

Atmosphere-ionosphere response to the *M*9 Tohoku earthquake revealed by multi-instrument space-borne and ground observations: Preliminary results

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Abstract We retrospectively analyzed the temporal and spatial variations of four different physical parameters characterizing the state of the atmosphere and ionosphere several days before the *M*9 Tohoku, Japan earthquake of March 11, 2011. The data include outgoing long wave radiation (OLR), GPS/TEC, lower Earth orbit ionospheric tomography and critical frequency foF2. Our first results show that on March 7th a rapid increase of emitted infrared radiation was observed from the satellite data and an anomaly developed near the epicenter. The GPS/TEC data indicate an increase and variation in electron density reaching a maximum value on March 8. Starting from this day in the lower ionosphere also there was confirmed an abnormal TEC variation over the epicenter. From March 3 to 11 a large increase in electron concentration was recorded at all four Japanese ground-based ionosondes, which returned to normal after the main earthquake. The joint preliminary analysis of atmospheric and ionospheric parameters during the *M*9 Tohoku, Japan earthquake has revealed the presence of related variations of these parameters implying their connection with the earthquake process. This study may lead to a better understanding of the response of the atmosphere/ionosphere to the great Tohoku earthquake.

Key words: Tohoku earthquake; thermal anomaly; GPS/TEC; earthquake precursor; early warning

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1 Introduction

The *M*9 Tohoku earthquake on March 11, 2011 was followed by a large number of powerful aftershocks. The possibility of a mega-earthquake in Miyagi prefecture was initially discussed by Kanamori et al. (2006). Strong earthquakes in this region were recorded since 1793 with average period of 37 ± 7 years. The latest great Tohoku earthquake matched this reoccurrence period since the last one

occurred in 1978. Figure 1 shows the location of Tohoku earthquake and data receivers as well as vertical ionosonde stations in Japan.

The observational evidence from the last twenty years, provide a significant pattern of transient anomalies preceding earthquakes (Tronin et al., 2002; Liu et al., 2004; Pulinets and Boyarchuk, 2004; Tramutoli et al., 2005; Parrot, 2009; Oyama et al., 2011). Several of the papers indicated that atmospheric variation was also detected prior to an earthquake. Despite these pre-earthquake atmospheric transient phenomenon (Ouzounov et al., 2006, 2007; Inan et al., 2008; Němec et al., 2009; Pulinets et al., 2009; Kon et al., 2010), there is still lack of consistent data necessary to

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understanding the connection between atmospheric and ionospheric associated with major earthquakes. In this present report we analyzed ground and satellite data to investigate the relationship between the behavior in atmosphere, ionosphere and the March 11 Tohoku earthquake.

We examined four different physical parameters characterizing the state of the atmosphere/ionosphere during the periods before and after the event: (1) Outgoing longwave radiation (OLR, infra-red 10–13 μm) measured at the top of the atmosphere; (2) GPS/TEC (Total Electron Content) ionospheric variability; (3) Low Earth orbiting (LEO) satellite ionospheric tomography; and (4) variations in ionosphere F2 layer at the critical foF2 frequency (the highest frequency at which the ionosphere is transparent) from four Japanese ionosonde stations. These multidisciplinary data provide a synopsis of the atmospheric/ionospheric variations related to tectonic activity.



Figure 1 Reference map of Japan with the location of the *M*9.0 Tohoku earthquake, March 11, 2011 with white circle, with black circles showing the location of the tomographic data receivers and with black triangles the location of vertical ionosonde stations in Japan.

2 Data observation and analysis

2.1 Earth radiation observation

One of the main parameters we used to characterize the Earth's radiation environment is the outgoing

long-wave-Earth radiation (OLR). OLR has been associated with the top of the atmosphere integrating the emissions from the ground, lower atmosphere and clouds (Ohning and Gruber, 1982) and has primarily been used to study Earth radiative budget and climate (Gruber and Krueger, 1984; Mehta and Susskind, 1999).

