

The Lithosphere-Atmosphere-Ionosphere coupling (LAIC) processes around the 2024 Wushi (China) M_w 7.1 earthquake

Xuemin Zhang^a, Angelo De Santis^{b,*}, Pan Xiong^a, Gianfranco Cianchini^b, Aisa Yisimayili^c, Saioa A. Campuzano^{b,f}, Na Yang^a, Serena D'Arcangelo^b, Jing Liu^a, Mariagrazia De Caro^b, Xinyan Li^d, Cristiano Fidani^b, Muping Yang^e, Martina Orlando^{b,g}, Xinyan Ouyang^a, Loredana Perrone^b, Hong Liu^a, Dario Sabbagh^b, Maoning Feng^a, Maurizio Soldani^b, Shukai Wang^a

^a Institute of Earthquake Forecasting, China Earthquake Administration, 100036 Beijing, China

^b Istituto Nazionale di Geofisica e Vulcanologia, 00143 Rome, Italy

^c Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, China

^d Earthquake Agency of Ningxia Hui Autonomous Region, 750001 Yinchuan, China

^e Liaoning Earthquake Agency, 110031 Shenyang, China

^f Department of Physics of the Earth and Astrophysics, Universidad Complutense de Madrid (UCM), 28040 Madrid, Spain

^g Dipartimento di Scienze, Università Roma TRE, 0154 Rome, Italy

ARTICLE INFO

Keywords:

Earthquake precursors

LAIC

Swarm satellites

CSES

ABSTRACT

This paper presents a comprehensive analysis on multiple parameters in the lithosphere, atmosphere and ionosphere, around the Wushi M_w 7.1 earthquake that occurred on 22 January 2024, in Xinjiang, China. Typical perturbations were picked up with different methods, with a limited time period for lithospheric parameters of longer than 3 years, 90 days before and 10 days after for most atmospheric and ionospheric parameters, in a limited distance within Dobrovolsky's area of about 1000 km. All the results show that about 60 anomalies were detected before the Wushi earthquake, with medium-term ones lasting about 1 year in the lithosphere, and short-term ones within 3 months in the atmosphere and ionosphere, where the outgoing long wave radiation covered the earthquake occurrence time from four days before to four days after, considered an imminent indicator. The thrust focal mechanism of this earthquake helps to explain the anisotropic feature in Earth's resistivity and orientation in the electric field, and also the weak variations in the b -value. By combining ground-based and spaceborne observations, a few parameters clearly illustrated the approaching earthquake location, which makes a certain contribution to future earthquake prediction. The accumulating rate of all the anomalies exhibited a fast exponential trend, which illustrates both direct and indirect lithosphere-atmosphere-ionosphere coupling mechanisms during the preparation stage of the Wushi earthquake.

1. Introduction

To illustrate the relationship among different anomalies in the lithosphere, atmosphere, and ionosphere, and their association with strong earthquakes, scientists have paid more and more attention to the lithosphere-atmosphere-ionosphere coupling (LAIC) processes. Three channels of coupling mechanisms have been proposed by Hayakawa (2004), including a chemical channel (also named the electric field coupling channel), an Acoustic Gravity Wave (AGW) channel, and an electromagnetic (EM) wave channel. The LAIC model was then detailed

by some fundamental works (Pulinets and Ouzounov, 2011; Freund, 2011), and validated by comprehensive analysis of multi parameters, especially those in ionosphere and atmosphere (Yang et al., 2019; Piersanti et al., 2020; Xie et al., 2021; De Santis et al., 2022). Due to the complex coupling processes among different layers and the lack of observations of some key parameters, it is often found that more than one channel acts together at the same time (Zhang et al., 2024), and sometimes it is hard to determine which one is dominant (Hayakawa et al., 2024). In our previous research, we divided the LAIC processes into two categories. Only the EM channel can be defined as a direct path, while,

* Corresponding author.

E-mail address: angelo.desantis@ingv.it (A.D. Santis).

<https://doi.org/10.1016/j.jseas.2025.106916>

Received 11 April 2025; Received in revised form 31 October 2025; Accepted 15 December 2025

Available online 16 December 2025

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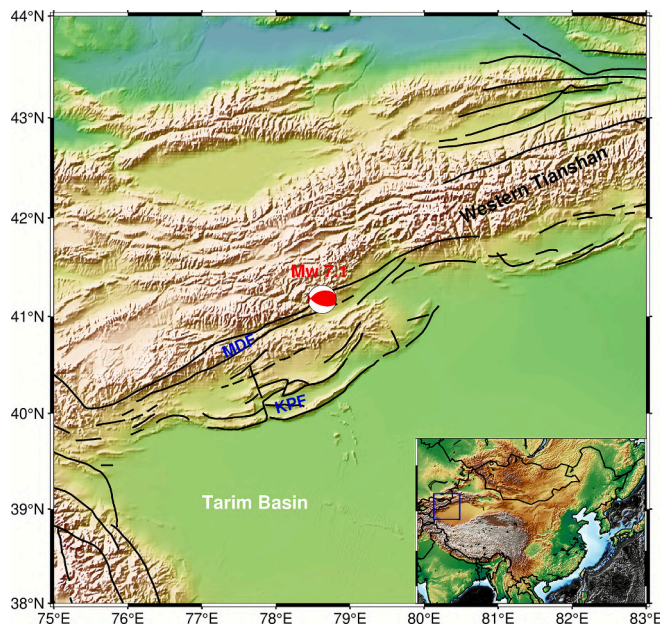


Fig. 1. Tectonic settings of the 2024 M_w 7.1 Wushi EQ. The focal mechanism solution for the 2024 Wushi EQ is represented by a red beachball. Major faults are depicted as black thick lines: MDF: Maidan fault; KPF: Keping fault.

the chemical and AGW channels require energy transfer and exchange with the atmosphere, ultimately causing disturbances in the ionosphere. Therefore, both are defined as indirect or delayed paths in LAIC (Zhang et al., 2024).

On January 23, 2024, at 02:09 BJT, (i.e. January 22, 2024, at 18:09 UT) an earthquake (EQ) with a magnitude of 7.1 occurred in Wushi, China, at 78.62°E and 41.26°N, with a focal depth of 22 km (Qiu et al., 2024). According to the Centroid Moment Tensor (CMT) products provided by USGS, the focal mechanism was predominantly thrust with a slight strike-slip, with nodal planes of 235°/45°/42° and 113°/62°/126° (<https://earthquake.usgs.gov/earthquakes/eventpage/us7000lsze/moment-tensor>).

The 2024 Wushi EQ took place at the junction between the southern Tianshan Mountains and the Wushi Basin, where the Tarim and southern Tianshan blocks converge (Guo et al. 2024; Fig. 1). Focal mechanism solutions indicate a thrust-dominated rupture, likely on a blind fault to the Holocene-active Maidan fault, which accommodates both compression and strike-slip movement along the Tianshan–Tarim boundary (Wang et al., 2000; Zubovich et al., 2010; Wang and Shen, 2020). InSAR observations (Qiu et al., 2024) reveal coseismic deformation consistent with reverse faulting, reflecting crustal shortening within the thick-skinned tectonics of the southern Tianshan.

The medium and short term predictions were made before the Wushi EQ, Song et al. (2024) summarized the prediction process and collected all the precursors including seismic quietness, banding, enhancement, high frequency events, b-value changes and source consistency for long, medium and short-term indicators, and geophysical anomalies such as ground tilt, gravitational changes, elevated fault gas radon levels, bedrock temperature variations, and geomagnetic shifts for medium and short term indicators. However no macroscopic anomalies were detected before the EQ, but unusual animal behaviors were recorded afterward. The geophysical precursors showed a spatial development pattern, from regional anomalies and then converge toward the epicenter in the short-term stage (Song et al., 2024). Zhu et al. (2024) studied the deformation features by using the GNSS baseline series and regional strain results, and they found differences between the east and west segments along the Maidan fault (MDF in Fig. 1), where the compressional slip rate was 4.1 ± 0.51 mm/a in the east and 1.0 ± 0.35 mm/a in the west. The EQ occurred at the boundary of a high-strain area

in the eastern part.

Zheng et al. (2024) examined the Wushi EQ using geodetic data to analyse the EQ's characteristics and its implications for regional tectonics. A geodetic model was also proposed by Famiglietti et al. (2025). Regarding some clear coseismic effects, Xu and Li (2024) showed some examples of coseismic landslides triggered by the EQ, providing valuable information for understanding the geological hazard associated with the EQ.

In addition, some studies about the preseismic phenomena have also been performed. In particular, Chen et al. (2024) analyzed disturbances in the ionosphere and atmosphere, contributing to understand EQ precursors. Wang et al. (2024) provided a comprehensive map of inter-seismic coupling distribution along the Maidan Fault before the Wushi EQ. Their research identified four distinct segments with varying coupling characteristics, offering insights into seismic hazard assessments in the region.

In this paper, observations from the lithosphere, atmosphere and ionosphere are analyzed, with a particular focus on EM parameters, for a further understanding of the LAIC processes around the Wushi EQ.

2. Data source

For the study of LAIC processes, specific datasets are required to validate the different channels. The whole data flow is presented in Fig. A1. When considering the standardization of different parameters, the spatial scale is constrained using the equation of $\rho = 10^{0.43M}$ (Dobrovolsky et al., 1979), which relates the strain radius ρ in km of a supposed circular EQ preparation region to magnitude M . The time period of analysis extends up to 90 days before the earthquake for most parameters.

2.1. Lithospheric data

Since the 1966 M_w 6.8 Xingtai earthquake, the Chinese government has focused on EQ monitoring and research. The China Earthquake Administration (CEA) has continuously expanded the Seismic Network and Precursor Monitoring Network across the mainland, with some stations operating for more than 40 years. In the Precursor Monitoring Network, EM technologies have been widely used, and multiple parameters have shown significant anomalies before some strong earthquakes, including earth resistivity, geomagnetic field, EM emissions, geoelectric field observations, etc. The EM method is considered one of the most promising geophysical techniques for a breakthrough in short-term and imminent earthquake prediction (Johnston and Uyeda, 1999; Bleier and Freund, 2005; Zhao et al., 2022), especially in research on LAIC processes. In the Xinjiang region, the station distribution is not very dense due to the low population density in this area. Near the Wushi EQ, several stations were installed: one for measuring Earth resistivity, four for recording the geomagnetic field, and three for monitoring the geoelectric field. All corresponding data were collected. Given the sensitivity of lithospheric parameters to underground stress variations, data from more than one year were analyzed to demonstrate the long-term evolution trend.

2.2. Atmospheric data

In the LAIC model concept, some atmospheric variables play an important role in the coupling processes and energy transfer and exchange during the earthquake preparation phase. To link lithospheric and ionospheric variations, atmospheric parameters were also analyzed in relation to the Wushi EQ.

The European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis v5 (ERA5) dataset provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. We focused on physical variables related to the thermal radiative interaction between the atmosphere and the surface, such as skin temperature (SKT)

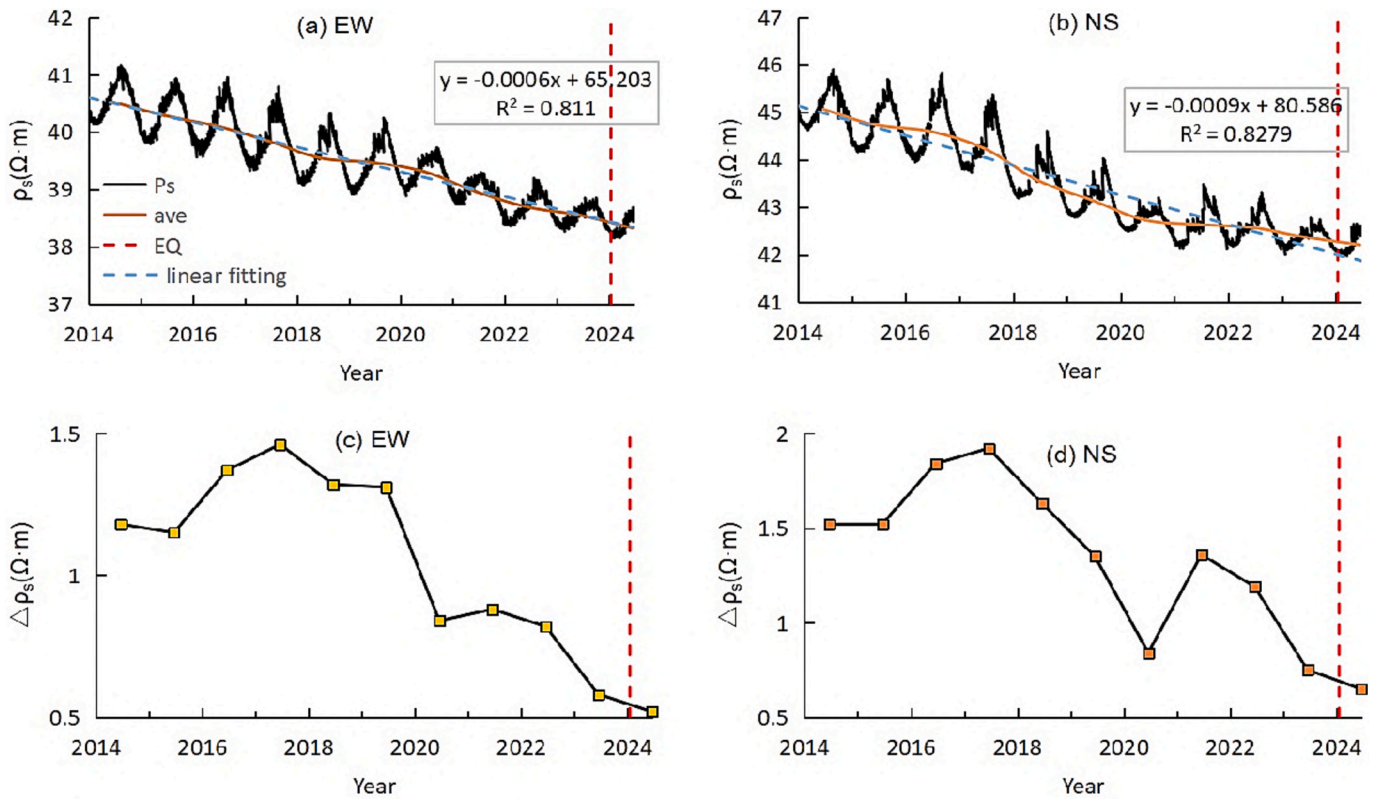


Fig. 2. The time series of Earth resistivity at Keping station during 2014 to 2024: (a) east–west direction; (b) north–south direction; (c) annual variation in the EW direction; (d) annual variation in the NS direction; the red vertical dashed line represents the date of the Wushi EQ.

and Outgoing Longwave Radiation (OLR). In our case, we limited the analysis to the epicentral region of the Wushi EQ, defined according to the Dobrovolsky strain radius (Dobrovolsky et al., 1979).

OLR data, specifically the Climate Prediction Center (CPC) daily blended product at a $1^\circ \times 1^\circ$ spatial resolution with daily averages, were utilized in this study for analysis (Gruber and Krueger, 1984). OLR refers to the energy density of EM waves emitted by the Earth-atmosphere system into outer space, measured in W/m^2 . It represents the radiation change of the entire Earth-atmosphere system, including the radiative information of the cloud top, surface, and the atmosphere above it.

2.3. Ionospheric data

The ionosphere can be monitored by multiple ground-based and space-borne technologies. On the ground, the ionosonde, an HF radar measuring the travel time of vertically transmitted signals at increasing frequency until reflection from the ionosphere and back, can detect various ionospheric parameters, e.g. the critical frequency of the F2 layer (f_oF_2), and information about the sporadic E (Es) layer, such as its critical frequency f_oE_s and virtual height $h'E_s$. The Total Electron Content (TEC), representing the integral of electron density (Ne) over a cylindrical path of 1 m^2 cross-section, can be obtained from Global Navigation Satellite System (GNSS) satellite signals recorded by the ground receivers. In mainland China, about 260 continuous Global Positioning System (GPS) and 170 GNSS receivers have been set up to monitor the crustal deformation, which can be used to obtain the TEC time series for each station. In addition, to analyze the spatial characteristics, especially local distribution and conjugate features, Global Ionospheric Map (GIM) TEC data can also be used in EQ studies (Le et al., 2011). These data, published by CODE, provide a high temporal resolution of 1 h and a spatial resolution of $2.5^\circ \times 5^\circ$ in latitude and longitude (<https://ftp.aiub.unibe.ch/CODE/>).

In general, satellites at Low Earth Orbit (LEO) can detect in-situ

plasma parameters and the EM field. The three Swarm satellites (Alpha, Bravo, and Charlie) have been operated since November 2013 by the European Space Agency (ESA), with data available on the magnetic field, Ne and electron temperature (Te), TEC, and other parameters (<https://swarm-diss.esa.int/>). The CSES-01 satellite (also known as ZH-1; data are published at <https://leos.ac.cn/#/dataService/dataBrowsingList> after registration) was launched in 2018, with eight payloads onboard, including: EFD to detect the electric field from DC to 3.5 MHz, HPM and SCM for the magnetic field, LAP to measure Ne and Te, PAP for ions (Ni, Ti, Vi, etc.), HEPP and HEPD for energetic particles, GOR and TBB to detect TEC and Ne profiles (Shen et al., 2018). Thus, multiple satellite-derived parameters can be used to study the Wushi EQ.

The ionospheric parameters are easily affected by space weather. In order to remove the disturbed days, Fig. A2 shows K_p , A_p and Dst indices within 90 days before and 10 days after the Wushi EQ during November 24, 2023 to February 1, 2024. When $K_p > 3$, $A_p > 20$ or $Dst < -30$, it means that day being disturbed. Also in the following analysis, these parameters are plotted together with a few parameters to compare with each other.

3. Analysis methods and results

3.1. Ground data analysis

3.1.1. Earth resistivity

In China, earth resistivity is always detected with two Schlumberger monitoring arrays along two perpendicular directions at a typical geoelectric station. In general, most stations observe seasonal variations, with valleys in the wet summer months (July–September) and peaks in the dry winter months (December–March) due to meteorological and hydrological factors. However, some stations exhibit the opposite pattern, showing high resistivity in the wet season. Lu et al. (2004) studied this characteristic at the Pixian station near the 2008 Wenchuan

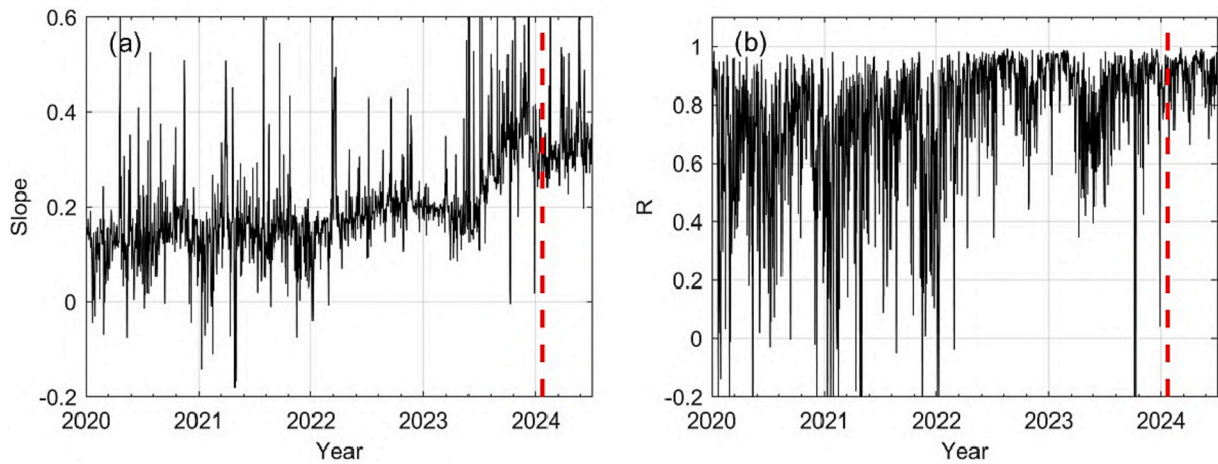


Fig. 3. The electric field direction (a) and coefficient (b) between EW and NS directions at Wenquan station.

EQ epicenter, and they found that Pixian is a multilayered Earth structure with a conductive substratum. Its first-order sensitivity coefficient is negative with respect to the surface layer, so seasonal rainfall variation causes an increase in apparent resistivity. Fig. 2 shows the time series of earth resistivity at Keping station, located 80 km from the Wushi epicenter. At Keping station, the power supply pole distance in the EW direction is 1,007 m, while 1,004 m in the NS direction. The observing pole distance is 300 m. It is clear that the earth resistivity at Keping exhibits regular seasonal variation, with higher values in summer and lower values in winter, which is similar to the pattern observed at Pixian station (Lu et al., 2004). From more than 10 years of data at Keping station, the resistivity shows a long-term decreasing trend, and the correlation coefficient from a linear fitting is larger than 0.9 in both directions. After removing the long-term decreasing trend by using an annual moving average, the seasonal variation amplitudes were calculated by subtracting the minimum value in winter from the maximum one in summer in each year (Figs. 2c and 2d), and the results showed the first sharp decrease in 2020 (about 4 years before the Wushi EQ) and the second decrease in 2023 (1 year before the Wushi EQ). This indicates two stress loading processes before the Wushi EQ. From Figs. 2b and 2d (Fig. 2), we can see that the peak resistivity value in the NS direction was reduced by half in 2020 compared to 2019. However, in 2021 and 2022, it recovered to the 2019 level. In 2023, the peak resistivity decreased again. Thus, in the epicentral area, the resistivity showed a long term accelerating decline over 4 years, and a mid-term acceleration within 1 year before the EQ.

3.1.2. Ground-based geoelectric field

The geoelectric field is detected by $E = \frac{\Delta V}{d}$, where ΔV is the potential difference between two electrodes, and d is the distance between them (either 300 m or 150 m, depending on whether it reflects far field or near field effects). Two perpendicular directions are used to measure the local electric field direction, which is calculated as $\varphi = \arctan(\frac{E_{EW}}{E_{NS}})$. The data, collected at four stations in the Xinjiang region with a 1-minute sampling rate, showed that two stations exhibited anomalies in the electric field. φ was obtained by linearly fitting one day of data (1440 points) from two perpendicular directions.

Fig. 3 presents the curves of φ (the angle of the electric field relative to north, + means to eastward and – means to westward) and the linear correlation coefficient R at Wenquan station from 2020 to 2024. Wenquan station is located NNE of Wushi, approximately 440 km away (80.8°E, 44.8°N). The results show that between 2020 and 2021, φ was around 8° with wide dispersion. At the end of 2022, it increased to 13° with narrow dispersion, and R became more concentrated above 0.6. After March 2023, φ further increased to 20° by the end of 2023. However, one month before the Wushi EQ, it decreased to 16°. Thus, both φ and R , showed significant variation starting in 2022, with accelerated changes in 2023, demonstrating a clear temporal relationship with the Wushi EQ.

As shown in Fig. 4, another station that exhibited geoelectric field anomalies was Wushi station, located in the same city as the Wushi $M_w 7.1$ EQ. The φ and R curves at Wushi from 2021 to 2024 showed a clear directional change in φ beginning in March 2023, from -42° to

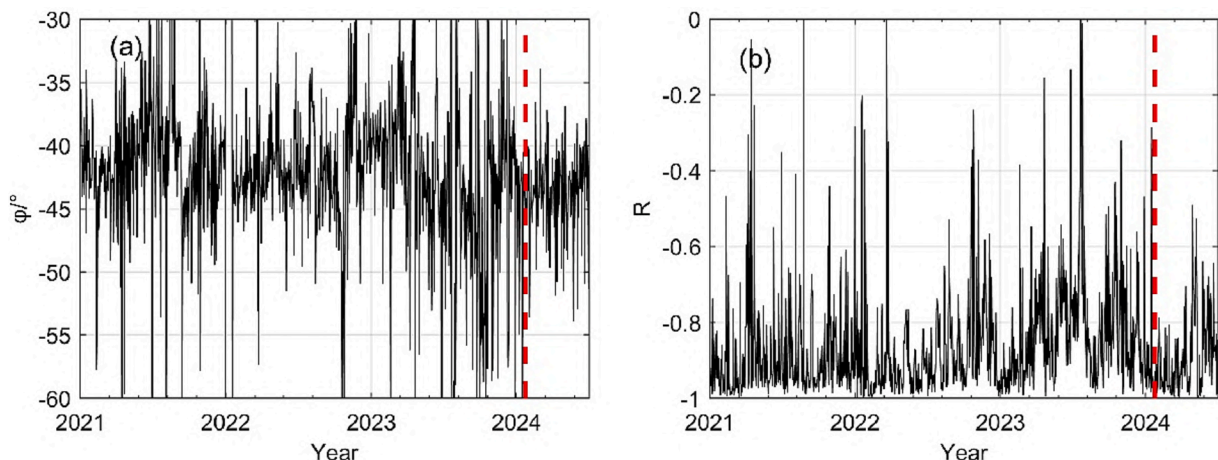


Fig. 4. The electric field direction (a) and coefficient (b) between EW and NS directions at Wushi station.

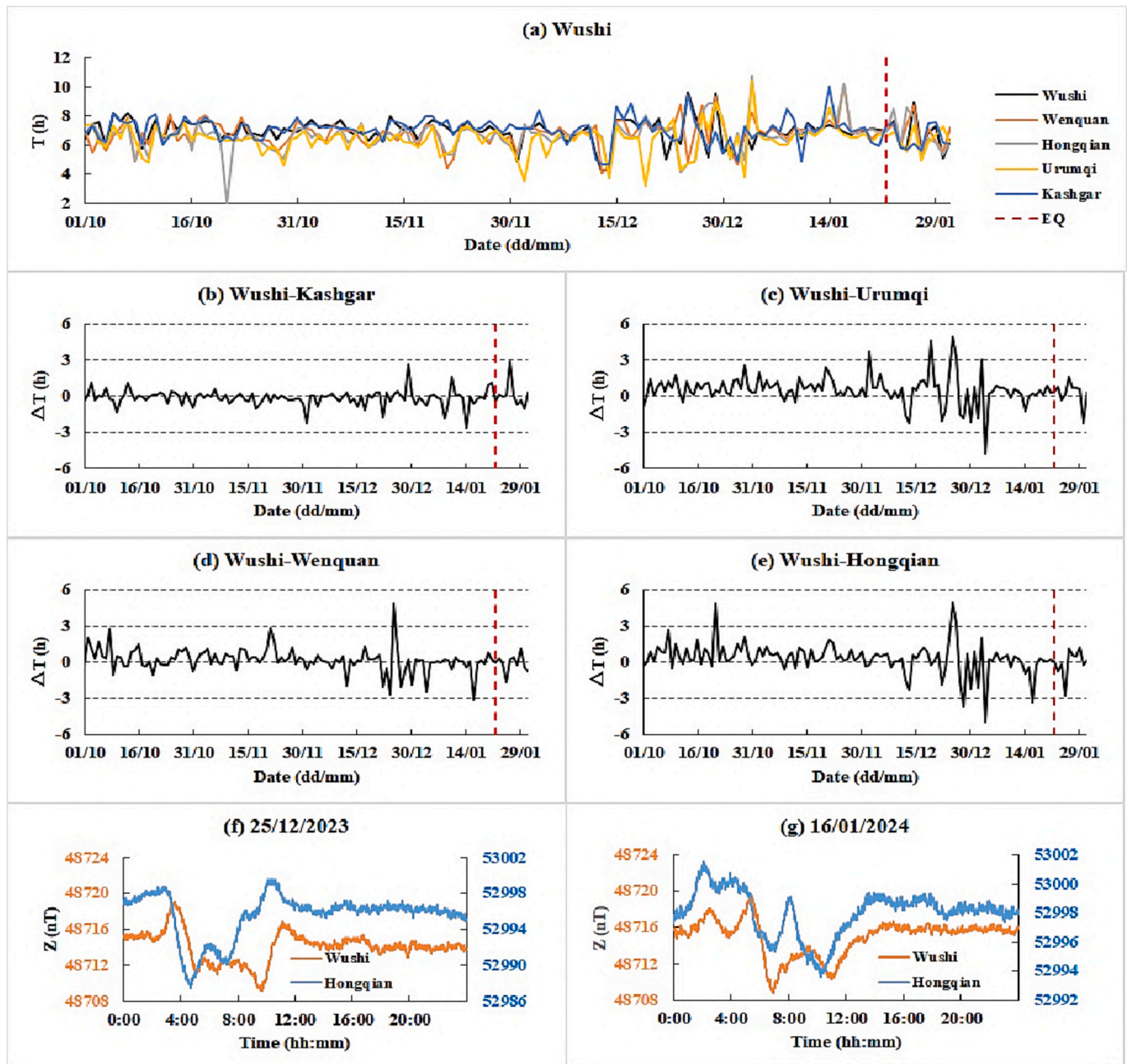


Fig. 5. The low point time comparison among 4 stations from 01/10/2023 to 31/01/2024: (a) time series of LPT at 4 stations; (b) the time difference between Wushi and Kashgar; (c) the time difference between Wushi and Urumqi; (d) the time difference between Wushi and Wenquan; (e) the time difference between Wushi and Hongqian; (f) daily curves of Z component on 25/12/2023 at Wushi and Hongqian; (g) daily curves of Z component on 16/01/2024 at Wushi and Hongqian).

-50° and even dropped below -55° with wide dispersion at the end of 2023. Meanwhile R decreased during the same period. Thus, both stations simultaneously showed an electric field direction shift, indicating that stress accumulation in the Wushi EQ preparation region led to the formation of new fractures. The movement of underground fluids along these fractures altered the geoelectric field direction.

3.1.3. Ground-based geomagnetic field

The variations in the geomagnetic field are attributable 70 % to the outer space currents and 30 % to the induced interior current in the lithosphere, which present the typical daily variation known as Sq and short periodic disturbances. During quiet days, the diurnal amplitude and phase are consistent within the same season at a stable station, and are similar within a longitudinal sector (Yamazaki and Maute, 2017).

Here the Z component of the geomagnetic field is collected, and the Low Point Time (LPT) in daily variation is recorded day by day. Fig. 5 shows the LPT curves at five stations (Fig. 5a), and they are primarily distributed at 6:00–8:00 UT, which correspond to 12:00–14:00 LT. Since November 30, 2023 the disturbances have become more and more frequent, especially from December 14, 2023 to January 3, 2024. Because the Wushi station is quite near the epicenter, we calculated the time differences between it and the other four stations and took 3 h as threshold for anomalous variations. Two anomalies were found on December 25, 2023 and January 16, 2024 with at least two stations showing $\Delta T > 3$ h. To ensure the reliability of both anomalies, the daily curve of the Z component was presented in Fig. 5 (Figs. 5f and 5g), in which the low point of Hongqian occurred at 4.5 UT, while that of Wushi was delayed until nearly 10 UT on December 25. On January 16, the low

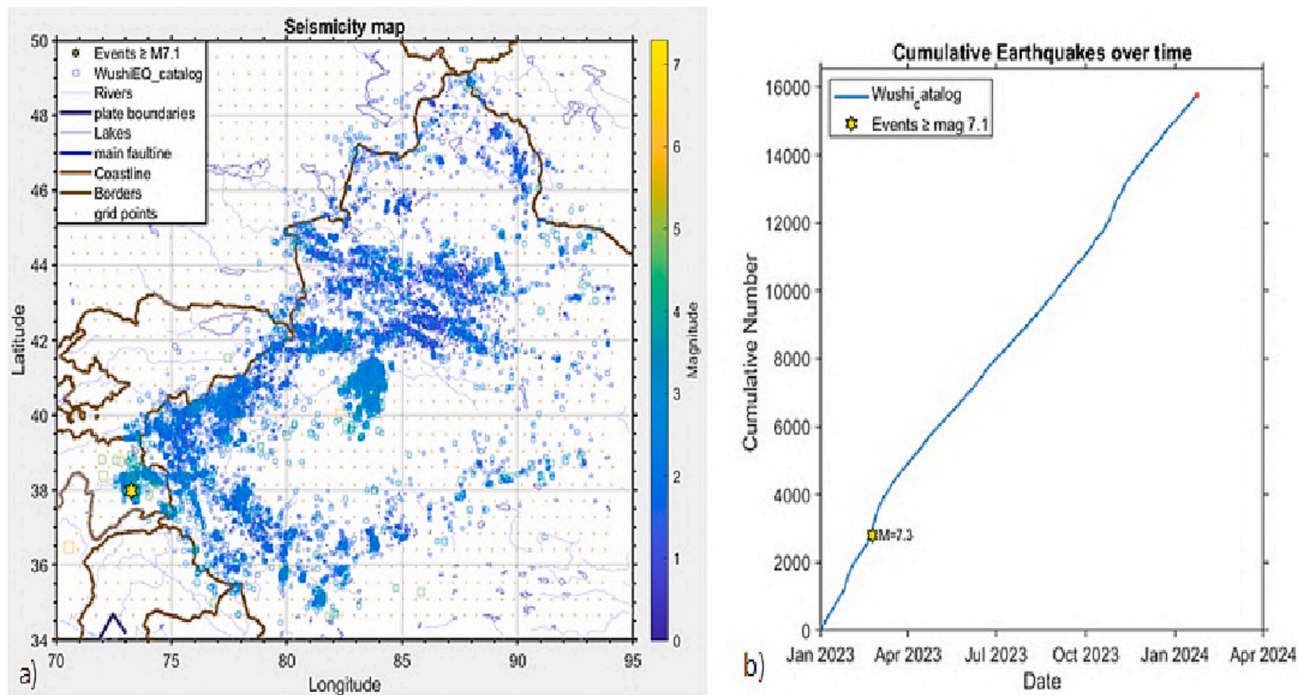


Fig. 6. Seismicity map for the analysed time period. b) Cumulative number of EQs over time.

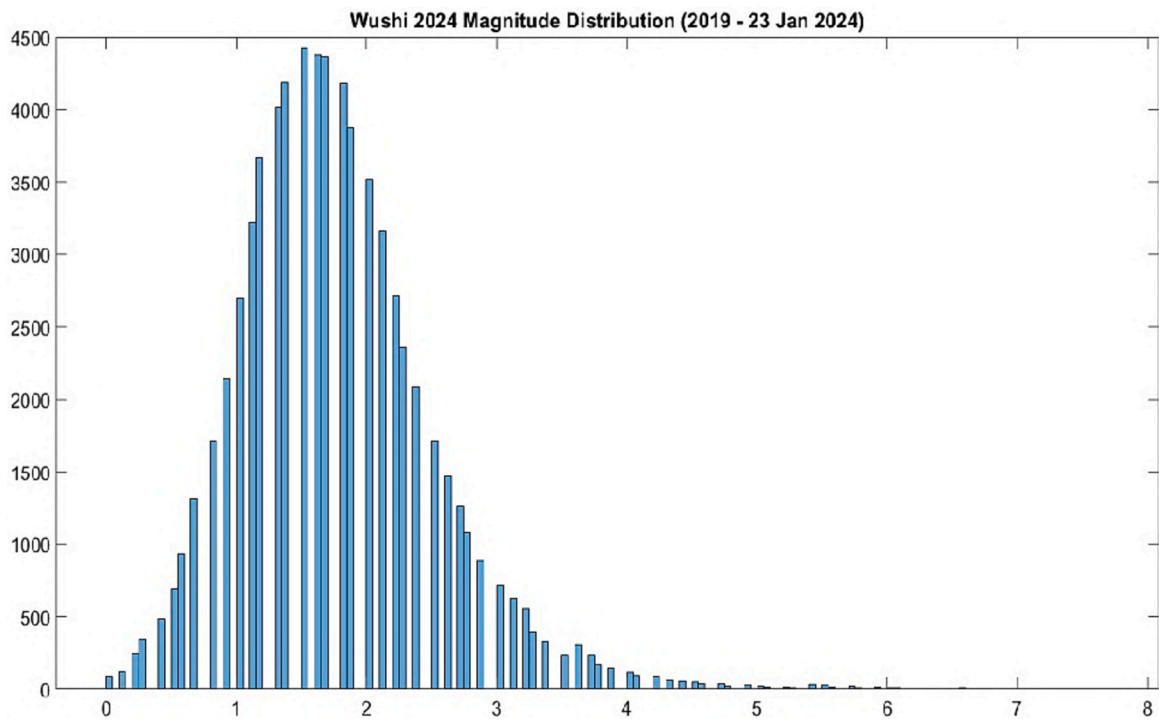


Fig. 7. Earthquake magnitude distribution of all events in the CENC catalogue from 2019 to 2024 for the Wushi County region.

point occurred at about 10 UT at Hongqian. This method effectively demonstrates the daily variation phase and detects anomalies in the studied geomagnetic field region. On December 25 and January 16, the minimum Dst values were -5nT and -9nT respectively, without any outer space effects on the geomagnetic observations. Therefore, these disturbances may be induced by underground currents resulting from the fluid movement along the faults.

3.1.4. Seismological data analysis

On the basis of the CENC catalogue we calculated b-value and applied the R-AMR (e.g. De Santis et al. 2015; Cianchini et al. 2020).

First of all, we started our analysis of seismic data by performing the analysis on the temporal anomalies in the regional b-value using the CENC. The temporal variation in the b-value (Gutenberg and Richter, 1944) analysis along the Maidan fault was investigated to assess the changes in seismicity patterns in the days leading up to the Wushi EQ.

The geographic area under investigation was defined based on the

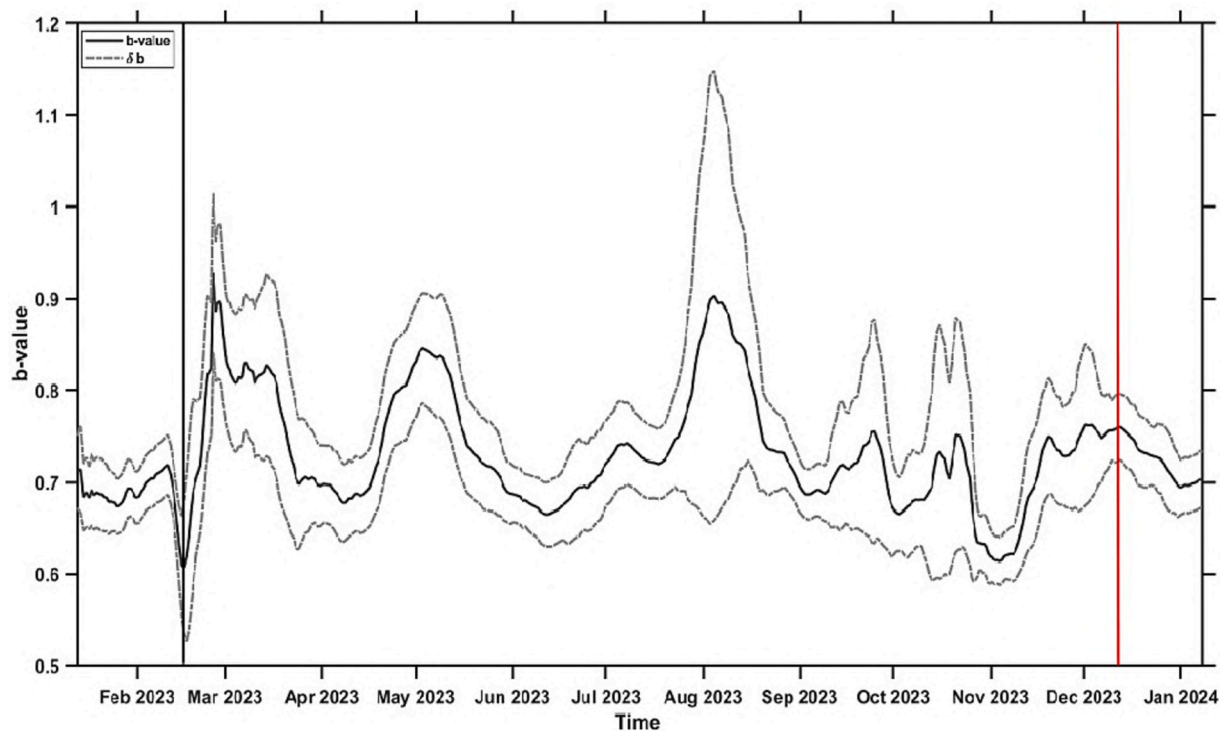


Fig. 8. Temporal variation of the b -value from 1 January 2023 to 23 January 2024. The vertical red line represents the estimated start of the decrease in the b -value.

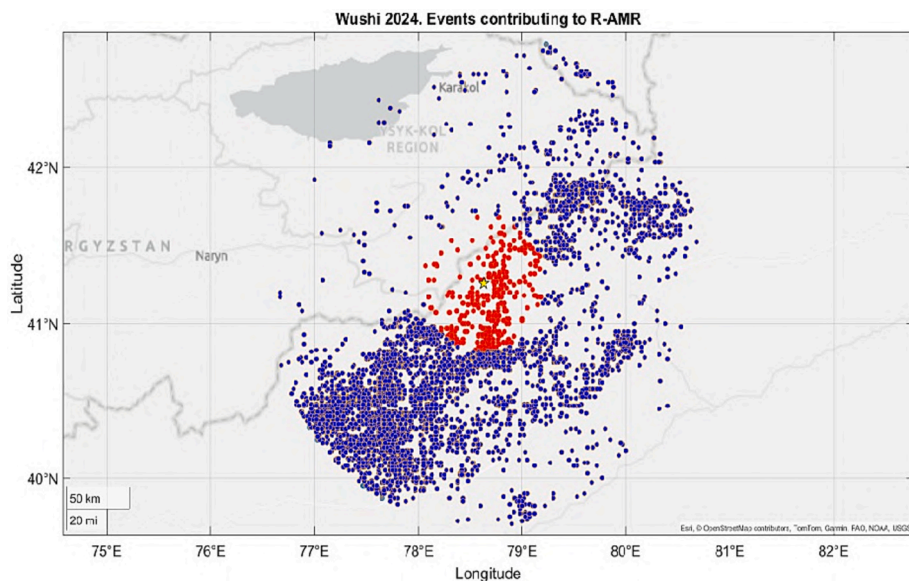


Fig. 9. The spatial distribution of the whole events contributing to the acceleration found in a radius of 175 km around the epicentre; red symbols are those interesting the theoretical rupture area (49 km).

circular region of EQ preparation (the Dobrovolsky area) centred on the epicenter. This resulted in the selection of a circular region with a radius of 1300 km. Within this area, a total of 15,753 seismic events were recorded from 01 January 2023 to 23 January 2024 (Fig. 6).

Looking at the magnitude distribution of EQs (Fig. 7) we can deduce that the magnitude of completeness (M_c), defined as the minimum magnitude above which all seismic events within a given space–time volume are assumed to be consistently detected and recorded, is estimated to be $M_c = 1.7$ applying the method in which 90 % of the data are included (Wiemer and Wyss, 2000), thus reducing the catalogue to 8,892 events.

