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# INVESTIGATION OF ANOMALOUS IONOSPHERIC SIGNATURE AS POSSIBLE PRECURSOR TO EARTHQUAKES

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A B S T R A C T

*We have examined the ionospheric response to a magnitude 6.6 earthquake that occurred in the Hindu Kush region of Afghanistan on March 21, 2023. This seismic event impacted the ionosphere in the Indian region. Our analysis utilized critical parameters of the F2 layer (foF2, h'F), obtained through Digisonde measurements from a low-mid latitude Indian station located in New Delhi (28.6°N, 77.2°E, 19.2°N geomagnetic latitude, 42.4°N dip).The routine day-to-day fluctuations in the ionosphere are removed by computing variations in the critical frequency and peak height of the F layer (ΔfoF2, Δh'F) in comparison to its standard normal behaviour during quiet periods. We observe noteworthy disturbances in the ionospheric F2 region over Delhi about 8 days before the earthquake event, leading to a substantial variation in peak electron density of approximately 90%. These observed perturbations suggest the potential existence of seismo-ionospheric coupling, given the solar and geomagnetic indices remained relatively quiet and stable during the period. Notably, the precursory impact of the earthquake was observed beyond the earthquake preparation zone, as given by Dobrovolsky et al. (1979).*



## 1. INTRODUCTION

The most devastating natural event, earthquakes, arise from the abrupt release of energy in the Earth's crust, producing seismic waves. Predicting an impending earthquake is a significant scientific challenge, and reliably forecasting them with high accuracy remains an ongoing pursuit. The notion of ionospheric anomalies as earthquake precursors was initially introduced by Antselevich in 1971. Subsequent to this, several

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lithosphere-atmosphere-ionosphere coupling mechanisms have been postulated, involving factors such as radon radioactivity, the release of CH4, CO2, He, and H2 carrier gases (Pulinets et al., 2000, 2002; Pulinets, 2004; Pulinets and Ouzounov, 2011). These mechanisms ionize the near-ground atmosphere (Sorokin and Hayakawa, 2013), generating an anomalous vertical electric field (Singh et al., 2012; Pundhir et al., 2015), which, in turn, perturbs the ionosphere (Pulinets and Davidenko, 2014).

Other proposed mechanisms include the generation of acoustic pressure waves (Astafyeva et al., 2013) and the underground emission of aerosols (Pulinets et al., 2000), emitting electromagnetic radiation that can alter the ionospheric electron density distribution. Importantly, not only the ionosphere above the earthquake epicenter but also its magnetically conjugated region (Pulinets et al., 2003, 2007) and the surrounding area known as the earthquake preparation zone (Dobrovolsky et al., 1979) are affected. The extent and intensity of these pre-earthquake ionospheric anomalies (PEIAs) depend on factors such as the earthquake's magnitude, depth, location, and the distance between its epicenter and the ionosphere monitoring station (Pulinets, 2004; Liu et al., 2006; Le et al., 2011, Bhardwaj et al., 2023).

PEIAs, in the form of changes in total electron content (TEC) and anomalies in F2, E, and Es layer ionospheric parameters, have been reported for various earthquake events. For instance, Ouzounov et al. (2015) found a close correlation between ionospheric anomalies and the M7.8 and M7.3 earthquakes in Nepal in April 2015. Similar studies by Pundhir et al. (2015) on the April 2013 M7.8 earthquake in Pakistan showed GPS TEC data anomalies 5–7 days before the event. Shah and Jin (2015) demonstrated ionospheric anomalies for events with M ≥ 6 and focal depth less than 60 km based on global M ≥ 5 earthquake events during 1998–2014. Liu et al. (2015) analyzed Electromagnetic Emissions Transmitted from Earthquake Regions data to reveal nighttime electron and ion density depression and daytime ion temperature enhancement 1–6 days prior to the epicenter of the May 2008 M8 Wenchuan earthquake. Other examples include anomalies detected around the epicenter of the 11 March 2011 M9 Tohoku-Oki earthquake in Japan (Heki, 2011), the 6 April 2009 M6.3 L'Aquila earthquake in Italy (Tsolis and Xenos, 2010), and the 20 September 1999 M7.7 Chi-Chi earthquake in Taiwan (Liu et al., 2001). In these cases, anomalies in ionospheric parameters were observed days to weeks before the seismic events, highlighting the potential of ionospheric monitoring for earthquake prediction. In light of above we examine whether (a) the earthquake event of March 21,2023 affected the ionospheric F2 region over the low-mid latitude Indian station, Delhi, (2) the effect of earthquake can be seen outside the radius of earthquake preparation zone, as given by Dobrovolsky et al. (1979), and if so, (c) the magnitude in electron density variation because of this earthquake event.