The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (<http://www.cdc.noaa.gov/>) provides daily and monthly OLR data and the OLR algorithm for analyzing the advanced very high resolution radiometer (AVHRR) data. OLR is not directly measured, but is calculated from the raw measurements between 10 and 13 μm that integrates these IR data using a separate algorithm (Gruber and Krueger, 1984). These data are mainly sensitive to near surface and cloud temperatures. A daily mean, covering a significant area of the Earth (90°N–90°S, 0 to 357.5°E) and with a spatial resolution of 2.5°×2.5° was used to study the OLR variability in the zone of earthquake activity (Liu, 2000; Ouzounov et al., 2007; Xiong et al., 2010). An increase in radiation and a transient change in OLR were proposed to be related to thermodynamic processes in the atmosphere over seismically active regions. This anomalous eddy was defined by us (Ouzounov et al., 2007) as an *E*_{index}. This index was constructed similarly to the definition of anomalous thermal field proposed by Tramutoli et al. (2001). The *E*_{index} represents the statically defined maximum change in the rate of OLR for a specific spatial locations and predefined times.

$$\Delta E_{\text{index}}(t) = \frac{[S^*(x_{i,j}, y_{i,j}, t) - \bar{S}^*(x_{i,j}, y_{i,j}, t)]}{\tau_{i,j}}, \quad (1)$$

where $t=1, K$, is time in day, $S^*(x_{i,j}, y_{i,j}, t)$, the current OLR value and $\bar{S}^*(x_{i,j}, y_{i,j}, t)$ the computed mean field, defined by multiple years of observations over the same location, local time and normalized by the standard deviation $\tau_{i,j}$.

In this study we analyzed NOAA/AVHRR OLR data between 2004 and 2011. The OLR reference field was computed for March 1 to 31 using all available data from 2004 to 2011 and using ± 2 sigma confidence level (Figure 2). During 21 to 24 February and 7 to 10 March, transient OLR anomalous fields were observed near the epicentral area and over the major faults, with a confident level greater than +2 sigma (Figure 3a). The initial anomalous change in OLR was detected on 7th of March and the largest change (in comparison to the ± 2 sigma level) in the formation of the transient atmospheric anomaly was detected on March 10th, one

