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Invited Paper

Integrated Search for Taiwan Earthquake Precursors (iSTEP)

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After the 21 September 1999 M7.6 devastating earthquake, a program entitled the integrated Search for Taiwan Earthquake Precursor (iSTEP-1, 2002/4/1−2006/3/31), which consists of a main project and five sub-projects, was conducted to search credible precursors in seismological variations, geomagnetic and gravity fields, ground surface deformations, and ionospheric electron density anomalies, as well as to evaluate the statistical significance of observed precursors in Taiwan. Results reveal that anomalies in P-wave velocity, ground surface deformation, geomagnetic field intensity, ionospheric electron density could appear few years, months, and days before large earthquakes in Taiwan, respectively. An integrated ground-based seismo-electromagnetic observation system, including eight networks of magnetometers, electrode arrays, corona probes, FM tuners, Doppler sounding systems, ionosondes, GPS receivers, and all sky cameras, has been constructed and routinely operating to monitor earthquake precursors in the lithosphere, atmosphere, and ionosphere and to find possible lithosphere-atmosphere-ionosphere coupling in the Taiwan area. Several statistical analyses were developed to validate the observed anomalies to be credible precursors. Due to its worldwide availability, the statistical results showed that the ionospheric total electron content (TEC) derived by ground-based GPS receivers were most likely to be a credible precursor. Succeeding the iSTEP-1, the iSTEP-2 (integrated Study for Taiwan Earthquake Precursors, 2006/8−2012/7) project adding with satellite observations was conducted to have a longer time period for data collection and analysis, as well as to develop physical and statistical models. Although it was not officially funded but supported by basic ionospheric research projects, the integrated ground-based observation still has been operating uninterruptedly. Many new observations possibly related to seismo-lithospheric precursors of the earth's surface magnetic field and the GPS surface deformation, seismo-atmospheric precursors of the infrasound signal, and seismo-ionospheric precursors (SIPs) in the electron density profile, the electron temperature, ion density, and neutral temperature probed by satellites were reported. The TEC in the global ionosphere map (GIM) routinely published (with a 2- or 4-day time delay) allows us to monitor temporal SIPs at a specific location, and to conduct spatial analysis discriminating the observed SIPs from global effects, such as solar flares, magnetic storms, etc. Statistical analyses for detecting both temporal and spatial precursors in the ionospheric TEC are developed. Meanwhile, ionospheric model simulations are also introduced to find causal mechanisms explaining the observed SIPs. The iSTEP-3 (integrated Study for Taiwan Earthquake Precursors, 2012/8−2016/7), which is proposed to focus on the SIP study, consisting of a main project and three sub-projects is formally funded. The main project continues to operate the integrated ground-based observation system, develops physical models, and compares model simulations with observed precursors, while the three sub-projects aim to develop a near real-time GIM with a 4-hour time delay for worldwide SIP monitoring, to monitor lithosphere, atmosphere, and ionosphere precursors, to find the precursor link, and to conduct earthquake hazard assessment with observed precursors, respectively.

Keywords : iSTEP, earthquake prediction, precursor, Taiwan, ionosphere, total electron content, GPS

1. Introduction

If short-term earthquake prediction is realized, it will be able to not only save human lives, but also reduce the economical damage considerably. However, the short-term prediction needs recognizable and reliable earthquake precursors, especially those of non seismological but electromagnetics ones[(1)-(4)].

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Due to intense collision between the Philippine Sea and Eurasian plates, Taiwan has been experiencing many disastrous earthquakes and inevitably will face earthquake hazards in the future. In the early morning (01:47 local time) of September 21, 1999, the largest earthquake of the 20th century in Taiwan (Mw7.6, M_L7.3) struck central Taiwan near the small town of Chi-Chi. The hypocenter was located by the Central Weather Bureau Seismological Center at 23.87°N, 120.75°E, with a depth of about 7 km. There were extensive ground surface ruptures for about 85 km along the Chelungpu fault with vertical thrust and left lateral strike-slip offsets. The maximum displacement of about 9.8 meters is among the largest fault movements ever measured for modern earthquakes. There was severe destruction in the towns of Chungliao, Nantou, Taichung, Feng Yuan, and Tungshi, with over 2300 fatalities and 8700 injuries (Ma et al., 1999)[(5)]. Liu et al.

