Resident Waves in the Ionosphere Before the M6.1 Dali and M7.3 Qinghai Earthquakes of 21–22 May 2021

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Abstract Geostationary BeiDou satellites monitor the total electron content (TEC) in the ionosphere over certain locations 24 hr per day without interruption and act as ionosphere-based seismometers. The system detected perturbations in TEC before both the M6.1 Dali and M7.3 Qinghai earthquakes that occurred during the night of 21–22 May 2021. The TEC perturbations reside mainly over an area within a distance of ~700 km from the epicenters of the earthquakes. The standing waves revealed a persistence of a subsurface wave source before the occurrences of the earthquakes, which differs from the co-seismic ionospheric distributions propagating away from the epicenters. The resident waves in TEC and ground vibrations share a frequency of ~0.004 Hz, which can be attributed to the resonant coupling between the lithosphere and ionosphere.

Plain Language Summary Large earthquakes seriously threat human life and induce economic loss. However, predicting an earthquake remains as a huge challenge due to the lack of reliable precursor signals. Something must be happened before a large earthquake. Therefore, we are looking for the reliable geophysical parameters for identifying the precursor that human beings are desired. In this study, the ionospheric total electron content (TEC) from the geostationary satellites of the Beidou global navigation satellite system recorded an unusual phenomenon of TEC perturbations resides in a particular area that appeared after mid-May in the post-sunset hours over China. The unusual phenomenon is significantly different from the morphologies of the traveling ionospheric disturbances and plasma bubbles over Asia in summer. The TEC perturbations reside over both two areas within a distance of ~700 km where cover the epicenters of the M6.1 Dali and M7.3 Qinghai earthquakes occurred during the night of 21–22 May 2021. The perturbations in TEC and ground vibrations share a frequency of ~0.004 Hz, which can be attributed to the resonant coupling between the lithosphere and ionosphere during the earthquakes.

1. Introduction

Ground-based global navigation satellite system (GNSS) receivers are usually utilized to navigate traffic tools and monitor crustal deformations (Bedford et al., 2020; Chen, Yeh, et al., 2011). Furthermore, GNSS systems can detect the total electron content (TEC) in the ionosphere and thus act as space buoys and seismometers to monitor co-seismic and tsunami waves at an altitude of ~350 km (Liu et al., 2011). Global navigation satellite system TEC (1 TECU [TEC unit] = 1 × 1016 el/m2) is the integration of the electron number density between a ground-based receiver and a GNSS satellite (Liu et al., 1996), estimated according to the delay and changes in electromagnetic waves transmitted from satellites passing through the ionosphere (Davies, 1990). Most GNSS satellites orbiting the Earth show the TEC as a function of elevation angle, latitude, longitude, and time. Ground-based receivers measure the TEC intermittently owing to their elevation cut-off angles. The TEC observations from the GNSS, such as the Global Positioning System (GPS), can efficiently record ionospheric plasma bubbles and traveling ionospheric disturbances (TIDs) that happened frequently in the ionosphere (e.g., Cheng et al., 2021; Sun et al., 2015). However, the BeiDou system includes five geostationary satellites over the equator of Asia (Su et al., 2018; Figure 1), and these can provide continuous TEC data as a function of time only.
Scientists study the LAI (Lithosphere, Atmosphere, and Ionosphere) coupling utilizing multiple geophysical parameters before earthquakes (Hayakawa, 2015, 2016). Acoustic-gravity waves originate near the Earth's surface and propagate upward into the ionosphere that is considered to be a potential channel in the LAI coupling before earthquakes (Hayakawa, 2011; Liu et al., 2016). However, the seismo-LAI coupling via the acoustic-gravity channel is generally referred to thermal anomalies due to that obvious ground vibrations are barely observed before earthquakes. Bedford et al. (2020) and Chen, Lin, et al. (2020) observed that ground vibrations persist in a large-scale area for a long time before earthquakes. Meanwhile, Chen, Sun, et al. (2020) reported that the frequencies of the ground vibrations vary from low (∼10−4 Hz) to high (∼10−3 Hz) through statistical methods. The ground vibrations share the frequency with the acoustic-gravity waves that drive us to investigate the seismo-LAI coupling via the acoustic-gravity channel. In this study, the TEC from the geostationary BeiDou satellites are utilized for mitigating influence due to orbiting satellites. Ground vibrations from the broadband seismometers are compared with the TEC to examine their relationship associated with two major earthquakes in China during the 21–22 May 2021.

