



Review

# Recent Advances and Challenges in the Seismo-Electromagnetic Study: A Brief Review

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**Abstract:** Due to their potential application in earthquake forecasting, seismo-electromagnetic phenomena were intensively studied for several decades all over the world. At present, measurements from ground to space have accumulated a large amount of observation data, proving an excellent opportunity for seismo-electromagnetic study. Using a variety of analytical methods to examine past earthquake events, many electromagnetic changes associated with earthquakes have been independently reported, supporting the existence of pre-earthquake anomalies. This study aimed to give a brief review of the seismo-electromagnetic studies preceding earthquakes and to discuss possible ways for the application of seismo-electromagnetic signals at the current stage. In general, seismo-electromagnetic signals can be classified into electric and magnetic changes in the lithosphere and perturbations in the atmosphere. We start with seismo-electromagnetic research in the lithosphere, and then we review the studies in the lower atmosphere and upper atmosphere, including some latest topics that aroused intense scholarly interest. The potential mechanisms of seismo-electromagnetic phenomena are also discussed. It was found that although a number of statistical tests show that electromagnetic anomalies may contain predictive information for major earthquakes, with probability gains of approximately 2–6, it is still difficult to make use of seismo-electromagnetic signals efficiently in practice. To address this, finally, we put forward some preliminary ideas about how to apply the seismo-electromagnetic information in earthquake forecasting.

**Keywords:** seismo-electromagnetic phenomena; precursors; earthquake forecast



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## 1. Introduction

Earthquake forecast is one of the most challenging scientific issues. The key to earthquake forecasting is to find the precursors that help predict impending earthquakes [1]. Science presented the great unsolved scientific mysteries of our time in the Special Issue marking the journal's 125th anniversary. Whether earthquake precursors that can help in prediction exist is one of them. To date, there have been many studies on earthquake forecasts, and most of them adopt a catalog-based probabilistic approach [2–5]. Although a certain amount of precursory information is available in earthquake catalogs [6], earthquake forecasting, especially short-term prediction, is still far from adequate [7,8]. Nevertheless, non-seismological approaches may provide additional useful information and broaden the knowledge for prediction [9,10]. The content of earthquake precursors includes many physical parameters such as mechanical deformation, gas emissions, groundwater level variations, ground temperature variations, fluctuations of the electromagnetic field, and so on. The detection of electromagnetic perturbations before fault ruptures was proposed as a useful way to monitor crustal activities and it has been proven to be a promising

phenomenon preceding earthquakes. To date, there have been many reports on electromagnetic field changes associated with earthquakes in a very wide frequency range from megahertz to quasi-DC [11–13]. These phenomena, known as seismo-electromagnetic phenomena, have been intensively studied for some decades [12,14–17] all over the world, from measurements on the ground to space detection. Based on the observation instruments in different spheres of the earth, seismo-electromagnetic phenomena can generally be classified into electric and magnetic changes in the lithosphere (measurement on the surface and/or underground), perturbations in the lower atmosphere (measurement above the surface and below the ionosphere), and the upper atmosphere (partially ionized or fully ionized regions).

## 2. Seismo-Electromagnetic Phenomena in the Lithosphere

The seismo-electromagnetic phenomena in the lithosphere are commonly recorded by passive ground-based observations of electric fields and/or magnetic fields [18]. Early seismo-electromagnetic studies measured perturbations of the electric potential difference between two electrodes buried in the ground. The case study of an M5.6 earthquake (depth = 17 km) was reported by Miyakoshi [19]. The observation carbon rod electrodes were set at an epicentral distance of 3 km. They found that potential differences changed clearly prior to the earthquake. This kind of signal was known as the seismic electric signal (SES). The most famous SES may be the one reported from Greece by Varotsos, Alexoupoulos, and Nicomos (VAN) [20–22]. They observed anomalous electric signals on both short (10–200 m) and long (1–3 km) dipoles with electric field amplitudes of up to 20  $\mu\text{V}/\text{m}$  and durations of a few minutes prior to several moderate–large earthquakes [21]. Varotsos et al. [22] issued some predictions of earthquakes since 1990 using the SES. These predictions soon drew lots of attention and aroused active debates (see details in Vol. 23 Issue 11, *Geophysical Research Letters*, 1996). In addition to seismic electric signals in Greece, there are some examples of SES observed in various earthquake-prone areas worldwide [23]. Recently, the natural time analysis of geoelectric field and seismicity changes were combined to study the precursory SES activity [24,25].

