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Effects of strong IMF B_z southward events on the equatorial and mid-latitude ionosphere

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Abstract. Dayside ionospheric response to five intense geomagnetic storms ($D_{st}<-120$ nT) that occurred in 2001–2005 was investigated by use of simultaneous TEC measurements by the CHAMP, SAC-C, TOPEX/Jason-1 satellites. Since the satellites passed over different longitudinal sectors and measured TEC in different range of altitudes, it was possible to obtain information about altitudinal and longitudinal ionosphere redistribution during these storms. Severe enhancements (up to ∼350%) of the equatorial and mid-latitude TEC above ∼430 km with concurrent traveling of the equatorial anomaly crests for a distance of 10–15° of latitude were observed during two of the five events analyzed here (6 November 2001 and 8 November 2004). This phenomenon, known as the dayside ionosphere uplift, or the "daytime super-fountain effect", occurred after sudden drop in IMF B_z and consequent penetration of the electric fields to the low-latitude ionosphere. However, the same order B_z negative events caused comparatively weak changes in the dayside TEC (up to ∼80 TECU) during the other three events of 18 June 2003, 11 February 2004 and 24 August 2005. At the main phase of these storms there were mostly observed formation of the "typical" dual peak structure of the equatorial anomaly rather than the reinforcement of the fountain effect and the anomaly itself. Possible reasons and factors responsible for the development of the extreme ionosphere effects are discussed in the paper.

Keywords. Ionosphere (Equatorial ionosphere; Mid-latitude ionosphere) – Radio science (Ionospheric physics)

1 Introduction

Despite numerous studies of the ionosphere response to geomagnetic storms performed for several decades (Gonzalez and Tsurutani, 1987; Gonzalez et al., 1994; Abdu et al., 1991; Huang et al., 2005; Mannucci et al., 2005; Zhao et al., 2005; Astafyeva et al., 2007; Basu et al., 2007), our understanding of the ionosphere storm at the area of the equatorial ionization anomaly (EIA) seems unsatisfactory.

The equatorial plasma distribution is controlled by the neutral winds and electric fields. The neutral winds induce the hemispheric asymmetry of the ionosphere with respect to the magnetic equator, with large plasma flow (towards the hemisphere of stronger poleward wind) and stronger anomaly crest occurring in opposite hemispheres. The zonal electric field at the magnetic equator, being eastward during the day, creates a steady upward $\boldsymbol{E}\times\boldsymbol{B}$ plasma drift. This plasma rises until the pressure forces are high enough that it starts to slide down the magnetic field lines, assisted by gravity. This creates the ionization trough at the magnetic equator and plasma density enhancements (the EIA crests) at ±15° magnetic latitudes during geomagnetically quiet conditions (Abdu et al., 1990; Fejer, 1991). Just after sunset the eastward electric field is enhanced and the F-region plasma can drift to even higher altitudes. The whole phenomenon is known as the fountain effect.

During the main phase of geomagnetic storms, when the interplanetary magnetic field (IMF) turns southward and intensifies, the interplanetary electric field can penetrate to the low-latitude ionosphere for many hours without decay (Huang et al., 2005). The reconnection between southward IMF and the Earth's magnetic field leads to a strong dawn-to-dusk electric field which moves the equatorial F-region plasma upward enhancing the fountain effect: the fountain rises up to 800–1000 km altitude at the equator and covers about ±30° of magnetic latitude (MLAT). Solar photoionization replaces the uplifted plasma at lower altitudes, leading

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Table 1. TOPEX/Jason-1, CHAMP and SAC-C satellite orbital parameters.

Satellite	Altitude, km	Orbital period, min	Orbit inclination, deg	Altitude range of TEC measurements, km
TOPEX/Jason-1	1336	112	66	0÷1336
CHAMP	350–430[a]	91	87	∼400÷20 200
SAC-C	715	99	98	715÷20 200

[a] the CHAMP orbital altitude changed from 430 km in 2001 to 350 km in 2005

to an overall increase in the ionosphere TEC (e.g., Vlasov et al., 2003; Tsurutani et al., 2004; Mannucci et al., 2005; Astafyeva et al., 2007; Basu et al., 2007). The phenomenon of the ionosphere dayside uplift due to "super fountain effect" (SFE) has been described and shown in detail for a very intense geomagnetic storm of 5–6 November 2001 (Tsurutani et al., 2004). Then, the dayside SFE was observed during the "Halloween storms" of 29–31 October 2003 (Mannucci et al., 2005; Basu et al., 2007; Tsurutani et al., 2007, 2008) and for intense geomagnetic storms of 21 October 2001, 7–8 September 2002 and 20 November 2003 (Astafyeva, 2009). It was shown that sudden drop of B_z IMF leads to a significant TEC increase above 715 km, exceeding 2–3 times the TEC level during geomagnetically quiet and/or moderate conditions (Astafyeva, 2009).

