthesis. Please consider summarizing the key findings of these previous studies to provide a more coherent and concise background.

Response:

Thanks for your suggestion.

Based on your comments, we are revising the introduction section. Previous studies are summarized to ensure more coherent and concise sentences. At the same time, we reduced the redundancy of the sentences to improve the coherence and comprehensiveness of the narrative. First, we deleted lines 37-41 of the original manuscript to remove the redundancy of sentences. At the same time, we modified lines 41-43 of the original manuscript to ensure the coherence of the sentence, and modified it to read “Researchers around the world have now explored a wide range of phenomena before and after earthquakes, covering different structural levels of the Earth, including the subsurface, surface and atmospheric realms.”. Second, we summarized the references in lines 45-50 of the original manuscript, revising them to “(Liu et al., 2023) used outward longwave radiation (OLR) data to find that thermal infrared anomalies synchronized with the tidal stress cycle preceded the 2023 M7.8 earthquake in Turkey, possibly reflecting the thermal response of tectonic stresses as they accumulate to a critical state.”. In addition, revise lines 50-53 of the original manuscript to read “(Guo et al., 2015) found significant anomalous ionospheric disturbances prior to the April 11, 2012 Sumatra Ms8.6 and Mexico Ms6.7 earthquakes using global total ionospheric electron content (TEC) data.”. We reduced the introduction of references in lines 53-58 of the original manuscript, as well as summarized the referenced research to ensure sentence brevity, revising it to “In addition, other scholars have also studied fields such as geomagnetism (Li et al., 2019), microwave bright temperature (MBT) (Qi et al., 2021), CO (Cui et al., 2024), and electron density (Han et al., 2023). The above studies provide abundant data support and theoretical basis for the exploration of earthquake precursors, and are of great significance to our understanding of earthquake mechanisms and potential impacts.”.

Lines 83-85 of the original manuscript were deleted due to the citation of (Li et al., 2024a) in line 104 of the original manuscript, which describes the removal of seasonal trends and tidal influence on borehole observations based on Variational Modal Decomposition (VMD). Therefore, we delete lines 83-85 of the original manuscript, and we revise lines 104-107 of the original manuscript to read “(Li et al., 2024a) successfully extracted the pre-seismic anomalies of the 7.0 magnitude earthquake in Jiuzhaigou by removing the effects of seasonal trends and tides on the borehole observations based on the variational modal decomposition (VMD) and combining with the Graph WaveNet model to process the multi-station data.”. Lines 111-120 of the original manuscript are too redundant, so we summarize them and modify them to read “Variational Modal Decomposition (VMD), as an adaptive signal decomposition method, is able to effectively extract the features of nonlinear and nonsmooth signals in the frequency domain, which is widely used in the analysis of complex waveforms such as steps, jumps, and burrs, and outperforms the traditional Empirical Modal Decomposition (EMD) and its derivatives in seismic signal processing (Rao et al., 2024; Li et al., 2018; Xue et al., 2019). However, with the increasing size and complexity of observed data, VMD has limitations such as high memory overhead in large-scale data processing.”. Finally, lines 126-128 of the original manuscript introduced too many references; we have retained only the more recent references, while ensuring that the references introduced are recent studies.

Comment 2

Line 64: Could you provide more details about the borehole strain gauges used to record earthquake precursor signals, such as installation depth, sampling frequency, and observation duration?

Response:

Thanks for your suggestion.

In the study of (Qiu et al., 2013), it was noted that the YRY-4 four-component borehole strain gauge was installed at a depth of about 40 m, and the sampling rate was one sample per minute. The unique design of the YRY-4 four-component borehole strain gauge allows quantitative estimation of the confidence of the data through self-consistency tests without the use of earth tides or any special signals. In addition, the study presents a relative correction method for norm sensitivity and demonstrates its effectiveness in improving data confidence. Therefore, this confirms that the YRY-4 four-component borehole strain gauge has the ability to continuously monitor the stress-strain changes in the earth's crust, which provides reliable data support for earthquake prediction and tectonic movement studies.

In addition, based on your comments we found that because lines 64-65 of the original manuscript did not specify what type of borehole strain gauges were used, we did not provide more details about the borehole strain gauges used to record the seismic precursor signals. However, we have adjusted it so that after presenting the type of borehole strain gauges used, we provide more more details about the borehole strain gauges. This makes our article, able to be more explicit. Therefore, we modify and supplement this paragraph. It should be revised as “As the main observation equipment of China's digital seismic observation network, China's self-developed YRY-4 four-component borehole strain gauge is usually installed at the bottom of bedrock at 40 meters, and has the capability of minute-level strain sampling, which can continuously record high-resolution stress and strain changes (Qiu et al., 2013).”.

Comment 3

Line 85: Please elaborate on the cited literature. For example, what findings did Liu et al. (2014) present? What specific anomalies were observed before and after the Lushan earthquake? Did the PBO program detect reliable precursory signals for particular earthquakes?

Response:

Thanks for your suggestion.

(1)What findings did Liu et al. (2014) present? What specific anomalies were observed before and after the Lushan earthquake?

(Liu et al., 2014) analyzed the observation data of four-component borehole strain gauges at Guzantai before and after the 2013 Lushan Ms7.0 earthquake by the S-transform method, and found that two clusters of significant high-energy anomalous signals appeared in the time-frequency domain. The first cluster of anomalies appeared in October 2012 and lasted for about 4 months; the second cluster of anomalies appeared from a few days before to after the earthquake, in which short-period signals decayed rapidly after the earthquake. By analyzing the effects of teleseismic co-seismic effect and construction disturbances around the station, they concluded that these anomalous signals are not related to external disturbances, and may be associated with the seismic process of the Lushan earthquake. The anomalous signals gradually decayed after the earthquake, and basically disappeared by the end of August 2013, and the strain records were restored to the normal solid-tide pattern. Compared with the strain changes before and after the 2008 Wenchuan Ms8.0 earthquake, the anomalous signals before and after the Lushan earthquake have a shorter duration and more discrete energy clusters, reflecting the differences in the strain evolution characteristics of different earthquakes. According to your suggestion, we have revised lines 87-89 of the original manuscript to read "(Liu et al., 2014) used the S-transform method to analyze the observation data of four-component borehole strain gauges at Guzantai before and after the Lushan Ms7.0 earthquake, and found that two clusters of high-energy clusters in the time-frequency domain may be related to the seismic activity in Lushan.".

(2) Did the PBO program detect reliable precursory signals for particular earthquakes? The U.S. Plate Boundary Observation (PBO) program consists of three components: a backbone of GPS receivers for general characterization of the entire plate boundary region. Observation units of GPS, borehole strain gauges, and laser strain gauges installed on tectonic zones in the western U.S. and southern Alaska. GPS units in areas not covered by installed stations (Ouyang, 2011). The seismic signals recorded by the PBO program have shown good reliability in terms of co-seismic response (Chen and Lü, 2019). Although the PBO program has achieved some results in the detection of seismic precursor signals, there is no conclusive evidence that it has detected reliable precursor signals for specific earthquakes. Meanwhile, due to the complexity of detecting and recognizing earthquake precursor signals, the current research is still in the exploratory stage (Thomas et al., 2011).

Comment 4

Line 79: You mention that "Zhu et al. (2020) observed the Wenchuan earthquake precursors by analyzing the eigenvalues and eigenvectors of the borehole strain data." Could you clarify how these mathematical features are physically related to pre-seismic processes?

Response:

Thanks for your suggestion.

(Zhu et al., 2020) conducted an anomaly extraction study on the pre-earthquake borehole strain data of Wenchuan earthquake by using principal component analysis (PCA) method to analyze the first eigenvalue and the first eigenvector of the borehole strain data, and to extract the anomalous features of the strain changes before the Wenchuan earthquake. The eigenvalue indicates the main intensity of the signal, and the anomalies may imply stress changes or earthquake precursors. The eigenvectors indicate the directional characteristics of the strain changes, and the changes in their spatial distribution can reveal the evolution of the fault from a steady state to a sub-stable state. The results of their analysis indicate that the spatial distribution of the eigenvectors and the accelerated occurrence of eigenvalue anomalies represent the stress evolution characteristics of the faults from steady state to sub-stable state in the rock experiments. Preliminary inferences suggest that this process may also be related to the preparation stage of a large earthquake. At the same time, they show that because the principle of crustal motion is complex, it is difficult to determine the physical significance of the eigenvalues and eigenvectors when applying principal component analysis to the study of strain earthquake precursors. The physical significance of eigenvalues and eigenvectors needs to be further explored.

