



Article

Analysis of Ionospheric TEC Anomalies Using BDS High-Orbit Satellite Data: A Regional Statistical Study and a Case Study of the 2023 Jishishan Ms6.2 Earthquake

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Highlights

What are the main findings?

- A statistically significant correlation was established, with 47.2% of 41 historical $M_w \geq 5.5$ earthquakes showing detectable TEC anomalies, revealing an inverse relationship between earthquake magnitude and anomaly detectability.
- The complementary capabilities of the BDS constellation were demonstrated: GEO satellites provide stable, continuous TEC time series, while IGSO satellites enable high-resolution mapping of co-seismic ionospheric disturbances (CIDs) propagating at AGW-consistent velocities.

What are the implications of the main findings?

- This study validates BDS, particularly its high-orbit satellites, as a powerful and precise tool for ionospheric seismology, advancing the observational capabilities for Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) research.
- The development of a multi-parameter space weather index provides a robust framework for discriminating between seismogenic signals, which is crucial for enhancing the reliability of future earthquake precursor identification systems.

Abstract

This study presents a comprehensive analysis of pre- and co-seismic ionospheric disturbances associated with the 2023 Ms6.2 Jishishan earthquake by leveraging the unique observational strengths of BDS, particularly its high-orbit satellites. A multi-parameter space weather index was employed to effectively isolate seismogenic signals from geomagnetic disturbances, confirming that the main shock occurred during geomagnetically quiet conditions. Statistical analysis of 41 historical earthquakes ($M_w \geq 5.5$) reveals that 47.2% were associated with detectable Total Electron Content (TEC) anomalies. An inverse correlation between earthquake magnitude and anomaly detectability within a 31-day window suggests prolonged precursor durations for larger events may produce longer-duration precursory signals, which challenge conventional detection methods. The synergistic capabilities of BDS Geostationary Earth Orbit (GEO) and Inclined Geosynchronous Orbit (IGSO) satellites were demonstrated: GEO satellites provide unprecedented temporal stability for continuous TEC monitoring, while IGSO satellites enable high-resolution spatial mapping of Co-seismic Ionospheric Disturbances (CIDs). The detected CIDs propagated at



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velocities below 1.6 km/s, consistent with acoustic gravity wave (AGW) mechanisms. A case study during a geomagnetically active period further reveals modulated CID propagation characteristics, indicating potential coupling between seismic forcing and space weather. Our findings validate BDS as a powerful and precise tool for ionospheric seismology and provide critical insights into Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) dynamics.

Keywords: ionospheric TEC; BDS; GEO; IGSO; co-seismic ionospheric disturbances (CIDs); 2023 Jishishan Ms6.2 earthquake

1. Introduction

Earthquakes constitute one of the most devastating natural hazards, posing severe threats to human safety, infrastructure, and socioeconomic stability. Despite significant advancements in seismology, the fundamental physical processes underlying earthquake nucleation and rupture propagation remain incompletely understood [1–3]. This persistent knowledge gap drives ongoing research into potential precursors and cross-system coupling mechanisms, among which investigations of Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) have gained considerable prominence [4–7]. Ionospheric disturbances, particularly those manifesting as Total Electron Content (TEC) anomalies, are increasingly regarded as potential indicators of impending seismic activity. This research paradigm was initiated by Davies and Baker [8], who first reported ionospheric anomalies preceding the 1964 Alaskan earthquake, sparking decades of interdisciplinary inquiry.

Current understanding of LAIC mechanisms is built upon two interrelated approaches: (1) statistical identification of pre-seismic ionospheric anomalies [9,10], and (2) physical modeling of the pathways through which energy and perturbations propagate from the lithosphere to the ionosphere [11,12]. These studies consistently report TEC enhancements or depletions hours to days before major earthquakes in active seismic zones. For instance, Heki [13] reported a distinctive TEC increase 40 min prior to the 2011 Tōhoku earthquake. Similarly, Liu et al. [14] analyzed ionospheric TEC anomalies caused by non-space weather effects and found that nearly 80% of these anomalies could be related to subsequent seismic events.

Theoretical LAIC model offers explanations for these observations. Pulinets and Boyarchuk [5] integrated various precursor phenomena into a coherent multi-stage energy transfer model. In this framework, pre-seismic stress accumulation triggers charge separation via piezoelectric and triboelectric effects. Subsequent radon emissions increase near-surface ionization, altering atmospheric conductivity. The resulting electric fields propagate upward, redistributing ionospheric plasma through $E \times B$ drifts. Concurrently, acoustic gravity waves (AGWs) generated by crustal movements or atmospheric oscillations provide another energy pathway, modulating electron density through adiabatic compression and plasma transport [15,16]. Together, these mechanisms produce detectable TEC variations, offering a potential means to probe subsurface tectonic processes.

The advent of Global Navigation Satellite System (GNSS) has revolutionized ionospheric monitoring by enabling continuous, global-scale TEC measurements using dual-frequency signals [17–19]. The differential phase advance of GNSS signals provides accurate estimation of slant TEC (STEC) along satellite-receiver ray paths, which is subsequently converted to vertical TEC (VTEC) using mapping functions [20]. However, satellite systems such as GPS and Galileo, whose constellations consist primarily of Medium Earth Orbit (MEO) satellites, exhibit inherent limitations for LAIC research. As these satellites

traverse their orbits, the resulting motion of their ionospheric piercing points (IPPs) causes derived TEC time series to inherently incorporate ionospheric horizontal gradient effects. Consequently, spatial interpolation or ionospheric modeling becomes necessary to derive location-specific TEC values, which may introduce approximation errors [21–23].

The BeiDou Navigation Satellite System (BDS) offers distinct advantages for ionospheric seismology through its unique hybrid constellation architecture, which integrates Geostationary Earth Orbit (GEO), Inclined Geosynchronous Orbit (IGSO), and MEO satellites [24]. Both GEO and IGSO satellites operate at altitudes exceeding 35,000 km, enabling extended observation periods of the same geographic region. This orbital characteristic yields prolonged and stable TEC time series with enhanced data quality when derived from these high-orbit satellites. Particularly noteworthy are the GEO satellites, which maintain fixed relative positions above the Earth’s surface at approximately 35,786 km altitude [25]. The stable viewing geometry significantly minimizes errors in the conversion from STEC to VTEC and substantially improves the detection capability for vertical electron density perturbations—especially those generated by acoustic gravity waves (AGWs) [26].

Recent applications of BDS GEO data have demonstrated improved performance in capturing pre-seismic ionospheric anomalies, validating their enhanced capability for LAIC research [23,25,27,28]. Motivated by these developments, this study employs high-rate STEC time series derived from BDS high-orbit satellites to investigate the response of subequatorial ionosphere to various heliophysical and geophysical conditions. We focus on the 2023 Jishishan earthquake (Ms 6.2), a significant tectonic event in the seismically active Linxia-Gansu region of China [29,30]. Although previous studies have established statistical correlations, the underlying physical coupling dynamics, especially for moderate-magnitude events, remain inadequately resolved.

This manuscript is organized as follows. Section 2 details the principles of retrieving STEC from dual-frequency BDS signals. Section 3 presents a statistical analysis of regional seismicity, establishes the correlation between earthquakes and TEC anomalies, and provides a comprehensive investigation of the spatiotemporal characteristics of CIDs during the Jishishan event using the complementary geometries of BDS GEO and IGSO observations. Section 4 synthesizes the results, interprets the observed CID propagation mechanisms within the established LAIC framework, and examines the modulating effects of concurrent space weather activity on disturbance signatures. Finally, Section 5 summarizes the main findings, highlights the validated capability of BDS for ionospheric seismology, and discusses the implications for future earthquake precursor research.

2. Materials and Methods

As GNSS signals propagate from space-based satellites to terrestrial receivers, they traverse the ionosphere—a dispersive medium in which radio waves interact with charged particles under the influence of Earth’s geomagnetic field [31,32]. The presence of the geomagnetic field causes the ionosphere to exhibit anisotropic behavior [33,34], making it necessary to account for both electromagnetic interactions and collisional processes between neutral atoms and charged particles (ions and electrons). Under such conditions, the refractive index n can be accurately described by the Appleton–Hartree formula. Given that GNSS signals operate in the L-band, where the signal frequency (f) is significantly higher than the typical ionospheric collision frequency ($\nu \sim \mathcal{F}(10^3 \text{ Hz})$), collision terms can be neglected, yielding the following simplified expression [35,36]:

$$n_p^2 = 1 - \frac{2X(1 - X)}{2(1 - X) - Y^2 \sin^2 \theta \pm \sqrt{Y^4 \sin^4 \theta + 4(1 - X)^2 Y^2 \cos^2 \theta}} \quad (1)$$

where $X = \frac{f_0^2}{f^2}$, with f_0 denoting the plasma frequency; $Y = \frac{f_g}{f}$, with f_g representing the gyrofrequency of electrons; and θ is the angle between the wave propagation direction and the geomagnetic field vector.

The plasma frequency f_0 , which characterizes the collective oscillation of electrons with density (N_e) under electromagnetic excitation, is defined as:

$$f_0^2 = \frac{N_e e^2}{4\pi^2 \epsilon_0 m_e} \approx 80.618 N_e \quad (2)$$

where $e = 1.602 \times 10^{-19} \text{ C}$ is the electron charge, $m_e = 9.109 \times 10^{-31} \text{ kg}$ denotes the electron mass, and $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ is the vacuum permittivity.

For typical GNSS frequencies, the dimensionless parameters X and Y are of the order of 10^{-5} and 10^{-3} , respectively. Expanding Equation (1) in inverse powers of frequency reveals that the first-order term dominates the propagation behavior, with the higher-order terms contributing less than 1% to the total phase delay (equivalent to centimeter-level range errors) [37]. Truncating to the first order yields:

$$n_p \approx 1 - \frac{1}{2}X = 1 - \left(\frac{f_0^2}{2f^2} \right) = 1 - 40.309 \frac{N_e}{f^2} \quad (3)$$

Equation (3) indicates that $n_p < 1$, implying a phase velocity $v_p = c/n_p$ that exceeds the speed of light in vacuum, resulting in a superluminal phase advancement.

When the radio wavelength $\lambda = c/f$ is much smaller than the characteristic spatial scales of ionosphere structures, geometrical optics can be applied. In this regime, the propagation path length (s) between the receiver and satellite can be expressed by integrating the phase velocity over the signal travel time Δt [38,39], yielding:

$$s = \int_{\Delta t} v_p dt = \int_{\Delta t} \frac{c}{n_p} dt \approx \int_{\Delta t} \frac{c}{1 - \left(\frac{f_0^2}{2f^2} \right)} dt = \int_{\Delta t} c \left(1 + \left(\frac{f_0^2}{2f^2} \right) \right) dt = c\Delta t + \frac{40.309}{f^2} \int_{\Delta t} N_e c dt \quad (4)$$

Substituting $ds = cdt$, Equation (4) becomes an integral of electron density along the signal path, defining the Slant TEC (STEC):

$$STEC = \int N_e ds \quad (5)$$

STEC is conventionally expressed in TEC units ($1 \text{ TECU} = 10^{16} \text{ electrons/m}^2$). Similarly, the vertical TEC (VTEC) is mathematically defined as:

$$VTEC = \int N_e dh \quad (6)$$

Equation (4) highlights a systematic discrepancy between the observed and geometric distances due to the ionospheric influence (I), which shortens the carrier-phase measured distance:

$$I = \frac{40.309}{f^2} \int_{\Delta t} N_e c dt = \frac{40.309}{f^2} \int N_e ds = \frac{40.309}{f^2} STEC \quad (7)$$

Neglecting satellite and receiver hardware delays, the dual-frequency phase observables can be expressed as:

$$\lambda_i \phi_i = s_i + c(\delta t^s - \delta t_r) + T - I_i - \lambda_i N_i + \varepsilon_{pi} \quad (8)$$

$$\lambda_j \phi_j = s_j + c(\delta t^s - \delta t_r) + T - I_j - \lambda_j N_j + \varepsilon_{pj} \quad (9)$$

where ϕ_i is the phase measurement at frequency i ; δt^s and δt^r denote satellite and receiver clock errors; T denotes the tropospheric delay; N is the integer phase ambiguity; and ε_p represents the measurement noise.