Fig. 8 shows the temporal evolution of the b -value as deduced from Aki (1965) expression. From Fig. 8, we notice a decrease in the b -value between February and March 2023, due to an EQ recorded in the study area on 23 February 2023, with a magnitude of 7.3 (see black line). Following this, a further decline is noted. Specifically, starting from 12 December 2023, i.e. 42 days before the Wushi EQ (see red line), the analysed parameter decreased from 0.76 to 0.70. This behaviour may be associated with strong stress accumulation along the nearby fault, indicating a potential impending rupture (Schorlemmer and Wiemer, 2005).

Furthermore, in search of possible acceleration in seismicity before

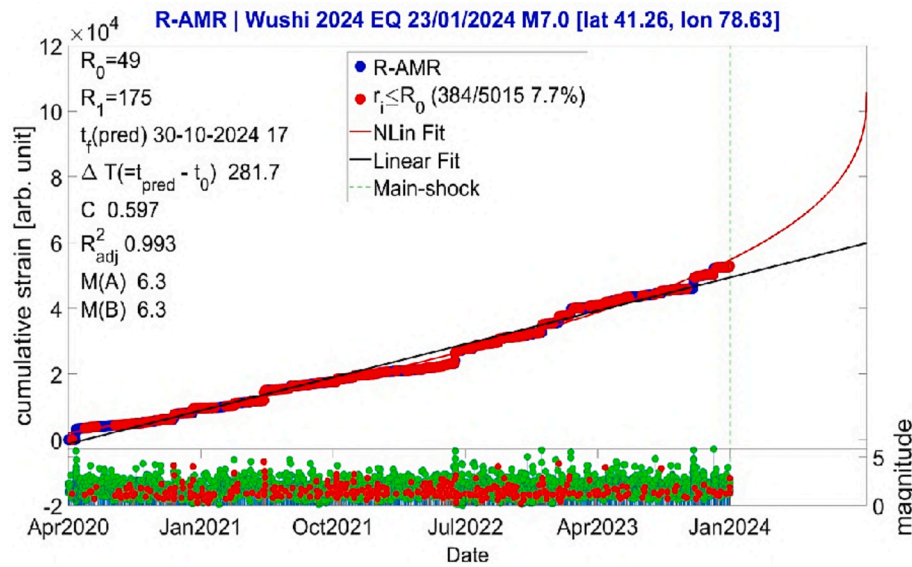


Fig. 10. The outcome of the R-AMR algorithm applied to the CENC catalogue for an area around the EQ epicentre.

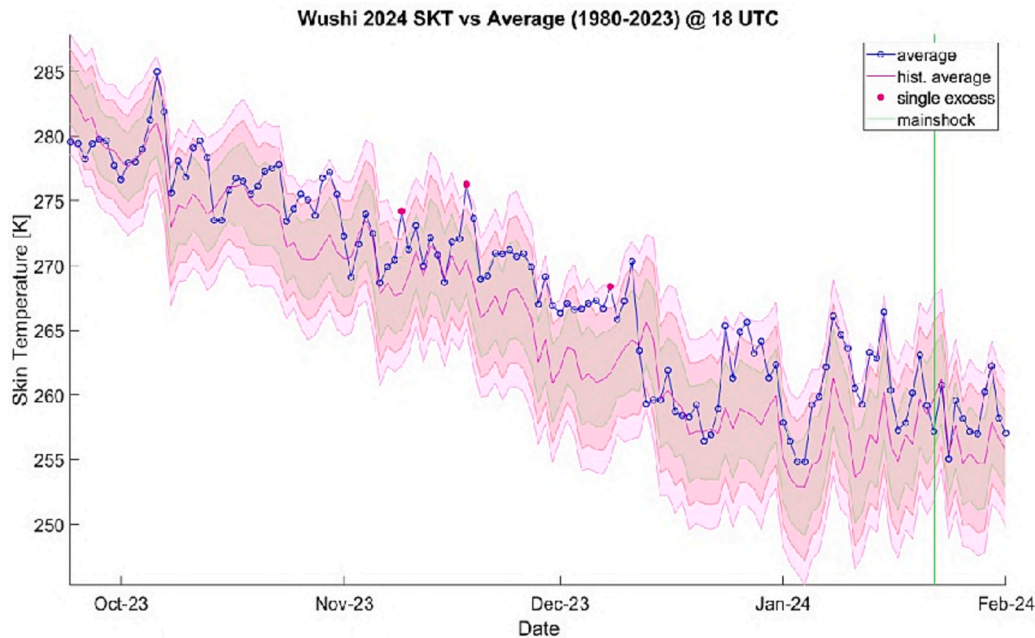


Fig. 11. The comparison between the recent SKT data and the historical one in the $7^\circ \times 7^\circ$ square around the epicentre. It shows some single anomalies (magenta color), when SKT exceeded two times the standard deviation of the historical data. No persistent (for at least two days) anomalies appeared.

the mainshock, we applied the the Revised-Accelerated Moment Release (R-AMR; De Santis et al., 2015; Cianchini et. al 2020) algorithm to the seismic catalogue. The focal search area was centred on the epicentre (i. e. the Mw 7.0 EQ), whose rupture length was estimated to be around 49 km (Fig. 9). According to the available catalogue, we set the maximum search distance to 1023 km (the Dobrovolsky radius), although the algorithm converged for a larger size of 175 km of radius when detected an acceleration with C-value (~ 0.60). Fig. 10 shows the results of this analysis (the mainshock was excluded from the analysis). The R-AMR algorithm detected the start of the acceleration in April 2020 (i.e. about 1,390 days before the EQ). The predicted magnitude was 6.3, just a little less than the real. However, the predicted rupture time (t_f) is not close to the mainshock, occurring almost 280 days later. This could indicate an already existing accumulation of stress that could lead to another large EQ in the area.

3.2. The atmospheric data analysis

3.2.1. SKT

In order to inspect the coupling through the atmosphere, we began analyzing the ECMWF SKT parameter during a period comprising 120 days before and 10 days after the 2024 mainshock, i.e. between 24 September 2023 to 2 February 2024. We selected data in an area of $7^\circ \times 7^\circ$ in latitude and longitude, respectively, corresponding to a square with a side equal to twice the Dobrovolsky radius for an M6 EQ. Since it is believed (Pulinets, 2023) that the radon concentration (an ionization source) decreases with distance from the epicenter, it is reasonable to avoid enlarging the area too much and to rule out spurious effects. We compared the spatial SKT average of the area with the historical time series of forty-three years, from 1980 to 2023. For each day of the aforementioned interval, we computed the space-time average and the

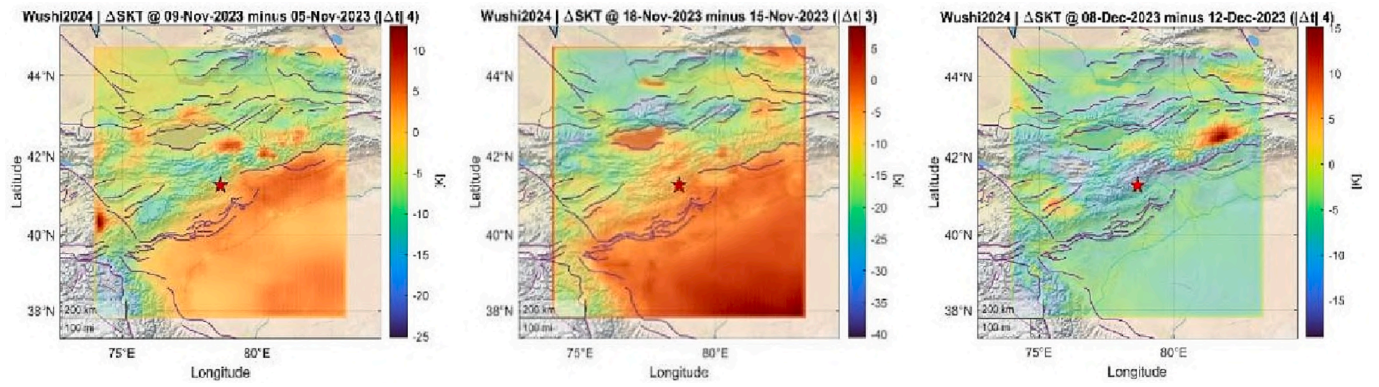


Fig. 12. Spatial distribution of the three SKT anomalies: each of them shows the residual temperature computed as the difference between the single anomalous day and the closer day, whose average temperature is comparable to the historical average (e.g. in c, the SKT difference between 8 December and 12 December 2024).

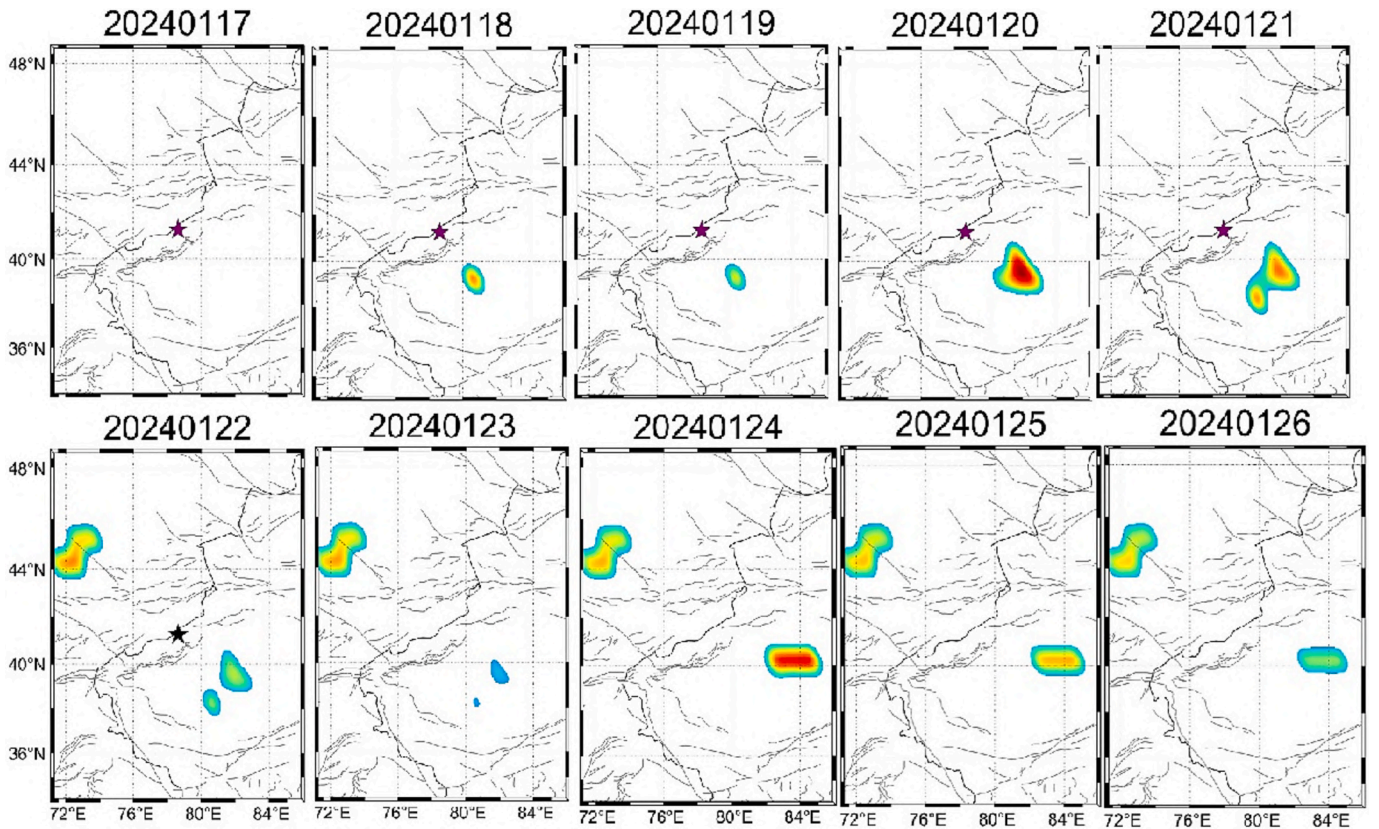


Fig. 13. The IPI distribution over the Wushi epicenter from Jan. 17 to 26, 2024.

corresponding standard deviation, which was then compared to the actual data: we identified anomalies when the data exceeded the historical mean by two standard deviations. The anomalies were considered “robust” when they persisted for at least two consecutive days. We mention that the applied algorithm is conceptually similar to that developed by Piscini et al. (2017), called Climatological Analysis for seismic PRecursor Identification (CAPRI), but it differs in this reformulation (hence called IRPAC) detrends the SKT time series for each pixel and then computes the spatial and temporal average, respectively.

The comparison between the recent SKT data and the historical one is shown in Fig. 11. No persistent anomalies occurred, only three single anomalous days (in magenta color) appeared, i.e. 9 and 18 November, and 8 December 2023. Fig. 12 shows the spatial distribution of the three anomalies. Since the 8 December 2023 anomaly is more spatially localized and of larger intensity, it is most probably associated with the

Wushi EQ.

3.2.2. OLR

The data preprocessing step aims to remove the multi-year variable background, and finally obtain a catalog of residual values from the time-varying series. The Improved Pattern Informatics (IPI) method was adapted to the Pattern Informatics method for OLR anomaly extraction with the following equations (Tian et al., 2024).

$$IPI_i(t_0, t_1, t_2) = (P_i(t_0, t_1, t_2) - \langle P_i(t_0, t_1, t_2) \rangle) / \sigma_i \quad (1)$$

In which t_0 is the starting time, the interval from t_1 to t_2 is the learning time, and P_i represents the probability of anomalies for each grid.

After calculating the IPI for each grid over the epicentral area of the Wushi EQ, some significant anomalies were observed. As shown in

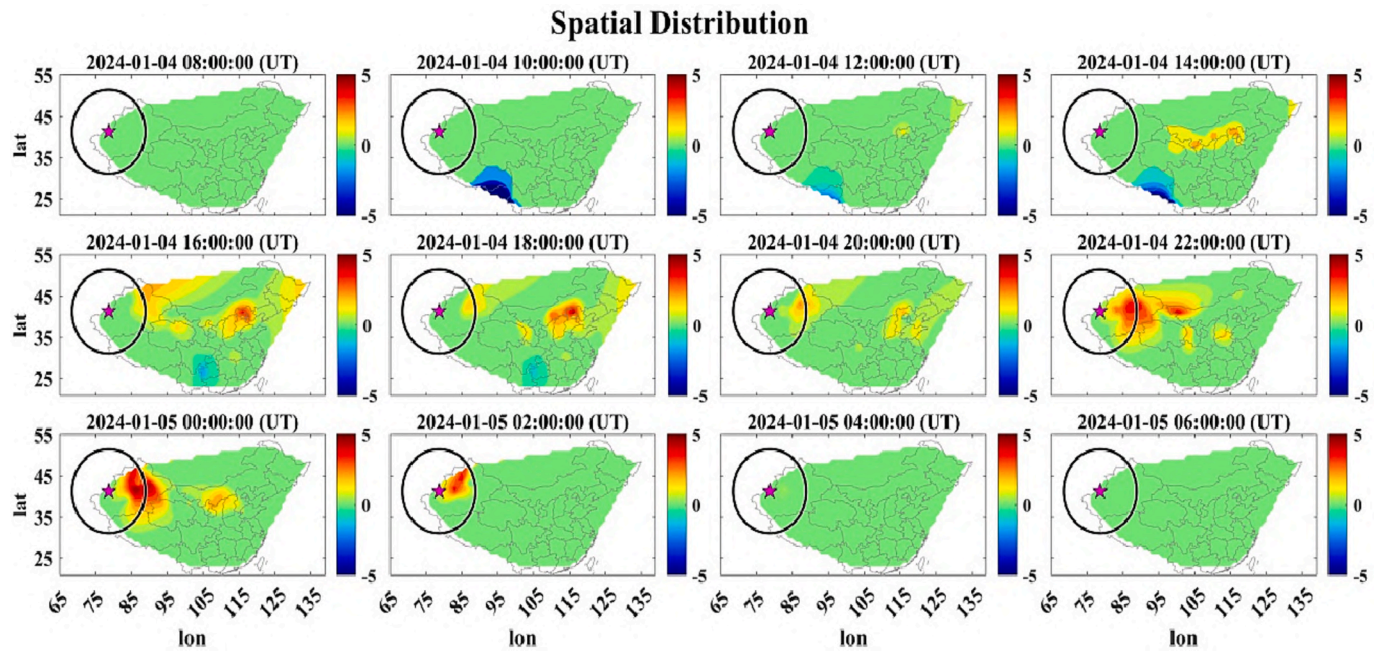


Fig. 14. The spatial distribution of ΔTEC in mainland China during 4–5 January 2024. The pink stars indicate the epicenter of Wushi EQ. The black circles represent the boundary of the preparation zone of Wushi EQ.

Fig. 13, starting from 18 January, i.e. 4 days before the EQ, an increase of anomalies occurred at the southeast of the epicenter, peaking on 20 January, and then declined until the EQ occurrence, while in the northwest, it began to intensify on 22 January. To illustrate the temporal evolution process, 90 days of data prior to the EQ were analyzed, revealing anomalies only in the northwest between October 31 to November 3, as well as December 25 to 28 (Table A1). All the OLR anomalies showed a close spatial relationship with the Wushi EQ, which may be linked to the direction of stress loading: starting from the northwest, developing to the southeast a few days before the EQ, then affecting both locations on the day of the event, and gradually disappearing afterward.

For both SKT and OLR anomalies, we found that no local meteorological events (e.g. strong rainfall, hurricane, cyclonic events, etc.)

occurred at the same days with earthquake precursors detected in this paper, with the meteorological factors at Wushi plotted in the Appendix as Fig. A3 to cover the time period of SKT in November of 2023 and Fig. A4 to cover January 17 to 26 for OLR anomalous days.

3.3. The ionospheric data analysis

3.3.1. GNSS TEC

The ionospheric perturbations have a close relationship with solar activity and magnetic storms. Here, several index datasets were collected and quiet days were defined as those meeting the following conditions for geomagnetic and solar indices: $K_p < 3$, $Dst > -30\text{nT}$, $AE < 500\text{nT}$, $F10.7 < 150\text{sfu}$, and no solar flares above the M-level. The GPS TEC data located in the preparation zone of the Wushi EQ were analyzed

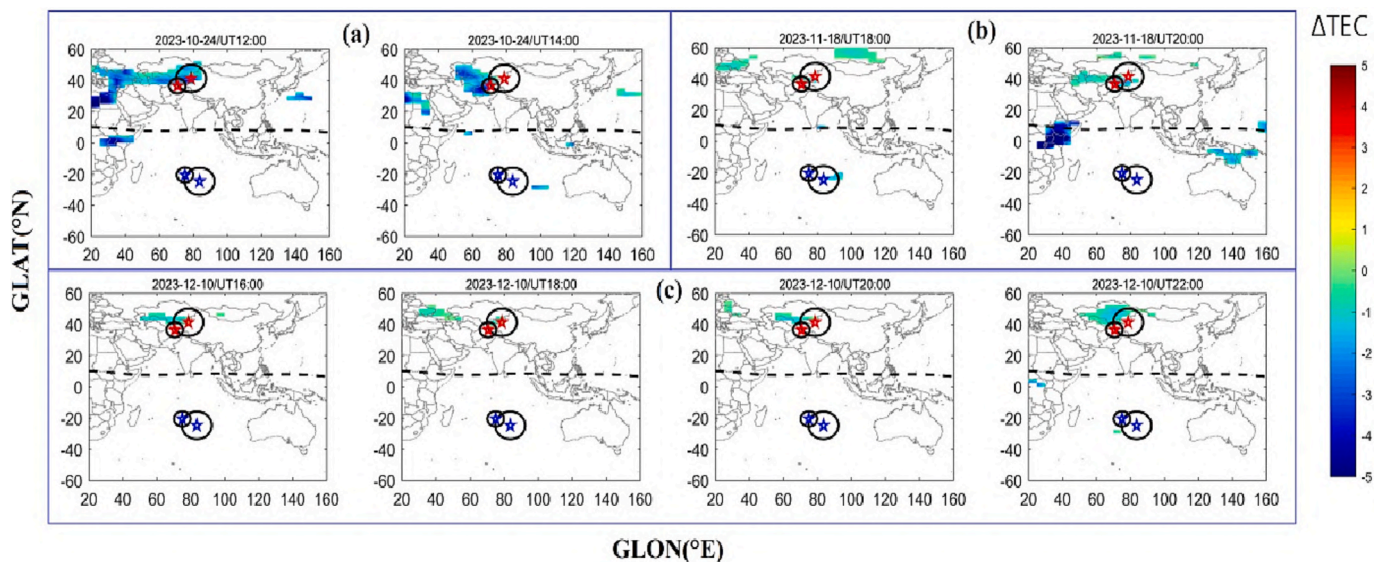


Fig. 15. The spatial distribution of CODE ΔTEC on 24 October (a), 18 November (b), and 10 December (c). The red stars indicate the epicenter of Wushi (on the right) and Afghanistan (on the left) EQs. The blue stars indicate the conjugate zones of Wushi and Afghanistan EQs. The black circles represent the boundary of the preparation zones of the two EQs.

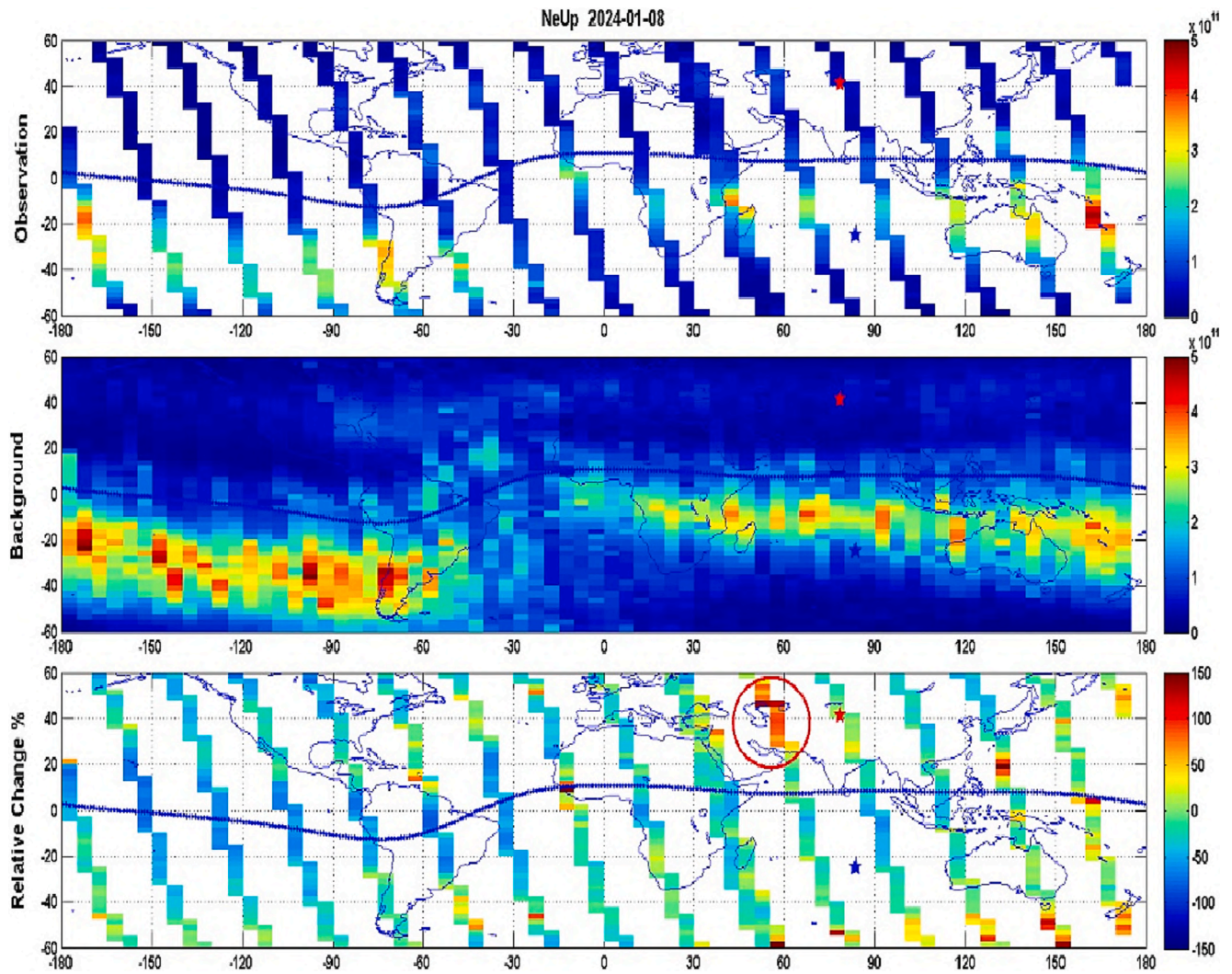


Fig. 16. The distribution of Ne observed by CSES at nighttime on 8 January 2024. The panels from top to bottom are as follows: the Ne observation, the 15-day background, and the relative change. The red and blue stars represent the epicenter and its conjugate point, respectively. The anomaly is marked by the red circle.

using the IQR (Inter-Quartile Range) method according to equation (2), where TEC_o is the raw data with a sampling rate of 15 min and 96 points per day at each station, TEC_m is the median of the previous 15 days at each point, and $k = 1.5$.

$$\Delta TEC = \begin{cases} TEC_o - (TEC_m + kIQR)TEC_o > TEC_m + kIQR \\ 0TEC_m - kIQR \leq TEC_o \leq TEC_m + kIQR \\ TEC_o - (TEC_m - kIQR)TEC_o < TEC_m - kIQR \end{cases} \quad (2)$$

The ΔTEC data for mainland China covering 90 days before the Wushi EQ were examined to find anomalies associated with the event. First, ΔTEC was calculated using equation (2) at each station, and then the regional ΔTEC was interpolated using the nearest distance method. The results show a total of six distinct anomalies, which occurred on 25 October, 11 and 18 November, 10 December in 2023, 4 and 5 January in 2024, respectively. The anomaly during 4–5 January is the longest lasting one and the final anomaly before the Wushi EQ. Fig. 14 shows the anomaly on 4–5 January. At ~ 16 UT on 4 January, an increasing anomaly appeared at the eastern boundary of the preparation zone of the Wushi EQ. After 22 UT on 4 January, the anomaly area expanded, and its intensity increased. At this time, the epicenter was located at the western boundary of the anomaly. After 00 UT on 5 January, the anomaly area shrank and disappeared after 02 UT on 5 January. The location of the anomaly on other anomalous days differed from that

observed on 4–5 January. The anomalies on 25 October, 11 and 18 November were located around the epicenter. The anomaly on 10 December was located to the south and southeast of the epicenter. The location of the anomaly changed over time. In addition, the duration of the anomaly gradually increased from two hours on 25 October to ten hours on 4–5 January, which may indicate a precursory signal to an impending EQ.

Since the CODE TEC data cover a global scale, and the preparation zone of the Wushi EQ covers regions other than China, the CODE TEC data can be used to detect anomalies outside China and in the conjugate zone of the Wushi EQ. Before the Wushi EQ, an Mw6.4 EQ occurred in Afghanistan on 11 January, at 70.7°E , 36.7°N . The northeastern part of the preparation zone of the Afghanistan EQ overlapped with the southwestern part of the Wushi EQ preparation zone (see Fig. 15). The CODE ΔTEC data for 90 days before the Wushi EQ show seven anomalies, which occurred on 24 October, 11 and 18 November, 10 and 27 December in 2023, 12 and 13 January in 2024, respectively. The anomalies (shown in Fig. 15) on 24 October, 18 November, and 10 December covered both the preparation zones of the Afghanistan and Wushi EQs, suggesting that these three anomalies may be associated with both EQs. The anomalies on 11 November and 27 December in 2023 were exclusively located in the preparation zone of the Wushi EQ, indicating a specific relationship with the Wushi EQ alone. However, the anomalies on 12 and 13 January in 2024 occurred after the Afghanistan

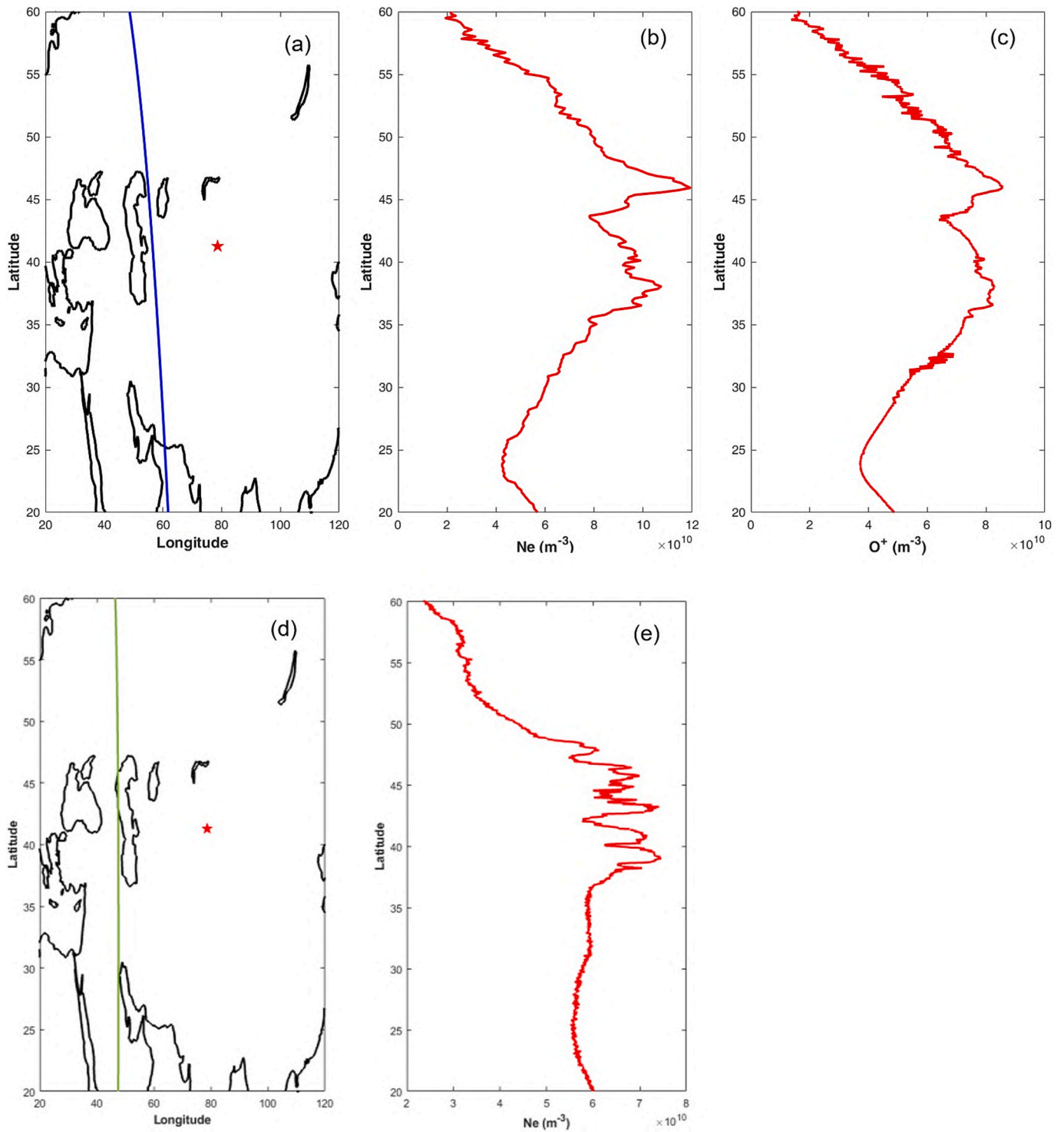


Fig. 17. The location along with the EQ epicenter represented by a red star (panel a), Ne (panel b) and O + density (panel c) of the orbit with an ionospheric anomaly on 8 January 2024 onboard CSES, orbit with EQ epicenter (panel d) and Ne curve (panel e) on Swarm A.

EQ, suggesting that they may represent new disturbances induced by the Wushi EQ. Additionally, no anomalies were found in the magnetic conjugate zones of the Wushi and Afghanistan EQs using GIM TEC data. The perturbations observed in GIM TEC on 11 and 18 November, and 10 December were consistent with the GPS TEC results for Mainland China.

3.3.2. Electron density from CSES and Swarm satellites

The spatial analysis method (Liu et al., 2022) was applied to analyze Ne observed by CSES. Three steps were taken to extract Ne disturbances

before the Wushi EQ. First, for the daytime and nighttime observations, the dataset was divided into 2.5° (latitude) $\times$ 5° (longitude) cells, and the median value of the data in each cell was calculated to represent the observational value for each day. Second, the relative change (R_c) was obtained using the following expression.

$$R_c = \frac{Od - Bd}{Bd} \times 100 \quad (3)$$

Od is the observation data calculated according to the first step, and

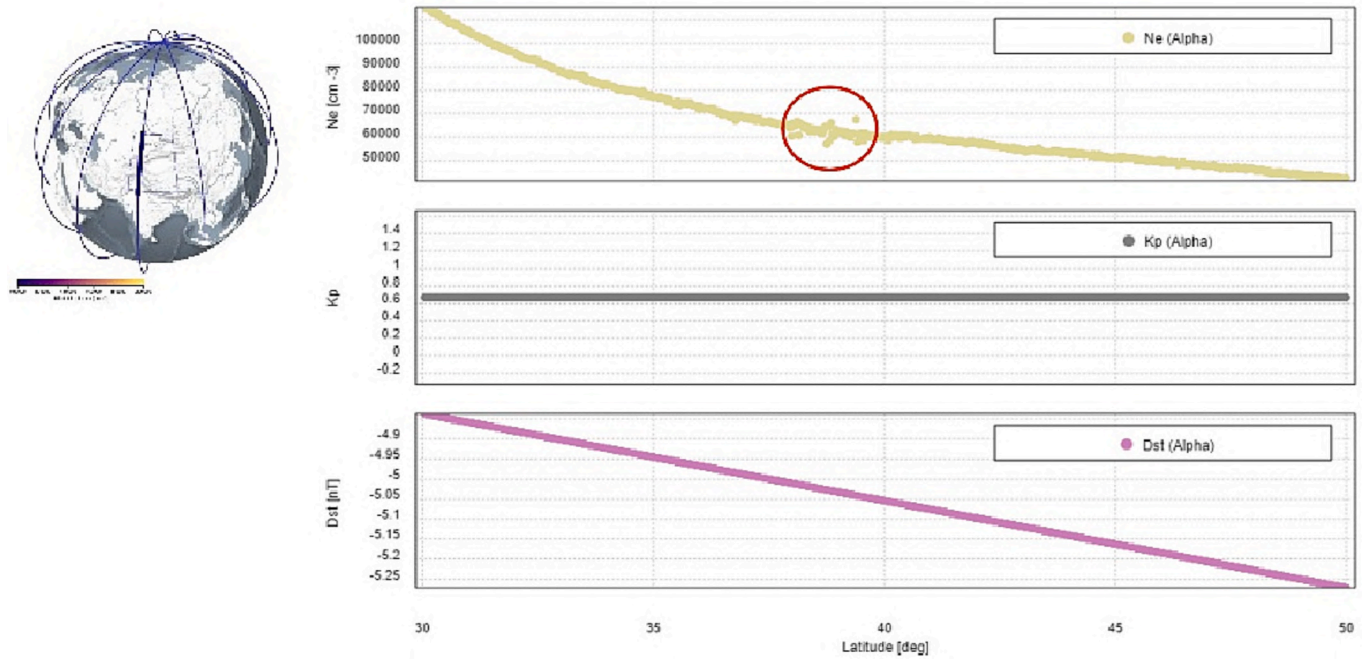


Fig. 18. Ne Swarm satellite anomaly (upper panel) found on 4 January 2024. The two lower panels show Kp and Dst geomagnetic indices. (Drawing obtained from Vires – Virtual Research Service- web program: <https://earth.esa.int/eogateway/tools/vires-for-swarm>).

Bd represents the background value, which is the median of the 15-day data before Od. Finally, except for the data at high latitudes, the obvious high or low Rc values around the epicenter and its conjugate point were considered anomalies potentially related to EQs.

The Ne data for 90 days before and 10 days after the Wushi EQ were analyzed using the spatial analysis method. Four anomalies were found on 13 and 28 December in 2023, 8 and 13 January in 2024 (Table A1). The anomaly detected at nighttime on 8 January 2024 is shown in Fig. 16 as an example. The panels from top to bottom show the following: the Ne observation, the 15-day background, and the relative change. In the bottom panel, it can be seen that the maximum relative change value appeared to the west of the epicenter, which is marked by the red circle. Furthermore, the raw data from this orbit is shown in Fig. 17, including the location (panel a), Ne (panel b) and O^+ density (panel c) along the latitude. Panel d and e show the same anomaly as found by Swarm Alpha, but it was not listed in Table A1 as it was detected slightly outside the Dobrovolsky region. Although the Ne and O^+ density were observed by different payloads, the patterns of these two parameters were almost identical, showing synchronous peaks and troughs. This confirms the reality of the perturbations detected at nighttime on 8 January 2024. But it should be noted that the peak anomaly position on January 8 is a little far from the epicenter, so it should be treated cautiously.

Fig. 18 shows the only Ne anomaly detected by Swarm satellite A, on 4 January 2024. Kp and Dst indices indicate that the geomagnetic field was calm.

3.3.3. ELF electric field from CSES

Before strong EQs, EM emissions have been widely reported (Parrot, 1994; Hayakawa et al., 2023), with disturbed frequencies spanning a wide range, especially in the Ultra Low Frequency (ULF) and Extremely Low Frequency (ELF) bands. To illustrate these perturbations, ELF electric field data were collected around 70 ± 20 Hz during local nighttime orbits over the epicentral area onboard CSES (Fig. 19). Due to data loss in December 2023, only the Power Spectrum Density (PSD) curves for January 2024 are presented here. It can be seen that five anomalies occurred, of which 4 and 24 January might be related to a

magnetic storm or substorm, with Kp near 3 or greater than 3, while on 22 January only Ey showed stronger disturbances. Compared with ground-based geomagnetic field observations, satellite electric field emissions were also detected on 16 January, which enhances the reliability of the anomalies on this day, and demonstrates the relationship between ground and satellite electromagnetic perturbations.

3.3.4. Parameters from ionosondes

The parameters foF2, foEs and h'Es were collected with a sampling rate of 1 h at the two ionosonde stations of Yili (40.2°N; 80.1°E) and Kashgar (39.5°N; 75.9°E), located over the epicentral area, respectively 170 km and 300 km away from the EQ epicentre. According to the multi-parameter method introduced by Korsunova and Khegai (2008) and applied in previous analyses (e.g., Perrone et al., 2018; Ippolito et al., 2020), abnormal variations within a few hours in the three parameters are used to define ionospheric anomalies possibly associated with pre-seismic activity. Through the comparison with background information based on 27-day hourly running medians, three anomalies were detected on quiet days without geomagnetic disturbances based on the ap geomagnetic index (i.e., not exceeding 10 nT), on November 29, December 22 and December 23, where on November 29 both stations showed anomalies simultaneously, while on the other two days, only Yili detected perturbations. Fig. 20 presents the variations on November 29, December 22 and December 23 at Yili and Kashgar, from which we can see that on November 29 (Fig. 20a) the Es layer was significantly uplifted, with a subsequent increase in the critical frequencies of both the Es and F2 layers, which correspond to an increase in the Ne in these layers. The same occurred on the other two days only at Yili, while at Kashgar no Es was observed. It should be noted that in the case of November 29, the value of the auroral electrojet (AE) index increased up to more than 400 nT since few hours before the strong foF2 increase detected at both stations, suggesting this anomaly to be the signature of a Travelling Ionospheric Disturbance (TID) due to the increase in auroral activity. For these reasons, the anomalies observed only by the Yili ionosonde (i.e., the closest to the epicentre) on December 22 and 23 (Fig. 20b and c) under actually quiet geomagnetic conditions can be considered more likely related to pre-seismic activity.

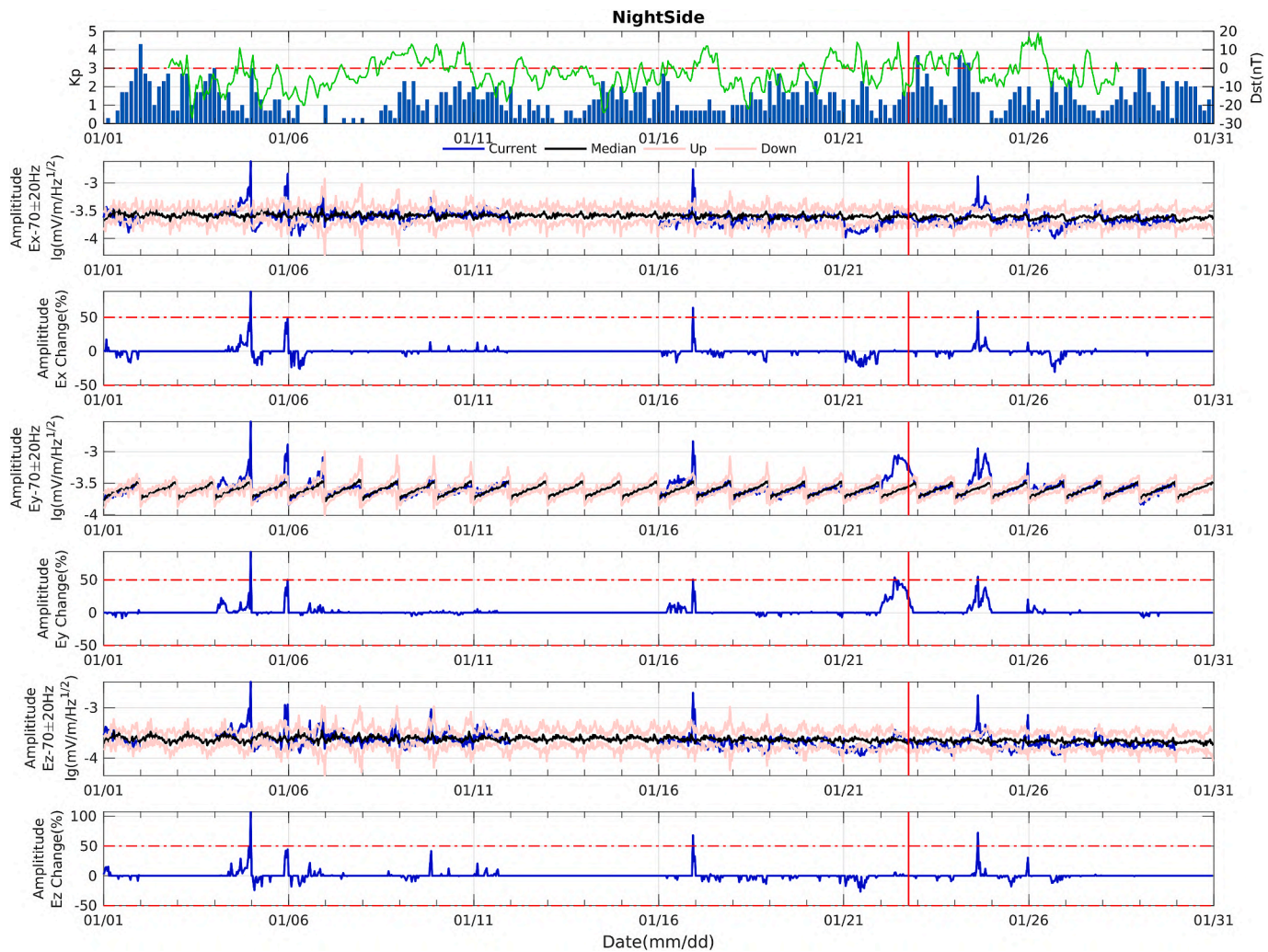


Fig. 19. The anomalies in the three components of the electric field at 70 Hz (± 20 Hz) from the EFD onboard CSES during nighttime from 1 – 30 January (top). At the top of each series, the magnetic indices Kp and Dst are shown. Vertical red line indicates the time of the Wushi EQ occurrence.