Therefore, we revised lines 79-80 of the original manuscript to read "(Zhu et al., 2020) studied the anomalous characteristics of the borehole strain data before the Wenchuan earthquake by using principal component analysis. By analyzing the first eigenvalue and the first eigenvector of the borehole strain data, the characteristics of pre-earthquake crustal strain changes are revealed.".

Comment 5

Line 121: What does SVMD stand for? Also, the manuscript lacks a clear explanation of how SVMD improves upon conventional VMD. Please provide comparative analysis in terms of computational efficiency, memory usage, or signal decomposition performance.

Response:

Thanks for your suggestion.

(1) What does SVMD stand for?

SVMD in line 121 of the original manuscript denotes Segmented Variational Modal Decomposition. As shown in Fig. 3 of the original manuscript, the SVMD method is based on the principle that we choose a sliding window mechanism with a size of 7 days and a sliding step of 1 day for data segmentation. First we set the initial window to all data from day one to day seven and perform Variational Modal Decomposition (VMD) on the data within that window. Starting from the second sliding window, only the results of the VMD decomposition of the current window are retained and superimposed with the decomposition results of the previous window, and in this logical order, the data are processed sequentially to finally obtain the complete data set after SVMD processing. Therefore, we have revised line 121 of the original manuscript to add the full form for the first time in the introduction and revised it to "Segmented Variational Modal Decomposition (SVMD)".

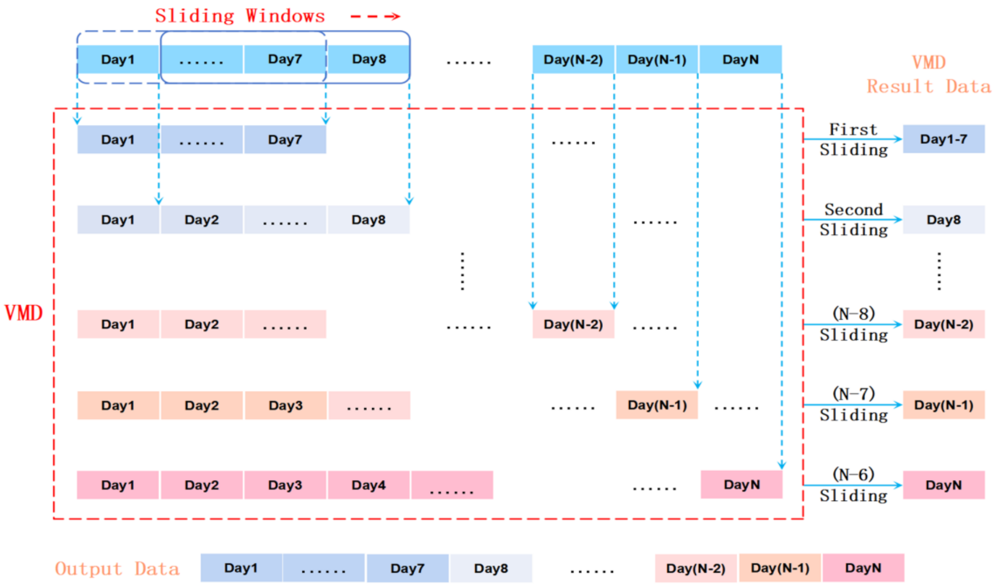


Figure 3 of the original manuscript. Schematic diagram of the Segmented Variational Modal Decomposition (SVMD).

(2) Also, the manuscript lacks a clear explanation of how SVMD improves upon conventional VMD. Please provide comparative analysis in terms of computational efficiency, memory usage, or signal decomposition performance.

In response to your question, we provide a detailed supplement and a comparative analysis of Segmental Variational Modal Decomposition (SVMD) and Variational Modal Decomposition (VMD).

Variational Modal Decomposition (VMD) has significant advantages in dealing with nonlinear and nonsmooth signals. However, using the VMD method for global search and solving the variational problem may pose computational challenges due to the large amount of data involved, such as slow processing speed and computer memory constraints, and the use of traditional data segmentation methods may result in the loss of data correlation between neighboring data segments. In order to solve these problems, we used a Segmented Variational Modal Decomposition (SVMD) method (Chi et al., 2023).

As shown in Table 1, we choose 7-day, 15-day and 30-day data for decomposition. The experimental results show that the SVMD method is better than the traditional VMD method in terms of computational efficiency and memory usage. Running device name: DESKTOP-FPCL3PM; Running device version: Windows 11 Professional; Running device processor: 12th Gen Intel(R) Core(TM) i7-12700F 2.10 GHz.

Table 1. SVMD and VMD in terms of computational efficiency, memory utilization. Comparative analysis table in terms of usage.

Method	Time(second)	Memory(MB)	Data Length(day)
VMD	1.53	6.28	7
SVMD	1.02	5.69	7
VMD	5.34	10.89	15
SVMD	2.49	7.09	15
VMD	15.14	20.06	30
SVMD	6.64	12.97	30

Comment 6

Line 127: Please provide the full forms of GRU and LSTM when first mentioned.

Response:

Thanks for your suggestion.

We have used the full form of the GRU and LSTM models first mentioned in line 127 of the original manuscript, modifying them to “Gated Recurrent Units (GRU)”, “Long Short-Term Memory (LSTM)”. We have also revised line 126 of the original manuscript to read “Fandom Forest (RF)” in order to maintain the uniformity of the article.

Comment 7

Lines 134 & 180: Please correct “Mado earthquake” to “Maduo earthquake”.

Response:

Thanks for your suggestion.

We have replaced “Mado earthquake” with “Maduo earthquake” in lines 134 and 180 of the original manuscript. At the same time, we have corrected the incorrect “Mado earthquake” to the correct “Maduo earthquake” in the rest of the manuscript.

Comment 8

(1)Line 135: Why was the Menyuan station selected for detecting precursors of the Maduo earthquake? A significant M6.9 earthquake occurred near Menyuan on January 1, 2022. It is more plausible that the signals from the Menyuan station correspond to the local mainshock rather than to the Maduo earthquake over 400 km away.

(2)Lines 190–195: As noted by the authors, I believe the signals described may be related to the Menyuan earthquake in 2022 rather than the Maduo earthquake in 2021.

Response:

Thanks for your suggestion.

We understand your legitimate concerns regarding the selection of the Menyuan station for detecting precursors of the Maduo earthquake. The Menyuan station is about 422.06 km from the epicenter of the Maduo earthquake, and the Menyuan station is about 35.44 km from the epicenter of the Menyuan earthquake. Both the Maduo and Mengyuan earthquakes are within the observation area of the Mengyuan station, and the drilling strain instruments are able to pick up the signals associated with the earthquakes. Therefore, your concern is reasonable.

However, it should be noted that the study of borehole strain data mainly focuses on short-term and proseismic anomaly characteristics (3 months before the earthquake). And many scholars have used borehole strain data to extract short-term and proseismic anomalies before earthquakes (Zhu et al., 2018; Ma and Zhang, 2014; Li et al., 2024a). In this study, the anomalies we extracted from the Menyuan station appeared about 3 and 2 months before the Maduo earthquake, a time scale consistent with typical short-term precursor characteristics. And our results are consistent with the theory of fault synergistic process of (Ma et al., 2014), and we believe that the anomalies observed before the Maduo earthquake are related to the gestation process of the earthquake. The time gap between the Menyuan magnitude 6.9 earthquake, which occurred on January 8, 2022, and our use of the Menyuan station to extract the pre-seismic anomalies of the Maduo earthquake is about 11 months, which is far beyond the time frame of short-term proseismic anomalies. Therefore, we believe that the anomalies extracted from the Mengyuan station this time belong to the pre-seismic precursor of the Maduo earthquake, rather than the Mengyuan earthquake. Therefore, we choose the Menyuan station to detect the precursor of the Maduo earthquake.

