



A spatial analysis on seismo-ionospheric anomalies observed by DEMETER during the 2008 M8.0 Wenchuan earthquake



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ABSTRACT

This paper examines seismo-ionospheric anomalies (SIAs) observed by the French satellite DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) during the 12 May 2008 M8.0 Wenchuan earthquake. Both daytime and nighttime electron density (Ne), electron temperature (Te), ion density (Ni) and ion temperature (Ti) are investigated. A statistical analysis of the box-and-whisker method is utilized to see if the four DEMETER datasets 1–6 days before and after the earthquake are significantly different. The analysis is employed to investigate the epicenter and three reference areas along the same magnetic latitude discriminating the SIAs from global effects. Results show that the nighttime Ne and Ni (daytime Ti) over the epicenter significantly decrease (increase) 1–6 days before the earthquake. The intersections of the global distribution of the significant differences (or anomalous changes) in the nighttime Ne, the nighttime Ni, and the daytime Ti 1–6 days before and after the earthquake specifically appear over the epicenter, which strongly suggests that DEMETER observes SIAs of the 2008 M8.0 Wenchuan earthquake.

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1. Introduction

Seismo-ionospheric anomalies (SIAs) have been intensively investigated (e.g. Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002; Pulnits and Boyarchuk, 2004). To discriminate SIAs from anomalies caused by global (such as solar disturbance and magnetic storm) effects, and to confirm them being related to earthquakes, a spatial analysis on global satellite observations is ideally employed. DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite is a micro-satellite that observes the region within 65° geomagnetic latitude in a 680 km altitude, 98.3° inclination orbit. It is a sun-synchronous satellite and passes in almost the same local time everywhere in the daytime at 1030 LT and the nighttime at 2230 LT. It was launched in June 2004 and stopped in December 2010. Its main scientific objectives are the detection

and characterization of ionosphere electrical and magnetic disturbances in connection with a seismic activity (Cussac et al., 2006). DEMETER carries 6 payloads: IAP (Instrument d'Analyse du Plasma) detecting the plasma density and the ion composition (Berthelier et al., 2006); ISL (Instrument Sonde de Langmuir) measuring the electron density and temperature (Lebreton et al., 2006); RNF (Réseau de Neurones Formel) performing an automatic identification and classification of the whistlers from ELF to VLF electric field measurements (Elie et al., 1999), and ICE (Instrument Champ Electrique), IMSC (Instrument Magnetic Search Coil), and IDP (Instrument for the Detection of Particle) recording the electric field, magnetic field, and high energy particles, respectively. Numerous research articles report density variation and amplitude change of electro-magnetic emissions above earthquake regions by means of DEMETER observations (cf., http://smc.cnes.fr/DEMETER/A_publications.htm).

A devastating earthquake with magnitude Mw8.0 occurring in eastern Sichuan (Wenchuan), China (30.986°N, 103.364°E, Depth 19 km) at 06:28:01UT on 12 May 2008 (<http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/us2008ryan.php>). Liu et al.