3.3.5. ULF magnetic field from Swarm and CSES

We have analysed the satellite magnetic field data from Swarm in order to search for electromagnetic anomalies that could be related to the Wushi EQ. Analysing a period between 90 days before and 10 days after the earthquake we have detected interesting magnetic field anomalies around 86 (e.g. Fig. 21) and 19 days before the EQ.

These preceding times match very well with the times when higher concentrations of anomalies were detected when a worldwide correlation analysis was applied using the same MASS technique (see De Santis et al., 2019). Other anomalies were found around 84 and 75 days before the EQ, but they are less clear.

Also, the magnetic field data from HPM onboard CSES have been analyzed; they were processed with a Butterworth filter in the frequency band of 0.1–0.4 Hz. By removing the days disturbed by space weather, only one anomaly was confirmed and detected at the conjugate region 82 days before, i.e. on November 1, 2023 (Fig. 22), which is on the same day as that detected by the Swarm A satellite (see Table A1).

3.3.6. Energetic particles from NOAA and CSES

To analyze possible Electron Bursts (EBs) correlated to the seismic event, data acquired using NOAA and MetOp satellites were analysed for the period between October 1, 2023, and January 31, 2024, while CSES-01 satellite data was analyzed for the period between January 6 and 22, 2024. Taking into account the Dobrovolsky area (Dobrovolsky et al. 1979), a circular area with a radius of 10° around 41.26°N and 78.63°E ,

was considered to investigate sudden and brief-duration electron losses. Indeed, only very short-duration (2–4 sec) EBs were counted in this case, as longer-duration EBs did not appear days before the EQ. Such EBs are known to be possibly induced by cosmic rays. CSES-01 also showed very short-duration EBs inside the Dobrovolsky area, all of which are reported in Fig. 23, along with the ap and Dst indices.

The investigated EBs did not appear to have any relationship with geomagnetic activity. At the same time, CSES-01 data were analyzed only during January 2024, when the geomagnetic activity was calm. Overall, there was no particular increase in very brief-duration electron precipitation in the Dobrovolsky area before the Wushi EQ. A slight excess appeared when direct and conjugate regions were differentiated, where EBs detected by NOAA and MetOp within the conjugate area (in blue) increased in intensity from about a month before the seismic event. However, such a difference does not seem to have any plausible interpretation.

If we consider only EBs anomalies in the Dobrovolsky area with electron flux greater than $5000 \text{ counts/cm}^2 \text{ ster}$, we find the following anomalous dates: 8, 23, 27, 28 December 2023 and 12 January 2024.

4. Discussion

4.1. The temporal evolution process

In the Appendix, Fig. A1 shows the data flow for the comprehensive

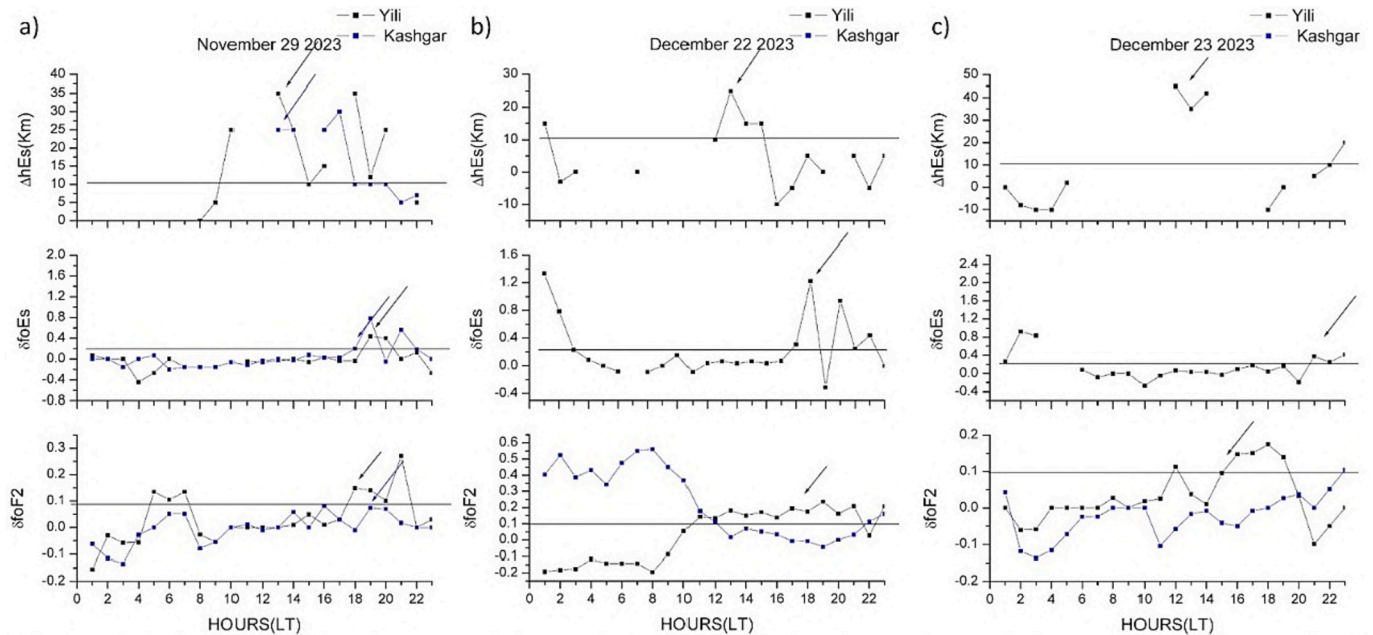


Fig. 20. The absolute (ΔhEs) and relative ($\delta foF2$, $\delta foEs$) variations of the parameters on November 29 (a), December 22 (b) and December 23 (c), 2023, from ionosonde observations at Yili (black) and Kashgar (blue). The horizontal lines represent the thresholds for the anomaly definition (please note that the time is in Local Time).

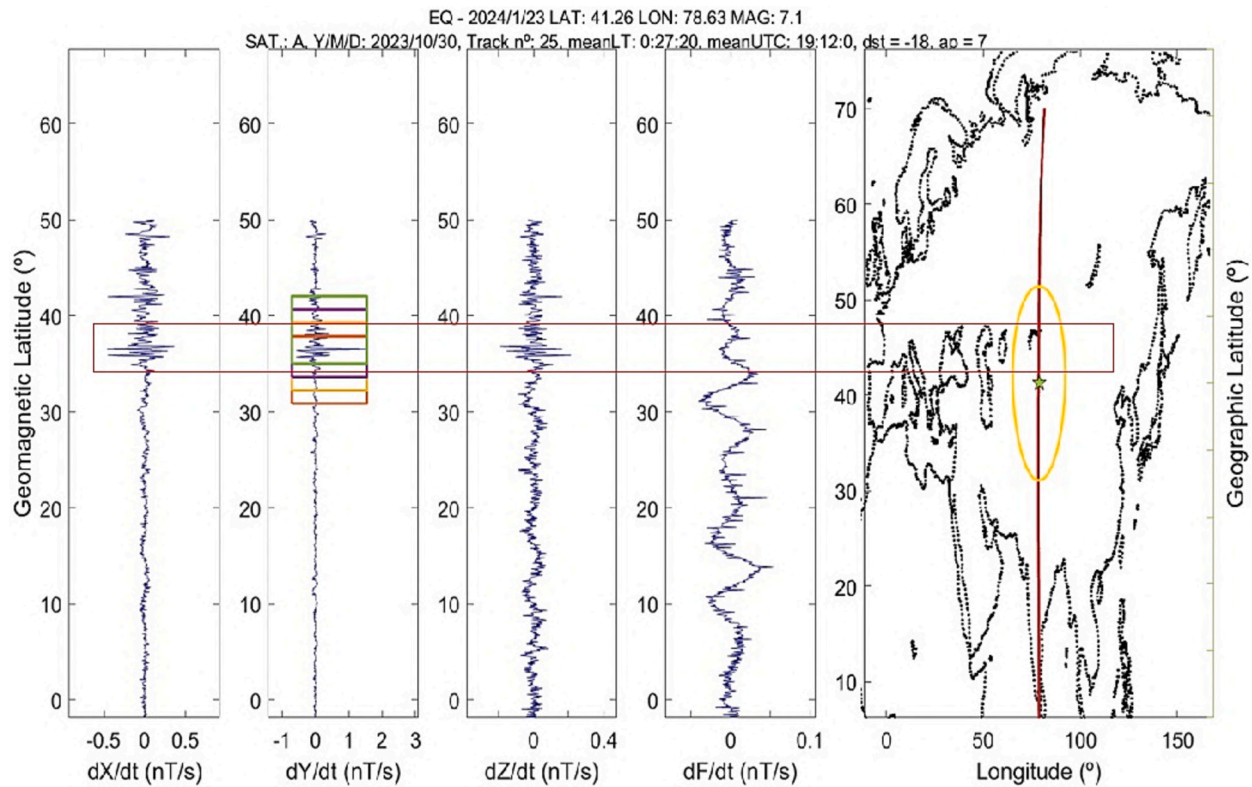


Fig. 21. Swarm A (from left to right panels) first differences (MASS method for magnetic data) of: X, Y, Z, F; and map with the location of the epicentre of the earthquake (green star), Dobrovolsky area (yellow circle) and analysed track (red line) for 30 October 2023 (i.e. 86 days before the earthquake). Coloured squares indicate the anomalous windows automatically detected by MASS (also the signal anomaly is red colored).

analysis, and Table A1 lists all anomalies found in this work. To better understand the pattern of anomalies leading up to the Wushi EQ, we plotted the cumulative number of anomalies in chronological order over the 1392 days preceding the mainshock, i.e. from the start of the seismic acceleration detected by the R-AMR method. As shown in Fig. 24, the

data follow an acceleration trend that converges toward the moment of the Wushi EQ.

In this comprehensive analysis of the anomalies, we present the cumulative number of anomalies detected. Notably, the anomalies generally appear sequentially over time, progressing from the lower regions

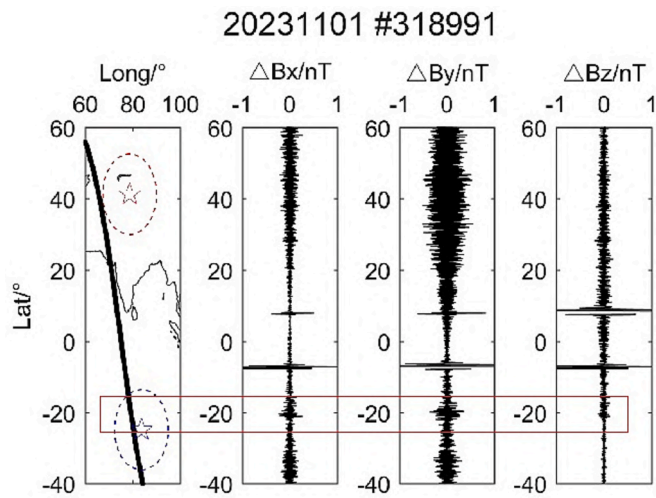


Fig. 22. The magnetic field disturbances on CSES in three components of X, Y, Z, along the orbit of #318991 on November 1 in 2023; and the left map with the location of the epicenter of the earthquake (red star, blue star indicate the conjugate point), Dobrovolsky area (red and blue circle), and analyzed orbit (black line). Red rectangle indicates the anomalous windows.

(seismic data in the lithosphere) to the upper layers (atmosphere and ionosphere). However, some anomalies are mixed, supporting the possibility of a two-way LAIC. Consistent with previous case studies, we can categorise the anomalies into two types: 1) “electromagnetic” anomalies, which show a direct coupling, and 2) “thermodynamic” anomalies, which create a diffusive, delayed progression from the lithosphere to the ionosphere, passing through the atmosphere (Zhang et al. 2024).

We could ask if the form of the cumulative number of anomalies is due to chance or deterministic. To this purpose, we focused on the last three months before the EQ, when most of the physical parameters are taken to determine whether the cumulative number of anomalies follow a random (linear) or non-random (non-linear) pattern. Therefore we applied a statistical test, such as the Kolmogorov-Smirnov test for uniformity (e.g. Massey 1951), with the following null hypothesis (H_0): The anomalies are uniformly distributed (random). The found result is that KS Statistic = 0.367, which is the maximum deviation between the

empirical cumulative distribution function (ECDF) and the theoretical uniform CDF. This value is greater than the critical value of 0.218 for a significance of α of 0.01, with $p\text{-value} = 1.16e^{-05}$, so $p \ll 0.01$. The conclusion is that the p -value is significant, so we reject H_0 . Therefore, the anomalies are not uniformly distributed and non-random.

In the LAIC model of Hayakawa (2004), the geochemical and AGW channels are related to radon or gas release. In this case, although no radon observations are available in the Wushi region, some underground fluid information can be referred to the EQ preparation area. According to the results of Song et al. (2024), the Zargandt well in Kazakhstan at an epicentral distance of 360 km, detected a sharp increase in water flow rate from 8 January 2024 until the EQ occurrence. Additionally, the hot spring hydrogen at Muji county in Xinjiang, located 438 km from the epicenter, showed a significant release between 7 and 22 January. During this time period, multi atmosphere and

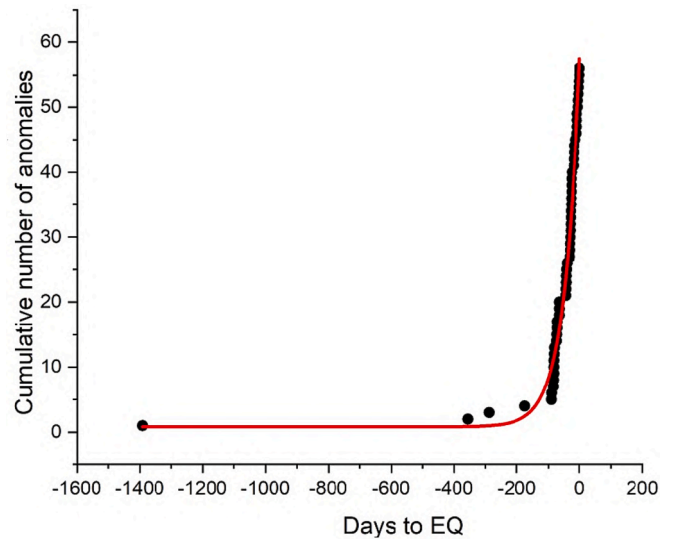


Fig. 24. Comprehensive cumulative number of all anomalies detected for Wushi EQ from around 1400 days before the EQ. The red curve represents the best exponential fit. List of the anomalies is shown in Table A1 of the Appendix.

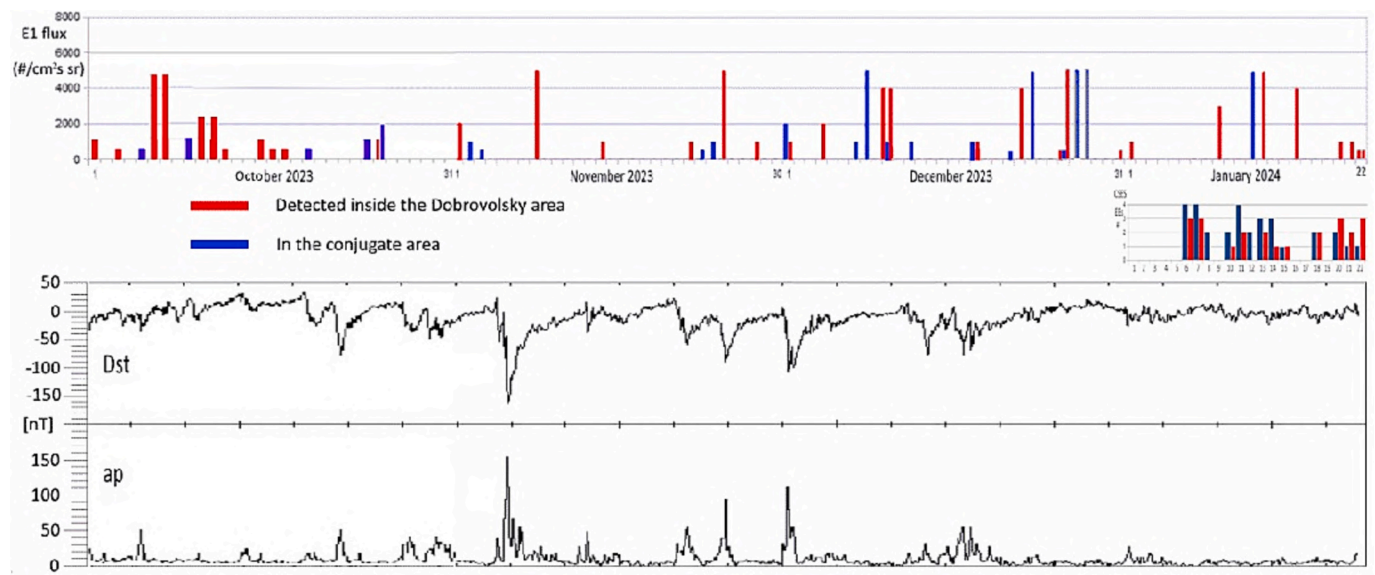


Fig. 23. In the upper panel, EB fluxes revealed by NOAA, MetOp, and numbers of CSES EBs in the periods between October 2023 and January 2024, and January 6 and 22, 2024. Red EBs were detected inside the Dobrovolsky area, while blue ones were detected inside the conjugate area. In the lower two panels, the geomagnetic indices of activity, Dst and ap are shown.

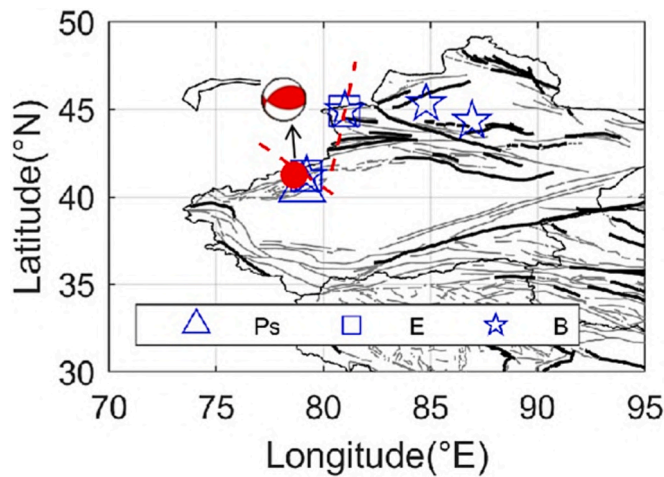


Fig. 25. The ground-based stations ($\triangle$ represents earth resistivity at Keping; $\square$ represents geoelectric field stations at Wushi and Wenquan with red dashed lines indicating their direction; $\star$ represents geomagnetic stations at Wushi, Wenquan, Urumqi, and Hongqian) and the focal mechanism of the Wushi EQ (red circle).

ionosphere anomalies were revealed, including OLR, ULF magnetic field at ground level, GIM TEC, ELF electric field from satellite data, which demonstrates the indirect coupling process during the impending stage of the EQ.

4.2. The relationship with focal mechanism

Because the Wushi EQ is located in the Xinjiang region, near the border of China, the ground stations are sparse within the studied area. We attempt to explain the characteristics of these anomalies in relation to this EQ with a thrust-focal mechanism. Keping station is located 76 km from the Wushi EQ epicenter, so it can represent the characteristics at the epicentral area. From previous studies, earth resistivity shows anisotropic features in different directions, with a larger amplitude in the direction perpendicular to the P-axis in focal mechanism (Du et al., 2007). For example, during the 2008 Wenchuan EQ, which also had a thrust focal mechanism, earth resistivity at the nearest station, Chengdu (about 35 km away), showed significant anisotropy, with a large decrease of 6.7 % in the NE direction (Xie et al., 2018) but no anomalies in the NW direction. Another station, Jiangyou, located 147 km away, showed a decrease of about 1.1 % at N70°W but no anomalies at N10°E (Xie et al., 2018). The azimuth of the P-axis for Wenchuan EQ is N51°W, which is almost perpendicular to the NE direction of Chengdu but much closer to the direction of Jiangyou at N70°W. In this case, earth resistivity at Keping decreased in both directions, for annual NS variations in 2023 showing a decrease of about 37 % and EW showing a decrease of 29 % relative to 2022. There is anisotropy in Earth resistivity at Keping, but the larger anomaly was in the NS direction, which is closer to the P-axis at about 174.91° for the Wushi EQ, rather than being perpendicular.

In addition, the geoelectric field observation includes two types of variations: (1) the stable underground natural electric field, and (2) the induced electric field from space currents. The change in electric field direction may indicate the expansion of micro-fractures and fluid movement. Here, we also compare this to the 2008 Wenchuan EQ. Three geoelectric field stations detected anomalies before the Wenchuan EQ (An et al., 2013; Xie et al., 2018), with the polarization orientation in the geoelectric field shifting from 45° to 60° at the Pingliang station (578 km away), from -90° to 88° at Chengdu station (35 km away), and from -90° to 65° at the Lugu station (445 km away). These studies found that the forward or reverse extension lines of these anomalies all pointed to the Wenchuan EQ epicenter. For the Wushi EQ in this study, two geoelectric field stations showed directional changes. The Wushi station,

with a distance of 53 km to the epicenter, recorded a shift of the electric field direction from -40° to -50°, while the Wenquan station, at a distance of 391 km, recorded a shift from 10° to 20°. The extension lines are plotted in Fig. 25, and both indicate the Wushi EQ epicenter as well.

As for the *b*-values studies, Zhao and Wu (2008) reported their results regarding the Wenchuan EQ, and found only a weak decreasing trend along the Longmenshan fault prior to the main shock, which was difficult to define as an indicator of an impending EQ. Chen and Zhu (2020) proposed a new computational strategy for *b*-values, and identified significant precursors only in a sub-region with a radius of 50 km around the Wenchuan EQ epicenter. In that case, the *b*-value increased to 1.25 in 2002 and remained elevated until 2007, dropped to 0.5 in November 2007 and remained low for about three months, then increased again starting in March 2008 until the occurrence of Wenchuan EQ. In the case of Wushi EQ, the *b*-value also showed a weak decrease in November 2023, but no rapid drop was observed over the preparation region within Dobrovolsky's radius. A decrease in *b*-value is interpreted as a consequence of increasing stress prior to a seismic event (Scholz 1968). Based on these two EQs, it may indicate that short-term or impending anomalies are not particularly clear for thrust-type EQs. Even for the 2011 Tohoku EQ with magnitude of 9.0, the *b*-values only showed long-term decreasing trend lasting for more than ten years (Nanjo et al., 2012), which further supports this feature. Alternatively, the studied area may need to be limited in a much smaller scale for this type of EQ.

4.3. The indicator for approaching earthquake location

Whatever the ground-based and space-borne detected parameters, the anomalies are always distributed in a larger area, especially for the ionospheric detection some disturbances may occur in a distance of beyond 2000 km. So how to define the future epicenter is still a hard problem. Firstly, we try to use the direction of the geoelectric field to indicate it. As shown in Fig. 26, we set up two lines with the slope of $\tan(90^\circ - \varphi)$ from two stations of Wenquan for $\varphi = 20^\circ$ and Wushi for $\varphi = 50^\circ$ respectively, and calculate their crossing point as 80.2°E and 40.3°N, being located at the southeast of the real epicenter with a distance difference about 160 km. It is interesting that the line of two anomaly points in OLR (Fig. 26) is also near the orientation of electric field at Wushi, pointing to the epicenter. If there are more stations around, better results may be expected.

For the satellite observations, the ULF magnetic field always showed more disturbances than others. Here we select Swarm A data to give a further analysis to indicate the future epicenter position. By using wavelet analysis for the magnetic field data with perturbations revealed in section 3.3.5, it is found that the abnormal signals were mainly distributed in the frequency band of 0.1–0.3 Hz. After removing the disturbed days, all the nighttime data were dealt with by wavelet spectrum, and the maxima values at 0.1–0.3 Hz were selected to be the disturbances. Then, the number of abnormal signals was scanned at each bin (1° interval in longitude and latitude) within a distance of 500 km, 1000 km and 1500 km respectively. Fig. 26 presented the frequency number of disturbances at each bin from September 2023 to January 2024. The results showed that in September and October of 2023 Fig. 26 a1-c2), the disturbances are mainly located at higher latitude above 50°, which may be related to the higher EM activity in higher latitudes. Since November 2023, the number increased at latitudes of 20–40°, but only for the distance of 1500 km Fig. 26 c3), the abnormal signals concentrated to the Wushi epicenter. In December (a4-c4 in Fig. 26), the signals were further enhanced, and the anomalies were clear in the epicentral area for a distance of 500 km, which indicates that the nearer the EQ will occur, the closer the perturbations concentrate to the epicenter. During the days before the Wushi EQ in January 2024 Fig. 26 a5-c5), it is similar for the distance of 500 km to that in December, but for 1000 km and 1500 km, more anomalies were located at the south part. After the Wushi EQ in January 2024 Fig. 26 a6-c6), the disturbances disappeared as those in September and October 2023. On the basis of the developing

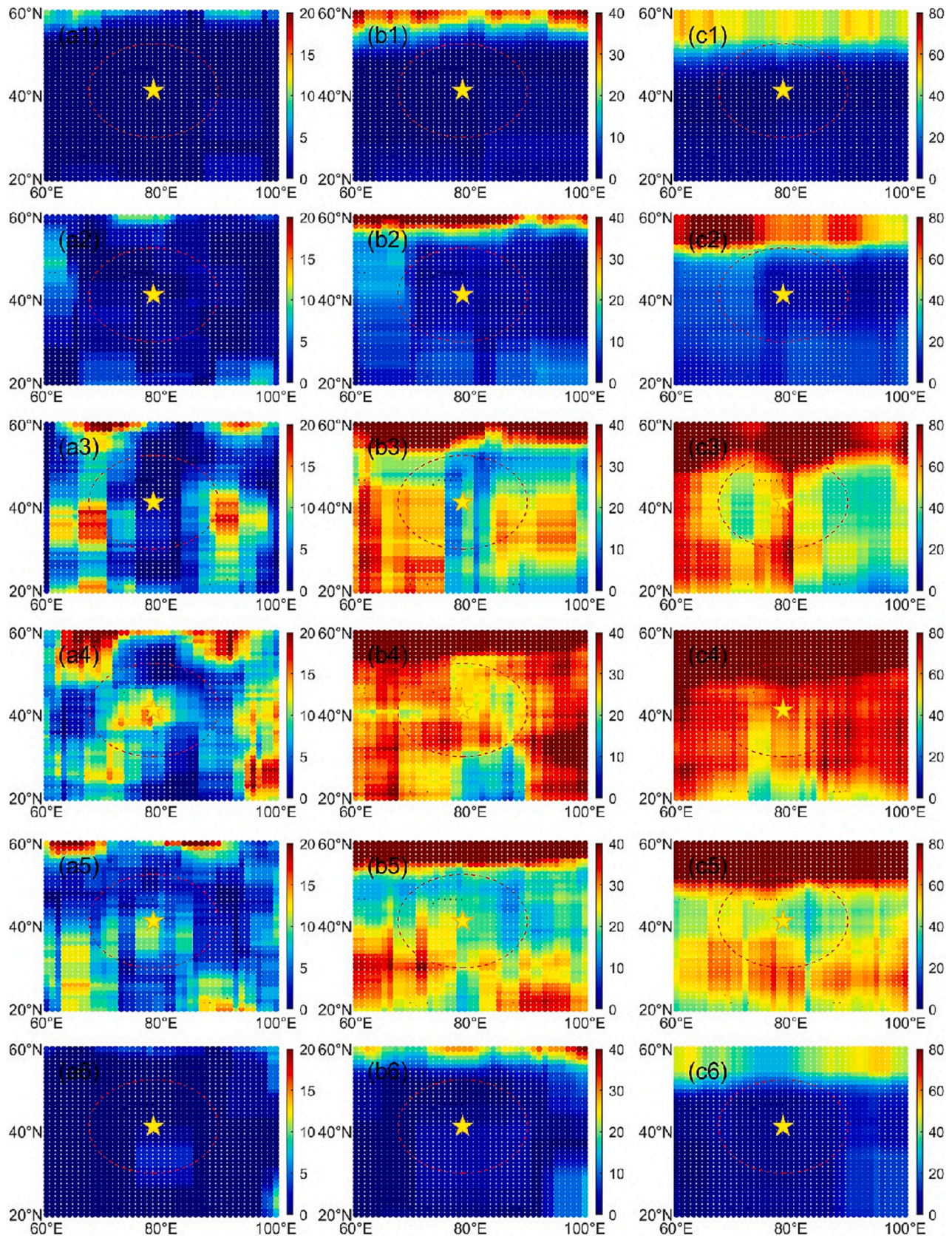


Fig. 26. The number of abnormal signals for Swarm A satellite from 09/2023 to 01/2024 (a1-c1 are corresponding to different distance of 500 km, 1000 km, 1500 km respectively in 09/2023, a2-c2 to 10/2023, a3-c3 for 11/2023, a4-c4 for 12/2023, a5-c5 for 01/2024 before Wushi earthquake, and a6-c6 for 01/2024 after Wushi earthquake; yellow star is the Wushi earthquake epicenter with red dashed line for preparation region radius).

processes of all the magnetic field perturbations in five months around Wushi EQ, it is demonstrated that since November 2023, the anomalies began to generate at a larger area with radius more than 1000 km, and then they gradually concentrated in the epicentral area in a smaller radius of 500 km till the earthquake occurrence, finally they disappeared after the EQ. One thing that should be noticed here that the effects from high latitudes or the equatorial region may influence the scanned results and cause the difficulty in the future earthquake location prediction.

5. Conclusions

In this paper, many parameters in the lithosphere, atmosphere and ionosphere were analyzed in relation to the 2024 Wushi earthquake, and 60 perturbations were revealed around it. The development processes during the preparation period and the relationship between anomaly features and the focal mechanism were discussed, and the earthquake location was also estimated using different parameters. Summarizing all the information obtained in this paper, it can be concluded as follows:

- (1) Lithospheric parameters, including earth resistivity and geoelectric field, showed anomalies several months before the earthquake, illustrating changes in underground conductivity and stress accumulation in the epicentral area. Their orientations indicate the EQ position. Moreover, the weak decreasing trend in *b*-values may be related to the thrust-type focal mechanism.
- (2) Significant perturbations were revealed in the atmosphere, especially during November and December 2023. In addition, OLR showed typical anomalies a few days before and after the EQ, which was the latest observed anomaly among all the parameters. Whether it can be considered a reliable indicator for an impending EQ needs further verification.
- (3) Ionospheric perturbations showed an increased acceleration rate two to three months before the EQ, while the ground-based geomagnetic field exhibited disturbances during the same time period, demonstrating its close relationship with ionospheric perturbations.
- (4) The LAIC process has been modeled around this EQ, and it demonstrates both direct and indirect pathways for abnormal signals propagating from the lithosphere to the ionosphere either directly, or through interactions with the atmosphere. Satellite observations offer advantages in both spatial and temporal coverage, but how to optimally utilize them for practical earthquake prediction, including determining the epicenter location, requires further study.

CRedit authorship contribution statement

Xuemin Zhang: Writing – original draft, Investigation, Funding acquisition. **Angelo De Santis:** Writing – review & editing, Funding acquisition, Formal analysis. **Pan Xiong:** Visualization, Investigation, Data curation. **Gianfranco Cianchini:** Visualization, Investigation, Data curation. **Aisa Yisimayili:** Investigation, Data curation. **Saioa A. Campuzano:** Visualization, Investigation, Data curation. **Na Yang:** Visualization, Investigation, Data curation. **Serena D’Arcangelo:** Visualization, Investigation, Data curation. **Jing Liu:** Visualization, Investigation, Data curation. **Mariagrazia De Caro:** Visualization, Investigation, Data curation. **Xinyan Li:** Investigation, Data curation. **Cristiano Fidani:** Visualization, Investigation, Data curation. **Muping Yang:** Investigation, Data curation. **Martina Orlando:** Visualization, Investigation, Data curation. **Xinyan Ouyang:** Investigation, Data curation. **Loredana Perrone:** Visualization, Investigation. **Hong Liu:** Visualization, Data curation. **Dario Sabbagh:** Visualization, Investigation, Data curation. **Maoning Feng:** Visualization, Investigation, Data curation. **Maurizio Soldani:** Visualization, Investigation, Data curation. **Shukai Wang:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is funded by NSFC project (42361144794, 42274106), the Special Fund of China Seismic Experimental Site (No. CEAIEF20230401), National Abroad Expert Plan (No. DL2023092001L), ISSI-BJ (2019IT#33), and Dragon-6 project (No. 95407, 95456). The Italian authors thank the Italian Space Agency for funding the Limadou Science + Project, and the Ministry of University and Research (MUR) for funding the Unitary Project in the framework of Pianeta Dinamico (“Working Earth”). Other funds came from the Space-It-Up project. The ground-based electromagnetic data and seismic catalog are provided by China Earthquake Networks Center. The Swarm satellite data is available at <https://swarm-diss.eo.esa.int/>. The CSES data is available at <https://www.leos.ac.cn/#/home> after registration. The indices data used here are obtained from GFZ Potsdam (<http://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/geomagnetic-kp-index>). Finally, we would like to thank prof. Roberto Battiston of the Limadou Collaboration Board who suggested to apply a statistical test to verify the determinism of the cumulative number of anomalies in the last three months before the earthquake.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jseae.2025.106916>.

Data availability

Data will be made available on request.

References

- An, Z.H., Du, X.B., Tan, D.C., Fan, Y.Y., Liu, J., Cui, T.F., 2013. Study on the geo-electric field variation of Sichuan Lushan MS7.0 and Wenchuan MS8.0 earthquake. *Chinese J. Geoph. (in Chinese)* 56, 3868–3876.
- Aki, K., 1965. Maximum likelihood estimate of *b* in the formula $\log_{10}N=a-bm$ and its confidence limits. *Bull. Earthquake Res.* 43, 237–239.
- Bleier, T., Freund, F., 2005. Impending earthquakes have been sending us warning signals and people are starting to listen. *IEEE Spectrum* INT 3, 3–7.
- Chen, J., Zhu, S.B., 2020. Spatial and temporal *b*-value precursors preceding the 2008 Wenchuan, China, earthquake ($M_w = 7.9$): implications for earthquake prediction. *Geomat. Nat. Haz. Risk* 11, 1196–1211.
- Chen, J., Xiong, P., Wu, H., Zhang, X.M., Zhang, X.X., Zhang, T., Ruan, Q., 2024. Pre-seismic anomalies and co-seismic disturbance induced by the 2024 M_w 7.1 Wushi earthquake: multi-GNSS observations and modeling. *Geomat. Nat. Haz. Risk* 15, 2422024.
- Cianchini, G., De Santis, A., Di Giovambattista, R., Abbattista, C., Amoroso, L., Campuzano, S.A., Carbone, M., Cesaroni, C., De Santis, A., Marchetti, D., Perrone, L., 2020. Revised accelerated moment release under test: fourteen worldwide real case studies in 2014–2018 and simulations. *Pageoph* 177, 4057–4087.
- De Santis, A., Cianchini, G., Di Giovambattista, R., 2015. Accelerating moment release revisited: examples of application to Italian seismic sequences. *Tectonophysics* 639, 82–98.
- De Santis, A., Marchetti, D., Pavón-Carrasco, F.J., Cianchini, G., Perrone, L., Abbattista, C., Alfonsi, L., Amoroso, L., Campuzano, S.A., Carbone, M., Cesaroni, C., De Franceschi, G., Santis, D.E., Di Giovambattista, R., Ippolito, A., Poiscini, A., Sabbagh, D., Soldani, M., Santoro, F., Spogli, L., Haagmans, R., 2019. Precursory worldwide signatures of earthquake occurrences on Swarm satellite data. *Sci. Rep.* 9, 20287.
- De Santis, A., Perrone, L., Calcarà, M., Campuzano, S.A., Cianchini, G., D’Arcangelo, S., Di Mauro, D., Marchetti, D., Nardi, A., Orlando, M., Piscini, A., Sabbagh, D., Soldani, M., 2022. A comprehensive multiparametric and multilayer approach to study the preparation phase of large earthquakes from ground to space: The case study of the June 15 2019, $M_{7.2}$ Kermadec Islands (New Zealand) earthquake. *Remote Sens. Environ.* 283, 113325.
- Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. *Pageoph* 117, 1025–1044.

