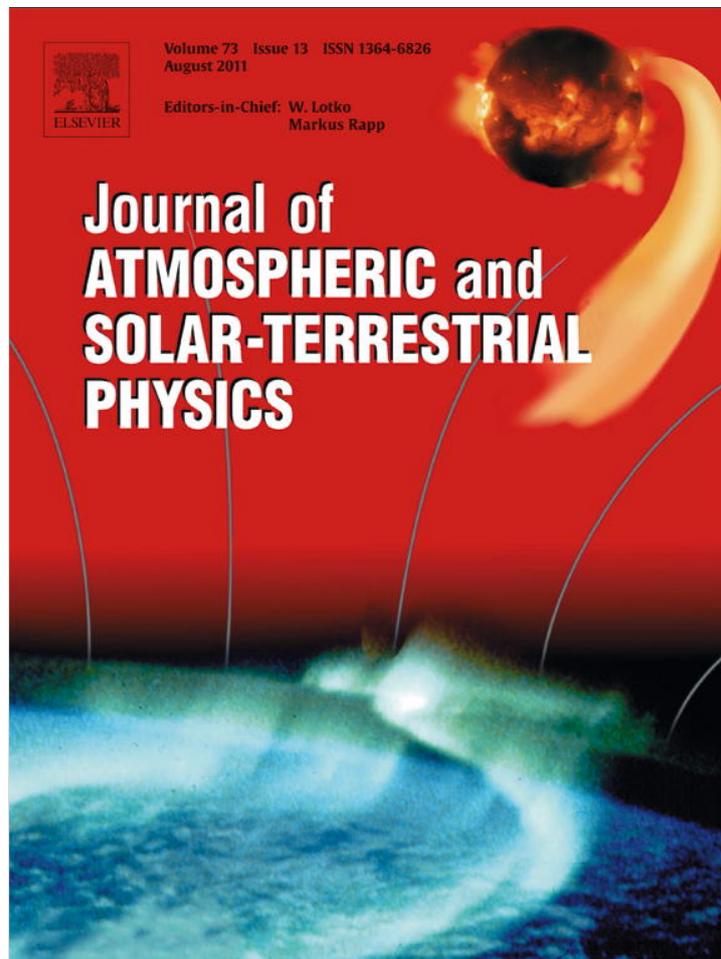


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

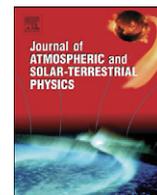
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Vertical TEC over seismically active region during low solar activity

Elvira Astafyeva^{a,b,*}, Kosuke Heki^c^a Institut de Physique du Globe de Paris–Sorbonne Paris Cité, Université Paris Diderot, UMR CNRS 7154, Equipe Géophysique Spatiale et Planétaire, 4, Avenue de Neptune, Saint Maur des Fossés 94107, France^b Institute of Solar–Terrestrial Physics SB RAS, 126, Lermontova Street, 664033 Irkutsk, Russian Federation^c Hokkaido University, Department of Natural History Sciences, N10W8, Kita-ku, Sapporo 060-0810, Japan

ARTICLE INFO

Article history:

Received 6 October 2010

Received in revised form

15 January 2011

Accepted 23 February 2011

Available online 12 April 2011

Keywords:

Vertical TEC

Ionosphere

Seismo-ionosphere relation

Low solar activity

IMF B_z

ABSTRACT

Using data of Japanese dense array of GPS receivers (GEONET) we analyzed variations of total electron content (TEC) over Japan during a period of low solar and geomagnetic activity in April–September 2008. During that time, five large earthquakes with magnitude $M > 6.8$ occurred around the Japanese Islands. We calculated vertical TEC with time resolution of 1 h and we compared the TEC over Japan with TEC over southwestern USA. In order to detect abnormal signals, we processed daily TEC based on median and quartile of preceding 15 days. Knowing that the decisive role in the ionosphere state is performed by space weather effects, we compared the estimated TEC values with time series of the B_z component of the interplanetary magnetic field (IMF), UV solar radiation, index of geomagnetic activity Dst and planetary index Kp. We have found that though the analyzed time period falls on the minimum of solar activity, the observed positive anomalies in the regional TEC correspond to fluctuations of IMF B_z and to the following increase in Kp and Dst indices. Other case of $\sim 25\%$ TEC increase in the duration of four days (DOY: 140–143) is, most likely, caused by increase in the solar UV radiation and coincides with growth of the global TEC. Other positive or negative abnormal TEC variations coincide with fluctuations of the global mean TEC or are of large spatial scale, i.e. much larger than the earthquake preparation zone. Therefore, it is rather difficult to find correlation between the observed anomalies and the five large earthquakes. Our results do not disprove the possibility of precursory phenomena but show the difficulties in identifying earthquake precursors in the ionosphere TEC on the background of TEC changes produced by space weather effects, even during solar minimum.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The Earth's ionosphere is known to be an irregular medium whose state is mainly determined by the solar radiation (Akasofu and Chapman, 1972). Apart from the well pronounced solar-driven variations, 27 day variations (Afraimovich et al., 2008) and 180 day and annual variations (Kakinami et al., 2009), the ionosphere reflects dynamics of thermosphere and occurrence of a variety of geophysical phenomena like planetary waves, atmospheric and lunar tides, etc. Storm-driven ionosphere changes are known to be of large amplitude. At solar maximum and during rising and falling parts of solar cycle there occur numerous geomagnetic storms that increase the amplitude of background ionospheric variations. Therefore, study of the ionosphere during low solar activity is very important

as it may show us clearer the occurrence of phenomena others than of solar and geomagnetic origin.

Pre-seismic ionosphere alterations are one of such “smaller-amplitude” phenomena that can be masked by high solar or geomagnetic activity. It was reported that large earthquakes are often preceded by signals of different nature: electric, magnetic, electromagnetic, luminous, etc. (Gokhberg et al., 1982; Parrot and Lefeuvre, 1985). Some of these signals can propagate into the ionosphere and generate variations of the ionosphere parameters such as critical plasma frequency f_oF2 , virtual height h_mF2 and of the ionospheric total electron content (TEC). The mechanism of appearance of the ionospheric anomalies includes direct coupling between the Earth's surface and the lower ionosphere through electric current (Pulinets et al., 2000), and triggering of atmospheric gravity waves by gas releases or thermal anomalies (Shalimov, 1992a, 1992b; Gokhberg et al., 1994, 1996; Pertsev and Shalimov, 1996; Molchanov and Hayakawa, 2001; Shvets et al., 2004). Thereby, at present, pre-seismic ionosphere anomalies seem to be well analyzed, and discussed in numerous papers (Pulinets, 1998; Pulinets et al., 2003; Pulinets and Boyarchuk, 2004; Liu et al., 2001, 2004, 2006; Zakharenkova et al., 2007).

* Corresponding author at: Institut de Physique du Globe de Paris–Sorbonne Paris Cité, Université Paris Diderot, UMR CNRS 7154, Equipe Géophysique Spatiale et Planétaire, 4, Avenue de Neptune, Saint Maur des Fossés 94107, France.
Tel.: +33 145114182.

E-mail addresses: astafyeva@ipgp.fr (E. Astafyeva), heki@mail.sci.hokudai.ac.jp (K. Heki).

In particular, Liu et al. (2000, 2001) found decrease of f_0F_2 and TEC from 1 to 6 days prior to the 1999 Chi-Chi earthquake in Taiwan (M 7.7). Pulinets et al. (2004) reported TEC decrease the day preceding the San Simeon earthquake of 22 December 2003 which occurred in central California, USA. Later, Liu et al. (2006) investigated the relationship between variations of the plasma frequency at the ionospheric F2 peak f_0F_2 and 184 earthquakes with magnitude $M > 5.0$ during 1994–1999 around the Taiwan area. The pre-earthquake ionospheric anomalies, defined as the abnormal decrease of more than $\sim 25\%$ in the ionospheric f_0F_2 during the afternoon period, 1200–1800 LT, occurred within 5 days before the earthquakes. More recently Liu et al. (2009) have analyzed TEC variations before the 12 May 2008 Wenchuan earthquake (M 7.9) using global ionosphere maps (GIM), and have found that TEC above the forthcoming epicenter anomalously decreased in the afternoon period 4–6 days before the earthquake, and in the late evening period 3e days before the earthquake. They also reported that TEC anomalously enhanced in the afternoon 3 days before the Wenchuan earthquake.