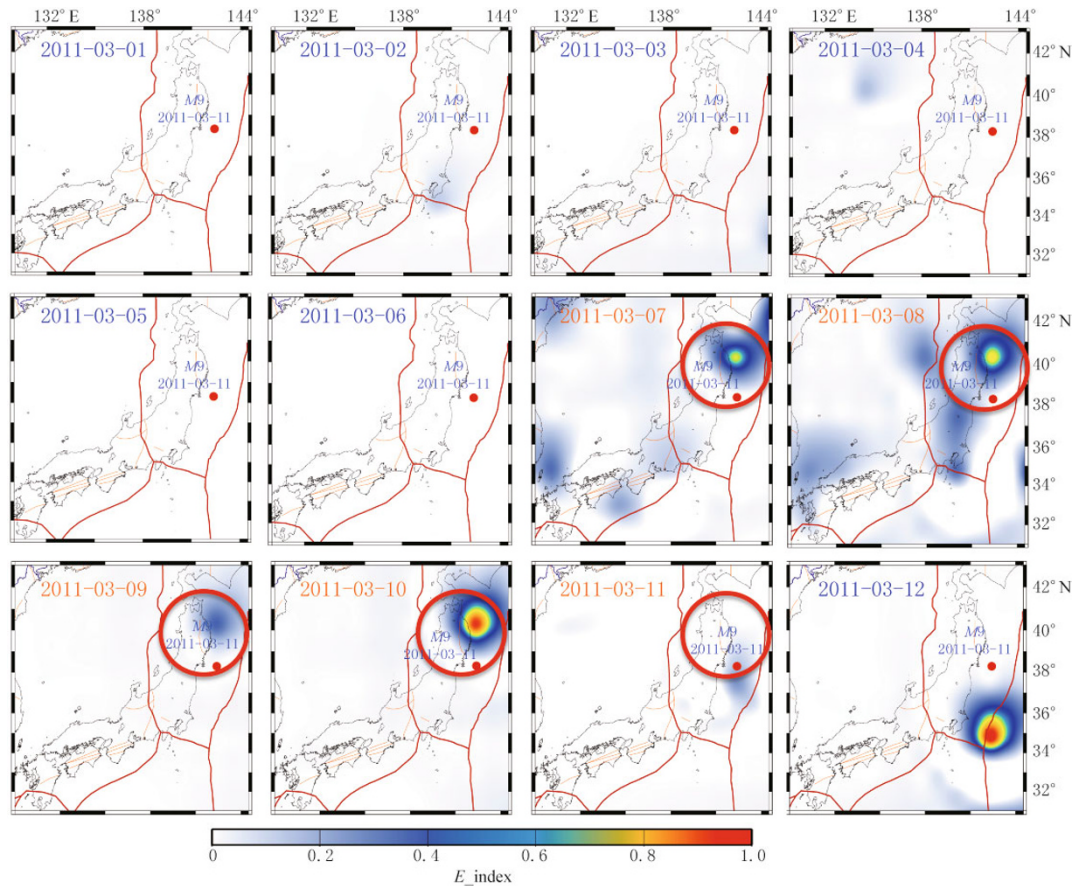


Figure 2 Time series of daytime anomalous OLR observed from NOAA/AVHRR (06:30 LT equatorial crossing time) for March 1–12, 2011. Tectonic plate boundaries are indicated with red lines and major faults by brown ones and earthquake location by open solid dots. Red circle show the spatial location of abnormal OLR anomalies within vicinity of $M9.0$ Tohoku earthquake.

day before the Tohoku earthquake, with a confidence level of two sigma above the historical mean value. The location of the OLR maximum on March 11, recorded at 06:30 LT, was collocated exactly with the epicenter. The 2010 time series for OLR anomaly (Figure 3c) show no significance change above ± 2 sigma level comparable with the 2011 anomaly. This rapid enhancement of radiation could be explained by an anomalous flux of the latent heat over the area of increased tectonic activity. Similar observations were observed within a few days prior to the most recent major earthquakes in China ($M7.9$, 2008), Italy ($M6.3$, 2009), Samoa ($M7$, 2009), Haiti ($M7.0$, 2010) and Chile ($M8.8$, 2010) (Pulinets and Ouzounov, 2011; Ouzounov et al., 2011a, b).

2.2 Ionospheric observation

The ionospheric variability around the time of the March 11 earthquake were recorded by three independent techniques: the GPS/TEC in the form of Global Ionosphere Maps (GIM), ionospheric tomography, using the signals from low-Earth orbiting COSMOS satellites,

and data from the ground based vertical sounding network in Japan. The period of this earthquake was very magnetically noisy since two (small and moderate) geomagnetic storms took place on the first and eleventh of March respectively (Figure 4b). There was a short period of quiet geomagnetic activity between March fifth and tenth but it was during a period of increasing solar activity. During period from 26 February through 8 March the solar F10.7 radio flux increased almost two-fold (from 88 to 155). So the identification of the ionospheric precursor was a search for a signal in this noise.

To reduce this noise we used the following criteria:

- 1) If an anomaly is connected with the earthquake, it should be local (connected with the future epicenter position) contrary to the global magnetic storms and solar activity that affected the entire ionosphere;
- 2) All anomalous variation (possible ionospheric precursor) should be present in the records of all three ionosphere-monitoring techniques used in our analysis;
- 3) The independent techniques concerning geomag-

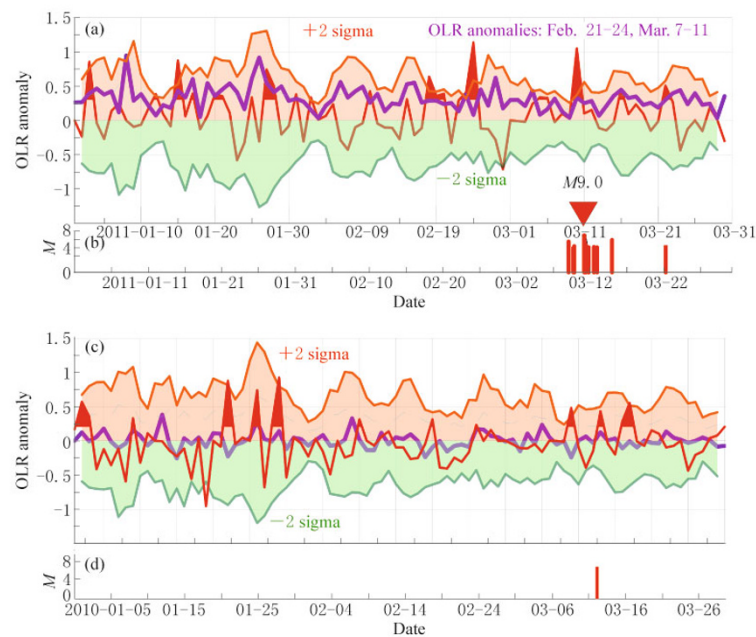


Figure 3 Time series of OLR atmospheric variability observed within a 200 km radius of the Tohoku earthquake. (a) Day-time anomalous OLR from January 1 to March 31, 2011 observed from NOAA/AVHRR (06:30 LT). (b) Seismicity ($M > 6.0$) within 200 km radius of the $M9.0$ epicenter. (c) Day-time anomalous OLR from January 1 to March 31, 2010 observed from NOAA/AVHRR (06:30 LT). (d) Seismicity ($M > 6.0$) within 200 km radius of the $M9.0$ epicenter for 2011.