- Du, X.B., Li, N., Ye, Q., Ma, Z.H., Yan, R., 2007. A possible reason for the anisotropic changes in apparent resistivity near the focal region of strong earthquake. *Chinese J. Geophys. (in Chinese)* 50, 1802–1810.
- Famiglietti, N.A., Cheloni, D., Caputo, R., Vicari, A., 2025. Geodetic model of the 2024 January 22 Mw 7.0 Wushi (northwestern China) earthquake and Mw 5.7 aftershock from inversion of InSAR data. *Geophys. J. Int.* 241, 941–953.
- Freund, F., 2011. Pre-earthquake signals: underlying physical processes. *J. Asian Earth Sci.* 41 (4–5), 383–400.
- Gruber, A., Krueger, A.F., 1984. The status of the NOAA outgoing longwave radiation data set. *Bull. Am. Meteorol. Soc.* 65, 958–962.
- Guo, N., Wu, Y., Zhu, S., Chen, C., 2024. Coseismic deformation and interseismic strain accumulation of the 2024 MS 7.1 Wushi earthquake in Xinjiang, China. *Adv. Space Res.* 74, 1586–1594.
- Gutenberg, B., Richter, C.F., 1944. Frequency of earthquakes in California. *Bull. Seismol. Soc. Am.* 34, 185–188.
- Hayakawa, M., 2004. Electromagnetic phenomena associated with earthquakes: a frontier in terrestrial electromagnetic noise environment. *Recent Res. Develop. Geoph.* 6, 81–112.
- Hayakawa, M., Schekotov, A., Izutsu, J., Nickolaenko, A.P., Hobara, Y., 2023. Seismogenic ULF/ELF Wave phenomena: recent advances and future perspectives. *Open J. Earthquake Res.* 12, 45–113.
- Hayakawa, M., Hobara, Y., Michimoto, K., Nickolaenko, A.P., 2024. The generation of seismogenic anomalous electric fields in the lower atmosphere, and its application to very-high-frequency and very-low-frequency/low-frequency emissions: a review. *Atmos.* 15, 1173.
- Ippolito, A., Perrone, L., De Santis, A., Sabbagh, D., 2020. Ionosonde data analysis in relation to the 2016 Central Italian earthquakes. *Geosciences* 10, 354.
- Johnston, M., Uyeda, S., 1999. Electromagnetic methods for monitoring earthquakes and volcanic eruptions. IUGG 99 abstract, Birmingham. A72–A83.
- Korsunova, L.P., Khagai, V.V., 2008. Analysis of seismo-ionospheric disturbances at the chain of Japanese stations for vertical sounding of the ionosphere. *Geomag. Aeron.* 48, 392–399.
- Le, H., Liu, L.Y., Liu, L., 2011. A statistical analysis of ionospheric anomalies before 736 M6.0+ earthquakes during 2002–2010. *J. Geophys. Res.* 116, A02303.
- Liu, J., Qiao, X., Zhang, X., Wang, Z., Zhou, C., Zhang, Y., 2022. Using a spatial analysis method to study the seismo-ionospheric disturbances of electron density observed by China seismo-electromagnetic satellite. *Front. Earth Sci.* 10, 811658.
- Lu, J., Xue, S.Z., Qian, F.Y., Zhao, Y.L., Guan, H.P., Mao, X.J., Ruan, A.G., Yu, S.R., Xiao, W.J., 2004. Unexpected changes in resistivity monitoring for earthquakes of the Longmen Shan in Sichuan, China, with a fixed Schlumberger sounding array. *Phys. Earth Planet. In.* 145, 87–97.
- Massey, F.J., 1951. The Kolmogorov-Smirnov Test for Goodness of Fit. *J. Am. Stat. Assoc.* 46 (253), 68–78.
- Nanjo, K.Z., Hirata, N., Obara, K., Kasahara, K., 2012. Decade-scale decrease in b value prior to the M9-class 2011 Tohoku and 2004 Sumatra quakes. *Geophys. Res. Lett.* 39, L20304.
- Parrot, M., 1994. Statistical study of ELF/VLF emissions recorded by a low-altitude satellite during seismic events. *J. Geophys. Res.* 99 (A12), 23339–23347.
- Perrone, L.; De Santis, Angelo; Abbattista, C.; Alfonsi, L.; Amoroso, L.; Carbone, M.; Cesaroni, C.; Cianchini, G.; De Franceschi, G.; De Santis, Anna, Di Giovambattista, R., Marchetti, D., Pavon-Carrasco, F.J., Piscini, A., Spogli, L., Santoro, F., 2018. Ionospheric Anomalies Detected by Ionosonde and Possibly Related to Crustal Earthquakes in Greece. *Ann. Geophys.* 36, 361–371.
- Piersanti, M., Materassi, M., Battiston, R., Carbone, V., Cicone, A., D'Angelo, G., Diego, P., Ubertini, P., 2020. Magnetospheric–Ionospheric–Lithospheric Coupling Model. 1: Observations during the 5 August 2018 Bayan Earthquake. *Remote Sens.* 2020, 12, 3299.
- Piscini, A., De Santis, A., Marchetti, D., Cianchini, G., 2017. A multi-parametric climatological approach to study the 2016 Amatrice–Norcia (Central Italy) earthquake preparatory phase. *Pure Appl. Geophys.* 174, 3673–3688.
- Pulinets, S.A., Ouzounov, D., 2011. Lithosphere-atmosphere-ionosphere coupling (LAIC) model: an unified concept for earthquake precursors validation. *J. Asian Earth Sci.* 41, 371–382.
- Pulinets, S.A., 2023. Physical bases of the short-term forecast of earthquakes. *Astron. Astrophys. Trans.* 34, 65–84.
- Qiu, J., Sun, J., Ji, L., 2024. The 2024 Mw7.1 Wushi earthquake: a thrust and strike-slip event unveiling the seismic mechanisms of the South Tian Shan's thick-skin tectonics. *Remote Sens. (Basel)* 16, 2937.
- Scholz, C.H., 1968. The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes. *Bull. Seismol. Soc. Am.* 58, 399–415.
- Schorlemmer, D., Wiemer, S., 2005. Microseismicity data forecasts rupture area. *Nature* 434, 1086.
- Shen, X.H., Zong, Q.-G., Zhang, X.M., 2018. Introduction to special section on the China Seismo-Electromagnetic Satellite and initial results. *Earth Planet. Phys.* 2, 439–443.
- Song, C.Y., Song, Z.P., Wen, Y.Y., Nie, X.H., Gao, G., Zhang, T., Aisa, Y., Cai, Q., 2024. Anomalies characteristics and prediction process before the 2024 Wushi Ms 7.1 earthquake in Xinjiang. *Earthquake Res. China* 40 (3), 551–562 in Chinese with English abstract.
- Tian, W., Zhang, Y., Ju, C., Zhang, S., Feng, M., Liu, F., 2024. An improved pattern informatics method for extracting ionospheric disturbances related to seismicity based on CSES data: a case study of the Mw7.3 Maduo earthquake. *Earth Space Sci.* 11, e2024EA003687.
- Wang, M., Shen, Z.K., 2020. Present-day crustal deformation of continental China derived from GPS and its tectonic implications. *J. Geophys. Res. Solid Earth* 125, e2019JB018774.
- Wang, Q., Ding, G., Qiao, X., Wang, X., You, X., 2000. Recent rapid shortening of crust across the Tianshan Mts. and relative motion of tectonic blocks in the north and south. *Chinese Sci. Bull.* 45, 1995–1999.
- Wang, X., Xu, C., Wen, Y., Zhao, X., Wang, S., Xu, G., 2024. Distribution of interseismic coupling along the Maidan Fault in Tianshan before the 2024 Mw 7.0 Wushi earthquake. *Geophys. Res. Lett.* 51, e2024GL111472.
- Wiemer, S., Wyss, M., 2000. Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the Western United States, and Japan. *Bull. Seism. Soc. Am.* 90, 85–869.
- Xie, T., Liu, J., Lu, J., Li, M., Yao, L., Wang, Y.L., Yu, C., 2018. Retrospective analysis on electromagnetic anomalies observed by ground fixed station before the 2008 Wenchuan Ms 8.0 earthquake. *Chinese J. Geophys. (In Chinese)* 61, 1922–1937.
- Xie, T., Chen, B., Wu, L., Dai, W., Kuang, C., Miao, Z., 2021. Detecting seismo-ionospheric anomalies possibly associated with the 2019 Ridgecrest (California) earthquakes by GNSS, CSES, and Swarm observations. *J. Geophys. Res. Space Phys.* 126, e2020JA028761.
- Xu, C., and Li, T., 2024. Examples of coseismic landslides triggered by the 2024 Wushi earthquake. *Knowledge Network for Biocomplexity*. 10. 5063/F1CR5RVN.
- Yamazaki, Y., Maute, A., 2017. Sq and EEJ—a review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. *Space Sci. Rev.* 206, 299–405.
- Yang, S.-S., Asano, T., Hayakawa, M., 2019. Abnormal gravity wave activity in the stratosphere prior to the 2016 Kumamoto earthquakes. *J. Geophys. Res. Space Phys.* 124, 1410–1425.
- Zhang, X., De Santis, A., Liu, J., Campuzano, S.A., Yang, N., Gianfranco, C., Ouyang, X.Y., D'Arcangelo, S., Yang, M.P., De Caro, M., Li, X.Y., Fidani, C., Liu, H., Orlando, M., Nie, L., Perrone, L., Piscini, A., Dong, L., Sabbagh, D., Soldani, M., Xiong, P., 2024. Pre-earthquake oscillating and accelerating patterns in the lithosphere-atmosphere-ionosphere coupling (LAIC) before the 2022 Luding (China) Ms6.8 earthquake. *Remote Sens.* 16, 2381.
- Zhao, G., Zhang, X., Cai, J., Zhan, Y., Ma, Q., Tang, J., Du, X.B., Han, B., Wang, L.F., Chen, X.B., Xiao, Q.B., Sun, X.Y., Dong, Z.Y., Wang, J.J., Zhang, J.H., Fan, Y., Ye, T., 2022. A review of seismo-electromagnetic research in China. *Sci. China Earth Sci.* 65, 1229–1246.
- Zhao, Y.Z., Wu, Z.L., 2008. Mapping the b-Values along the Longmenshan Fault Zone before and after the 12 May 2008, Wenchuan, China, MS 8.0 Earthquake. *Nat. Hazards Earth Syst. Sci.* 8, 1375–1385.
- Zheng, R., Zou, R., Dong, R., Fang, Z., Wang, Q., 2024. The 2024 Mw 7.0 Wushi earthquake in Southern Tianshan Convergent zone: finite-fault model for the Coseismic rupture and aftershock. *Seismol. Res. Lett.* 96 (2A), 816–827.
- Zhu, S., Zhan, W., Liu, X., Liang, H.B., 2024. Deformation characteristics before the M7.1 earthquake in Wushi, Xinjiang, from GNSS observation data. *China Earthquake Eng. J.* 46, 973–981. In Chinese with English abstract.
- Zubovich, A., Wang, X., Scherba, Y., Schelochkov, G., Reilinger, R., Reigber, C., Mosienko, O., Molnar, P., Michajljow, W., Makarov, V., Li, J., Kuzikov, S., Herring, T., Hamburger, M., Hager, B.H., Dang, Y., Bragin, V., Beisenbaev, R., 2010. GPS velocity field for the Tien Shan and surrounding regions. *Tectonics* 29, TC6014.



Deep multiparameter analysis of the precursory lithospheric, atmospheric and ionospheric anomalies before and during the 28 March 2025 Mw7.7 Myanmar-Burma earthquake

Angelo De Santis^{a,*}, Xuemin Zhang^b, Saioa A. Campuzano^{a,c}, Pan Xiong^b, Gianfranco Cianchini^{a,d}, Jing Liu^b, Serena D'Arcangelo^a, Na Yang^b, Mariagrazia De Caro^a, Xinyan Ouyang^b, Martina Orlando^{a,e}, Maoning Feng^b, Loredana Perrone^a, Yongxian Zhang^b, Dario Sabbagh^a, Xinyi Jia^b, Maurizio Soldani^a, Hong Liu^b, Ariana Varela-Mendez^c

^a Istituto Nazionale di Geofisica e Vulcanologia, 00143 Rome, Italy

^b Institute of Earthquake Forecasting, 100036 Beijing, China

^c Department of Physics of the Earth and Astrophysics, Universidad Complutense de Madrid (UCM), 28040 Madrid, Spain

^d IAPS-INAF Istituto di Astrofisica e Planetologia Spaziali, 00133 Rome, Italy

^e Dipartimento di Scienze, Università Roma TRE, 00154 Rome, Italy

ARTICLE INFO

Keywords:

Earthquake precursors
Lithosphere-Atmosphere-Ionosphere Coupling (LAIC)
Myanmar earthquake
Critical point
Sigmoid pattern

ABSTRACT

On March 28, 2025, at 06:20:52 UTC (12:50:52 LT), a catastrophic Mw 7.7 earthquake occurred in central Myanmar-Burma, marking one of the most devastating seismic events in recent history. The earthquake occurred along the Sagaing Fault (SF), a highly active right-lateral strike-slip fault that accommodates the northward motion of the Indian Plate relative to the Sunda Plate. A multiparametric approach has been applied in order to study the preparation phase of this great earthquake, analyzing data from ground, atmosphere and satellite, with a total of eleven kinds of potential earthquake precursors. The results show a sigmoid pattern of all anomalies before and during the earthquake occurrence, typical of a critical system approaching a critical point. The sequence of the anomalies and their space and time concentration support the lithosphere-atmosphere-ionosphere coupling (LAIC) model.

1. Introduction

On March 28, 2025, at 06:20:52 UTC (12:50:52 LT), a powerful Mw 7.7 earthquake struck central Myanmar (Burma), marking one of the most devastating seismic events in the region's recent history. With an epicenter located near Mandalay (21.996°N, 95.926°E) and a focal depth of approximately 10 km, the shallow nature of the earthquake contributed to severe ground shaking and widespread destruction across central and southern Myanmar. Urban centers such as Mandalay, Sagaing, Bago, and Yangon experienced intense shaking, resulting in substantial damage to buildings, critical infrastructure, and loss of life. The earthquake's effects were felt far beyond Myanmar's borders, with ground motion reported in neighboring Thailand, India, and Bangladesh, where precautionary evacuations and structural impacts underscored the regional significance of this tectonic rupture.

The earthquake occurred along the Sagaing Fault (SF), a highly active right-lateral (dextral) strike-slip fault, product of oblique convergence between India and Sunda plates (Pivnik et al., 1998; Kundu and Gahalaut, 2012), that plays a key role in accommodating the northward motion of the Indian Plate relative to the Sunda Plate. The SF runs for ~1200 km in a north-south orientation across the length of Myanmar and has long been recognized as a major seismic hazard. The relative plate motion in this region—estimated at approximately 20 mm/year—drives a continuous buildup of tectonic stress along the fault, periodically released in the form of large-magnitude earthquakes (Wang et al., 2014).

Seismological analysis indicates that this big event was driven by horizontal slip along a ~ 200 km segment of the fault, consistent with past strike-slip faulting mechanisms observed in the region. Historical records highlight the recurrence of major earthquakes along this

* Corresponding author.

E-mail address: angelo.desantis@ingv.it (A. De Santis).

<https://doi.org/10.1016/j.tecto.2026.231101>

Received 24 September 2025; Received in revised form 8 January 2026; Accepted 25 January 2026

Available online 30 January 2026

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structure, including the 1839 Ava earthquake (M 8.3), the 1930 Swa earthquake (M 7.3), the 1995 Myanmar-China border event (M 7.3), and the 2012 Thabeikkyin–Shwebo earthquake (M 6.8). The 2025 earthquake now joins this sequence as further evidence of the fault's sustained seismicogenic potential.

Geodetic and seismological studies over the past two decades had increasingly pointed to the middle segment of the SF as a zone of elevated seismic hazard. Vigny et al. (2003) identified crustal deformation patterns indicating strain accumulation. Hurukawa and Maung Maung (2011) documented seismic gaps along the SF, while Wang et al. (2014) estimated strain rates between 18 and 20 mm/year—suggesting high tectonic loading. More recent research by Yang et al. (2023, 2024) applied probabilistic hazard assessment and seismicity analysis (e.g., *b*-values) to confirm that the central section of the fault was both locked and critically stressed.

Despite these scientific warnings, rapid urbanization and limited implementation of earthquake-resilient infrastructure left Myanmar's population vulnerable. Aung et al. (2020) stressed the urgent need for revised building codes and early warning systems, while Traitangwong et al. (2024) observed possible precursory quiescence— anomalies that may serve as useful signals in future prediction frameworks.

The 2025 Myanmar–Burma earthquake thus serves not only as a tragic reminder of the region's vulnerability to major tectonic events, but also as a valuable case study for understanding active strike-slip fault dynamics in continental collision zones. This paper aims to analyze the pre-seismic features and regional implications of the event, while also exploring its broader significance for earthquake forecasting.

As a pure seismological approach to study the earthquake preparation phase can be weak with a few exceptions (e.g. Sobolev, 2001), in this study we will combine the latter with a multiparametric approach, including also non-seismic data (e.g. Cicerone et al., 2009). In particular, seismic data were analysed, together with three atmospheric parameters, i.e. SKT (skin temperature), SLHF (surface latent heat flux), and OLR (outgoing longwave radiation). Additionally, ionospheric data, including Global Ionospheric Map (GIM) TEC, magnetic field and electron density (Ne) measurements from Swarm satellites, were examined to detect potential precursory signals. These data have been presented to illustrate variations leading up to the earthquake, taking into account that on March 26 and 27, 2025 there were two magnetic storms of G2 and G1 levels, respectively.

The multiparametric approach here applied is similar to the one already applied to other recent case studies, i.e. the February 6, 2023 Mw 7.9 Kahramanmaraş earthquake Doublet in SE Türkiye (Cianchini et al., 2024) and the January 22, 2024 Mw7.1 Wushi earthquake (Zhang et al., 2026). This approach complements the seismological methods, e.g. Melgar et al. (2023) for the former case and Qiu et al. (2024) for the latter case, extending the investigation backward in time, i.e. to the earthquake preparation phase, and in space, i.e. to the above atmosphere and ionosphere.

2. Geological setting

Myanmar occupies a tectonically complex region at the boundary between the Indian Plate and the Sunda Plate, within the broader convergence zone of the Indo-Eurasian collision system. The ongoing oblique convergence between these plates has given rise to a diverse array of geological structures, including active subduction zones, fold-and-thrust belts, and strike-slip fault systems. Among these, the SF is the dominant active fault accommodating much of the right-lateral motion between the Indian and Sunda plates.

The SF is a north–south trending fault, extending from the Andaman Sea in the south to the eastern Himalayan syntaxis in the north. It bisects Myanmar longitudinally, passing through or near major population centers such as Yangon, Bago, Mandalay, and Myitkyina. The fault effectively accommodates the northward movement of the Indian Plate, which advances at an average rate of ~20 mm/year relative to the

Sunda Plate (Wang et al., 2011, 2014). This rapid motion leads to the accumulation of significant shear strain, making the SF one of the most seismically hazardous structures in Southeast Asia.

Geological and geodetic investigations have revealed heterogeneous behaviour along the fault's length. Multiple segments exhibit varying slip rates, degrees of coupling, and seismic histories. The central segment—where the 2025 Mandalay earthquake occurred—is particularly significant. It had previously been identified as a locked section with elevated strain accumulation and seismic quiescence, indicative of a potential rupture gap (Yang et al., 2023; Xiong et al., 2017; Traitangwong et al., 2024).

The structural expression of the SF is clearly visible in the geomorphology of central Myanmar. Linear valleys, offset river channels, and strike-slip scarps mark its trace. Paleoseismological and GPS studies (e.g., Vigny et al., 2003; Aung et al., 2020) have documented both Holocene activity and present-day crustal deformation patterns, highlighting the fault's long-term significance in shaping the tectonic evolution of Myanmar.

The proximity of the SF to densely populated urban areas amplifies the seismic risk it poses. Inadequate enforcement of building codes, combined with rapid urban expansion along the fault corridor, has created high levels of exposure and vulnerability. Consequently, the SF is not only a geological boundary but also a critical societal hazard, demanding sustained attention from both the scientific and policy-making communities.

3. Seismic data analysis

The earthquake that struck central Myanmar on March 28, 2025, was recorded by several international seismological centers, each reporting slightly different estimates of the hypocentral depth, epicentral location, and magnitude. The “United States Geological Survey” (USGS) estimated a 7.7 moment magnitude (*M_w*) indicating a location with coordinates 22.001° N latitude, 95.925° E longitude and a shallow depth of 10 km (<https://earthquake.usgs.gov/earthquakes/eventpage/us7000pn9s/executive>).

The “Istituto Nazionale di Geofisica e Vulcanologia” (INGV) confirmed the same *M_w*7.7, with the epicenter located at 21.8109° N latitude and 95.8604° E longitude, at a depth of 17 km (<https://terremoti.ingv.it/event/42162362>). The Thai Earthquake Catalog, however, reported a slightly higher magnitude of 8.2, with epicentral coordinates of 21.682° N and 96.121° E, and a depth of 17 km, consistent with the INGV data (<https://earthquake.tmd.go.th/inside-info.html?earthquake=12893>).

The discrepancies in the magnitude estimates are likely due to different regional attenuation models and moment tensor solutions. However, in the following, for convenience, we used the earthquake information as given by USGS.

Based on the USGS information, the strike-slip fault mechanism is consistent with the known kinematics of the SF. The rupture was characterized by right-lateral (dextral) displacement along a nearly vertical fault plane with a north-south direction. Initial modeling indicated a rupture length of approximately 200 km, lasting around 90 s. Subsequent waveform inversion and aftershock distribution analyses revised the rupture extent to about 460 km with a width of 15 km, suggesting complex segmentation and possibly multi-fault interaction (<https://earthquake.usgs.gov/earthquakes/eventpage/us7000pn9s/executive>). This rupture length is consistent with other major events along the SF and aligns with known fault geometry and historical rupture patterns.

3.1. *b*-value

This study estimates the *b*-value from the Gutenberg–Richter law (Gutenberg and Richter, 1944) and the Revised Accelerated Moment Release (R-AMR) as key components of the seismological analysis.

The *b*-value is a key empirical parameter that characterizes the

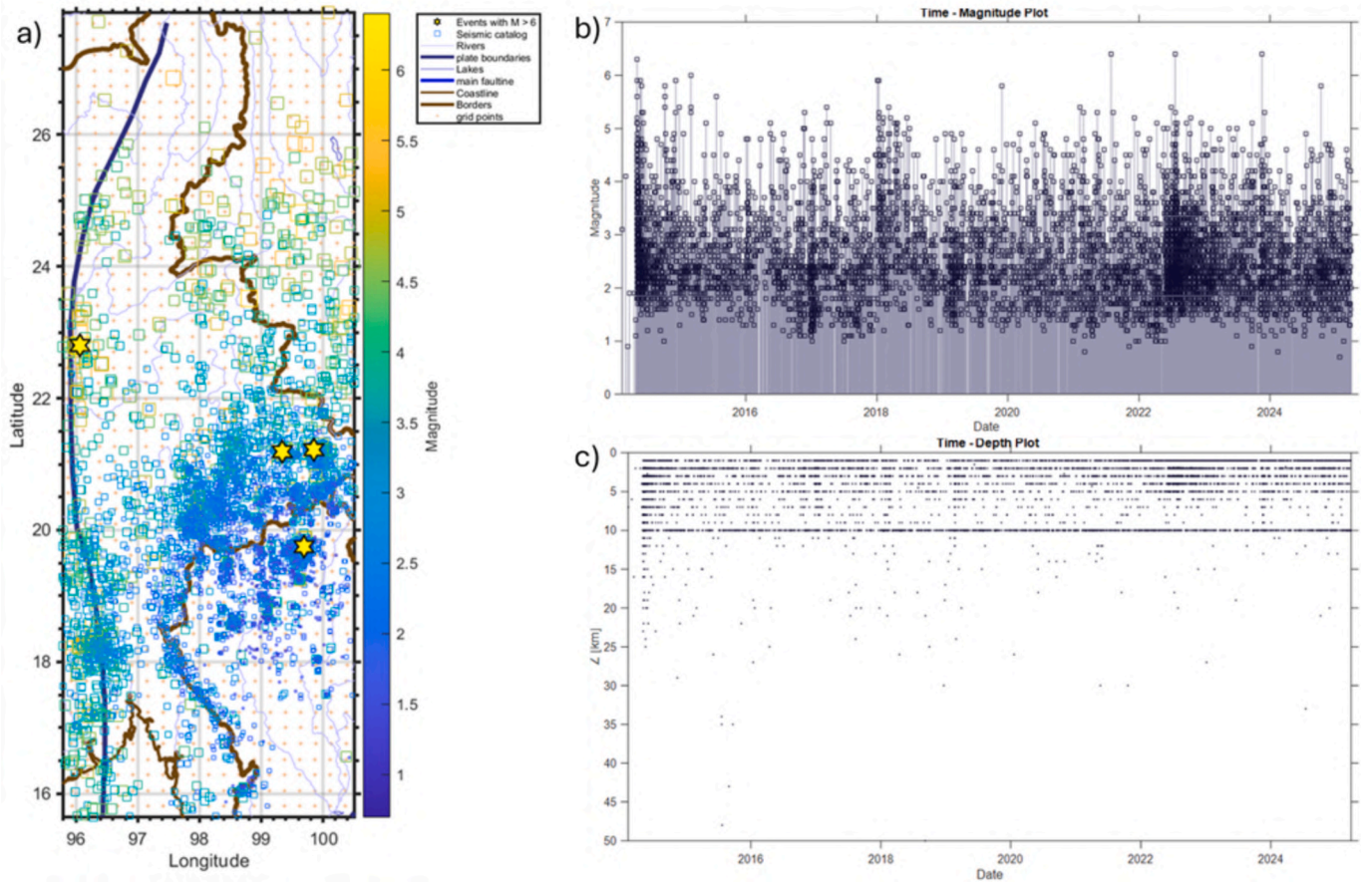


Fig. 1. a) Spatial distribution of events from 2014- 02-11 to 2025-03-27. The yellow stars represent events with $M > 6$ in the area of interest. b) Magnitude distribution over time; c) Depth distribution of events over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

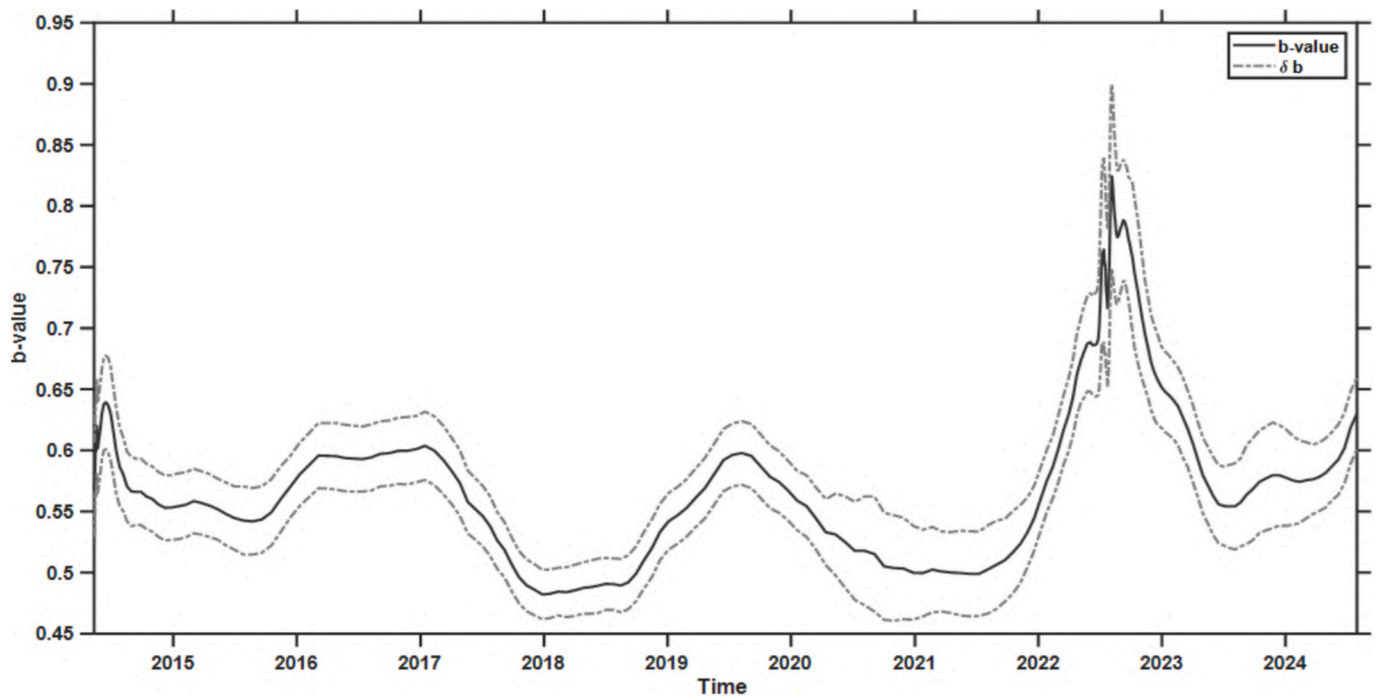


Fig. 2. Trend of the b-value over time (from February 11, 2014, to March 27, 2025).

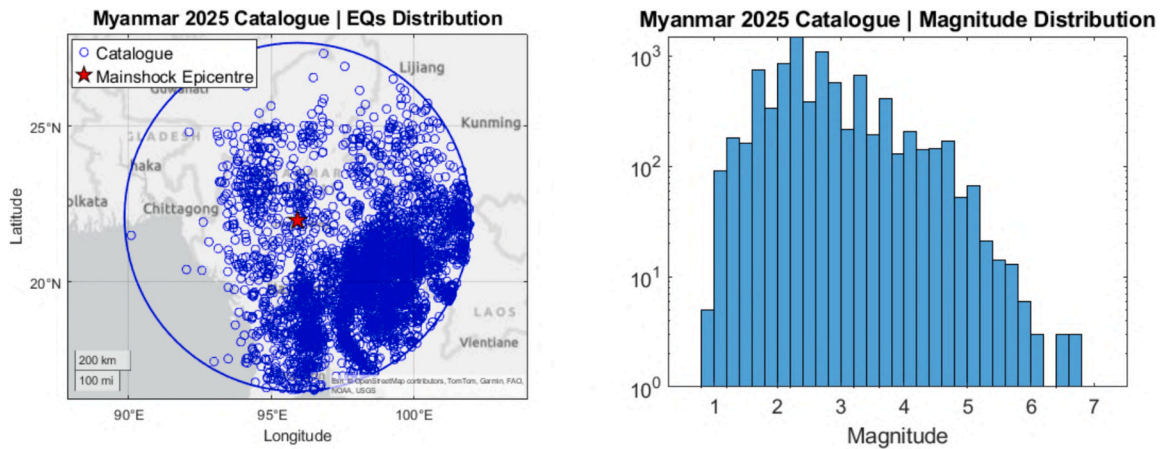


Fig. 3. Left: Spatial distribution of the earthquakes (small blue circles) of the catalog within an area of 600 km of radius (delimited by the large blue circle) around the epicenter of the mainshock (red star) for the interval 2014–2025; Right: Magnitude distribution of the analysed events. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

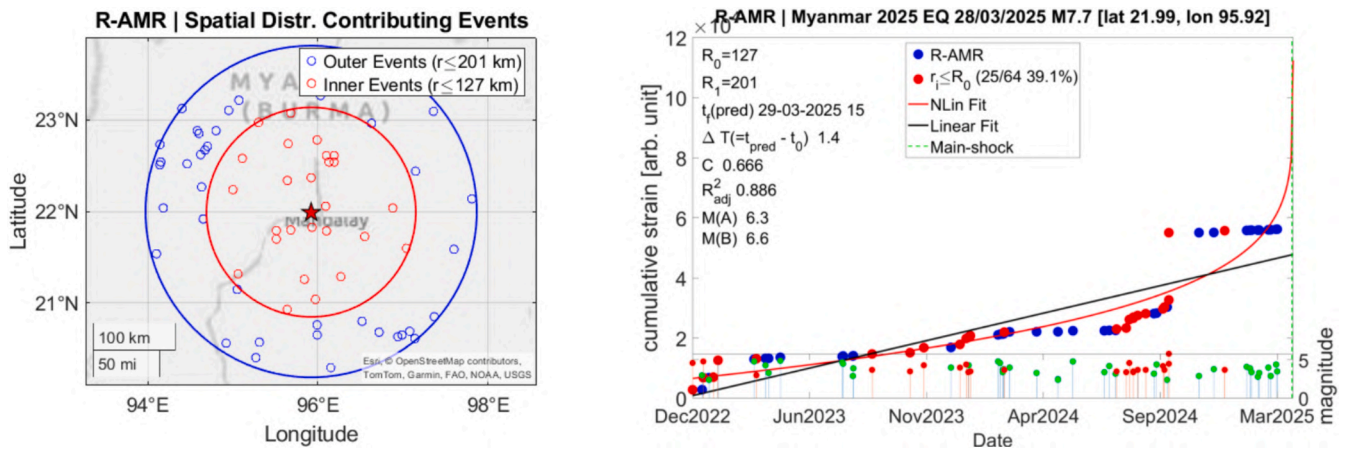


Fig. 4. Left: Spatial distribution of the earthquakes that contributed to the accelerating character of the seismicity in a region of 201 km radius (large blue circle with radius R_1) as result of the R-AMR analysis; the red circles are those events (inner events) on the seismogenic fault (within the large red circle with radius R_0). Right: Cumulative strain with time from the selected earthquakes with significant acceleration ($C \cong 0.66$) as detected from December 2022 to the mainshock (28 March 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

frequency-magnitude distribution of earthquakes. It provides valuable insight into the seismicity of a region and is strongly influenced by the stress conditions within the Earth's crust. Notably, several studies have observed that the b -value tends to decrease prior to major seismic events, indicating increasing stress and a heightened occurrence and intensity of foreshocks (Scholz, 1968; Nuannin, 2006; Gulia and Wiemer, 2019).

To ensure a reliable estimate of the b -value, it is essential to accurately determine the magnitude of completeness (M_c), the minimum magnitude above which the earthquake catalog is considered complete. The value of M_c is influenced by the sensitivity and spatial coverage of the seismic network in the study area.

Thus, the analysis focused on the region surrounding SF. It was observed that, during the early years of seismic monitoring, the catalog had some gaps, particularly the absence of depth data for many events prior to February 2014. To ensure a reliable and consistent dataset, the analysis was restricted to the period from February 11, 2014, to March 27, 2025, i.e. to the day before the mainshock. During this time, 7405 earthquakes were recorded, with magnitudes ranging from 0.7 to 6.6 and focal depths between 1 and 50 km (Fig. 1).

In this study, the value of M_c was calculated using the maximum curvature method (Wiemer and Wyss, 2000), one of the most widely used techniques for estimating the completeness threshold in seismic catalogs, yielding a value of 2.2. As a result, an additional filter was

applied to the dataset, analyzing only $M \geq 2.2$ earthquakes in the same space and time intervals, which allowed for the estimation of the b -value over time, using the Aki (1965) formula applied to a reduced dataset of 5059 events (Fig. 2).

It is interesting to note that low values (<1.0) are persistent throughout the studied period, particularly in the segment that later ruptured during the March 28 earthquake. This low b -value, along with a significant reduction in smaller events before the main shock, could reflect the suppression of foreshocks due to fault locking, a phenomenon commonly observed in major surface faulting systems before rupture. These findings are in agreement with recent literature identifying seismic gaps and stress build-up in this region (e.g., Yang et al., 2024; Traitangwong et al., 2024). A large peak emerges in 2022 due to some significant seismicity in the area (a M6.1 earthquake near Kengtung in Shan State on July 21; and several other magnitude M5+ events, in Sagaing and Mawlaik), after which a significant decrease occurred lasting for about one year and ending just one year before the Myanmar-Burma earthquake and finally a little increase.

3.2. Revised accelerated moment release

The Accelerated Moment Release (AMR) is a way to test the character of the seismicity in a certain active region by means of the analysis

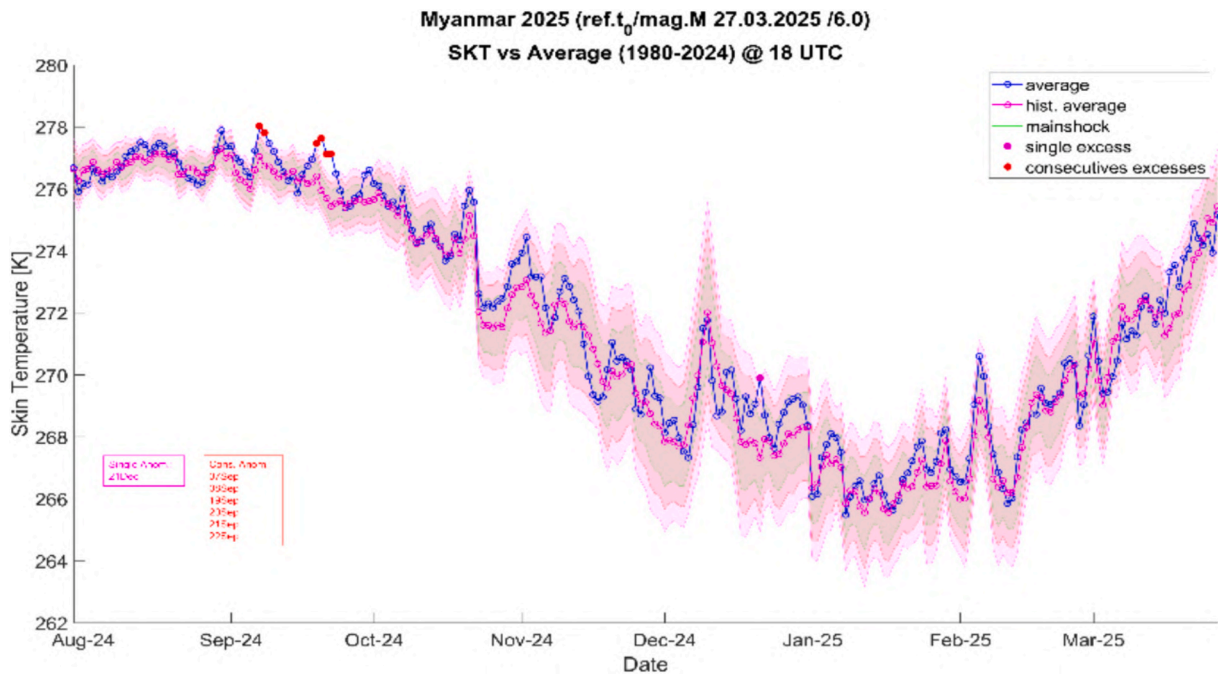


Fig. 5. Temporal behaviour of the SKT in eight months before the mainshock.

of the cumulative moment (or strain, when the square root of the energy of the events is considered) behaviour (see De Santis et al., 2015; Cianchini et al., 2020 for details). Fig. 3 shows the spatial and magnitude distribution of the analysed catalog: while the analysis was conducted on the catalog limited to the period indicated above (2014–2025, mainshock excluded), the area remained maximized to the Dobrovolsky's radius ($\rho = 10^{0.43M}$; Dobrovolsky et al., 1979), letting the R-AMR algorithm select the best regions, where acceleration may be disclosed (Cianchini et al., 2020).

The R-AMR analysis has evidenced a clear acceleration ($C\text{-value} \cong 0.66$) in a narrow region close to the mainshock epicenter and due to activity both on the fault (red dots) and around it (blue dots) within a distance of around 200 km: here, a total number of 64 events contributed to giving an accelerated character to the seismicity of the area before the mainshock (see Fig. 4).

What emerges particularly, is the crucial contribution given by the large foreshock ($M5.8$, 11 October 2024) occurring on the fault. After that, some other earthquakes followed there near driving the accelerating character of the seismicity. One of the most striking results is the proximity of the calculated failure time t_f to that of the mainshock ($\Delta t \cong 1.4$ day late), although the computed expected magnitudes $M(A)$ and $M(B)$ are slightly underestimated (6.3–6.6 instead of 7.7).

The R-AMR analysis highlights a progressive intensification of cumulative deformation in the period preceding the earthquake of March 28, 2025. The nonlinear model describes the evolution of the series more effectively than linear regression, as suggested by the high value of R^2_{adj} , indicating that the release growth does not proceed uniformly but shows a recognizable acceleration. The critical time estimated by the fit, close to March 29, 2025, is almost coincident with the time of the mainshock, suggesting that the forecast function correctly identifies the moment of rupture within the analysed interval. The distribution of the events included in the analysis (with approximately 39% within R_0) and their contribution to the cumulative moment indicate that the accelerated trend does not depend on a single anomalous event (outlier), but on a progressive evolution of the catalog. Overall, the observed behaviour is consistent with the theoretical predictions of the R-AMR model and suggests that, in this region, deformation showed a nonlinear increase approaching the main earthquake.

The convergence of evidence from independent catalogs and

multiple analytical methods highlights several key pre-earthquake indicators:

- Persistent seismic quiescence along the central SF
- Decreasing b -value, lasting about one year from two years before the earthquake and consistent with fault stress accumulation
- Low magnitude of completeness (M_c) confirming catalog robustness
- Extended rupture length (~ 400 km) indicating a major structural release
- Accelerated seismicity detected by R-AMR

These findings support the notion that the 2025 Myanmar-Burma earthquake was preceded by measurable precursory seismic patterns and modern seismological tools—particularly b -value mapping and R-AMR analysis—can provide valuable foresight into the preparatory phases of major fault ruptures.

4. Atmospheric data analysis

The study of atmospheric anomalies before major earthquakes has gained significant attention in recent years as part of multidisciplinary efforts to identify reliable precursors to seismic events (e.g. Tronin, 2000; Ouzounov et al., 2018; Tramutoli et al., 2018). For the 2025 Mw 7.7 Myanmar-Burma earthquake, three key atmospheric parameters were analysed: SKT, SLHF, and OLR.

4.1. SKT

SKT refers to the radiative temperature of the Earth's surface, which can be influenced by geophysical processes such as tectonic stress accumulation. Prior to the 2025 earthquake, anomalies in SKT were observed in the epicentral region (Figs. 5 and 6). These anomalies likely resulted from increased heat flux caused by stress-induced crustal deformation along the SF. Elevated SKT values have been documented in previous studies of large earthquakes and are thought to reflect thermal anomalies associated with fault slip or fluid migration (e.g. Piscini et al., 2017; De Santis et al., 2020).

Please note that the time interval of the atmospheric data analysis is shorter than that used for seismology. This difference reflects the

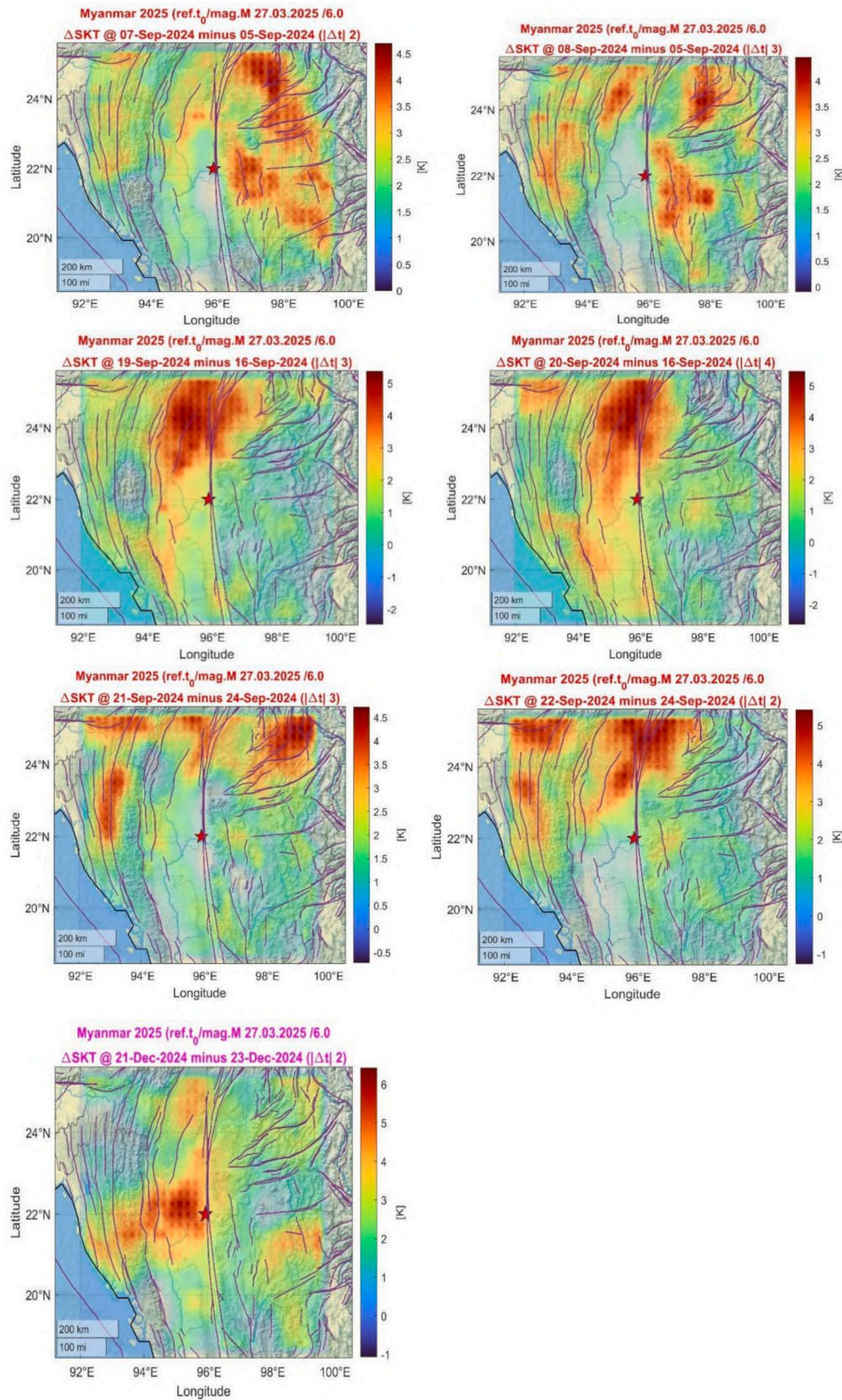


Fig. 6. SKT spatial distribution for the detected anomalies. The maps show the spatial distribution of the difference between the "anomalous" SKT -represented in Fig. 5 by red dots (for persistent, i.e. at least 2-days lasting anomalies) and by magenta (for less than 2-day anomalies) - and the closest (in time) SKT, for which the average almost equals the actual present value. So, for example, the first map is the difference between 7 Sept. (the first anomalous day) and 5 Sept, the closest day when average and actual value almost coincide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

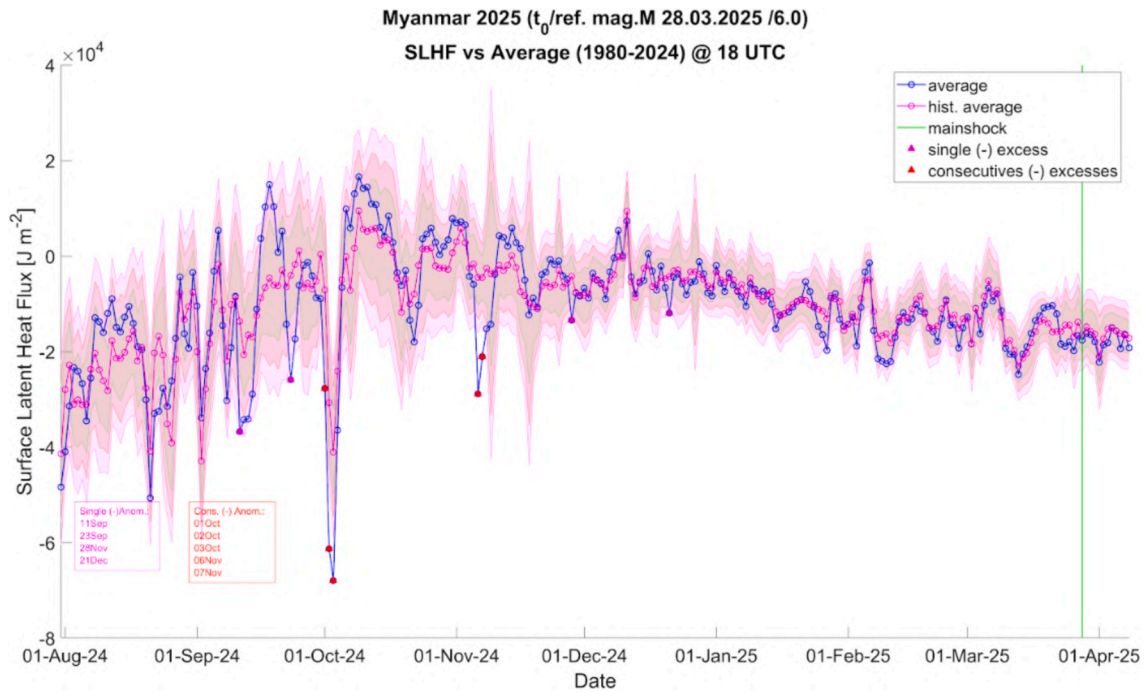


Fig. 7. Temporal behaviour of the SLHF in eight months before the mainshock.

underlying physical model: as the main rupture approaches, following the dilatancy scheme of Scholz and Koczyński (1979), enhanced release of ionizing gases (e.g., radon) increases latent heat release during water vapour condensation (Pulinets and Ouzounov, 2011). Therefore, the causal relationship between SKT anomalies and the earthquake preparation phase is expected to be strongest close to the impending mainshock. For the same reason, the analysis of all non-seismic parameters is limited to roughly eight months before the mainshock.

