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Editorial

Editorial of Special Issue "Remote Sensing Observations to Improve Knowledge of Lithosphere–Atmosphere–Ionosphere Coupling during the Preparatory Phase of Earthquakes"

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1. Introduction

We launched this Special Issue with the aim of collecting papers that use satellite data and new methodologies to understand the preparatory phase of medium–large earthquakes in the world. In recent decades, several satellite observations have been used for the precise estimation of co-seismic effects (such as ground displacement estimated using the InSAR technique) and to search for possible precursor signals [1]. Some satellites have been launched for this purpose, such as CSES-01 (China Seismo Electromagnetic Satellite), successfully in orbit since 2 February 2018 [2]. Other satellites especially dedicated to Earth observation (e.g., meteorological observatories and Earth geomagnetic field monitoring) can be used to investigate eventual pre-earthquake pieces of evidence [3]. Several models have been proposed to explain these phenomena with different physical or chemical mechanisms [4,5]. In addition, statistical studies support the existence of seismo-induced phenomena [6,7] as well as single earthquake investigations such as the case of the widely investigated M7.8 Nepal 2015 earthquake [8–10]. This Special Issue addresses these points in a modern geophysical approach, searching for possible signatures of Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) before the earthquake's occurrence, including new methodologies and points of view.

2. Content and Coverage of the Published Papers in This Special Issue

This Special Issue comprises 15 papers and this Editorial, a list of which is provided after Conclusion in section "List of contributions", and a graphical representation is shown in Figure 1. In total, 71 authors from 19 institutions and 8 countries (China, Italy, Spain, Japan, Iran, United Kingdom, United States of America, and Kazakhstan) ensured the success of this Special Issue, and we, the Guest Editors, are grateful to all of them.

Due to the wide coverage of this topic, the papers in this Special Issue can be read and downloaded as an open-access book and are even available as a printed book. So, we suggest the "List of contributions" an order of reading, but each contribution is independent, and the reader can choose a different order to read the contents of this Special Issue.

A graphical representation of the contributions in this Special Issue is provided in Figure 1. For each paper, a figure has been reproduced in a dimension of a stamp. These are the graphical abstracts where available or a significant figure from the content of the specific paper. The authors, the year of publication, and a few words about the content of the paper are reported. The papers have been organised in Figure 1 according to their main layer of investigation. Still, four of them have been placed in a separate box on the left, representing the papers that focused more on multi-layer investigations. Despite this, the papers on the right side also investigated mutual interactions, especially with the lithosphere. Hence, the distinction is not strict, but we think it will help readers to search for specific content and also illustrates that all the layers and their possible investigations have been discussed in the papers in this Special Issue.