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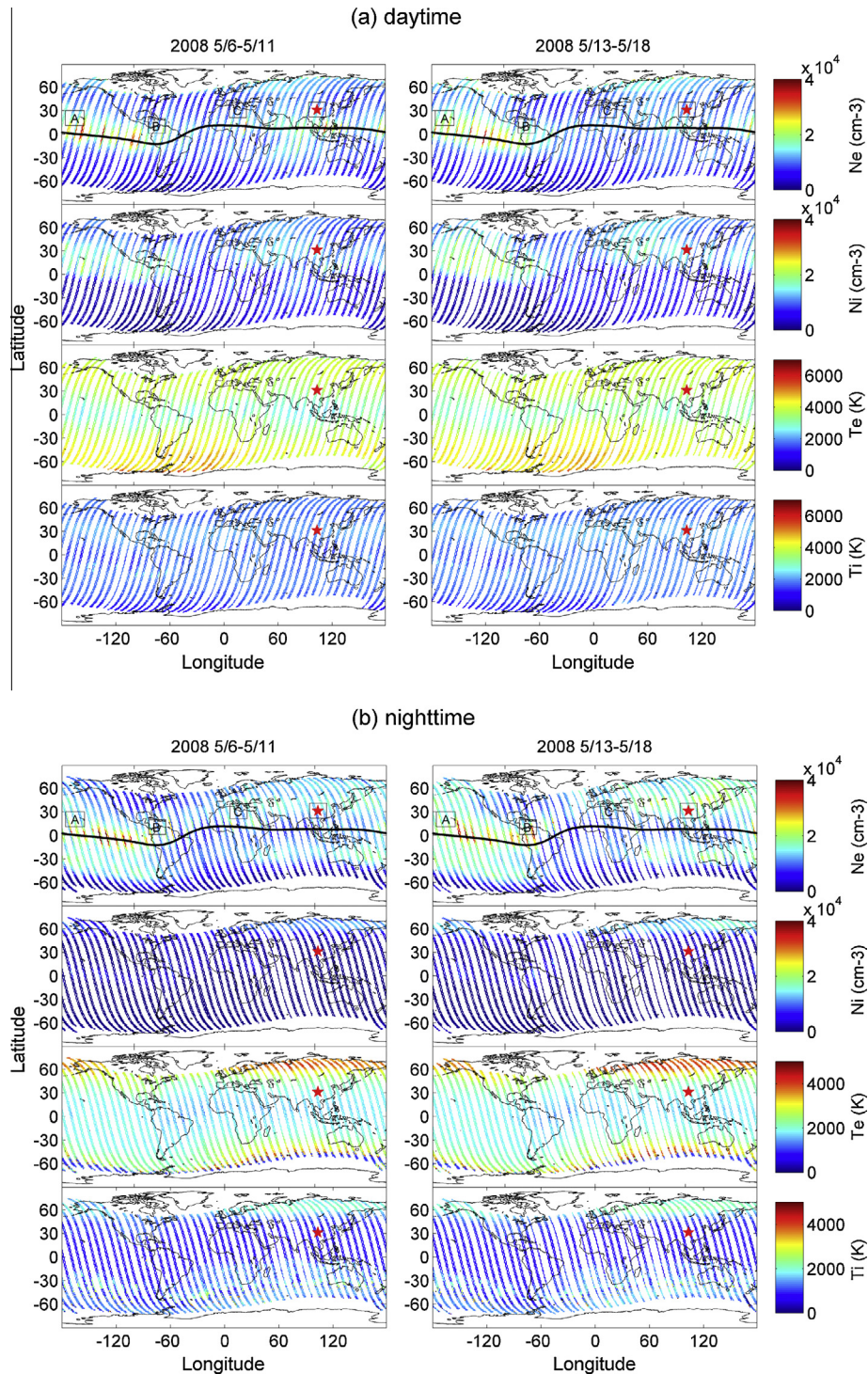


Fig. 1. The global distributions of DEMETER Ne, Ni, Te, and Ti (from top to bottom) 1–6 days before and after (right and left) the 2008 M8.0 Wenchuan earthquake. (a) Daytime at global 1030 LT and (b) nighttime at global 2230 LT. The red star denotes the epicenter (30.986°N, 103.364°E) and 3 reference regions (A: 190°E, B: 280°E, C: 10°E) in the same magnetic latitude (17°N) but separated by 90°, 180° and 270° are indicated. The black curve is the geomagnetic equator. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(2009) examine the seismo-ionospheric anomalies of the GPS TEC (Total Electron Content) associated with large earthquakes by means of the GIM (Global Ionosphere Map, <ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex>). They find that the GIM TEC above the epicenter often pronouncedly decreases day 3–5 before 17 M ≥ 6.3 earthquakes during a 10-year period of 1 May 1998–30 April 2008, as well as significantly decreases 2–6 days before

the 2008 M8.0 Wenchuan earthquake. On the other hand, anomalies in the plasma density, ion temperature, electric field, and ELF/VLF/ULF emissions around the epicenter region have been proved by DEMETER being associated with the 12 May 2008 M8.0 Wenchuan earthquake (He et al., 2009; Zhang et al., 2009a,b, 2010, 2012; Błęcki et al., 2010; Li et al., 2010; An et al., 2011; Zhu and Wang, 2011; Yan et al., 2012).