In addition, we calculated the monitoring range of the short-term precursor anomaly of this Maduo Ms7.4 based on the empirical equations of magnitude-short-term precursor anomaly time and magnitude-short-term precursor range given by (Su, 1991). The empirical formulas are shown below:

$$logT = 0.49M - 1.25 \quad (1)$$

$$logR^{(0)} = 0.182M + 1.4 \quad (2)$$

where M denotes the magnitude and R denotes the short-term precursor monitoring range of the borehole strain gauge. Based on the above empirical formula, we substitute the magnitude Ms7.4 for the present study, and obtain that the anomaly time of the strain short-term precursor corresponding to an earthquake of magnitude 7.4 is about 237 days (about 7.9 months). The monitoring range of the short-term precursor of the borehole strain gauge is about 559 km. The distance between the Menyuan station and the epicenter in this study is 422.06 km, which indicates that the station we chose has the ability to receive the short-term precursor anomalies of the borehole strain gauge. Meanwhile, the anomaly time of the strain short-term precursor corresponding to the magnitude 7.4 earthquake is about 7.9 months, which indicates that the strain short-term precursor of the Menyuan earthquake is not the pre-seismic anomaly of the Maduo earthquake that we extracted. Therefore, we believe that the anomaly we extracted from the Mengyuan station records the Maduo earthquake, not the Mengyuan earthquake.

Finally, we very much agree with your important point about the correlation of anomalous signals with local earthquakes. In fact, this is one of the special concerns in our study. In order to further verify this conclusion, we will carry out the extraction and analysis of pre-seismic precursor anomalies of the Mengyuan earthquake for the Mengyuan station in our follow-up study.

Comment 9

Line 140: When decomposing the borehole strain data, is there a risk that potential precursor signals might be lost or distorted in the process?

Response:

Thanks for your suggestion.

According to your proposal, we may have distorted precursor signals when disaggregating the borehole strain data, but did not lose potential precursor signals. In order to verify that we are not losing the potential precursor signals when decomposing the borehole strain data, we randomly selected the raw data of three anomalous days as shown in Fig. 1. It is clear in Fig. 1 that the anomalous days we defined exhibit short-period, high-frequency oscillatory signals in the raw waveforms, suggesting that these days are related to crustal activity. After we processed them using SVMD, we were still able to successfully extract these days as anomalous days. Therefore, it can be shown that our study did not lose the precursor signals when decomposing the borehole strain data. We may have distorted precursor signals when decomposing the borehole strain data. However, we studied the data from the perspective of amplitude and frequency, not from the perspective of data morphology. Therefore, the distortion of anomalous morphology will not affect the results of this study.

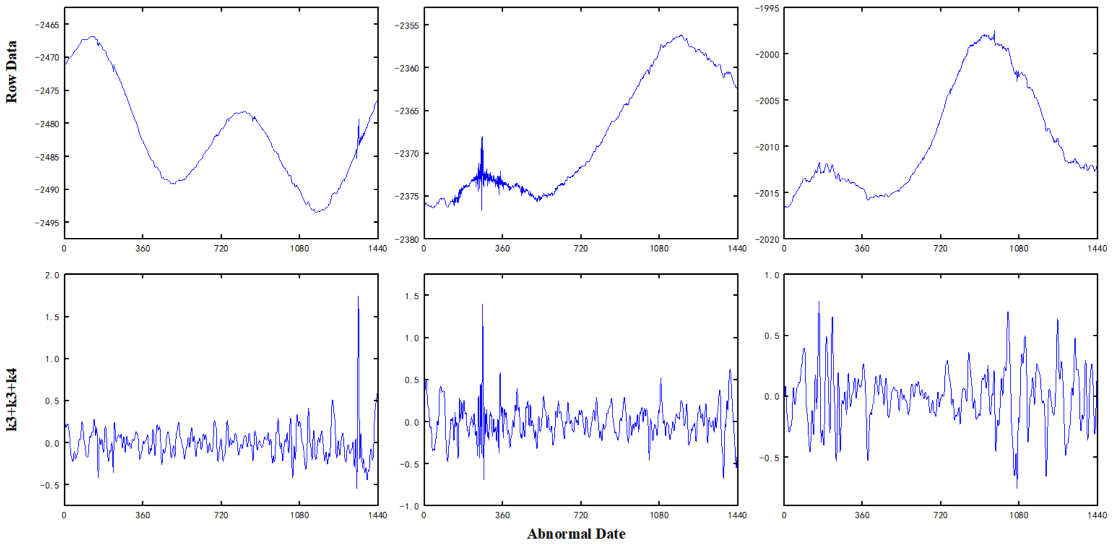


Figure 1. Plot of raw data for three randomly selected anomalous days.

Comment 10

Line 230: You use a 7-day sliding window with a 1-day step for anomaly detection. Please justify this choice and provide statistical or empirical evidence supporting the selected window size and step.

Response:

Thanks for your suggestion.

In the SVMD method, our criteria for selecting the sliding window size are based on the equipment capacity and the efficiency of data processing to start with, and the optimal window size is selected through experiments. Our preprocessed dataset is the borehole strain data recorded from January 1, 2020 to May 31, 2021 at the Mengyuan station. As shown in Table 2, we chose sliding window sizes of 7, 15 and 30 days, respectively, and the time and memory size needed for the calculation process are given in Table 2. The correlation between the data cannot be maintained if the sliding window is chosen too small. Whereas, a window that is too large significantly increases the memory consumption and computation time, resulting in the program not being able to be executed. Considering the time spent on the SVMD calculation process and the memory size of the computer. Therefore, we choose a parameter configuration with a window length of 7 days and a sliding step of 1 day. Running device name: DESKTOP-FPCL3PM; Running device version: Windows 11 Professional; Running device processor: 12th Gen Intel(R) Core(TM) i7-12700F 2.10 GHz.

Table 2. The experimental results of SVMD correspond to different sliding window sizes.

Window(day)	Time(second)	Memory(MB)
7Days	1.12	5.90
15Days	2.39	6.89
30Days	7.24	13.68

Comment 11

Line 334. The study uses strain data from January 2020 to May 2021. However, this relatively short time span may not sufficiently capture long-term pre-seismic cycles. Please discuss the temporal adequacy of the dataset.

Response:

Thanks for your suggestion.

In this study, we choose the borehole strain data from January 2020 to May 2021 at Menyuan station because the study of borehole strain data mainly focuses on short-term and near-seismic anomalies. Meanwhile, in order to show that our study focuses on short-term and near-seismic anomalies, we add the phrase “For short-term and proseismic anomaly extraction from borehole strain data.” in line 333 of the original manuscript.

In addition, it can be observed from Fig. 9 of the original manuscript that, compared with other anomalies, the anomalous range coverage of our extracted borehole strain data is more comprehensive, and at the same time, it can better reflect the anomalous characteristics of the short-term pre-earthquake and near-earthquake phases. Therefore, it shows that our selection of the borehole strain data from January 2020 to May 2021 for the study has a certain degree of temporal appropriateness.

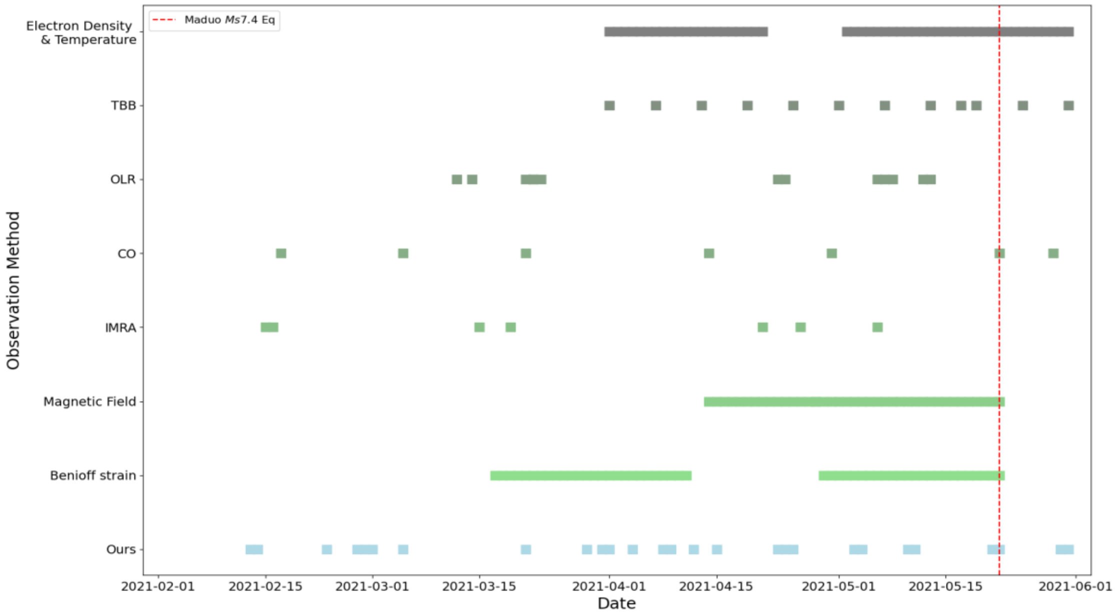


Figure 9 of the original manuscript. Summary of our study of borehole strain anomalies (light blue) versus subsurface-to-atmosphere anomalies (from light green to gray) for the Maduo Ms7.4 earthquake. The red dashed line indicates the date of the earthquake.