## 2. METHODOLOGY

The ionosphere's temporal variability, spanning hourly to seasonal scales and responding to solar activity, necessitates round the clock monitoring. The Digisonde instrument, situated at the "low mid-latitude ionospheric monitoring Indian station" in Delhi (28.6°N, 77.2°E, 19.2°N geomagnetic latitude, 42.4°N dip), is employed for our study. Operating at 5-minute intervals, it generates ionograms, showcasing sounding frequency on the x-axis and virtual reflection height on the y-axis (Gupta and Upadhayaya, 2017).

Ionogram data manually scaled with SAO-X software to derive critical ionospheric parameters (foF2, h'F2).The critical parameters exhibit variation whichallow us to quantify ionospheric variability by measuring the deviation of these parameters from their normal statistical behavior. Ionospheric parameters (foF2, ΔfoF2, h'F and Δh'F) are analyzed15 days prior and 20 days after ((i.e. from March 6, 2023, to April 10, 2023). ) the seismic event of 21 March 2023Ionospheric variabilities stem from day-to-day, hourly, and seasonal fluctuations, observed as deviations from average values based on ten geomagnetically quiet days (IQD).The deviation of foF2 is then estimated based on these comparisons (Gupta and Upadhayaya, 2017).

$$\Delta foF2\ (MHz) = foF2 - quiet \qquad (1)$$

"Quiet" denotes the median foF2 from ten IQDs. Positive $\Delta$foF2 signifies increased critical frequencies and electron density, while negative $\Delta$foF2 indicates decreased electron density. Electron density variations were calculated as percentage change using the following equation.

$$ElectronDensity\ (\%) = \left(\frac{foF2 - quiet}{quiet}\right) X\ 100 \qquad (2)$$


**Figure 1.** Schematic of earthquake epicentre to Ionospheric monitoring station(NPL, New Delhi)

**Table 1.** Details of Earthquake Event

| Earthquake date | Detail of Earthquake | | | | | Distance from Delhi (Km) | Radius of Influence Zone "R" (Km) |
|---|---|---|---|---|---|---|---|
| | Lat.(deg.) | Long.(deg.) | Depth(Km) | Mag. | Time(UT) | | |
| 21 Mar 2023 | 36.09° N | 71.35° E | 156 | 6.6 | 16.47 | 988 | 668.65 |

## 3. OBSERVATIONS AND ANALYSIS

We examine the earthquake event of 21 March 2023 with a magnitude greater than 6.0 in the Hindu Kush region with epicentre in Tajikistan (36.09° N, 71.35° E) with a focal depth of 156 km. This area is marked by intense seismic activity, resulted from collisional tectonics between the Indian Plate and Eurasian Plate. Ionospheric observations were conducted in Delhi, India. It can be noticed from Table 1 that the distance of the observing station, Delhi (~1105 km), was outside the radius of earthquake preparation zone (~1023 km) as given by (Dobrovolsky et al. (1979)).

Figures 1a–1e depict the $F_2$ layer critical frequency, the deviation in F2 layer frequency (ΔfoF2), and the background space weather conditions during 6$^{th}$ March to 11$^{th}$ April 2023.The global geomagnetic storm index (Kp), the Disturbance Storm Time Index (Dst), an index of magnetic activity, and the solar index F10.7 in sfu (solar flux unit, 1 SFU = $10^{-22}$ W/m$^2$/Hz) are shown in Figure to ascertain the space weather conditions during the period of investigation. On March 15th, the Dst indices exhibited a minimum of -38 nT at 23 UT, accompanied by a Kp index of 5.6. While the Dst index remains tranquil and steady, the Kp index suggests an elevated level of geomagnetic activity. It's important to note that although there exists a general correlation between Dst and Kp, these metrics gauge distinct facets of geomagnetic activity and are influenced by different factors. Typically, during geomagnetic storm episodes, both Dst and Kp are prone to register elevated values. Nevertheless, in certain instances, such as on March 15th, Kp may be heightened while Dst does not exhibit a corresponding significant negative deviation. This inconsistency might arise when the effects of the storm are unevenly distributed across the Earth. Additionally, when evaluating the influence of geomagnetic storms at equatorial and low to low–mid latitude stations, the Dst (Disturbance Storm Time) index, offering a measure of the global, low-latitude disturbance in the Earth's magnetic field, is generally more appropriate than the Kp index. The geomagnetic and solar conditions depicted in Figures 1c, 1d, and 1e before the earthquake event, barring the disturbance observed in Kp on the 15$^{th}$, are quiet and stable. This presents an ideal scenario to examine potential anomalous ionospheric variations triggered by other sources, such as earthquakes, sudden stratospheric warming, etc.