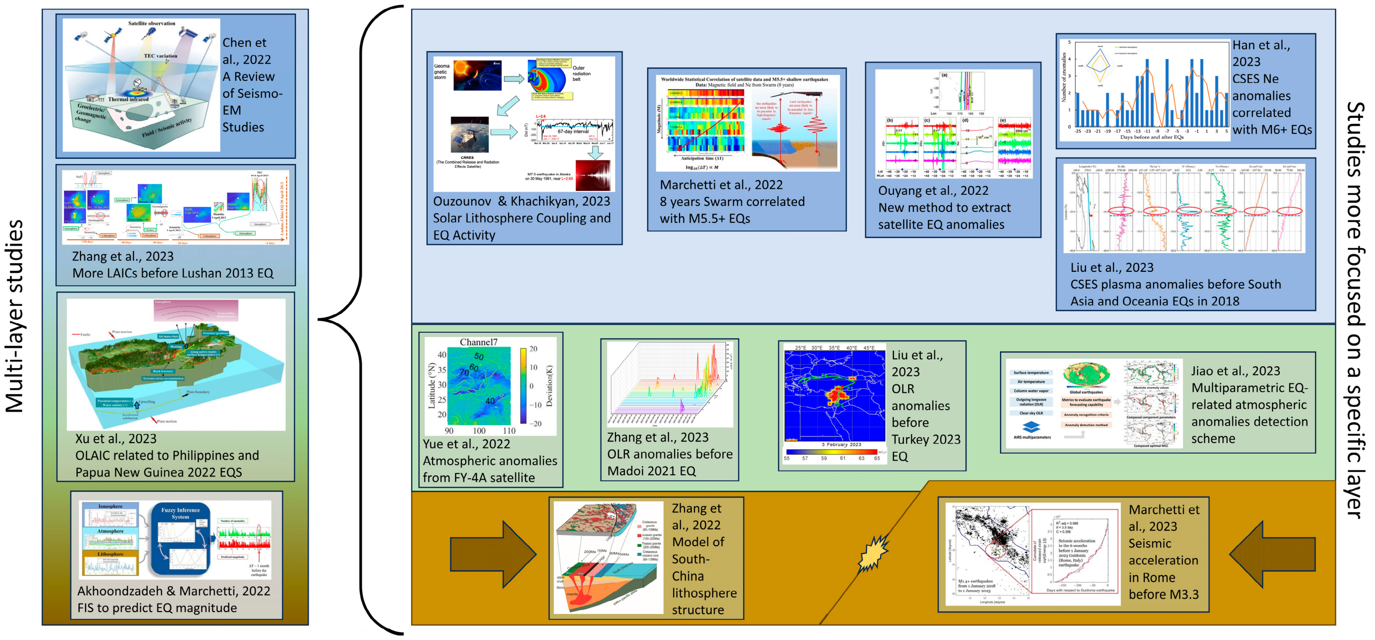

Figure 1. A visual summary of all the contributions in this Special Issue. The studies have been divided into those that focus more on multi-layer investigation (on the **left**) and those that focus more on a specific layer among the lithosphere, atmosphere, and ionosphere. This division is not as strict as dividing all the papers according to whether they are related to the observation of the earthquake or the lithosphere, but we think it may help the reader in providing a quick reference of what to expect to find in each specific paper.

3. Summary of the Content of This Special Issue

A wide and comprehensive review of seismo-electromagnetic pre-earthquake processes has been provided in Paper #1, and it constitutes a very good introduction to the topic of this Special Issue, also providing some future perspectives on how machine learning and artificial intelligence could contribute to the topic. Paper #2 presented a seismic tomography method to reconstruct the lithospheric structure of Southern China. This paper, even if focused on the lithosphere, reminds the LAIC community how important a precise and detailed knowledge of the lithosphere is in the area that the source of events under investigation is located. Paper #3 investigated the lithosphere, atmosphere, and ionosphere six months before a small earthquake of magnitude 3.3 occurred in the surrounding area of Rome (Italy). The only result likely connected to the earthquake in this "Communication" is a seismic acceleration, and for this reason, it is considered a paper that contributed to the lithosphere analysis.

Paper #4 proposes an interesting investigation of infrared data acquired by the Chinese satellite FengYun-4 (FY-4A). The authors searched for possible thermal infrared anomalies eventually related to the M7.4 Madoi (also known as Madou) and M6.4 Yangbi earthquakes that occurred on the same day (21 May 2021) in China. In the last part of the paper, the authors provided a spatio-temporal statistical analysis of thermal infrared anomalies on eleven seismic events in China with a magnitude between M5.0 and M7.4 from March to September 2021, showing a good correlation for nine out of eleven events with an estimated gain of 1.9 with respect to random expectation. A complementary work on longwave infrared anomalies before the Madoi earthquake is provided in Paper #5, showing that the intensity and number of anomalies increased before the mainshock. Paper #6 analysed Outgoing Longwave Radiation (OLR) with an added component: a comparison with tidal stress showing cross-interactions of the geolayers and tidal forces before and after the occurrence of the recent catastrophic earthquake that occurred on 6 February 2023 in Turkey. Finally, Paper #7 provided a method based on machine learning to systematically search for atmospheric multiparametric (surface and air temperature, column water vapour OLR and clear sky OLR) anomalies from remote sensing data of the AQUA/AIRS satellite possibly related to shallow (depth $\leq$ 0 km) global M6+ earthquakes that occurred from 2006 to 2020. The authors provided statistical coefficients of prediction capability divided into three earthquake location types: inland, oceanic, and coastal.