Taking the difference of Equations (8) and (9) and substituting Equation (7) allows STEC to be derived as:

$$STEC = \frac{f_i^2 f_j^2}{40.309(f_j^2 - f_i^2)} (\lambda_i \phi_i - \lambda_j \phi_j + \lambda_i N_i - \lambda_j N_j) \quad (10)$$

Although the integer ambiguities (N_i and N_j) preclude absolute TEC determination, relative TEC variations can be recovered with high precision [40]. The derived STEC values are influenced by differential code biases (DCBs, ~ 0.5 TECU/day variability), step errors, and measurement noise. Among these, step errors and noise are generally negligible, whereas DCBs introduce quasi-constant offsets with typical variation below 0.5 TECU/day. These biases can be effectively removed via background subtraction [41]. Therefore, unless otherwise specified, the TEC values analyzed in this study refer to the smoothed and background-corrected STEC data.

3. Results

3.1. Earthquake Statistics and Data Sources

The 2023 Jishishan earthquake, with a surface-wave magnitude of M_s 6.2 (moment magnitude M_w 5.9), occurred on 18 December 2023 at 15:59:30 UTC (corresponding to 23:59:30 local time) in Jishishan Bonan-Dongxiang-Salar Autonomous County, Linxia Prefecture, Gansu Province. The event was a shallow-focus earthquake with a focal depth of approximately 10 km, and its epicenter was located at 35.70°N , 102.79°E .

The epicentral region lies on the eastern margin of the Tibetan Plateau, representing a critical transition zone between the plateau and the Loess Plateau. This area forms part of China's north–south seismic belt, characterized by intense tectonic deformation resulting from the ongoing convergence of the Indian and Eurasian plates. The region is densely populated with Quaternary folds, thrust faults, and strike–slip faults. Seismicity in this zone is relatively frequent [42].

The mainshock was identified as a thrust faulting event, with the seismogenic structure being the North Marginal Fault of the Lajishan range. The ruptured plane exhibited a SE–NW strike, with the rupture propagating northwestward from the epicenter. By 20 December 2023, 07:00 UTC, a total of 355 precisely relocated aftershocks had been recorded, including 9 events with magnitudes ≥ 3.0 (<https://www.gsdzj.gov.cn>). The initial aftershock distribution primarily displayed an NNW orientation, with focal depths concentrated between 6 and 15 km [43].

The spatial extent for potential precursory deformation can be defined as a circular area centered on the earthquake epicenter, with its radius R (in kilometers) estimated using the empirical relation [44]:

$$R = 10^{0.43M} \quad (11)$$

where M denotes the earthquake magnitude.

According to earthquake catalogs from the U.S. Geological Survey (USGS; <http://earthquake.usgs.gov/earthquakes/search>, accessed on 1 October 2025), the maximum magnitude recorded in the region over the past 25 years does not exceed 7.5. Substituting $M = 7.5$ into Equation (11) yields a strain-influence radius of approximately 1678 km. Our analysis encompasses 76 earthquakes of moment magnitude ($M_w \geq 5$) that occurred within this radius of the Jishishan region between 2000 and 2024.

Figure 1, overlaid on a high-resolution satellite basemap (ESRI World Imagery), visualizes the spatial distribution of seismic events, with symbol colors scaled according to magnitude (Mw 5.5–7.5). The 2023 Jishishan Earthquake (Mw 5.9) is highlighted with a red triangle. Epicenters are predominantly clustered along the northeastern margin of the Tibetan Plateau margin, aligning with major fault systems such as the Longmenshan and East Kunlun Fault faults—key tectonic boundaries accommodating the ongoing of Indo–Eurasian collision [45].

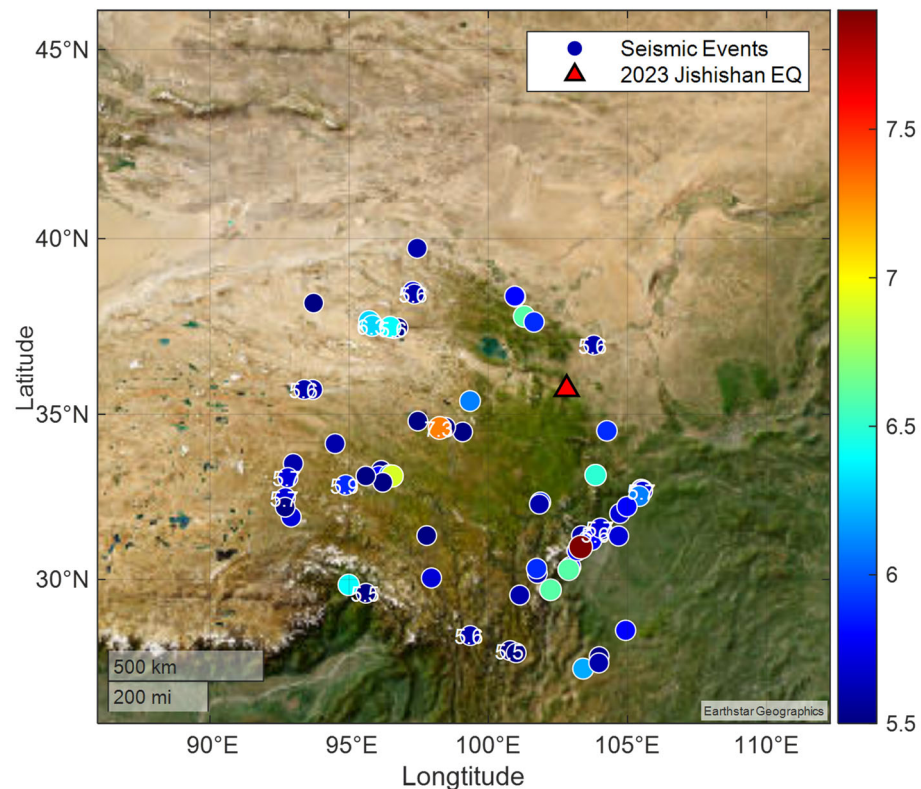


Figure 1. Epicenters of 76 $M_w \geq 5.5$ earthquakes within a 1678 km radius of the Jishishan area during 2000–2024. Epicenters are overlaid on ESRI World Imagery basemap, with symbol colors scaled by magnitude (Mw 5.5–7.5).

To further elucidate the spatiotemporal and geophysical patterns, we analyzed the 76 seismic events through three complementary perspectives (Figure 2). Subplot 1 illustrates temporal evolution of seismicity, with focal depths color-coded. A clear clustering of events is observed between 2008–2022, accounting for 73.7% of the total. The 2008 Wenchuan earthquake (Mw 7.9) dominates the catalog, followed by secondary clusters in 2010 (Qamdo Mw 6.9), 2013 (Linqiong Mw 6.6), and 2021 (Qinghai Mw 7.3). This temporal pattern suggests cyclical stress accumulation and release along the Longmenshan and East Kunlun fault systems, driven primarily by ongoing Indo–Eurasian convergence at contraction rates of -3.2 ± 0.6 mm/year [46,47].

Subplot 2 quantifies magnitude distribution through kernel density estimation. The mean magnitude (Mw 5.84) confirms the dominance of moderate seismic activity, while the right-skewed distribution (mean > median of 5.70) suggests occasional high-magnitude outliers (>7.0), consistent with abrupt ruptures in collision zones. The low standard deviation (0.44) further indicates that most magnitudes are tightly clustered around the mean.

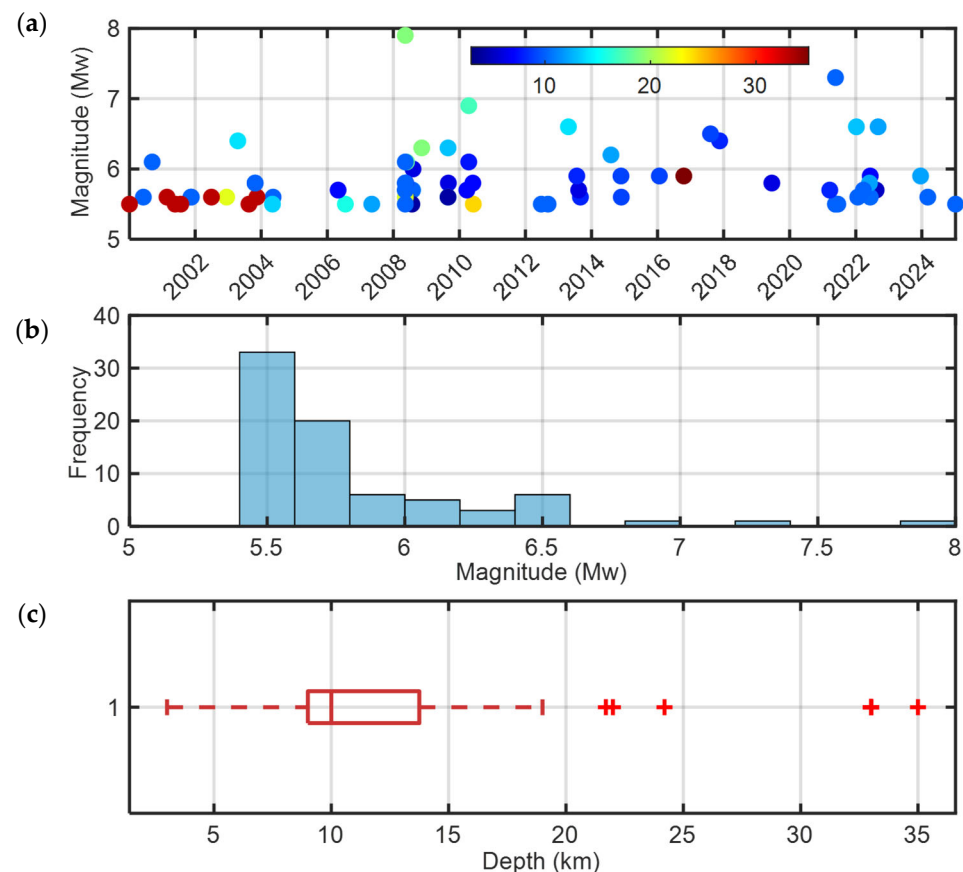


Figure 2. Multi-perspective analysis of 76 $M_w \geq 5.5$ earthquakes near Jishishan (2000–2024). (a) Temporal evolution of seismicity, with color-coded focal depths; (b) Kernel density estimation of magnitude distribution, revealing right-skewed characteristics with mean M_w 5.84; (c) Tukey boxplots of focal depths, indicating predominant upper-crustal seismicity (median depth 10 km).

Subplot 3 employs Tukey boxplots to characterize focal depths. The median depth of 10 km and interquartile range (IQR) of 8–13 km indicate that most seismic events occurred in the upper crust. Most events (78%) occur at depths less than 20 km, consistent with brittle failure in the upper crust, though deeper events like the Wenchuan earthquake suggest the involvement of locked mid-crustal segments. Notably, the increased frequency of events after 2020 (5.13 events/year versus 4.23 events/year before 2020 for $M_w \geq 5.5$) may be linked to accelerated uplift of the Tibetan Plateau or evolving regional stress fields [48].