The maps in Fig. 6 show the spatial distribution of the difference between the “anomalous” SKT -represented in Fig. 5 by red dots (for persistent, i.e. at least 2-days lasting anomalies) and by magenta (for less than 2-day anomalies) - and the closest (in time) SKT, for which the average almost equals the actual present value. So, for example, the first map is the difference between 7 Sept. (the first anomalous day) and 5 Sept, the closest day when average and actual value almost coincide.

4.2. SLHF

SLHF (Surface Latent Heat Flux) measures the rate of heat transfer from the Earth's surface to the atmosphere. It is a key component of the surface energy balance and has been studied as a potential precursor of earthquakes (e.g. Dey and Singh, 2003). A reduction in SLHF was observed in the months leading up to the earthquake, suggesting a decrease in surface-atmosphere energy exchange. This phenomenon is consistent with the hypothesis that tectonic stress buildup inhibits normal heat dissipation, potentially contributing to localized warming near the fault zone.

We found only negative SLHF anomalies (see Fig. 7). Among these, interesting are the consecutive ones, i.e. 1–3 October and 6–7 November 2024.

4.3. OLR

OLR represents the infrared radiation emitted by the Earth's surface and atmosphere. We applied a modified Improved Pattern Informatics (MIPI) method, considering 12 months for the background and a training window of 174 days.

Anomalously low OLR values were detected over central Myanmar

prior to the earthquake. Such reductions in OLR are often interpreted as indicators of increased cloud cover or changes in atmospheric dynamics driven by seismic activity. The observed OLR anomalies align with findings from other major earthquakes, where pre-seismic thermal and atmospheric disturbances have been reported (e.g. Xiong et al., 2010).

In summary, we noticed four stages of OLR anomalies in the epicentral region (Fig. 8): 1. 31 December 2024–27 January 2025 (i.e. 87–60 days before the mainshock), the anomalies began to occur at the south of the epicenter; 2. 28 January 2025–21 February 2025 (i.e. 59–36 days), the anomalies were enhanced to cover the Sagaing fault, and then weakened; 3. 25 February 2025–6 March 2025 (32–23 days), weak anomalies occurred at the epicenter; 4. 13 March 2025–28 March 2025 (16–0 days), the anomaly occurred at 300 km of the north direction, and showed the developing processes of weakened-enhanced-weakened-disappeared.

We acknowledge that the OLR figure covers approximately 3 months (December 31, 2024 – March 30, 2025), while SKT and SLHF figures span ~8 months. This difference arises from the MIPI methodology, which requires a 12-month background period and a 174-day training window. The displayed period (87 days before to 2 days after the earthquake) represents the interval when statistically significant OLR anomalies were detected. Extending the OLR analysis to earlier months showed no significant anomalies meeting our detection criteria, which is why we focus on the period with meaningful signals. The onset of OLR anomalies at ~87 days before the earthquake is consistent with the accelerating phase of pre-earthquake preparation identified in our multiparameter analysis.

5. Ionospheric data analysis

5.1. GIM TEC

TEC measures the total number of free electrons in a column of the ionosphere, which can be influenced by geomagnetic activity and seismic processes. In the weeks preceding the 2025 earthquake, significant deviations in GIM TEC were observed over the epicentral region. These deviations included both positive and negative anomalies, indicative of complex ionospheric perturbations. Positive TEC anomalies are

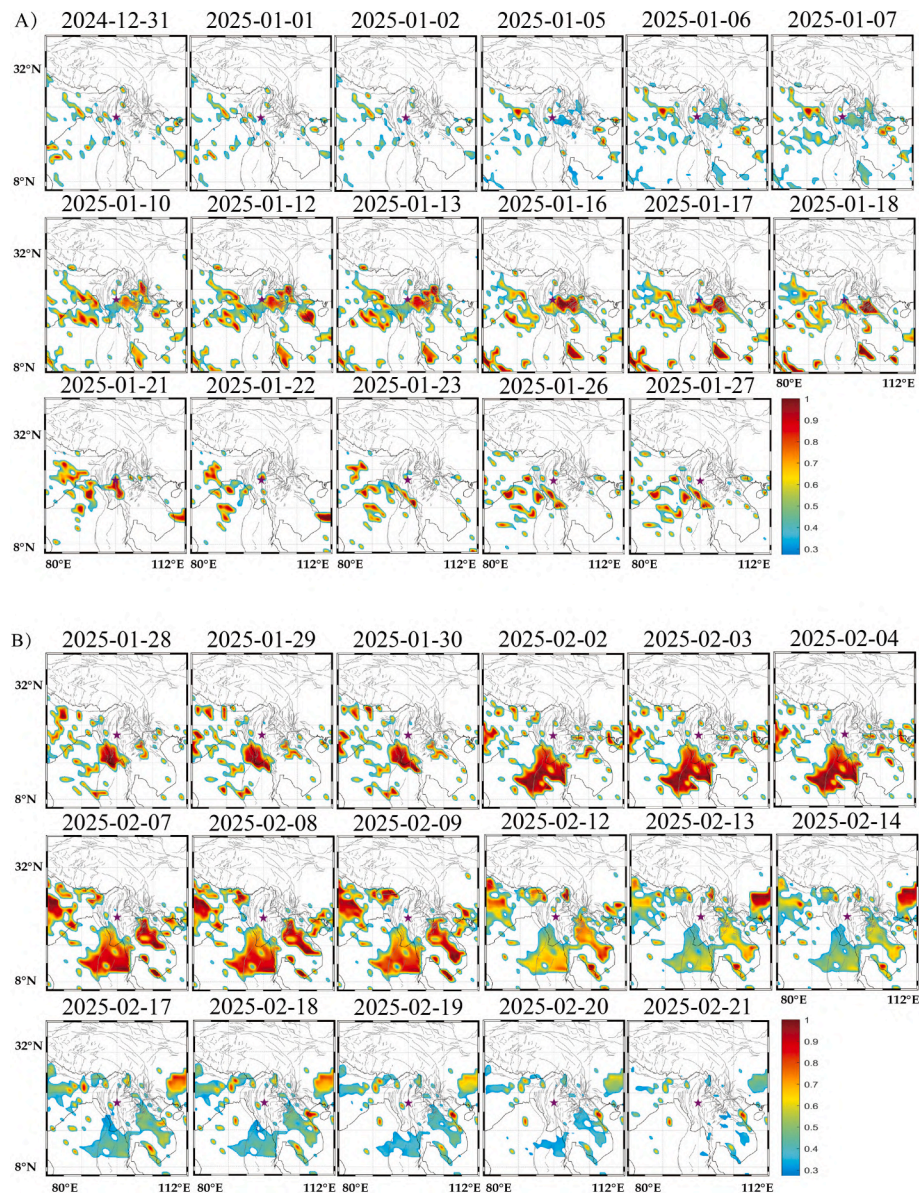


Fig. 8. Spatial evolution of OLR anomalies during the first two stages of the pre-earthquake period, detected using the Modified Improved Pattern Informatics (MIPI) method. (A) Stage 1 (December 31, 2024 – January 27, 2025; 87–60 days before the mainshock): Anomalies initially appeared south of the epicenter (purple star). (B) Stage 2 (January 28 – February 21, 2025; 59–36 days before): Anomalies intensified and expanded to cover the Sagaing Fault region, then gradually weakened. The colour scale represents the MIPI anomaly index (dimensionless, ranging from 0.3 to 1.0). See Fig. S1 for stages 3–4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

often attributed to enhanced ionization caused by radon gas emissions or acoustic-gravity waves generated by crustal stress. Negative anomalies, on the other hand, may result from electron depletion due to recombination processes triggered by seismic activity.

Reliable anomalies were observed 17 days before the earthquake, primarily showing a decreasing trend with notable conjugate effects (Fig. 9). Additional anomalies appeared multiple times within the week preceding the earthquake (Fig. 10, with the minimum of daily Dst is -41 nT on 23 March, -47 nT on 24 March, -43 nT on 25 March and -52 nT on 27 March). However, due to possible magnetic storm interference, the reliability of these anomalies was slightly reduced. Nevertheless, given their strong localized nature, they could still reflect the influence of the Myanmar-Burma earthquake, especially on 25 March, when the distribution of TEC anomalies showed quite similar features with those on 11 March with decreasing TEC over the epicenter area and its magnetic conjugate region.

From Figs. 9 and 10, it can be seen that the conjugate effects were not consistently observed just as those over the epicenter area, during most times the duration of the anomalies over the earthquake being longer than that at the conjugate. It demonstrates that the major source of these anomalies are dominantly from the epicenter region, and the conjugate anomalies were induced by the movement of electrons and ions along the magnetic field line over the epicenter and interaction with the conjugate ionosphere. The conjugate effects were affected by the strength of anomalies over the epicenter and the plasma background at the conjugate point at different local time. Consequently, the conjugate signatures cannot be expected to match the source-region anomalies in a strictly one-to-one manner.

Despite the large magnitude of the Myanmar-Burma earthquake, the routine GIM TEC monitoring detected only one anomaly on a geomagnetically quiet day, suggesting a low frequency of anomaly occurrences. This may indicate a locked fault zone near the epicenter, resulting in

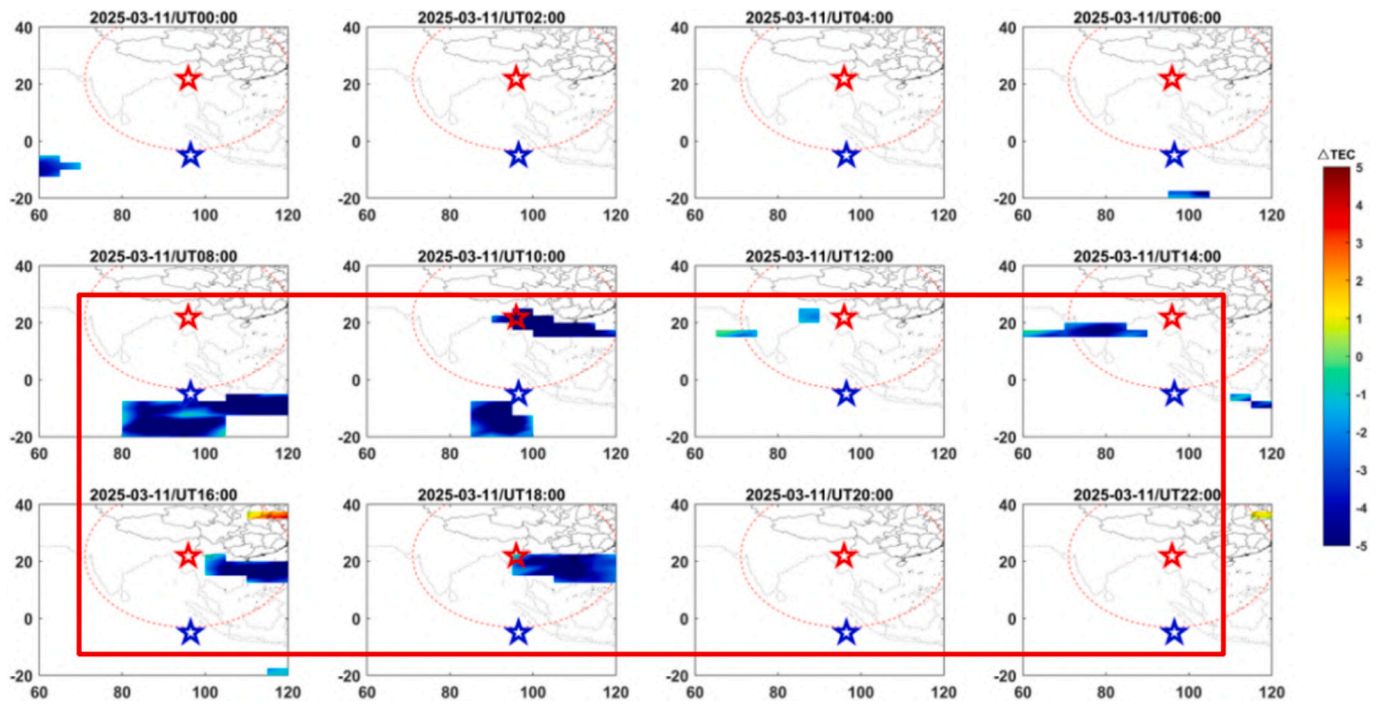


Fig. 9. GIM TEC anomalies within red rectangle on 11 March 2025 with 2 h interval for each panel since UT 00:00 to UT 22:00 over the epicenter (red star) and the conjugate (blue star) region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

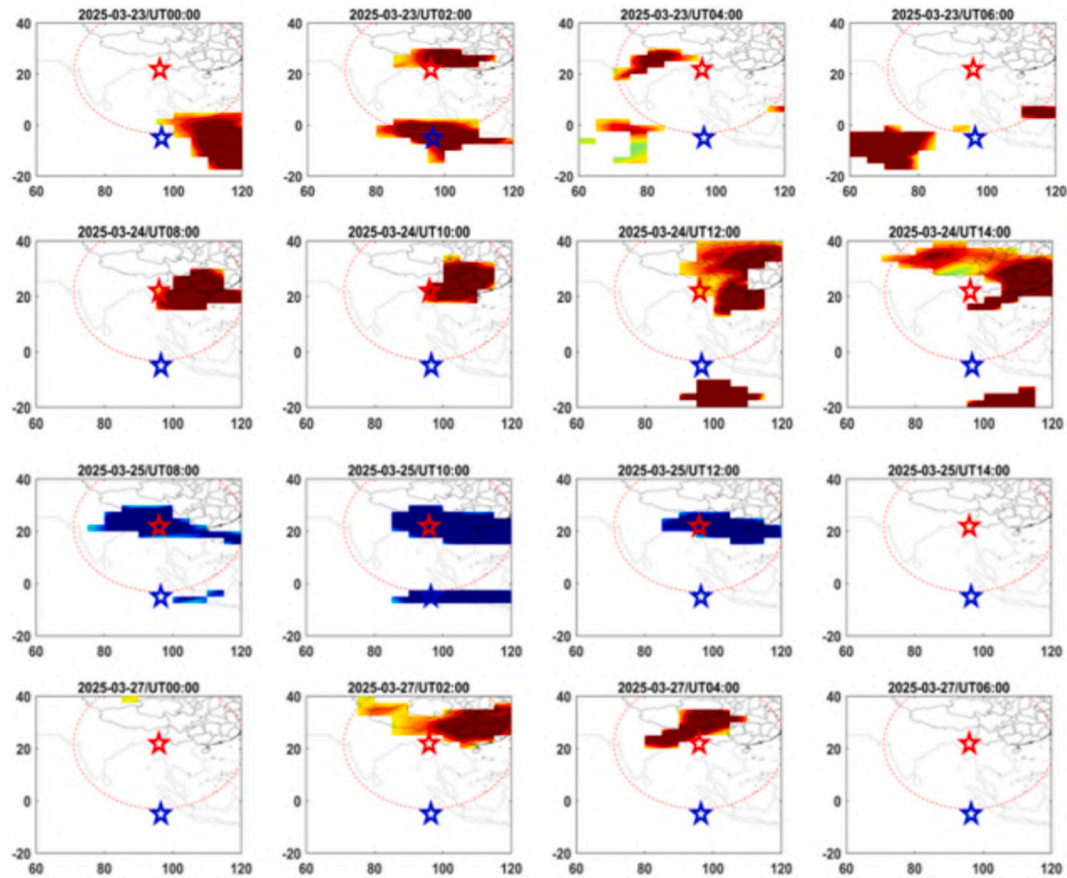


Fig. 10. GIM TEC anomalies occurred on 23 (UT 00:00–06:00, 2 h interval, the top row), 24 (UT 08:00–14:00, the second row), 25 (UT 08:00–14:00, the third row), 27 (UT 00:00–06:00, the bottom row) March 2025 over the epicenter (red star for epicenter, and the red dotted circle around it is the Dobrovolsky preparation area) and the conjugate (blue star) region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
GIM TEC anomalies with the possible associated earthquake (EQ).

GIM TEC	Date	$\Delta t/d$	P/N	Dst/nT	EQ
1	2025-01-13	0/23/74	N	-23	01-13 Dingri Ms5.0/ 03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
2	2025-02-04	29/52	P	0	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
3	2025-02-05	30/51	P	1	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
4	2025-02-06	31/50	P	-17	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
5	2025-02-18	15/38	P	-28	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
6	2025-03-03	2/25	N	0	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9
7	2025-03-11	17	N	-20	03-28 Burma Ms7.9
8	2025-03-23	5	P	-41	03-28 Burma Ms7.9
9	2025-03-24	4	P	-47	03-28 Burma Ms7.9
10	2025-03-25	3	N	-43	03-28 Burma Ms7.9
11	2025-03-27	1	P	-52	03-28 Burma Ms7.9
12	2025-04-03	-6/10	N	-36	03-28 Burma Ms7.9/ 04-13 Burma Ms5.4

fewer ionospheric anomalies. Additionally, if tracing back further, the anomalies could be influenced by the Myanmar M5.4 earthquake on March 5. This event serves as another warning for monitoring strong earthquakes in low-to-mid latitude regions. There remains significant work to be done in advancing earthquake applications based on space-based Earth observation technologies. More satellite detection methods need to be promptly translated into practical applications to improve monitoring and prediction capabilities for major earthquakes. Furthermore, as shown in Table 1, another anomaly occurred on 3 April, i.e. 6 days after the Myanmar 7.7 earthquake under weak magnetic storm activity, which indicates the precursor of the significant after-shock of Ms. 5.4 on 13 April, so some localized anomaly appearing under

weak geomagnetic storm days may be taken into consideration in future application for GIM TEC.

5.2. TEC from GNSS (BeiDou) satellites

The BeiDou Navigation Satellite System (BDS), which has been independently developed by China, is the only navigation system globally that incorporates Geostationary Earth Orbit (GEO) satellites (Yang et al., 2019; Chen et al., 2020). Given the stationary nature of the GEO satellite in relation to Earth, the ground-based receiving stations are able to continuously acquire TEC data for the fixed ionospheric pierce points (IPPs) in the ionosphere. The data utilized in this study is obtained from the Crustal Movement Observation Network of China (CMONOC), with a temporal resolution of 30 s. Currently, approximately 170 stations are capable of receiving GEO satellite data for CMONOC, and the IPPs are shown in Fig. 11.

In order to extract the perturbation related to the backgrounds, the sliding interquartile range (IQR) method was employed to analyze the time series of TEC at each IPP, and the detailed processes are as follows.

1) The median (M) and IQR of 15 days before each observation were calculated based on the preceding background and the disturbances were extracted using the threshold of $M \pm 1.5IQR$.

2) The calculation of abnormal values (Ab) was carried out using the following Eq. (1) which can highlight the anomalies. Values exceeding $M + 1.5IQR$ were considered as positive anomalies, while values below $M - 1.5IQR$ were negative anomalies. For values exceeding the threshold, we calculate the relative change (Ab%) between the observed data (Obs) and the threshold, assigning the value of 0 to those that do not exceed the threshold value:

$$Ab\% = \frac{Obs - (M + 1.5IQR)}{(M + 1.5IQR)} \times 100 \text{ if } Obs > M + 1.5IQR$$

$$Ab\% = 0 \text{ if } M - 1.5IQR \leq Obs \leq M + 1.5IQR \quad (1)$$

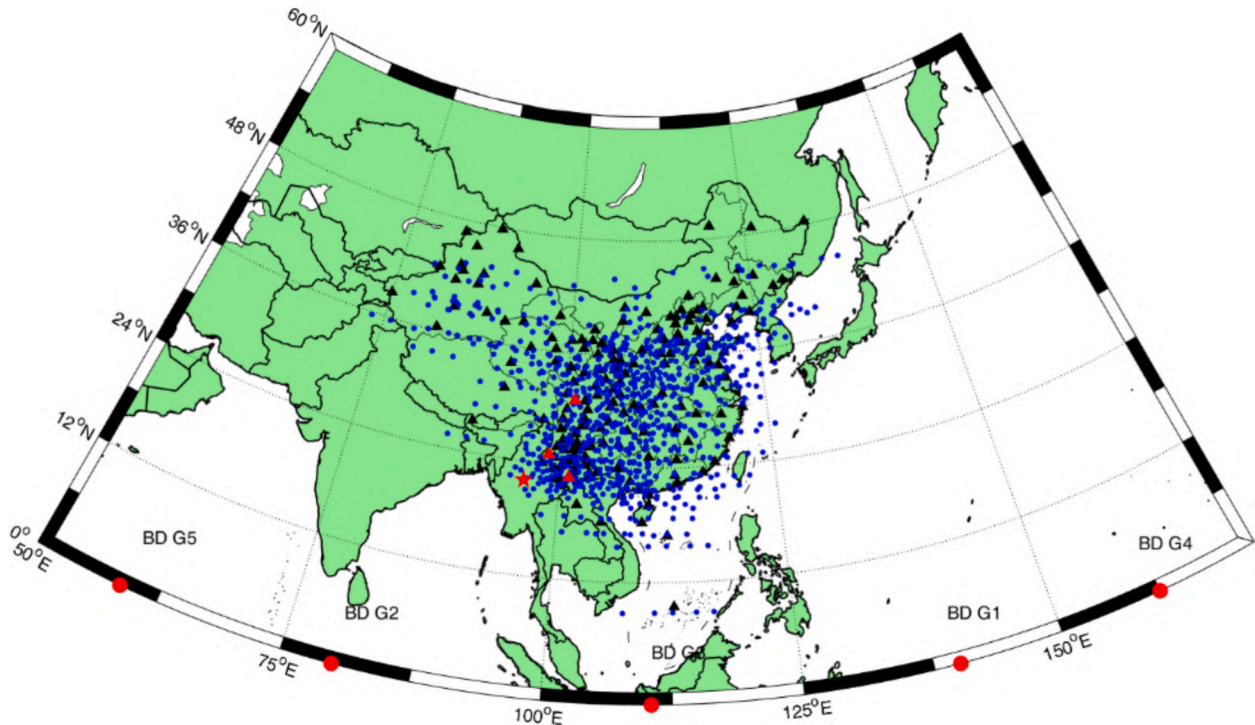


Fig. 11. The distributions of IPPs for BeiDou GEO satellites in China Continental Tectonic Environment Monitoring Network (CMONOC). The black triangles represent the ground receivers, and the blue points denote the IPPs. The red points along the equator are the locations of BeiDou satellites, and the 'G' represents the number of the satellite. The red star denotes the epicenter. The red triangles represent the location of three ionosondes used in this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

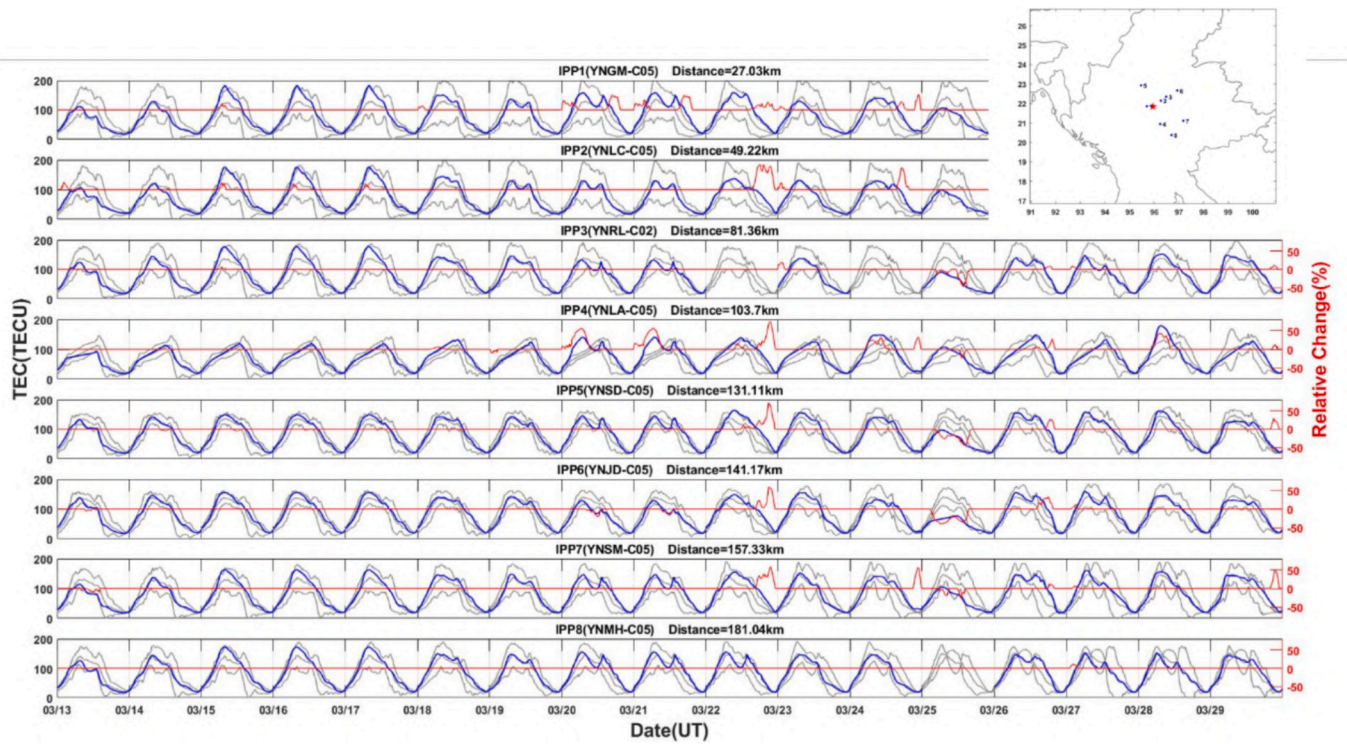


Fig. 12. TEC from some GNSS (BeiDou) receivers around the mainshock epicenter (locations are shown in the small upper right picture). The TEC observation is shown in blue line, and upper and lower thresholds calculated by sliding IQR are shown in grey lines. The red curve in the bottom of each panel indicates the relative change of data, which exceeds the threshold by more than 2 h. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

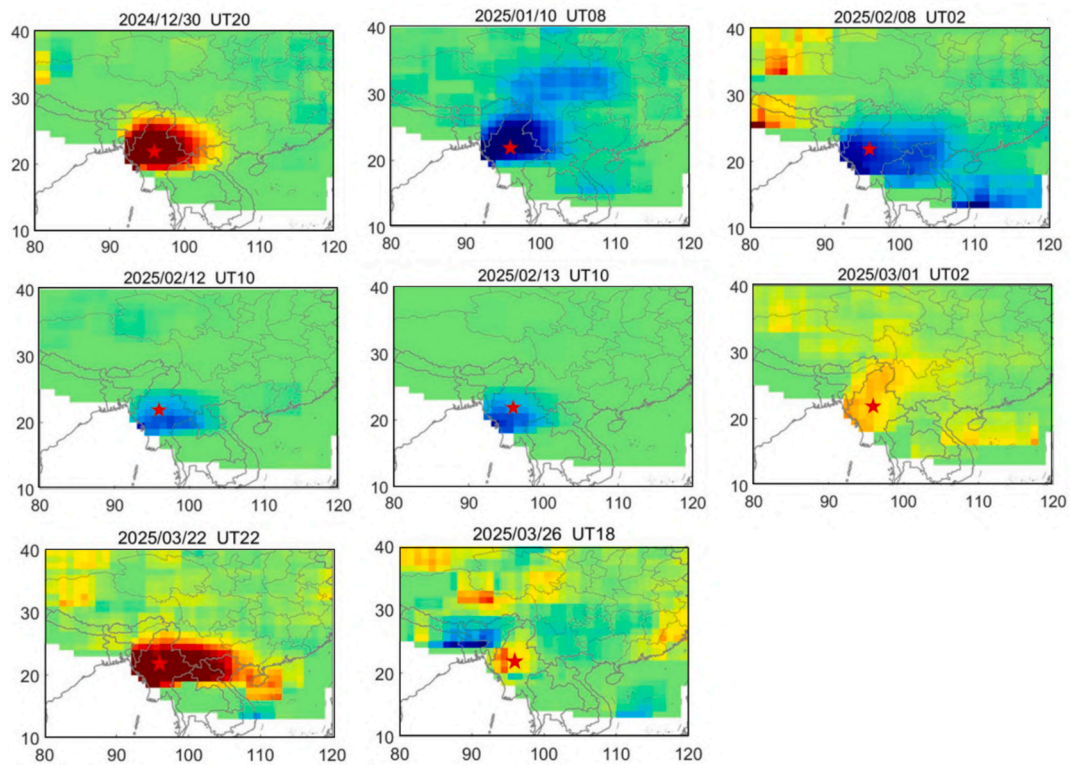


Fig. 13. Spatial distribution of BD GEO TEC anomalies with local characteristics on 30 December 2024, 10 January, 8, 12, 13 February, and 1, 22 and 26 March 2025 around the mainshock epicenter (red star). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

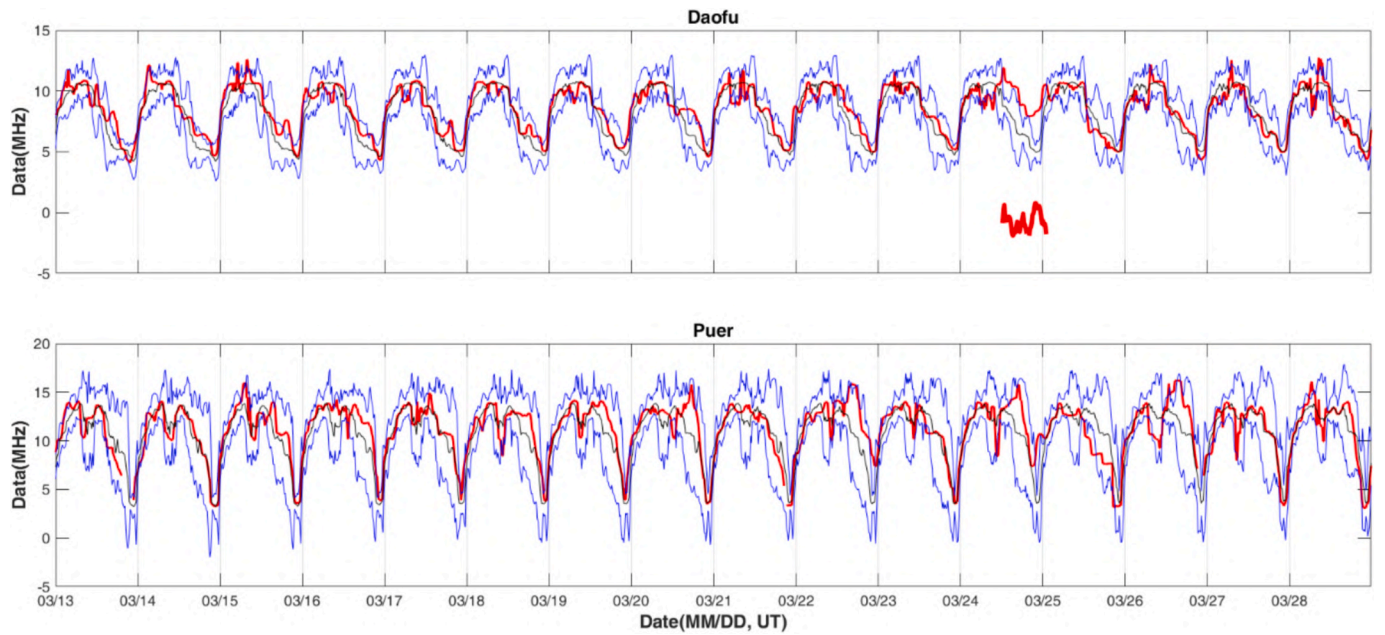


Fig. 14. The foF2 for two ionosonde stations (Doufu and Puer) in the period 13–28 March 2025.

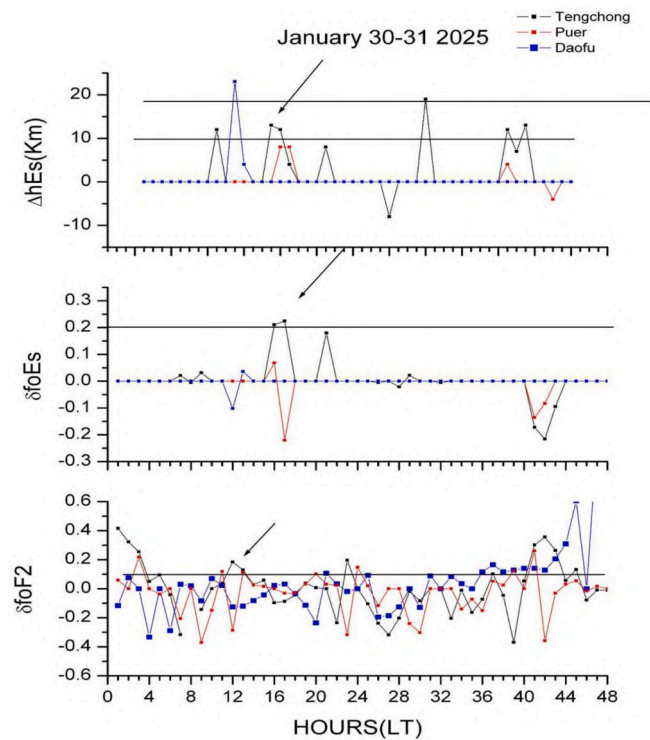


Fig. 15. Ionosonde behaviour of the analysed three stations on 30–31 January 2025. The arrows indicate the anomalies in Tengchong station, the closest to the earthquake epicenter.

$$Ab\% = \frac{Obs - (M - 1.5IQR)}{(M - 1.5IQR)} \times 100 \text{ if } Obs < M - 1.5IQR$$

3) To eliminate the interference of abrupt jumps and ensure that anomalies have a certain duration, only disturbances with a non-zero Ab % value persisting for over 2 h were highlighted. Eight IPPs were selected around the Myanmar-Burma earthquake region, and the data from 28 December 2024 to 7 April 2025 (90 days before and 10 days after earthquake) were analysed. Due to space constraints, the data

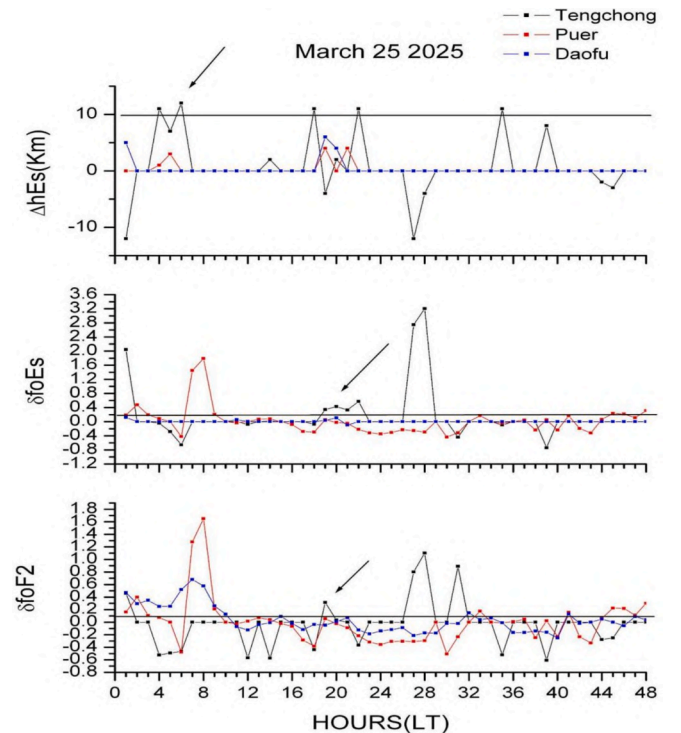


Fig. 16. Ionosonde behaviour of the analysed three stations on 25–26 March 2025.

13–29 March were taken as an example to show the analysis result (Fig. 12), in which the relative change of data exceeding the threshold more than 2 h is highlighted with the red line in each panel. To check if synchronous disturbances (data exceeding the threshold more than 3 IPPs in time series analysis) has the local characteristics, we produced maps of BDS TEC anomalies based on the observation of CMONOC. The process is as follows. First, the mean value of ± 5 min data was calculated for each two hours. Then, when data surpassed the threshold calculated same as time series analysis, their relative changes were

Table 2
Ionosonde anomalies together with associated information, including the Ap and AE indices, detected at Tengchong station, the closest ionosonde station to the earthquake epicenter.

Date	Hour [UT]	$\Delta h'Es$ [km]	$\delta foEs$	$\delta foF2$	ΔT [days]	Ap Index	AE index
30-01-2025	08–09	30	1.22	2.4	56.92	6 nT	<400 nT
24-03-2025	21–22	12	0.43	0.31 (1 value)	3.33	14 nT	>2000 nT

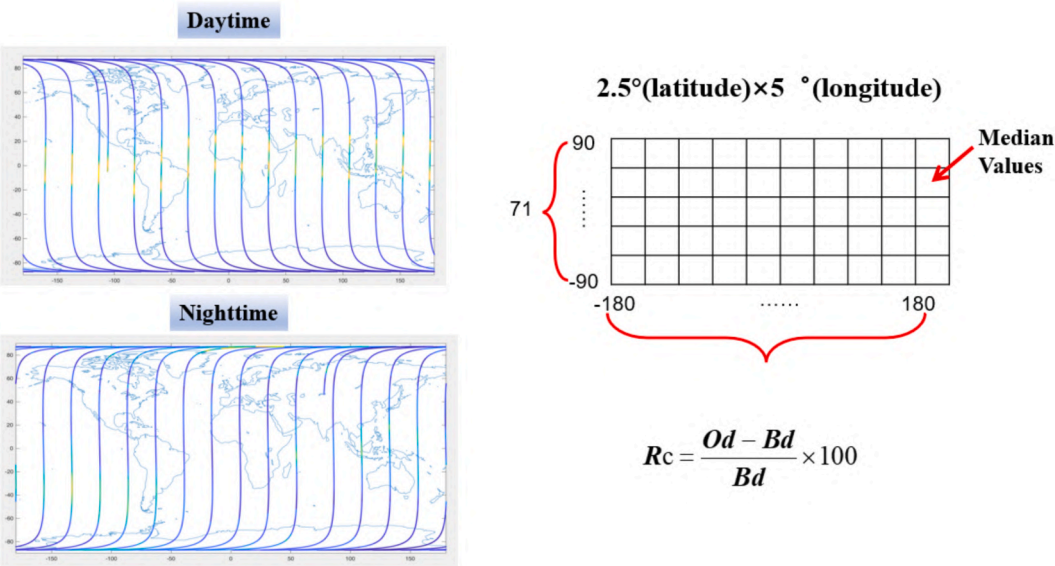


Fig. 17. Left: Daytime and night-time orbits. Right: Grid division to estimate the background Bd . The formula expresses the way to calculate the relative change Rc by observation data (Od) to Bd .

Table 3
Summary of Ne anomalies detected by NeAD algorithm. The tracks with an anomaly detected slightly under the threshold are reported in red (EQ = earthquake).