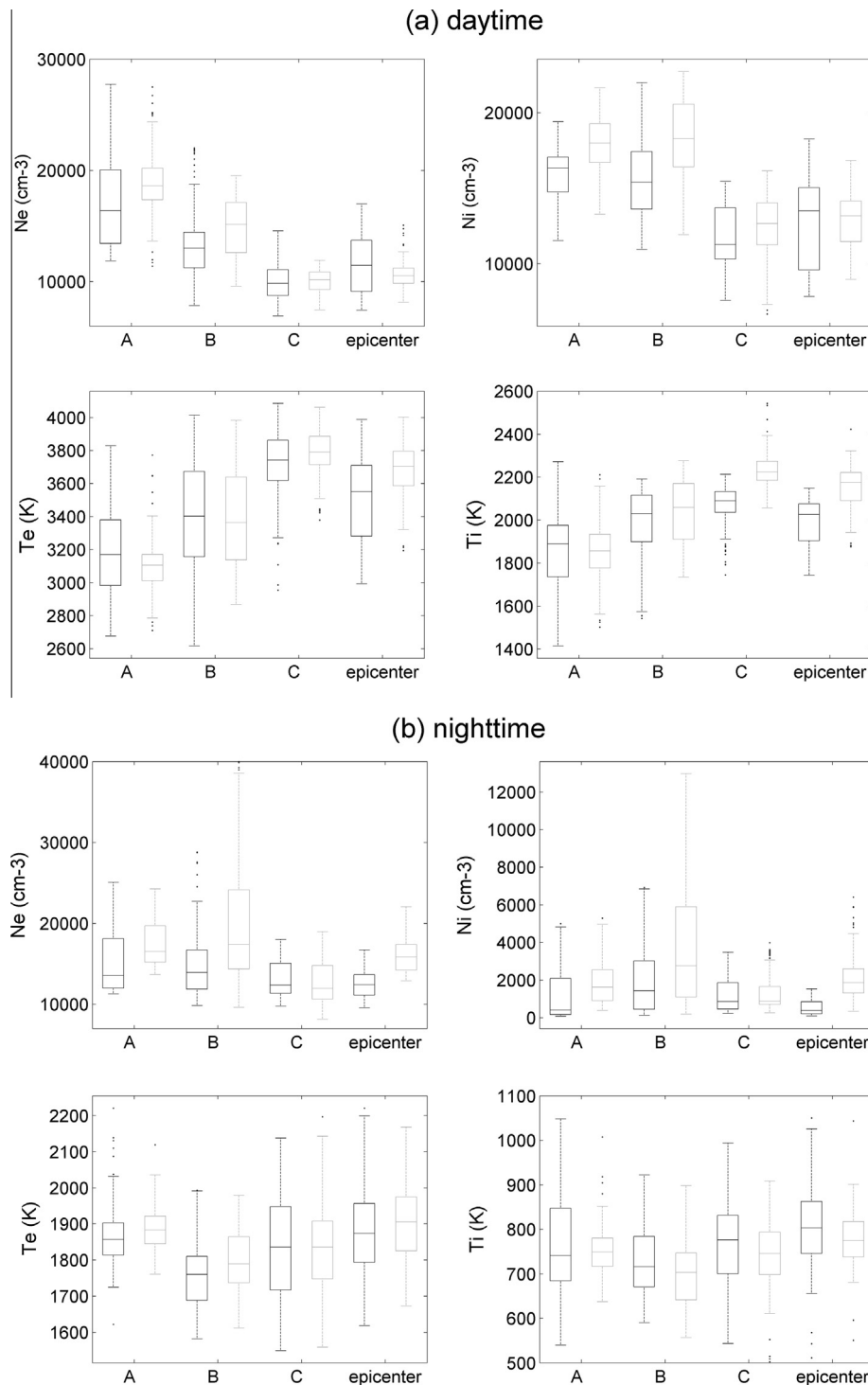


Fig. 2. The statistical analysis of the DEMETER Ne, Ni, Te, and Ti over the reference regions A–C, and the epicenter region 1–6 days before and after the Wenchuan earthquake. (a) Daytime at global 1030 LT and (b) nighttime at global 2230 LT. The black and gray boxes denote data observed before and after the Wenchuan earthquake, respectively.

In this paper, to confirm if seismo-electromagnetic anomalies specifically appear over the Wenchuan epicenter, we globally examine the daytime (1030 LT) and nighttime (2230 LT) electron density (Ne), electron temperature (Te), ion density (Ni), ion temperature (Ti) recorded by DEMETER 1–6 days before and after the M8.0 Wenchuan earthquake. We cross compare the four DEMETER quantities over the epicenter and 3 reference regions in the same magnetic latitude but separated by 90°, 180° and 270° in longitude 1–6 days before and after the earthquake.