Our analysis incorporated high-resolution global ionospheric maps (2 h temporal resolution; 2.5° latitude $\times$ 5° longitude spatial grids) from the International GNSS Service (IGS). These datasets enabled systematic detection of seismic-ionospheric disturbances through TEC analysis. TEC time series were generated using two complementary approaches: (1) spatial interpolation of IONEX grid data at epicentral regions, and (2) processing of 30 s GNSS measurements based on standardized ionospheric delay equations. To ensure data consistency and reliability, the study focuses on 41 post-2010 seismic events (as shown in Table 1), as pre-2010 data coverage is insufficient for robust comparison. It is noteworthy that earthquake events occurring within a 24-h interval are highlighted in bold in the table.

Ionospheric variability is influenced by numerous non-seismic factors, including solar-geomagnetic activity, anthropogenic emissions, and equatorial/polar atmospheric dynamics [49,50]. To isolate potential seismogenic anomalies, we implemented multi-layered space weather scheme. Beyond conventional indices such as Kp, Dst, and F10.7 used in precursor studies [51,52], our framework integrates six geomagnetic parameters—Dst, Kp, Bz fluctuations, proton density (Pd), and proton flux (Pf)—and solar indices (F10.7).

Geomagnetic indices were sourced from NASA’s Goddard Space Flight Center (GSFC) OMNI database.

Table 1. Seismicity catalog of $M_w \geq 5.5$ events within the Jishishan earthquake zone (2010–2024).

Time	Latitude ¹	Longitude ¹	Depth ²	Mag	magType ³
2023-12-18 15:59:30	35.7386	102.8149	12	5.9	Mww
2023-05-31 11:20:14	25.1051	96.2315	10	5.9	Mww
2022-11-10 05:01:05	28.3835	94.4118	15	5.5	Mww
2022-09-05 04:52:19	29.6786	102.236	12	6.6	Mww
2022-08-14 08:20:00	33.1157	92.7977	5	5.7	Mww
2022-06-09 17:28:35	32.3726	101.8721	7	5.9	Mww
2022-06-09 16:03:26	32.3152	101.8363	10.14	5.6	Mww
2022-06-01 09:00:08	30.3951	102.9582	12	5.8	Mww
2022-03-25 16:21:03	38.5365	97.2898	10	5.7	Mww
2022-01-23 02:21:19	38.4613	97.3425	10	5.6	Mww
2022-01-07 17:45:30	37.8283	101.2900	13	6.6	Mww
2021-06-16 08:48:58	38.2061	93.7234	10	5.5	Mww
2021-05-21 18:13:01	34.4808	99.0805	10	5.5	Mb
2021-05-21 18:12:15	34.617	98.4674	10	5.5	Mb
2021-05-21 18:04:13	34.5983	98.2513	10	7.3	Mww
2021-05-21 13:48:37	25.7274	100.0082	9	6.1	Mww
2021-04-28 02:21:26	26.7813	92.4565	34	6	Mww
2021-03-19 06:11:27	31.9246	92.9151	8	5.7	Mww
2019-07-19 09:22:15	27.7188	92.8302	15	5.5	Mww
2019-06-17 14:55:44	28.4056	104.9333	6	5.8	Mww
2019-04-23 20:15:50	28.4073	94.5605	14	5.9	Mww
2017-11-17 22:34:19	29.8333	94.9838	8	6.4	Mww
2017-08-08 13:19:49	33.1926	103.8552	9	6.5	Mww
2016-10-17 07:14:50	32.8959	94.8768	35	5.9	Mww
2016-01-20 17:13:13	37.6709	101.6409	9	5.9	Mww
2014-11-25 15:19:08	30.1884	101.7618	9	5.6	Mwb
2014-11-22 08:55:26	30.3398	101.7374	9	5.9	Mww
2014-08-03 08:30:13	27.1891	103.4086	12	6.2	Mww
2013-08-31 00:04:17	28.2425	99.3502	8	5.6	Mww
2013-08-11 21:23:41	30.0464	97.9565	6	5.7	Mww
2013-07-21 23:45:56	34.512	104.262	8	5.9	Mww
2013-04-20 00:02:47	30.308	102.888	14	6.6	Mww
2013-01-09 01:41:53	25.329	95.048	93	5.8	Mww
2012-09-07 03:19:42	27.575	103.983	10	5.5	Mww
2012-07-01 04:13:52	25.592	94.696	58	5.6	Mwb
2012-06-24 07:59:34	27.767	100.781	10	5.5	Mww
2010-06-03 05:35:44	33.335	96.15	24.2	5.5	Mwc
2010-05-29 02:29:48	33.165	96.07	7	5.8	Mwc
2010-04-14 01:25:15	33.195	96.449	7.6	6.1	Mwc
2010-04-13 23:49:38	33.165	96.548	17	6.9	Mwc
2010-03-24 02:06:10	32.509	92.708	7	5.7	Mwc

¹ Coordinate precision: locations reported in decimal degrees (WGS84). ² Depth: hypocentral depth rounded to one decimal place. ³ Magnitude types: moment magnitude, denoted as “Mww” in USGS catalog, Mb (body-wave magnitude).

3.2. Statistical Detection of Seismo-Ionospheric Anomalies and Correlation Analysis

The detection of seismogenic ionospheric anomalies has been widely investigated using various statistical paradigms, including quartile analysis, moving average filtering, sliding window techniques, and principal component decomposition [53–55]. Building upon these established methodologies, the present study employs a robust median-based confidence interval approach combined with interquartile range (IQR) thresholding to quantify TEC deviations potentially linked to seismic events.

Adopting the framework of Liu et al. [56], a 31-day reference period (15 days before and 15 days after the main shock of each seismic event) was used to establish the baseline ionospheric behavior, thereby minimizing the influence of diurnal and seasonal variability. The analytical procedure, applied to 36 distinct seismic sequences from 2010–2024, comprised the following principal steps:

(1) Data Extraction and Epicentral TEC Time Series Construction

For each seismic sequence, GIMs in IONEX format were retrieved for the 31-day window. The TEC value at the epicenter was extracted for each temporal snapshot (typically at 1 h intervals) via bilinear interpolation of the surrounding GIM grid points. This produced a continuous 31-day VTEC time series for each epicentral location, comprising 744 data points and encompassing multiple full diurnal cycles.

(2) Baseline Characterization and Threshold Definition

For each resulting time series, the median (μ) and IQR were computed as robust measures of central tendency and statistical dispersion. Confidence bounds for anomaly identification were then defined as: the lower bound (LB) = $\mu - 1.5 \times \text{IQR}$, and the upper bound (UB) = $\mu + 1.5 \times \text{IQR}$. Under a Gaussian distribution assumption, this coefficient of 1.5 corresponds approximately to ± 2.7 standard deviations, effectively flagging significant outliers [57].

(3) TEC Anomaly Identification

Any TEC value within the 31-day window that fell outside the [LB, UB] range was classified as a statistically significant perturbation. As illustrated in Figure 3, a comprehensive statistical analysis was conducted using IGS global ionospheric maps (GIMs) in IONEX format for 36 distinct seismic sequences (derived from 41 $M_w \geq 5.5$ earthquakes) in the Jishishan region during 2010–2024. Box-and-whisker plots summarize TEC variations near epicenters (25–46°N, 92–113°E), with red markers indicating medians, boxes representing the IQR, and black whiskers showing the LB/UB thresholds. Outliers, indicating potential anomalies, are marked as red crosses.

The analysis reveals that 47.2% of the pre- and post-seismic TEC series exhibited values beyond the IQR-based thresholds ($p < 0.05$), providing evidence for lithosphere–ionosphere coupling in a substantial proportion of the analyzed sequences. A notable finding is the inverse relationship between earthquake magnitude and the detectability of ionospheric anomalies within the 31-day window: clear perturbations were observed for 58.3% of M_w 5.5–5.9 events, compared to only 29.4% of $M_w \geq 6.0$ events. This counterintuitive pattern may be attributed to the prolonged duration of precursory ionospheric disturbances associated with larger earthquakes, which may exceed the 31-day analytical window and lead to baseline contamination. Nevertheless, the results demonstrate that moderate-magnitude earthquakes can generate statistically significant ionospheric anomalies in their source regions.

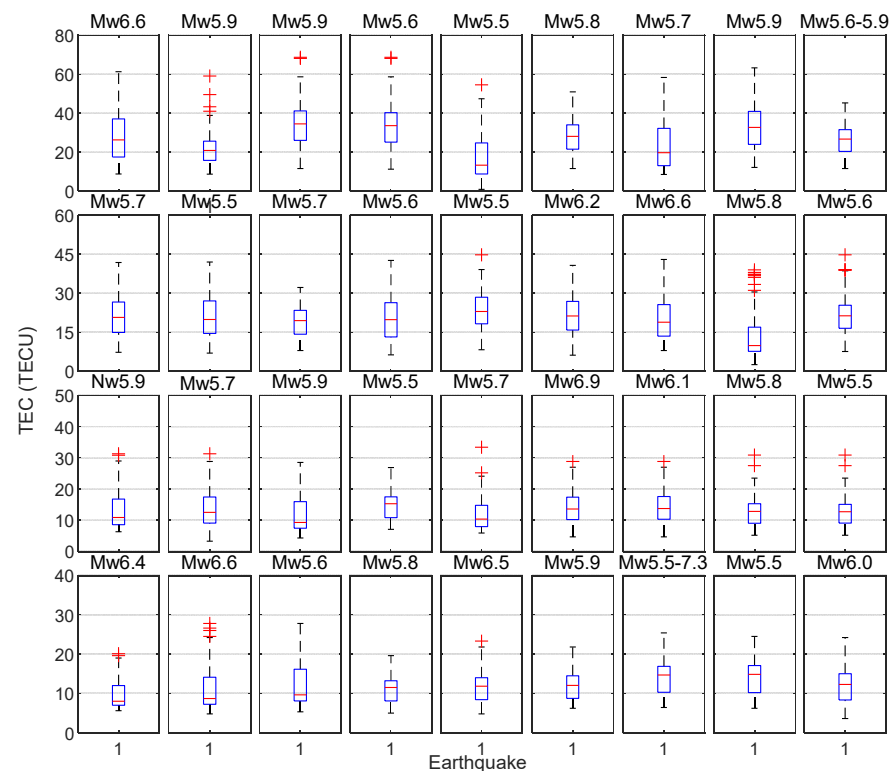


Figure 3. Statistical distribution of ionospheric TEC anomalies preceding and following 36 distinct seismic sequences (originating from 41 Mw $\geq$ 5.5 earthquakes) in the Jishishan region during 2010–2024, analyzed within 31-day windows. Outliers, marked by red crosses, represent TEC values exceeding the median-centered threshold bounds (LB/UB). The black boxes indicate the IQR.

To further investigate temporal patterns in TEC variability, paired 15-day windows before and after the 36 distinct seismic sequences were analyzed (Figure 4). Initial screening with Grubbs' test ($\alpha = 0.01$) identified anomalous TEC values in 36.1% of the time series. Notably, 93% of the affected sequences contained no more than two outliers, with the exception of the 2013 Mw 5.8 event which exhibited seven outliers.

Subsequent F-test analysis was conducted to evaluate the homogeneity of variances between pre-seismic and post-seismic TEC sequences. Using the two-sample F-test implementation, we tested the null hypothesis that the paired TEC datasets were drawn from normal distributions with equal variances, against the alternative hypothesis of different variances. The test results showed that 41.7% of the sequence pairs led to the rejection of the null hypothesis at the 5% significance level ($p < 0.05$), indicating statistically significant differences in variance homogeneity between the pre- and post-seismic periods. This provides evidence for systematic distinctions in the distribution characteristics, suggesting that pre- and post-seismic TEC anomalies should be treated as distinct statistical populations.