2. Results and Discussion

Figure 1. Locations of the ground-based global navigation satellite system (GNSS) receivers and geostationary BeiDou satellites. The black triangles indicate the locations of the ground-based receivers. The blue dots are the ionospheric pierce points of the five geostationary satellites (C01–C05; the red dots) of the BeiDou system, located at an altitude of 350 km over the equator of Asia. The two pentagrams indicate the epicenters of the M6.1 Dali and M7.3 Qinghai earthquakes. The red triangle indicates the location of the system monitoring vibrations and perturbations in the lithosphere, atmosphere, and ionosphere that provides continuous seismic waveform and total electron count data from the broadband seismometer and the ground-based GNSS receiver, respectively (http://geostation.top/).

Fluctuations in TEC have been observed by the novel instrumental system named “Monitoring Vibrations and Perturbations in Lithosphere, Atmosphere, and Ionosphere” (MVP-LAI; 29.6°N, 103.9°E; Chen et al., 2021; http://geostation.top/) during the night since mid-May 2021 (Figure 2). The TECs from the geostationary BeiDou satellites reach their maxima near noontime and exhibit highly perturbed in the night time. To examine the perturbations in detail, the moving average with a 60-min temporal window was removed from the raw TEC time series to mitigate the variations in local time caused by dynamo and photochemical processes (Davies, 1990). The perturbations with amplitudes of ~0.2 TECU occurred in both the day and night before May. The pronounced perturbations (~1 TECU amplitude) persisted for ~40 days after 18 May and attenuated gradually in late June (Figure 2). The middle-scale traveling ionospheric disturbances (MSTIDs) in the GPS TECs prefer to occur over China in the night time of summer (Chen et al., 2019; Ding et al., 2011). Typically, the MSTIDs with velocity of ~100 m/s to ~200 m/s propagate in various directions in day and night (Cheng et al., 2021; Otsuka et al., 2021). The amplitude of the MSTIDs observed by GPS is less than 1 TECU that is smaller than that observed by the
Geostationary BeiDou satellites at the MVP-LAI system after 18 May (Figure 2). Atmospheric gravity waves could cause the daytime MSTIDs, and electro-dynamical forces, such as the Perkins instability, could cause the nighttime MSTIDs (Otsuka et al., 2021). The MSTIDs mainly propagate in the southwest direction from high to low latitudes in nighttime (Otsuka et al., 2009; Saito et al., 1998). On the other hand, ionospheric plasma bubbles can cause large TEC changes in night time. However, according to the GPS TEC and ROCSAT in-situ observations, ionospheric plasma bubbles should be weak over Asia in the summer under the low solar activity condition (Su et al., 2006; Sun et al., 2015) of 2021.

Two major earthquakes occurred in May 2021 in China; the first, with a magnitude of 6.1, occurred in Dali (25.765°N, 100.012°E) at 21:48:37 on 21 May (UTC+8) and the other, with a magnitude of 7.3, occurred in southern Qinghai (34.613°N, 98.246°E) at 2:04:13 on 22 May (UTC+8; https://earthquake.usgs.gov/earthquakes/search/; also, see Figure 1). The M7.3 Qinghai earthquake is the largest event after the 2008 M8.0 Wenchuan earthquake in mainland China. The GNSS receivers of the MVP-LAI system are ~573 and ~771 km away from
The occurrence of the two earthquakes accompanied by the pronounced TEC perturbations in night time.

A sufficient quantity of the TEC data observed by the GNSS network covered the period of the two earthquakes, which benefits to investigate if or how the perturbations are related to the two earthquakes. A total of 170 ground-based GNSS receivers that are operated by the Crustal Movement Observation Network of China and receive electromagnetic signals from the five geostationary BeiDou satellites were utilized to retrieve continuous TEC data (Figure 1). These retrieved TEC data were then utilized to investigate the pronounced fluctuations at the pierce points at an altitude of 350 km in the spatiotemporal domain (Liu et al., 1996). TEC perturbations with an amplitude of >1 TECU distributed mainly over an area south of the epicentre of the Dali earthquake in the post-sunset hours of 21 May 2021, nearly 1.5 hr before the earthquake occurrence (Figures 3a and 3b; also, see Figures S1–S2 in Supporting Information S1 and Movie S1). The perturbations reside over an area almost within a distance of ∼700 km from the epicentre of the earthquake (marked by the rectangle in Figure 3c). Moreover, the co-seismic perturbations in TEC propagated away from the epicentre at a velocity of ∼150 m/s (Figure 3c). The co-seismic perturbations can be seen on the map in Figures 3d and 3e near the epicentre of the Dali earthquake.