Magnetic field changes associated with earthquakes were also observed. One of the most promising candidates is the measurement of ultralow frequency (ULF) electromagnetic phenomena (less than 1 Hz), because of their deeper skin depths [12,14,15]. To date, now, a large number of ULF electromagnetic phenomena associated with earthquakes have been reported [10,11,26–41]. One of the most well-known ULF seismo-magnetic phenomena was the magnetic field changes related to the Ms7.1 Loma Prieta earthquake that happened on 18 October 1989, reported by Fraser-Smith et al. [40]. They found that the amplitude of ULF magnetic fields, especially at the frequency of 0.01 Hz, began to increase significantly about two weeks before the main shock. Due to the limitations of observation equipment, only the averaged amplitude of the magnetic field in the horizontal component was registered, which made it very difficult to analyze detailed waveforms for further study. Other case studies of the 1988 Spitak earthquake (M6.9) and the 1993 Guam earthquake (M 8.0) reported by the Russian group [41] and the Japanese group [42], respectively, also showed potential changes in the magnetic field before earthquakes. Hattori et al. [43] analyzed the geomagnetic data associated with the 1997 Kagoshima earthquakes (M6.5 and M6.3). By employing several reference stations, they eliminated the influence of global ionospheric disturbances and detected anomalous changes in the magnetic field, possibly related to the two large earthquakes.

The 2000 Izu earthquake swarm was another important case for seismo-electromagnetic study, as there were both electric and magnetic measurements in the vicinity of the epicenters. By analyzing these data simultaneously, Uyeda et al. [44] reported very robust results for seismo-electromagnetic phenomena. The ratio of electric potential between the two different observation dipoles at the frequency of 0.01 Hz has shown clear anomalous changes about two months before the earthquake swarm. These anomalies were unique against a 3-year-long background. The principal component analysis (PCA) of geomagnetic

data also showed anomalies before the swarm. The electromagnetic phenomena associated with the 2000 Izu earthquake swarm may be one of the most plausible results, as many reports have been published using different kinds of methodologies, such as PCA [44,45], singular spectral analysis (SSA) [46], fractal analysis [31,47,48], spectral density analysis [49], and direction-finding analysis [26]. In general, in addition to the above methods used for seismo-electromagnetic anomaly recognition, there are also other methods such as polarization analysis [49,50], wavelet analysis [51], diurnal variation analysis [35], and so on.

Whether these magnetic anomalies contain precursory information and how they can improve the forecasting of sizable earthquakes were not fully discussed. A sensitive geomagnetic network was installed in Kanto, Japan, to verify and clarify the ULF electromagnetic phenomena preceding large earthquakes. Plenty of data associated with moderate-large earthquakes have been accumulated. Researchers have analyzed the geomagnetic data observed during the past decade in the Izu and Boso Peninsulas. Hattori et al. [52] conducted some statistical studies of ULF seismo-magnetic phenomena in these areas and verified the correlation between ULF magnetic anomalies and sizeable local earthquakes. Previous studies showed that the earthquake-related magnetic signals may decrease with the epicentral distance and increase with the magnitude of the earthquake event [12,13,30,53], suggesting that augmenting earthquake forecasting with magnetic anomalies might involve their distance and magnitude dependences. The performance of trial forecasts based on ULF geomagnetic anomalies from the Kakioka Geomagnetic Observatory was evaluated by Han et al. [13]. They used the deep-night 0.01 Hz band data to avoid man-made noise, and the results showed that approximately 20% of the target earthquakes were preceded by the hypothesized type of magnetic anomaly related to the earthquake's occurrence. The authors rejected the concern that the successful forecasts were aftershocks and post-seismic disturbances of earthquakes, by demonstrating that trial forecasting based on recent seismicity is no better than random. Recently, Han et al. evaluated the optimal parameter for earthquake forecasting in the Kanto region, Japan [10], by utilizing long-term magnetic data observed in the region during the period 2000–2010 and applying Molchan's error diagram [54,55].