At the same time, as the Earth's ionosphere is characterized by diurnal, seasonal or latitudinal natural fluctuations, sometimes it is difficult to identify pre-seismic effects out of the background ionosphere variability and of alterations produced by high solar or geomagnetic activity. Afraimovich and Astafyeva (2008) have shown that decreases and/or increases of the local ionosphere TEC, which can be taken as pre-seismic signals, often reflect global changes of the ionization caused by the 27 day variations along with other fast alterations by solar and geomagnetic activities. Apart from that, it should be taken into account that parameters of the interplanetary medium, such as interplanetary magnetic field (IMF), play an important role in variability of ionosphere parameters (Astafyeva, 2009). Therefore, the key problem is to distinguish the ionosphere changes caused by enhanced pre-seismic activity from those by various phenomena of "space" origin. Whether the ionospheric anomalies that we observe in the area of future epicenter arrive down from space or they come up from the lithosphere? With time, this question becomes quite a controversial point for scientists.

Pulinets (2007) has proposed a special index of the ionosphere variability, that is sensitive to the pre-earthquake variations and much less sensitive to the magnetic storm variations. Studies of correlation between the records of GPS receivers in different areas showed that in a majority of cases the correlation coefficient grows during geomagnetic disturbances. However, before earthquakes, the correlation coefficient drops within about a 700 km diameter around the earthquake epicenter. In particular, Pulinets et al. (2004) showed that a few days before the California's 16 October 1999 Hector Mine earthquake (M 7.1) the variability index was higher than the index during strong ($Dst \sim -250$ nT) geomagnetic storms. At the same time, analysis of the same 1999 Hector Mine earthquake by Afraimovich et al. (2004) showed that the behavior of TEC was rather controlled by the local time and by fairly moderate geomagnetic activity than by the earthquake preparation.

Dautermann et al. (2007) have investigated ionosphere TEC variations before the San Simeon (22 December 2003, M 6.6) and Parkfield (29 September 2004, M 6.0) earthquakes in Southern California, using the dense network of 256 continuous GPS stations centered in Los Angeles basin. TEC time series averaged over the entire network were found to be dominated by diurnal (24 h) and semidiurnal (12 h) periods reflecting daily solar activity and lunar tides. It has also been found that the period surrounding the San Simeon earthquake suffered from significant space weather effects, so that the precursory event reported by Pulinets et al. (2004), most likely, was an artifact resulting from the enhanced space weather activity.

Apart from the dominating influence of solar and geomagnetic activity the research of ionosphere precursors of earthquakes is

complicated by the shortness of analyzed time intervals, which are usually limited to some number of days before earthquakes. Thus, some anomalies, e.g. those by planetary waves, can appear in the ionosphere periodically, and therefore analyses through insufficient time windows can lead to wrong conclusions about ionosphere pre-seismic alterations (Rishbeth, 2006).

In this study, we analyze behavior of vertical TEC over Japan during seismically active period in April–September 2008 by taking advantage of the high spatial resolution provided by GEONET. For our analysis we take a period of ~ 160 days, which is long enough to exclude ionosphere TEC changes caused by planetary waves, which have periods of $\sim 2, 5, 10, 16$ days (Pancheva et al., 1991; Shalimov, 2001; Lastovicka, 2009), along with other kinds of non-pre-seismic variability. Note that the mentioned period falls on the minimum of solar activity, so that the space weather influence was minimum at that time. Moreover, analysis of solar and geomagnetic activity from 2005 to 2010 showed that the selected period of time belongs to the quietest interval for the last 5 years. All these facts give us a unique opportunity for search of TEC anomalies possibly connected with pre-seismic activity. A special feature of this paper lies in the idea to analyze the ionosphere over seismically active region as it is, i.e. without selection of a certain number of days before/after an earthquake. This is the first study of such kind performed with GEONET.

2. Methods of data processing: estimation of vertical TEC from GPS data

GPS ionospheric sounding is known to be one of the most powerful tools for remote sensing of the ionosphere. The dispersive nature of the ionosphere lets dual frequency GPS measurements (1.2 and 1.5 GHz) provide integral information by the carrier phase differences at ground-based receivers. Methods of TEC calculation have been described in detail in a number of papers (Calais and Minster, 1995; Afraimovich et al., 2001). Slant TEC is expressed as follows:

$$I(t) = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} (L_1 \lambda_1 - L_2 \lambda_2 + \text{const} + nL), \quad (1)$$

where $L_1 \lambda_1$ and $L_2 \lambda_2$ are additional paths of the radio signal caused by the phase delay in the ionosphere (m), L_1 and L_2 represent the number of phase rotations at the frequencies f_1 and f_2 , respectively, λ_1 and λ_2 stand for the corresponding wavelengths (m); const is unknown initial phase path, caused by the unknown number of total phase rotations along the line-of-sight (LOS) and nL are errors in determining the phase path; the constant 40.308 has the dimension (m^3/s^2). For convenience, TEC is usually measured in TEC units, TECU ($1 \text{ TECU} = 10^{16} \text{ m}^{-2}$). Since TEC is an integral parameter, it is impossible to determine the height of TEC disturbance. However, the main contribution to TEC variations would occur around the height of the maximum ionization. This allows us to consider the ionosphere as a thin layer located at the height h_{max} of the ionosphere F2 layer, and TEC represents a point of intersection of a line-of-sight with the thin layer. In this study we assumed h_{max} as 300 km.

We estimated site-specific vertical TEC and the satellite-specific constant biases (sum of the third and the fourth terms in parenthesis of Eq. (1)) using the least-square method. We assumed vertical TEC (VTEC) as the product of slant TEC (STEC) and cosine of the zenith angle Z , an angle between LOS and local zenith at the ionospheric penetration points (IPP), i.e.

$$\text{STEC}(t) = \text{VTEC}(t)/\cos Z + \text{const} \quad (2)$$

Because the constant does not depend on elevation angles, we can separate these two parameters (VTEC and the constant) by observing GPS satellites at various elevations. To avoid arbitrary discontinuities at day boundaries, we concatenated raw GPS observation data files of 3 consecutive days, and assumed that the constant in Eq. (2) does not change over the 3 days period. We let VTEC change continuously (i.e., without jumps) throughout the period as lines with hourly breaks in slopes (piecewise linear function). We also assumed that ionospheric TEC are locally frozen in the space in short-time scales and converted the differences in longitude of IPP into the temporal difference in TEC. If IPP is 15° to the west of the GPS station, we treat the STEC there as VTEC 1 h ahead in time (i.e., we assume slightly different t at the right and left sides of Eq. (2)). Then we extract VTEC changes in the middle day and move the window 1 day ahead. By repeating this process, we finally get time series of VTEC above a particular GPS receiver. In this work we calculated vertical TEC above 50 GPS sites of the Japanese dense Network of GPS receivers GEONET (Fig. 1).

To detect abnormal signals of the GPS TEC variations, we performed data analysis similar to that of Liu et al. (2009). For each moment of time we computed the median M using the TEC values at the same local time for the preceding 15 days. We obtained the deviation of the observed TEC from the computed median, and then calculated the first (or lower) and the third (or upper) quartiles, denoted by LQ and UQ , respectively. It should be noted that under the assumption of a normal distribution with mean m and standard deviation σ for the GPS TEC, the expected values of M and LQ or UQ are m and 1.34σ , respectively (Klotz and Johnson, 1983). To have a stringent criterion, we set the lower bound, $LB = M - 1.5(M - LQ)$ and $UB = M + 1.5(UQ - M)$. Therefore, the probability of a new GPS TEC in the interval (LB, UB) is approximately 65%. The median together with

the associated LB and UB then provides references for the GPS TEC variations on the day in question. Thus, when an observed GPS TEC on that day is greater or smaller than the median of the previous 15 days by UB or LB , we consider it as an upper or lower abnormal GPS TEC value.

In order to understand spatial scale of the detected abnormal TEC, we conducted spatial analysis. For this purpose we used data of GIM (CODE). For each grid point and time moment we computed the median TEC for the preceding 15 days. We further calculated the difference between the observed TEC value and the associated median. Thus the median represents the undisturbed background TEC value, whereas negative or positive deviations indicate reduction or enhancement, respectively.

3. Observations

During the period from 111 to 269 DOY 2008, five large earthquakes with magnitudes from 6.8 to 7.0 occurred around the Tohoku and Hokkaido regions of Japan (<http://earthquake.usgs.gov>, Fig. 1, Table 1).