However, perturbations with amplitudes greater than 1 TECU appeared around the time of the Qinghai earthquake (Figures 3d and 3e; also, see Figures S1–S2 in Supporting Information S1 and Movie S1). They were distributed mainly within a distance of ∼850 km from its epicentre (marked by the rectangle in Figure 3f). The waves resided over the Qinghai earthquake from 20:30–23:30 local time (marked by the rectangle in Figure 3f). In short, the perturbations in TEC resided over the areas within ∼700 km of the epicenters of the two earthquakes before their occurrences even though they exhibit distinct characteristics. The persistence of ionospheric perturbations over a particular location suggests a wave source beneath the perturbations (Chou et al., 2017; Sun et al., 2019). Typically, MSTIDs propagate in the southwest direction with velocity of ∼100 to ∼200 m/s from higher latitude.
Bubbles usually occur at low latitudes and propagate eastward with phase velocity of \( \sim 100 \text{ m/s} \) (Haase et al., 2011; Saito et al., 2008). However, the TEC waves as shown in Figure 3 (also see Figures S1–S2 in Supporting Information S1 and Movie S1) persisted mainly over a specific location. Accordingly, the pronounced TEC perturbations recorded by the geostationary BeiDou satellites during the study period are unlikely the signature of the typical MSTIDs or bubbles.

The persistence of ionospheric perturbations can be contributed from variations of the atmospheric boundary layer. Pulinets and Davidenko (2018) observed the positive anomaly in TEC formed at nighttime (i.e., between sunset and sunrise) emerging within a few days before strong earthquakes. The positive anomaly is referred to regulations of the height distribution of cluster ions due to the formation in the ionosphere bound with the diurnal dynamics of the atmospheric boundary layer (Pulinets & Davidenko, 2018). Alternatively, the perturbations can be dominated by ground vibrations in the lithosphere. A previous study (Liu et al., 2016) utilized the multiple instruments to verify vibrations and/or motions in the lithosphere, triggering changes in the TEC in the ionosphere. Long-term crustal vibrations can be found in regions where earthquakes are forthcoming; these have been detected by multiple instruments including broadband seismometers, ground-based GNSS receivers, and magnetometers distributed over a wide spatial area (Chen, Lin, et al., 2020). These long-term crustal vibrations exhibit variable frequency characteristics at frequencies of \( \sim 5 \times 10^{-4} \text{ Hz} \) tending to \( \sim 5 \times 10^{-3} \text{ Hz} \) along the approaches of forthcoming earthquakes due to variations in areas with increased seismicity (Chen, Sun, et al., 2020). Continuous seismic data from a broadband seismometer in the MVP-LAI system show the variable frequency characteristics associated with the two earthquakes (Figure 4a). Enhancements in the power spectrum density from the ground vibrations were observed at a frequency of \( \sim 0.003 \text{ Hz} \) in mid-April 2021; the frequencies of such enhancements tended to be high over time and reached \( \sim 0.005 \text{ Hz} \) a few days before the occurrence of

Figure 4. Time-frequency-power distribution of continuous seismic and total electron count (TEC) observations from the system monitoring vibrations and perturbations in the lithosphere, atmosphere, and ionosphere. The seismic and TEC observations were continuous for the period 20:00–24:00 local time from 1 April to 28 May 2021. The continuous seismic data were calibrated using the instrument response function, and both data were transformed into the frequency domain using the Fourier transform. Trends in the power spectrum density function of the frequency were removed; the trend-free density was smoothed to reveal instinct characteristics. The dashed lines indicate the evolution of frequency from 0.004 to 0.005 Hz during the period 30 April to 20 May. The vertical lines and red pentagrams indicate the occurrence of the earthquakes.
the two earthquakes (Figure 4a). The enhancements with frequencies varying from 0.003 to 0.005 Hz shown in Figure 4a confirmed the existence of the phenomenon of the variable frequency of ground vibrations before major earthquakes, as reported in previous studies (e.g., Chen, Lin, et al., 2020; Chen, Sun, et al., 2020).