In the United States, a research project named QuakeFinder (QF) is carried out by the aerospace company Stellar Solutions. The goal was to develop a methodology to detect and analyze pre-earthquake electromagnetic (EM) signals in order to produce earthquake forecasts. As of April 2018, the array comprised 168 stations, most located in California, along the San Andreas Fault, and some located in Peru, Chile, Greece, and Sumatra [56]. The researchers discovered increases in ultra-low frequency magnetic pulse activity starting two weeks before the nearby seismic events in some cases and disappearing after the event [57]. The discovery is consistent with the statistical results of ULF seismo-magnetic phenomena in Japan [13]. In addition to the single earthquake's electromagnetic signals, some studies used 15+ years of data to statistically test whether electromagnetic signals do exist before significant earthquakes (close to the magnetometer stations) [58,59]. The algorithmic framework for investigating the temporal relationship of magnetic field pulses and earthquakes has been proposed, and some studies of searching for pre-earthquake signals such as long-term air ion monitoring have been investigated [58]. Recently, the case-control study on a decade of ground-based magnetometers in California conducted by QF and Google revealed signals in the frequency domain of 0.016–25 Hz before earthquakes [59], and the artificial intelligence method used can improve the efficiency and accuracy of anomaly detection. When compared to the statistical results of papers by Han et al. [13], the above results added to the evidence that there is a legitimate electromagnetic signal prior to medium-to-large earthquakes. However, more work needs to be conducted to refine the algorithms and to characterize and remove the known noise sources.

In China, a mobile geomagnetic monitoring network has been established in the last 20 years, covering most of the country's potential earthquake zones, and the geomagnetic anomaly provides very important support for the prediction of earthquake location [60]. Some research about the pre-seismic anomaly characteristics of geomagnetic changes was

reported. For example, the amplitude ratio of geomagnetic harmonic waves was significantly enhanced before the Ms5.5 Eryuan earthquake in 2013 [61], and the geomagnetic and geoelectric data show abnormal variations before the Wenchuan earthquake [33]. There were also some reports about the apparent resistivity changes before and after earthquakes [62–65]. The apparent resistivity change revealed by magnetotelluric (MT) measurements is a well-accepted technique, and some tests on the relation between earthquakes and apparent resistivity changes were revealed by repeated MT methods [66,67]. Further rigorous analysis based on continuous MT observation is required to ensure the reliability of the results.

On the other hand, some researchers claim that there were no electromagnetic changes prior to earthquakes. For example, Kappler et al. [68] analyzed the geomagnetic data associated with the 2004 Parkfield Earthquake (September 28, Mw 6.0, depth 8 km) by several methods, and they found no clear change of magnetic fields before the main shock. At present, there are still active debates in the geophysical community on seismo-electromagnetic phenomena [69–71].

### 3. Seismo-Electromagnetic Phenomena in the Lower Atmosphere

The seismo-electromagnetic phenomena in the lower atmosphere include atmospheric electric field perturbations, earthquake lights [72,73], thermal anomalies [74–76], and so on. The anomaly of atmospheric electric fields, possibly associated with earthquakes, is an interesting seismo-electromagnetic phenomenon in the lower atmosphere. There are some independent observations of earthquake-related anomalies of the atmospheric electric field after the Ms 7.8 Tangshan earthquake in China. To verify the reliability of the atmospheric electric precursors, one research group of the Institute of Geophysics has made continuous observations and carried out some studies on this topic since 1976. They obtained empirical relationships between the anomalies of the atmospheric electric field and earthquakes, and applied them to some earthquake prediction tests [77]. Recently, anomalous negative signals observed by ground-based atmospheric electric field instruments under fair weather conditions were considered a novel earthquake prediction approach [78]. One of the best-documented observations of earthquake lights is from Japanese earthquakes, where bright lights at the ground level were photographed from 20 to 200 m in diameter with a duration from 10 s to 2 min, restricted to mountain summits in a quartz-diorite faulted rock [73]. Luminous phenomena were reported, starting at approximately nine months before the 6 April 2009 earthquake and continuing until approximately five months after the shock [72]. A statistical study of lightning activity and  $M \geq 5.0$  earthquakes in the Taiwan region showed lightning activities tending to appear around the forthcoming epicenter and being enhanced a few days before shallow land earthquakes [79]. Possible explanations about earthquake lights include ultrashort-period air oscillations and generation of potential differences by the piezoelectric effect [80].

The thermal anomalies include atmospheric temperature, brightness temperature, surface latent heat flux (SLHF), outgoing longwave radiation, thermal infrared spectral range (TIR), etc. For example, the preseismic anomalies of SLHF were observed by Qin et al. [81], and they reported surface temperature anomalies before two major earthquakes [82]. Ouzounov et al. [76,83] reported thermal radiation anomalies associated with some major earthquakes, showing that infrared signals were observed near the epicenter areas and stayed from several hours to a few days. Genzano et al. [84] adopted the broadly used robust satellite technique data analysis methodology to identify the significant sequence of thermal anomalies acquired by multi-functional transport satellite (MTSAT) over Japan, confirming a noncausal correlation between anomalies and earthquakes. Tramutoli et al. [74] proposed a statistically well-founded definition of TIR anomalies for satellite TIR surveys. A probability gain of up to 3.7 was achieved as far as only significant sequences of TIR anomalies preceding earthquakes were considered. In practice, the remote sensing of thermal infrared anomalies can be affected by cloud coverage [85], and sometimes it is

hard to discriminate thermal contributions that are possibly connected to seismic activity in cloudy conditions [86].