As seen from Fig. 1 and Table 1, events #1, #3, #5 (DOY 128, 201 and 255) are off shore events whereas events #2 (DOY 165, M 6.9) and #4 (DOY 205, M 6.9) are inland ones. It has been proposed that pre-seismic anomalies can appear within an area called the radius of earthquake preparation area of the lithosphere ("strain circle"), which scales with magnitude M of an earthquake as $\rho = 10^{0.43M}$ km (Dobrovolsky et al., 1979). For M 6.8–7.0 earthquakes this parameter is about 900–1100 km, so that all the territory of Japan can be considered as earthquake preparation area.

Variations of solar-geophysical parameters during April–September 2008 are presented in Fig. 2a–d. Fig. 2e shows fluctuations of global mean TEC, which we calculated from global ionosphere maps (GIM, available from <ftp://ftp.unibe.ch/aiub/CODE/>) by summation of the absolute vertical TEC values for every GIM cell and divided by the total number of GIM cells (Afraimovich et al., 2008). During the analyzed time interval there are no large or moderate geomagnetic storms observed but, despite the minimum of solar activity cycle, there occurred at least four sufficiently large B_z negative events, which could affect the low-latitude ionosphere: on 114, 167, 194 and 248 days. Other large sudden short-term B_z increase occurred on 222 day. These B_z events coincide in time with sharp variations in Dst and Kp values (Fig. 2c, d). Apart from variations of geophysical parameters, there observed two substantial peaks in the intensity of the solar UV radiation on 110–112 and 136–139 days (Fig. 2a), which may cause increase in daily TEC values 4–5 days later (Afraimovich et al., 2008). Another smaller spike in the intensity of the UV flux occurred on 120–123 days. Therefore, from this figure, we can expect effects of UV flux increase in the ionosphere TEC on 114–116 days and from day 140 to 144. Indeed, such peaks in the global mean TEC are seen in Fig. 2e. Increase of global TEC from 122 to 125 is, most likely, related to the spike of UV on 120–123 days. Other significant enhancements of global TEC correspond to the mentioned B_z -negative events of day 167, 194 and 248 and to B_z -positive event of day 222.

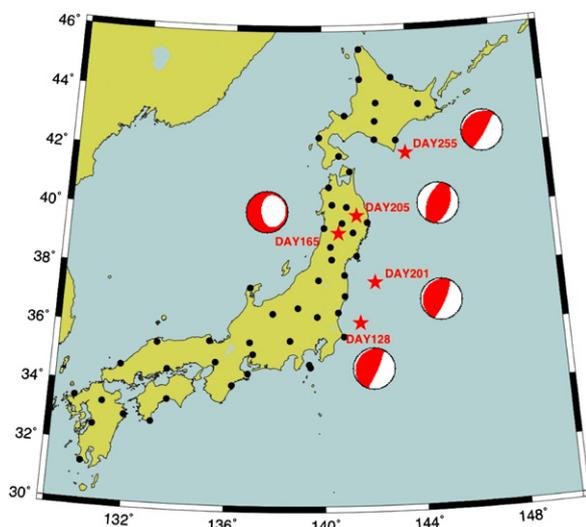


Fig. 1. Locations of the three $M > 6.9$ earthquakes that occurred around the Tohoku area of Japan on 7 May (128 day), 13 June (165 day), 19 July (201 Day), 21 July (205 day) and 11 September (255 day). The stars denote the epicenters and the dots denote location of 50 GPS receivers whose data were used for the analysis.

Table 1
Information on the earthquakes.

	Date	DOY	UT	Epicenter	Depth, (km)	Focal mechanism	Magnitude
#1	7 May 2008	128	16:45	36.16°N; 141.53°E	27	Thrust	6.9
#2	13 June 2008	165	23:43	39.22°N; 140.67°E	8	Thrust	6.9
#3	19 July 2008	201	02:39	37.55°N; 142.2°E	22	Thrust	7.0
#4	23 July 2008	205	15:26	39.81°N; 141.47°E	111	Normal	6.9
#5	11 September 2008	255	00:20	41.89°N; 143.75°E	25	Thrust	6.8

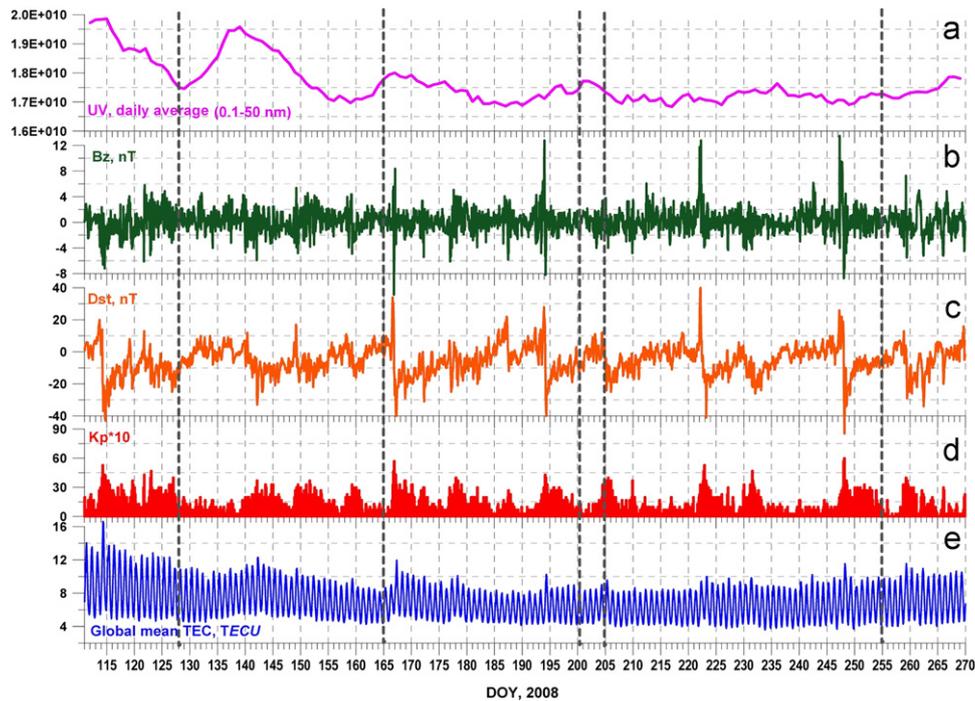


Fig. 2. Variations of the solar UV flux (a), IMF B_z component (b), index of geomagnetic activity Dst (c), of planetary index Kp (d) and of global mean TEC (e) during the period from 15 May to 21 August 2008 (days 135–234). Vertical dashed lines indicate the time of five large earthquakes on 7 May, 13 June, 19 July, 23 July and 11 September 2008. Beachballs are presented in order to indicate the focal mechanisms of the earthquakes.