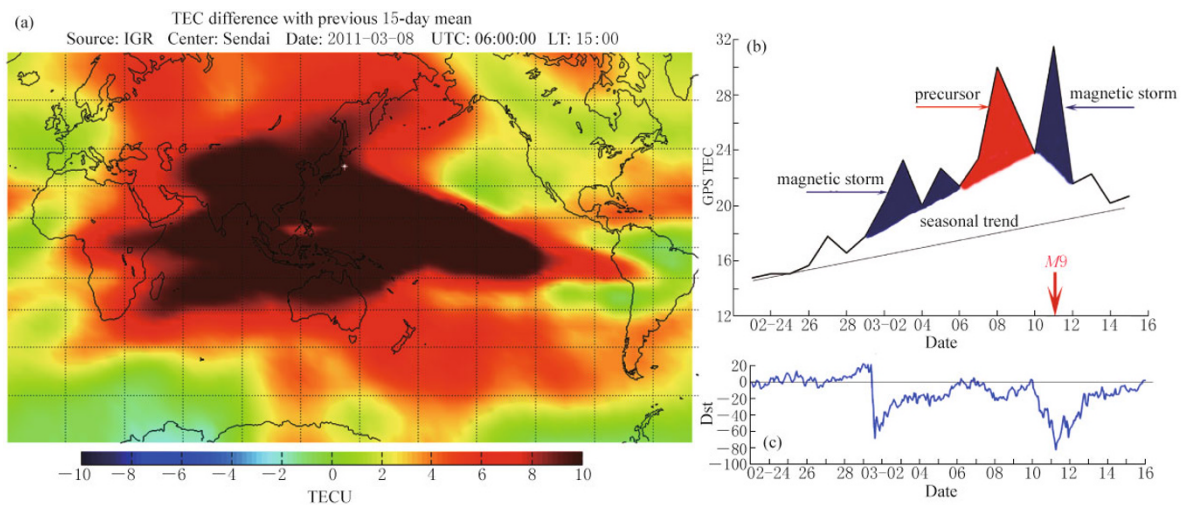


Figure 4 GIM GPS/TEC analysis. (a) Differential TEC map of March 8, 2011 at 15:00 LT. (b) Time series of GPS/TEC variability observed from February 23 to March 16, 2011 for the grid point closest to epicenter for the 15:00 LT. (c) Dst index for the same period. The Dst data were provided by World Data Center (WDC), geomagnetism, Kyoto, Japan.

netic activity that were previously developed (Pulinets et al., 2004) were used.

The only data source where we were able to get three spatially coincident anomalies was GPS/TEC.

We made four types of analysis: (1) differential maps, (2) global electron content (GEC) calculations (Afraimovich et al., 2008), (3) determination of the local character of ionospheric anomaly, and (4) variation

of GPS/TEC measurements in the IONEX grid point (Pulinets et al., 2004) closest to the Tohoku earthquake epicenter.

To estimate variability of the GIM, a map using the average of the previous 15 days, before March 11, was calculated and the difference of DTEC between the two TEC maps was obtained by subtracting the current GIM from the 15-day average map. This value was selected at 06:00 UTC corresponding to 15:00 LT, when the equatorial anomaly is close to a maximum (one might expect the strongest variations at this local time). The most remarkable property of the differential maps was the sharp TEC increase during the recovery phase of March 5 through 8 with the strongest deviation from the average being recorded on March 8. This distribution is shown in Figure 4a. To understand if this increase was a result of an abrupt increase in solar activity and has an either local or global character we calculated the global electron content (GEC) according to Afraimovich et al. (2008). In Figure 5, the solar F10.7 index variation is shown in comparison with GEC. Both parameters were normalized for a comparison. It is interesting to note that on the increasing phase both parameters are very close, the recovery phase shows their difference after two or three days of ionospheric reaction. We see a delay in comparison with F10.7, which also corresponds to the conclusions of Afraimovich et al. (2008). Two small peaks on the ionospheric curve on 1 and 13 March correspond to two small geomagnetic storms (see, Dst index in Figure 4b). To determine if there is any local anomaly in the region near the epicenter we integrated the GEC, in a circular area with a 15° radius centered on the epicenter. This normalized curve (with the same scale as the first two) is given by a thick solid line. Note the significant peak on March

8. This date corresponds to the day of the differential GIM shown in Figure 4a. The local character of the ionospheric anomaly has been demonstrated by this test.