#### 4. Seismo-Electromagnetic Phenomena in the Upper Atmosphere

The seismo-electromagnetic phenomena in the upper atmosphere are usually detected by using satellite observations and/or ground-based transmitter signals [17,87–91]. Since the 1990s, Hayakawa et al. continuously published some research papers that confirm the correlation between very low frequency (VLF) (3–30 kHz)/low frequency (LF) (30–300 kHz) radio signals and earthquakes [42,92–94]. They found significant shifts in the terminator times and phase before the main shock for the signal's propagation characteristics. Their statistical study suggested that the VLF/LF ionospheric perturbation in terms of amplitude (trend) show a statistically significant precursory behavior (3–5 days before the earthquake), and the enhancement of dispersion (fluctuation) is clearly visible for  $M \geq 6.0$  earthquakes. The statistical results also confirm and support previous results by Rozhnoi et al. [95]. The VLF from the direction of the source of earthquakes was reported by Asada et al. [96], though without establishing statistical significance as 'earthquake-preceding phenomena'. Five megahertz-sampling rates of VLF recorders were developed in Japan, and Nagao et al. determined the source location using the arrival time difference [97]. They examined the data for 5 days before and 1 day after an earthquake on 25 June 2017, and found seven similar pulses located within 20 km of the hypocenter. There was no light in that time window. There are also two sites observing VLF pulses, ultra-low frequency, and atmospheric electric fields at Kuroshio-town in Kochi, Japan [98]. In the past ten years, the application of ground-based and satellite signals in seismic monitoring was developed in China, and VLF/LF artificial source signal monitoring has become one of the main technical means of seismic disturbance analysis [99,100].

The French satellite DEMETER was the first seismo-electromagnetic satellite devoted to investigating seismo-electromagnetic phenomena. The pre-earthquake disturbances in the ionosphere were observed by the DEMETER satellite. Parrot et al. [101] and Sarkar et al. [17] demonstrated several examples of variations in the plasma parameters recorded by DEMETER satellites over the epicenters of earthquakes before their occurrence. Zeng et al. [102] analyzed the DEMETER data and their results indicated that the electron concentration, temperature, and oxygen ion changed rapidly 5 days before the Wenchuan earthquake. Akhoondzadeh et al. [103] investigated the electron and ion density variations before strong earthquakes ( $M > 6.0$ ) using DEMETER and GPS data. They found that the anomalous deviations prior to earthquakes had different signs from case to case, and their amplitude depended on the magnitude of the earthquake. There were positive and negative anomalies in both DEMETER and GPS-TEC data for 1–5 days before all the studied earthquakes during quiet geomagnetic conditions. These results were verified by subsequent studies [104–109], suggesting that the ionosphere might have some response prior to large earthquakes. Additionally, the VLF field intensity observed by the DEMETER satellite was found to be statistically significant [110]. The field intensity was found to take a minimum at the time when the satellite was closest to the epicenter of the upcoming earthquake. The pre-seismic changes were observed by satellite only after stacking many cases due to the noises.

After the DEMETER satellite ended in 2010, the European Space Agency launched the Swarm satellite in 2013. Marchetti et al. [111–113] reported the seismo-ionospheric anomalies from Swarm satellite data around the time of the strong earthquake and the worldwide statistical correlation of eight years of satellite data with  $M5.5+$  earthquakes. The precursory worldwide signatures study found some clear concentrations of electron density and magnetic anomalies from more than two months to some days before the earthquake occurrences, and the epicenter location was related to the detected anomalies [112,114]. There were also some reports about the detection of ionospheric signals in the region magnetically conjugate to the earthquake zone [115].

The China Seismo-Electromagnetic Satellite (CSES) mission, launched in 2018, is the first satellite in China to measure seismo-associated phenomena in the near-Earth electro-