The observed differences were particularly pronounced for shallow-focus earthquakes (depth < 15 km). This spatiotemporal pattern aligns with acoustic gravity wave (AGW) propagation models, where the efficiency of crustal deformation signal transmission to the ionosphere decreases exponentially with increasing focal depth. Although visually discernible differences in standard deviation were not immediately apparent from the raw data, the statistical analysis confirmed significant distinctions in distribution characteristics. This finding further underscores the necessity of applying rigorous multivariate statistical methods in seismo-ionospheric coupling research.

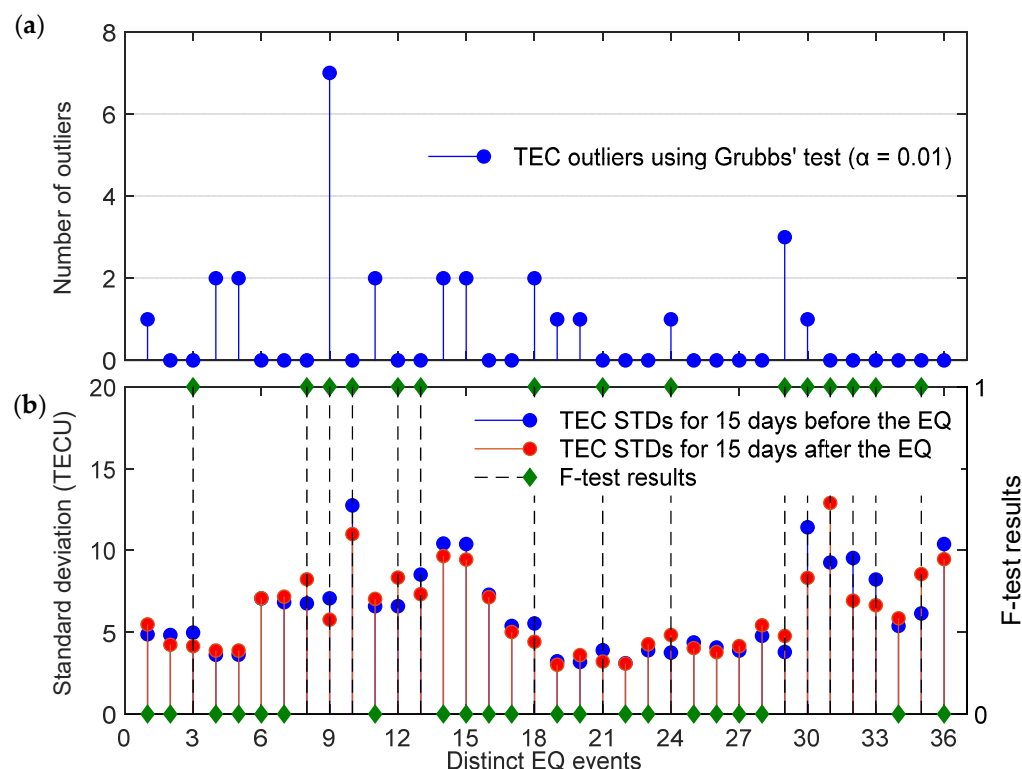


Figure 4. Statistical comparison of TEC variability during 15-day pre-seismic and post-seismic intervals for 36 distinct earthquake sequences in the Jishishan region (2010–2024). (a) Number of TEC outliers identified per sequence using Grubbs' test ($\alpha = 0.01$). (b) Comparison of standard deviation between pre-seismic (blue) and post-seismic (red) TEC intervals. Rhombus (◇) indicates statistically significant differences in variance homogeneity based on F-test results ($p < 0.05$).

3.3. Geospace Parameter Evolution During the 2023 Jishishan Earthquake

Reliable detection of seismogenic ionospheric anomalies requires rigorous discrimination from space weather-induced perturbations, particularly for moderate-magnitude events where signal amplitudes are comparable to background variability. Following the precursor validation established by the Pulinets-Legen'ka [58], we conducted a comprehensive analysis of solar-geomagnetic parameters during the 2023 Jishishan earthquake (Ms6.2/Mw5.9) to isolate seismogenic signatures from exogenous influences.

Figure 5 details the evolution of key geospace indices spanning 31 days (3 December 2023–2 January 2024), including the planetary geomagnetic index (K_p ; 3 h resolution), disturbance storm-time index (Dst; hourly), sunspot number (SN; daily) and solar radio flux (F10.7; adjusted to 1 AU) [59–61]. The pre-seismic phase (DOY 337–345) exhibited quiet space weather conditions, with all parameters remaining below conventional activity thresholds ($K_p < 3.6$, $Dst > -32$ nT, $SN < 130$, $F10.7 < 140$ sfu). A notable transition occurred on DOY 346 (12 December), when both SN and F10.7 indices increased sharply, indicating a rise in solar activity. The SN index peaked at 136 on December 18—a 48% increase from December 12—before declining to a minimum of 52 by December 31. Similarly, the F10.7 series exhibits a bimodal structure, with maxima of 150.3 sfu (December 14) and 189.1 sfu (December 20). Correspondingly, the K_p index reached 4.5 on December 14 and 5.3 on December 17, while Dst responded with concurrent minima of -77 nT and -69 nT, confirming the occurrence of two moderate geomagnetic storms.

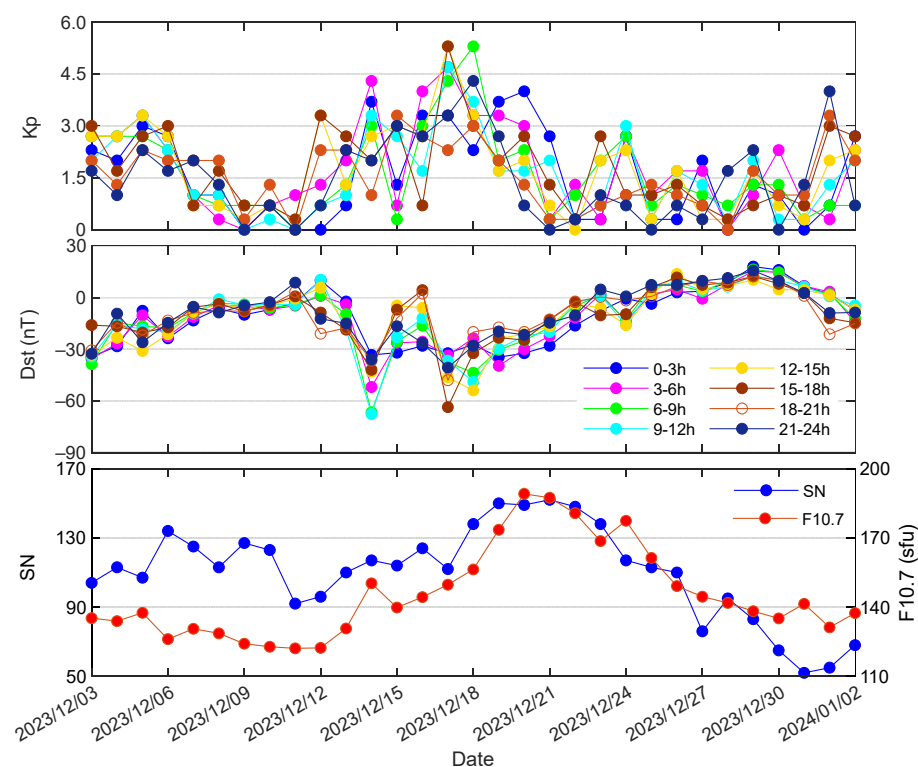


Figure 5. Multi-parameter geospace evolution (3 December 2023–2 January 2024): Temporal progression of planetary geomagnetic index (K_p ; 3-h), disturbance storm-time index (Dst ; nT), sunspot number (SN), and solar radio flux ($F_{10.7}$; sfu) before/after the Jishishan Mw5.9 earthquake (18 December 2023).

Applying conservative space weather thresholds ($K_p \geq 4.5$, $Dst \leq -60$ nT, $SN \geq 150$, $F_{10.7} \geq 150$ sfu), we identified two distinct disturbance events:

- (1) Event 1 (DOY 348): A Dst -driven storm (minimum -77 nT) despite sub-threshold K_p (4.3).
- (2) Event 2 (DOY 351–352): A full-threshold storm satisfying all criteria ($K_p = 5.3$, $Dst = -69$ nT, $F_{10.7} = 189$ sfu).

To address potential ambiguities in single-index interpretations, Figure 6 supplements the analysis by incorporating additional parameters: the interplanetary magnetic field component ($IMF B_z$; nT), polar cap electric field (E_y ; mV/m), solar wind plasma temperature (P_t ; K) and proton density (P_d ; cm^{-3}) [61,62]. A clear anti-correlation is observed between $IMF B_z$ and E_y , consistent with the theoretical relation ($E_y = \mathbf{V}_x \times \mathbf{B}_z$), where $\mathbf{V}_x$ denotes the sunward component of solar wind velocity. This relationship originates from the Lorentz force formalism ($\mathbf{F} = q \times \mathbf{v} \times \mathbf{B}$), in which plasma motion across geomagnetic field lines induces an electric field. Crucially, southward IMF ($B_z < 0$) combined with positive $\mathbf{V}_x$ enhances duskward E_y , directly facilitating magnetospheric energy injection and substorm development [63,64]. In contrast, P_t and P_d show no statistically significant correlation, revealing fundamentally distinct governing mechanisms.

The limitations of single-parameter analysis are highlighted by the event on 14 December 2023. Although proton temperatures ($P_t = 3.8 \times 10^5$ K) remained below the conventional storm threshold (4.0×10^5 K), simultaneous southward $IMF B_z$ (-8.3 nT) and enhanced E_y (4.1 mV/m) triggered localized magnetospheric activation. This decoupling phenomenon underscores the necessity for a multi-parameter composite approach.

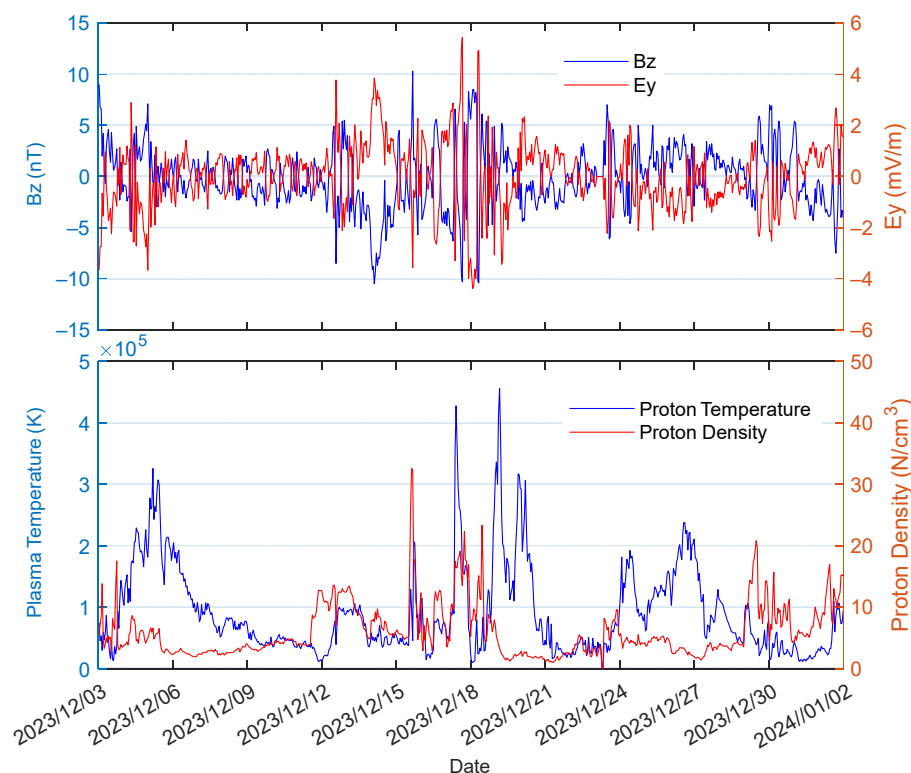


Figure 6. Solar wind-magnetosphere coupling parameters: Interplanetary magnetic field Bz component (nT), dawn-dusk electric field Ey (mV/m), plasma temperature (eV), and proton density (cm^{-3}) during the 2023 Jishishan earthquake.