Prior to the earthquake event, enhancement more than 15 MHz in foF2 are seen on 7$^{th}$, 9$^{th}$, 13$^{th}$, 16$^{th}$ and 19$^{th}$ March 2023. However, after de-trending (ΔfoF2) two notable peaks (shown in green) are observed on March 16 and March 13 leading to an electron density variation of 120% and 90% respectively.On average, variations range 15-25%, corresponding to day-to-day ionospheric changes. This abrupt increase in ΔfoF2 on March 16 and on March 13 signifies a distinctive anomaly in the ionosphere prior to the earthquake event. The increase in ΔfoF2 on March 16 could be because of the increase in geomagnetic activity however, the enhancement seen in ΔfoF2 on 13$^{th}$ March warrant a detailed investigation.

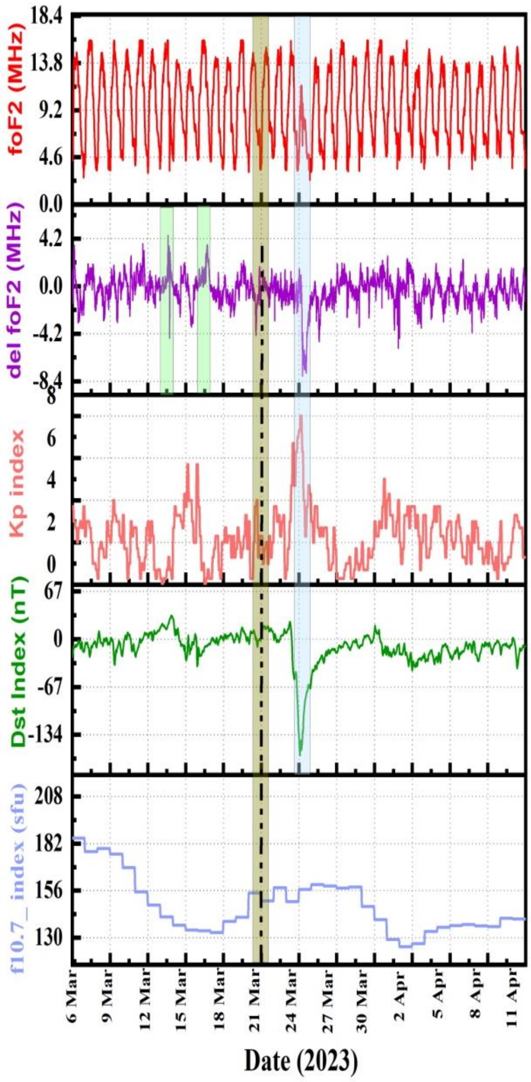


**Figure 2.** Plots depicting ionospheric parameters, geomagnetic, and solar indices from March 6$^{th}$ to April 11$^{th}$, 2023.

In Figure 2, the plot shows the variation in F2 layer critical frequency (foF2) from March 6$^{th}$ to April 10$^{th}$, 2023. It includes the median value on quiet days and highlights its fluctuations on March 13th and 24th, where anomalous variations were observed. It can be seen from this figure that prominent large variation varying from 3 to 16 MHz is seen on 13th March. Furthermore, there is a distinct decrease mostly in foF2 throughout the day in comparison to other days, aligning with the geomagnetic storm on March 24th (-163nT).