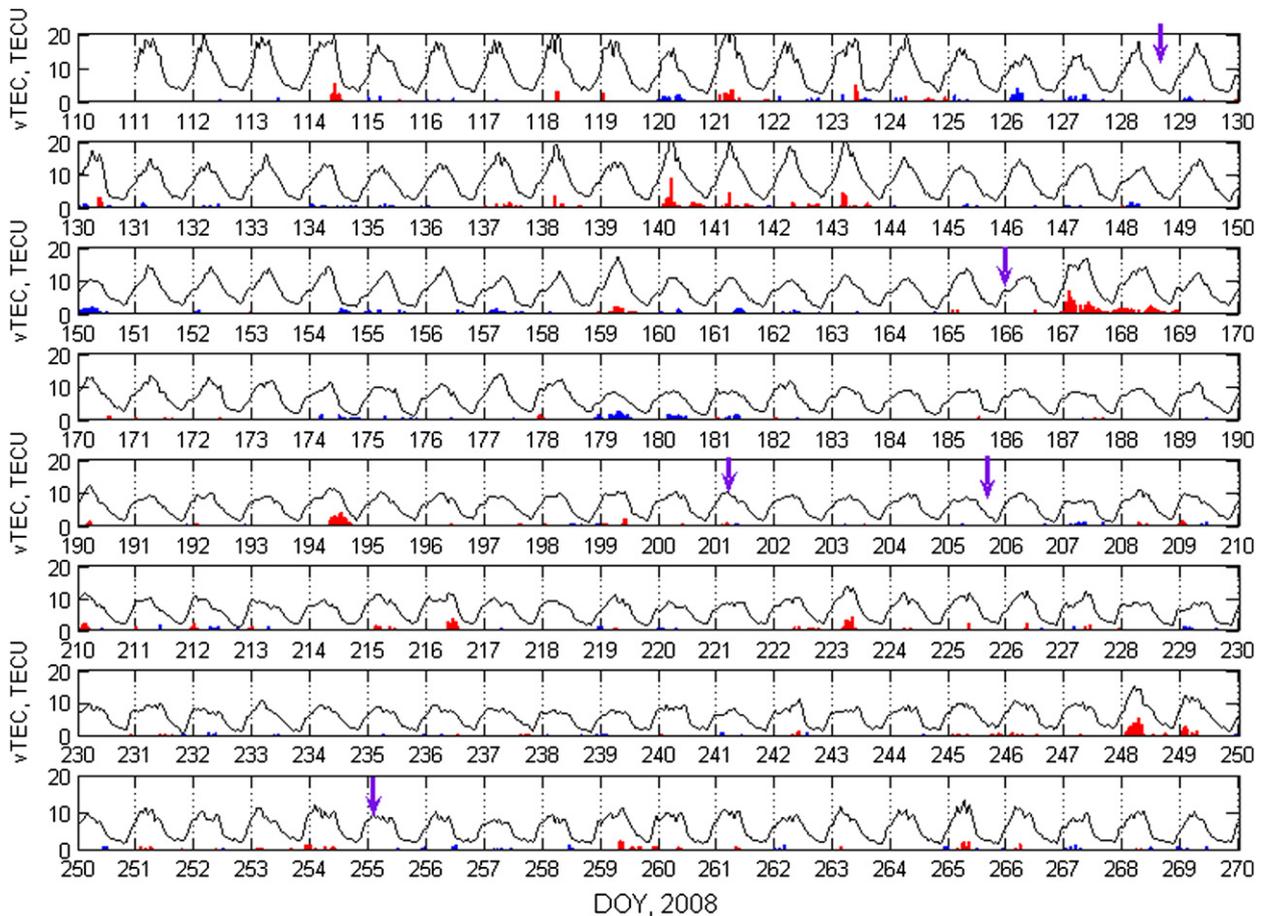


Fig. 3. Time series of vertical TEC within the earthquake preparation area. Thick black line indicates the observed TEC. Blue and red bars show "abnormal" TEC values, i.e. differences between the observed TEC and the lower and upper bounds, respectively. Purple arrows show the time of the five large earthquakes (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 3 displays average vertical TEC derived from 50 GPS receivers of GEONET from day 111 to 269 (from 20 April to 25 September) of 2008 and TEC “anomalies”. Large positive anomalies of 25–40% (red bars) appeared on day 114, 121, 123, 140–143, 167–168, 194, 223 and 248. However, comparing Figs. 2 and 3, we conclude that all these large-amplitude anomalies are of space weather origin. Thus, the abnormal increase of daytime TEC on 140–143 days occurred due to the increase of the UV solar flux, whereas the substantial and long-lasting TEC increase on 167–168 days appeared to be the response to B_z negative event and to the following moderate geomagnetic storms with minimal Dst value of -40 nT and Kp index value of 5. Somewhat smaller positive TEC anomalies of day 194, 223 and 248 correspond to the periods of enhanced geomagnetic activity as well. It is interesting to note that these anomalies appeared within ~ 27 – 29 days one after another, i.e. with the period of solar spin. There are also small-amplitude positive TEC anomalies of duration of 2–4 h: in the morning on 159, 165 and 190 days and in the evening on 177 day. Detailed comparative analysis shows that the anomalous TEC increase of day 159 is correlated with a jump of ~ 1 TECU in the value of global mean TEC. At the same time, IMF B_z decreased to

-6 nT and Dst index dropped to -15 nT. Apparently, such little variations of IMF were enough to cause the following fluctuations of geophysical indices and changes in the global TEC. Similar conclusion can be done for the anomaly of day 177, which coincides with growth of global mean TEC for ~ 1.5 TECU (Fig. 2). The anomalies of days 165 and 190 have no apparent correlation with changes of global TEC or interplanetary and geophysical indices. Therefore, they are “local” anomalies, i.e. appear only around Japan, and their spatial scale should be further analyzed in more detail by plotting maps of differential TEC (Figs. 4–7). Fig. 4a and b does not reveal any discernible TEC enhancement over Japan, but it shows that the value of TEC at 2–4 UT, ~ 3 TECU, exceeded the median value within a very large area. The anomaly of day 190 that occurred at 4–6 UT over Japan is a part of a larger area of high TEC centered at $(25^\circ\text{N}; 160^\circ\text{E})$ (Fig. 4c, d).

Apart from the positive anomalies, we also observed small-amplitude negative anomalies (blue bars in Fig. 3): in the morning on 126, 127, 150, 157, 179–181, 207 and 232 days, in the afternoon on 154 day and in the evening on 218 day. The TEC decrease that occurred on 126–127, 157 and 207 days coincides

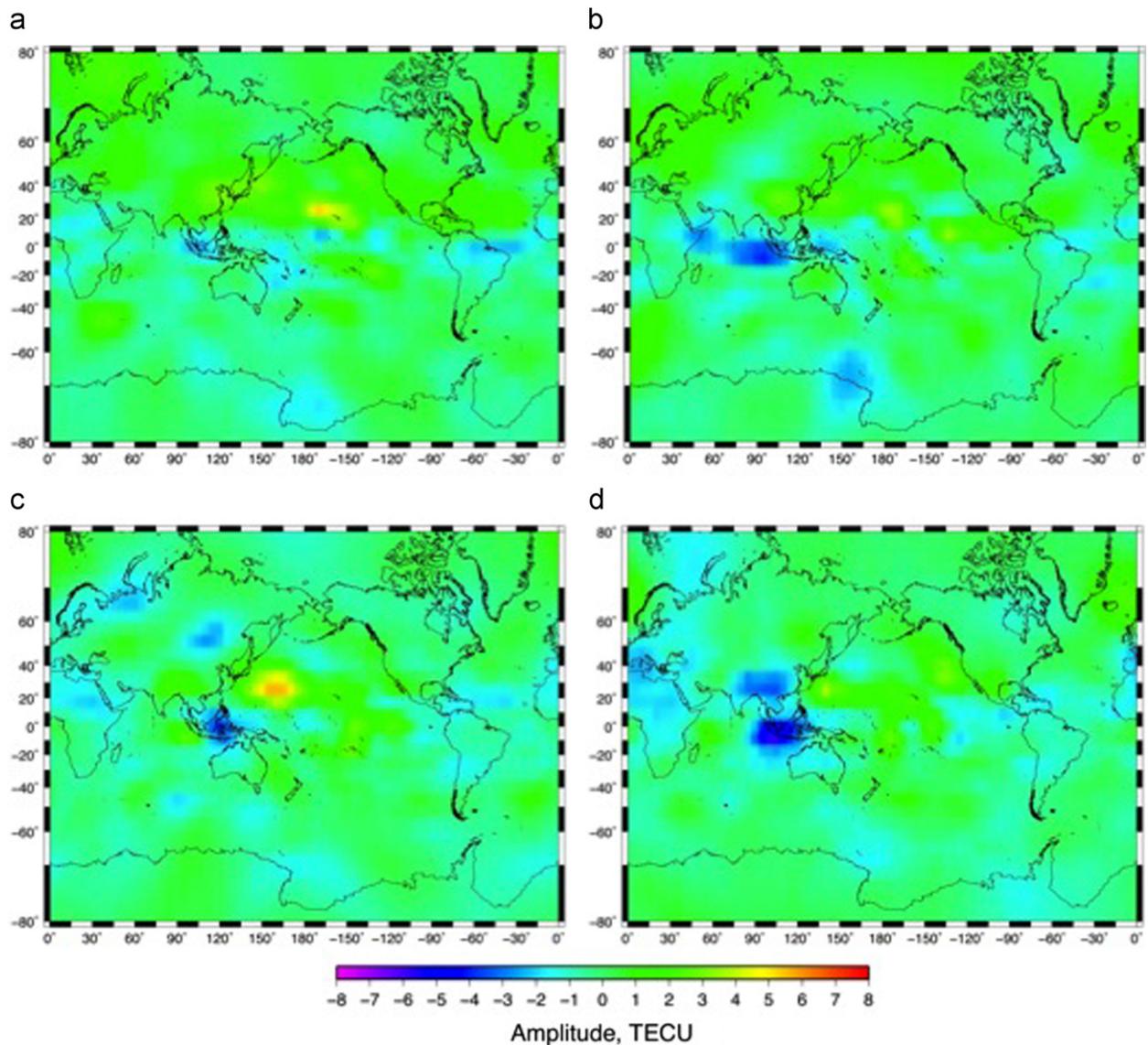


Fig. 4. Maps of differential TEC from 2 to 4 UT on day 165 (a, b) and from 4 to 6 UT on day 190 (c, d). Color denotes the difference between the observed TEC value and the median value calculated for the previous 15 days (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