Satellite	Anomalies	Days before EQ
Swarm A	18/01/2025	69
	21/01/2025	66
	23/01/2025 track 17	64
	23/01/2025 track 19	64
	30/01/2025	57
	16/03/2025	12
	20/03/2025	8
Swarm B	29/12/2024	82
	05/02/2025	51
	07/02/2025	49
	19/02/2025	37
	23/2/2025	33
	03/03/2025	25
	06/03/2025	22
	20/03/2025	8
Swarm C	30/12/2024	89
	18/01/2025	69
	29/01/2025	58

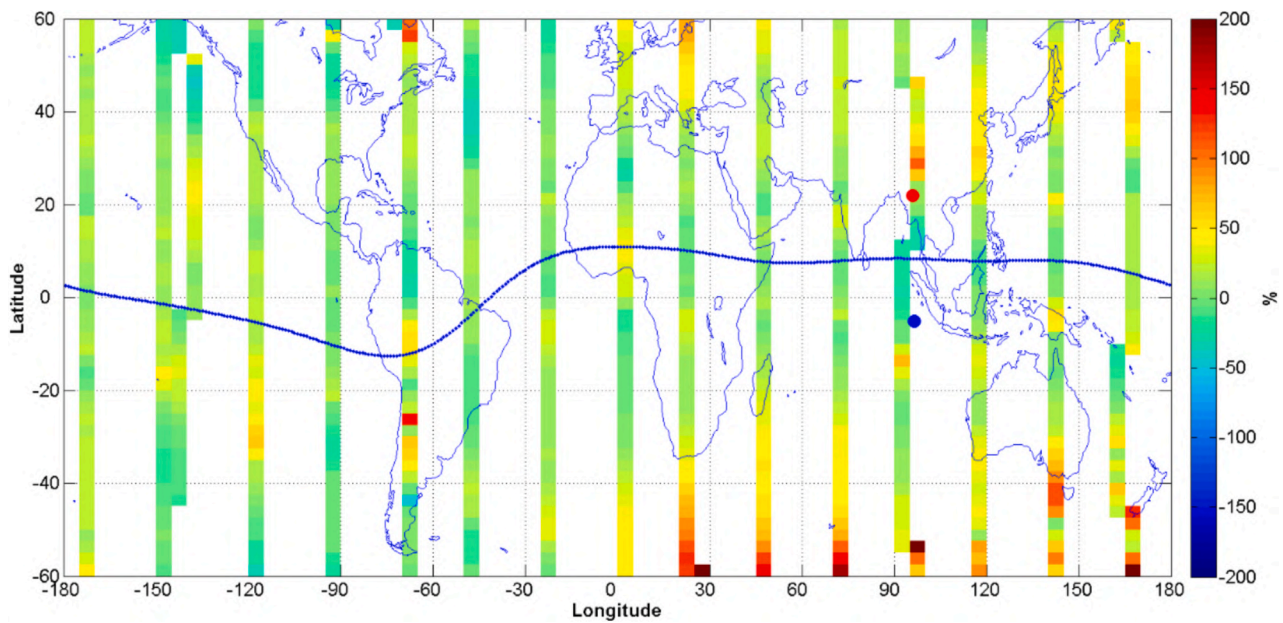


Fig. 18. Swarm Charlie Ne on 24 March 2025. Red and blue dots denote the epicenter and its conjugate point, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

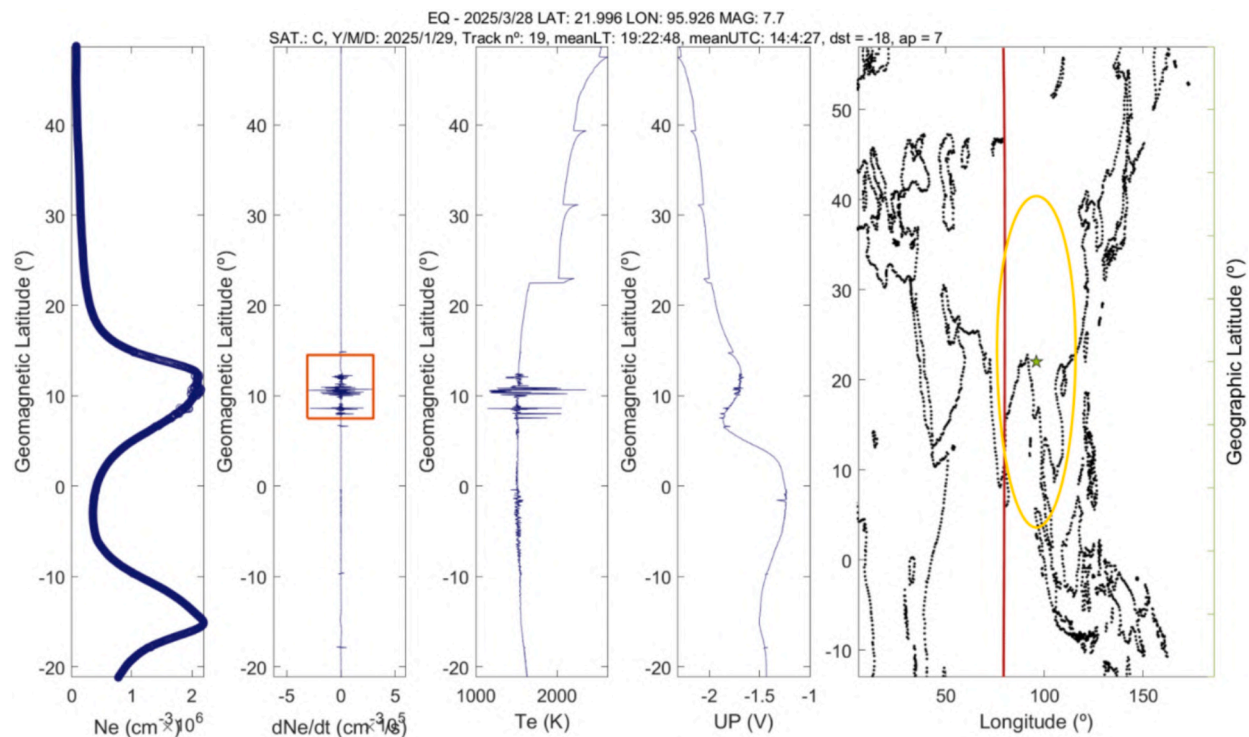


Fig. 19. Swarm Charlie Ne, its first differences, electron temperature (Te) and spacecraft potential (UP) on 29 January 2025, i.e. 58 days before the earthquake. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

computed. Conversely, their relative changes were considered as zero. Values with unrealistically large relative changes were removed to avoid spurious spikes. Next, the data in a $1^\circ \times 1^\circ$ grid will be assigned their values to a $3^\circ \times 3^\circ$ grid to ensure the spatial connectivity of data. When multiple values were assigned to a single grid, the arithmetic mean of these values shall be adopted. At last, if the TEC disturbances extracted in the time series analysis also had the local characteristics in spatial distribution (Fig. 13), they may be considered as anomalies potentially

associated with earthquakes. Based on the data analysis from 1 January to 31 March, the anomalies extracted from BD GEO TEC data were on 30 December 2024, 10 January, 8,12, 13, February and 1,22,26 March 2025.

5.3. Ionosonde data analysis

Two ionosonde stations in China were selected to analyze the foF2

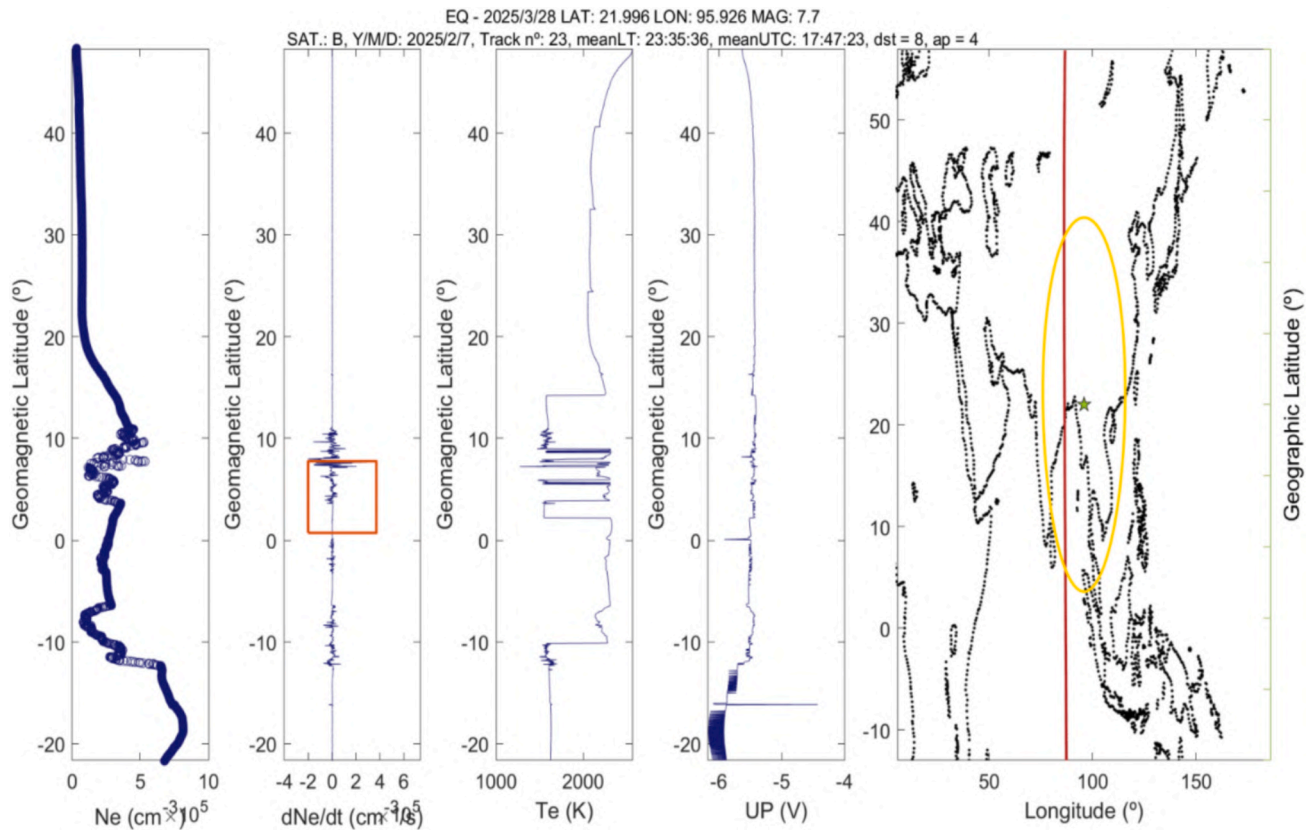


Fig. 20. Swarm Bravo Ne, its first differences, electron temperature (Te) and spacecraft potential (UP) on 7 February 2025, i.e. 49 days before the earthquake. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

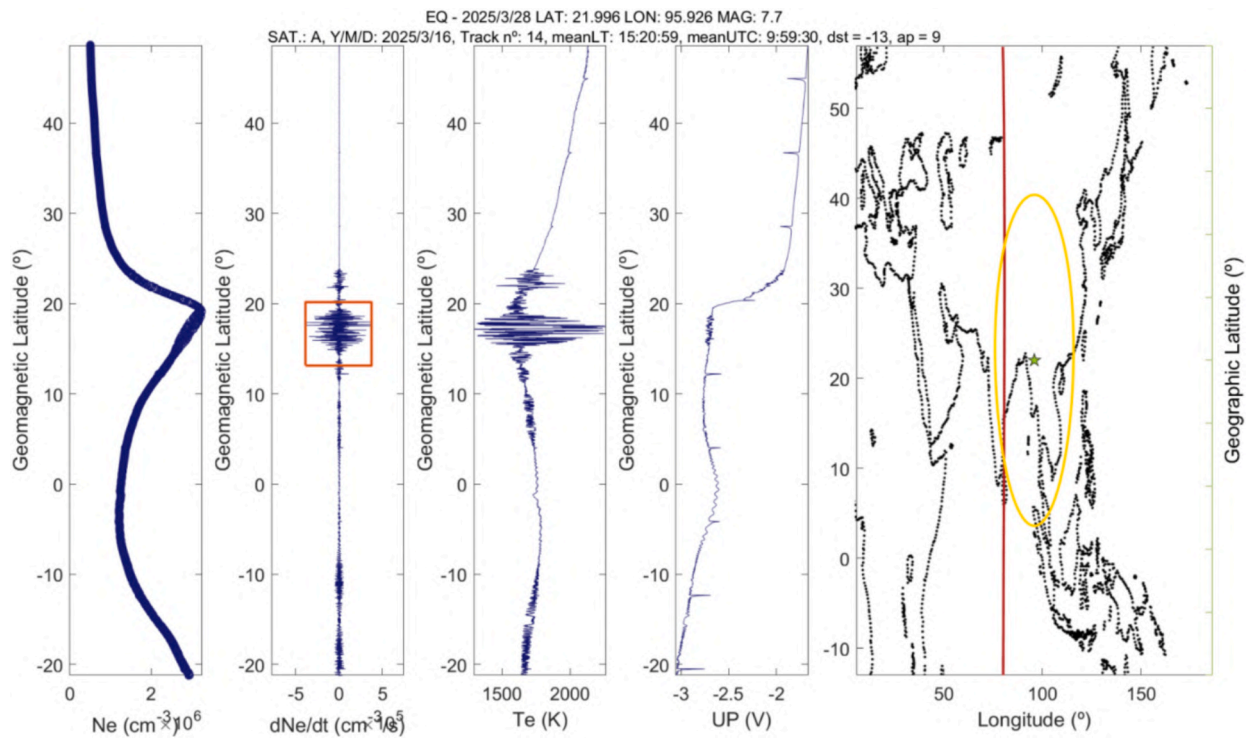


Fig. 21. Swarm Alpha Ne and Te Swarm Alpha Ne, its first differences, electron temperature (Te) and spacecraft potential (UP) on 16 March 2025, i.e. 12 days before the earthquake. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Swarm Magnetic field anomalies associated with the closer earthquake (EQ).

No	Date	$\Delta t/d$	Dst/nT	EQ	Swarm Satellites
1	2025-03-02	26	-14	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9	A & B & C
2	2025-03-03	25	3	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9	A & B & C
3	2025-03-06	22	-5	03-05 Burma Ms5.4/ 03-28 Burma Ms7.9	A & C
4	2025-03-11	17	-19	03-28 Burma Ms7.9	B
5	2025-03-20	8	-19	03-28 Burma Ms7.9	A & B & C
6	2025-03-30	-2	3	03-28 Burma Ms7.9/ 04-13 Burma Ms5.4	B
7	2025-03-31	-3	-5	03-28 Burma Ms7.9/ 04-13 Burma Ms5.4	B
8	2025-04-01	-4	-14	03-28 Burma Ms7.9/ 04-13 Burma Ms5.4	A & B & C

data, with Daofu (31.0° N; 101.12°E) in Sichuan Province, and Puer (22.7° N; 101.05°E) in Yunnan Province. The analysis method is the same as the time series analysis of BDS TEC data, which was deeply illustrated in the above section. Fig. 14 gives out the result of time series analysis of foF2 data (Thengchong station had some transmitter malfunction so it was not considered). Anomalies have been found on late 24 March 2025 and beginning 25 March 2025.

To investigate potential pre-earthquake ionospheric anomalies, we applied a multi-parameters approach specifically designed for ionosonde data. A distinctive aspect of this method is its use of multiple ionospheric parameters, simultaneously analyzing variations in both the sporadic E (Es) and the regular F2 layers under magnetically quiet conditions (Perrone et al., 2010, 2018; Ippolito et al., 2020).

The method considers the occurrence of an abnormally elevated Es layer, characterized by $\Delta h'Es \geq 10$ km, followed by a simultaneous increase of more than 20% in foEs (the maximum frequency of the ionogram trace associated with the Es layer) and more than 10% in foF2 (the critical frequency of the F2 layer) within a 2–3 h window on the same day. These variations are calculated relative to 27-day running medians.

This method has been applied to hourly data from the three ionosondes of Tengchong (24.98°N, 98.51°E), Puer (22.73°N, 101.05°E) and Daofu (31.00°N, 101.12°E), respectively located approximately at 444 km, 544 km and 1149 km from the earthquake epicenter. Through the comparison with background information based on 27-day hourly

running medians, one ionospheric anomaly is found on 30 January at Tengchong during quiet days without geomagnetic disturbances based on the ap geomagnetic index (i.e., not exceeding 10 nT) (see Fig. 15), while on 24 March another anomaly has been found under disturbed conditions (see Fig. 16). These anomalies are reported in Table 2 along with the associated information.

5.4. Swarm Ne and magnetic field

5.4.1. Swarm Ne

A specific spatial analysis method was applied to analyze Ne observed by Swarm. Three steps were taken to extract Ne disturbances before the Myanmar-Burma earthquake, which is shown in Fig. 17. Firstly, the dataset was divided into 2.5° (latitude) $\times$ 5° (longitude) cells, and the median value of the data falling into each cell was calculated to represent the observational values on every day. Secondly, the relative change (R_c) was obtained using the formula in Fig. 17. Od are observation data calculated according to the first step, and Bd represents the background, which is the median value of the 15-day data before the Od . Finally, except for the data at high latitudes, the maximum or minimum values of R_c around the epicenter in one day were considered as disturbances potentially related to the earthquake.

Through the analysis by spatial method, main anomalies were found on 20, 24 and 25 March 2025 in Alpha and Charlie satellites, and on 22 March 2025 on the Bravo satellite.

We applied to the Swarm electron density also the NeAD algorithm (De Santis et al., 2019). The tracks of the anomalies found with this method are reported in Table 3. The main anomalies found on 20, 24 and 25 March 2025 in Alpha and Charlie satellites, and on 22 March 2025 on the Bravo satellite are not observed clearly using NeAD (Figs. 18–21).

5.4.2. Swarm magnetic field

Alimoradi et al. (2025) analysed Swarm magnetic field before Myanmar earthquake with the objective to confirm the found relationships between duration and amplitude of anomalies and the earthquake magnitude (Alimoradi et al., 2024). A similar approach is made here but with the different objective to collect all magnetic field anomalies around the earthquake epicenter and compare them in space and time with all anomalies from the other parameters. To exclude the effects from solar activity, the quiet days were selected with $Dst > -30$ nT and $Kp < 3$, and only the local nighttime orbits were analysed by using wavelet spectrum method to distinguish the perturbations in the

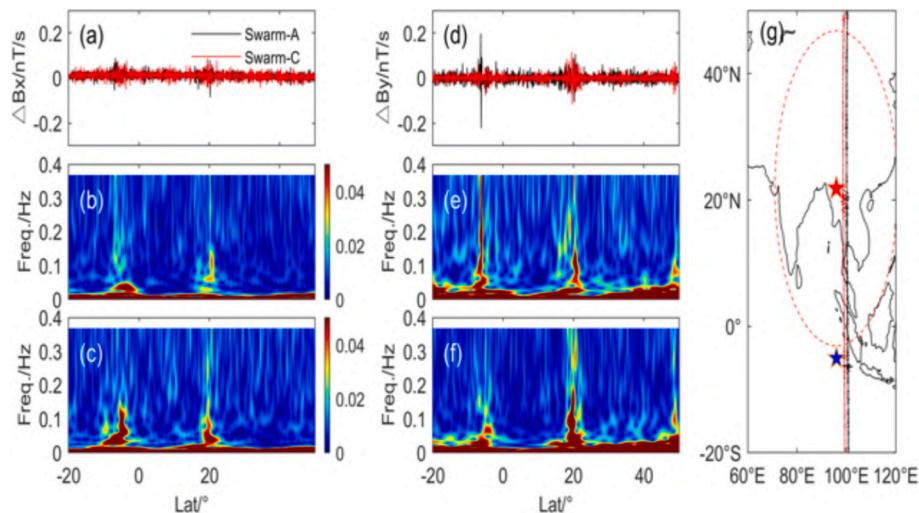


Fig. 22. The wavelet spectrum of magnetic field in Bx and By onboard Swarm A and C on 6 March 2025. (a): the filter curves of Bx within frequency band of 0.1–0.3 Hz; (b): the wavelet spectrum of Bx for Swarm A; (c): the wavelet spectrum of Bx for Swarm C; (d–f) are the same results for By component; (g): the orbits position for both satellites, in which the red star is the Myanmar earthquake with dashed red circle for Dobrovolsky's area, and the blue one is its conjugate point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

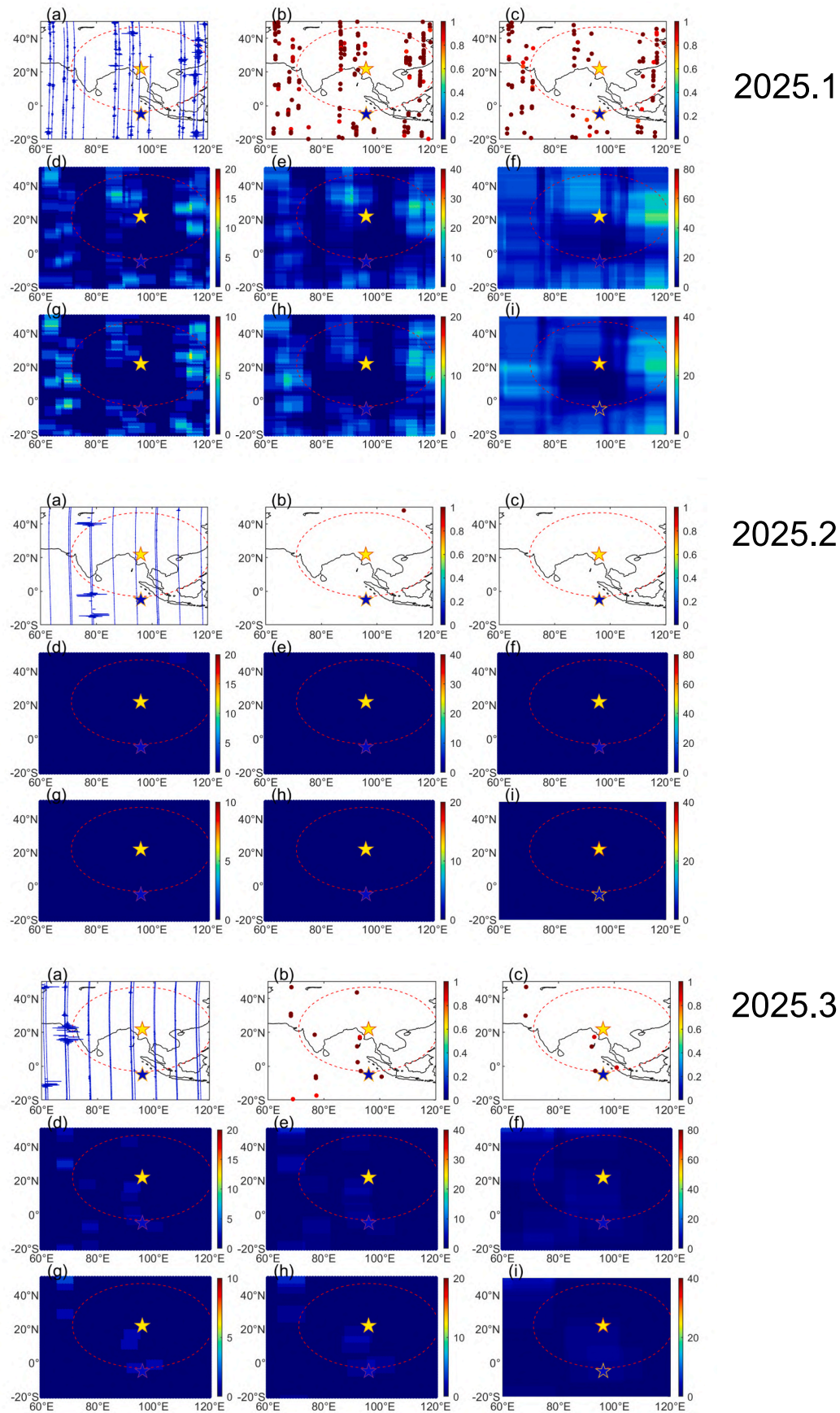


Fig. 23. Swarm magnetic field in January, February and March 2025 (from top).

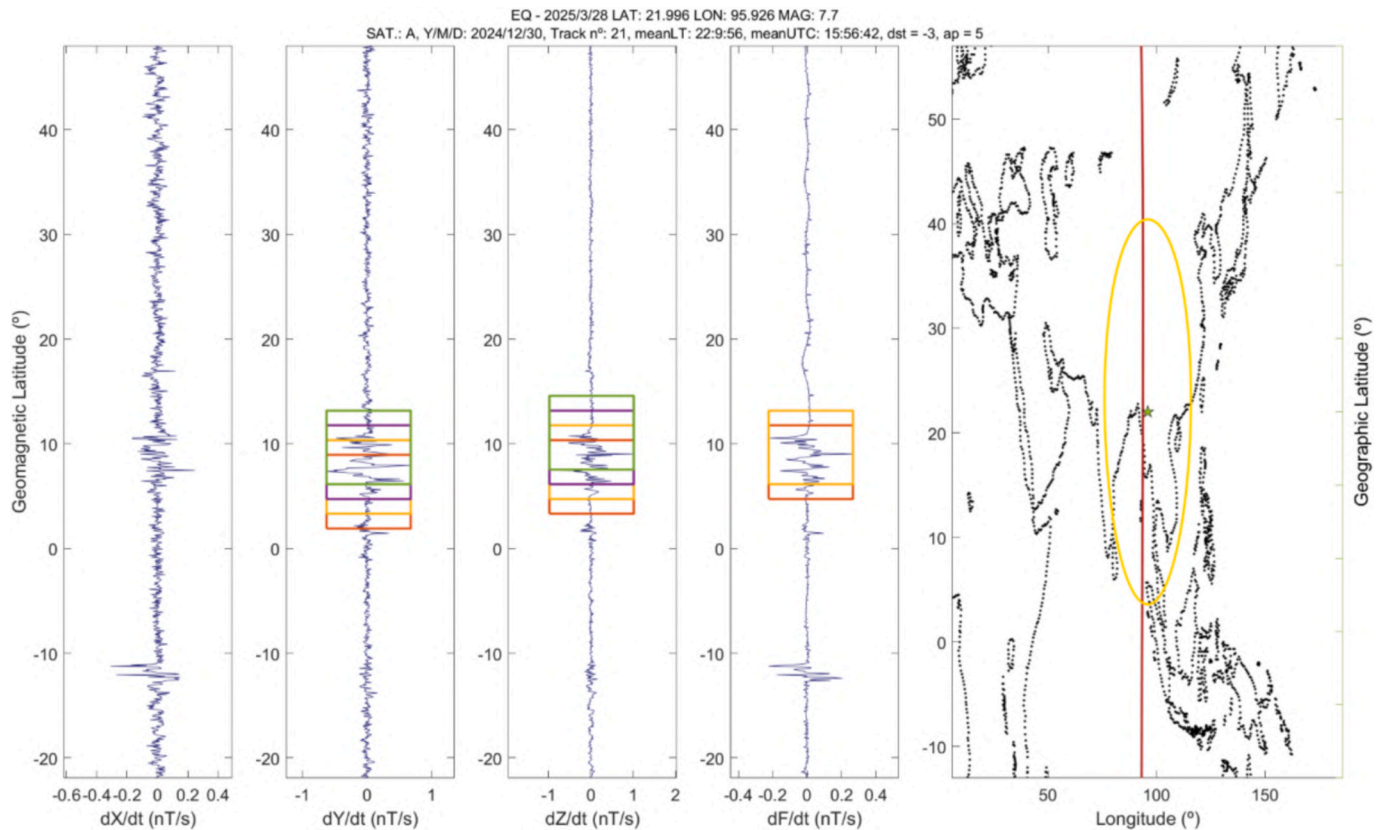


Fig. 24. Swarm Alpha magnetic field on 30 Dec. 2024, i.e. 88 days before the earthquake. The first differences of X, Y, Z and F are shown. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

magnetic field of Swarm satellites. In addition, other earthquakes in near region during the 90 days before the Myanmar earthquake should be considered, including Dingri Ms. 6.8 earthquake (28.5°N, 87.45°E) on 7 January in Tibet, China, and Burma Ms. 5.4 earthquake (24.45°N, 94.5°E) on 5 March, which are all located in the Dobrovolsky's area of Myanmar earthquake. Here the magnetic field anomalies were detected within and 8 days prior to the mainshock (Table 4), the anomalies were exhibited with characteristics similar to those of GIM TEC, prominently developing over the epicenter and its conjugate region (Figs. 18 and 22). Three of them on 6, 11 and 20 March were just prior to the Myanmar earthquake, with less relationship of other earthquakes in this region, and on 20 March three Swarm satellites all detected anomalies at different local time and altitudes, which indicate the long time duration of more than a few hours. Since these anomalies occurred on geomagnetically quiet days, their credibility is high, indicating that satellite magnetic anomalies have a good correlation with large earthquakes. Further tracking and application of such observations should be explored. After the mainshock, a few anomalies in the magnetic field were detected on Swarm satellites, on 30 and 31 March, 1 April. Combining these disturbances and those in GIM TEC, a Ms5.5 earthquake is expected in this seismic region before the end of April, and finally a Ms. 5.4 earthquake took place on April 13. It demonstrates a successful short-term and impending prediction application for a strong aftershock by using the multi ionospheric monitoring technologies. (See Figs. 23–26)

In addition, we applied the MASS algorithm (De Santis et al., 2017) to Swarm magnetic field data.

Table 5 lists the detected magnetic field anomalies from Swarm satellites. The comparison with the previous analysis shows that the reported anomalies detected by Swarm A and C are not seen by applying the MASS methodology. In the case of Swarm B we see that the

anomalies of 3, 20 and 30 March are also seen here. A summary of common B and Ne anomalies are given in Table 6.

As it is clear, some the found anomalies depend on the method applied. For our convenience, we will finally consider all anomalies detected (e.g. in Fig. 30): of course, this will overcount the number of anomalies, but we choose to include all, rather than possibly exclude some of them.

5.5. Electron bursts

Bursts of high-energy electrons in the ionosphere above the SF zone possibly connected to the seismic event were concentrated in the days prior to the earthquake, at the epicenter position, and are hypothesized to be linked to electromagnetic emissions from the stressed lithosphere. Electron bursts have been proposed as a potential precursor to large earthquakes, although the mechanism of their origin remains under investigation (e.g. Aleksandrin et al., 2003).

The geomagnetic conditions were evaluated by the ap index, which quantifies disturbances in the Earth's magnetic field caused by solar wind and ionospheric currents. Notably, moderate geomagnetic activity was recorded in the months leading up to the earthquake, with occasional spikes in the ap index coinciding with periods of anomalous TEC and electron bursts. While geomagnetic storms can complicate the interpretation of ionospheric data, the observed anomalies were spatially correlated with the epicentral region, suggesting a connection to tectonic processes rather than external solar influences.

Taking into account these observations and in order to analyze these possible electron bursts, we analysed the period from December 2024 to March 2025.

The data of NOAA-15, 18 and 19 and MetOp-1 and 3 were downloaded by the relative website (<https://www.ncei.noaa.gov/product>)

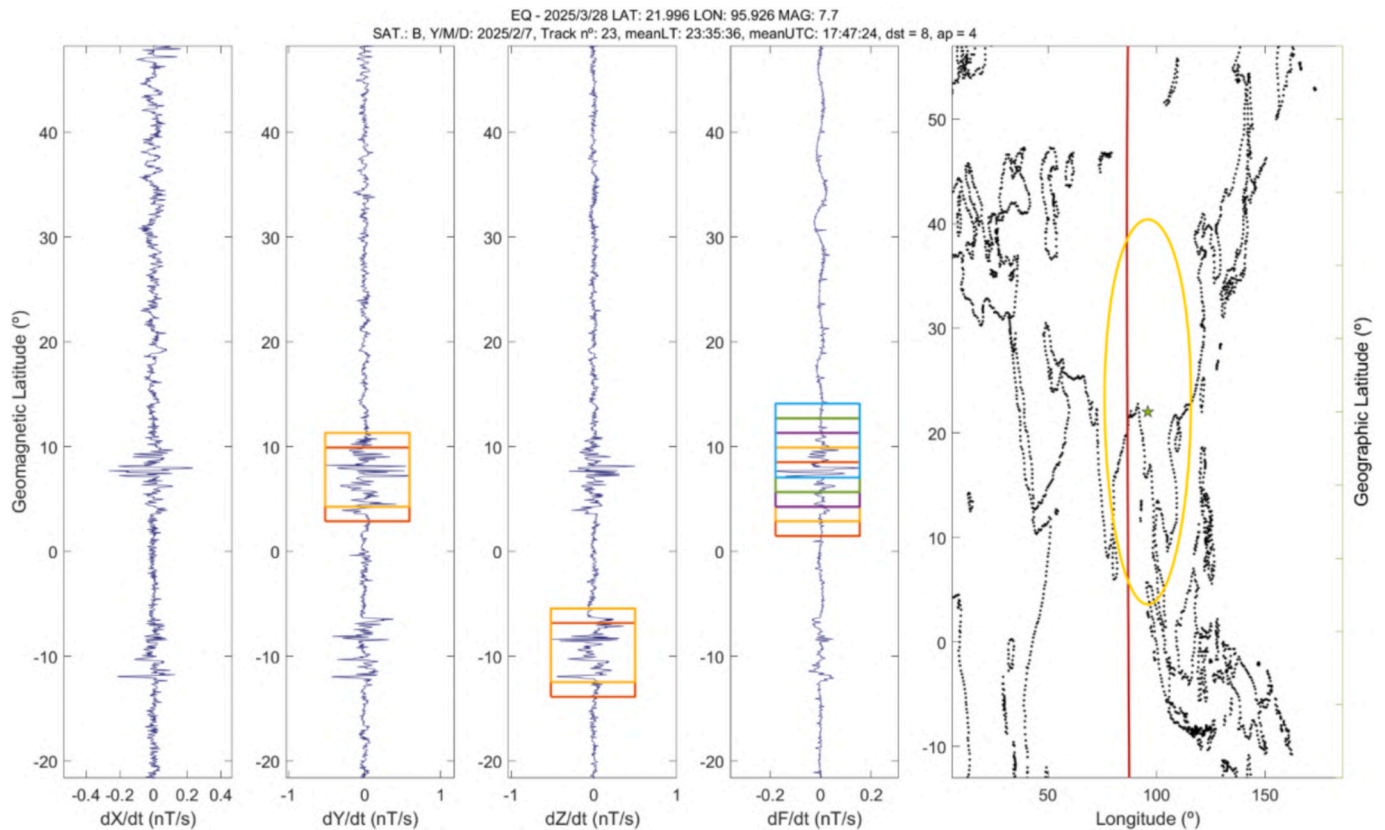


Fig. 25. Swarm Bravo magnetic field on 7 February 2025, i.e. 49 days before the earthquake. The first differences of X, Y, Z and F are shown. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

s/poes-metop-space-environment-monitor). We now describe what we found on the base of Figs. 27–29.

Regarding December 2024, we found two different electron bursts: one detected by NOAA-15 on December 10, 2024 with a west deviation on longitude and one on December 16, seen by NOAA-19.

January 2025 showed an intense electron burst in the conjugate point at January 18 observed by NOAA-18, another smaller electron burst seen by the same satellite in the conjugate point was identified on January 22. At the epicenter position, NOAA-18 showed two electron bursts on January 1 and 9, while a small EB was detected by NOAA-15 on January 14.

February 2025 presented only two electron bursts possibly correlated to the seismic event, one on February 3 in the conjugate point and one on February 18, as evidenced by NOAA-19 and MetOp-1, respectively.

As mentioned above, March 2025 was characterized by an intense geomagnetic activity that culminated with a geomagnetic storm. For this reason, we observed only two electron bursts by NOAA-18 on March 13 in the conjugate point and on March 24 there were several electron bursts on the epicenter position.

6. Discussion

The convergence of seismic, atmospheric and ionospheric anomalies provides evidence for non-random, time-correlated anomalies potentially associated with the preparatory phase of the 2025 Myanmar-Burma earthquake. Key observations include:

- Seismicity: An acceleration of the seismicity started about 27 months before the mainshock.
- Thermal and Radiative Anomalies: Elevated SKT, reduced SLHF, and decreased OLR suggest that tectonic stress accumulation altered

surface and atmospheric energy dynamics.

- Ionospheric Perturbations: Deviations in GIM TEC and electron bursts detected by satellites indicate significant ionospheric disturbances linked to the earthquake preparation phase.

- Temporal Correlation: The timing of these anomalies—peaking in the weeks and days before the mainshock—supports their interpretation as precursory phenomena.

Table S1 in the Supplementary Material lists all anomalies with date of occurrence, day w.r.t. the earthquake, type of anomaly.

A comprehensive plot of all anomalies for the five months before the earthquake (so among other few initial anomalies we also excluded the beginning of the seismic acceleration), has been then fitted by a sigmoid of the form: $Y = L/[1 + e^{-k(X-X_0)}]$, with L (asymptote), k (growth rate) and X_0 (inflection point) to be determined by using a nonlinear regression method (e.g. Bates and Watts, 1988). Please note that the cumulative number was properly increased by the number of anomalies in each day, i.e. by 1 for a single anomaly, by 2 for a couple of anomalies from different types of observations, and so on. It is evident that the final plot presents an acceleration toward the occurrence of the mainshock, typical of a critical system approaching a critical state and a subsequent recovery after the mainshock (Fig. 30).

We also made the Kolmogorov-Smirnov (KS) statistical test to confirm that this accumulation of anomalies is not due to a random sequence. Statistical analysis using the KS test (e.g. Massey, 1951) rejected the null hypothesis ($p = 2.4e-06$), indicating non-uniform distribution of anomalies. Model comparisons revealed that a sigmoid function ($R^2 = 0.993$, normally distributed residuals) provided a significantly better fit than a linear model ($R^2 = 0.902$), capturing the S-shaped growth of anomalies. The sigmoid parameters—inflection point ($X_0 = -58$ days), growth rate ($k = 0.061$), and asymptote ($L = 52$)—suggest a critical acceleration phase ~ 58 days pre-earthquake, possibly

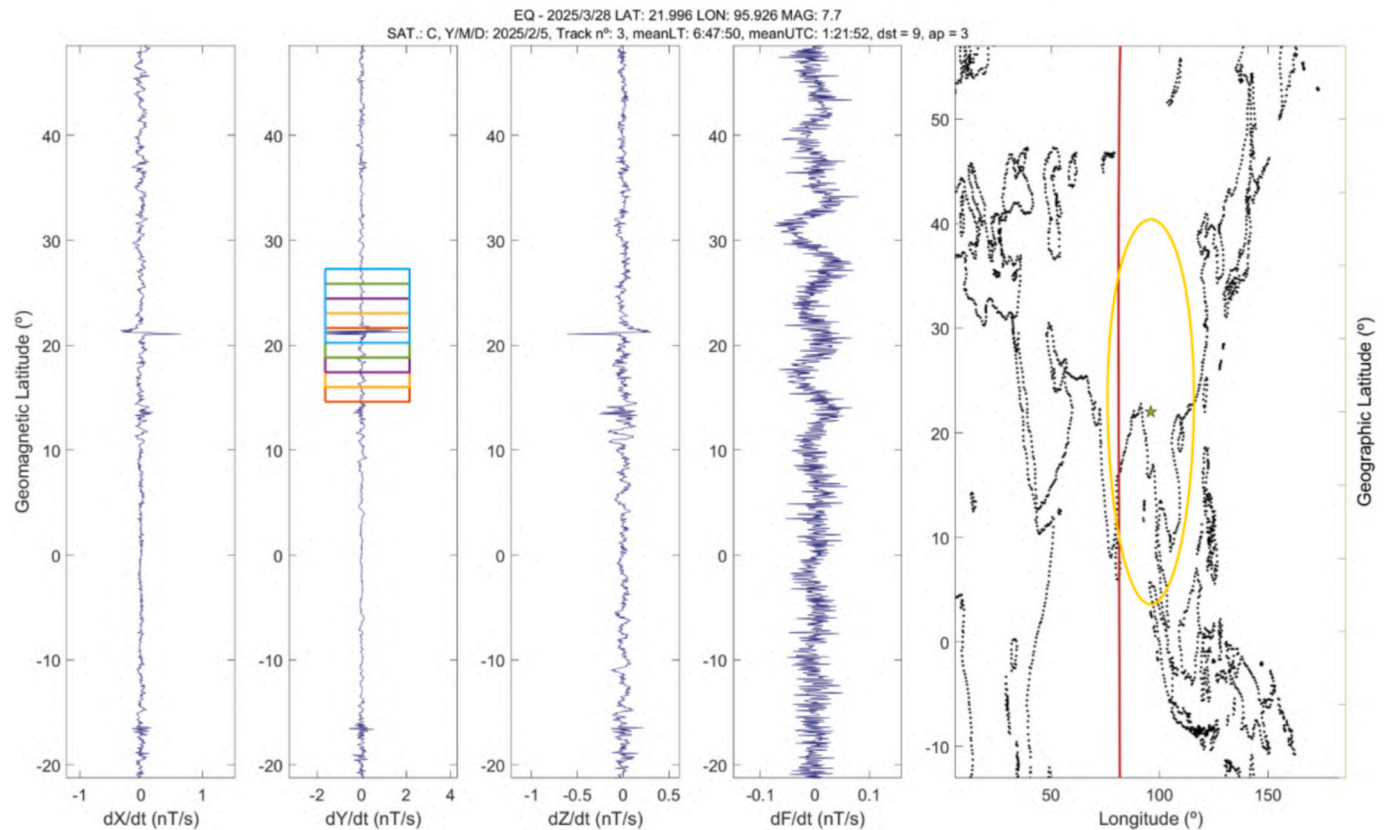


Fig. 26. Swarm Charlie magnetic field on 5 February 2025, i.e. 51 days before the earthquake. The first differences of X, Y, Z and F are shown. The geographic map shows the analysed satellite track (red line), the epicenter of the earthquake (green star) and the Dobrovolsky area (yellow circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Summary of magnetic field anomalies detected by MASS algorithm. A tracks with an anomaly detected slightly under the threshold is reported in red (EQ = earthquake).

Satellite	Anomalies	Days before EQ
Swarm A	30/12/2024	88
	21/01/2025	66
	23/01/2025	64
	25/01/2025	62
	04/02/2025	52
Swarm B	27/01/2025	60
	07/02/2025	49
	19/02/2025	37
	21/02/2025	35
	23/02/2025	33
	03/03/2025	25
	06/03/2025 track 19	22
	06/03/2025 track 21	22
	07/03/2025	21
	20/03/2025	8
Swarm C	20/03/2025	8
	30/03/2025	−2
	30/12/2024	88
	08/01/2025	79
	18/01/2025	69
	23/01/2025 track 17	64
	23/01/2025 track 19	64
	04/02/2025	52
	05/02/2025	51

linked to stress accumulation or fluid migration, with system saturation matching total observed anomalies. Bootstrapped confidence intervals (k : [0.057, 0.065]; X_0 : [−59.5, −57.1]) confirmed robustness. Together, these results support a deterministic, sigmoidal pattern in pre-seismic

Table 6
Summary of common B/Ne anomalies detected by MASS/NeAD algorithms.