This last check was made by studying the TEC variation at the grid point closest to the epicenter as shown in Figure 4b. One should keep in mind that only data for 06:00 UTC were taken, so we have only one point for this day. Again a strong and very unusual increase of TEC was registered on March 8 marked by red in Figure 4. The effect of magnetic storms is marked in blue in this figure. Note the gradual trend of background TEC values, which is probably, connected with the general electron density increase at the equinox transition period (passing from winter to summer electron concentration distribution). From a point measurement we observe that the most anomalous day is March 8.

The data used to derive an image of the base of the ionosphere tomography (Figures 1 and 6) were obtained from the coherent receivers chain on the Sakhalin island.

Computing a base of the ionospheric tomography utilizes the phase-difference method (Kunitsyn and Tereshchenko, 2001) which is contained in the applied tomography software (Romanov et al., 2009). A coherent phase difference of 150 and 400 MHz was used to measure the relative ionosphere TEC values. The source signals are from the COSMOS-2414 series, OSCAR-31 series and RADCAL, low-Earth orbiting satellites with near-polar orbits. An ionosphere irregularity was observed from the relatively slanting TEC variations (increasing to 1.5 TECU above background) and in the ionosphere electron concentration tomography reconstruction. These data from the Yuzhno-Sakhalinsk and Poronajsk receivers and DMSP F15 satellite signals (maximum elevation angle 70°) were used for calculating ionospheric tomography. A tomography image anomaly was located at 45°N – 46°N . It extends some 100–150 km along 45°N and has a density that is 50% higher than background. The structure at 19:29 UTC on March 8, 2011 was an anomalous F2 layer located by the significant anomalous electron concentration anomaly recorded from a series of reconstructions of the ionospheric tomography (Figure 6a). The strength and position of the detected anomaly can be estimated from Figure 6b. It should be noted that as in the case of GIM maps the most anomalous ionospheric tomography was recorded on March 8. This result from the ionospheric tomography confirms the conclusion of our previous analysis concerning March 8 as an anomalous day.

Data from the four Japanese ground based

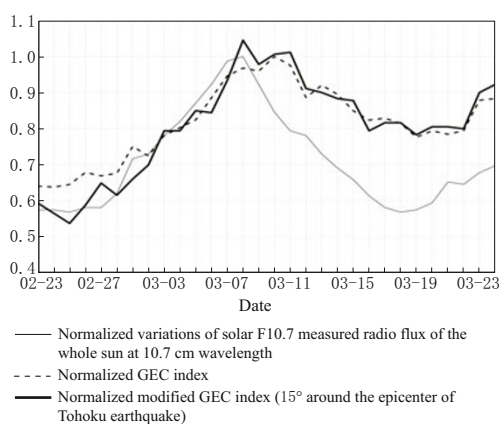


Figure 5 Normalized variations of solar F10.7 measured radio flux of the whole sun at 10.7 cm wavelength.