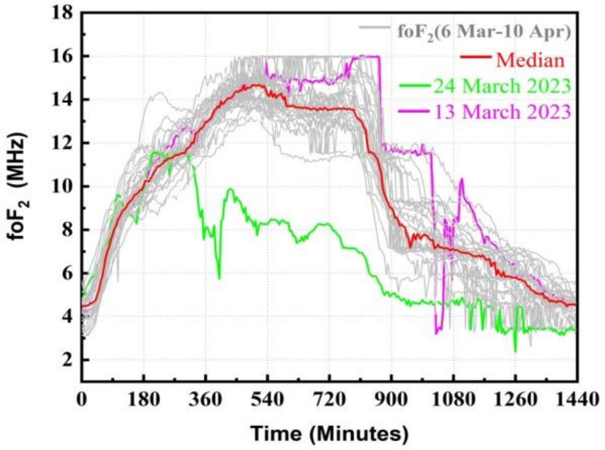


**Figure 3.** foF$_2$ variations from 06 March 2023 to 10 April 2023.

A clear anomalous variation in F2 layer frequency on 13th March can be seen in Figure 3 where, we have plotted the variation in the deviation of F2 layer frequency (△foF2) from the median values observed during quiet days in the month of March. A positive deviation of 4.5 MHz at 14.30 UT followed by a negative deviation of -4.6 MHz is seen at 17.25 UT. This anomalous variation of about 9 MHz on 13th March happened in just four hours of interval is strange and unexpected.

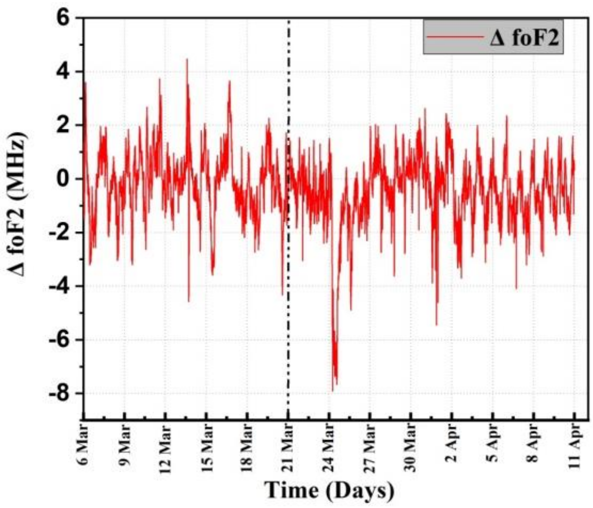


**Figure 4.** H'Fvariatoin from 06 March 2023 – 10 April 2023

We further examine the F layer base height behaviour during 6th March 2023 to 11th April 2023 for this earthquake event. In figure 4, the variation in F layer base height (h'F) is plotted, for the period from 6th March to 10th April 2023, the median value of quiet days along with its variation on 13th and 24th March respectively. On the Geomagnetic storm day of March 24, 2023, a considerable fluctuation of approximately 425 km in h'F is evident. However, despite the notable variation in foF2, no significant disturbances were noted in h'F on March 13th.

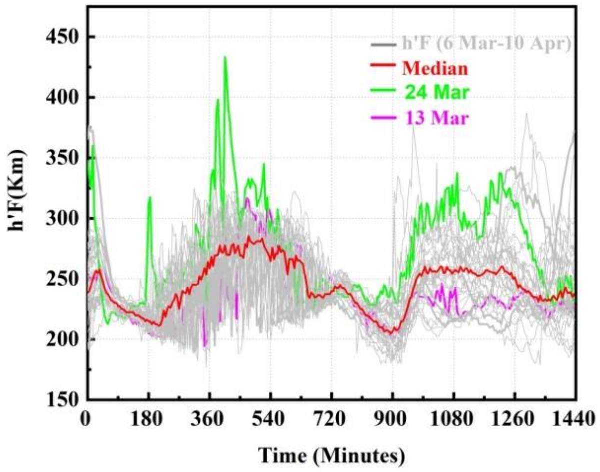


**Figure 5**. Plot of variation in h'F from March 6, 2023, to April 10, 2023.

Similar behaviour, i.e., no prominent variation in △h'F was seen on 13th March 2023 as can be seen in Figure 5, where the deviation in F layer base height (△h'F) from the quiet median is plotted, for the period from 6th March to 10th April 2023. However, a large variation of 175 km and 125 km was observed on 24th March and 16th March respectively.