	Swarm A	Swarm B	Swarm C
Days with commonly detected anomalies	2	5	3
Date	21-01-2025	07-02-2025	30-12-2024
	23-01-2025	19-02-2025	18-01-2025
	track 19	23-02-2025	
		03-03-2025	
		06-03-2025	
		track 21	

anomalies, with variability in kinetics tied to tectonic settings. It is interesting to note that residuals with respect to the sigmoid fit are oscillating up and down around the fit, as it was found in other case studies (e.g. Zhang et al., 2024). Another way to show the parallel occurrence of all anomalies is given with Fig. 31. On the basis of the Fig. 31, the temporal evolution of the multiparameter anomalies can be divided into three stages. The first stage (28 December 2024–3 February 2025) includes anomalies in all seven parameters, with particularly strong coupling between atmospheric and ionospheric indicators at the end of January and early February. The second stage (4 February–20 March 2025) involves five parameters; during this interval the OLR anomalies weaken while four ionospheric parameters remain active, suggesting a reduced but still significant atmosphere–ionosphere interaction. The final stage, after the main-shock, is characterized mainly by magnetic field disturbances observed by Swarm, which may be associated with the preparation of the M5.4

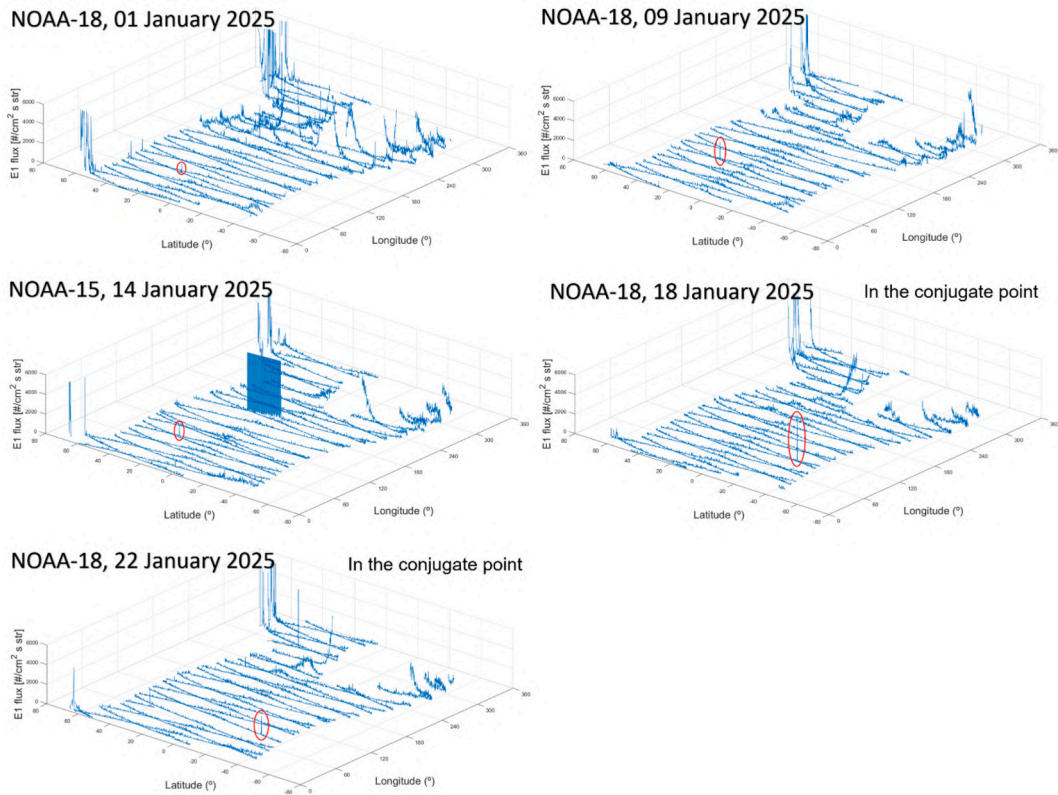


Fig. 27. Major EBs in January 2025.

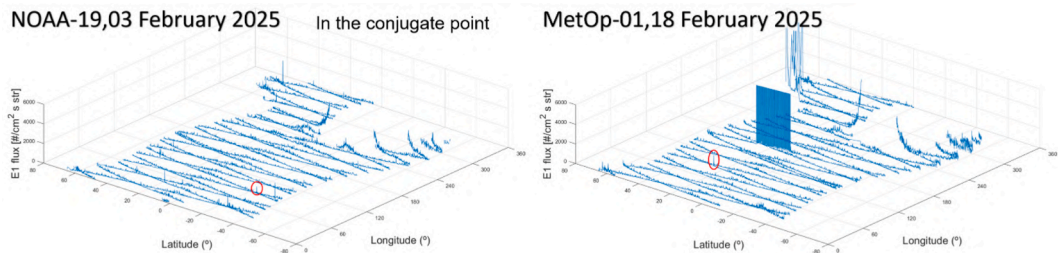


Fig. 28. Major EBs in February 2025.

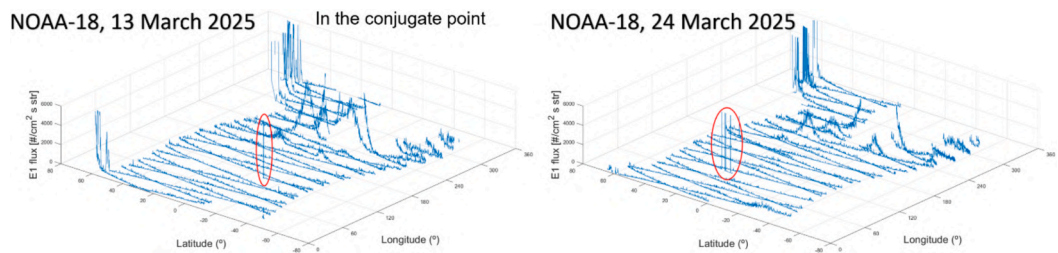


Fig. 29. Major EBs in March 2025.

aftershock on 13 April. Taken together, these stages suggest an evolution from indirect coupling mechanisms (e.g., acoustic-gravity waves or geochemical pathways) toward predominantly electromagnetic coupling as the system approaches and passes through the main rupture.

All these findings align with the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) model, which posits that stress-induced changes in the Earth's crust can propagate upward, influencing atmospheric and ionospheric conditions. While further research is needed to establish causal

relationships and refine predictive capabilities, the atmospheric and TEC analyses for the 2025 earthquake underscore the potential of multidisciplinary approaches in earthquake forecasting.

6.1. The mixed effects from the earthquake and weak geomagnetic storms

To remove the effects from solar activity and geomagnetic storms during the earthquake analysis, generally only the quiet days with $|Dst|$

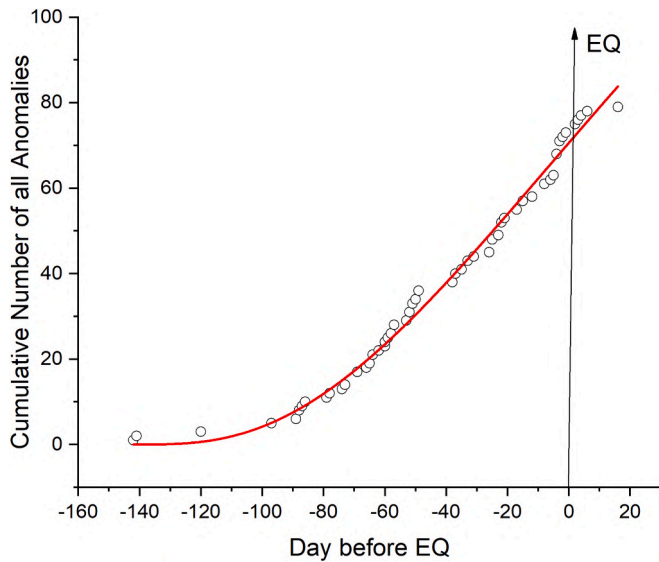


Fig. 30. Cumulative number of all anomalies for the five months before the earthquake (28 March 2025, indicated as $x = 0$ in the plot and a vertical arrow). The red curve is the best-fit with a sigmoid function. Please refer to the Table 1S for the date and type of anomalies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$< 20\text{nT}$ and $a_p < 10$ are investigated in the earthquake research. Around this Myanmar-Burma EQ, some typical anomalies were detected during the weak geomagnetic storm time of March 23–27 with $|Dst| < 30\text{nT}$ in multi parameters, including GIMTEC, Beidou TEC, ionosonde data, Swarm Ne, and electron bursts. Some anomalies showed quite similar local features with those occurring in quiet days in GIM TEC, which indicate a new question if these anomalies are really related to the earthquake, or it is just from the weak geomagnetic storm. It is well known that the geomagnetic storms always make global or regional perturbations, which is significantly different with local disturbances related to earthquakes. A typical case is around 2008 Wenchuan earthquake, when Zhao et al. (2008) found regional TEC enhancement on March 3 with $Dst = -21\text{nT}$, which helps to confirm the anomaly on March 3 to be related to weak geomagnetic storms. The conditions with solar activity and geomagnetic storms had been faced before the 2011 M9 Tohoku earthquake (Le et al., 2013), and the significant enhancement of TEC occurred on March 8 with $F10.7 = 122\text{ sfu}$ and $Dst = -24\text{nT}$. After comparison with the empirical model NeQuick and the theoretical model TIME-IGGCAS, and taken consideration of a

geomagnetic disturbance with $Kp = 4$ on March 7, they demonstrated that the TEC enhancement on March 8 concentrated over the epicentral region and its conjugate point with duration time of 16 h was mainly induced by this M9 earthquake, while partly from the solar activity and geomagnetic storm (Le et al., 2013). For the conditions in this research, the local and conjugate characteristics for the anomalies during Mar 23–27 (Fig. 10) were all clear under weak geomagnetic storms, so the Myanmar-Burma earthquake contributed predominantly to their construction. In the future, if we can make the localization or its conjugate feature together as a distinguishing tool for the earthquake-related ionospheric disturbances during weak geomagnetic storm days, maybe more anomalies can be abstracted and help to indicate and predict the approaching strong earthquake.

6.2. The effects from plasma irregularities

Myanmar-Burma earthquake is located at low latitude, where two kinds of structures always exist, EIA (Equatorial Ionospheric Anomaly) and small scale irregularities like plasma bubbles (PBs). Liu et al. (2010) studied the strength, location and formation time of EIA crests, and their relationship with earthquakes in Taiwan, and they found that EIA crests significantly move equatorward (poleward) and appears in an earlier (later) time of the afternoon period a few days before (after) the earthquakes along the Taiwan longitude. They indicate the location and occurrence time can be employed to detect earthquake-associated ionospheric precursors. In our case, the GIM TEC anomalies were located at the EIA region, and with conjugate features, but almost half of the anomalies were negatives ones, such as that on Mar 11 in Fig. 9. If we consider the effects of solar activity, it will enhance the EIA, so the disturbances of TEC in this case may be resulted from the Myanmar-Burma strong earthquake. In addition, it is noticed that, the anomalies whatever in electron density or magnetic field from Swarm satellites, showed the similar location with EIA crest, but they are not the EIA itself, much likely overlapped some high frequency perturbations as shown in Fig. 19. Because Swarm satellites cannot continuously observe the EIA along the earthquake longitude, it is hard to evaluate if the EIA crest moved equatorward with the approaching time of earthquake occurrence. These anomalies in Ne and magnetic field were possibly the small scale irregularities in the topside ionosphere, such as equatorial PB (EPB). EPB has higher occurrence rate during high solar activity year and solstice seasons in Asian region, especially in Spring equinox (Sun et al., 2016). In March 2025, a few anomalies were indeed detected, including March 3, 6 and 20. To check if they are EPBs, the data in 2015 were collected around the epicenter area under similar solar activity condition. The results as shown in Fig. 32, on March 5 and 10, along the nearest orbits to the epicenter. The disturbances in magnetic field were also revealed over the epicenter and its conjugate points,

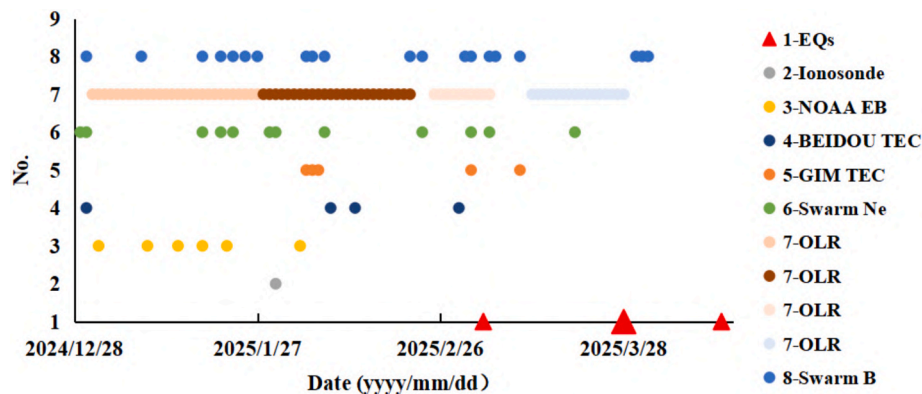


Fig. 31. The temporal distributions of anomalies only within quiet days in multi parameters (marked with different numbers) during -90 days before to 10 days after the major 28 March 2025 Myanmar earthquake (with a M5.4 earthquake on March 5 and a strong aftershock with M5.4 on April 13 also included as referred in the paper).

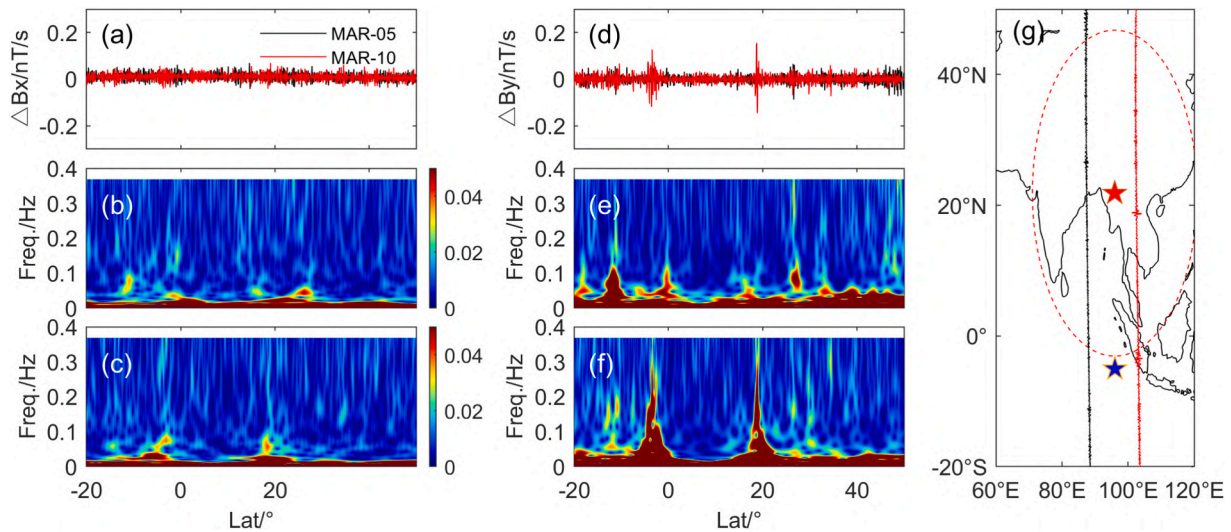


Fig. 32. The wavelet spectrum of magnetic field in Bx and By onboard Swarm B on 5 and 10 March 2015 (a: the filter curves of Bx within frequency band of 0.1–0.3 Hz; b: the wavelet spectrum of Bx for 5 March; c: the wavelet spectrum of Bx for 10 March; d–f are the same results for By component; g: the orbits position for both days, in which the red star is the Myanmar earthquake with dashed red circle for Dobrovolsky's area, and the blue one is its conjugate point). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

especially in By component. Taken account of these effects, the disturbances occurred at the equatorial area should be treated quite carefully, and its relationship with earthquakes cannot be verified easily. Although the disturbances were much stronger in 2025 (Fig. 22) than those in 2015, we cannot validate that earthquake can trigger or enhance the construction of EPBs.

7. Conclusions

The 2025 Myanmar-Burma earthquake serves as both a tragic reminder of the region's vulnerability to major tectonic events and a valuable case study for understanding active strike-slip fault dynamics in continental collision zones. This paper aims to analyze the pre-seismic features and regional implications of the event, while also exploring its broader significance for earthquake forecasting.

The multiparameter analyses for the 2025 Myanmar-Burma earthquake reveal a range of precursory signals, including seismicity changes, thermal anomalies, ionospheric disturbances, and geomagnetic variations. Although we cannot trust on all anomalies as due to the preparatory phase of the earthquake, since some could be due to other kinds of ionospheric perturbations, the cumulative number of anomalies is statistically attributable to a non-random process, likely earthquake-related.

These observations highlight the importance of integrating seismological, atmospheric, and space-based data to better understand the complex processes underlying major earthquakes. Continued advancements in satellite technology and data analysis methods hold promise for improving our ability to detect and interpret such precursors, ultimately enhancing earthquake preparedness and mitigation efforts.

Many perturbations were detected in the ionosphere, and the results suggest that localization and conjugate features may help identify more anomalies during weak geomagnetic storm days. Since the earthquake position is consistent with the EIA, and most anomalies were concentrated in the equatorial area, they should be interpreted with caution. At present, these anomalies cannot be clearly distinguished from small scale irregularities, such as EPBs, normally occurring in this region.

CRediT authorship contribution statement

Angelo De Santis: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding

acquisition, Conceptualization. **Xuemin Zhang:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Saioa A. Campuzano:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Pan Xiong:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Gianfranco Cianchini:** Writing – review & editing, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Jing Liu:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Serena D'Arcangelo:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Na Yang:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation. **Mariagrazia De Caro:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Xinyan Ouyang:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Martina Orlando:** Writing – review & editing, Visualization, Validation, Software, Formal analysis, Data curation. **Maoning Feng:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Loredana Perrone:** Writing – review & editing, Visualization, Validation, Investigation, Funding acquisition, Formal analysis. **Yongxian Zhang:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Dario Sabbagh:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Xinyi Jia:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Maurizio Soldani:** Writing – review & editing, Validation, Software, Methodology, Investigation, Funding acquisition. **Hong Liu:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Ariana Varela-Mendez:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation.

Submission declaration

- the work described has not been published previously except in the form of a preprint, an abstract, a published lecture, academic thesis or registered report.
- the article is not under consideration for publication elsewhere.

- the article's publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out.
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Funding

For the Italian authors, this work was supported by the following projects: Unitary (Working Earth), with funds of the Italian Ministry of University and Research (MUR), Limadou Science+ and EXPO, with funds of the Italian Space Agency (ASI), and Space it up, with funds of ASI and MUR.

Declaration of competing interest

All authors have not any financial and personal relationships with other people or organizations that could inappropriately influence or bias their work.

We have no competing interests.

Acknowledgements

This work was supported by the following projects: Unitary (Working Earth), with funds of the Italian Ministry of University and Research (MUR), Limadou Science+ and EXPO, with funds of the Italian Space Agency (ASI), and Space it up, with funds of ASI and MUR. Chinese authors acknowledge NSFC project (42361144794, 42274106), Central Public-interest Scientific Institution Basal Research Fund (CEAIEF20250301), National Abroad Expert Plan (No. DL2023092001L), and Dragon-6 project (No. 95407, 95456).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tecto.2026.231101>.

Data availability

Data will be made available on request.

References

- Aki, K., 1965. Maximum likelihood estimate of b in the formula $\log_{10}N=a-bm$ and its confidence limits. *Bull. Earthquake Res.* 43, 237–239.
- Aleksandrin, S.Yu., Galper, A.M., Grishantzeva, L.A., Koldashov, S.V., Maslennikov, L.V., Murashov, A.M., Picozza, P., Sgrigna, V., Voronov, S.A., 2003. High-energy charged particle bursts in the near-Earth space as earthquake precursors. *Ann. Geophys.* 21, 597–602. <https://doi.org/10.5194/angeo-21-597-2003>.
- Alimoradi, H., Rahimi, H., De Santis, A., 2024. Successful tests on detecting pre-earthquake magnetic field signals from space. *Remote Sens.* 16 (16), 2985. <https://doi.org/10.3390/rs16162985>.
- Alimoradi, H., Rahimi, H., De Santis, A., 2025. Detection of pre-seismic magnetic field anomalies using Swarm satellite data: a case study of the 2025 Mw7.7 Myanmar earthquake. *Sci. Rep.* 15, 36965. <https://doi.org/10.1038/s41598-025-20901-1>.
- Aung, L.T., Oo, K.Z., Win, K.M., Moore, G.F., Tun, S.T., Naing, W., 2020. Active deformation of the Central Myanmar forearc basin: insight from post-Pleistocene inversion of the Pyay fault. *J. Asian Earth Sci.* X 4, 100037. <https://doi.org/10.1016/j.jaesx.2020.100037>.
- Bates, D.M., Watts, D.G., 1988. *Nonlinear Regression Analysis and its Applications*. Wiley.
- Chen, J., Wang, A., Zhang, Y., Zhou, J., Yu, C., 2020. BDS satellite-based augmentation service correction parameters and performance assessment. *Remote Sens.* 12, 766. <https://doi.org/10.3390/rs12050766>.
- Cianchini, G., De Santis, A., et al., 2020. Revised accelerated moment release under test: fourteen worldwide real case studies in 2014–2018 and simulations. *Pure Appl. Geophys.* 177 (9), 4057–4087.
- Cianchini, G., Calcarà, M., De Santis, A., Piscini, A., D'Arcangelo, S., Fidani, C., Sabbagh, D., Orlando, M., Perrone, L., Campuzano, S.A., De Caro, M., Nardi, A., Soldani, M., 2024. The preparation phase of the 2023 Kahramanmaraş (Turkey) major earthquakes from a multidisciplinary and comparative perspective. *Remote Sens.* 16, 2766. <https://doi.org/10.3390/rs16152766>.
- Cicerone, R.D., Ebel, J.E., Britton, J., 2009. A systematic compilation of earthquake precursors. *Tectonophysics* 476 (3–4), 371–396. <https://doi.org/10.1016/j.tecto.2009.06.008>.
- De Santis, A., Cianchini, G., Giovambattista, Di, 2015. Accelerating moment release revisited: examples of application to Italian seismic sequences. *Tectonophysics* 639, 82–98. <https://doi.org/10.1016/j.tecto.2014.11.015>.
- De Santis, A., Balasis, G., Pavón-Carrasco, F.J., Cianchini, G., Manda, M., 2017. Potential earthquake precursory pattern from space: the 2015 Nepal event as seen by magnetic Swarm satellites. *Earth Planet. Sci. Lett.* 461, 119–126. <https://doi.org/10.1016/j.epsl.2016.12.037>.
- De Santis, A., Marchetti, D., Pavón-Carrasco, F.J., et al., 2019. Precursory worldwide signatures of earthquake occurrences on Swarm satellite data. *Sci. Rep.* 9, 20287. <https://doi.org/10.1038/s41598-019-56599-1>.
- De Santis, A., Cianchini, G., Marchetti, D., Piscini, A., Sabbagh, D., Perrone, L., Campuzano, S.A., Inan, S., 2020. A multiparametric approach to study the preparation phase of the 2019 Ridgecrest (California) earthquake. *Front. Earth Sci.* <https://doi.org/10.3389/feart.2020.540398>.
- Dey, S., Singh, R.P., 2003. Surface latent heat flux as an earthquake precursor. *Nat. Hazards Earth Syst. Sci.* 3, 749–755. <https://doi.org/10.5194/nhess-3-749-2003>.
- Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. *Pure Appl. Geophys.* 117, 1025–1044. <https://link.springer.com/article/10.1007/BF00876083>.
- Gulia, L., Wiemer, S., 2019. Real-time discrimination of earthquake foreshocks and aftershocks. *Nature* 574, 193–199. <https://doi.org/10.1038/s41586-019-1606-4>.
- Gutenberg, B., Richter, C.F., 1944. Frequency of earthquakes in California. *Bull. Seismol. Soc. Am.* 34, 185–188. <https://doi.org/10.1785/BSSA0340040185>.
- Hurukawa, N., Maung Maung, P., 2011. Two seismic gaps on the Sagaing Fault, Myanmar, derived from relocation of historical earthquakes since 1918. *Geophys. Res. Lett.* 38, L01310. <https://doi.org/10.1029/2010GL046099>.
- Ippolito, A., Perrone, L., De Santis, A., Sabbagh, D., 2020. Ionosonde data analysis in relation to the 2016 Central Italian earthquakes. *Geosciences* 10 (9), 354. <https://doi.org/10.3390/geosciences10090354>.
- Kundu, B., Gahalaut, V.K., 2012. Earthquake occurrence processes in the Indo-Burmese wedge and Sagaing fault region. *Tectonophysics* 524–525, 135–146. <https://doi.org/10.1016/j.tecto.2011.12.031>.
- Le, H., Liu, L., Liu, J.-Y., Zhao, B., Chen, Y., Wan, W., 2013. The ionospheric anomalies prior to the M9.0 Tohoku-Oki earthquake. *J. Asian Earth Sci.* 62, 476–484. <https://doi.org/10.1016/j.jseas.2012.10.034>.
- Liu, J.-Y., Chen, Y.-I., Chuo, Y.-J., Chen, C.-S., 2010. A statistical study of ionospheric earthquake precursors monitored by using equatorial ionization anomaly of GPS TEC in Taiwan. *Journal of Asian Earth Sciences* 39 (1–2), 76–80. <https://doi.org/10.1016/j.jseas.2010.02.012>.
- Massey, F.J., 1951. The Kolmogorov-Smirnov test for goodness of fit. *J. Am. Stat. Assoc.* 46 (253), 68–78.
- Melgar, D., Taymaz, T., Ganas, A., Crowell, B., Öcalan, T., Kahraman, M., Tsironi, V., Yölsal-Çevikbilen, S., Valkaniotis, S., Irmak, T.S., Eken, T., Erman, C., Özkan, B., Dogan, A.H., Altuntaş, C., 2023. Sub- and super-shear ruptures during the 2023 Mw 7.8 and Mw 7.6 earthquake doublet in SE Türkiye. *Seismica* 2 (3). <https://doi.org/10.26443/seismica.v2i3.387>.
- Nuannin, P., 2006. The potential of b -value variations as earthquake precursors for small and large events. In: *Acta Universitatis Upsaliensis. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 183. 46 pp. Uppsala.
- Ouzounov, D., Pulnits, S., Kafatos, M.C., Taylor, P., 2018. Thermal radiation anomalies associated with major earthquakes. In: Ouzounov, D., Pulnits, S., Hattori, K., Taylor, P. (Eds.), *Pre-earthquake Processes: a multidisciplinary approach to earthquake prediction studies*. <https://doi.org/10.1002/9781119156949.ch15>.
- Perrone, L., Korsunova, L.P., Mikhailov, A.V., 2010. Ionospheric precursors for crustal earthquakes in Italy. *Ann. Geophys.* 28, 941–950. <https://doi.org/10.5194/angeo-28-941-2010>.
- Perrone, L., De Santis, A., Abbattista, C., Alfonsi, L., Amoroso, L., et al., 2018. Ionospheric anomalies detected by ionosonde and possibly related to crustal earthquakes in Greece. *Ann. Geophys.* 36, 361–371. <https://doi.org/10.5194/angeo-36-361-2018>.
- Piscini, A., De Santis, A., Marchetti, D., Cianchini, G., 2017. A multi-parametric climatological approach to study the 2016 Amatrice–Norcia (Central Italy) earthquake preparatory phase. *Pure Appl. Geophys.* 174 (10), 3673–3688.
- Pivnik, D.A., Nahn, J., Tucker, R.S., Smith, G.O., Nyein, K., Nyunt, M., Maung, P.H., 1998. Polyphase deformation in a Fore-Arc/Back-Arc Basin, Salin Basin, Burma (Burma). *Am. Assoc. Pet. Geol. Bull.* 82, 1837–1856. <https://doi.org/10.1306/1D9BD15F-172D-11D7-8645000102C1865D>.
- Pulnits, S., Ouzounov, D., 2011. Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) mode - An unified concept for earthquake precursors validation. *J. Asian Earth Sci.* 41 (4–5), 371–382. <https://doi.org/10.1016/j.jseas.2010.03.005>.
- Qiu, J., Sun, J., Ji, L., 2024. The 2024 Mw7.1 Wushi earthquake: a thrust and strike-slip event unveiling the seismic mechanisms of the South Tian Shan's thick-skin tectonics. *Remote Sens.* 16, 2937.
- Scholz, C.H., 1968. The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes. *BSSA* 58 (1), 399–415.
- Scholz, C.H., Kocynski, T.A., 1979. Dilatancy anisotropy and the response of rock to large cyclic loads. *J. Geophys. Res. Solid Earth* 84 (B10), 5525–5534. <https://doi.org/10.1029/JB084iB10p05525>.

- Sobolev, G., 2001. The examples of earthquake preparation in Kamchatka and Japan. *Tectonophysics* 338 (3–4), 269–279. [https://doi.org/10.1016/S0040-1951\(01\)00082-8](https://doi.org/10.1016/S0040-1951(01)00082-8).
- Sun, L., Xu, J., Wang, W., Yuan, W., Li, Q., Jiang, C., 2016. A statistical analysis of equatorial plasma bubble structures based on an all-sky airglow imager network in China. *J. Geophys. Res. Space Physics* 121 (11), 11,495–11,517. <https://doi.org/10.1002/2016ja022950>.
- Traitangwong, P., Khamsiri, S., Pailoplee, S., 2024. Precursory seismic quiescence of major earthquakes along the Sagaing fault zone, Central Myanmar: application of the pattern informatics technique. *Geosci. Lett.* 11, 33. <https://doi.org/10.1186/s40562-024-00351-9>.
- Tramutoli, V., Filizzola, C., Genzano, N., Lisi, M., 2018. Robust satellite techniques for detecting pre-seismic thermal anomalies. In: Ouzounov, D., Pulinet, S., Hattori, K., Taylor, P. (Eds.), *Pre-earthquake Processes: a multidisciplinary approach to earthquake prediction studies*. <https://doi.org/10.1002/9781119156949.ch14>.
- Tronin, A.A., 2000. Thermal IR satellite sensor data application for earthquake research in China. *Int. J. Remote Sens.* 21 (16), 3169–3177. <https://doi.org/10.1080/01431160050>.
- Vigny, C., Socquet, A., Rangin, C., Chamot-Rooke, N., Pubellier, M., Bouin, M.-N., Bertrand, G., Becker, M., 2003. Present-day crustal deformation around Sagaing fault, Myanmar. *J. Geophys. Res.* 108, 25–33. <https://doi.org/10.1029/2002JB001999>.
- Wang, Y., Sieh, K., Aung, T., Min, S., Khaing, S.N., Tun, S.T., 2011. Earthquakes and slip rate of the southern Sagaing fault: insights from an offset ancient fort wall, lower Burma (Myanmar). *Geophys. J. Int.* 185 (1), 49–64. <https://doi.org/10.1111/j.1365-246X.2010.04918.x>.
- Wang, Y., Sieh, K., Tun, S.T., Lai, K.-Y., Myint, T., 2014. Active tectonics and earthquake potential of the Myanmar region. *J. Geophys. Res. Solid Earth* 119, 3767–3822. <https://doi.org/10.1002/2013JB010762>.
- Wiemer, S., Wyss, M., 2000. Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the western United States, and Japan. *Bull. Seismol. Soc. Am.* 90, 859–869. <https://doi.org/10.1785/0119990114>.
- Xiong, P., Shen, X.H., Bi, Y.X., Kang, C.L., Chen, L.Z., Jing, F., Chen, Y., 2010. Study of outgoing longwave radiation anomalies associated with Haiti earthquake. *Nat. Hazards Earth Syst. Sci.* 10, 2169–2178. <https://doi.org/10.5194/nhess-10-2169-2010>.
- Xiong, X., Shan, B., Zhou, Y.M., Wei, S.J., Li, Y.D., Wang, R.J., Zheng, Y., 2017. Coulomb stress transfer and accumulation on the Sagaing Fault, Myanmar, over the past 110 years and its implications for seismic hazard. *Geophys. Res. Lett.* 44, 4781–4789. <https://doi.org/10.1002/2017GL072770>.
- Yang, S., Xiao, Z., Wei, S., He, Y., Mon, C.T., Hou, G., Thant, M., Sein, K., Jiang, M., 2023. Detailed earthquake catalog in Central Myanmar and seismic waveform data from China-Myanmar Geophysical Survey in the Myanmar Orogen (CMGSMO) project [Dataset]. In: WDC for Geophysics. <https://doi.org/10.12197/2023GA010>.
- Yang, S., Xiao, Z., Wei, S., He, Y., Mon, C.T., Hou, G., Thant, M., Sein, K., Jiang, M., 2024. New insights into active faults revealed by a deep-learning-based earthquake catalog in Central Myanmar. *Geophys. Res. Lett.* 51, e2023GL105159. <https://doi.org/10.1029/2023GL105159>.
- Yang, Y., Gao, W., Guo, S., Mao, Y., Yang, Y., 2019. Introduction to BeiDou-3 navigation satellite system. *Navigation* 66. <https://doi.org/10.1002/navi.291>.
- Zhang, X., De Santis, A., Liu, J., Campuzano, S.A., Yang, N., Cianchini, G., Ouyang, X., D'Arcangelo, S., Yang, M., De Caro, M., Li, X., Fidani, C., Liu, H., Orlando, M., Nie, L., Perrone, L., Piscini, A., Dong, L., Sabbagh, D., Soldani, M., Xiong, P., 2024. Pre-earthquake oscillating and accelerating patterns in the lithosphere-atmosphere-ionosphere coupling (LAIC) before the 2022 Luding (China) Ms6.8 earthquake. *Remote Sens.* 16 (13), 2381. <https://doi.org/10.3390/rs16132381>.
- Zhang, X., De Santis, A., Xiong, P., Cianchini, G., Yisimayili, A., Campuzano, S.A., Yang, N., D'Arcangelo, S., Liu, J., De Caro, M., Li, X., Fidani, C., Yang, M., Orlando, M., Ouyang, X., Perrone, L., Liu, H., Sabbagh, D., Feng, M., Soldani, M., Wang, S., 2026. The lithosphere-atmosphere-ionosphere coupling (LAIC) processes around the 2024 Wushi (China) Mw7.1 earthquake. *J. Asian Earth Sci.* 297, 106916. <https://doi.org/10.1016/j.jseas.2025.106916>.
- Zhao, B., Yu, T., Wang, M., Wan, W., Lei, J., Liu, L., Ning, B., 2008. Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake? *J. Geophys. Res.* 113, A11304. <https://doi.org/10.1029/2008JA013613>.



OPEN Detection of pre-seismic magnetic field anomalies using Swarm satellite data: a case study of the 2025 Mw7.7 Myanmar earthquake

Homayoon Alimoradi¹, Habib Rahimi¹✉ & Angelo De Santis²✉

This study investigates magnetic field anomalies as precursors to the Mw7.7 Myanmar earthquake (March 28, 2025) using Swarm satellite data. We analyzed vector magnetic field (X, Y, Z) measurements over the Dobrovolsky region during the 10 days preceding the earthquake, applying cubic-spline filtering to identify residual anomalies. Our results revealed Y-component anomalies in 22 of 85 half-orbits, detectable up to 8 days before the event. Magnitude estimates were obtained using four empirical equations based on anomaly parameters such as duration, amplitude (“energy”), timing, and satellite–epicenter distance. Among these, the distance-based relation provided the most accurate estimate ($M \approx 7.2$), showing reasonable agreement with the observed magnitude ($M = 7.7$). Interestingly, anomaly energy values consistently clustered within a narrow range (570–577), which may represent a characteristic signature of earthquake-related anomalies. These findings suggest that satellite-based magnetic anomalies could contribute to short-term earthquake forecasting systems, although further validation with larger datasets is needed to assess the robustness and general applicability of the approach.

Keywords Precursors, Earthquake, Magnetic field, Swarm, Satellite data

Earthquake prediction remains one of the most challenging problems in seismology. Despite substantial efforts, no reliable method exists to predict the time, location, and magnitude of major earthquakes with low uncertainty. While the general public often expects short-term predictions, the economic and social implications of false alarms, especially in urban regions with critical infrastructure, significantly limit the practicality of such uncertain forecasts^{1,2}.

Nonetheless, research into earthquake precursors continues to expand. These precursors refer to observable physical or chemical changes—especially in the lithosphere, atmosphere, or ionosphere—that precede seismic events³. Although no universal precursor has been confirmed, satellite and ground-based observations have detected several anomalies associated with large earthquakes, such as ultra-low frequency (ULF) electromagnetic emissions, thermal infrared (TIR) anomalies, and ionospheric disturbances in electron density and magnetic field variations^{4–15}.

A widely discussed framework for explaining such earthquake-related anomalies is the Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model. According to this concept, stress accumulation in the lithosphere can trigger a chain of processes, including radon emanation, atmospheric ionization, and changes in conductivity, which can propagate upward and produce detectable disturbances in the ionosphere and the geomagnetic field. This coupling mechanism provides a plausible physical basis for interpreting magnetic and ionospheric anomalies as possible precursors of seismic events^{16–18}.

The increasing availability of satellite data and cloud-based analysis platforms (e.g., Google Earth Engine, NASA Giovanni) has accelerated the detection of such anomalies¹⁹. Notably, the DEMETER satellite mission (2004–2010) provided pioneering observations of seismo-ionospheric phenomena, while the currently active Swarm constellation continues to advance global monitoring in this field^{20–22}. Previous studies have already provided evidence that Swarm satellite magnetic data can reveal potential precursory signatures of strong earthquakes. For instance, Alimoradi et al. (2024)⁷ reported a statistical correlation between magnetic field anomalies in Swarm data and parameters such as earthquake magnitude, time-to-event, and satellite–epicenter distance. More recently, Özsöz and Pamukçu (2025)²³ and Özsöz et al. (2024)²⁴ analyzed Swarm data over Turkey

¹Institute of Geophysics, University of Tehran, Tehran, Iran. ²Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy. ✉email: rahimi.h@ut.ac.ir; angelo.desantis@ingv.it

and Greece, confirming time-dependent magnetic anomalies before several $M \geq 6$ earthquakes. Together with earlier theoretical models^{25,26}, these findings emphasize the potential of Swarm-based observations as a valuable tool for short-term earthquake precursor research, and provide the context for the present Myanmar case study. Empirical evidence suggests that parameters such as Total Electron Content (TEC)⁴, electromagnetic wave propagation, and outgoing longwave radiation (OLR)^{11,12} may undergo detectable variations prior to significant earthquakes.

On March 28, 2025, a Mw 7.7 strike-slip earthquake struck the Sagaing region of Myanmar, causing widespread damage across several countries and resulting in over 5,000 fatalities^{27–29}. Myanmar lies at the complex junction of four tectonic plates, including the highly active Sagaing Fault, a known source of destructive earthquakes³⁰ (Fig. 1). The recurrence of large events along this fault highlights the urgent need for effective short-term warning tools.

Recent studies by Alimoradi et al. (2024)⁷ using Swarm satellite data have revealed that certain magnetic field anomalies, especially in the Y component, are statistically correlated with earthquake magnitude, satellite-epicenter distance, and time before the event. These studies introduced four empirical equations that estimate earthquake magnitude based on anomaly features such as duration, amplitude (“anomaly energy”), and observation timing (see Data Processing). These empirical relations were specifically developed using Swarm vector magnetic field (VFM) anomalies. Their applicability to other ionospheric parameters, such as plasma

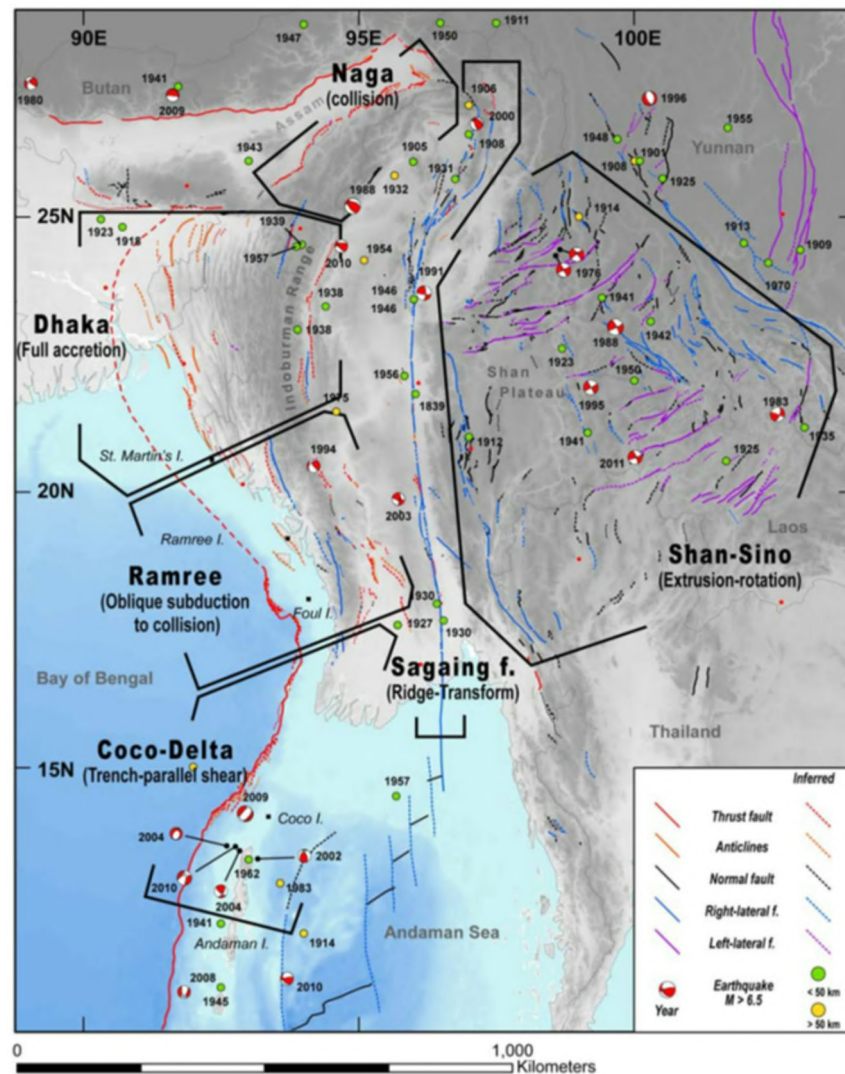


Fig. 1. Simplified neotectonic map of the Myanmar region, reproduced from Wang (2013), Earthquake Geology of Myanmar, Ph.D. dissertation, California Institute of Technology (doi:<https://doi.org/10.7907/XW.W9P26>), and from Wang et al. (2013), J. Geophys. Res., 118, 1–15 (doi:<https://doi.org/10.1002/2013JB010762>), published under the Creative Commons Attribution Non-Commercial No Derivatives License (CC BY-NC-ND 3.0). Black lines encompass the six neotectonic domains defined by Wang (2013). Green and yellow dots show epicenters of major 20th-century earthquakes (source: Engdahl and Villaseñor, 2002). Red and white beachballs are focal mechanisms of significant modern earthquakes (source: GCMT database since 1976).

density (Ne) or electron temperature (Te), has not yet been systematically tested. Future investigations may extend these equations to a broader set of parameters within a multi-parameter framework.

This study aims to investigate the presence of pre-seismic magnetic field anomalies before the March 28, 2025 Mw7.7 Myanmar earthquake by analyzing Swarm vector magnetic field data over the 10-day period preceding the event. Our objectives are to test whether the detected anomalies are consistent with the earthquake’s seismic parameters, to evaluate their potential role as short-term precursors within the framework of satellite-based earthquake monitoring, and to apply recently developed empirical equations for magnitude estimation to this case study. The novelty of this work lies in its application of these empirical relations to a new large earthquake, and in highlighting that the anomaly “energy” values consistently fall within a narrow range, which may serve as a potential diagnostic feature of earthquake-related anomalies.

In this work, we adopt an empirical statistical approach, applying previously developed equations to Swarm magnetic anomalies in order to evaluate their potential as short-term earthquake precursors.