Finally, the global distributions of the detected anomalies in the four DEMETER quantities are investigated to see if the observed SIAs specifically appear over the epicenter and in turn are possibly associated with the earthquake.

2. Observation and data analysis

Fig. 1a and b displays global fixed-local-time distributions of the daytime (1030 LT) and nighttime (2230 LT) Ne, Ni, Te, and Ti

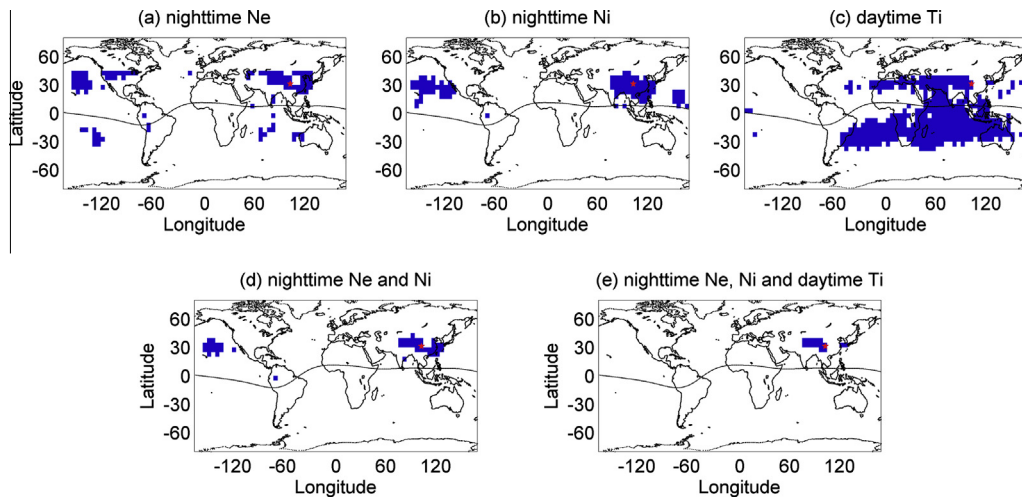


Fig. 3. The global distributions of the significant differences between 1 and 6 days before and those after the earthquake in (a) the nighttime Ne; (b) the nighttime Ni; and (c) the daytime Ti. The intersection of the global distributions of the significant differences of (d) the nighttime Ne and nighttime Ni; and (e) the nighttime Ne, nighttime Ni, and the daytime Ti.