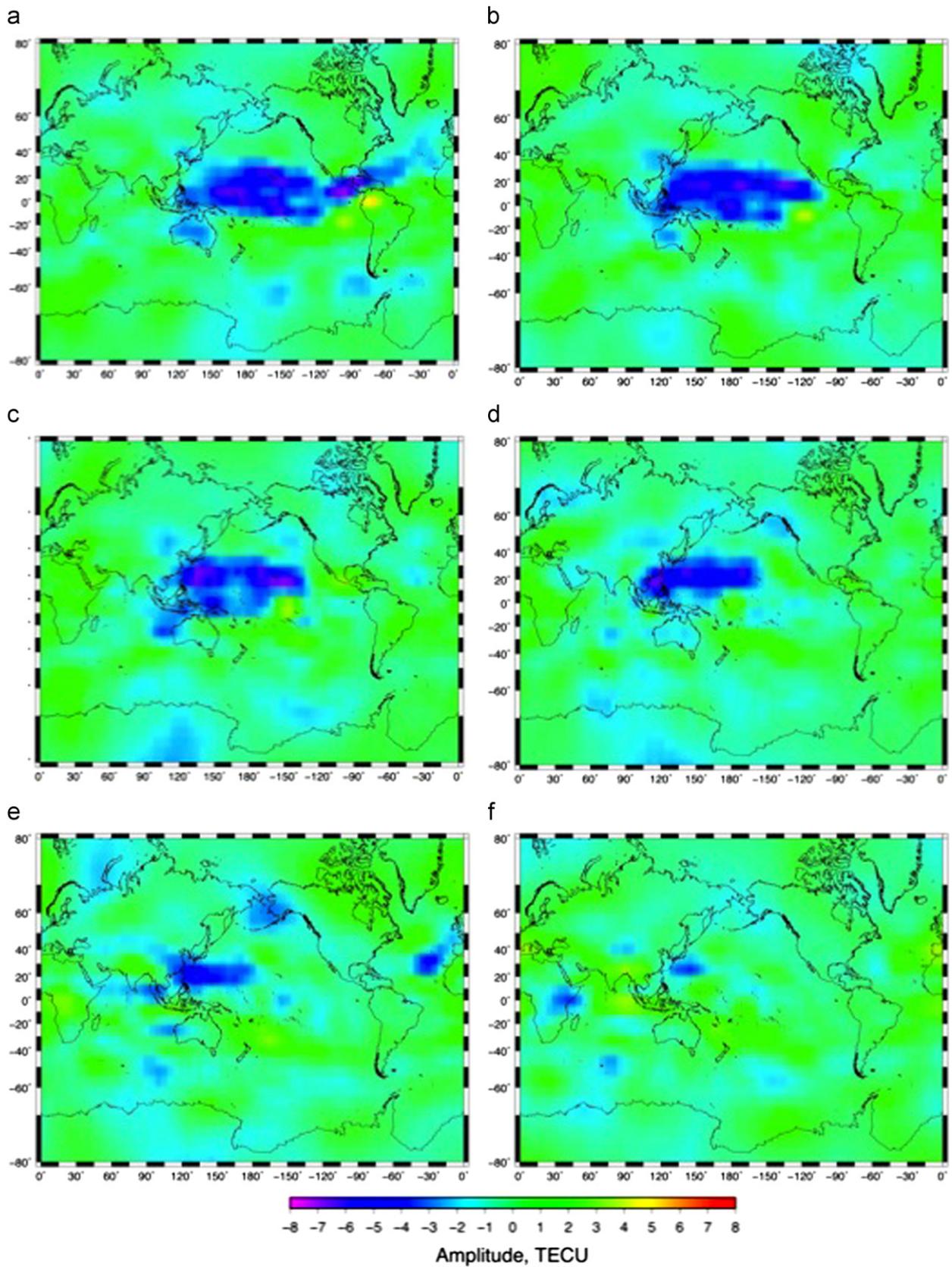


Fig. 5. Maps of differential TEC from 0 to 10 UT on day 150. Color denotes the difference between the observed TEC value and the median value calculated for the previous 15 days. (a) Day 150, 0 UT, (b) Day 150, 2 UT, (c) Day 150, 4 UT, (d) Day 150, 6 UT, (e) Day 150, 8 UT and (f) Day 150, 10 UT (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

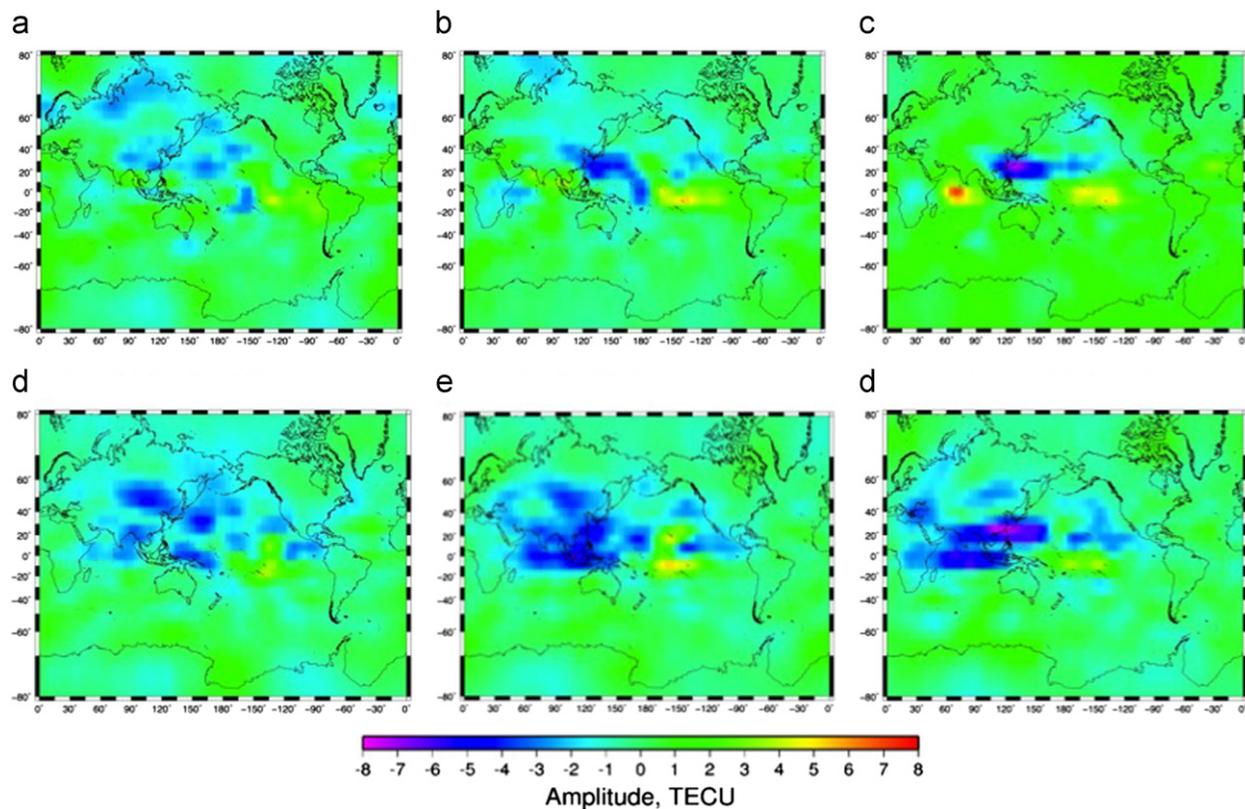


Fig. 6. Maps of differential TEC from 4 to 8 UT for day 179 (a)–(c) and day 180 (d)–(f). Color denotes the difference between the observed TEC value and the median value calculated for the previous 15 days (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

with decrease of the global mean TEC, whereas for the other anomalies we do not find correlation with global TEC variations or with other parameters in Fig. 2. However it is rather difficult to confirm causal relationships of the observed negative anomalies with pre-earthquake phenomena, since these anomalies, apart from the space weather and forcing from above, can be caused by forcing from below by thermosphere, atmospheric meteorology-driven influences, tides, gravity and planetary waves, etc. Thus, before claiming the connection of the anomalies with earthquakes, the locality of these anomalies should be analyzed.