Results and discussion

Vector magnetic field (VMF) data—including all three components (X, Y, Z) and the total magnetic field intensity (F)—were analyzed using observations from the Swarm satellite constellation. During the 10-day period preceding the Myanmar earthquake (Mw 7.7), 85 half-orbits from Swarm Alpha, Bravo, and Charlie passed over the Dobrovolsky region (as defined in Eq. 1 in the Methods section). Among these, 22 half-orbits showed detectable magnetic anomalies (Table 1), representing a significant proportion of possible precursory activity.

A detailed analysis was conducted on Swarm Alpha’s orbit 63,682, which passed within ~ 50 km of the earthquake epicenter on March 24, 2025—four days prior to the event (Fig. 2). This orbit exhibited a pronounced magnetic anomaly in the Y component, consistent with earlier findings that this component is the most sensitive to earthquake-related signals^{7,39}. Given the satellite’s velocity, which covers approximately one latitudinal degree in 15 seconds^{19,31}, this anomaly lasted for about 135 s.

Additional orbits (62867 and 63678) also displayed anomalous signals (Figs. 3 and 4), reinforcing the presence of magnetic disturbances in proximity to the epicenter. As shown in the figures, the earthquake epicenter is marked with a green star. The geographic map on the right side of the figure illustrates the Dobrovolsky region. Additionally, the satellite’s trajectory is indicated with a red line and the detected anomaly is marked with a red rectangle. The values of the geomagnetic indices Dst and Kp are also shown, indicating quiet geomagnetic conditions. Table 2 summarizes the key points of the anomalous half-orbits in Figs. 2, 3 and 4. Further details and additional examples are provided in the supplementary materials.

After identifying all the anomalies and calculating their durations, as well as determining the anomaly energy, the timing of the anomaly relative to the earthquake day, and the distance between the satellite’s ground track (where the anomaly was detected) and the earthquake epicenter, all necessary parameters for estimating the earthquake magnitude using Eq. (2) to (5) were available. The results of the magnitude estimation using each individual orbit and for all three Swarm satellites—Alpha, Bravo, and Charlie—based on all four equations are presented in Table 3. In the same Table, the magnitudes derived from Eq. (2) to (5) for each orbit are labeled as M1, M2, M3, and M4, respectively.

A general overview of the Table reveals that Eq. (3), which incorporates the effect of the distance between the satellite orbit and the earthquake epicenter, has estimated the earthquake magnitude more accurately than the other three equations. However, in this case, each satellite has several orbits that show anomalies within a specific region, and each orbit yields a separate magnitude estimate. Therefore, to gain a clearer understanding, the average magnitude obtained from each of the four equations for each satellite should be calculated. This has been done in Table 4.

Based on Table 4—and as observed in Table 3—we notice that, in general, magnitude averages do not depend on the satellite. In addition, M1, M2 and M4 underestimate the real magnitude, while M3 overestimates that value. When we exclude the estimates taken in geomagnetic disturbed times and too far from the earthquake epicentre (at distances larger than 1000 km), final averages are usually a little better. Table 4 confirms that the best magnitude estimate was obtained using Eq. (3). It is also important to note that the present analysis is restricted to magnetic field anomalies. Applying and validating these equations with additional parameters, such as plasma density (Ne) and electron temperature (Te), remains an important task for future research and may improve the robustness of earthquake precursor detection in a multi-parameter framework. Considering the actual magnitude of the Myanmar earthquake (7.7) and the estimated magnitude from Eq. (3), which is approximately 7.2, it can be claimed that this is a reasonable estimate, because a typical uncertainty in magnitude

SAT.	Number of half-orbits analyzed	Number of anomalous half-orbits	Percentage (%)
SW-A	29	8	27.6
SW-B	30	8	26.7
SW-C	26	6	23
total	85	22	25.9

Table 1. The number of orbits from each of the Swarm satellites—Alpha, Bravo, and Charlie—that passed through the dobrovolsky region during the 10-day observation window was analyzed. Additionally, the number of anomalous orbits identified for each satellite was determined. The percentage of anomalous orbits relative to the total number of analyzed orbits was also calculated.

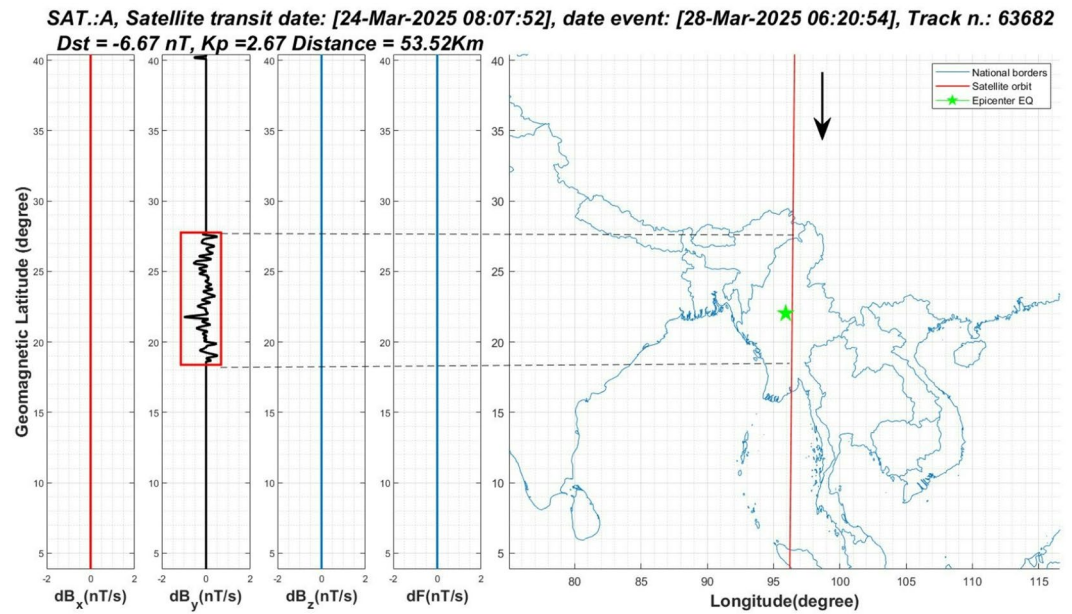


Fig. 2. Identified magnetic anomalies. Anomalous event detected on March 24th, 2025, by SW-A, which is four days before the March 28th, 2025, Mw = 7.7 Myanmar earthquake. The event occurred at a horizontal distance of 53 km from the epicenter. The epicenter is marked by a green star, and the geographic map on the right side of the figure illustrates the Dobrovolsky region. The red line depicts the path of the satellite. At the top of the figure, the following information is provided: the satellite name (Alpha = A), the date and time of the satellite passing through the specified area, the date and time of the earthquake, the track number, geomagnetic indices (Dst, Kp), and the closer distance of the orbit from the epicenter of the earthquake. The direction of satellite movement is indicated by a black arrow. In this case the orbit is descending.

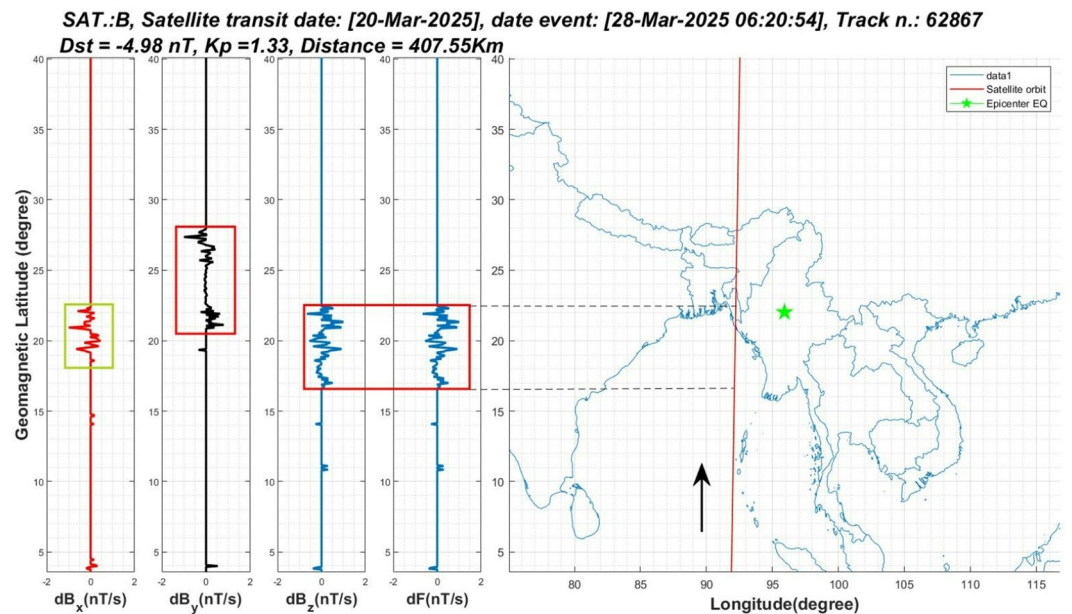


Fig. 3. Identified magnetic anomalies. Anomalous event detected on March 20th, 2025, by SW-B, which is eight days before the March 28th, 2025, Mw = 7.7 Myanmar earthquake. The event occurred at a distance of 407 km from the epicenter. The epicenter is marked by a green star, and the geographic map on the right side of the figure illustrates the Dobrovolsky region. The red line depicts the path of the satellite. At the top of the figure, the following information is provided: the satellite name (Bravo = B), the date and time of the satellite passing through the specified area, the date and time of the earthquake, the track number, geomagnetic indices (Dst, Kp), and the closer distance of the orbit from the epicenter of the earthquake. The direction of satellite movement is indicated by a black arrow. In this case the orbit is ascending.

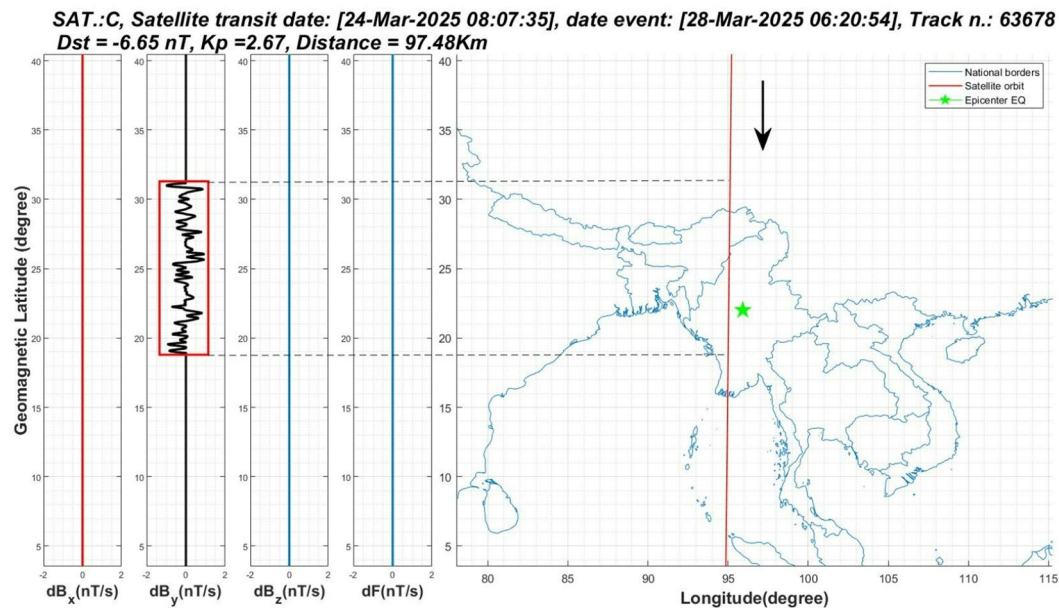


Fig. 4. Identified magnetic anomalies. Anomalous event detected on March 24th, 2025, by SW-C, which is four days before the March 28th, 2025, Mw = 7.7 Myanmar earthquake. The event occurred at a distance of 97 km from the epicenter. The epicenter is marked by a green star, and the geographic map on the right side of the figure illustrates the Dobrovolsky region. The red line depicts the path of the satellite. At the top of the figure, the following information is provided: the satellite name (Charlie = C), the date and time of the satellite passing through the specified area, the date and time of the earthquake, the track number, geomagnetic indices (Dst, Kp), and the closer distance of the orbit from the epicenter of the earthquake. The direction of satellite movement is indicated by a black arrow. In this case the orbit is descending.

	Figure 2	Figure 3	Figure 4
Orbit details			
Satellite	Swarm Alpha	Swarm Bravo	Swarm Charlie
Orbit number	63,682	62,867	63,678
Date of overpass	March 24, 2025 (4 days to the EQ)	March 20, 2025 (8 days to the EQ)	March 24, 2025 (4 days to the EQ)
Horizontal distance from epicenter	50 km	407 km	97 km
Anomaly description			
Component affected	Y	X, Y,Z	Y
Latitudinal extent	From 27.8° to 18.6° (approx. 9° latitude)	Latitudes from 16° to 22°	Latitudes from 18.8° to 31°
Duration	~ 135 s (satellite velocity ~ 1° per 15 s)	~ 90 s	~ 185 s
Satellite motion			
Direction	Descending	Ascending	Descending

Table 2. Key points of the case of satellite orbits 63,682 (Fig. 2), 62,867 (Fig. 3) and 63,678 (Fig. 4).

estimation is 0.5⁴⁰, while those taken with Eqs. (2) and (5) underestimate the real magnitude, by almost a unit. On the other hand, the method based on Eq. (4), overestimates the real magnitude by about 1.5. Why this latter Equation overestimates the magnitude could be due to its use of the amplitude (or “energy”) of the anomaly, that could depend on the satellite altitude, that usually decreases with time, causing a little larger amplitude of the magnetic anomaly and, in turn, an overestimation of the resulting magnitude.

However, this Eq. (4), which is the only one that is based on the anomaly “energy” (or amplitude), has an interesting feature. As shown in Table 3, the energy values of the detected anomalies mostly fall within a specific range of 570 to 577 (14 out of 22). Although the magnitudes estimated using anomaly energy involve a greater margin of error, the fact that the energy of the identified anomalies for this earthquake consistently lies within the 570–577 range may, if confirmed in other cases, serve as a distinguishing feature between earthquake-related anomalies and other types. This finding could also be considered a promising subject for future research.

Another noteworthy point concerns the anomaly identified in orbit number 63,682, which passed directly over the causative fault of the earthquake and the area that experienced the highest intensity. This overlap indicates that the detected anomaly, which lasted for 138 s, corresponds precisely to the region of maximum

Orbit	Satellite	Anomaly (sec)	Distance (Km)	Energy	Time (days)	M1	M2	M3	M4
63682	A	137.50	53.52	468.40	4.00	8.25	6.25	9.00	8.03
63651	A	57.70	903.38	473.40	6.00	7.02	7.40	9.02	7.36
63620	A	85.60	1758.40	520.40	8.00	7.58	8.02	9.16	8.35
63697	A	71.20	921.00	461.30	3.00	7.32	7.53	8.98	6.66
63667	A	39.40	813.31	571.00	5.00	6.48	7.11	9.29	6.54
63666	A	64.40	1768.96	571.00	5.00	7.18	7.86	9.29	7.25
63660	A	10.00	1302.32	577.00	6.00	4.55	6.58	9.31	4.82
63606	A	12.50	1686.24	571.00	9.00	4.86	6.87	9.29	5.73
62942	B	60.00	1935.80	577.00	3.00	7.08	7.87	9.31	6.41
62913	B	30.00	1611.71	577.00	5.00	6.10	7.35	9.31	6.15
62867	B	86.60	407.55	547.10	8.00	7.60	7.17	9.23	8.36
62904	B	73.30	856.56	577.00	5.00	7.36	7.51	9.31	7.44
62859	B	28.50	547.42	375.80	8.00	6.03	6.69	8.68	6.75
62852	B	21.90	874.88	577.00	9.00	5.65	6.81	9.31	6.54
62843	B	46.60	1594.36	577.00	9.00	6.72	7.61	9.31	7.64
62829	B	40.00	1481.14	577.00	10.00	6.51	7.47	9.31	7.57
63678	C	184.70	97.48	577.00	4.00	8.67	6.77	9.31	8.46
63647	C	71.10	752.39	557.30	6.00	7.32	7.41	9.26	7.66
63693	C	14.40	770.44	571.00	3.00	5.06	6.49	9.29	4.34
63662	C	43.30	1618.00	571.00	5.00	6.62	7.57	9.29	6.68
63655	C	20.20	1129.15	460.60	6.00	5.54	6.91	8.98	5.84
63616	C	45.00	1607.27	571.00	8.00	6.67	7.59	9.29	7.42

Table 3. Results of earthquake magnitude Estimation M1 to M4, using Eq. (2) to (5), respectively, based on the parameters derived from the identified Anomalies. Anomalies during the half-orbits 63,682, 62,867 and 63,678 are shown in Figs. 1, 2 and 3, respectively. The other anomalies are presented in the supplementary materials as Figs. 1–19 S. In red we show the anomalies occurred during some disturbed conditions (higher geomagnetic indices) and in blue those that have been detected at distances greater than 1000 km. In the satellite column, A stands for Alpha, B for Bravo and C for Charlie.

Satellite	Avg(M1)	Avg(M2)	Avg(M3)	Avg(M4)
A	6.66 (7.27)	7.20 (7.07)	9.17 (9.07)	6.84 (7.15)
B	6.63 (6.82)	7.31 (7.93)	9.22 (8.96)	7.11 (7.56)
C	6.65 (6.87)	7.12 (6.63)	9.24 (9.30)	6.73 (6.40)
Avg	6.65 (6.99)	7.21 (7.21)	9.21 (9.11)	6.89 (7.04)

Table 4. Average estimated magnitude for each satellite using Eq. (2) to (5). Within brackets there are the averages of black values in Table 3 (i.e. those without external geomagnetic disturbances - red values in Table 3 - and within 1000 km from epicentre - outside are given as blue values in Table 3).

seismic intensity. Therefore, it can be confidently stated that this magnetic anomaly was associated with pre-seismic processes and appeared four days before the mainshock.

As shown in Fig. 5, the causative fault of the earthquake lies along the longitude of 96° E and between the latitudes of 16° N to 25° N, which is the area of highest intensity according to the USGS shake map. On the other hand, the path of orbit 63,682, as shown in Fig. 2, also crosses longitude 96° E, and the magnetic anomaly appears between latitudes 27° N and 18° N, demonstrating a strong spatial correlation.

Based on this, it can be concluded that the satellite successfully detected a magnetic anomaly caused by the earthquake-related processes four days prior to the event. Although this method is still in development and has certain limitations, the findings suggest that with more precise monitoring of known active faults and higher-resolution data acquisition in seismically active regions, there is potential to advance the science of earthquake precursors and move closer to the goal of earthquake prediction.

Overall, these results confirm the presence of significant magnetic field anomalies prior to the Myanmar earthquake, and demonstrate that empirical models based on Swarm data can provide useful estimates of earthquake magnitude. However, while promising, such anomalies must be interpreted with caution due to the influence of external geomagnetic activity and orbit geometry. Continued validation with larger datasets and diverse seismic events remains essential.

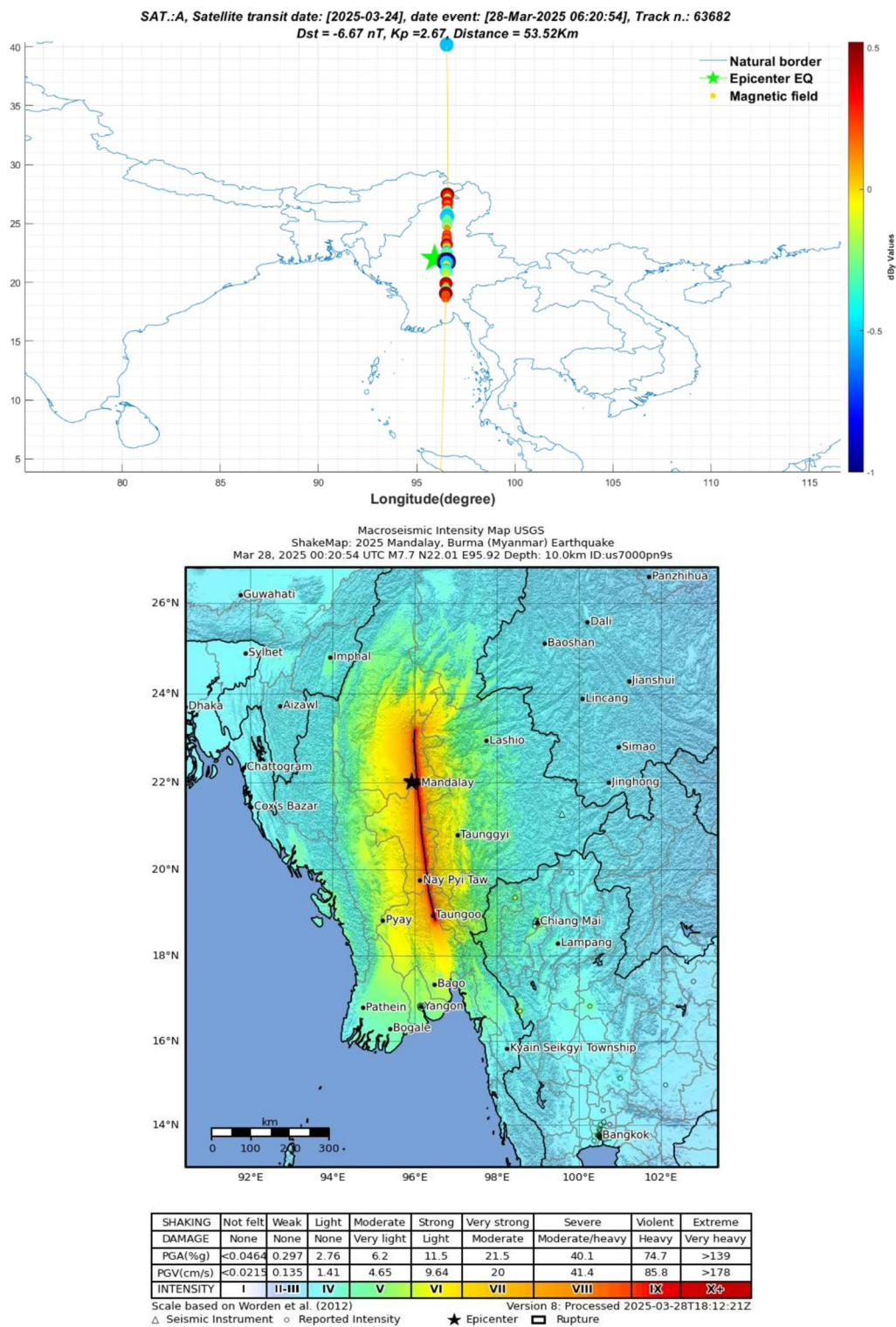


Fig. 5. Top figure: Orbit number 63,682 from the Swarm Alpha satellite is shown. The satellite’s trajectory and the data sampling points along this path are displayed on the geographical map. The color of each point represents the measured value. Bottom figure: USGS intensity map for the Myanmar earthquake with a magnitude of 7.7 on March 28, 2025, reproduced from the U.S. Geological Survey (public domain, <https://earthquake.usgs.gov/>).

Conclusion

This study demonstrates the potential of satellite-based magnetic field measurements in detecting precursory phenomena related to seismic events. Using data from the Swarm satellite mission, we identified significant magnetic anomalies in the region surrounding the Myanmar earthquake epicenter, which occurred up to ten days before the event. These anomalies were detected in multiple components of the magnetic field (X, Y, Z), with the Y-component showing the most pronounced changes. The correlation between the detected anomalies and the earthquake magnitude is promising, with the magnitude estimates based on these anomalies aligning closely with the actual earthquake magnitude. The analysis further highlights that magnetic anomalies detected in the vicinity of active fault zones could serve as valuable indicators of pre-seismic processes, potentially advancing the field of earthquake prediction. While further research is needed to refine the methods and validate the findings in different seismic regions, this study marks an important step toward understanding the role of magnetic field anomalies as precursors to earthquakes. Future studies should analyze a larger dataset of M7+ earthquakes to validate empirical equations, and understand why some are better than others, and why one (M3) provides an overestimate of the actual magnitude. With improved data resolution and monitoring, magnetic field data may one day contribute significantly to early earthquake warning systems a few days in advance.

Materials and methods data

The Swarm constellation, launched in late 2013, consists of three satellites (Alpha, Bravo and Charlie) designed to study the Earth's magnetic field²². The satellites operate in different orbits: Alpha and Charlie fly in nearly identical orbits at approximately 450 km altitude, while Bravo orbits at around 512 km. This configuration enables simultaneous measurement of aligned current flows in the radial direction of the field³¹ and long-term monitoring across a full solar cycle (11 years). Each satellite carries precision instrumentation, including VMF magnetometers for 3D magnetic field measurements; electric field instruments for ionospheric plasma characterization, accelerometers, and GPS receivers. These observations are provided as b1 level data, which include calibrated time series formatted for specific use, such as magnetic field measurements taken by all three Swarm satellites. The research objectives dedicated to this mission are: (1) Studies of core dynamics, geodynamic processes, and the mantle-core interaction; (2) Mapping of lithospheric polarization and its geological interpretation; (3) Determining the 3D electrical conductivity of the mantle; and (4) Investigating the electric currents flowing in the magnetosphere and ionosphere. However, one challenging aspect is the separation of different sources in the core, lithosphere, ionosphere, magnetosphere, and so on, which together contribute to the overall measured magnetic field³². Some of the main results obtained so far by the Swarm satellite mission include: mapping of the lithospheric magnetic field with a high resolution of 250 km³³, the effect of ocean tides on the geomagnetic field, and the electromagnetic induction generated by ocean circulation^{34,35}.

In this paper, we used VFM level 1-b data, with a sampling rate of 1 s, from 10 days before the earthquake to the day of the event, along paths passing through the Dobrovolsky region. The Dobrovolsky region is calculated using the following equation, where R is the radius of the area from the earthquake's epicenter in kilometers, and M is the magnitude of the earthquake³⁶.

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

According to studies conducted, most of the precursor phenomena have been observed in this region^{37,38}.

In addition to the magnetic field observations, we also used geomagnetic indices Kp and Dst, which are standard measures of global geomagnetic activity. The Kp index quantifies planetary-scale magnetic disturbances on a quasi-logarithmic scale from 0 (quiet) to 9 (extreme storm), while the Dst index represents the intensity of the equatorial ring current in nanotesla (nT). In this study, we used the auxiliary Kp and Dst data provided directly by the Swarm mission. Although the F10.7 solar radio flux index is commonly used as an indicator of solar activity, it was not included in this study. The F10.7 index does not always correlate directly with ionospheric disturbances caused by geomagnetic storms, and high F10.7 values (typically above 110–150 SFU) can significantly reduce the amount of usable Swarm data⁴¹. For these reasons, we focused on Kp and Dst indices, which more directly reflect geomagnetic conditions relevant to distinguishing seismic-related anomalies. Nevertheless, future multi-parameter approaches could include the F10.7 index to provide complementary information.

Data processing

First, the Swarm magnetic field data are downloaded from the Swarm satellite website (<https://earth.esa.int/eogateway/missions/swarm>) according to the magnitude and date of each earthquake. Subsequently, the following analysis is performed on the data.

Using VFM, all measurements of the magnetic components X (north), Y (east), and Z (vertical) are considered. All the paths passing through the Dobrovolsky region from 10 days before the earthquake until the day of its occurrence are taken into account. First, the derivative with respect to time is calculated for each of these paths. This method eliminates most of the slow fluctuations in the magnetic signal. Then, the best-fit curve, obtained using the cubic-spline algorithm with knot points set at 6 s, is applied to the paths, and we subtract the time series. The residuals obtained are then plotted. The scale remains constant within the range, allowing for comparison of the residuals of one path with another. These residuals are highly sensitive to any abrupt changes in the original signal³⁹. For magnitude estimation, we applied four empirical relations previously introduced by Alimoradi et al. (2024)⁷. These equations relate anomaly features such as duration (Du), distance from the epicenter (Dist), anomaly amplitude normalized to the orbit average ("energy", En), and the time of occurrence before the earthquake (Time), to the estimated earthquake magnitude. They are expressed as follows:

$$M1 = 1.414 \times \ln(Du) + 1.29 \quad (2)$$

$$M2 = 0.587 \times \ln(Du \cdot Dist) + 1.022 \quad (3)$$

$$M3 = 1.469 \times \ln(En) - 0.032 \quad (4)$$

$$M4 = 1.449 \times \ln(Du \times Time) - 1.113 \quad (5)$$

In the above equations, M1, M2, M3 and M4 are different estimates of earthquake magnitude from each equation. *Du* is the duration of the anomaly in seconds, *Dist* is the horizontally projected distance in km between the detected satellite anomaly and the earthquake epicenter. The “energy” (*En*) is the anomaly amplitude divided by the average amplitude of the whole half-orbit. Time is the time in days of the anomaly occurrence before the earthquake.

Finally, we examine the obtained plots to identify clear anomalies with the following features:

1. A peak-to-peak amplitude larger than or equal to 0.3 nT.
2. The persistence of anomalies for at least ten seconds.
3. Occurrence during periods when geomagnetic indices are in calm conditions.
4. Located in the Dobrovolsky region around the earthquake’s epicenter.

For each identified anomaly, four parameters were determined: (1) duration (*Du*), which represents the length of the detected anomaly along the satellite ground track and was converted into seconds according to the Swarm orbital velocity; (2) distance (*Dist*), the horizontal ground distance between the anomaly location and the earthquake epicenter; (3) anomaly “energy” (*En*), calculated as the amplitude of the anomaly divided by the average amplitude of the entire half-orbit; and (4) time (*Time*), the number of days before the earthquake when the anomaly was observed. These values were then substituted into Eqs. (2)–(5) to provide four independent magnitude estimates for each anomalous half-orbit. Since 22 anomalous half-orbits were identified, this procedure yielded 88 magnitude estimates in total.

Ionospheric parameters are influenced by solar activity. Geomagnetic indices, such as *Kp* and *Dst*, serve as indicators of solar activity. Generally, geomagnetic disturbances have less impact at mid-latitudes. The criterion for calm geomagnetic indices is usually defined as ($Kp < 3$, $|Dst| < 20$ nT)^{42–44}. These indices were applied as criteria to exclude anomalies occurring during disturbed geomagnetic conditions, ensuring that only candidate seismic-related anomalies within quiet periods were considered. For each satellite half-orbit, the average values of these indices were calculated and used to assess whether geomagnetic conditions were sufficiently quiet ($Kp < 3$, $|Dst| < 20$ nT) or disturbed. As a result, to distinguish between potential ionospheric seismic disturbances and solar geomagnetic disturbances, *Kp* and *Dst* indices were analyzed.

The main difference between the effects of the ionosphere caused by geomagnetic storms and the ionospheric effects potentially caused by seismic events is that the former has a global impact and is observed worldwide, whereas the latter is localized and only observed near the earthquake’s epicenter^{43,44}.

Data availability

Swarm magnetic field data are publicly available from the ESA Swarm mission portal (https://earth.esa.int/eo_gateway/missions/swarm). Additional processed datasets generated and analyzed during the current study are available from the first author, Homayoon Alimoradi (alimoradi.h@ut.ac.ir), upon reasonable request.

Received: 14 July 2025; Accepted: 17 September 2025

Published online: 22 October 2025

References

1. Garmaise, M. J. & Moskowitz, T. J. Catastrophic risk and credit markets. *J. Financ.* **64**, 657–707. <https://doi.org/10.1111/j.1540-6261.2009.01446.x> (2009).
2. Mignan, A., Ouillon, G., Sornette, D. & Freund, F. Global earthquake forecasting system (GEFS): the challenges ahead. *Eur. Phys. J. Spec. Top.* **230**, 473–490. <https://doi.org/10.1140/epjst/e2020-000261-8> (2021).
3. Akhoondzadeh, M. & Marchetti, D. Study of the Preparation phase of turkey’s powerful earthquake (6 February 2023) by a geophysical Multi-Parametric fuzzy inference system. *Remote Sens.* **15**, 2224. <https://doi.org/10.3390/rs15092224> (2023).
4. Le, H., Liu, J. Y. & Liu, L. A statistical analysis of ionospheric anomalies before 736 M6.0+ earthquakes during 2002–2010. *J. Geophys. Res. Space Phys.* **116**, A02303. <https://doi.org/10.1029/2010JA015781> (2011).
5. Hattori, K. ULF geomagnetic changes associated with large earthquakes. *Terr. Atmos. Ocean. Sci.* **15**, 329–360 (2004).
6. Alimoradi, H., Rahimi, H. & Moakhar, M. O. Investigation of changes in the cumulative number of magnetic anomalies before and after earthquakes using satellite data. *Adv. Space Res.* **75** (1), 895–907. <https://doi.org/10.1016/j.asr.2024.09.012> (2025).
7. Alimoradi, H., Rahimi, H. & De Santis, A. Successful tests on detecting pre-earthquake magnetic field signals from space. *Remote Sens.* <https://doi.org/10.3390/rs16162985> (2024).
8. Smirnov, S. Association of the negative anomalies of the quasistatic electric field in atmosphere with Kamchatka seismicity. *Nat. Hazards Earth Syst. Sci.* **8**, 745–749. <https://doi.org/10.5194/nhess-8-745-2008> (2008).
9. Hayakawa, M. et al. A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes. *J. Geophys. Res.* **115**, A09305. <https://doi.org/10.1029/2009JA015143> (2010).
10. Genzano, N., Aliano, C., Filizzola, C., Pergola, N. & Tramutoli, V. Robust satellite technique for monitoring seismically active areas: the case of Bhuj-Gujarat earthquake. *Tectonophysics* **431**, 197–210. <https://doi.org/10.1016/j.tecto.2006.04.024> (2007).
11. Ouzounov, D. et al. Outgoing long wave radiation variability from IR satellite data prior to major earthquakes. *Tectonophysics* **431**, 211–220. <https://doi.org/10.1016/j.tecto.2006.05.042> (2007).
12. Fu, C.-C., Lee, L.-C., Ouzounov, D. & Jan, J.-C. Earth’s outgoing longwave radiation variability prior to M_{6.0} earthquakes in the Taiwan area during 2009–2019. *Front. Earth Sci.* **8**, 364. <https://doi.org/10.3389/feart.2020.00364> (2020).

13. Parrot, M. et al. Examples of unusual ionospheric observations made by the DEMETER satellite over seismic regions. *Phys. Chem. Earth*. **31**, 486–495. <https://doi.org/10.1016/j.pce.2006.02.011> (2006).
14. N’emec, F., Santolik, O. & Parrot, M. Decrease of intensity of ELF/VLF waves observed in the upper ionosphere close to earthquakes: a statistical study. *J. Geophys. Res.* **114**, A04303. <https://doi.org/10.1029/2008JA013972> (2009).
15. Anagnostopoulos, G. C., Vassiliadis, E. & Pulinet, S. Characteristics of flux-time profiles, Temporal evolution, and Spatial distribution of radiation-belt electron precipitation bursts in the upper ionosphere before great and giant earthquakes. *Ann. Geophys.* **55**, 21–36. <https://doi.org/10.4401/ag-5365> (2012).
16. Pulinet, S. & Ouzounov, D. Lithosphere–Atmosphere–Ionosphere coupling (LAIC) model—An unified concept for earthquake precursors validation. *J. Asian Earth Sci.* **41** (4–5), 371–382 (2011).
17. Pulinet, S. A., Legen’ka, A. D. & Alekseev, V. A. Pre-earthquake ionospheric effects and their possible mechanisms. In *Dusty and Dirty plasmas, noise, and Chaos in Space and in the Laboratory* 545–557 (Springer US, 1994).
18. Marchetti, D. et al. Possible Lithosphere–Atmosphere–Ionosphere coupling effects prior to the 2018 Mw = 7.5 Indonesia earthquake from seismic, atmospheric and ionospheric data. *J. Asian Earth Sci.* **188**, 104097 (2020).
19. De Santis, A. et al. Magnetic field and electron density data analysis from swarm satellites searching for ionospheric effects by great earthquakes: 12 Case Studies from 2014 to 2016. *Atmosphere* **10**, 371. <https://doi.org/10.3390/atmos10070371> (2019).
20. Parrot, M. DEMETER Satellite and detection of earthquake signals. In *Natural Hazards* 1st edn (eds Singh, R. et al.) 115–138 (Boca Raton, FL, 2018). <https://doi.org/10.1201/9781315166841>.
21. De Santis, A. et al. Precursory worldwide signatures of earthquake occurrences on swarm satellite data. *Sci. Rep.* **9**, 20287. <https://doi.org/10.1038/s41598-019-56599-1> (2019).
22. Friis-Christensen, E., Lühr, H. & Hulot, G. Swarm: A constellation to study the earth’s magnetic field. *Earth Planet Space*. **58** (4), 351–358. <https://doi.org/10.1186/BF03351933> (2006).
23. Özsöz, İ. & Pamukçu, O. A. Analysing pre-earthquake magnetic and ionospheric anomalies using swarm satellite data: findings from the February 6, 2023, Pazarcık, Türkiye earthquake. *Adv. Space Res.* **75** (7), 5460–5476 (2025).
24. Özsöz, İ., Pamukçu, O. A. & Timoçin, E. Time-dependent magnetic anomaly variations in Turkey and Greece using Swarm satellites: A comprehensive precursory multi-track analysis of $M \geq 6$ earthquakes from 2017 to 2020. *J. Atmos. Solar Terr. Phys.* **258**, 106210 (2024).
25. Akhoondzadeh, M. Earthquake prediction using satellite data: advances and ahead challenges. *Adv. Space Res.* **74** (8), 3539–3555 (2024).
26. Pulinet, S. A., Ouzounov, D. P., Karelin, A. V. & Davidenko, D. V. Physical bases of the generation of short-term earthquake precursors: A complex model of ionization-induced geophysical processes in the lithosphere-atmosphere-ionosphere-magnetosphere system. *Geomag. Aeron.* **55** (4), 521–538 (2015).
27. <https://www.usgs.gov/news/featured-story/m77-mandalay-burma-myanmar-earthquake>
28. https://en.wikipedia.org/wiki/2025_Myanmar_earthquake
29. Zhao, J. J., Chen, Q., Yang, Y. H. & Xu, Q. Coseismic faulting model and post-seismic surface motion of the 2023 Turkey–Syria earthquake doublet revealed by InSAR and GPS measurements. *Remote Sens.* **15** (13), 3327. <https://doi.org/10.3390/rs15133327> (2023).
30. Wang, Y. Earthquake Geology of Myanmar. Dissertation (Ph.D.), California Institute of Technology. doi:10.7907/XWW9P26. <http://resolver.caltech.edu/CaltechTHESIS:06062013-135816595> (2013).
31. Ritter, P., Lühr, H. & Rauberg, J. Determining field-aligned currents with the swarm constellation mission. *Earth Planet Space*. **65**, 1285–1294. <https://doi.org/10.5047/eps.2013.09.006> (2013).
32. Olsen, N. et al. The Swarm satellite constellation application and research facility (SCARF) and Swarm data products. *Earth Planet Space*. **65**, 1189–1200. <https://doi.org/10.5047/eps.2013.07.001> (2013).
33. Olsen, N., Ravat, D., Finlay, C. C. & Kother, L. K. LCS-1: a high-resolution global model of the lithospheric magnetic field derived from CHAMP and Swarm satellite observations. *Geophys. J. Int.* **211** (3), 1461–1477. <https://doi.org/10.1093/gji/ggx381> (2017).
34. Grayver, A. V. et al. Satellite tidal magnetic signals constrain oceanic lithosphere–asthenosphere boundary. *Sci. Adv.* **2** (9), e1600798. <https://doi.org/10.1126/sciadv.1600798> (2016).
35. Irrgang, C., Saynisch, J. & Thomas, M. Utilizing oceanic electromagnetic induction to constrain an ocean general circulation model: A data assimilation twin experiment. *J. Adv. Model. Earth Syst.* **9** (3), 1703–1720. <https://doi.org/10.1002/2017MS000951> (2017).
36. Dobrovolsky, I. R., Zubkov, S. I. & Myachkin, V. I. Estimation of the size of earthquake Preparation zones. *Pure Appl. Geophys.* **117**, 1025–1044. <https://doi.org/10.1007/BF00876083> (1979).
37. Plastino, W., Bella, F., Catalano, P. G. & Di Giovambattista, R. Radon groundwater anomalies related to the Umbria–Marche, September 26, 1997, earthquakes. *Geofis. Int.* **41** (4), 369–375 (2002).
38. Vizzini, F. & Brai, M. In-soil radon anomalies as precursors of earthquakes: a case study in the SE slope of Mt. Etna in a period of quite stable weather conditions. *J. Environ. Radioact.* **113**, 131–141. <https://doi.org/10.1016/j.jenvrad.2012.05.027> (2012).
39. De Santis, A., Balasis, G., Pavón-Carrasco, F. J., Cianchini, G. & Manda, M. Potential earthquake precursory pattern from space: the 2015 Nepal event as seen by magnetic Swarm satellites. *Earth Planet. Sci. Lett.* **461**, 119–126. <https://doi.org/10.1016/j.epsl.2016.12.037> (2017).
40. Hanks, T. C. & Kanamori, H. A moment magnitude scale. *J. Phys. Res.* **84** (B5), 2348–2350. <https://doi.org/10.1029/JB084iB05p02348> (1979).
41. Mayaud, P. N. Derivation, meaning, and use of geomagnetic indices. AGU Geophysical Series. <https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/GM022> (1980).
42. Riswadkar, A. V. & Dobbins, B. *Solar storms: protecting your operations against the sun’s dark side* 1–12 (Zurich Services Corp, 2010).
43. Zerbo, J. L. et al. Solar wind and geomagnetism: Toward a standard classification of geomagnetic activity from 1868 to 2009. *Ann. Geophys.* **30**, 421–426. <https://doi.org/10.5194/angeo-30-421-2012> (2012).
44. Pulinet, S. & Boyarchuk, K. Ionospheric precursors of earthquakes. Springer Science & Business Media (2004).

Acknowledgements

The authors acknowledge the European Space Agency (ESA) for providing Swarm mission data and the U.S. Geological Survey (USGS) for publicly available seismic information. We also thank the Swarm mission science and operations teams for their continuous efforts.

Author contributions

Conception and design of the work HR, HA; Acquisition and analysis HA; interpretation of data ADS, HR; first draft of the work HA; significant revision ADS; All authors read, revised and approved the paper submitted.

Funding

ADS received funds from UNITARY Project within the “Pianeta Dinamico” initiative, funded by the Ministry

of University and Research (MUR), and from Space it up, funded by the Italian Space Agency (ASI) and MUR.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-20901-1>.

Correspondence and requests for materials should be addressed to H.R. or A.D.S.

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