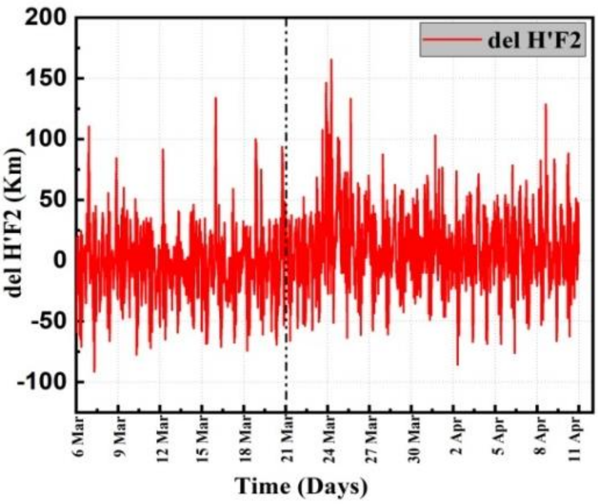


**Figure 6.** Plot of variation in △h'F from March 6, 2023, to April 10, 2023.

## 4. DISCUSSION

The investigation of the ionospheric response in the F2 region to the earthquake event on March 21, 2023, with a magnitude of 6.6 on the Richter scale, at the low-mid latitude Indian station, Delhi, has revealed two significant anomalous disturbances on March 16 and March 13, resulting in electron density variations of 120% and 90%, respectively.The anomaly detected in the F layer of the ionosphere on March 16 appears to be associated with geomagnetic factors, as evidenced by a registered Kp value of 5.6 on March 15. Conversely, the disruptions noted in the ionosphere on March 13 seem to be attributable to the seismo-ionospheric coupling effect, arising from the earthquake event, as the geomagnetic and solar indices remained tranquil and stable during this timeframe. Many researchers have documented comparable ionospheric disturbances occurring within the two weeks preceding the onset of the earthquake event for e.g. (Liu *et al*., 2008; Liu *et al*., 2010; Tojiev*et al*., 2013; Gupta and Upadhayaya, 2017; Tariq *et al*., 2021; (Eshkuvatov*et al*., 2023). Therefore, the anomalous variation observed on March 13, eight days before the earthquake event, can be regarded as a precursor to the earthquake event of March 23, 2023. However, the complexity and thus the elusiveness of the F2 region are well known. Often unexpected variability in the ionospheric F2 region is seen even at times when the solar and geomagnetic indices are low and quite stable also such abrupt variations in ionosphere is also linked to sudden stratospheric warming events however; it affects the ionosphere in winter time. In our previous study (Gupta & Upadhayaya, 2017); from the same monitoring station as well as in other reports, we have noted unusual perturbations in foF2 occurring one to two weeks before an earthquake. These observations have been recognized as potential precursors to seismic events. In the absence of any alternative source to which we can attribute the observed large variations in △foF2, and based on our prior observations, we believe that these variations resulted from the earthquake event.

On the precursor day, March 13th, there were minimal variation in the F layer height; nevertheless, these changes were not as noticeable as those observed in the frequencies. (Maruyama et al., 2011) in their study noted F2-layer height increase at Kokubunji station, 440 km from the Tohoku-Oki earthquake epicentre, supporting the notion of layer height changes. The main ionospheric variations what is being insisted occur prior to earthquakes, and the behavior of ionospheric base height (h'F) in relation to seismic events is a complex phenomenon that is not fully understood. It is established that some earthquakes can trigger disturbances in the ionosphere, causing changes in h'F. However, not every earthquake will necessarily have such effects. Several factors play a role, including the magnitude and depth of the earthquake (smaller or deeper earthquakes may have minimal or undetectable impact on the ionosphere), the distance between the epicenter and the observation point (effects may be unnoticed if the earthquake is far from the measurement area), and the specific ionospheric conditions at the time (pre-existing disturbances or irregularities may overshadow earthquake-induced effects). However, a depth of 156 km is unusual for a magnitude of (6.6) earthquake, researchers (Kon et al., 2011) analyzed seismic events with focal depths exceeding 40 km, even for low-magnitude earthquakes and showed Ionospheric anomalies associated with the event.

The seismic event under investigation occurred at a considerable distance from the Delhi station, beyond its zone of influence. Our findings are reinforced by the reported work of Dabas et al. (2007), who examined foF2 variations at Varanasi and Delhi in response to moderate to low-magnitude earthquakes exceeding 1000 km away. These earthquakes, with magnitudes ranging from 5 to 7.5, were primarily located in China, Myanmar, Indonesia, and Japan.