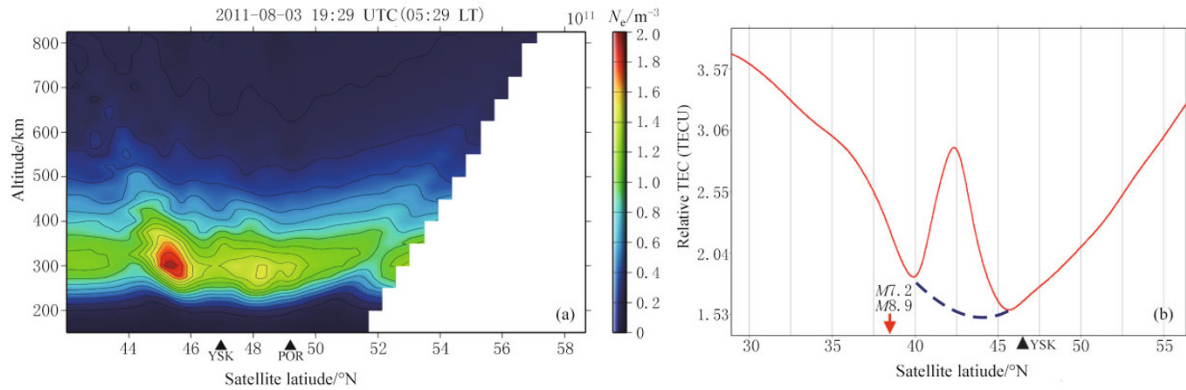


Figure 6 Ionospheric tomography reconstruction over Japan using COSMOS (Russia) satellites and receivers (see Figure 1) installed at Sakhalin Island. (a) Tomography map of March 8, 2011, 05:29 LT. (b) Ionospheric reconstruction over Japan for March 2011. Blue dashes line is the TEC reference line without earthquake influence, red arrow is location of M9.0 earthquake, and triangles, location of the ground receiver. YSK and POR represent the ground receivers Yuzhno-Sakhalinsk and Poronajsk.

ionosondes (location shown in Figure 1) were analyzed. All stations indicated a sharp increase in the concentration of electrons at the beginning of March, but as it was demonstrated by GIM analysis, this increase is most probably due to the increase in solar activity. It was shown by Pulinets et al. (2004) that from a cross-correlation analysis between these daily variations and the critical frequency (or vertical TEC) one could determine ionospheric precursors even in presence of a geomagnetic disturbances. This explained the fact that ionospheric variations connected with the solar and geomagnetic disturbances (in the case when the stations are in similar geophysical conditions and not too far apart) are very similar to a cross correlation coefficient greater than 0.9. At the same time, taking the physical mechanism of seismo-ionospheric disturbances into account (Pulinets and Boyarchuk, 2004), ionospheric variations registered by station closest to an epicenter would be different from ones recorded by more distant receivers. The pair of stations Kokubunji-Yamagawa can be used to test such an analysis. Kokubunji is the closest station to the earthquake epicenter, and the latitudinal difference of four degrees between Kokubunji and Yamagawa is not significant and we can neglect the latitudinal gradient (Figure 1). Pulinets et al. (2004) demonstrated that the cross-correlation coefficient for a pair of stations with differing distances to an earthquake epicenter drops a few days before the earthquake. In Figure 7 the cross-correlation coefficient shows the maximum drop on March 8. From ground-based ionospheric sounding data we received confirmation that March 8 was an anomalous day and the ionospheric variations

were most likely connected with the earthquake. Our results show that three independent methods for ionosphere monitoring were anomalous on March 8 and that ionospheric variations recorded on this day were related to the Tohoku earthquake.

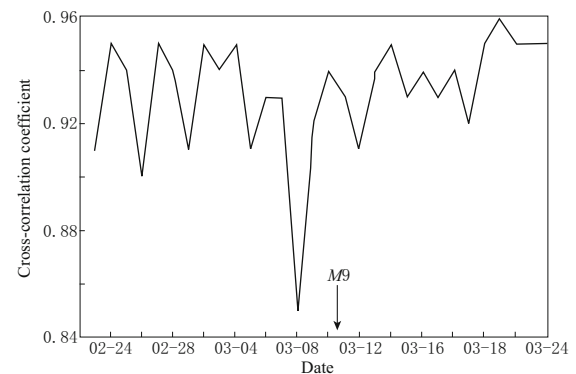


Figure 7 FoF2 data cross-correlation coefficient between daily variations at Kokubunji and Yamagawa stations.

3 Discussion and conclusions

The joint analysis of atmospheric and ionospheric parameters during the M9 Tohoku earthquake has demonstrated the presence of correlated variations of ionospheric anomalies before the earthquake implying a connection with this event. One of the possible explanations for this relationship is the lithosphere-atmosphere-ionosphere coupling mechanism (Pulinets and Boyarchuk, 2004; Pulinets and Ouzounov, 2011), which provides the physical links between the different

geochemical, atmospheric and ionospheric variations and tectonic activity. Briefly, the primary process is the ionization of the air produced by an increased emanation of radon (and other gases) from the Earth's crust in the vicinity of an active fault (Toutain and Baubron, 1998; Omori et al., 2007; Ondoh, 2009). The increased radon emanation launches the chain of physical processes, which leads to changes in the conductivity of the air and a latent heat release (increasing air temperature) due to water molecules attachment (condensation) to ions (Prasad et al., 2005; Pulnits et al., 2006, 2007; Cervone et al., 2006). Our results show evidence that this process is related to the Tohoku earthquakes of March 11 with a thermal build up near the epicentral area (Figures 2 and 3). The ionosphere immediately reacts to these changes in properties of the ground layer measured by GPS/TEC over the epicenter area, which have been confirmed as spatially localized increase in the DTEC on March 8 (Figure 4a). The TEC anomalous signals were registered between two minor and moderate geomagnetic storms, but the major increase of DTEC on March 8 was registered during a geomagnetically quiet period (Figures 4a and 4b). A sharp increase in the electron concentration from the Japanese ionospheric stations (Figure 7) were observed with a maximum on March 8 and then returned to normal a few days after the main earthquake of March 11.