(2000)[6] found that the ionospheric electron density at the F2-peak recorded by a local ionosonde (ionospheric radar) anomalously deceases in the afternoon period on 1, 3, and 4 days before the Chi-Chi earthquake, which agrees with the statistical result of 13 $M \geq 6.0$ earthquakes in Taiwan during 1994−1999 that the ionospheric electron density tends to reduce significantly in the afternoon period 1−5 days before the earthquakes in Taiwan (Liu et al., 2000)[6]. Liu et al. (2001)[7] further confirmed seismo-ionospheric anomalies in the electron density observed before the Chi-Chi with measurements of ground-based GPS receivers in Taiwan that the ionospheric total electron (TEC) concurrently deceases in the afternoon period on 1, 3, and 4 days prior to the earthquake. These two papers prompted us to pursue further whether there are recognizable and reliable earthquake precursors for earthquake prediction.

2. iSTEP-1

After the Chi-Chi earthquake, in order to find possible answers for above question, a project entitled ‘Research on Seismo-Electromagnetic Precursors of Earthquakes’ granted by Program for Promoting University Academic Excellence of Ministry of Education has been carried out aiming for integrated Search for Taiwan Earthquake Precursors (iSTEP-1, 2002/4/1−2006/3/31). Figure 1 shows that the iSTEP-1 includes a main project and five sub-projects (Sub-project I: Seismological Variations, Sub-project II: Variations of Geomagnetic and Gravity Fields, Sub-project III: Radar Interferometry for Detection of Ground Surface Deformation, Sub-project IV: Ionospheric Variations, Sub-project V: Statistical study of electromagnetic precursors of earthquakes). Thus, the iSTEP-1 encompasses an all-inclusive set of observations, including seismological variations, ground deformation, and seismo electromagnetic signals in the lithosphere, atmosphere, and ionosphere, that are essential for monitoring and identifying possible Taiwan earthquake precursors.

Several reflection corners as reference points to precisely and correctly determine ground deformation by using satellite remote sensing technology were set up. To observe seismo-electromagnetic anomalies in the lithosphere, atmosphere, and ionosphere, eight networks of magnetometers, electrode arrays, corona probes, FM tuners, Doppler sounding systems, ionosondes (ionospheric radars), GPS receivers, and all sky cameras have been constructed and routinely operated. The ionosonde data analyses were suggested by Dr. S. A. Pulinets at Russian Academy of Sciences. The electrode network was deployed to monitor the underground electric property by Dr. K. Hattori at Chiba University, while the corona probe network observing the atmospheric field and FM tuner network probing the atmospheric irregularity were set up by Dr. M. Kamogawa at Tokyo Gakugei University. Many useful suggestions and comments are provided by Dr. S. Uyeda at Japan Academy, Dr M. Hayakawa at University of Electro-Communications, Dr. F. Freund at NASA. Owing to these international collaborations, the iSTEP-1 constructed a most comprehensive ground-based observation system of the world for searching and detecting seismo-electromagnetic anomalies, and studying possible link of lithosphere-atmosphere-ionosphere (LAI) coupling.

In addition to establishment of above infrastructure for earthquake precursor observations, results of the iSTEP-1 are also very fruitful (Tsai et al., 2004, 2006)[8][9]. Sub-project I found that *P*-wave velocity variations may provide precursory information before large earthquakes (Lee and Tsai, 2004)[10] and stress changes due to a main shock may shed some light on locations of its aftershocks (Ma et al., 2005)[11]. Sub-project II completed a survey of the geomagnetic field intensity island wide and observed apparent anomalies in geomagnetic total intensity near the two