Furthermore, Gupta and Upadhayaya (2017) also investigated ionospheric anomalies associated with seismic events, analyzing five earthquakes. Interestingly, the effects of the earthquakes were observed even when the observation station was located outside the earthquake preparation zone.

It's important to emphasize that while there is evidence of ionospheric anomalies preceding earthquakes, the exact mechanisms and causal relationships are still not fully understood. One possible explanation could be the generation of a powerful electric field in the vicinity of the Earth's surface. Pulinets(2004) proposed a coupling model providing a block diagram of seismo-ionospheric coupling mechanism that suggested that radon is emitted from the region where the earthquake epicentre is located, both during and preceding the occurrence of the earthquake. Other similar schematic depiction of the causative mechanism is reported by (Xiong et al., 2021, Revathi et al., 2011). The increased concentration of ions in the seismic zone initiates a process known as nucleation, leading to the formation of ion clusters (Pulinets and Ouzounov, 2011). The diffusion of radon is facilitated by carbon dioxide and methane (Khilyuk et al., 2000), which, in turn, incite the generation of acoustic gravity waves. The movement of air disrupts the ion clusters, causing a rapid enrichment of ions in the near-Earth atmosphere. Consequently, an anomalously strong vertical electric field of approximately kV/m magnitude is produced through a process of charge separation. This intense electric field can penetrate into the ionosphere, altering its dynamics and electron density (Pulinets et al., 2000).

## 4. CONCLUSION

Following our examination of the ionospheric response to the seismic event that occurred on March 21, 2023, in the Hindu Kush region of Afghanistan, registering 6.6 on the Richter scale, the following conclusions are drawn from the analysis.

a) Distinct ionospheric perturbations are observed at the low-mid latitude Indian station, Delhi, indicating the impact of the seismo-ionospheric coupling mechanism.

These perturbations manifested eight days prior to the earthquake event, exhibiting both enhancements and depressions in foF2, corresponding to a maximum peak electron density variation of approximately 90%.

b) The anomalous perturbation in foF2 can be taken as precursor to earthquakes. However, no notable variations are observed in h'F that could be identified as distinctive signatures of earthquake events.

c) The ionospheric perturbations caused by the earthquake event are seen even when the observing station is located outside the earthquake preparation zone (Dobrovolsky et al., 1979).

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## References:

Astafyeva, E., Shalimov, S., Olshanskaya, E., & Lognonné, P. (2013). Ionospheric response to earthquakes of different magnitudes: Larger quakes perturb the ionosphere stronger and longer. *Geophysical Research Letters*, *40*(9), 1675-1681.https://doi.org/10.1002/grl.50398.

Bhardwaj, A., Gupta, A., Ahmed, Q., Singh, A., Gupta, S., Sarkhel, S., ... & Upadhayaya, A. K. (2023). Signature of Y-forking in ionogram traces observed at low-mid latitude Indian station, New Delhi, during the earthquake events of 2020: ionosonde observations. *Frontiers in Astronomy and Space Sciences*, *10*, 1170288. doi: 10.3389/fspas.2023.1170288.

Dabas, R. S., Das, R. M., Sharma, K. & Pillai, K. G. M. (2007). Ionospheric pre-cursors observed over low latitudes during some of the recent major earthquakes. *Journal of Atmospheric and solar-terrestrial physics*, *69(15)*, 1813-1824.doi: 10.1016.j.jastp.2007.09.005

Dobrovolsky, I. P., Zubkov, S. I., & Miachkin, V. I. (1979). Estimation of the size of earthquake preparation zones. *Pure and applied geophysics*, *117*(5), 1025-1044. doi:10.1007/BF00876083

Eshkuvatov, H. E., Ahmedov, B. J., Tillayev, Y. A., Tariq, M. A., Shah, M. A., & Liu, L. (2023). Ionospheric precursors of strong earthquakes observed using six GNSS stations data during continuous five years (2011–2015). *Geodesy and Geodynamics*, *14*(1), 65-79. doi: 10.1016/j.geog.2022.04.002.