Our preliminary results from recording atmospheric and ionospheric conditions during the *M*9 Tohoku earthquake using four independent techniques: (1) OLR monitoring on the top of the atmosphere, (2) GIM-GPS/TEC maps, (3) low-Earth orbit satellite ionospheric tomography, and (4) ground based vertical ionospheric sounding show the presence of anomalies in the atmosphere and ionosphere occurring consistently over the region of maximum stress near the Tohoku earthquake epicenter. Due to their long duration over the Sendai region these results do not appear to be of meteorological or magnetic activity. Our initial results suggest the existence of an atmosphere/ionosphere response triggered by the coupling processes between lithosphere, atmosphere and ionosphere preceding the *M*9 Tohoku earthquake of March 11, 2011.

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References

- Afraimovich E L, Astafyeva E I, Oinats, Yasukevich Y V and Zhivetiev I V (2008). Global electron content: A new conception to track solar activity. *Ann Geophys* **26**: 335–344.
- Cervone G, Maekawa S, Singh R P, Hayakawa M, Kafatos M and Shvets A (2006). Surface latent heat flux and nighttime LF anomalies prior to the $M_W=8.3$ Tokachi-Oki earthquake. *Nat Hazards Earth Syst Sci* **6**: 109–114.
- Gruber A and Krueger A (1984). The status of the NOAA outgoing longwave radiation dataset. *Bull Amer Meteorol Soc* **65**: 958–962.
- Inan S, Akgu T, Seyis C, Saatc R, Baykut S, Ergintav S and Bas M (2008). Geochemical monitoring in the Marmara region (NW Turkey): A search for precursors of seismic activity. *J Geophys Res* **113**: B03401, doi:10.1029/2007JB005206.
- Kanamori H, Miyazawa M and Mori J (2006). Investigation of the earthquake sequence off Miyagi prefecture with historical seismograms. *Earth Planets Space* **58**: 1 533–1 541.
- Kon S, Nishihashi M and Hattori K (2010). Ionospheric anomalies possibly associated with $M \geq 6.0$ earthquakes in the Japan area during 1998–2010: Case studies and statistical study. *Journal of Asian Earth Sciences* **41**(4–5): 410–420, doi:10.1016/j.jseases.2010.10.005.
- Kunitsyn V and Tereshchenko E (2001). *Ionosphere Tomography*. Springer, Berlin, 260pp.
- Liu D (2000). Anomalies analyses on satellite remote sensing OLR before Jiji earthquake of Taiwan Province. *Geo-Information Science* **2**(1): 33–36 (in Chinese with English abstract).
- Liu J Y, Chuo Y J, Shan S J, Tsai Y B, Chen Y I, Pulnits S A and Yu S B (2004). Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurement. *Ann Geophys* **22**: 1 585–1 593.
- Mehta A and Susskind J (1999). Outgoing longwave radiation from the TOVS Pathfinder path A data set. *J Geophys Res* **104**(D10): 12 193–12 212.
- Němec F, Santolík O, Parrot M and Berthelier J J (2009). Spacecraft observations of electromagnetic perturbations connected with seismic activity. *Geophys Res Lett* **35**: L05109, doi:10.1029/2007GL032517.
- Ohring G and Gruber A (1982). Satellite radiation observa-