magnetic environment, having a lot of application prospects in the study of seismology, geophysics, space sciences, and so on [91]. This was planned to operate for 5 years. During its five-year operation time, CSES records many kinds of data, such as multi-band waveform and the spectra of electric and magnetic fields; in situ plasma parameters (including the densities and temperatures of electrons and ions); electron density profiles and tomography; energetic particle flux and energy spectra. Many reports showed that the performance of the payload can satisfy the requirement of the scientific objectives of the mission [116–122]. Next, we discuss some of the last published results. Yan et al. [123] reported the observations of unusual ionospheric irregularities by CSES before four earthquakes. Zhang et al. [65] investigated ionospheric perturbations in very low-frequency transmitters recorded by CSES, and they claimed that the perturbations to the satellite were more likely related to the overlapped electric field in the earthquake preparation area. An investigation into the characteristics of pre-earthquake ionospheric effects related to four shallow-focus earthquakes in Indonesia was conducted by Song et al. [124]. Significant positive perturbations 1–7 days before earthquakes were revealed. Recently, Zhu et al. [125] published the CSES data analysis of electron density (Ne) and temperature (Te), to support a temporal-spatial correlation between the earthquakes and the observation of positive Ne variations/negative Te variations before the seismic events. Xiong et al. [126,127] and Zhong et al. [128] analyzed the pre-earthquake electromagnetic, ionospheric, or space electric field perturbations by machine learning. However, similarly to other reports on earthquake precursors, the anomalous variation of parameters has not been revealed in all studied earthquakes, and the perturbations seem to occur at various temporal and spatial distances to the earthquake. Other possible sources of the observed anomalies in the ionospheric and geomagnetic dynamics driven by solar activity may not be fully ruled out. On the other hand, the satellite orbits the earth at a high speed, and the observed anomalous variations cover a large zone even up to a 2000 km range. Overall, due to the relatively low resolution power, the applications based on the satellite may face a challenge of the better constraint size and location of earthquake preparation areas. Even though the reported analyses from CSES are not conclusive now, the second mission of the CSES series, CSES-02, will be launched in 2023. It will have the same multi-instrumental payload and similar orbital parameters as the first satellite, but will allow for reducing the revisit time of the same geographic region. The large number of observations will help in studying the frequencies, amplitudes, and characteristics of ionospheric perturbations related to earthquakes and generation mechanisms.

Among the seismo-electromagnetic phenomena in the ionosphere, anomalous changes in the ionospheric total electron content (TEC) are one of the most frequently reported phenomena preceding large earthquakes [129–140]. TEC is a measure of integrated density along a straight line between the satellite and ground GPS stations. One TEC unit (TECU) is equal to  $10^{16}$  electrons/m<sup>2</sup>. Various GPS stations can be utilized for ground-based TEC observations, including the International GNSS Station (IGS), the Crustal Movement Observation Network of China (CMONC), the GPS Earth Observation Network (GEONET), and so on. Two-dimensional TEC maps derived from ground-based observations are widely used, such as the data from the Center for Orbit Determination of Europe (CODE), and they are regarded as one of the most precise available Global Ionosphere Maps (GIM) and treated as a high-accuracy reference [141]. In contrast, space-borne TEC data are rare due to the lack of processing TEC data in the satellite platform. However, satellite systems can overcome the problem that ground stations are not available in the ocean [142], and act as a supplement to GIM-TEC.

The method to detect anomalies in the ionosphere includes the mean/median statistical envelope method [143,144], cubic fit analysis [140], pattern recognition analyses [139,145,146], etc. The mean/median statistical envelope methods use the N-day mean or median techniques to detect anomalies, becoming a common and popular method. However, there is no clear justification for the selection of N-day used in studies, and the method faces the challenge of accounting for TEC changes owing to different sources such

as space weather and seismic effects. The confidence level, which defines the normal ionospheric variations, also needs to be ascertained in the mean statistical envelope methods. The cubic fit analysis was adopted by Heki to obtain the anomalies about five TECU several hours/minutes before the 2011 Tohoku earthquake. The study indicated that similar pre-seismic TEC anomalies were seen in the 2010 Chile earthquake (Mw8.8), the 2004 Sumatra (Mw9.2), and the 1994 Hokkaido (Mw8.3) earthquake, but not in smaller earthquakes [140]. The anomalies even increased to 10 TECU before the Sumatra earthquake (Mw9.2). Some scholars point out that it might yield erroneous interpretations about anomalies [147,148]. Iwata and Umeno introduced the correlation analysis method and detected the pre-seismic TEC anomalies before the 2011 Tohoku earthquake and the 2016 Kumamoto earthquake, whose characteristic patterns do not depend on the choice of extrapolation functions for nonlinear regression [149,150].