Regarding the ionosphere, Paper #8 proposed a new vision of the earthquake phenomenon from a different point of view, i.e., including a possible "trigger" from geomagnetic activity. In fact, it showed the formation of a new radiation belt with a compatible L-shell before large seismic events. Paper #9 confirmed previous studies reporting significant ionospheric electromagnetic disturbances detected by Swarm satellites before global shallow (depth $\leq$ 50 km) M5.5+ earthquakes and that their anticipation time increases with magnitude. In addition, it was found that the frequency of magnetic anomalies seems higher for anomalies recorded before sea earthquakes compared with land seismic events with slower-frequency magnetic signals. Analogously to the previous study, Paper #10 statistically investigated the CSES-01 Ne anomalies before the M6.8+ global and M6.0+ China earthquakes in the first five years of the mission. Also, the work considers the classification of anomalies and earthquakes as a function of marine/land, magnitude, and hemisphere of occurrence, suggesting that anomalies seem to point from the epicentre toward the equator (southward in the Northern Hemisphere and northward in the Southern Hemisphere). Paper #11 proposed a new method to extract Swarm magnetic anomalies likely related to earthquakes, finding linear polarisation to be a possible seismo-induced feature in good candidates after excluding anomalies resulting from geomagnetic activity and other known sources. Paper #12 investigated the composition of ionospheric plasma before four strong earthquakes in Southeast Asia and North Oceania, identifying promising pre-earthquake ionospheric disturbances.

Finally, we have three contributions in this Special Issue that explicitly investigated possible interactions between the lithosphere, atmosphere, and ionosphere. In particular, Paper #13 investigated six months of data from the three geolayers before the Lushan (China) 2013 earthquake. It identified three possible LAICs 130 days, 48~40 days, and 20~6 days before the mainshock, which are explainable by different mechanisms due to the involved parameters, suggesting that different LAIC models are not in contrast to each other but describe different ways of coupling. Paper #14 proposed the use of a continuous logic system known as Fuzzy (instead of Boolean) to predict the incoming earthquake magnitude, through analysing the anomalies recorded in the lithosphere, atmosphere, and ionosphere, finding promising indications around one month before the five investigated strong earthquakes. Finally, Paper #15 investigated two large earthquakes on the sea coast, proposing a new framework of LAIC: Ocean–Lithosphere–Atmosphere–Ionosphere Coupling (OLAIC). The paper identified an important role of the oceanic mass in influencing the anomalies and how they propagate to the atmosphere up to the ionosphere.

4. Conclusions

An important point provided by different contributions in this Special Issue is the effect of geomagnetic activity. We would clarify that the exclusion of the anomalies likely induced by geomagnetic disturbances as carried out, for example, in Papers #9–11 is not in conflict with the new vision proposed by Ouzounov and Khachikyan in Paper #8 as this second phenomenon would be a trigger for the earthquake, and the source of the ionospheric anomalies produced by "classic" LAIC would be the nucleation source of the earthquakes or their preparation area in the lithosphere. However, excluding the geomagnetic active time could obscure critical phenomena induced by the lithosphere in the ionosphere, even though, due to more complex ionospheric conditions, it is undoubtedly more difficult to distinguish between external and possible internal disturbance induced by an earthquake. With this Special Issue, several contributions statistically confirmed the existence of pre-earthquake anomalies, and specific papers investigated possible patterns of anomalies (see Papers #13, #15), suggesting several LAIC models. It is still unclear why several earthquakes show different patterns, and this needs to be a major research direction in the near future. Some suggestions from this Special Issue also suggested that tectonic settings and water (ocean) may play a major role (e.g., Paper #9, #15) but are insufficient to explain the different results completely.

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List of Contributions:

Paper number #:

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Studies about lithosphere

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Studies about atmosphere

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