Comment 12

Line 340: Key model parameters (e.g., SVMD bandwidth = 2000, convergence threshold = 1e-7, Informer layers = 128) are presented without any sensitivity analysis. The authors should evaluate how parameter changes affect signal decomposition quality (e.g., signal-to-noise ratio). Additionally, please include uncertainty bounds in prediction intervals (e.g., in Figure 7) to better reflect model confidence and variability.

Response:

Thanks for your suggestion.

(1) Line 340: Key model parameters (e.g., SVMD bandwidth = 2000, convergence

threshold = 1e-7, Informer layers = 128) are presented without any sensitivity analysis. The authors should evaluate how parameter changes affect signal decomposition quality (e.g., signal-to-noise ratio).

The noise reduction function of SVMD is realized by applying Wiener filtering to remove Gaussian noise for each mode during the decomposition process. The parameter α controls the bandwidth of the Wiener filter, when the value of parameter α is larger, the Wiener filter will remove more noise, however, too large a value of parameter α will affect the convergence of the algorithm. On the contrary, if a smaller α is chosen, the algorithm will converge more easily, but more noise will remain (Wu et al., 2018). In SVMD decomposition, the value of the parameter α affects the accuracy of the decomposition and the length of the decomposition time, and too high a value of α can cause the program to enter a dead loop (Priyanka et al., 2015). The parameter α can be chosen manually based on numerical experiments, and in this paper, 2000 is chosen as the optimal value. Reducing the convergence tolerance parameter can make the algorithm converge to more accurate results, but it will also increase the computation time. Therefore,for comprehensive consideration we choose 1e-7.

In order to analyze the bandwidth of the appropriate SVMD decomposition, we choose one month's data from the Mengyuan station for the decomposition. The decomposition results are shown in Fig. 3, Fig. 4, and Fig. 5.

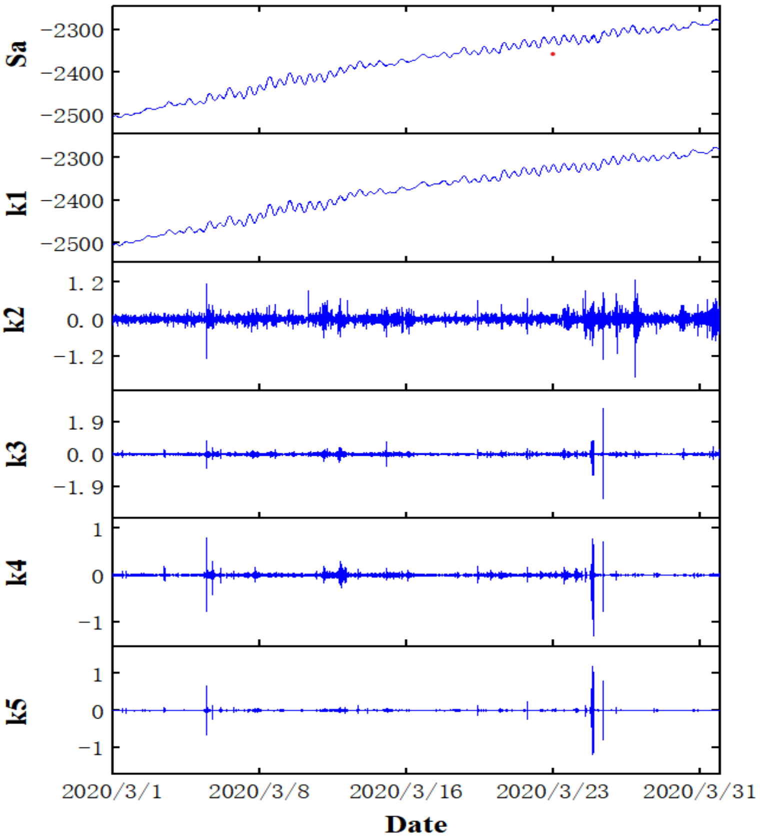


Fig.3. Decomposition results of SVMD with bandwidth equal to 100.

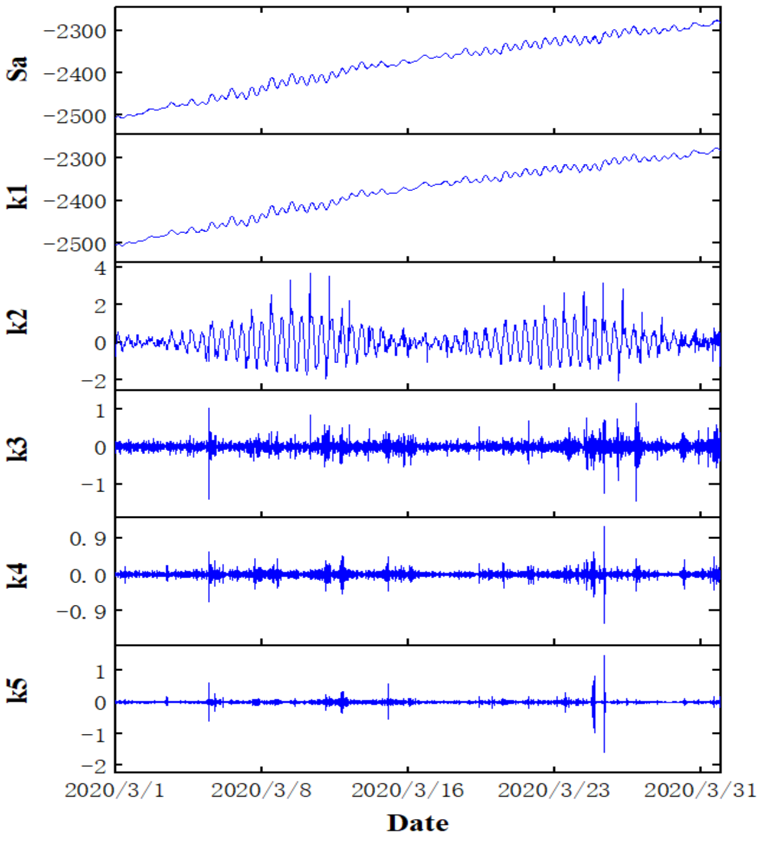


Fig.4. Decomposition results of SVMD with bandwidth equal to 1000.