In the research on seismo-electromagnetic phenomena in the ionosphere, the effects of other sources should be considered because the TEC perturbations are the integrated product of space weather and other kinds of sources such as earthquakes, tsunamis, volcanic eruptions [151], etc. The choice of space weather indices could be justified based on the location, depending on the data availability and station coverage [152]. When defining the space effect levels, some consensus values should be used based on the authoritative parameters from space physics, and all relevant space weather indices should be verified for quiet or low activity in order to ensure the space-related influences on ionospheric perturbations [142]. Some technological methods were developed to eliminate the effect of space weather activity without the use of arbitrary space indices to detect pre-earthquake TEC anomalies, including wavelet analyses [153], singular spectrum analysis [151,154], etc. In addition, demonstrating the three-dimensional structure of ionospheric disturbances can better reshape the morphological characteristics [155,156]. In general, it is very important to establish a reliable normal background field, exclude the interference effects, and identify reliable anomalies related to seismic activity [157].

In the review report of Pulinets et al. [16], the total electron content (TEC) over the epicenter usually increased or decreased for approximately 4–6 h on 1–5 days before earthquakes, and the TEC anomalous amplitude was related to the earthquake magnitude and local time, ranging from  $\pm 30\%$  to  $\pm 100\%$ . Meanwhile, some statistical investigations into the relationship between earthquakes and TEC anomalies were performed. Liu et al. [158] statistically examined the ionospheric plasma frequency (or electron density) in ionograms recorded by a local ionosonde and found that the critical frequency of the F2-peak, foF2, significantly decreased 1–5 days prior to 13  $M \geq 6.0$  earthquakes in Taiwan during the period 1994–1999. Kon et al. [159] analyzed the TEC anomalies before the earthquakes in Japan and found that the positive TEC anomalies were usually observed 1–5 days before  $Mw > 6.0$  earthquakes with a focal depth of less than 40 km. Hirooka et al. [135,136] found that the electron density in the F-layer decreased by approximately 6 TECU for 3 days before the earthquakes in the low geomagnetic latitudinal regions. Chen et al. [160] gave the statistical evidence that the electron density decreased 1–5 days before  $M \geq 6.0$  earthquakes in mainland China. Zhu et al. [161] found that the occurrence rates of TEC disturbances within 5 days before the inland earthquakes were higher than those after earthquakes, and the biggest difference of spatial distribution lies in the epicenter area. He and Heki [162] found possible ionospheric electron density enhancement detected before the large earthquakes by analyzing the vertical total electron content data observed by GNSS stations near epicenters, and these pre-seismic signals were mostly within 5 TECU. It is quite interesting to find that the TEC anomalies prior to large earthquakes can be either positive (Japan region) or negative (Taiwan region). In addition, TEC variability in seismically active regions is greater than in non-seismically active regions [142].

There are also some studies that focused on the changes associated with earthquakes in the magnetosphere, for example, a study of charged particle precipitation from van Allen radiation belts during a land earthquake and an ocean earthquake was reported [163]. Particle bursts (PBs) were found to be accumulated only around the earthquake day,

reaching their maximum on the day of the earthquake and with a complete absence of such events on days away from the event day. Some statistical studies showed significant bursts of high-energy particles observed by SOHO satellite in the magnetosphere before earthquakes [164]. In general, since the magnetosphere is mostly affected by solar activity, it might be more complicated to study seismo-electromagnetic phenomena there.

Regarding the preparation zone of the earthquake, the most widely used equation is  $R = 10^{0.43M_w}$ , where  $R$  is the radius (km) and  $M_w$  is the magnitude [165]. The equation gained only used 24 earthquake events and did not account for ionospheric anomalies, although the authors concluded that it could be used to estimate the effective precursor manifestation zone [165]. Based on data from Benioff (i.e., crustal) strains, Bowman et al. found that the exponent in the equation should be increased for  $M_w \geq 6.0$  earthquakes as they rupture the entire crust [166], so using the equation straightforwardly might result in errors. In addition, most scholars agreed that pre-earthquake TEC anomalies are most significant close to the epicenter [167], while other studies reported that they are greatest at the edge of the preparation zone [168]. Liu and Xu [169] revealed that the most perturbed ionospheric regions were located south of the epicenter and the zone was greater than 1000 km. Consequently, arguments have been put forward that earthquake preparation on the ionosphere/magnetosphere could have a larger radius [170]. The most complicated part of earthquake forewarning to use the ionosphere/magnetosphere perturbation is the large preparation zone based on the anomalies [142], so the surface observation should be combined to constrain potential earthquake locations.