1–6 days before and after the M8.0 Wenchuan earthquake, respectively. It seems that the four quantities before and after the earthquake in both the daytime and nighttime yields no obvious difference. To conduct a rigorous/quantitative study, and to see whether the anomalous changes mainly occur around the epicenter, we isolate and examine the four quantities within a 10° -latitude \times 10° -longitude center the epicenter (30.986°N , 103.364°E) and 3 reference regions (A: 190°E , B: 280°E , C: 10°E) in the same magnetic latitude (17°N) but separated by 90° , 180° and 270° in longitude 1–6 days before and after the earthquake.

It is known that ionospheric data are positive values, which inhabit a right-skewed and heavy-tailed distribution, and therefore, a median base analysis is suitable to be applied. The box-and-whisker procedure (Wilcox, 2010) is one kind of median base analyses, which has an advantage of visually observing the significant difference among multi-datasets simultaneously. Here we statistically investigate each quantity 1–6 days before and after the earthquake in the epicenter and 3 reference regions with box-and-whisker (box) plots in the daytime (Fig. 2a) and the nighttime (Fig. 2b). The lower (upper) quartile is the number such that at least 25% (75%) of the sorted observations are less (greater) than or equal to it. In the plot, the ends of a box are the upper and lower

quartiles. The horizontal line in the box denotes the statistical median. The dots are the outliers which exceed 1.5 times the interquartile range from the end of the box and are unusually small or large. The lines extending out from the box are called whiskers. The ends of the whiskers mark the smallest and largest values which are not outliers. When one median (i.e. horizontal line) is not overlapped with the other's upper and lower quartiles (i.e. box), the two are declared to be different under significance level $0.06 (=0.25 \times 0.25)$ (Wilcox, 2010). Fig. 2a (b) reveals that in general there are no significant differences in the four quantities over the 4 regions, except Ti over the epicenter and C regions (except Ne and Ni over the epicenter region) in the daytime (in the nighttime).

Although the nighttime Ne and Ni, and the daytime Ti over the epicenter region 1–6 days before significantly differ from those after the earthquake, it still cannot be confirmed that they are possibly the earthquake related, because global effects, such as solar radiations, solar winds, magnetic storms, and neutral winds (cf. Liu et al., 2004, 2006, 2013), could result in similar changes/anomalies. To discriminate the global and earthquake (local) effects, we conduct a global search to find the spatial distribution of the significant difference of the nighttime Ne, the nighttime Ni, and the daytime Ti. Fig. 3a and b reveals that the

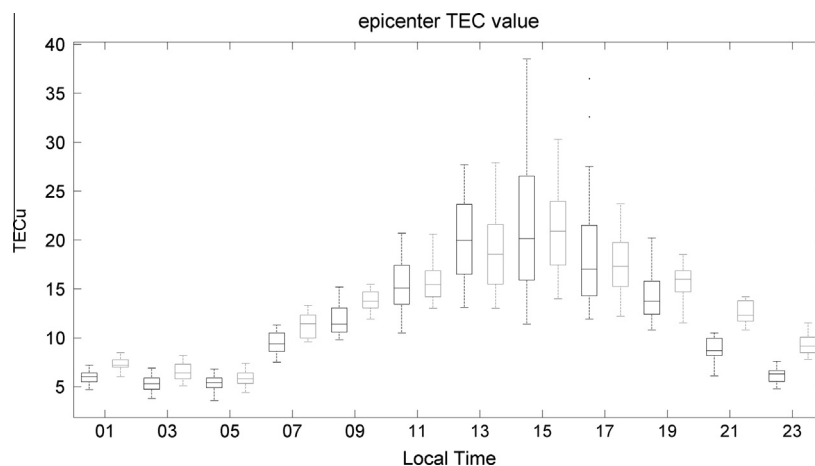


Fig. 4. The statistical analysis on the GIM TEC at various time points over the epicenter region 1–6 days before and after the Wenchuan earthquake. The black and gray boxes denote data observed before and after the Wenchuan earthquake, respectively.

significant differences of the nighttime Ne and the nighttime Ni mainly appear around the epicenter region and east Pacific area, and some significant differences of the nighttime Ne also occur in the associated conjugated points. On the hand, the significant differences of the daytime Ti appear in 2 large belts, which are around $\pm 30^\circ\text{N}$ (especially in the southern hemisphere) from -50 to 160°E (Fig. 3c).