The goal of this paper is to examine ionosphere TEC response to five strong B_z negative events followed by intense geomagnetic storms, using TEC measurements of the satellite altimeters TOPEX and Jason-1, as well as CHAMP and SAC-C GPS data. The main subject of this study are the most prominent dayside effects produced at middle and low-latitudes by geomagnetic storms. Because the southward IMF B_z events of long duration (>3 h) and large intensity (<-10 nT) are known to be the dominant parameter responsible for the development of the storm's main phase (Gonzalez and Tsurutani, 1987), there were selected events with drop of IMF B_z below -12–15 nT that lasted no less than $\sim$3 h and which consequently led to decrease of D_{st} index to -120–150 nT. Comparative analysis of the ionosphere TEC effects of the five intense geomagnetic storms will be performed and the principal factors responsible for the development of the ionosphere super-storms will be discussed in the last section of this paper. This study is of particular interest also because extremely intensive ionosphere disturbances can severely affect space-based communications and GPS application systems, so the results could be useful for prediction the effects on global navigation satellite systems.

1.1 Methods of data analysis

Table 1 contains orbit parameters of the TOPEX/Jason-1, CHAMP and SAC-C satellites and range of TEC measurements provided.

The dual-frequency satellite altimeters TOPEX and Jason-1 perform 1-s measurements of VTEC beneath the satellites, i.e. between the water surface and the orbit height of about of 1335 km (Fu et al., 1994; http://www.aviso.oceanobs.com/html/missions/welcome_uk.html). Satellite altimeter observations of ice and sea surface heights are affected by the retardation/refraction of the altimeter signal in the ionospheric plasma. By measuring the heights above the Earth surface at two frequencies the ionosphere electron content between the ground and the satellite can be determined. Thus, dual-frequency altimeters provide TEC measurements as a byproduct of the sea surface height observations. The data of satellite altimeters are very helpful while making observations in the areas with the lack of ground-based instruments for observing the ionosphere, e.g. above oceans. However, since the altimeters were designed to measure only ocean heights, there are data gaps over landmasses. To analyze the ionosphere response to geomagnetic storm on 5–6 November 2001 there were used data of the TOPEX altimeter, and for the other events – data of Jason-1.

CHAMP passes practically at the altitude of the ionosphere maximum of ionization (350–400 km) in a meridional direction (http://op.gfz-potsdam.de/champ) and provides TEC value between its orbit height and the orbit of GPS satellite 20 200 km. Thus, CHAMP passes are close to the height of the F2 layer peak density in a meridional direction which makes it possible to estimate the contribution of the upper ionosphere to TEC. From the whole set of CHAMP TEC measurements there were selected data for those GPS satellites that had the maximum elevation angles at the time of observations. The disadvantage of this method is that TEC value may change by jumps at the points of changing a satellite with the maximum elevation angle. However, such approach provides reliable information about changes of the vertical TEC. The method of TEC retrieval from the data of on-board GPS receivers was described by Afraimovich et al. (2005).

SAC-C is a joint project of the USA, Argentina, Brazil, Denmark, Italy and France (http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/sac-c.htm). The altitude of SAC-C satellite orbit is 715 km (Fig. 1), so data from SAC-C allow estimating TEC within the range of altitudes from 715 km to 20 200 km. The SAC-C data were selected and processed in a manner similar to that of CHAMP.

2 Observations

Figures 2–6a, b show TEC measured by the satellites during the days, preceding the storm days (representing quiet

Table 2. Values of D_{st}, B_z, F10.7 and AE during the geomagnetic storms.

Date	Day of year	Time when B_z turned southward	Time and value of minimum B_z, nT	Time and value of minimal D_{st}, nT	Solar 10.7 cm Flux, daily, sfu	AE index, nT
5–6 November 2001	309–310	01:00 UT	−64 nT at 06:00 UT	−292 nT at 18:00 UT	186	∼2000
7–8 November 2004	312–313	20:00 UT	−44 nT at 01:00–02:00 UT	−380 nT at 05:00–06:00 UT	129	>2000
11 February 2004	042	10:00 UT	−13.9 nT at 13:00–14:00 UT	−110 nT at 17:00 UT	114	∼1000
24 August 2005	236	09:00 UT	−38.3 nT at 10:00 UT	−220 nT at 11:00 UT	98	>2000
18 June 2003	169	03:00–04:00 UT	−16.7 nT at 06:00 UT	−141 nT at 09:00 UT	120	∼1200

periods). Figures 2–6c–h show TEC changes during the intense geomagnetic storms of 2001–2005. Panels (c), (d), (e), (f) correspond to the main phase of the storms, (g), (h) to the restoring phase of the storms. The traces of the satellites from panels (a), (b) coincide with those shown on panels (c), (e), so it is possible to compare TEC values within the same longitude and local time sector during geomagnetically quiet and disturbed periods. Table 2 shows variations of F10.7, D_{st}, B_z and AE during the analyzed geomagnetic storms.