## 5. Possible Mechanisms of Seismo-Electromagnetic Phenomena

To understand the mechanisms of seismo-electromagnetic phenomena in the lithosphere, various experiments and simulations have been conducted [171–181]. The mechanisms proposed for the generation of electromagnetic signals include: electrokinetic effects [182,183], piezo-electric effects [184], piezomagnetic effects [185], triboelectric effects [186], induction effects [187,188], microfracture effects [89,189], and P-holes [190–193]. For most of these models, electromagnetic signals are more or less related to stress or strain changes. The numerical simulation of coupled seismic and electromagnetic waves in multilayered porous media were developed to explain the coseismic electromagnetic signals [194,195]. However, field observations can hardly record strong, clear co-rupture signals [11]. The selectivity phenomenon of SES might explain why some electromagnetic anomalies are observed before earthquakes and others are not [175]. One of the most studied issues in the physics of earthquake precursors is the role of seismic-induced radon exhalation in the generation of electromagnetic disturbances. It has been proposed that the enhancement of the total rock surface due to failure would increase the emissions of radon and other gases from grains and facilitate migration. This would be in agreement with the enhancement of radon concentration observed in aftershocks and some laboratory experiments [196] which showed the growth of radon emissions of granites under compressional stress.

Although a number of studies have discussed possible mechanisms of pre-earthquake disturbances in the atmosphere [129,192], the generation process is still not well understood. Most hypotheses were based on the propagation of EM waves, which originated from the ground due to certain mechanisms such as piezo-electric effects [80], the triboelectric effect [186], and positive holes (P-holes) [190]. Pulinets and Boyarchuk [129] discussed a model based on the emissions of radioactive gases or metallic ions. Pulinets and Ouzounov [197] proposed a unified concept for the pre-earthquake atmospheric disturbances, named the “Lithosphere–Atmosphere–Ionosphere Coupling (LAIC)” model. According to the LAIC model, radon can generate local ionization in the lower layers of the atmosphere that can facilitate water vapor condensation, leading to the release of latent heat exhalation (that could explain thermal fluctuations) and local variation of the conductivity, thereby impacting the electric circuit over the earthquake preparation zone and generating the observed seismo-associated ionospheric anomalies. Harrison et al. [198] argued that enhanced ionization in the lower atmosphere would increase the vertical cur-

rent flow in fair weather, which might help understand earthquake–cloud coupling [199] through the global atmospheric electric circuit [200]. Kuo et al. [201,202] performed some numerical simulations and showed ionosphere plasma bubbles and density variations induced by pre-earthquake rock currents and associated surface charges. Other mechanisms including the atmospheric gravity waves (AGWs) triggered by gas releases or thermal anomalies [203] and electric current of seismic origin due to the convective transfer of charged soil aerosols [204,205] can also explain pre-earthquake disturbances in the atmosphere to some extent [206]. The coseismic lower atmospheric and ionospheric perturbation triggered by seismic waves through acoustic and/or gravity waves was verified for the M9.0 Tohoku earthquake [207].

Some researchers present a potential physics-based research approach that takes into account the interaction among observation, data processing methodology, and physical model [208]. The coupling between the lithosphere and atmosphere requires multiple instruments installed on and near the Earth’s surface and space satellites. Recently, a novel system for monitoring vibrations and perturbations in the lithosphere, lower atmosphere, and upper atmosphere was established in the countryside of Leshan City, Sichuan Province, China, in 2021 [209]. The system combines all kinds of observation instruments collecting data from the lithosphere and atmosphere, to gain abundant measurements across different layers preceding earthquakes. As a novel systematic observing platform, it can provide researchers with more information about the preparation process for forthcoming earthquakes in the future.

## 6. Applications of Seismo-Electromagnetic Signals in Earthquake Forecasting

There are some methods to evaluate whether the seismo-electromagnetic phenomena contain precursory information, among which the receiver operating characteristic (ROC) curve and Molchan’s error diagram are the two most widely used [160,210]. Statistical tests have shown that the electromagnetic anomalies may contain predictive information for major earthquakes, with probability gains of approximately 2–6 [74,160,210]. In addition to seismo-electromagnetic phenomena, other precursors were also observed. A representative event of which various geophysical precursors were documented is the 2011 Tohoku earthquake (Mw 9.0) [38,140,211–220]. Locations of seismo-geomagnetic anomalies in spatial distribution showed a good correlation with the epicenter of the earthquake [38,220]. These spatiotemporal results were consistent with those obtained from other independent observations such as the groundwater level and GPS displacements [219]. The related precursory characteristics of the earthquake are listed in the Table 1 below. The coupling of multiple pre-earthquake phenomena provides new insights on earthquake preparation process, suggesting that incorporating multi-geophysical information might be a possible means of improving earthquake forecast.