3. Discussion and conclusion

Liu et al. (2009) report the GIM TEC over the 2008 M8.0 Wenchuan earthquake anomalously decreases in the afternoon period of day 6–4 and in the late evening period of day 3 before the earthquake. Chen et al. (2015) statistically investigate the relationship between the GIM TEC and $56 M \geq 6.0$ earthquakes during 1998–2013 in China, and find that the TEC significantly decrease 0600–1000 LT 1–6 days before the earthquake. Figs. 2 and 3 show that the DEMETER Ne and Ni significantly decrease 1–6 days before the 2008 M8.0 Wenchuan earthquake, which generally agree with Liu et al. (2009) and Chen et al. (2015). However, it should be noticed that the DEMETER Ne and Ni significantly decrease in the nighttime of 2230 LT, while the GIM TEC anomalously decrease in the afternoon period of 1200–1800 LT reported by Liu et al. (2009) and in the morning period of 0600–1000 LT by Chen et al. (2015). In fact, Chen et al. (2015) also report that the GIM TEC can significantly decrease in the afternoon period 1–6 days before $M \geq 6.5$ earthquakes in China. To clarify this discrepancy, we also examine the difference in the GIM TEC over the epicenter 1–6 days before and after the Wenchuan earthquake in various local time points. Fig. 4 shows that the GIM TEC becomes different from 1900 to 0900 LT, significantly 2100 to 0300 and 0900 LT.

Based on the plasma characteristics of quasi-neutrality, the densities of Ne and Ni should be nearly identical. Thus, the significant differences of the nighttime Ne and Ni would concurrently occur. The superposition (or intersection) of Fig. 3a and b reveals that the significant differences of the nighttime Ne and the nighttime Ni mainly appear around the epicenter region and a small region in the east Pacific area (Fig. 3d). Oyama et al. (2008) reported that Te of the HINOTORI satellite decreased around the epicenters within 5 days before and after the $3 M \geq 6.6$ earthquakes during 1981–1982. Akhondzadeh et al. (2010a,b) found that DEMETER Te decreased 4 days before but increased 2 days before the 2009 M8.1 Samoa earthquake. On the other hand, Ho et al. (2013) find that the DEMETER Te yields no obvious changes but its Ti slightly increases 10–20 days before the 2010 M8.8 Chile earthquake. Results in the previous and current study show that Ti and Te variation are rather complex, and then less significant than those of Ni and Ne. Fig. 3c reveals that the significant differences of the daytime Ti occur in two rather large areas. Since the different seismo-ionospheric anomalies often coexist and generally last for a long period of time, therefore the significant differences of the nighttime Ne, the nighttime Ni, and the daytime Ti could be further superimposed/intersected. Fig. 3e displays that the three significant differences concurrently and specifically appear around the Wenchuan epicenter. In conclusion, in the nighttime the DEMETER Ne and Ni around the epicenter significantly decrease 1–6 days before the 2008 Wenchuan earthquake. The spatial analysis on the global distribution of the significant differences confirms that the nighttime Ne and Ni anomalous decrease are associated with the 2008 M8.0 Wenchuan earthquake.