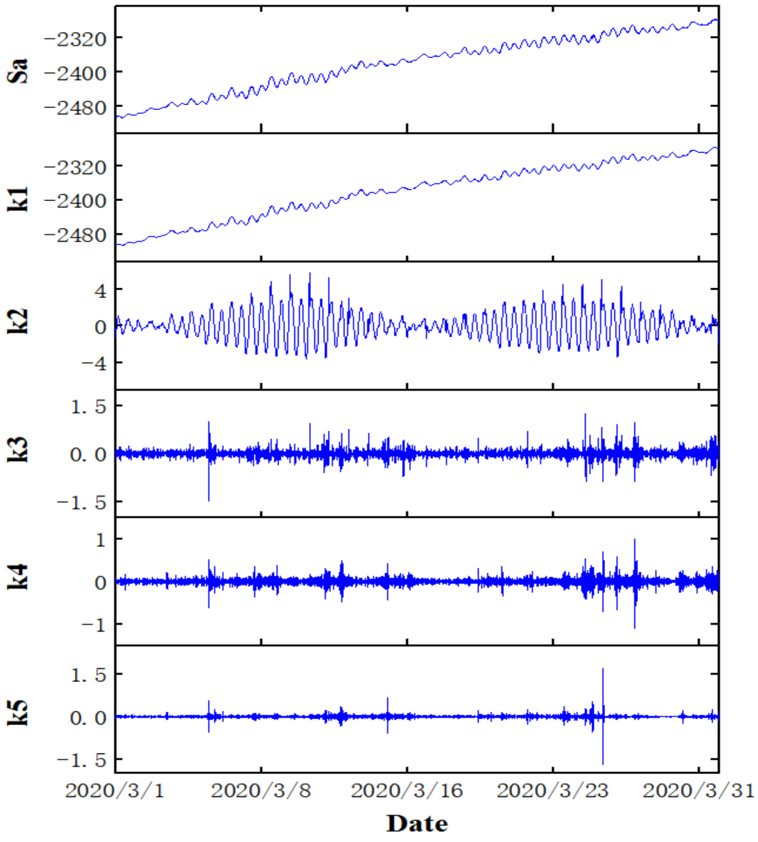


Fig.5. Decomposition results of SVMD with bandwidth equal to 2000.

From Figs. 3, 4, and 5 we can observe that in Figs. 3 and 4, when the bandwidth is small, the k1 layer contains significant periodic variations, resulting in a failure to separate the trend term from the solid tides. Therefore, we cannot choose a value with a small bandwidth. And when the bandwidth is large, it causes the program to enter a dead loop. Therefore, by manual selection, this study chooses the bandwidth equal to 2000 as the optimal value,as shown in Fig. 5.

In addition, for the selection of the dimensionality of the SVMD-informer model, we reduced the model fit by decreasing the number of layers of the model. As shown in Figs. 7 and 8, when the dimensionality of the model is too high, the SVMD-informer model outputs obvious overfitting between the predicted values and the real values, which leads to the inability to effectively extract the anomalous precursors before the earthquake. When the model dimension is too low, the model learns fewer features, resulting in a higher deviation between the predicted and real values, and the overall prediction performance decreases. We finally chose the number of model layers as 128 through a large number of experiments. As shown in Fig. 6, a model dimension of 128 layers can effectively reduce the fit between the predicted values and the true values output from the SVMD-informer model, and can successfully extract the pre-seismic anomaly precursors. In addition, moderately reducing the model dimension can also reduce the consumption of computational resources and improve the overall experimental efficiency.

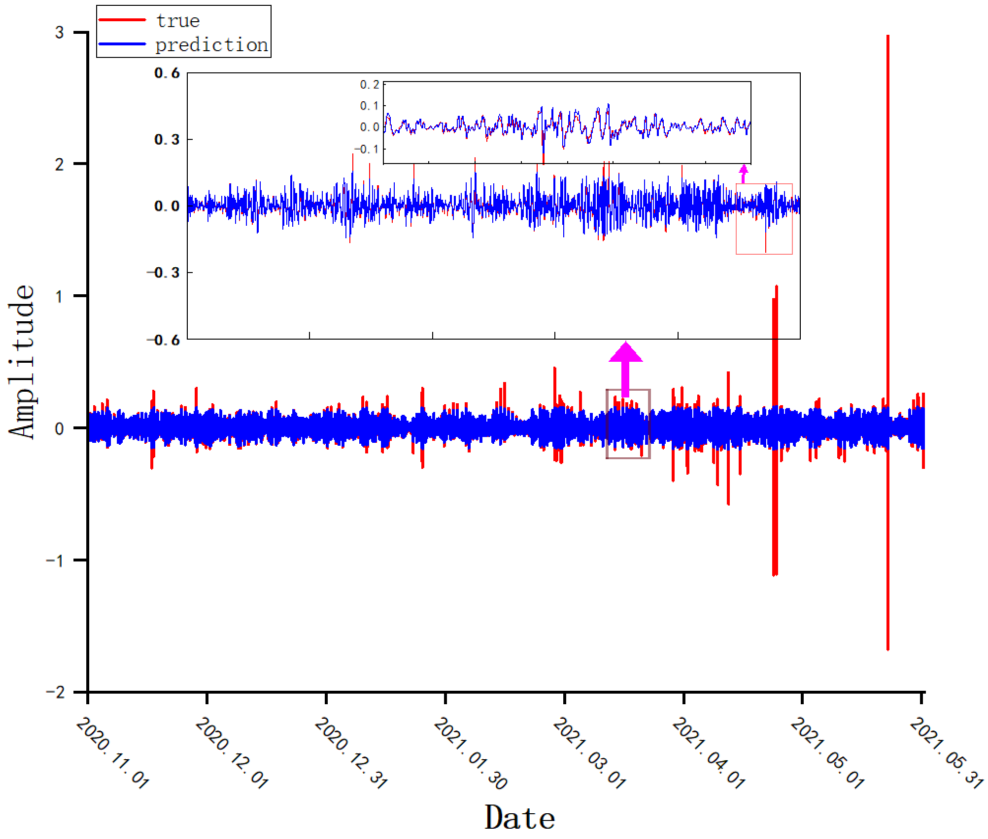


Figure 6. informer model with 128 layers.

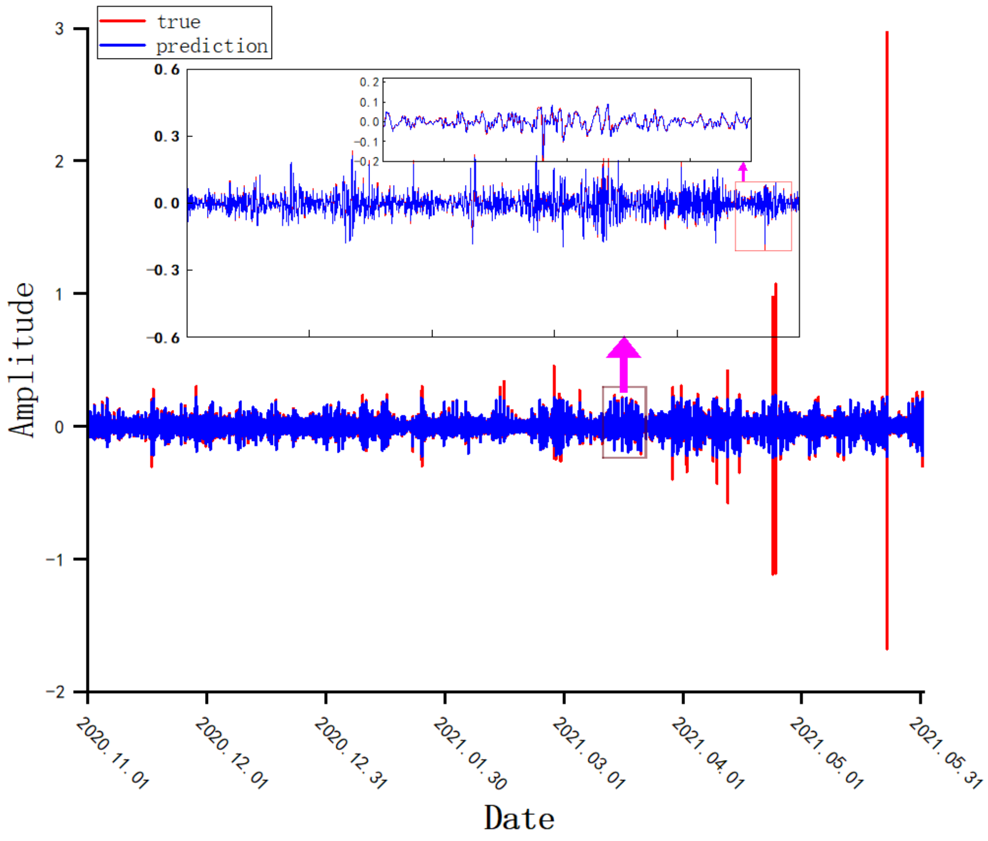


Figure 7. informer model with 256 layers.

