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Editorial

Lithosphere–Atmosphere–Ionosphere Coupling Processes for Pre-, Co-, and Post-Earthquakes

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In recent years, many ionospheric perturbations have been detected around strong earthquakes, especially after the launching of earthquake-related electromagnetic satellites, including DEMETER and CSES [1,2]. Ionospheric anomalies exhibit significant short-term and imminent features in the time domain, illustrating their important role in short-term earthquake prediction. To validate the relationship between ionospheric disturbances and earthquakes, lithosphere–atmosphere–ionosphere coupling (LAIC) concepts and models have been proposed and simulated [3–7]. However, due to the lack of part parameters in different layers, big differences, and even contradictions, still exist between the models and real observations [8]. On the one hand, stereo-observation systems have gradually been developed with an increasing number of parameters for detection. Based on this, complete links from the lithosphere to the ionosphere are expected to be constructed and traced back. On the other hand, improvements must be made to theoretical models by increasing consistency at the layer boundaries with actual observations. Both methods are important in earthquake research for developing a deeper understanding of the coupling processes of Earth's spheres during earthquake preparation and occurrence.

In this Special Issue on "Lithosphere–Atmosphere–Ionosphere Coupling Processes for Pre-, Co-, and Post-earthquakes", we present 11 original research articles describing: ground-based observations from multiple parameters around strong earthquakes, including instrument improvement; ionospheric responses observed by satellites; and coupling processes from the surface to the ionosphere. The papers mainly focus on investigations of continental earthquakes in China and its neighboring regions. In addition to the electromagnetic field, the studies also combine the geochemical field and other ground-based observations.

The China Seismo-Electromagnetic Satellite (CSES, also named ZH-1) has been in operation for almost 5 years (since February 2018), and has eight scientific payloads onboard [2]. The satellite data are used in five of the papers presented in this issue, in which new satellite data processing methods are developed. Li et al. [9] studied ion and electron density variations before the occurrence of two large earthquakes (Maduo Ms7.4 in 2021 and Menyuan Ms6.9 in 2022) in northwest China, and found an enhancement in plasma density within the 15 days prior to the earthquakes under quiet geomagnetic conditions. They concluded that impending earthquake prediction in China using satellite observations was still difficult due to the uncertainty of the location and magnitude. Zhao et al. [10] summarized ionospheric anomalies around 12 earthquakes with magnitudes larger than 6.0 in western mainland China from 2019 to 2021; both the ion and electron density anomalies showed strong correlations with thrust and strike-slip earthquakes but not with normal fault earthquakes. Du and Zhang [11] employed the revisited orbit comparison and wavelet transform methods to obtain similar frequency features in perturbations of electron density, temperature, and ion compositions from CSES before the occurrence of the Yangbi Ms6.4 and Maduo Ms7.4 earthquakes in China from 21 to 22 May 2021. Combined with the electron density from CSES and GIM TEC (global ionospheric mapping, total electron content) published by CODE, Guo et al. [12] determined the seismo-ionospheric effects around two strong earthquakes with magnitudes of 6.7 and 6.3 in the Taitung sea in 2022; they illustrated a geochemical coupling channel on the basis of gas radon, water radon, and F^- observations. They also presented the statistical results for 138 $M \geq 5.0$ earthquakes using CSES data from February 2019 to March 2022 in the Taiwan region in China; moreover, the occurrence of ionospheric anomalies increased with the impending time of earthquakes and earthquake magnitudes. In addition to the plasma parameters from CSES, Liu et al. [13] combined other ionospheric monitoring technologies, including foF2 from ionosonde, TEC from a GPS receiver, GIM TEC, etc. They found simultaneous negative variations 5–7 days before the Maerkang Ms6.0 earthquake swarm in Sichuan province, China. Upon analyzing nine earthquakes in southwest China with magnitudes larger than 6.0 from 2019 to 2022, ground-based ionospheric monitoring techniques exhibited higher continuity and reliability than the satellite one.

The Crustal Movement Observation Network of China (CSMONOC) has been operating in mainland China since the 1990s, and has 260 stable GPS receivers and 170 GNSS receivers to receive signals from GPS and the Beidou satellite system. TEC is inverted based on this ground-based network and widely used to monitor ionospheric disturbances. Dong et al. [14] collected GPS TEC data and analyzed their disturbances around the Yangbi Ms6.4 and Maduo Ms7.4 earthquakes from 21 to 22 May 2021. The temporal and spatial distributions of anomalies in GPS TEC were studied, with positive disturbances mainly detected over the seismogenic region on 5–10 May, and enhanced TEC detected in the conjugate region on 5–6 May from GIM TEC.

To illustrate the LAIC links, a vertical monitoring system was developed. Based on the multi-observations at LESH station (MVP-LAI), with ground vibration, atmospheric pressure, TEC, etc., Chen et al. [15] verified the seismo-LAIC frequency band from 10^{-3} to 10^{-2} Hz before the occurrence of an M6 earthquake in Luxian in Sichuan province, China; this suggests the occurrence of acoustic gravity waves triggered by ground vibration at a relatively low frequency of ~10^{-3} Hz, and of atmospheric resonance caused by micro-cracks at a frequency of ~10^{-2} Hz. Salikhov et al. [16] accumulated observations of near-surface atmosphere and gamma rays, geoacoustic emissions, and temperature in a borehole 40 m in depth, and performed Doppler sounding on a low-inclined radio pass at the Tien Shan Mountain Station in northern Tien Shan; they found bay-like drops of the gamma ray flux 2–8 days before the occurrence of seven M5.0–6.2 earthquakes at a 15–354 km distance. Meanwhile, anomalies in geoacoustic emissions, temperature, and gamma radiation in subsoil rock layers and in the near-surface occurred simultaneously 7–10 days prior to an M4.2 earthquake 5.3 km from the station. These observations confirmed the anomaly's origin in the radon emission and acoustic gravity waves in atmospheric coupling. Wang et al. [17] integrated GPS measurements, the spatiotemporal evolution of the load/unload response ratio, geochemical monitoring, and apparent resistivity, and found that underground resistivity variations reflected the three stages of medium elastic deformation, followed by microdamage with gas seepage, until the stress triggered the earthquake.

In this issue, one paper reported coseismic variations in ground temperature at three stations within 50 km of each other [18]. Significant coseismic geothermal changes of 0.0432 °C were observed at the Xikeer observatory at a depth of 33.38 m, at a distance of 1.4 km from the 2020 Jiashi Ms6.4 earthquake in China, and smaller changes of ~0.0001 °C at the other two stations. Their results showed that the temperature increases at the hypocentral area were higher than expected due to the coseismic stress transfer.

In a monitoring system, the instrument plays an important role, as its accuracy and resolution greatly affect its ability and reliability in distinguishing anomalies. He et al. [19] analyzed the effects of temperature and instrument drift between comparative instruments for geomagnetic field observation. The linear influence of temperature on the comparative data was shown and the relative temperature coefficient changed around the temperature inflection point with a V-type distribution, which was consistent with the laboratory experiments. The long-term time drift between the comparative instruments exhibited a linear pattern. These results could benefit the correction of data agreement in long-term comparative geomagnetic vector observations.

Collectively, this group of articles provides updated information on LAIC processes in earthquake research, the significant LAI anomalies related to different types of earthquakes in different regions, the use of new satellite data, and modern methods in data analysis. We thank the authors for their excellent contributions and hope that this Special Issue leads to new methods of linking earthquake-associated disturbances, as well as helping researchers to obtain more definite precursors for use in short-term earthquake prediction for effective disaster reduction.

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