However, enhancements in the TEC appear mainly in a frequency band between 0.004 and 0.006 Hz (Figure 4b). Enhancements with frequencies varying from ~0.004 to ~0.005 Hz can also be observed during 30 April to 20 May. Previous studies (Chou et al., 2020; Dautermann et al., 2009) have reported that tsunamis, volcanic eruptions, and Rayleigh waves in the lithosphere can trigger such variations in the TEC. Observations and numerical simulations indicate that ground vibrations and the TEC share a frequency of ~0.004 Hz (Chen, Saito, et al., 2011; Dautermann et al., 2009; Liu et al., 2011; Matsumura et al., 2012; Saito et al., 2011) due to the resonant coupling in the lithosphere, atmosphere, and ionosphere. The evolution of similar frequencies in the ground velocity and the waves persistently reside over the epicenters before the two earthquakes that suggest the TEC resident waves due to the resonant LAI coupling. Notably, the anomalous frequency band observed in this study is close to it associated with acoustic waves. The factor of the acoustic waves can be entirely excluded after an examination of ground vibrations leading to the TEC anomalies.

3. Conclusion

Observations of the TEC made by geostationary BeiDou satellites suggest that the resonant coupling caused perturbations in the TEC before the M6.1 Dali and the M7.3 southern Qinghai earthquakes. Perturbations with amplitudes >~1 TECU resided persistently over the epicenters of these earthquakes owing to the resonant coupling. Ground vibrations with variable frequencies close to 0.005 Hz are promising candidates for the sources of the TEC perturbations. Perturbations in the TEC associated with resident waves due to the resonance at a frequency of ~0.004 Hz were clearly identified as occurring both after the earthquakes as previous studies (Dautermann et al., 2009; Saito et al., 2011) had shown—and before them. The results suggest that the TECs recorded by the BeiDou satellites can function as space-based seismometers detecting perturbations from the subsurface. The resonant coupling differs from the electric field dynamo, which is one of the major candidates for ionospheric earthquake precursors recommended in previous studies (Sun et al., 2019 and references therein). Atmospheric gravity waves that propagate from near the Earth’s surface and reach and break around the dynamo region can be examined further (Liu et al., 2009, 2011; Oyama et al., 2016; Sun et al., 2011).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data are available at the link Chen, 2021 (https://doi.org/10.6084/m9.figshare.16608050.v2).

References

Bedford, J. R., Moreno, M., Deng, Z., Oncken, O., Schurr, B., John, T., et al. (2020). Months-long thousand-kilometre-scale wobbling before great subduction earthquakes. *Nature*, 580, 628–635.

Chen, C.-H. (2021). Resident waves in the ionosphere before the M6.1 Dali and M7.3 Qinghai earthquakes of 20–21 May 2021 [Dataset]. Figshare. https://doi.org/10.6084/m9.figshare.16608050.v2

Chen, C.-H., Lin, L.-C., Yeh, T.-K., Wen, S., Yu, H., Chen, Y., et al. (2020). Determination of epicenters before earthquakes utilizing far seismic and GNSS data. *Insights from ground vibrations*. *Remote Sensing*, 12, 3252. https://doi.org/10.3390/rs12193252

Chen, C.-H., Saito, A., Lin, C. H., Liu, J. Y., Tsai, H. F., Tsugawa, T., et al. (2011). Long-distance propagation of ionospheric disturbance generated by the 2011 off the Pacific coast of Tohoku earthquake. *Earth Planets and Space*, 63(7), 881–884. https://doi.org/10.5047/eps.2011.06.026

Chen, C.-H., Sun, Y.-Y., Lin, K., Zhou, C., Xu, R., Qing, H., et al. (2021). A new instrumental array in Sichuan, China, to monitor vibrations and perturbations of the lithosphere, atmosphere and ionosphere. *Surveys in Geophysics*, 42, 1425–1442. https://doi.org/10.1007/s10712-021-09665-1

Chen, C.-H., Sun, Y.-Y., Wen, S., Han, P., Lin, L.-C., Yu, H., et al. (2020). Spatiotemporal changes of seismicity rate during earthquakes. *Natural Hazards and Earth System Sciences*, 20, 3333–3341. https://doi.org/10.5194/nhess-20-3333-2020