To address this, we integrated geospacer parameters into daily activity states (S_{activity}) using a weighted scoring system:

$$S_{\text{activity}} = \sum_{i=1}^k w_i \cdot \frac{I_i - I_{\text{thres},i}}{I_{\text{max},i} - I_{\text{thres},i}} \quad (12)$$

where w_i and $I_{\text{thres},i}$ denote the weight and threshold of the parameter I_i . The weighting scheme prioritizes energy injection metrics: Kp (18%), Dst (25%), and Bz (28%), while auxiliary parameters (SN, F10.7, Pt, Pd, Ey) provide contextual validation. To avoid multicollinearity, only Bz—the primary driver of magnetospheric coupling—was retained, and Ey was excluded due to its functional dependence on Bz [65].

Days with activity scores exceeding the threshold of 0.5 (relative to the 31-day mean) were classified as geospatially active. As shown in Figure 7, the composite activity scores, derived from a weighted integration of seven key parameters (Kp, Dst, SN, F10.7, Bz, Pt, Pd), exhibit pronounced temporal variability throughout the observation period. Only two events exceeded the active-day threshold (dashed line): 14 December 2023 (score: 1.00) and 17 December 2023 (score: 0.62), indicating substantial space weather disturbances.

Notably, the Jishishan earthquake (18 December 2023) occurred during geomagnetically quiet conditions (score: 0.35), with all parameters below activation thresholds ($K_p < 4.5$, $\text{Dst} > -60$ nT, $\text{F10.7} < 150$ sfu). This temporal decoupling between space weather activity and seismic events suggests that observed ionospheric anomalies near the epicenter likely originated from lithospheric processes rather than solar-terrestrial interactions.

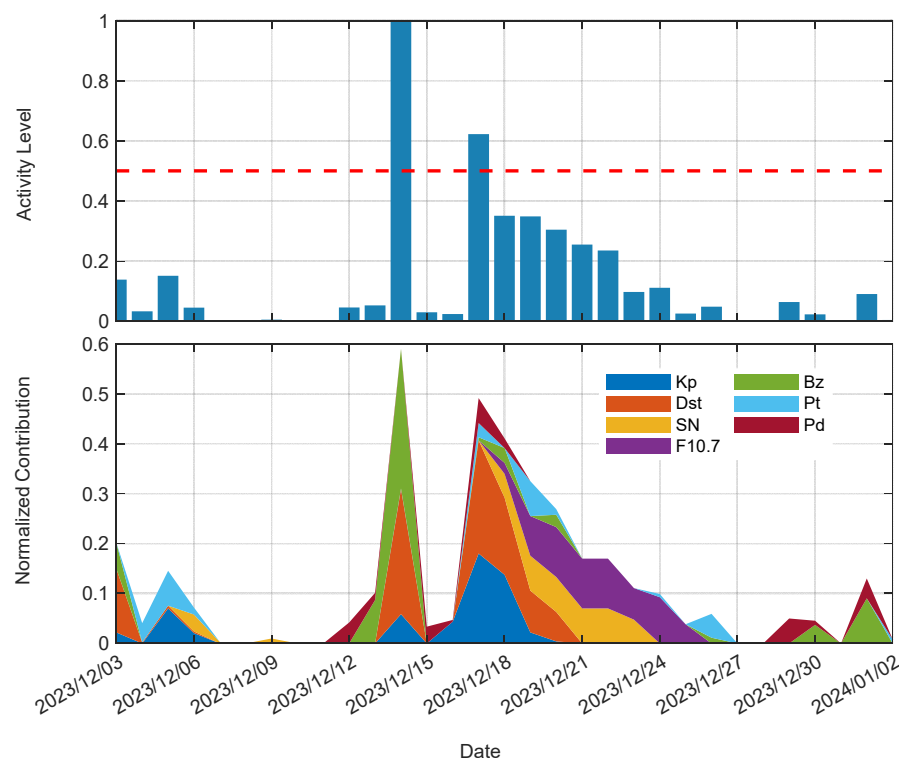


Figure 7. Evolution of the composite space weather activity score and normalized parameter contributions during the 31-day observational period. The stacked area chart depicts the relative weights of seven geophysical parameters (Kp, Dst, SN, F10.7, Bz, Pt, Pd) in the daily integrated score.

3.4. TEC Time Series Analysis of GNSS Stations Within Seismogenic Zone of the Jishishan Earthquake

The seismogenic zone of Jishishan earthquake spans a rectangular region between 25–46°N and 92–113°E, covering approximately 2.3×10^6 km². A network of 29 GNSS stations capable of tracking BDS multi-frequency signals has been used across this region, as illustrated in Figure 8. The epicenter, marked by a green pentagram, is located in the central-northwestern part of China. Within a 100 km radius, 12 Continuously Operating Reference Stations (CORS) are situated (shown in the bottom-right subfigure). Within an 800 km range, four International GNSS Service (IGS) monitoring stations are deployed, while the remaining stations lie beyond this radius. This configuration enables multi-scale ionospheric monitoring: proximal stations (within 400 km) capture localized ionospheric disturbances, whereas distal stations can help characterize large-scale traveling ionospheric disturbances (TIDs).

Figure 9 presents ionospheric monitoring results from BDS-2 GEO satellite (PRN: C03) on 18 December 2023. GEO satellites provide geometrically stable IPP tracks (blue lines in Figure 9a), making them ideal for long-term TEC monitoring. Their quasi-fixed IPP geometry, confined to a longitudinal drift of less than $\pm 3^\circ$, ensures observational consistency. The derived differenced TEC (dTEC) series generally remain below 0.1 TECU; accordingly, a threshold of 0.3 TECU was applied to suppress noise. Figure 9b depicts the relationship between dTEC and IPP–epicenter distance over 24 h. Notably, IPPs cover only a limited area within the effective zone defined by Equation (11). Although eight stations were within 450 km of the epicenter, no significant ionospheric disturbances were detected. This may be attributed to GEO satellites' inability to resolve azimuthally propagating disturbances due to IPP stagnation.



Figure 8. Geospatial distribution of GNSS stations tracking BDS dual-frequency measurements in the Jishishan region ($25\text{--}46^\circ\text{N}$, $92\text{--}113^\circ\text{E}$). The seismic epicenter (green pentagram) and GNSS stations (red circles) are overlaid with concentric buffers (blue dash-dotted circles) at 100 km intervals up to 800 km radius, delineating ionospheric observation zones for co-seismic disturbance analysis.

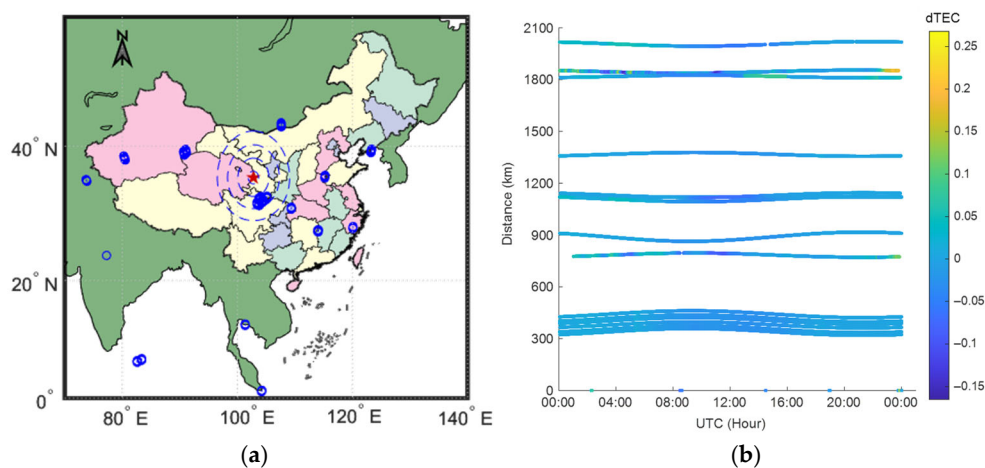


Figure 9. BDS-2 GEO (PRN: C03) ionospheric monitoring results on 18 December 2023: (a) spatial distribution of IPPs derived from GNSS stations; (b) corresponding differenced TEC (dTEC) series as a function of IPP–epicenter distance.

In contrast, Figure 10 displays ionospheric disturbance characteristics derived from the BDS-2 IGSO satellite (PRN: C07). Its inclined geosynchronous orbit (55° inclination) enables superior spatial coverage around the epicenter, practically enhancing signal reception in the southern sector (Figure 10a). Linear regression of coherent dTEC features yields a propagation velocity of 0.10 km/s (dashed lines in Figure 10b), consistent with acoustic gravity waves (AGWs) generated by vertical crustal displacements [66].

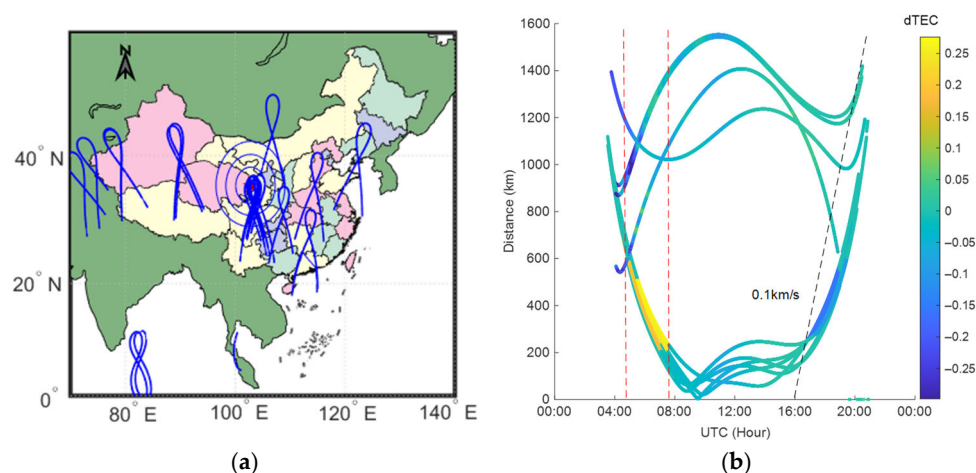


Figure 10. BBDS-2 IGSO (PRN: C07) ionospheric monitoring results on 18 December 2023: (a) IPP spatial distributions derived from GNSS stations; (b) Corresponding differenced TEC (dTEC) series as a function of IPP–epicenter distance.

The primary ionospheric phase exhibited negative polarity perturbations ($dTEC \approx -0.15$ TECU) initiating at 16:30 UT and persisting for about 120 min. The amplitude follows an exponential attenuation model:

$$A(r) = A_0 \cdot e^{-r/\lambda} \quad (13)$$

where $A_0 = 0.25$ TECU is the initial amplitude and $\lambda = 300$ km is the attenuation scale length. Disturbances became statistically indistinguishable from background noise beyond 600 km, demonstrating strong source proximity dependence.

A secondary pre-dawn perturbation (05:00–07:30 UT) displayed bipolar behavior: positive dTEC (+0.18 TECU) within 400 km transitioning to negative values beyond 600 km. This spatial reversal can be attributed to the modulation of ionospheric current by coupled AGWs and electric field variations, where near-field compressional effects transition to rarefactional effects at larger distances.