Fig. 5 shows the differential TEC maps for day 150, from 0 to 10 UT. At 0 UT we can see a huge-amplitude and largely spatially spread TEC depletion that is stretched for the whole sunlit side of the Earth, with maximum value of TEC ~ 8 TECU in the local evening (~ 18 – 19 LT). Note that this TEC depletion is confined within $\pm 20^\circ$ of latitude (Fig. 5a) and, most likely, it was caused by the proper dynamics of the low-latitude ionosphere. Then, the anomaly that we see in Japan presents a part of a huge “cloud” of negative TEC. Two hours later, the anomaly lessens in both magnitude and spatial scale. By 4 UT the anomaly further fades and diminishes more noticeably by 6–8 UT, remaining centered along $+20^\circ$ N (Fig. 5b–e). The depletion almost disappears by 20 LT. (10 UT, Fig. 5f).

Fig. 6 demonstrates the differential TEC maps for day 179 (a–c) and day 180 (d–f), both from 4 to 8 UT. Although Japan is covered by the ionization depletion these negative anomalies are widely spread, i.e. the observations by GEONET reflect just a part of the large-scale TEC redistribution. Because the spatial scales of the observed anomalies are much larger than the earthquake’s preparation area, it is rather difficult to claim any geophysical relevance between the TEC anomalies and the earthquakes.

In order to additionally check the spatial occurrence of the observed anomalies, we calculated vertical TEC in the area of the same geomagnetic latitudes as the epicentral area of the five

considered earthquakes. As a “check”-region we took the area (34 – 40° N; 237 – 248° E) in southwestern USA and we performed the same sort of data processing in order to reveal anomalous TEC changes (Fig. 7). It should be noted that the difference in local time between Japan and western USA is 18 h, so that we expect the anomalies to be time-shifted in these two regions with respect to each other. Fig. 7 confirms the above stated conclusions on the global character of the majority of the found TEC anomalies. We observe sufficiently large TEC enhancements on 114, 115, 117, 118, 137–140, 167, 204, 210 and 223 days and TEC depletions on 124, 127, 156, 161, 164, 178, 180, 188, 217, 249 and 250 days. Most of these anomalies appear within the area of earthquake preparation (Fig. 3). Note that the above mentioned large-amplitude anomalies of days 194 and 248 in Japan are quite small in data series of Fig. 8. The B_z negative event started at 5 UT (15 LT in Japan and 20 LT in the Californian region) and lasted for 3 h. It is known that TEC increase starts about 3 h after the IMF B_z turns southward (Astafyeva, 2009). Therefore, we could expect the dayside TEC to grow from 8 UT.

Maps of differential TEC for day 194 show TEC enhancements around the area of Japan (Fig. 8). The amplitude of the anomaly reaches its maximum by 10–12 UT (Fig. 8b, c). It is obvious that the observed increase of TEC over Japan reflects and is a part of the TEC enhancement of much larger spatial scale than the area of the earthquake’s preparation. We observe TEC increase in the whole sunlit side of the Earth and this increase is located within 20 – 30° N. Such phenomena are caused by the storm-time dynamics of the EIA and reinforcement of the fountain effect as a reaction to B_z negative events (Astafyeva, 2009). From 14 UT the value and the spatial scale of differential TEC decrease (Fig. 8d), so that this anomaly does not reach the western coast of North America, i.e. the check-region. Similar situation was observed for the event of day 248.

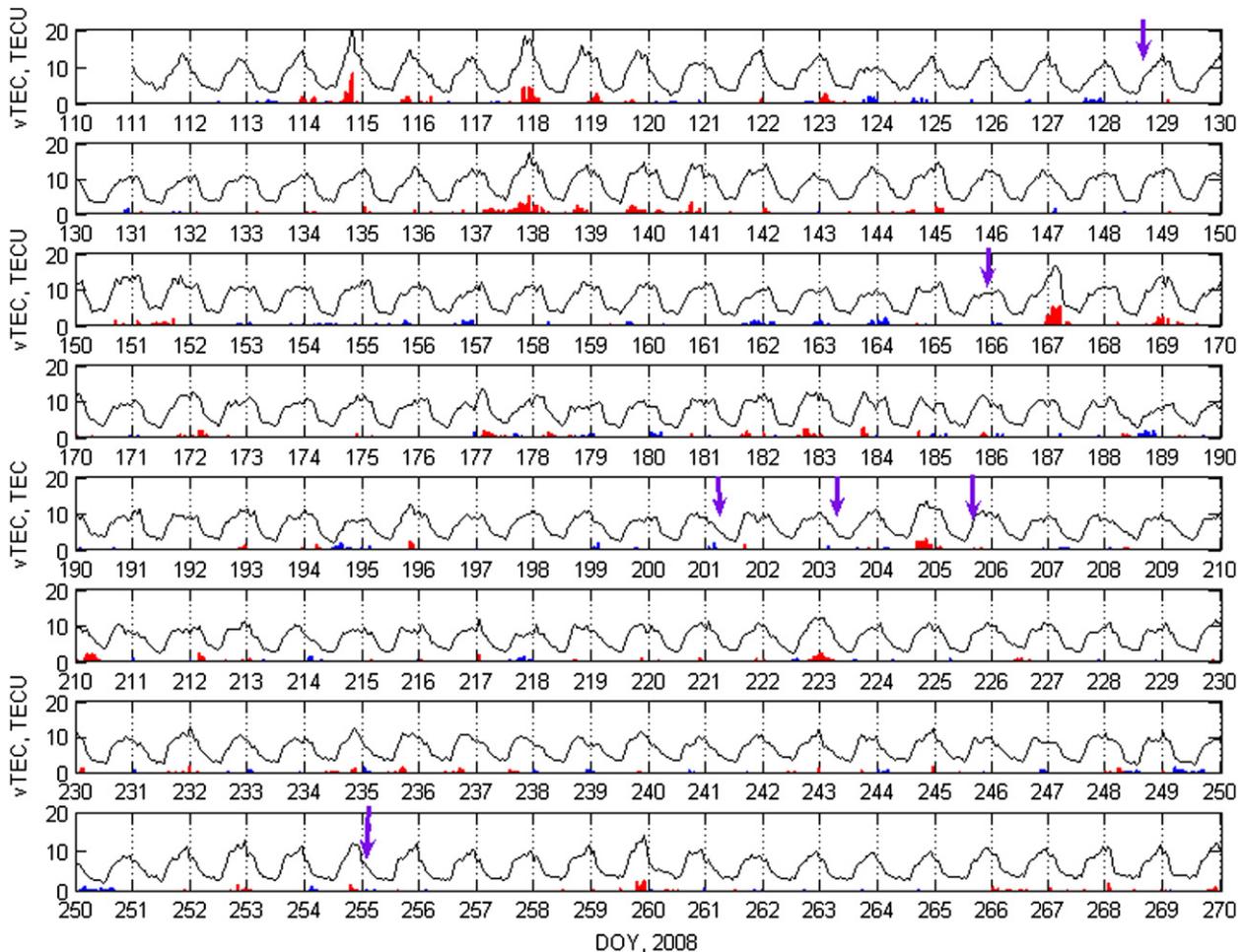


Fig. 7. Time series of vertical TEC within a “check”-region in North America (36–40°N; 113–117°W). Thick black line indicates the observed TEC. Blue and red bars show “abnormal” TEC values. Purple arrows show the time of the five large earthquakes (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4. Conclusions

Using data of GEONET we have analyzed vertical TEC over Japan during seismically active period in April–September 2008. Although we did observe abnormal positive and negative TEC signatures, it is rather difficult to find correlation between the anomalies and the five large earthquakes that occurred in Japan in May–August 2008.