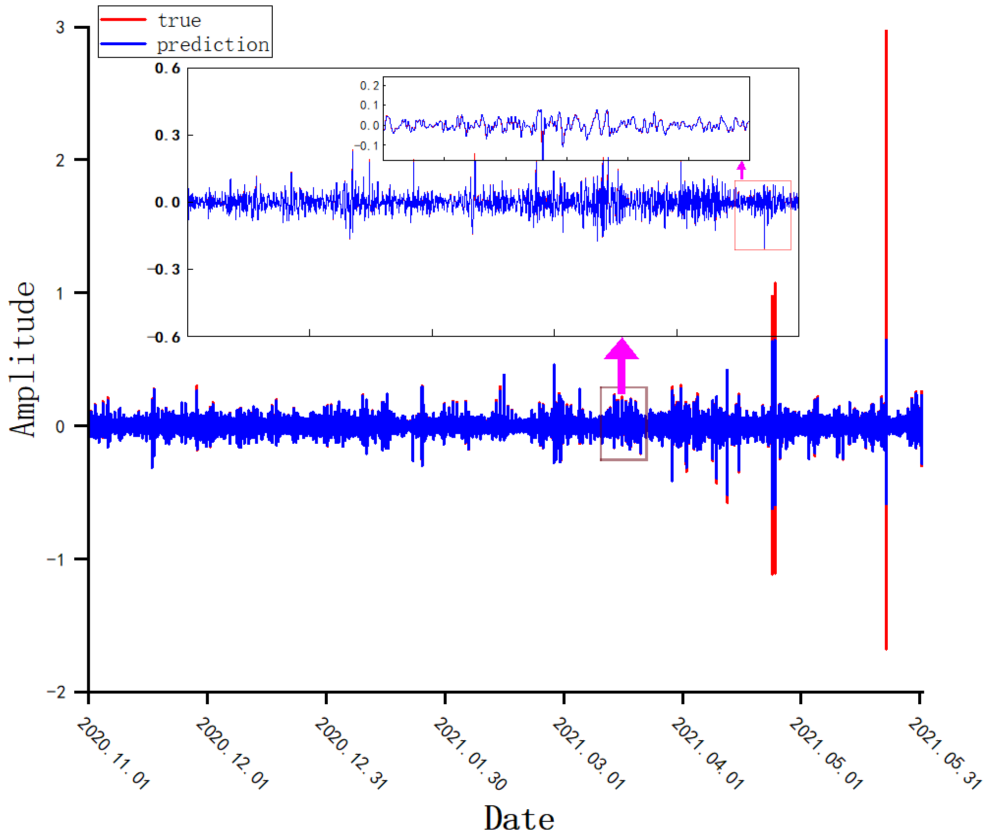


Figure 8. informer model with 512 layers.

(2) Additionally, please include uncertainty bounds in prediction intervals (e.g., in Figure 7) to better reflect model confidence and variability.

Regarding your question “please include uncertainty bounds in prediction intervals”, we have carefully considered and supplemented our analysis. Our SVMD-Informer model is determined by the upper and lower bounds of the prediction sequence output by the decoder, using the normal distribution method. The prediction interval of the network consists of the upper and lower bounds, and this prediction interval serves the same purpose as the confidence interval you mentioned. As you say, Figure 7 in the original manuscript does not indeed convey the reliability and variability of the results in a completely clear way, so we have supplemented it with statistics on daily anomaly rates. We did a count of the eligible judgment results for each day and used the statistical results as the number of anomalies for each day, and calculated the daily anomaly rate based on the number of anomalies for each day, as shown in Figure 9.

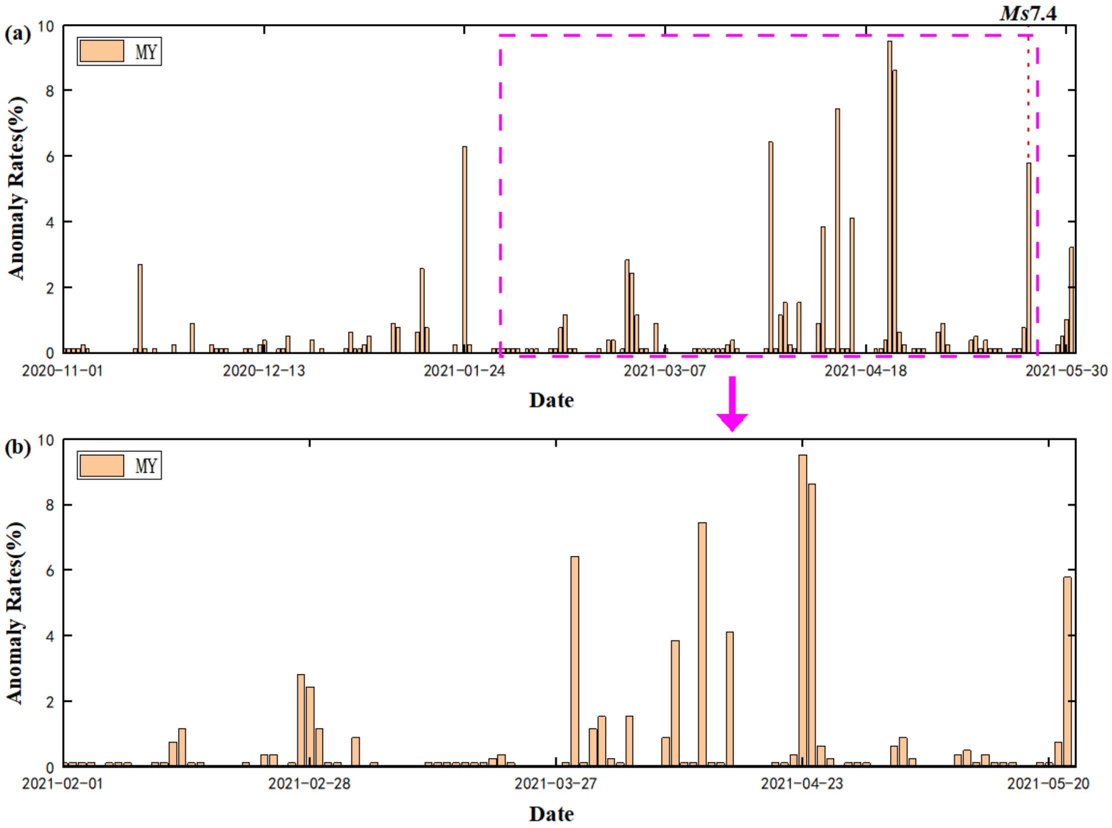
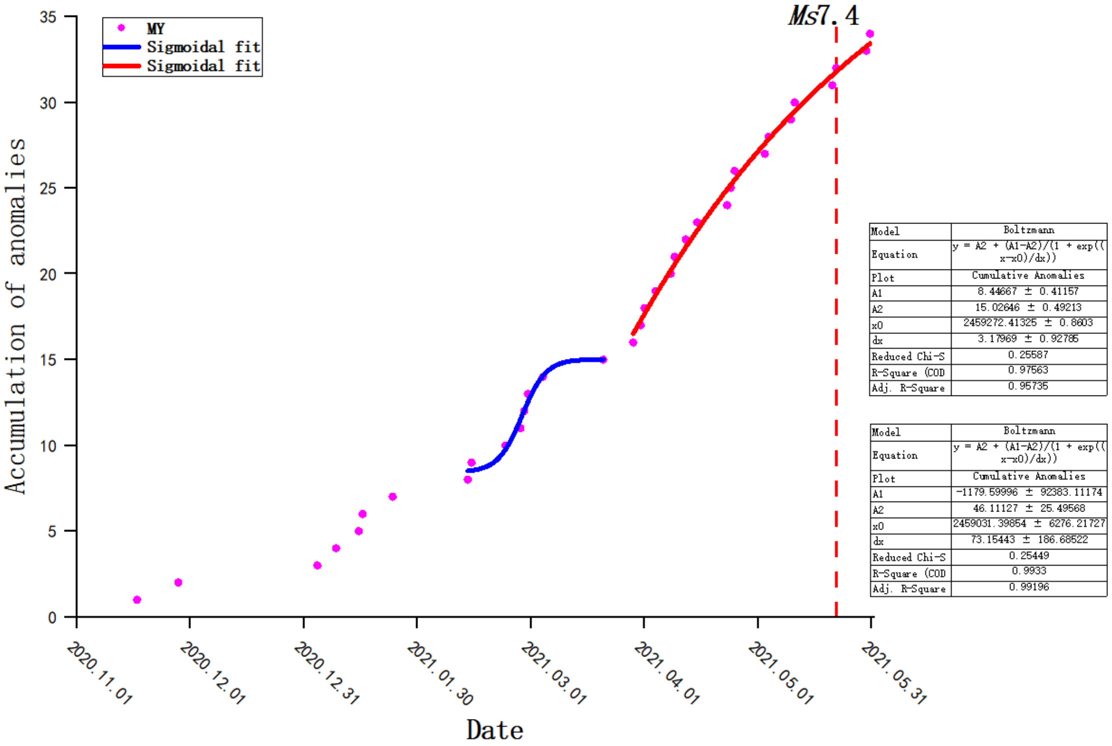


Fig. 9. Statistical results of daily anomaly rate at Mengyuan station. (a) Statistical results of daily anomaly rate from November 1, 2020 to May 31, 2021 . (b) Results of daily anomaly rate statistics from February 1, 2021 to May 22, 2021.