Gupta, S., & Upadhayaya, A. K. (2017). Preearthquake anomalous ionospheric signatures observed at low-mid latitude Indian station, Delhi, during the year 2015 to early 2016: Preliminary results. *Journal of Geophysical Research: Space Physics*, *122*(8), 8694-8719.https://doi.org/10.1002/2017JA024192

Heki, K. (2011). Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake. *Geophysical Research Letters*, *38*(17).https://doi.org/10.1029/2011GL047908.

Khilyuk, L. F., Chilingar, G. V., Robertson, J. O., & Endres, B. (2000). "Chapter 15 - gas migration," in Gas migration. Editors L. F. Khilyuk, G. V. Chilingar, J. O. Robertson, and B. Endres (Houston: Gulf Professional Publishing), 223–237. doi:10.1016/B978- 088415430-3/50016-1.

Kon, S., Nishihashi, M., & Hattori, K. (2011). Ionospheric anomalies possibly associated with M⩾ 6.0 earthquakes in the Japan area during 1998-2010: Case studies and statistical study. *Journal of Asian Earth Sciences*, *41*(4), 410-420.doi: 10.1016/j.jseaes.2010.10.005

Le, H., Liu, J. Y., & Liu, L. (2011). A statistical analysis of ionospheric anomalies before 736 M6. 0+ earthquakes during 2002–2010. *Journal of Geophysical Research: Space Physics*, *116*(A2).https://doi.org/10.1029/2010JA015781

Liu, J. Y., Chen, Y. I., Chuo, Y. J., & Tsai, H. F. (2001). Variations of ionospheric total electron content during the Chi-Chi earthquake. *Geophysical Research Letters*, *28*(7), 1383-1386.https://doi.org/10.1029/2000GL012511

Liu, J. Y., Chuo, Y. J., Shan, S. J., Tsai, Y. B., Chen, Y. I., Pulinets, S. A. & Yu, S. B. (2004). Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. In *AnnalesGeophysicae*, *22*(5), 1585-1593.doi: 10.5194/angeo-22-1585-2004

Liu, J. Y., Tsai, H. F., Lin, C. H., Kamogawa, M., Chen, Y. I., Lin, C. H., ... & Yeh, Y. H. (2010). Coseismic ionospheric disturbances triggered by the Chi-Chi earthquake. *Journal of Geophysical Research: Space Physics*, *115*(A8). https://doi.org/10.1029/2010JA015313

Liu, J. Y., Tsai, Y. B., Chen, S. W., Lee, C. P., Chen, Y. C., Yen, H. Y., ... & Liu, C. (2006). Giant ionospheric disturbances excited by the M9. 3 Sumatra earthquake of 26 December 2004. *Geophysical Research Letters*, *33*(2). https://doi.org/10.1029/2005GL023963

Liu, J. Y., Y. I. Chen, C. C. Huang, M. Parrot, X. H. Shen, S. A. Pulinets, Q. S. Yang, & Ho, Y. Y. (2015), A spatial analysis on seismo-ionospheric anomalies observed by DEMETER during the 2008 *M*8.0 Wenchuan earthquake, *J. Asian Earth Sci.*, *114*, 414–419, doi:10.1016/j.jseaes.2015.06.012.

Maruyama, T., T. Tsugawa, H. Kato, A. Saito, Y. Otsuka, & Nishioka, M. (2011). Ionospheric multiple stratifications and irregularities induced by the 2011 off the Pacific coast of Tohoku earthquake, *Earth,planetsand space*, *63*(7), 869–873. doi: 10.5047/eps.2011.06.008.

Ouzounov, D., Pulinets, S., & Davidenko, D. (2015). Revealing pre-earthquake signatures in atmosphere and ionosphere associated with 2015 M7. 8 and M7. 3 events in Nepal. Preliminary results. *arXiv preprint arXiv:1508.01805*. https://doi.org/10.48550/arXiv.1508.01805.

Pulinets, S. (2004). Ionospheric precursors of earthquakes: *Recent advances in theory and practical applications. Terr. Atmos. Ocean. Sci*. *15*, 413–435. doi:10.3319/TAO.2004.15.3.413(EP).

Pulinets, S. A., Boyarchuk, K. A., Hegai, V. V., & Karelin, A. V. (2002). Conception and model of seismo-ionosphere-magnetosphere coupling. *Seismo-Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling*, 353-361.