Though the studied period can be characterized as a period of lowest solar and geomagnetic activity from 2005 to 2010, the observed large positive regional TEC anomalies were found to correspond to variations of solar flux and interplanetary magnetic field parameters. For instance, anomalous $\sim 20\%$ augmentation of VTEC of days 114, 121 and 123 corresponds to surges in solar UV flux. Another example of $\sim 25\%$ increase in dayside TEC that started on 140 day and lasted for 4 consecutive days was also caused by a surge of the UV radiation. These anomalies coincided with the growth of the global TEC. Noticeable VTEC enhancements of days 167, 168, 194, 223 and 248 occurred shortly after the fluctuations of the intensity of the IMF B_z and the following changes in Kp and Dst indices. It is known that reconnection between intensive southward IMF B_z and the Earth’s magnetic field leads to appearance of strong dawn-to-dusk electric field which moves the equatorial F-region plasma upward and enhances the fountain effect (Tsurutani et al., 2004). Thus, sharp drop of the IMF B_z down to -30 and -40 nT leads to drastic

growth of TEC within the EIA along with displacements of the EIA crests to $\pm 30^\circ$ of magnetic latitude (Tsurutani et al., 2004; Astafyeva et al., 2007; Astafyeva, 2009). Here we show that a drop of the IMF B_z down to -5 and -7 nT is enough to produce $\sim 20\text{--}30\%$ excess of regional VTEC over the 15 day median values. Global maps of differential VTEC allow tracking the peculiarities of the spatial response to such “small-amplitude” IMF B_z events. From Figs. 2, 3 and 5, it is seen that VTEC increment starts ~ 3 h after the B_z turned southward, the maximum changes occurred within the equatorial latitudes in the evening longitudinal sector.

Other than the space weather origin ones, the observed negative and small-amplitude positive anomalies were found to be of a large spatial scale so that they covered the area above the future earthquakes. Therefore, it is unlikely that those anomalies were caused by the earthquakes’ preparation processes, but, most likely, they were associated with the ionospheric “natural” variability by thermosphere, stratosphere (Goncharenko et al., 2010), tidal effects, changes in neutral composition, etc.

Special attention should be paid on the periodicity in the appearance of the anomalies, both positive and negative. It is important to cut out the influence of periodical phenomena such as solar rotation, planetary waves or tides, so that periodical abnormal signals could not be mistakenly taken as precursory signals. For instance, the large-amplitude positive anomalies of days 114, 140–142, 167, 194, 223 and 248 occur within a period of $\sim 26\text{--}29$ days one after another. The fact of appearance of TEC

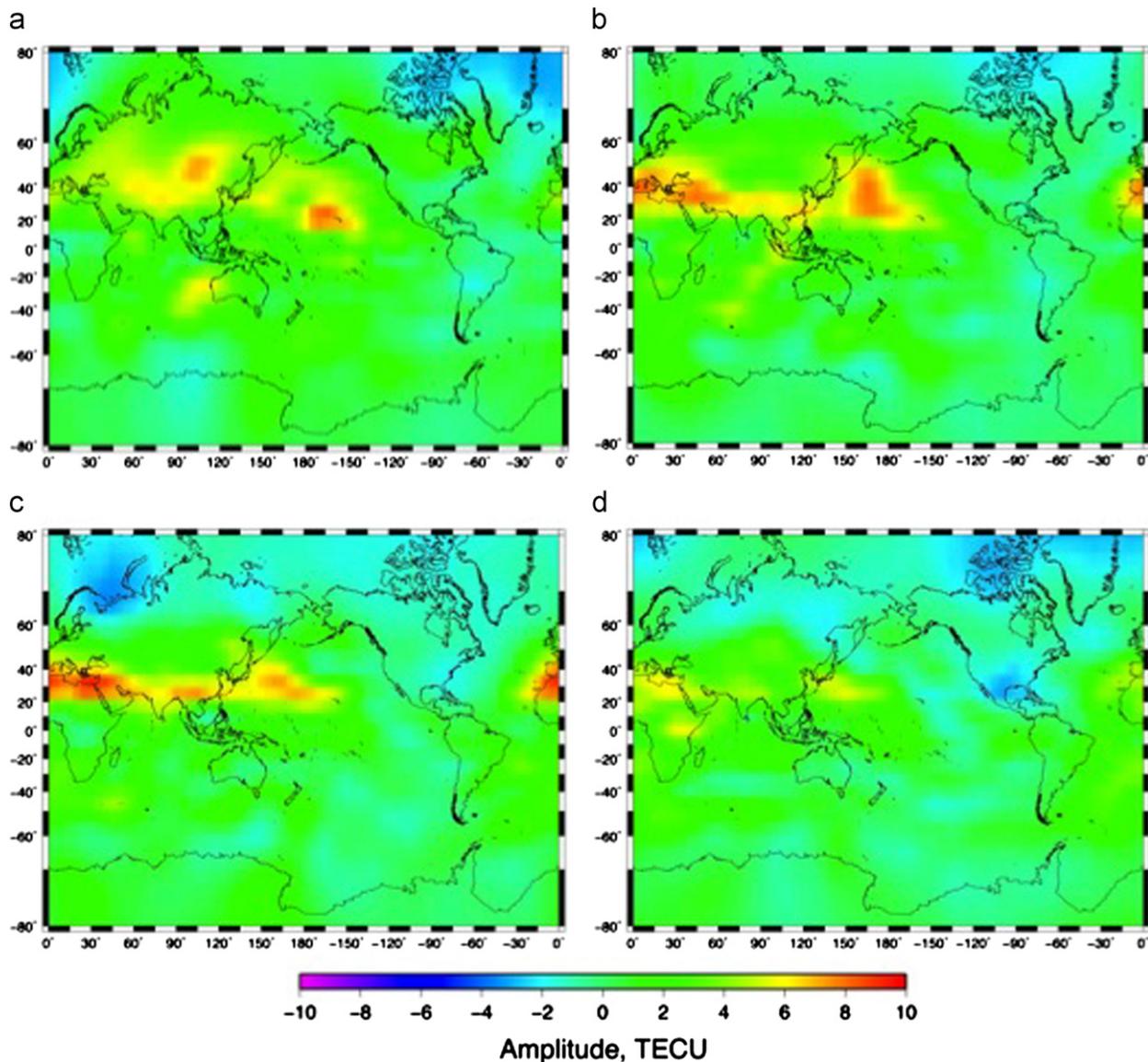


Fig. 8. (a–d) Maps of differential TEC from 8 to 14 UT on day 194. Color denotes the difference between the observed TEC value and the median value calculated for the previous 15 days (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

increase with the period of solar rotation confirms the involvement of the Sun in these anomalous enhancements. The same range of periodicity is observed in the occurrence of negative anomalies on 150, 179–181, 207 and 232 days. Other periods in appearance of TEC anomalies can be caused by planetary waves, which have periods of $\sim 2, 5, 10$ and 16 days (Pancheva et al., 1991; Shalimov, 2001; Lastovicka, 2009).

Focal mechanism of a future earthquake could possibly influence the enhancement of pre-seismic activity in the near-epicentral area. The five mentioned earthquakes are of different focal mechanisms—the earthquakes of days 128, 165, 201 and 255 are of thrust type whereas the earthquake of day 205 is normal fault. However, we did not see any specific peculiarities before these events. The location of the earthquakes' hypocenters (inland for days 165 and 205 and underwater for days 128, 201 and 255) does not seem to change our conclusion either.

This study does not corroborate previous works on ionosphere precursors of earthquakes and it does not disprove the possibility of the existence of precursory phenomena. Our work demonstrates the difficulties of searching the earthquake precursors in the ionosphere

TEC, in particular, with the help of GPS. It should be noted that earthquake #2 (DOY 165, M 6.9) was the largest inland earthquake that occurred in Japan since the dense GPS array was deployed. Moreover, a period of low solar activity means small observational noises from space weather effects, so that appearance of some pre-earthquakes signatures in the ionosphere could be expected. Absence of clear precursory signals in TEC for this earthquake may suggest that the monitoring of TEC could not be practical for short-term earthquake predictions even if such precursors exist. Generally speaking, TEC is an integral parameter of the ionosphere that makes it impossible to localize the height of an ionosphere disturbance. On the other hand, GPS is a powerful tool to study the ionosphere since it provides continuous TEC measurements and good spatial coverage. Creation of precise maps of ionospheric vertical TEC along with good time resolution would perhaps give more information about the background short-time TEC changes that is of high importance and should be quite useful for the issue of ionospheric precursors of earthquakes. This study makes a step towards better understanding of background TEC variations during a period of low solar activity and of high seismic activity and of use of GPS for such purposes.

Acknowledgments

A part of this study was performed while E.A. had worked at Hokkaido University as JSPS Post-Doctoral Fellow (Fellowship by the Japanese Society for the Promotion of Science). E.A. acknowledges support of CNES for the Post-Doctoral position during which this work was finalized. This is IGP contribution no. 3152.