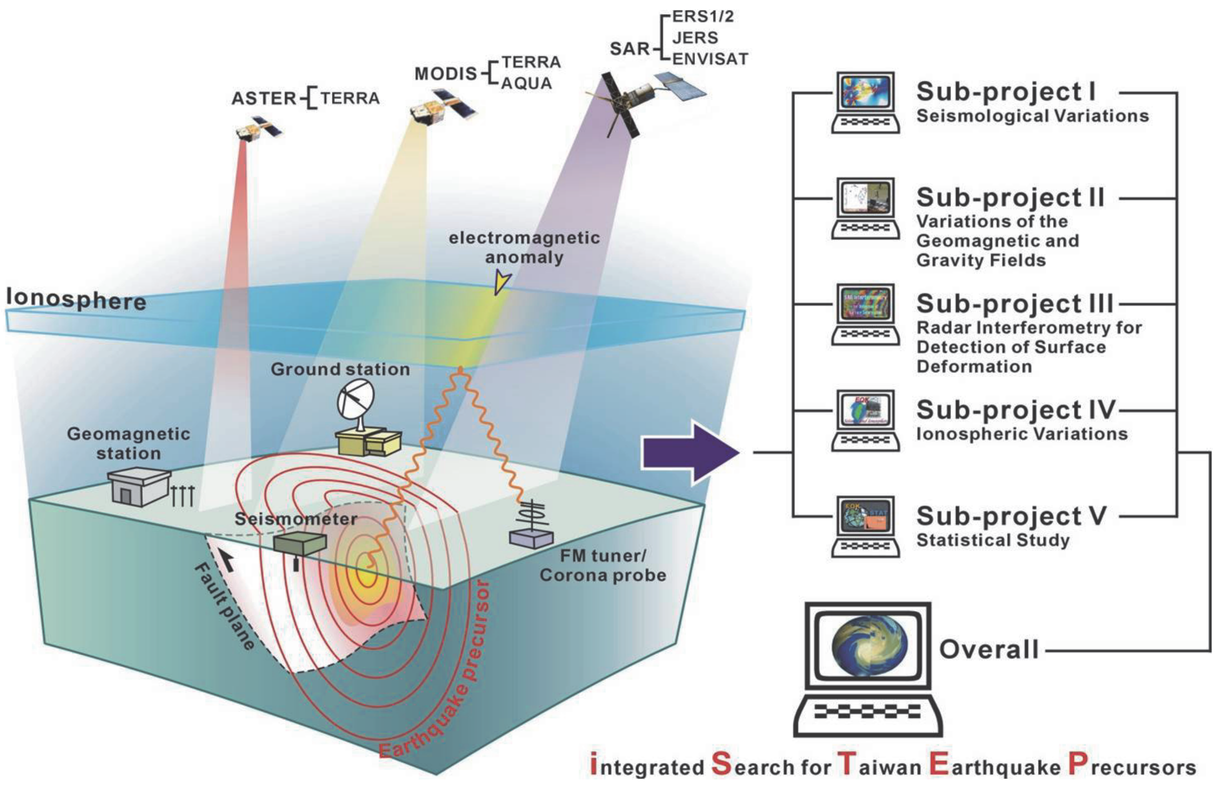

Fig. 1. The iSTEP-1 project

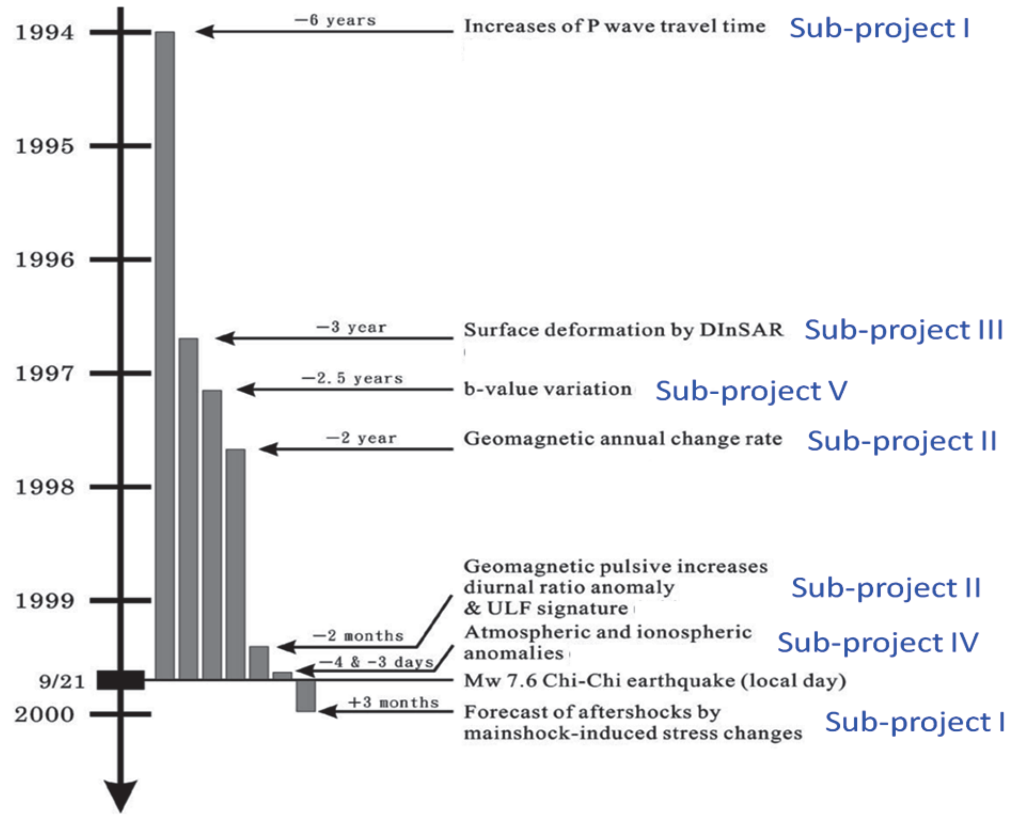

Fig. 2. Time lines of the precursors of the 1999 Chi-Chi, Taiwan Earthquake, as identified under the iSTEP-1; Adapted from Tsai et al. (2006)

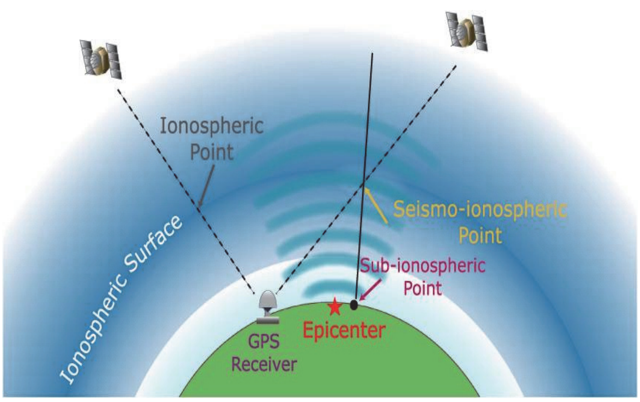

Fig. 3. Monitoring SIPs and STIDs in the ionospheric TEC by using ground-based GPS receivers; Liu et al. (2001)[3] pioneer probing SIPs in the GPS TEC; The iSTEP-1 project introduces the GPS TEC for the routine monitoring

ends of the Chelungpu fault at least one month before the 1999 Chi-Chi earthquake (Yen et al., 2004)[12]. For Sub-project III, new InSAR techniques were developed and ground surface deformation was found about one year before the Chi-Chi earthquake (Tsai et al., 2006)[9]. Sub-project IV reported anomalous fluctuations of atmospheric electric field and confirm significant decreases of ionospheric electron density 1−5 days before large earthquakes (Liu et al., 2004, 2006)[13][14]. Sub-project V validated statistically these precursory signals (Chen et al., 2004)[15]. Liu et al. (2006)[14] statistically investigate the relationship between variations of the plasma frequency at the ionospheric F2 peak foF2 and 184 earthquakes with magnitude $M \geq 5.0$ during 1994−1999 in the Taiwan area. They find that the ionospheric foF2 anomalously/significantly decreases in the afternoon period, 1200−1800 LT, within 5 days before the earthquakes. The chance observing such anomalies is proportional to the earthquake magnitude. Note that this statistical result well agrees with that the ionospheric foF2 significantly decreases in the afternoon period on 1, 3, and 4 day before the 21 September 1999 M_W7.6, (M_L)7.3 Chi-Chi earthquake (Liu et al., 2000)[6]. Figure 2 synthesizes precursors of the Chi-Chi earthquake observed by the sub-projects of iSTEP-1 in a common time frame. This is a typical example of integrated search for Taiwan earthquake precursors. Meanwhile, the iSTEP-1 project introduces the GPS TEC for the routine monitoring (Fig. 3).