As shown in Figure 9(a), only a small number of phenomena meeting the criteria for anomalous days occurred between 7 months before the earthquake and 3 months before the earthquake, while from 3 months before the earthquake until the earthquake occurred, there was a significant increase in the number of anomalous phenomena. Figure 9(b) highlights the detailed changes from 3 months before the earthquake to the occurrence of the earthquake. We find that the daily anomaly rate increases from mid-February to mid-March. Similarly, the occurrence daily anomaly rate increases rapidly from the end of March to the time of the earthquake. These results corroborate with the

S-fit results in Fig. 8 of the original manuscript and provide a more complete picture of the process of anomaly changes before the earthquake. Thus, it can better reflect the confidence and variability of our model.



Model	Boltzmann
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))
Plot	Cumulative Anomalies
A1	8.44667 ± 0.41157
A2	15.02646 ± 0.49213
x0	2459272.41325 ± 0.8603
dx	3.17969 ± 0.92785
Reduced Chi-S	0.25587
R-Square (COD	0.97563
Adj. R-Square	0.95735

Model	Boltzmann
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))
Plot	Cumulative Anomalies
A1	-1179.59996 ± 92383.11174
A2	46.11127 ± 25.49568
x0	2459031.39854 ± 6276.21727
dx	73.15443 ± 186.68522
Reduced Chi-S	0.25449
R-Square (COD	0.9933
Adj. R-Square	0.99196

Figure 8 of the original manuscript. Cumulative results of anomalous days of borehole data at Mengyuan station (MY). The red dashed line indicates the date of the earthquake, and the blue and red curves indicate the results of the S-fit function for the first and second phases, respectively.

Comment 13

Line 340: The patterns shown appear more indicative of the coseismic effects of the Maduo earthquake, rather than its precursors. Please consider adding information in Figure 6 to clarify and support the presence of pre-seismic signals.

Response:

Thanks for your suggestion.

In response to your comments, and in order to clarify and support the existence of a pre-seismic signal, we have added more detailed information to Figure 6 of the original manuscript. As shown in Figure 6 of the original manuscript, k1 indicates the trend, k2 indicates the solid tide, and k3+k4+k5 indicate the strain associated with the earthquake. From the figure, we can clearly see that the anomalies in the borehole strain data at the Menyuan station before the earthquake are more likely to be precursor signals of the Maduo earthquake rather than co-seismic effects of the Maduo earthquake.

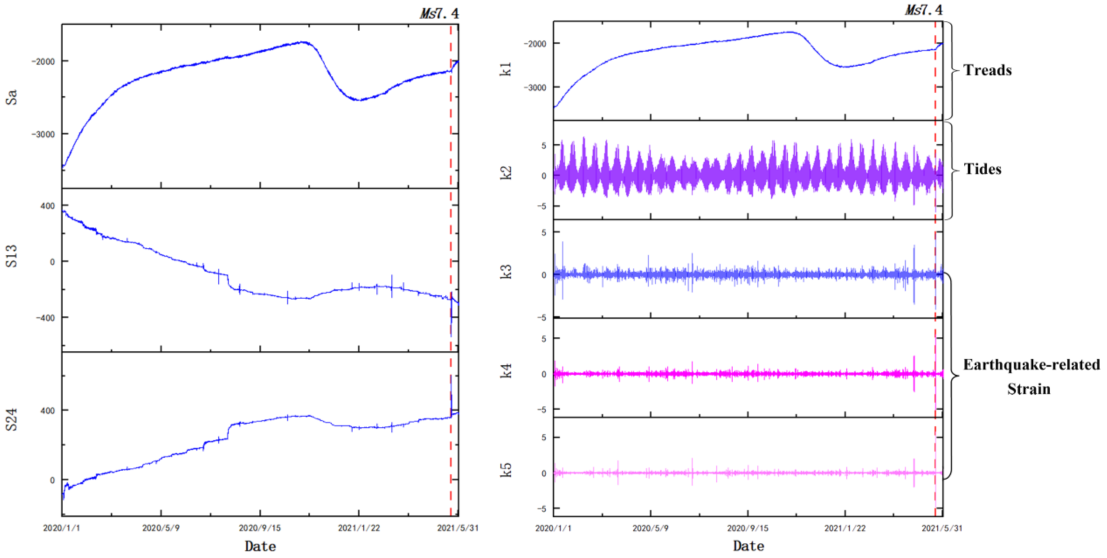


Figure 6 of the original manuscript. Data for S_a,S_{13},S_{24} at the Mengyuan station and the results of the SVMD decomposition of S_a. k1 denotes the trend term, k2 denotes the earth tides, and k3, k4, and k5 denote the strains associated with the earthquakes. The red dashed line indicates the date of the earthquake.

Comment 14

Line 380: The two-stage S-shaped anomaly accumulation (Figure 8) is interesting, but no underlying mechanism is provided. Moreover, the upward trend of pre-seismic acceleration could plausibly be associated with the Menyuan earthquake in January 2022 instead of the Maduo event.

Response:

Thanks for your suggestion.

In response to your suggestion, we have revised lines 400-404 of the original manuscript to better clarify the mechanism behind the two-stage S-type anomaly accumulation by revising it to read, “In addition, the two-stage accelerated growth of the borehole strain accumulation results may reveal two preparatory mechanisms prior to the mainshock. This is consistent with the theory of fault synergistic process of (Ma et al., 2014). They found that the occurrence of earthquakes is closely related to the three-stage synergistic evolution of faults through an indoor experimental study of plane-walk-slip faults. In the first stage, the initial stress nonlinear divergence leads to localized weakening and the formation of discrete strain release zones. The second stage is characterized by an increase in stress and a widening of the strain release zone. In the final stage, the expansion of the strain-release region and the rapid increase in the strain level in the strain-accumulation region. The anomalous cumulative acceleration about 3 months before the Maduo earthquake corresponds to the first and second stages in the theory, which is manifested by the deviation of the stress curve from linearity and the beginning of the formation and slow expansion of the discrete release zone. The acceleration 2 months before the earthquake reflects the characteristic changes of the third stage, which is characterized by the accelerated expansion of the release zone and the sharp increase of the strain in the accumulation zone. Therefore, we believe that the anomalies observed before the Maduo earthquake are related to the process of earthquake incubation.". By modifying this paragraph we explain in detail the mechanism behind the two-stage S-type anomaly accumulation. Therefore, we conclude that the accelerated rise of the two-stage S-type anomaly accumulation in this study is related to the Maduo earthquake rather than the Mengyuan earthquake.

Comment 15

Line 415: The study references various anomalies (CO, TBB, electron density), but does not sufficiently address the possibility of false positives caused by anthropogenic or environmental factors. Please discuss the limitations of borehole strain data, including potential sensitivity to non-tectonic influences such as groundwater fluctuations or temperature changes.

Response:

Thanks for your suggestion.

(1) Line 415: The study references various anomalies (CO, TBB, electron density), but does not sufficiently address the possibility of false positives caused by anthropogenic or environmental factors.