References

- Akasofu, S.I., Chapman, S., 1972. *Solar–Terrestrial Physics*. Pergamon, Oxford 512 p.
- Afraimovich, E.L., Perevalova, N.P., Plotnikov, A.V., Uralov, A.M., 2001. The shock-acoustic waves generated by the earthquakes. *Ann. Geophys.* 19 (4), 395–409.
- Afraimovich, E.L., Astafyeva, E.I., Gokhberg, M.B., Lapshin, V.M., Permyakova, V.E., Steblou, G.M., Shalimov, S.L., 2004. Variations of the total electron content in the ionosphere from GPS data recorded during the Hector Mine earthquake of October 16, 1999, California. *Russ. J. Earth Sci.* 6 (5), 339–354.
- Afraimovich, E.L., Astafyeva, E.I., Zhivetiev, I.V., Yasukevich, Yu.V., Oinats, A.V., 2008. Global electron content: a new conception to track solar activity. *Ann. Geophys.* 26, 335–344.
- Afraimovich, E.L., Astafyeva, E.I., 2008. TEC anomalies—local TEC changes prior to earthquakes or TEC response to solar activity changes? *Earth Planets Space* 60, 961–966.
- Astafyeva, E.I., Afraimovich, E.L., Kosogorov, E.A., 2007. Dynamics of total electron content distribution during strong geomagnetic storms. *Adv. Space Res.* 39, 1313–1317. doi:10.1016/j.asr.2007.03.006.
- Astafyeva, E., 2009. Effects of strong IMF B_z southward events on the equatorial and mid-latitude ionosphere. *Ann. Geophys.* 27, 1175–1187.
- Calais, E., Minster, J.B., 1995. GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake. *Geophys. Res. Lett.* 22 (9), 1045–1048.
- Dautermann, T., Calais, E., Haase, J., Garrison, J., 2007. Investigation of ionospheric electron content variations before earthquakes in southern California, 2003, 2004. *J. Geophys. Res.* 112, B02106. doi:10.1029/2006JB004447.
- Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. *Pure Appl. Geophys.* 117, 1025–1044.
- Gokhberg, M.B., Morgounov, V.A., Yoshino, T., Tomizawa, I., 1982. Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan. *J. Geophys. Res.* 87, 7824–7828.
- Gokhberg, M.B., Nekrasov, A.K., Shalimov, S.L., 1994. A new approach to the problem of the lithosphere–ionosphere coupling before the earthquakes. In: Hayakawa, M., Fujinawa, Y. (Eds.), *Electromagnetic Phenomena Related to Earthquake Prediction*. Terra Sci. Publ. Co., Tokyo, pp. 619–625.
- Gokhberg, M., Nekrasov, A., Shalimov, S., 1996. On influence of unstable greenhouse gas outflow in seismically active region upon the ionosphere. *Phys. Solid Earth* 8, 52–55 in Russian.
- Goncharenko, L.P., Chau, J.L., Liu, H.-L., Coster, A.J., 2010. Unexpected connections between the stratosphere and ionosphere. *Geophys. Res. Lett.* 37, L10101. doi:10.1029/2010GL043125.
- Kakinami, Y., Chen, C.H., Liu, J.Y., Oyama, K.-I., Yang, W.H., Abe, S., 2009. Empirical models of total electron content based on functional fitting over Taiwan during geomagnetic quiet condition. *Ann. Geophys.* 27, 3321–3333.
- Klotz, S., Johnson, N.L. (Eds.), 1983. *Encyclopedia of Statistical Sciences*. John Wiley, Hoboken, N.J.
- Lastovicka, J., 2009. Lower ionosphere response to external forcing: a brief review. *Adv. Space Res.* 43, 1–14.
- Liu, J.Y., Chen, Y.I., Pulinets, S.A., Tsai, Y.B., Chuo, Y.J., 2000. Seismo-ionospheric signatures prior to $M \geq 6.0$ Taiwan earthquakes. *Geophys. Res. Lett.* 27, 3113–3116.
- Liu, J.Y., Chen, Y.I., Chuo, Y.J., Tsai, H.F., 2001. Variations of ionospheric total electron content during the Chi-Chi earthquake. *Geophys. Res. Lett.* 28 (7), 1383–1386.
- Liu, J.Y., Chuo, Y.J., Shan, S.J., Tsai, Y.B., Chen, Y.I., Pulinets, S.A., Yu, S.B., 2004. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. *Ann. Geophys.* 22, 1585–1593.
- Liu, J.Y., Chen, Y.I., Chuo, Y.J., Chen, C.S., 2006. A statistical investigation of pre-earthquake ionospheric anomaly. *J. Geophys. Res.*, Ill, A05304. doi:10.1029/2005JA011333.
- Liu, J.Y., Chen, Y.I., Chen, C.H., Liu, C.Y., Chen, C.Y., Nishibashi, M., Li, J.Z., Xia, Y.Q., Oyama, K.I., Hattori, K., Lin, C.H., 2009. Seismo-ionosphere GPS TEC anomalies observed before the 12 May 2008 Mw 7.9 Wenchuan Earthquake. *J. Geophys. Res.* 114, A04320. doi:10.1029/2008JA013698.
- Molchanov, O.A., Hayakawa, M., 2001. VLF monitoring of atmosphere–ionosphere boundary as a tool to study planetary waves evolution and seismic influence. *Phys. Chem. Earth C* 26, 453–458.
- Pancheva, D., Lastovicka, J., de la Morena, B.A., 1991. Quasi-periodic fluctuations in ionospheric absorption in relation to planetary activity in the stratosphere. *J. Atmos. Terr. Phys.* 53, 1151–1156.
- Parrot, M., Lefevre, F., 1985. Correlation between GOES VLF emissions and earthquakes. *Ann. Geophys.* 3, 733–748.
- Pertsev, N., Shalimov, S., 1996. Generation of atmospheric gravity waves in seismically active regions and their influence upon the ionosphere. *Geomagn. Aeron.* 36 (2), 111–118 in Russian.
- Pulinets, S.A., 1998. Seismic activity as a source of the ionospheric variability. *Adv. Space Res.* 22 (6), 903–906.
- Pulinets, S.A., Boyarchuk, K., Hegai, V.V., Kim, V.P., Lomonosov, A.M., 2000. Quasielectrostatic model of atmosphere–thermosphere–ionosphere coupling. *Adv. Space Res.* 26, 1209–1218.
- Pulinets, S.A., Legen'ka, A.D., Gaivoronskaya, T.V., Depuev, V.K., 2003. Main phenomenological features of ionospheric precursors of strong earthquakes. *J. Atmos. Sol. Terr. Phys.* 65, 1337–1347.
- Pulinets, S.A., Boyarchuk, K., 2004. *Ionospheric Precursors of Earthquakes*. Springer, Berlin, Germany 315 p.
- Pulinets, S.A., Gaivoronska, T.B., Ciralo, L., 2004. Correlation analysis technique revealing ionospheric precursors of earthquakes. *Nat. Hazards* 4, 697–702.
- Pulinets, S.A., 2007. Natural radioactivity, earthquakes, and the ionosphere. *EOS Trans. Am. Geophys. Union* 88 (20), 217–218.
- Rishbeth, H., 2006. Ionospheric precursors of earthquakes? *EOS Trans. Am. Geophys. Union* 87 (32), 316–317.
- Shalimov, S.L., 1992a. Lithosphere–ionosphere relationship: A new way to predict earthquakes? *Int. Geosci. Newsmag. Episodes* 15 (4), 252–254.
- Shalimov, S., 1992b. Influence of long-period earth's oscillations on the ionosphere. *Phys. Solid Earth* 7, 89–94 in Russian.
- Shalimov, S.L., 2001. Ionospheric irregularities initiated by planetary waves. *Cosmic Res.* 39 (N6), 559–563.
- Shvets, A., Hayakawa, M., Maekawa, S., 2004. Results of subionospheric radio LF monitoring prior to the Tokachi ($M=8$, Hokkaido, 25 September 2003) earthquake. *Nat. Hazards* 4, 647–653.
- Tsurutani, B., Mannucci, A., Iijima, B., Abdu, M.A., Sobral, J.H.A., Gonzalez, W., Guarneri, F., Tsuda, T., Saito, A., Yumoto, K., Fejer, B., Fuller-Rowell, T.J., Kozyra, J., Foster, J.C., Coster, A., Vasiliunas, V.M., 2004. Global dayside ionospheric uplift and enhancement associated with interplanetary electric fields. *J. Geophys. Res.* 109, A08302.
- Zakharenkova, I.E., Shagimuratov, I.I., Krankowski, A., Lagovsky, A.F., 2007. Precursor phenomena observed in the total electron content measurements before great Hokkaido earthquake of September 25, 2003 ($M=8.3$). *Stud. Geophys. Geod.* 51 (2), 267–278.