3. iSTEP-2

Following the iSTEP-1, an extended project, called 'integrated Study for Taiwan Earthquake Precursors' (iSTEP-2, 2006/4−2010/3) was proposed to have a longer time period for data collection and analysis, as well as to construct physical and statistical models to reach the heart of earthquake precursor/prediction. The iSTEP-2 was to consist of a main project and four inter-related sub-projects (Sub-project I: Seismological Variation, Sub-project II: Measurement and Characterization of Crustal Deformation, Sub-project III: Lithosphere-Atmosphere-Ionospheric Coupling, Sub-project IV: Statistics for Earthquake Hazard). In addition to the existing ground-based networks, latest satellite observations (DEMETER (France), QuakeSat (US), ESPERIA-ISA (Italy), VULCAN & COMPASS (Russia), and FORMOSASAT-3/COSMIC (Taiwan-US)) were planned to add. While the iSTEP-2 ground-based observations can monitor ground surface deformation by ground-based GPS receivers (instead of radar interferometry), magnetic field, atmospheric electric field, upper atmospheric

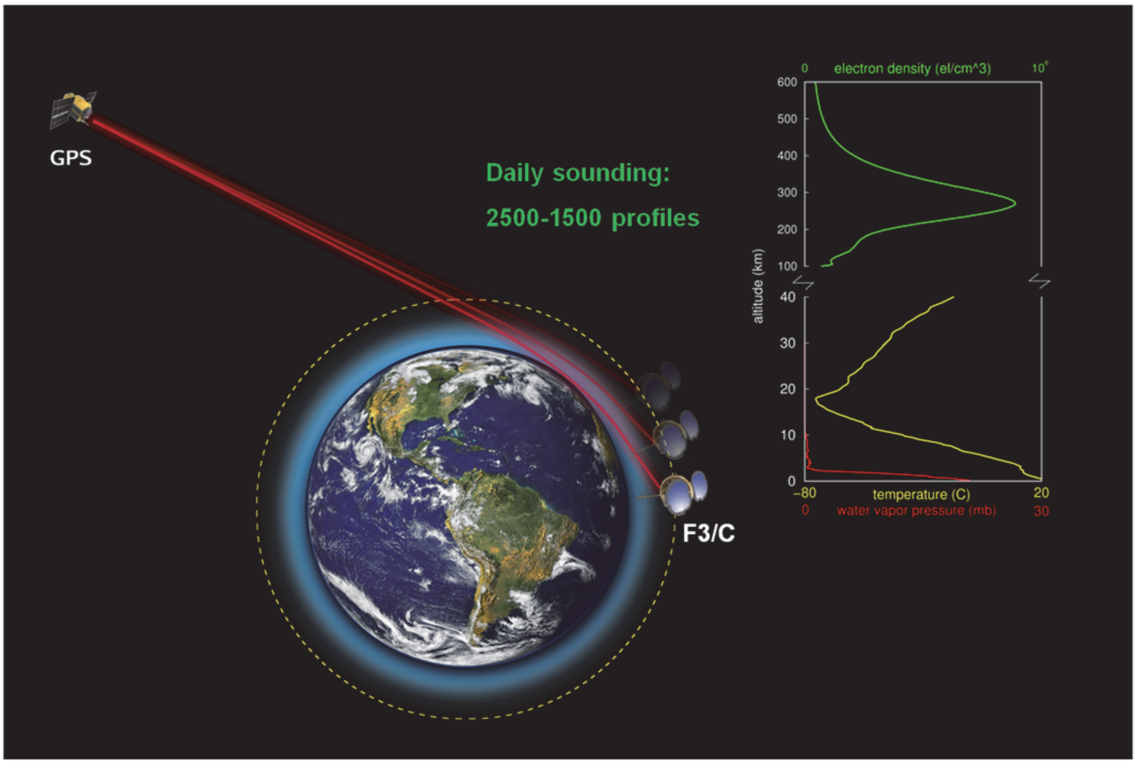

Fig. 4. The iSTEP-2 project adds FORMOSAT-3/COSMIC (F3/C) ionospheric observations for studying SIPs three dimensionally; From UCAR/COSMIC

irregularity, ionospheric electron density, and TEC in Taiwan, the FORMOSASAT-3/COSMIC (or F3/C in short) can provide daily more than 2000 ionospheric electron density profiles from 100 to 800 km altitude worldwide (Fig. 4). These data for the first time allow scientists to probe three dimensional structure and dynamics of the ionospheric electron density (cf., Liu et al., 2010a)[16].

Although the infrastructures were set up and the iSTEP-1 results were productive, as well as satellite observations were added, the iSTEP-2 was unfortunately not granted. To avoid any unwanted setback, Sub-project III together with Sub-project IV of the proposed iSTEP-2 was partially supported by basic geosciences research projects of National Science Council during 2006/8−2012/7. In this very low-budget 6-year period of the iSTEP-2, the exiting integrated ground-based observation system have been continuously maintained and operated, and numerous seismo-related precursors have been constantly searched and studied. The iSTEP-2 also found anomalies in the magnetic field (Chen et al., 2009, 2010)[17][18] and the surface deformation (Chen et al., 2011)[19] of the seismo-lithospheric precursors; abnormal infrasonic waves (Xia et al., 2011)[20] of the seismo-atmospheric precursors; and anomalies in the electron temperature (Oyama et al., 2008)[21], the ion density (Oyama et al., 2011)[22], and the neutral temperature of the seismo-ionospheric precursor possibly associated with large earthquakes. The electrode and FM tuner networks were gradually phased out, while the corona probe network was gradually replaced by field mill one to observe the atmospheric field and an infrasonic wave network has been installed and operating.

Meanwhile, global ionospheric maps (GIMs) of the GPS TEC with a 2-hour time resolution have been published daily and routinely by several centers, which have been used to estimate ionospheric effects on radio propagation and the provide correction for single frequency GNSS navigation (Fig. 5). The spatial resolutions of the GIM within region of the ±87.5°N latitude and ±180°E longitude are 2.5° and 5°, respectively. Thus, each map consists of 5183 (=71×73) lattices, which can be employed to detect the SIPs at a given location, and to discriminate the local effect (such as earthquakes) from global effect (solar disturbances, magnetic storms, etc.) by applying the spatial analysis. However, owing to the 2- to 4-day time delay, the GIM TEC can only be used for retrospective analyses. Nevertheless, Liu et al. (2010b, 2009, 2011)[23]-[25] reported SIPs in the GIM TEC associated with the 26 December 2004 M9.3 Sumatra-Andaman Earthquake, the 12 May 2008 Mw8.0 Wenchuan earthquake, and the 12 January 2010 M7.0 Haiti earthquake. Statistical analyses showed that the GPS TEC over the epicenter anomalously increased and/or decreased few days before large earthquakes in China (Liu et al., 2009)[24] and of the globe (Le et al., 2011)[26]. Le et al. (2011)[26] statistically examine the TEC anomalies around the epicenter of 736 M≥6.0 earthquakes of the globe during 2002−2010. They report that a larger and shallower (depth less than 20 km) earthquake has a better chance observing the TEC anomalies few days before the quake. Their statistical result are supported by that the TEC anomalies appear few days before devastating earthquakes[7][23]-[25]. Liu et al. (2009)[24] observe temporal and spatial precursors in the GIM TEC and electron density profiles probed by F3/C associated with the 12 May 2008 Mw8.0 Wenchuan earthquake. Liu et al. (2011)[25] for first time apply the spatial analysis to confirm increase anomalies in the GIM TEC being related to the 12 January 2010 M7.0 Haiti earthquake. They also apply physical based model simulations to show that the seismo-electric field generated around the epicenter results in the observed anomalies.