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References

- Akhondzadeh, M., Parrot, M., Saradjian, M.R., 2010a. Electron and ion density variations before strong earthquakes ($M > 6.0$) using DEMETER and GPS data. *Nat. Hazards Earth Syst. Sci.* 10, 7–18.
- Akhondzadeh, M., Parrot, M., Saradjian, M.R., 2010b. Investigation of VLF and HF waves showing seismo-ionospheric anomalies induced by the 29 September 2009 Samoa earthquake ($M_w = 8.1$). *Nat. Hazards Earth Syst. Sci.* 10, 1061–1067.
- An, Z.H., Du, X.B., Fan, Y.Y., Liu, J., Tan, D.C., Chen, J.Y., Xie, T., 2011. A study of the electric field before the Wenchuan 8.0 earthquake of 2008 using both space-based and ground-based observational data. *Chin. J. Geophys.* 54 (11), 2876–2884. <http://dx.doi.org/10.3969/j.issn.0001-5733.11.017>.
- Berthelier, J., Godefroy, M., Leblanc, F., Seran, E., Peschard, D., Gilbert, P., Artru, J., 2006. IAP, the thermal plasma analyzer on DEMETER. *Planet. Space Sci.* 54 (5), 487–501.
- Blečki, J., Parrot, M., Wronowski, R., 2010. Studies of the electromagnetic field variations in ELF frequency range registered by DEMETER over the Sichuan region prior to the 12 May 2008 earthquake. *Int. J. Remote Sens.* 31 (13), 3615–3629.
- Chen, Y.L., Huang, C.S., Liu, J.Y., 2015. Statistical evidence of seismo-ionospheric precursors of the GPS total electron content in China. The iSTEP special issue of Journal of Asian Earth Sciences (submitted for publication).
- Cussac, T., Clair, M., Ulte-Guerard, P., Buisson, F., Lassalle-Balier, G., Ledu, M., Elisabellar, C., Passot, X., Rey, E., 2006. The DEMETER microsatellite and ground segment. *Planet. Space Sci.* 54 (5), 413–427.
- Elie, F., Hayakawa, M., Parrot, M., Pinçon, J.-L., Lefeuvre, F., 1999. Neural network system for the analysis of transient phenomena on board the DEMETER microsatellite. *IEICE Trans. Fundam. Electron. Commun. Comput. Sci.* E82-A (8), 1575–1581.
- Hayakawa, M., 1999. *Atmospheric and Ionospheric Electromagnetic Phenomena with Earthquakes*. Terra Scientific, Tokyo, Japan.
- Hayakawa, M., Fujinawa, Y., 1994. *Electromagnetic Phenomena Related to Earthquake Prediction*. Terra Scientific, Tokyo, Japan.
- Hayakawa, M., Molchanov, O.A., 2002. *Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling*. Terra Scientific, Tokyo, Japan.
- He, Y.F., Yang, D.M., Chen, H.R., et al., 2009. SNR changes of VLF radio signals detected onboard the DEMETER satellite and their possible relationship to the Wenchuan earthquake. *Sci. China Ser. D – Earth Sci.* 52 (6), 754–763. <http://dx.doi.org/10.1007/s11430-009-0064-5>.
- Ho, Y.Y., Liu, J.Y., Parrot, M., Pinçon, J.L., 2013. Temporal and spatial analyses on seismo-electric anomalies associated with the 27 February 2010 $M = 8.8$ Chile earthquake observed by DEMETER satellite. *Nat. Hazards Earth Syst. Sci.* 13, 3281–3289. <http://dx.doi.org/10.5194/nhess-13-1-2013>.
- Lebreton, J.-P., Stverak, S., Travnicek, P., Maksimovic, M., Klinge, D., Merikallio, S., Lagoutte, D., Poirier, B., Blelly, P.-L., Kozacek, Z., Salasquarda, M., 2006. The ISL Langmuir probe experiment processing onboard DEMETER: scientific objectives, description and first results. *Planet. Space Sci.* 54 (5), 472–486.
- Li, X.Q., Ma, Y.Q., Wang, H.Y., Lu, H., Zhang, X., Wang, P., Shi, F., Xu, Y.B., Huang, J.P., Meng, X.C., Wang, H., Zhao, X.Y., 2010. Observation of particle on space electromagnetic satellite during Wenchuan earthquake. *Chin. J. Geophys.* 53 (10), 2337–2344. <http://dx.doi.org/10.3969/j.issn.0001-5733.2010.10.007>.
- Liu, J.Y., Lin, C.H., Tsai, H.F., Liou, Y.A., 2004. Ionospheric solar flare effects monitored by the ground-based GPS receivers: theory and observation. *J. Geophys. Res.* 109. <http://dx.doi.org/10.1029/2003JA009931>.
- Liu, J.Y., Lin, C.H., Chen, Y.L., Lin, Y.C., Fang, T.W., Chen, C.H., Chen, Y.C., Hwang, J.J., 2006. Solar flare signatures of the ionospheric GPS total electron content. *J. Geophys. Res.* 111, A05308. <http://dx.doi.org/10.1029/2005JA011306>.
- Liu, J.Y., Chen, Y.L., Chen, C.H., Liu, C.Y., Chen, C.Y., Nishihashi, M., Li, J.Z., Xia, Y.Q., Oyama, K.-I., Hattori, K., Lin, C.H., 2009. Seismo-ionospheric GPS TEC anomalies observed before the 12 May 2008 $M_w 7.9$ Wenchuan Earthquake. *J. Geophys. Res.* 114 (A04320), 2009. <http://dx.doi.org/10.1029/2008JA013698>.
- Liu, J.Y., Yang, W.H., Lin, C.H., Chen, Y.L., Lee, I.T., 2013. A statistical study on the characteristics of ionospheric storms in the equatorial ionization anomaly region: GPS-TEC observed over Taiwan. *J. Geophys. Res. Space Phys.* 118, 3856–3865. <http://dx.doi.org/10.1002/jgra.50366>.
- Oyama, K.-I., Kakinami, Y., Liu, J.Y., Kamogawa, M., Kodama, T., 2008. Reduction of electron temperature in low-latitude ionosphere at 600 km before and after large earthquakes. *J. Geophys. Res.* 113 (A11). <http://dx.doi.org/10.1029/2008JA013367>.
- Pulinets, S., Boyarchuk, K., 2004. *Ionospheric Precursors of Earthquakes*. Springer, New York, USA.