Figure 11 shows the spatiotemporal characteristics of ionospheric disturbances detected by the BDS-3 GEO satellite (PRN: C60). Similar to BDS-2 GEO, the IPP tracks remain confined to tight circular clusters. However, temporal analysis reveals distinct CIDs: a foreshock-associated phase propagating at 0.24 km/s (05:30 UT) and a post-seismic phase accelerating to 0.76 km/s (16:10 UT). These velocities straddle the theoretical boundary between atmospheric sound waves (0.3–2 km/s) and gravity waves (0.1–0.3 km/s), suggesting hybrid excitation through ionospheric–acoustic coupling modulated by ionospheric plasma dynamics.

Notably, the bimodal velocities (0.24/0.76 km/s) and extended propagation range (~3200 km) strongly implicate sound waves as the dominant excitation mechanism. The velocity differential likely reflects post-seismic atmospheric waveguide effects, with the faster post-event phase resulting from stratospheric ducting of acoustic energy and the slower foreshock phase corresponds to direct tropospheric propagation.

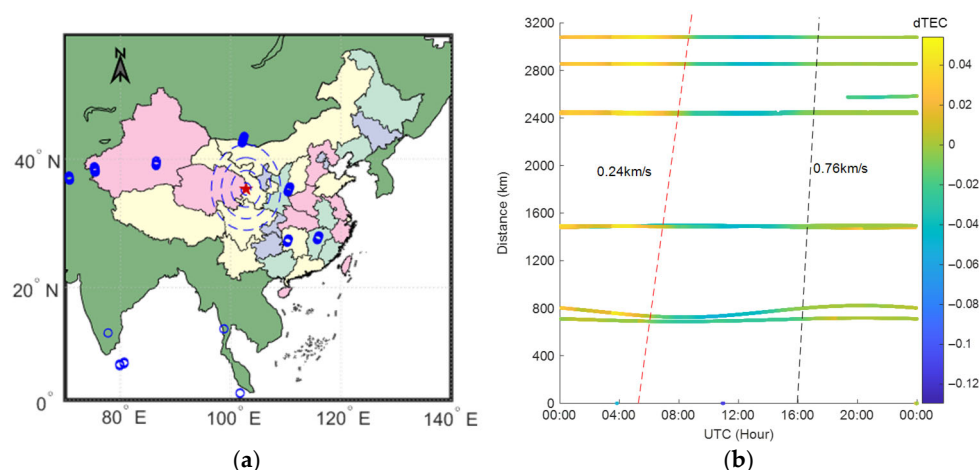


Figure 11. BDS-3 GEO (PRN: C60) ionospheric monitoring results on 18 December 2023: (a) IPP spatial distributions derived from GNSS stations; (b) Corresponding differenced TEC (dTEC) series as a function of IPP–epicenter distance.

Figure 12 illustrates the ionospheric disturbances detected by the BDS-3 IGSO satellite (PRN: C39). The 55° inclined orbit enables quasi-uniform IPP distribution around the epicenter (Figure 12a), providing omnidirectional coverage essential for resolving azimuthally propagating disturbances. Panel (b) reveals gravity wave signatures with a propagation velocity of 0.26 km/s and a peak dTEC amplitude of 0.25 TECU. A 60 min post-seismic delay is identified, with the linear regression intercept at 17:00 UT consistent with theoretical AGW vertical coupling timescales.

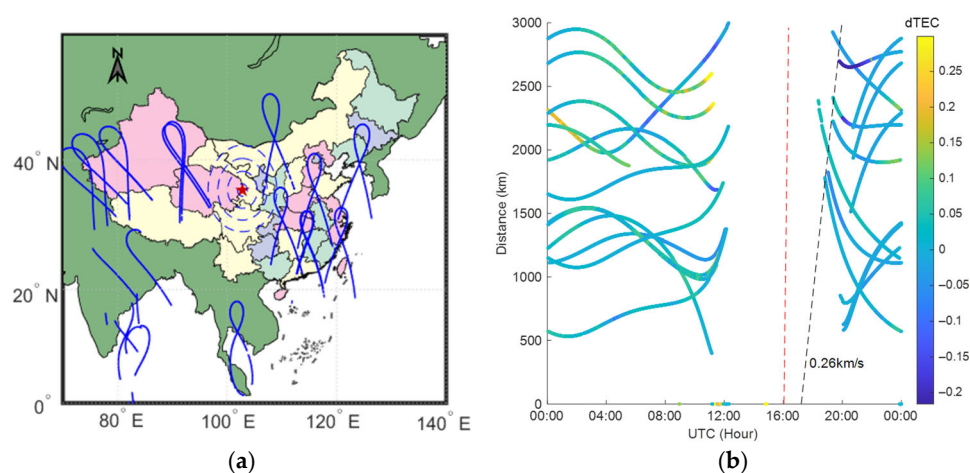


Figure 12. BDS-3 IGSO (PRN: C39) ionospheric monitoring results on 18 December 2023: (a) IPP spatial distributions derived from GNSS stations; (b) Corresponding differenced TEC (dTEC) series as a function of IPP–epicenter distance.

Notably, CID magnitudes show a non-monotonic relationship with epicentral distance, increasing by 38% (0.18 to 0.25 TECU) within 0–1500 km before stabilizing. This pattern, likely attributed to constructive interference of multiple wavefronts in the thermosphere-ionosphere system, contrasts with the exponential decay observed in BDS-2 IGSO data (Figure 10). The absence of stations beyond 3000 km precludes analysis of long-range propagation, highlighting a critical gap in current GNSS networks for global-scale disturbance tracking.

4. Discussion

While prior investigations have elucidated the mechanisms of lithosphere-ionospheric coupling under geomagnetically quiescent conditions, the potential modulation of these coupling processes during periods of enhanced space weather activity remains poorly understood [67,68]. This section systematically examines the characteristics of ionosphere TEC response during concurrent seismic preparation phases and elevated space weather activity. As delineated in Figure 7, 17 December 2023 was identified as a space weather-active day through our multi-parameter diagnostic algorithm, characterized by concurrent geomagnetic disturbances ($K_p = 5.3$, $Dst = -77$ nT, $F10.7 = 149.7$ sfu) and solar wind enhancements ($B_z = -10.3$ nT, $E_y = 5.4$ mV/m, $P_d = 22.3$ N/cm³).

We analyze the dTEC series derived from available GNSS stations within the seismogenic zone. As illustrated in Figure 13, in contrast to geomagnetically quiescent periods, the space weather-active day (17 December 2023) exhibits pronounced peak-trough coherence in dTEC variations derived from BDS-2 GEO measurements (PRN: C03). Linear regression yields propagation velocities of 0.9~1.6 km/s across all monitoring stations within 3000 km of the epicenter (Figure 13a). When focusing on proximal stations within the seismogenic zone (<450 km epicentral distance, Figure 13b), CID propagation velocities remain constrained to 1.1~1.5 km/s, demonstrating enhanced waveform synchronization. This velocity persistence under combined space weather and seismic forcing suggests two potential mechanisms:

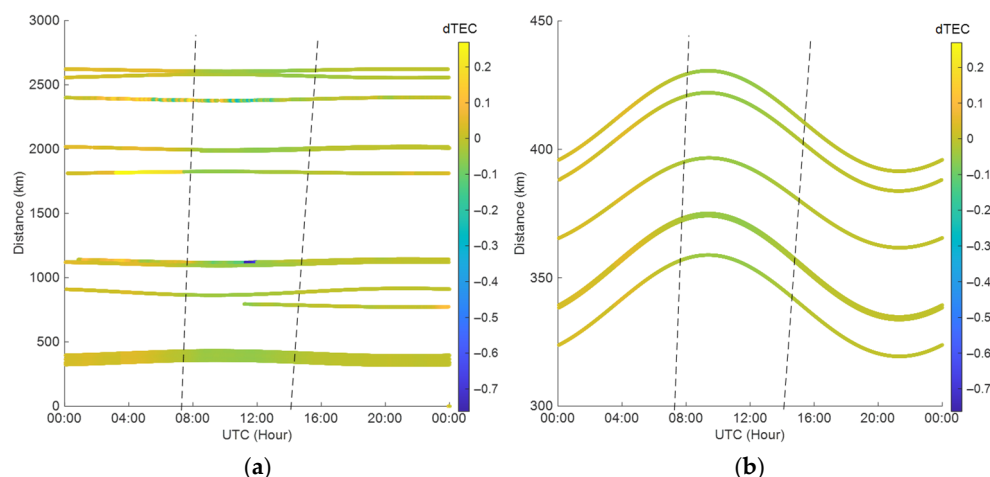


Figure 13. dTEC series derived from BDS-2 GEO (PRN: C03) measurements as a function of IPP-epicenter distance during the space weather-active day of 17 December 2023: (a) all monitoring stations; (b) stations within 500 km of the epicenter.

(1) Acoustic gravity waves generated by co-seismic crustal displacements propagate efficiently through lower thermosphere ducts, maintaining phase coherence.

(2) Enhanced ionospheric plasma turbulence during geomagnetic activity amplifies seismogenic perturbations through nonlinear wave-particle interactions.

Notably, the narrower velocity range (1.1–1.5 km/s) near to the epicenter aligns with theoretical predictions for vertically coupled Lithosphere–Atmosphere–Ionosphere energy transfer, contrasting with the broader distribution at regional scales that reflects heterogeneous medium properties.

Analysis of dTEC variations derived from BDS IGSO (PRN: C13 and C39) observations during this geomagnetically active period reveals distinct propagation characteristics under the combined influence of lithospheric and space weather forcing (Figure 14). Unlike GEO satellites which maintain nearly constant IPP-epicenter geometry, the inclined orbit of

IGSO satellites result in obvious distance variations (exceeding 1000 km in IPP–epicenter distance), leading to intermittent observational coverage (~65% per day).

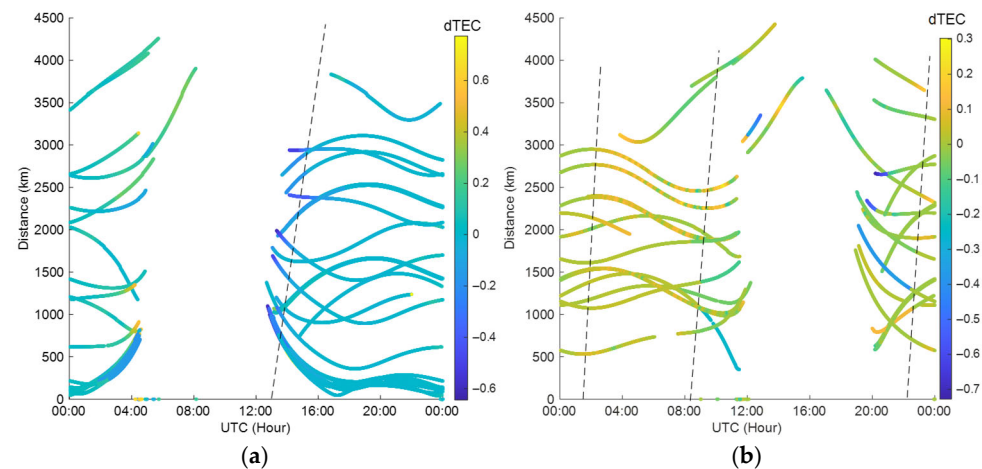


Figure 14. dTEC series derived from BDS IGSO measurements as a function of IPP–epicenter distance during the space weather-active day of 17 December 2023: (a) PRN: C13; (b) PRN: C39.

Despite the discontinuous dTEC sequences, systematic patterns emerge through peak/trough alignment analysis. The derived CIDs propagate at 0.42~0.58 km/s with observed propagation ranges exceeding 3000 km. This velocity regime can correspond to atmospheric acoustic gravity waves modulated by lithosphere–ionosphere coupling and space weather effects.