Meanwhile, with dense ground-based GPS receivers in Taiwan and Japan, Liu et al. (2010c, 2011)[27][28] observe seismo-traveling ionospheric disturbances (STIDs) triggered by the 21 September

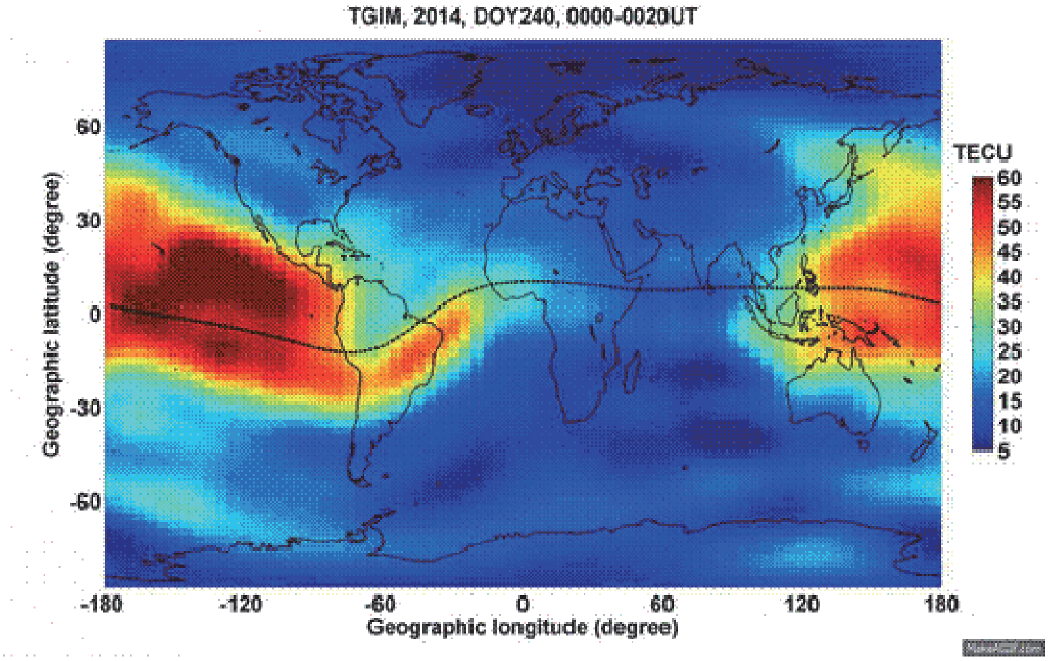

Fig. 5. Global ionospheric maps (GIMs) of the GPS TEC; The iSTEP-2 applied the GIM published by CODE, JPL, etc, while the iSTEP-3 develops a rear real time GIM for practical SIP monitoring

M7.6 Chi-Chi earthquake and the 11 March 2011 M9.0 Tohoku earthquake and tsunami, respectively. In fact, Liu et al. (2011)(28) for the first time observe the tsunami origin. A cross-comparison shows that the precursors and co-seismic disturbances result from the electromagnetic and the mechanical processes, respectively.

4. iSTEP-3

An ongoing project entitled 'Seismo-ionospheric Precursor', (or integrated Study for Taiwan Earthquake Precursors; iTSEP-3, 2012/8/1−2016/7/31), is granted by Science Vanguard Research Program of Ministry of Science and Technology. In addition to continue operating the integrated ground-based observation system, developing the simulation model, searching new seismo-precursors in the lithosphere, atmosphere, and ionosphere, and finding the LAI coupling signatures, another main goal is to find statistical evidence for credible and useful SIPs, and to construct a new monitoring system for practical real-time applications on the temporal and spatial precursor detection. A new dense magnetometer network donated by QuakeFinder of US and a new Doppler sounding system set up by Dr. J. Chum at CAS, Czech Republic are further added to enhance the integrated ground-based observation system.