- Wilcox, R.R., 2010. *Fundamentals of Modern Statistical Methods: Substantially Improving Power and Accuracy*. Springer, New York, USA.
- Yan, X., Shan, X., Gao, J.B., Tan, J., Wang, F.F., 2012. Seismoionospheric anomalies observed before Wenchuan earthquake using GPS and DEMETER data. *Seismol. Geol.* 34 (1), 160–171. <http://dx.doi.org/10.3969/j.issn.0253-4967.2012.01.01> (in Chinese with English abstract).
- Zhang, X., Shen, X., Liu, J., Ouyang, X., Qian, J., Zhao, S., 2009a. Analysis of ionospheric plasma perturbations before Wenchuan earthquake. *Nat. Hazards Earth Syst. Sci.* 9, 1259–1266.
- Zhang, X., Shen, X., Ouyang, X., Cai, J., Huang, J., Liu, J., Zhao, S., 2009b. Ionosphere VLF electric field anomalies before Wenchuan M 8 earthquake. *Chin. J. Radio Sci.* 24 (6), 1024–1032 (in Chinese with English abstract).
- Zhang, X., Shen, X., Liu, J., Ouyang, X., Qian, J., Zhao, S., 2010. Ionospheric perturbations of electron density before the Wenchuan earthquake. *Int. J. Remote Sens.* 31 (13), 3559–3569.
- Zhang, X., Chen, H., Liu, J., Shen, X., Miao, Y., Du, X., Qian, J., 2012. Ground-based and satellite DC-ULF electric field anomalies around Wenchuan M8.0 earthquake. *Adv. Space Res.* 50, 85–95.
- Zhu, T., Wang, L.-W., 2011. LF electric field anomalies related to Wenchuan earthquake observed by DEMETER satellite. *Chin. J. Geophys.* 54 (3), 712–717. <http://dx.doi.org/10.3969/j.issn.0001-5733.2011.03.011> (in Chinese with English abstract).