The distinct response patterns observed between GEO and IGSO satellites underscore the value of multi-satellite analysis for characterizing complex ionospheric disturbances. GEO satellites maintain stationary viewing geometry, enabling continuous monitoring well-suited for tracking temporal evolution. In contrast, IGSO satellites deliver superior spatial sampling, which is essential for resolving wave propagation characteristics. Despite their different observational geometries, both satellite types consistently detected co-seismic ionospheric disturbances. This consistency confirms the validity of the observed phenomena. It further indicates that the disturbances represent genuine ionospheric responses to coupled seismic and space weather forcing, rather than artifacts arising from observation geometry.

The modulation of LAIC signatures by space weather, as demonstrated here, has profound implications for the search for reliable earthquake precursors. It necessitates a move beyond static, “one-size-fits-all” detection thresholds towards adaptive, context-aware algorithms that integrate real-time space weather diagnostics. Paradoxically, the elevated and more coherent signals during active periods could enhance detectability, provided the confounding space weather effects can be accurately modeled and isolated. Future work should prioritize: (1) the development of coupled thermosphere-ionosphere models to quantitatively dissect the relative contributions of the proposed amplification mechanisms; (2) assembling and analyzing a larger statistical sample of earthquakes occurring under a wide spectrum of space weather conditions to establish robust, physics-based discrimination criteria.

5. Conclusions

This study presents an integrated analysis of seismo-ionospheric coupling associated with the 2023 Jishishan earthquake, combining the distinctive capabilities of the BDS high-orbit constellation with a multi-parameter space weather analysis framework. Three principal conclusions can be drawn, which collectively enhance our understanding of LAIC:

(1) The results provide evidence for a non-random correlation between regional seismic activity and ionospheric TEC anomalies. An observed inverse relationship between earthquake magnitude and anomaly detectability within conventional analysis windows highlights a previously underappreciated complexity in precursor manifestation. This pattern suggests that the preparatory processes of larger earthquakes may produce longer lasting and more spatially diffuse ionospheric perturbations, which are not captured by traditional detection methods.

(2) This research substantiates the advantages of BDS GEO and IGSO satellites for LAIC studies. Their complementary geometries—delivering either unrivaled temporal stability or essential spatial resolution—enable a more comprehensive and reliable characterization of CIDs than previously achievable with MEO-based GNSS systems. The detected AGW-driven CIDs, propagating at velocities between 0.10 and 0.76 km/s, supply valuable observational constraints for physical modeling.

(3) The composite space weather activity score developed in this study played a critical role in unambiguous signal attribution. It helped confirm the lithospheric origin of ionospheric anomalies during the mainshock by showing that they occurred under geomagnetically quiet conditions. Additionally, analysis during an active space weather period revealed potential synergistic forcing effects, suggesting that the ionospheric response to seismic events can be modulated by the background geospace environment.

In summary, this research validates BDS as a potent tool for advancing ionospheric seismology, and also provides a refined methodological framework for future precursor studies. The findings underscore the imperative of multi-constellation GNSS monitoring and sophisticated space weather contextualization. Future efforts should focus on expanding dense GNSS networks, developing data assimilation techniques for integrated space weather–seismic models, and pursuing a systematic statistical survey across diverse tectonic settings to progress towards a deterministic understanding of LAIC.

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Data Availability Statement: The multi-GNSS observation data from the IGS networks are available at <https://cddis.nasa.gov/archive/gps/data/daily/>, accessed on 1 December 2025. The multi-GNSS broadcast ephemeris data are available at <https://cddis.nasa.gov/archive/gnss/data/campaign/mgex/daily/rinex3/>, accessed on 1 December 2025. The GIM and DCB products from IGS can be obtained at <https://cddis.nasa.gov/archive/gnss/products>, accessed on 1 December 2025. The OMNI data are obtained from the GSFC/SPDF OMNIWeb interface (<http://omniweb.gsfc.nasa.gov>, accessed on 1 October 2025).

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Conflicts of Interest: Author Penggang Tian was employed by the Shaanxi Construction Engineering Holding Group Corp. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BDS	BeiDou Navigation Satellite System
GEO	Geostationary Earth Orbit
IGSO	Inclined Geosynchronous Orbit
TEC	Total Electron Content
CID	Co-seismic Ionospheric Disturbance
TID	Traveling Ionospheric Disturbance
LAIC	Lithosphere–Atmosphere–Ionosphere Coupling
AGW	Acoustic gravity Wave
IPP	Ionospheric Piercing Point
CORS	Continuously Operating Reference Stations

References

- Ohnaka, M. Earthquake source nucleation: A physical model for short-term precursors. *Tectonophysics* **1992**, *211*, 149–178. [\[CrossRef\]](#)
- Lapusta, N.; Rice, J.R. Nucleation and early seismic propagation of small and large events in a crustal earthquake model. *J. Geophys. Res. Solid Earth* **2003**, *108*, 2205. [\[CrossRef\]](#)
- Kanamori, H.; Brodsky, E.E. The physics of earthquakes. *Rep. Prog. Phys.* **2004**, *67*, 1429–1496. [\[CrossRef\]](#)
- Molchanov, O.; Fedorov, E.; Schekotov, A.; Gordeev, E.; Chebrov, V.; Surkov, V.; Rozhnoi, A.; Andreevsky, S.; Iudin, D.; Yunga, S.; et al. Lithosphere-atmosphere-ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. *Nat. Hazards Earth Syst.* **2004**, *4*, 757–767. [\[CrossRef\]](#)
- Pulinets, S.A.; Ouzounov, D.P. Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model—An unified concept for earthquake precursors validation. *J. Asian Earth Sci.* **2011**, *41*, 371–382. [\[CrossRef\]](#)
- Kuo, C.L.; Lee, L.C.; Huba, J.D. An improved coupling model for the lithosphere-atmosphere-ionosphere system. *J. Geophys. Res. Space Phys.* **2014**, *119*, 3189–3205. [\[CrossRef\]](#)
- Pulinets, 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. *Geomagn. Aeron.* **2015**, *55*, 521–538. [\[CrossRef\]](#)
- Davies, K.; Baker, D.M. Ionospheric effects observed around the time of the Alaskan earthquake of March 28, 1964. *J. Geophys. Res.* **1965**, *70*, 2251–2253. [\[CrossRef\]](#)
- Oikonomou, C.; Haralambous, H.; Pulinets, S.; Khadka, A.; Paudel, S.R.; Barta, V.; Muslim, B.; Kourtidis, K.; Karagioras, A.; İnyurt, S. Investigation of pre-earthquake ionospheric and atmospheric disturbances for three large earthquakes in Mexico. *Geosciences* **2020**, *11*, 16. [\[CrossRef\]](#)
- Boudjada, M.Y.; Biagi, P.F.; Eichelberger, H.U.; Nico, G.; Galopeau, P.H.M.; Ermini, A.; Solovieva, M.; Hayakawa, M.; Lammer, H.; Voller, W.; et al. Analysis of pre-seismic ionospheric disturbances prior to 2020 Croatian earthquakes. *Remote Sens.* **2024**, *16*, 529. [\[CrossRef\]](#)
- Marchetti, D.; De Santis, A.; Shen, X.; Campuzano, S.A.; Perrone, L.; Piscini, A.; Di Giovambattista, R.; Jin, S.; Ippolito, A.; Cianchini, G.; 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.* **2020**, *188*, 104097. [\[CrossRef\]](#)
- Zhang, X.; De Santis, A.; Liu, J.; Campuzano, S.A.; Yang, N.; Cianchini, G.; Ouyang, X.; D’arcangelo, S.; Yang, M.; De Caro, M.; et al. Pre-Earthquake Oscillating and Accelerating Patterns in the Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) before the 2022 Luding (China) Ms6. 8 Earthquake. *Remote Sens.* **2024**, *16*, 2381. [\[CrossRef\]](#)
- Heki, K. Ionospheric electron enhancement preceding the 2011 Tohoku–Oki earthquake. *Geophys. Res. Lett.* **2011**, *38*, L17312. [\[CrossRef\]](#)
- Liu, J.Y.; Chuo, Y.J.; Shan, S.J.; Tsai, Y.B.; Chen, Y.I.; Pulinets, S.A.; Yu, S.B. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. *Ann. Geophys.* **2004**, *22*, 1585–1593. [\[CrossRef\]](#)
- Yeh, K.C.; Liu, C.H. Acoustic-gravity waves in the upper atmosphere. *Rev. Geophys.* **1974**, *12*, 193–216. [\[CrossRef\]](#)
- Stiassnie, M. Tsunamis and acoustic-gravity waves from underwater earthquakes. *J. Eng. Math.* **2010**, *67*, 23–32. [\[CrossRef\]](#)