Regarding the 11 March 2011 M9.0 Tohoku, several precursors in surface displacements (Chen et al., 2014)(29) and SIPs in the TEC (Le et al., 2013)(30), as well as co-seismic disturbances (Kakinami et al., 2012, 2013; Kamogawa et al., 2012)(31)-(33) are observed. Moreover, the model simulation (Kim et al., 2012)(34), some new seismo-precursors in the surface deformation (Chen et al., 2013a)(35), high-conductivity anomalies (Chen et al., 2013b, 2015a)(36)(37), ground water level (Chen et al., 2013c)(38), multiple-anomalies in the lithosphere (Chen et al., 2015b, 2015c; Wen et al., 2015)(39)-(41), multiple-anomalies of the LAI coupling (Zeng et al., 2015; Chen et al., 2015b)(39)(42), ionospheric anomalies (Liu et al., 2013, 2015; Su et al., 2013, Ho et al., 2013a, 2013b)(43)-(47) are reported.

A major advance of the iSTEP-3 is that a statistical analysis of the receiver operating characteristic (ROC) curve is introduced to evaluate the efficiency of SIPs of the GIM TEC (Chen et al., 2015d)(48). Results show SIPs to be credible and useful for earthquake prediction and/or forecast. Meanwhile, to shorten the 2- to 4-day time delay of the current GIM down to every 4-hour, the iSTEP-3 has been working on combining the massive F3/C ionospheric dataset with the existing GIM TEC data to construct the TIGER (Taiwan Ionospheric Group for Education and Research) GIM. The TIGER GIM with a 15-minute time resolution shall be available to the public for SIP monitoring and detection in the near future.

5. Summary

The three iSTEP projects have provided about 30 MS/PhD thesis research topics, trained more than 20 domestic/foreign postdoctoral fellows, and invited more than 50 foreign experts. These project results have produced more than 100 well-known journal papers including 2 special issues. The projects successfully observed anomalies of the seismological variation, ground surface deformation, groundwater level, electric field, and magnetic field in the lithosphere; abnormal signals of the electric field, and infrasonic wave in the atmosphere; and SIPs of the electron density, TEC, electron temperature, neutral temperature, and ion density in the ionosphere before large earthquakes. The GIM TEC can be employed to detect the SIP temporal and spatial precursors for discriminating between local and global effects. In fact, the GIM TEC has detected the SIPs associated with the 1999 M7.6 earthquake, 2004 M9.3 Sumatra earthquake, 2008 M8.0 Wenchuan earthquake, the 2010 M7.0 Haiti earthquake, and the 2011 M9.0 Tohoku earthquake. Thus far, anomalies of GPS surface deformation, the geomagnetic field, and ionospheric TEC are found to be useful and credible precursors for earthquake forecast and predication.

Currently, the international earthquake precursor communities have highly recognized the iSTEP progress, and concluded that the achievements mainly result from (i) active involvement and support from seismologists and geoscientists, (ii) innovative space technology applications, (iii) rigorous integrated observations of the lithosphere, atmosphere, and ionosphere, and (iv) statistical validations. Since the TIGER GIM with a 15-munute time resolution and a 5183-lattice spatial regulation as well as the 4-hour delay time will be available soon for real time detection of the SIP in the ionospheric TEC, and monitoring systems of the GPS surface deformation and ground-based magnetic field detection are developed, the iSTEP-4 (integrated Study and Test for Earthquake Precursors, 2016/8−2020/7) will be proposed to find the relationship between precursor strength and earthquake occurrence, and to conduct attendant earthquake hazard assessment. It is our hope to reach the goal of earthquake prediction eventually.

Acknowledgements

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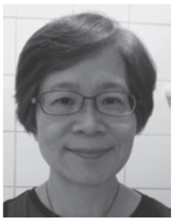

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