- tions and climate theory. *Adv Geophys* **25**: 237–304.
- Omori Y, Yasuoka Y, Nagahama H, Kawada Y, Ishikawa T, Tokonami S and Shinogi M (2007). Anomalous radon emanation linked to preseismic electromagnetic phenomena. *Nat Hazards Earth Syst Sci* **7**: 629–635.
- Ondoh T (2009). Investigation of precursory phenomena in the ionosphere, atmosphere and groundwater before large earthquakes of $M > 6.5$. *Adv Space Res* **43**: 214–223.
- Ouzounov D, Bryant N, Logan T, Pulinets S and Taylor P (2006). Satellite thermal IR phenomena associated with some of the major earthquakes in 1999–2004. *Phys Chem Earth* **31**: 154–163.
- Ouzounov D, Liu D, Kang C, Cervone G, Kafatos M and Taylor P (2007). Outgoing long wave radiation variability from IR satellite data prior to major earthquakes. *Tectonophysics* **431**: 211–220.
- Ouzounov D, Pulinets S, Hattori K, Kafatos M and Taylor P (2011a). Atmospheric signals associated with major earthquakes: A multi-sensor approach. In: Hayakawa M ed. *Frontier of Earthquake Short-term Prediction Study*. NSTSS, Japan (in press)
- Ouzounov D, Hattori K, Pulinets S, Liu T, Partot M, Kafatos M, Taylor P, Yang F, Oyama K and Kon S (2011b). Integrated sensing, analysis and validation of atmospheric signals associated with major earthquakes. *Geophysical Research Abstracts*, Vol. 13, EGU2011-11932-1, EGU General Assembly.
- Oyama K-I, Kakinami Y, Liu J Y, Abdu M A and Cheng C Z (2011). Latitudinal distribution of anomalous ion density as a precursor of a large earthquake. *J Geophys Res* **116**: A04319, doi:10.1029/2010JA015948.
- Parrot M (2009). Anomalous seismic phenomena: View from space in electromagnetic phenomena associated with earthquakes. In: Hayakawa M ed. *Electromagnetic Phenomena Associated with Earthquakes* Transworld Research Network, Trivandrum, India, Chapter 8, 205–234.
- Prasad B S N, Nagaraja T K, Chandrashekara M S, Paramesh L and Madhava M S (2005). Diurnal and seasonal variations of radioactivity and electrical conductivity near the surface for a continental location Mysore, India. *Atmospheric Research* **76**: 65–77.
- Pulinets S and Boyarchuk K (2004). *Ionospheric Precursors of Earthquakes*. Springer, Berlin, Germany, 315pp.
- Pulinets S, Gaivoronska T A, Leyva-Contreras A and Ciralo L (2004). Correlation analysis technique revealing ionospheric precursors of earthquakes. *Nat Hazards Earth Syst Sci* **4**: 697–702.
- Pulinets S and Ouzounov D (2011). Lithosphere-atmosphere-ionosphere coupling (LAIC) model: An unified concept for earthquake precursors validation. *Journal of Asian Earth Sciences* **41**(4–5): 371–382.
- Pulinets S, Ouzounov D, Karelin A, Boyarchuk K and Pokhmelnikh L (2006). The physical nature of thermal anomalies observed before strong earthquakes. *Physics and Chemistry of the Earth* **31**: 143–153.
- Pulinets S, Kotsarenko A N, Ciralo L and Pulinets I A (2007). Special case of ionospheric day-to-day variability associated with earthquake preparation. *Adv Space Res* **39**: 970–977.
- Pulinets S A, Romanov A A, Urlichich Yu M, Romanov A A, Doda J L N and Ouzounov D (2009). The first results of the pilot project on complex diagnosing earthquake precursors on Sakhalin. *Geomagnetism and Aeronomy* **49**(1): 115–123.
- Romanov A A, Trusov S V and Romanov A A (2009). Automated information technology for ionosphere monitoring of low-orbit navigation satellite signals. In: *Proceedings of the Fourth Workshop on the Okhotsk Sea and Adjacent Areas North Pacific*. PICES Sci. Rep. No. 36, 203–207.
- Tramutoli V, Bello Di G, Pergola N and Piscitelli S (2001). Robust satellite techniques for remote sensing of seismically active areas. *Ann Geophys* **44**(2): 295–312.
- Tramutoli V, Cuomo V, Filizzola C, Pergola N and Pietrapertosa C (2005). Assessing the potential of thermal infrared satellite surveys for monitoring seismically active areas. The case of Kocaeli [Izmit] earthquake, August 17th, 1999. *Remote Sensing of Environment* **96**: 409–426.
- Tronin A, Hayakawa M and Molchanov O (2002). Thermal IR satellite data application for earthquake research in Japan and China. *J Geodynamics* **33**: 519–534.
- Toutain J-P and Baubron J-C (1998). Gas geochemistry and seismotectonics: A review. *Tectonophysics* **304**: 1–27.
- Xiong P, Shen X H, Bi Y X, Kang C L, Chen L Z, Jing F and Chen Y (2010). Study of outgoing longwave radiation anomalies associated with Haiti earthquake. *Nat Hazards Earth Syst Sci* **10**: 2 169–2 178.