Pulinets, S. A., Boyarchuk, K. A., Hegai, V. V., Kim, V. P., & Lomonosov, A. M. (2000). Quasielectrostatic model of atmosphere-thermosphere-ionosphere coupling. *Advances in Space Research*, *26*(8), 1209-1218. doi:10.1016/S0273-1177(99)01223-5

Pulinets, S. A., Kotsarenko, A. N., Ciraolo, L., &Pulinets, I. A. (2007). Special case of ionospheric day-to-day variability associated with earthquake preparation. *Advancesin Space Research*, *39*(5), 970-977. https://doi.org/10.1016/j.asr.2006.04.032

Pulinets, S. A., Legen'Ka, A. D., Gaivoronskaya, T. V., &Depuev, V. K. (2003). Main phenomenological features of ionospheric precursors of strong earthquakes. *journal of atmospheric and solar-terrestrial physics*, *65*(16-18), 1337-1347. https://doi.org/10.1016/j.jastp.2003.07.011

Pulinets, S., & Davidenko, D. (2014). Ionospheric precursors of earthquakes and global electric circuit. *Advances in Space Research*, *53*(5), 709-723. https://doi.org/10.1016/j.asr.2013.12.035

Pulinets, S., & Ouzounov, D. (2011). Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model–An unified concept for earthquake precursors validation. *Journal of Asian Earth Sciences*, *41*(4-5), 371-382. doi:10.1016/j.jseaes.2010.03.005.

Pundhir, D., Singh, B., Lakshmi, D. R., & Reddy, B. M. (2015). A study of ionospheric precursors associated with the major earthquakes occurred in Pakistan region. *J Ind Geophys Union*, *19*(1), 71-76.

Revathi, R., Brahmanandam, P. S., Vishnu, T., & Uma, G. (2011). Possible prediction of earthquakes by utilizing multi precursor parameters in association with ground and satellite-based remote sensing techniques. *International Journal of Earth Sciences and Engineering*, *4*(6), 978-981.

Shah, M., & Jin, S. (2015). Statistical characteristics of seismo-ionospheric GPS TEC disturbances prior to global Mw≥ 5.0 earthquakes (1998–2014). *Journal of Geodynamics*, *92*, 42-49. https://doi.org/10.1016/j.jog.2015.10.002

Sharma, K., Dabas, R. S., Sarkar, S. K., Das, R. M., Ravindran, S., & Gwal, A. K. (2010). Anomalous enhancement of ionospheric F2 layer critical frequency and total electron content over low latitudes before three recent major earthquakes in China. *Journal of Geophysical Research: Space Physics*, *115*(11), 1-14. doi: 10.1029/2009JA014842

Sorokin, V., & Hayakawa, M. (2013). Generation of seismic-related DC electric fields and lithosphere-atmosphere-ionosphere coupling. *Modern Applied Science*, *7*(6), 1.doi:10.5539/mas.v7n6p1

Singh, A. K., Kumar, S., Singh, R., & Singh, A. K. (2012). Pre-earthquake ionospheric anomalies observed using ground based multi-instruments. *Int. J. Adv. Earth Sci*, *1*(1), 13-19.

Tariq, M. A., Shah, M., Li, Z., Wang, N., Shah, M. A., Iqbal, T., & Liu, L. (2021). Lithosphere ionosphere coupling associated with three earthquakes in Pakistan from GPS and GIM TEC. *Journal of Geodynamics*, *147*(1), 1-11. doi: 10.1016/j.jog.2021.101860

Tojiev, S. R., Ahmedov, B. J., Tillayev, Y. A., & Eshkuvatov, H. E. (2013). Ionospheric anomalies of local earthquakes detected by GPS TEC measurements using data from Tashkent and Kitab stations. *Advance in. Space Research*, *52*(6), 1146-1154. doi: 10.1016/j.asr.2013.06.011

Tsolis, G. S., & Xenos, T. D. (2010). A qualitative study of the seismo-ionospheric precursors prior to the 6 April 2009 earthquake in L'Aquila, Italy. *Natural Hazards and Earth System Sciences*, *10*(1), 133-137. https://doi.org/10.5194/nhess-10-133-2010

Xiong, P., Long, C., Zhou, H., Battiston, R., De Santis, A., Ouzounov, D., ... & Shen, X. (2021). Pre-earthquake ionospheric perturbation identification using CSES data via transfer learning. *Frontiers in Environmental Science*, *9*, 779255. doi:10.3389/fenvs.2021.779255.

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