Chen, C.-H., Yeh, T. K., Liu, J. Y., Wang, C. H., Wen, S., Yen, H. Y., & Chang, S. H. (2011). Surface deformation and seismic rebound: Implications and applications. *Surveys in Geophysics*, 32(3), 291–313. https://doi.org/10.1007/s10712-011-9117-3

Chen, G., Zhou, C., Liu, Y., Zhao, J., Tang, Q., Wang, X., et al. (2019). A statistical analysis of medium-scale traveling ionospheric disturbances during 2014–2017 using the Hong Kong CORS network. *Earth Planets and Space*, 71, 52. https://doi.org/10.1186/s40623-019-1031-9
Cheng, P. H., Lin, C., Otsuka, Y., Liu, H., Rajesh, P. K., Chen, C. H., et al. (2021). Statistical study of medium-scale traveling ionospheric disturbances in low-latitude ionosphere using an automatic algorithm. *Earth Planets and Space*, 73, 105. https://doi.org/10.1186/s40623-021-01432-1

Chou, M.-Y., Chen, C.-H., Liu, J.-Y., & Petalebattla, N. M. (2020). The persistent ionospheric responses over Japan after the impact of the 2011 Tohoku earthquake. *Space Weather*, 18, e2019SW002302. https://doi.org/10.1029/2019SW002302

Chou, M.-Y., Liu, C.-C. H., Yue, J., Tsai, H.-F., Sun, Y.-Y., Liu, J.-Y., & Chen, C. H. (2017). Concentric traveling ionosphere disturbances triggered by Super Typhoon Meranti (2016). *Geophysical Research Letters*, 44, 1219–1226. https://doi.org/10.1002/2016GL072205

Dautermann, T., Calais, E., Lognonné, P., & Mattioli, G. S. (2009). Lithosphere—Atmosphere—ionosphere coupling after the 2003 explosive eruption of the Soufriere Hills Volcano, Montserrat, Geophys. *Journal of Intelligence*, 179, 1537–1546. https://doi.org/10.1111/j.1365-246X.2009.04390.x

Davies, K. (1990). Ionospheric radio. Peregrinus.

Ding, F., Wan, W., Xu, G., Yu, T., Yang, G., & Wang, J. (2011). Climatology of medium-scale traveling ionospheric disturbances observed by a GPS network in central China. *Journal of Geophysical Research*, 116, A09327. https://doi.org/10.1029/2011JA016545

Haase, J. S., Dautermann, T., Taylor, M. J., Chapagain, N., Calais, E., & Pautet, D. (2011). Propagation of plasma bubbles observed in Brazil from GPS and airlow data. *Advances in Space Research*, 47(10), 1758–1776. https://doi.org/10.1016/j.asr.2010.09.025

Hayakawa, M. (2011). Probing the lower ionospheric perturbations associated with earthquakes by means of subionospheric VLF/LF propagation. *Earthquake Science*, 24(6), 609–637.

Hayakawa, M. (2015). *Earthquake prediction with radio techniques*. John Wiley & Sons, Singapore Pte Ltd.

Hayakawa, M. (2016). Earthquake prediction with electromagnetic phenomena. *AIP Conference Proceedings*, 1709.

Liu, J.-Y., Chen, C.-H., Lin, C.-H., Tsai, H.-F., Chen, C.-H., & Kanogawa, M. (2011). Ionospheric disturbances triggered by the 11 March 2011 M9.0 Tohoku earthquake. *Journal of Geophysical Research*, 116, A06319. https://doi.org/10.1029/2011JA016761

Liu, Y.-Y., Chen, C.-H., Liu, C.-Y., Chen, C.-Y., Nishihiashi, M., Li, J. Z., et al. (2009). Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 Mw7.9 Wenchuan earthquake. *Journal of Geophysical Research*, 114, A04320. https://doi.org/10.1029/2008JA013698

Liu, J.-Y., Chen, C.-H., Sun, Y.-Y., Chen, C.-H., Tsai, H.-F., Yen, H. Y., et al. (2016). The vertical propagation of disturbances triggered by seismic waves of the 11 March 2011 M9.0 Tohoku Earthquake over Taiwan. *Geophysical Research Letters*, 43, 1759–1765. https://doi.org/10.1002/2015GL067487

Liu, J.-Y., Tsai, H.-F., & Jung, T. K. (1996). Total electron content obtained by using the Global Positioning System. *Terrestrial, Atmospheric and Oceanic Sciences*, 7, 107.