Based on your comments, we will discuss whether external influences may have an effect on other anomalies. (Shi et al., 2024) showed that the epicenter of the Maduo earthquake was far away from the industrial and densely populated areas, the CO was little influenced by human factors, and the atmospheric background concentration of CO was more stable, which could well reflect the characteristics of the local environmental changes, and it was a good case to study the relationship between seismic activities and gas anomalies. Meanwhile, they analyzed the April CO data from 2014-2022 at the epicenter. The results showed that the CO concentration in April 2021 was significantly higher than the levels in the same period of other years, and the peak occurred on April 30th. Similar anomalies were only observed during the same period in 2015 and 2016, which corresponded to the previous Ms4.1 earthquake. This suggests that the CO anomaly in 2021 is more likely to originate from seismic activity rather than seasonal factors. (Yang et al., 2024) systematically excluded environmental interference such as meteorological factors, diurnal variations and earth rotation by combining wavelet transform and Fourier transform to ensure the specificity of TBB anomaly signals. Specifically, the db8 wavelet base is used to filter out high and low frequency interferences and retain the effective signal in the middle frequency. Meanwhile, effects such as solar radiation are further circumvented by night-time data selection and power spectrum analysis, thus effectively distinguishing seismic-related anomalies from environmental noise. In addition, (Tian et al., 2023) used the Improved Pattern Informatics (IPI) method to effectively reduce the interference of anthropogenic and environmental factors through multiple technical means. Firstly, an adaptive background trend removal algorithm is utilized to eliminate systematic biases caused by long-term space weather activities such as solar radiation and geomagnetic storms, while space weather parameters such as the Kp index and the Dst index are combined for simultaneous screening in order to exclude anomalous data during magnetic disturbances. Finally, the influence of environmental noise such as short-term atmospheric gravity waves is suppressed by statistical normalization of sliding time windows, and continuous anomalies with seismic correlation are effectively distinguished from transient disturbances with the help of cross-validation of diurnal and nocturnal orbital data. Therefore, all of the above researchers have excluded the influence of anthropogenic or environmental factors on the anomalies they extracted.

(2)Please discuss the limitations of borehole strain data, including potential sensitivity to non-tectonic influences such as groundwater fluctuations or temperature changes.

Borehole strain monitoring is a technical means of recording rock or crustal deformation by installing strain sensors deep underground. This monitoring method can accurately capture the crustal microstrain induced by plate tectonic movement or seismic activity, and provide an important basis for studying the dynamics of the regional tectonic stress field. Strain data are usually particularly sensitive to changes in geostress caused by fault activity, and can provide valuable information for the extraction of earthquake precursors and the study of seismicity mechanisms.

At the same time, we fully agree that borehole strain data, while highly sensitive to tectonic deformation, can also be affected by non-tectonic environmental factors or human interference. Borehole strain gauges are susceptible to factors such as instrument drift, solid tide, temperature, barometric pressure and rainfall. Without adequate preprocessing, they may be mistaken for tectonic strain signals. In the data preprocessing, we adopted the Segmented Variational Modal Decomposition (SVMD) method, which effectively strips out low-frequency components such as annual cycle and solid tide. Meanwhile, I added the analysis for temperature, barometric pressure and rainfall data for the study time range, as shown in Fig. 10.

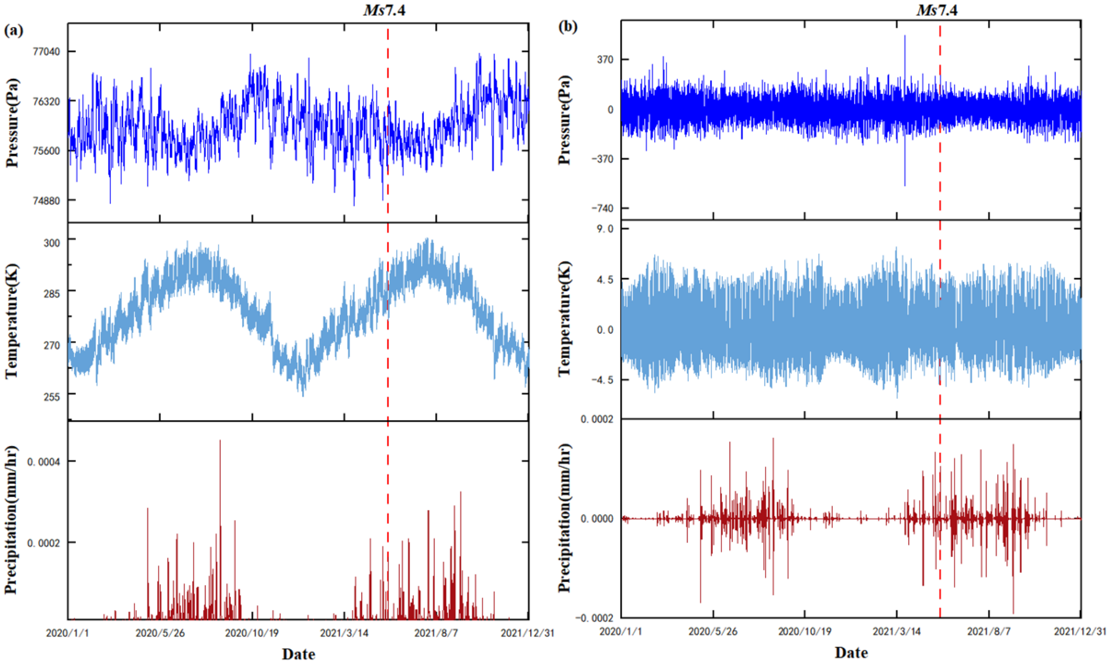


Figure 10. (a) Three-hourly regional variations of barometric pressure, temperature and precipitation in the Mengyuan area during the period from January 1, 2020 to May 31, 2021. (b) Differential processing results of three-hourly regional variations of barometric pressure, air temperature and precipitation in Mengyuan area during the period from January 1, 2020 to May 31, 2021.

In Fig. 10(a), we analyze the three-hourly regional variations of barometric pressure, temperature, and rainfall in the Mengyuan area (35.97 to 39.97°N, 99.4 to 103.4°E) from NASA's Giovanni-4 platform (https://giovanni.gsfc.nasa.gov/giovanni, last accessed May 9, 2025) , with a time frame of January 1, 2020 to December 31, 2021. The results show that the barometric pressure and air temperature fluctuate inversely within a certain range, while the rainfall gradually decreases year by year after peaking in summer, reflecting a significant annual cycle. In addition, in order to minimize the influence of external factors on the borehole strain data, we carried out differential processing on the three-hourly regional averages of barometric pressure, air temperature and rainfall in Mengyuan area. Differential processing was utilized to remove the effect of cyclic variations, thereby highlighting anomalies in the data. The results of the processing are shown in Fig. 10(b), which shows that there are no anomalous changes in the three-hourly regional averages of barometric pressure and air temperature and rainfall in Mengyuan. We exclude the influence of temperature, barometric pressure and rainfall on the anomalies observed in the pre-earthquake borehole data from Maduo. Therefore, we have reason to believe that the anomalies we extracted before the Maduo earthquake are related to the earthquake genesis process. Also add in line 426 of the original manuscript " Although borehole strain monitoring techniques are capable of accurately capturing crustal microstrain induced by plate tectonic movements or seismic activity, they are susceptible to factors such as temperature, air pressure, and rainfall. For this purpose we analyzed regional three-hourly variations of barometric pressure, air temperature and rainfall in the Mengyuan area (35.97 to 39.97°N, 99.4 to 103.4°E) from NASA's Giovanni-4 platform (https://giovanni.gsfc.nasa.gov/giovanni, last accessed May 9, 2025) , with a time frame of January 1, 2020 to December 31, 2021. In Fig. 10(a), the barometric pressure and air temperature fluctuate inversely within a certain range, while the rainfall gradually decreases year by year after peaking in summer, reflecting a significant annual cyclicity. In addition, in order to minimize the influence of external factors on the borehole strain data, we performed differential processing on the three-hourly regional averages of barometric pressure, air temperature, and rainfall in the Mengyuan area. Differential processing was utilized to remove the effect of cyclic variations, thereby highlighting anomalies in the data. The results of the processing are shown in Fig. 10(b), which shows that the three-hourly regional means of barometric pressure, air temperature, and rainfall in Mengyuan do not show any anomalous changes. We exclude the influence of barometric pressure, air temperature and rainfall on the anomalies observed in the pre-earthquake borehole data from Maduo. Therefore, we have reason to believe that the anomalies we extracted before the Maduo earthquake are related to the earthquake genesis process.".

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