17. Shanmugam, S.; Jones, J.; MacAulay, A.; Van Dierendonck, A.J. Evolution to modernized GNSS ionospheric scintillation and TEC monitoring. In Proceedings of the 2012 IEEE/ION Position, Location and Navigation Symposium, Myrtle Beach, SC, USA, 23–26 April 2012.
18. Singh, D.; Singh, B.; Pundhir, D. Ionospheric perturbations due to earthquakes as determined from VLF and GPS-TEC data analysis at Agra, India. *Adv. Space Res.* **2018**, *61*, 1952–1965. [\[CrossRef\]](#)
19. Tariq, M.A.; Shah, M.; Hernández-Pajares, M.; Iqbal, T. Pre-earthquake ionospheric anomalies before three major earthquakes by GPS-TEC and GIM-TEC data during 2015–2017. *Adv. Space Res.* **2019**, *63*, 2088–2099. [\[CrossRef\]](#)
20. Alizadeh, M.M.; Schuh, H.; Todorova, S.; Schmidt, M. Global ionosphere maps of VTEC from GNSS, satellite altimetry, and Formosat-3/COSMIC data. *J. Geod.* **2011**, *85*, 975–987. [\[CrossRef\]](#)
21. Zhao, X.; Jin, S.; Mekik, C.; Feng, J. Evaluation of regional ionospheric grid model over China from dense GPS observations. *Geod. Geodyn.* **2016**, *7*, 361–368. [\[CrossRef\]](#)
22. Jin, S.; Jin, R.; Kutoglu, H. Positive and negative ionospheric responses to the March 2015 geomagnetic storm from BDS observations. *J. Geod.* **2017**, *91*, 613–626. [\[CrossRef\]](#)
23. Padokhin, A.M.; Tereshin, N.A.; Yasyukevich, Y.V.; Andreeva, E.S.; Nazarenko, M.; Yasyukevich, A.; Kozlovtsseva, E.; Kurbatov, G. Application of BDS-GEO for studying TEC variability in equatorial ionosphere on different time scales. *Adv. Space Res.* **2019**, *63*, 257–269. [\[CrossRef\]](#)
24. Yang, Y.; Li, J.; Xu, J.; Tang, J.; Guo, H.; He, H. Contribution of the compass satellite navigation system to global PNT users. *Chin. Sci. Bull.* **2011**, *56*, 2813–2819. [\[CrossRef\]](#)
25. Tang, J.; Gao, X.; Yang, D.; Zhong, Z.; Huo, X.; Wu, X. Local persistent ionospheric positive responses to the geomagnetic storm in August 2018 using BDS-GEO satellites over low-latitude regions in Eastern Hemisphere. *Remote Sens.* **2022**, *14*, 2272. [\[CrossRef\]](#)
26. Hu, L.; Lei, J.; Sun, W.; Zhao, X.; Wu, B.; Xie, H.; Yang, S.; Wu, Z.; Zheng, J.; Ning, B.; et al. Latitudinal variations of daytime periodic ionospheric disturbances from Beidou GEO TEC observations over China. *J. Geophys. Res. Space Phys.* **2021**, *126*, e2020JA028809. [\[CrossRef\]](#)
27. Zawdie, K.; Belehaki, A.; Burleigh, M.; Chou, M.Y.; Dhadly, M.S.; Greer, K.; Halford, A.J.; Hickey, D.; Inchin, P.; Kaeppler, S.R.; et al. Impacts of acoustic and gravity waves on the ionosphere. *Front. Astron. Space Sci.* **2022**, *9*, 1064152. [\[CrossRef\]](#)
28. Wang, J.; Tang, J.; Xu, C.; Zhang, L.; Wang, Y. Ionospheric disturbances detection based on BDS-GEO observations with Prophet model over China: A case study of May 2017 geomagnetic storm. *J. Geophys. Res. Space Phys.* **2025**, *130*, e2024JA033472. [\[CrossRef\]](#)
29. Yang, W.; Ouyang, C.; Xiang, W.; An, H. Mechanism analysis and numerical simulation of the Zhongchuan loess earthflow induced by the MS 6.2 Jishishan earthquake in Gansu, China. *Eng. Geol.* **2025**, *344*, 107828. [\[CrossRef\]](#)
30. Gao, X.; Shu, L.; Ma, Z.; Tian, P.; Pan, L.; Zhang, H.; Yang, S. An Investigation of Pre-Seismic Ionospheric TEC and Acoustic–Gravity Wave Coupling Phenomena Using BDS GEO Measurements: A Case Study of the 2023 Jishishan Ms6. 2 Earthquake. *Remote Sens.* **2025**, *17*, 2296. [\[CrossRef\]](#)
31. Kintner, P.M.; Ledvina, B.M. The ionosphere, radio navigation, and global navigation satellite systems. *Adv. Space Res.* **2005**, *35*, 788–811. [\[CrossRef\]](#)
32. Jin, S.; Occhipinti, G.; Jin, R. GNSS ionospheric seismology: Recent observation evidences and characteristics. *Earth-Sci. Rev.* **2015**, *147*, 54–64. [\[CrossRef\]](#)
33. Khazanov, G.V.; Koen, M.A.; Konikov, Y.V.; Sidorov, I.M. Simulation of ionosphere-plasmasphere coupling taking into account ion inertia and temperature anisotropy. *Planet. Space Sci.* **1984**, *32*, 585–598. [\[CrossRef\]](#)
34. Heelis, R.A.; Maute, A. Challenges to understanding the Earth’s ionosphere and thermosphere. *J. Geophys. Res. Space Phys.* **2020**, *125*, e2019JA027497. [\[CrossRef\]](#)
35. Sen, H.K.; Wyller, A.A. On the generalization of the Appleton-Hartree magnetoionic formulas. *J. Geophys. Res.* **1960**, *65*, 3931–3950. [\[CrossRef\]](#)
36. Hoque, M.M.; Jakowski, N. Estimate of higher order ionospheric errors in GNSS positioning. *Radio Sci.* **2008**, *43*, 1–15. [\[CrossRef\]](#)
37. Hoque, M.M.; Jakowski, N. Higher order ionospheric effects in precise GNSS positioning. *J. Geod.* **2007**, *81*, 259–268. [\[CrossRef\]](#)
38. Langley, R.B.; Teunissen, P.J.; Montenbruck, O. Introduction to GNSS. In *Springer Handbook of Global Navigation Satellite Systems*; Springer: Cham, Switzerland, 2017; pp. 3–23.
39. Medina, D.; Ortega, L.; Vilà-Valls, J.; Closas, P.; Vincent, F.; Chaumette, E. Compact CRB for delay, Doppler, and phase estimation—application to GNSS SPP and RTK performance characterisation. *IET Radar Sonar Navig.* **2020**, *14*, 1537–1549. [\[CrossRef\]](#)
40. Jia, X.; Liu, J.; Zhang, X. The analysis of ionospheric TEC anomalies prior to the Jiuzhaigou Ms7. 0 earthquake based on BeiDou GEO satellite data. *Remote Sens.* **2024**, *16*, 660. [\[CrossRef\]](#)
41. Jin, R.; Jin, S.; Feng, G. M_DCB: Matlab code for estimating GNSS satellite and receiver differential code biases. *GPS Solut.* **2012**, *16*, 541–548. [\[CrossRef\]](#)
42. Guo, X.; Zhang, X.; Yin, X.; Yi, L.; Wang, A.; Peng, C.; Wang, S.; Zhang, B.; Zhang, L.; Li, Z. Rupture process of the 2023 MW 6.1 Jishishan (China) earthquake in a compressional stress regime and implications for seismic hazards. *Geomat. Nat. Hazards Risk* **2025**, *16*, 2562272. [\[CrossRef\]](#)

43. Wang, S.G.; Xu, G.Y.; Li, S.; Yang, T.; Shi, L.; Zhang, L.; Tang, F.T.; Fang, L.H. Analysis of earthquake sequence and seismo genic structure of the 2023 MS6.2 Jishishan earthquake, Gansu Province, China. *Acta Seismol. Sin.* **2024**, *46*, 953–968.
44. Dobrovolsky, I.P.; Zubkov, S.I.; Miachkin, V.I. Estimation of the size of earthquake preparation zones. *Pure Appl. Geophys.* **1979**, *117*, 1025–1044. [\[CrossRef\]](#)
45. Wang, Q.; Li, S.; Li, X.; Wu, Y.; Zhao, P.; Gao, Y. Deep tectonics and seismogenic mechanisms of the seismic source zone of the Jishishan M s 6.2 earthquake on 18 December 2023, at the northeast margin of the Tibetan Plateau. *Earth Planet. Phys.* **2024**, *8*, 514–521. [\[CrossRef\]](#)
46. DeCelles, P.G.; Robinson, D.M.; Zandt, G. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. *Tectonics* **2002**, *21*, 12-1–12-25. [\[CrossRef\]](#)
47. Wang, H.; Liu, M.; Cao, J.; Shen, X.; Zhang, G. Slip rates and seismic moment deficits on major active faults in mainland China. *J. Geophys. Res. Solid Earth* **2011**, *116*. [\[CrossRef\]](#)
48. Ding, L.; Kapp, P.; Cai, F.; Garzione, C.N.; Xiong, Z.; Wang, H.; Wang, C. Timing and mechanisms of Tibetan Plateau uplift. *Nat. Rev. Earth Environ.* **2022**, *3*, 652–667. [\[CrossRef\]](#)
49. Palmer, S.J.; Rycroft, M.J.; Cermack, M. Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface. *Surv. Geophys.* **2006**, *27*, 557–595. [\[CrossRef\]](#)
50. Feng, J.; Zhang, Y.; Li, W.; Han, B.; Zhao, Z.; Zhang, T.; Huang, R. Analysis of ionospheric TEC response to solar and geomagnetic activities at different solar activity stages. *Adv. Space Res.* **2023**, *71*, 2225–2239. [\[CrossRef\]](#)
51. Yau, A.W.; Peterson, W.K.; Shelley, E.G. Quantitative parametrization of energetic ionospheric ion outflow. *Model. Magnetos. Plasma* **1988**, *44*, 211–217.
52. Maggiolo, R.; Kistler, L.M. Spatial variation in the plasma sheet composition: Dependence on geomagnetic and solar activity. *J. Geophys. Res. Space Phys.* **2014**, *119*, 2836–2857. [\[CrossRef\]](#)
53. Zhang, X.; Ren, X.; Wu, F.; Chen, Y. A new method for detection of pre-earthquake ionospheric anomalies. *Chin. J. Geophys.* **2013**, *56*, 213–222.
54. Ke, F.; Wang, J.; Tu, M.; Wang, X.; Wang, X.; Zhao, X.; Deng, J. Enhancing reliability of seismo-ionospheric anomaly detection with the linear correlation between total electron content and the solar activity index F10. 7: Nepal earthquake 2015. *J. Geodyn.* **2018**, *121*, 88–95. [\[CrossRef\]](#)
55. Saqib, M.; Şentürk, E.; Sahu, S.A.; Adil, M.A. Ionospheric anomalies detection using autoregressive integrated moving average (ARIMA) model as an earthquake precursor. *Acta Geophys.* **2021**, *69*, 1493–1507. [\[CrossRef\]](#)
56. Liu, J.Y.; Chen, Y.I.; Chuo, Y.J.; Chen, C.S. A statistical investigation of preearthquake ionospheric anomaly. *J. Geophys. Res. Space Phys.* **2006**, *111*, A05304. [\[CrossRef\]](#)
57. Shah, M.; Abbas, A.; Adil, M.A.; Ashraf, U.; de Oliveira-Júnior, J.F.; Tariq, M.A.; Ahmed, J.; Ehsan, M.; Ali, A. Possible seismo-ionospheric anomalies associated with Mw > 5.0 earthquakes during 2000–2020 from GNSS TEC. *Adv. Space Res.* **2022**, *70*, 179–187. [\[CrossRef\]](#)
58. Pulnits, S.A.; Legen'ka, A.D. Spatial-temporal characteristics of large scale disturbances of electron density observed in the ionospheric f-region before strong earthquakes. *Cosmic Res.* **2003**, *41*, 221–230. [\[CrossRef\]](#)
59. Carpenter, D.L. Relations between the dawn minimum in the equatorial radius of the plasmopause and Dst, Kp, and local K at Byrd Station. *J. Geophys. Res.* **1967**, *72*, 2969–2971. [\[CrossRef\]](#)
60. Turner, N.E.; Baker, D.N.; Pulkkinen, T.I.; McPherron, R.L. Evaluation of the tail current contribution to Dst. *J. Geophys. Res. Space Phys.* **2000**, *105*, 5431–5439. [\[CrossRef\]](#)
61. Iijima, T.; Shibaji, T. Global characteristics of northward IMF-associated (NBZ) field-aligned currents. *J. Geophys. Res. Space Phys.* **1987**, *92*, 2408–2424. [\[CrossRef\]](#)
62. Terasawa, T.; Fujimoto, M.; Mukai, T.; Shinohara, I.; Saito, Y.; Yamamoto, T.; Machida, S.; Kokubun, S.; Lazarus, A.J.; Steinberg, J.T.; et al. Solar wind control of density and temperature in the near-Earth plasma sheet: WIND/GEOTAIL collaboration. *Geophys. Res. Lett.* **1997**, *24*, 935–938. [\[CrossRef\]](#)
63. Angelopoulos, V.; Baumjohann, W.; Kennel, C.F.; Coroniti, F.V.; Kivelson, M.G.; Pellat, R.; Walker, R.J.; Lühr, H.; Paschmann, G. Bursty bulk flows in the inner central plasma sheet. *J. Geophys. Res. Space Phys.* **1992**, *97*, 4027–4039. [\[CrossRef\]](#)
64. Zhang, L.Q.; Baumjohann, W.; Wang, C.; Dai, L.; Tang, B.B. Bursty bulk flows at different magnetospheric activity levels: Dependence on IMF conditions. *J. Geophys. Res. Space Phys.* **2016**, *121*, 8773–8789. [\[CrossRef\]](#)
65. Gonzalez, W.D.; Echer, E. A study on the peak Dst and peak negative Bz relationship during intense geomagnetic storms. *Geophys. Res. Lett.* **2005**, *32*, L18103. [\[CrossRef\]](#)
66. Hocke, K.; Schlegel, K. A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995. *Ann. Geophys.* **1996**, *14*, 917–940. [\[CrossRef\]](#)

-
67. Hayakawa, M.; Hobara, Y. Current status of seismo-electromagnetics for short-term earthquake prediction. *Geomat. Nat. Hazards Risk* **2010**, *1*, 115–155. [[CrossRef](#)]
 68. Hayakawa, M.; Raulin, J.P.; Kasahara, Y.; Bertoni, F.C.P.; Hobara, Y.; Guevara-Day, W. Ionospheric perturbations in possible association with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF propagation data. *Nat. Hazards Earth Syst. Sci.* **2011**, *11*, 513–518. [[CrossRef](#)]

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