Matsumura, M., Shinagawa, H., & Iyemori, T. (2012). Horizontal extension of acoustic resonance between the ground and the lower thermosphere. *Journal of Atmospheric and Solar-Terrestrial Physics*, 75–76, 127–132.

Otsuka, Y., Shinbori, A., & Tsugawa, T. (2021). Solar activity dependence of medium-scale traveling ionospheric disturbances using GPS receivers in Japan. *Earth Planets and Space*, 73, 22. https://doi.org/10.1186/s40623-020-01353-5

Otsuka, Y., Shinohara, K., Ogawa, T., Yokoyama, T., & Yamamoto, M. (2009). Spatial relationship of nighttime medium-scale traveling ionospheric disturbances and F region field-aligned irregularities observed with two spaced all-sky airglow imagers and the middle and upper atmosphere radar. *Journal of Geophysical Research*, 114, A05302. https://doi.org/10.1029/2008JA013902

Oyama, K.-I., Devi, M., Ryu, K., Chen, C. H., Liu, J. Y., Liu, H., et al. (2016). Modifications of the ionosphere prior to large earthquakes: Report from the ionospheric precursor study group. *Geoscience Letters*, 3(1), 6. https://doi.org/10.1186/s40562-016-0038-3

Pulinets, S. A., & Davidenko, D. V. (2018). The nocturnal positive ionospheric anomaly of electron density as a short-term earthquake precursor and the possible physical mechanism of its formation. *Geomagnetism and Aeronomy*, 58, 559–570. https://doi.org/10.1134/S0016793218040126

Saito, A., Fukao, S., & Miyazaki, S. (1998). High resolution mapping of TEC perturbations with the GSI GPS network over Japan. *Geophysical Research Letters*, 25, 3079–3082.

Saito, A., Tsugawa, T., Otsuka, Y., Nishihiashi, M., Iyemori, T., Matsumura, M., et al. (2011). Acoustic resonance and plasma depletion detected by GPS total electron content observation after the 2011 off the Pacific coast of Tohoku earthquake. *Earth Planets and Space*, 63, 863–867. https://doi.org/10.5047/eps.2011.06.034

Saito, S., Maruyama, T., Ishii, M., Kubota, M., Ma, G., Chen, Y., et al. (2008). Observations of small- to large-scale ionospheric irregularities associated with plasma bubbles with a transsequatorial HF propagation experiment and spaced GPS receivers. *Journal of Geophysical Research*, 113, A12313. https://doi.org/10.1029/2008JA013149

Su, S.-Y., Liu, C. H., Ho, H. H., & Chao, C. K. (2006). Distribution characteristics of topside ionospheric density irregularities: Equatorial versus midlatitude regions. *Journal of Geophysical Research*, 111, A06305. https://doi.org/10.1029/2005JA011330

Su, X., Meng, G., Sun, H., & Wu, W. (2018). Positioning performance of BDS observation of the crustal movement observation network of China and its potential application on crustal deformation. *Sensors*, 18, 3353. https://doi.org/10.3390/s18103353

Sun, Y.-Y., Liu, J. Y., Chao, C. K., & Chen, C. H. (2015). Climatology of low-latitude nighttime F-region ionospheric density irregularities observed by ROCSAT and ground-based GPS receivers in solar maximum. *Journal of Atmospheric and Solar-Terrestrial Physics*, 123, 92–101. https://doi.org/10.1016/j.jastp.2014.12.013

Sun, Y.-Y., Liu, J.-Y., Wu, Y.-Y., & Chen, C.-H. (2019). Global distribution of persistence of total electron content anomaly. *Atmosphere*, 10, 297. https://doi.org/10.3390/atmos10080297

Sun, Y.-Y., Oyama, K.-I., Liu, J. Y., Jhun, H. K., & Cheng, C. Z. (2011). The neutral temperature in the ionospheric dynamo region and the ionospheric F region density during Wenchuan and Pingtung Doublet earthquakes. *Natural Hazards and Earth System Sciences*, 11, 1759–1768. https://doi.org/10.5194/nhess-11-1759-2011