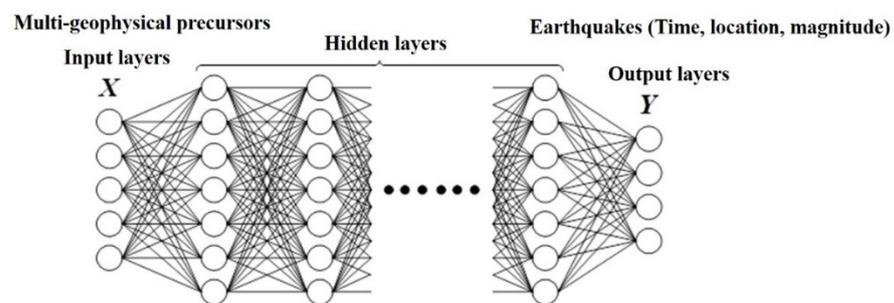
**Table 1.** Representative precursory characteristics before the 2011 Tohoku earthquake.

Observation	Leading Time	Characteristic	Reference
Seismic activity	23 years	Seismic quiescence in rupture region	(Katsumata, 2011 [211])
	6 years	Decade-scale decrease in b value	(Nanjo et al., 2012 [212])
	A few months	Seismicity exhibited distinct minima	(Sarlis et al., 2013 [213])
	1 month	Foreshock sequence and slow slip	(Kato et al., 2012 [214])
Deformation	2 months	Crustal movement changes	(Chen et al., 2014 [215])
	1 month	Slow slip event	(Ito et al., 2013 [216])
	1 month	GPS surface motion	(Hattori et al., 2014 [217])
Fluid	3 months	Groundwater level decrease	(Orihara et al., 2016 [218])
Geomagnetism	2 months	Geomagnetic diurnal variation changes	(Han et al., 2016 [219])
Ionosphere	40 min	TEC enhancement	(Heki, 2011 [140])

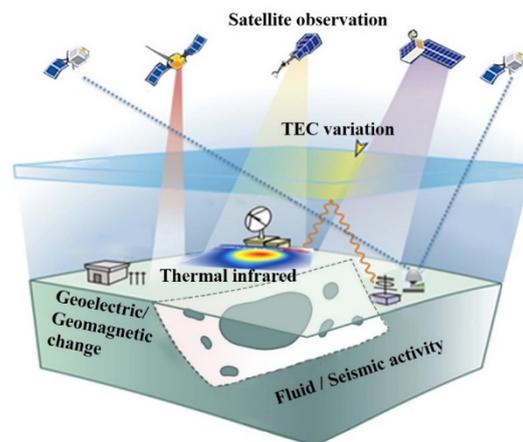
As the earthquake process is rather complex, the earthquake preparation phase cannot be easily monitored using a single approach. To improve the reliability of earthquake forecasting, the two following models that could integrate precursory information from different approaches were proposed. One is the earthquake model that combines self-exciting and mutually exciting elements from the Hawkes process [62,221,222]. The core idea of this combined model is that the status of the earthquake event at present is controlled by the event itself (self-exciting) and all the external factors (mutually exciting) in the past. The conditional intensity function is a time-varying point process with rate  $\lambda(t)$  written as

$$\lambda(t) = \mu + \lambda_s(t) + \lambda_E(t) \quad (1)$$

where  $\mu$  represents the constant background rate,  $\lambda_s(t)$  is the self-exciting term that models the information from past seismic events, and  $\lambda_E(t)$  is the external excitation term that models the information from non-seismic observations such as the seismo-electromagnetic anomalies. The other is a network model based on machine learning, where multi-geophysical precursor information is taken as the input layer, and the factors of earthquakes such as time, location, and magnitude are taken as the output layers, as shown in Figure 1. Some important features in discriminating pre-earthquake perturbations may be established by the machine learning network. Overall, the forecast model combining the integrated observations (shown in Figure 2) is a worthwhile study in the future.



**Figure 1.** Earthquake forecast network based on machine learning.



**Figure 2.** Multi-geophysical observation system for earthquake modeling and forecasting (modified from [83]).

## 7. Conclusions

As a kind of potential precursor of the earthquake, the seismo-electromagnetic phenomena were paid considerable attention and play a crucial role in the study of seismic hazards, although there are some controversial problems deserving further study. After reviewing the seismo-electromagnetic study in the lithosphere, the lower and upper atmosphere, and discussing the possible mechanisms, we present the related achievements

and the potential applications in implementing seismo-electromagnetic phenomena for earthquake forecasting. The challenges include the variability of the detected intensity, frequencies, spatial, and temporal distribution around the epicenter, etc. Since the electromagnetic signal contains certain pieces of precursor information, achieving a better understanding of the physics of seismo-electromagnetic phenomena and developing multi-geophysical integrated forecast models is worth the efforts being made by the scientific community worldwide.

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