2.1 Storm of 5–6 November 2001

The event started with the abrupt changes of B_z IMF from −10 nT at 01:00 UT to −64 nT at 03:00 UT on 6 November 2001. B_z continued to turn steadily southward for ∼3 h and caused an intense geomagnetic storm with the following decrease of D_{st} to its minimum value of −292 nT at 06:00 UT (Fig. 1a, Table 2).

Figure 2a, b shows TEC changes that occurred on 5 November 2001 (the day before the storm) at ∼02:00 UT (panel a) and at ∼04:00 UT (panel b). The current value of D_{st} varied from −19 nT (at 02:00 UT) to −8 nT (at 04:00 UT), so that this time can be characterized as a period of low geomagnetic activity. The quiet-time measurements by the TOPEX in the afternoon sector (crossing the equator at ∼15:00 LT) showed well pronounced EIA structure. The bulk of TEC was concentrated in the equatorial region with maximum TEC level of ∼125–130 TECU. The trough TEC value was ∼2–5 TECU less than the crests value. The crests of the EIA were centered about ±13–15° MLAT, i.e., normal position. Similar TEC distribution was observed by the CHAMP satellite which passed along the ∼19:00 LT sector, but the TEC value within the EIA crests was ∼100–110 TECU. From the observations of the SAC-C satellite in the forenoon sector (crossing the equator ∼10:30 LT) it is obvious that the quiet-time TEC level above 715 km did not exceed 25–35 TECU.

The satellite observations within the same longitudinal sectors show that after the start of the southward IMF B_z event on 6 November 2001, the distribution in the equatorial and mid-latitude dayside TEC significantly changed (Fig. 2c, d and 2e, f). According to the TOPEX measurements in the early afternoon sector, the EIA crests moved poleward for ±5–7° of latitude compared to their "quiet-time" position (Fig. 2a, b and 2d). The TEC value within the crests increased up to 150 TECU whereas the TEC value in the equatorial trough decreased to ∼120 TECU. The maximum of the storm-time TEC effects was attained by 05:00 UT (Fig. 2e, f), when the equatorial TEC below TOPEX reached 160–175 TECU (Fig. 2e, f) and the trough TEC further went down to ∼100 TECU.

The most significant TEC enhancements were observed by CHAMP in the dusk sector. The TEC above ∼430 km increased from ∼100 TECU at 02:00 UT on 5 November to 150 TECU at 03:00 UT on 6 November (Fig. 2a, b and 2d). During the next daytime pass, TEC above CHAMP further enhanced to 180 TECU with concurrent increase of the EIA crest-to-trough ratio as an evidence of penetration of electric fields and the fountain effect reinforcement.

At the same time, according to SAC-C observations (∼10:30 LT), the TEC value above 715 km of altitude went up to 65 TECU (Fig. 2c, d) that is 2.5 times more than during the quiet-time (Fig. 2a, b). By 05:00 UT the TEC above the SAC-C decreased to 45–50 TECU (Fig. 2e, f), but still ∼2 times exceeded the quiet-time values.

By 09:00–10:00 UT, and after B_z IMF turned northward, the crests of the EIA moved back equatorward combining into a singular equatorial peak and concurrently the maximum TEC value decreased to ∼100–115 TECU, according to the CHAMP and TOPEX measurements (Fig. 2g, h). At the same time, TEC above the SAC-C satellite decreased to 35–40 TECU.

Thus, use of the satellite measurements made it possible to observe the phenomenon of the ionosphere dayside uplift during geomagnetic storm of 5–6 November 2001. The abrupt changes in B_z caused severe modifications in the equatorial TEC, so that the signatures of the super fountain effect were observable for ∼3–4 h in the longitudinal sector from 10:30 LT to 19:00 LT. The difference in the character of TEC changes in the afternoon and the dusk sectors can be explained by different longitudinal conditions in these sectors. The afternoon TEC enhancements correspond to positive ionospheric disturbance produced by either southward wind or an eastward electric fields coupled with a small

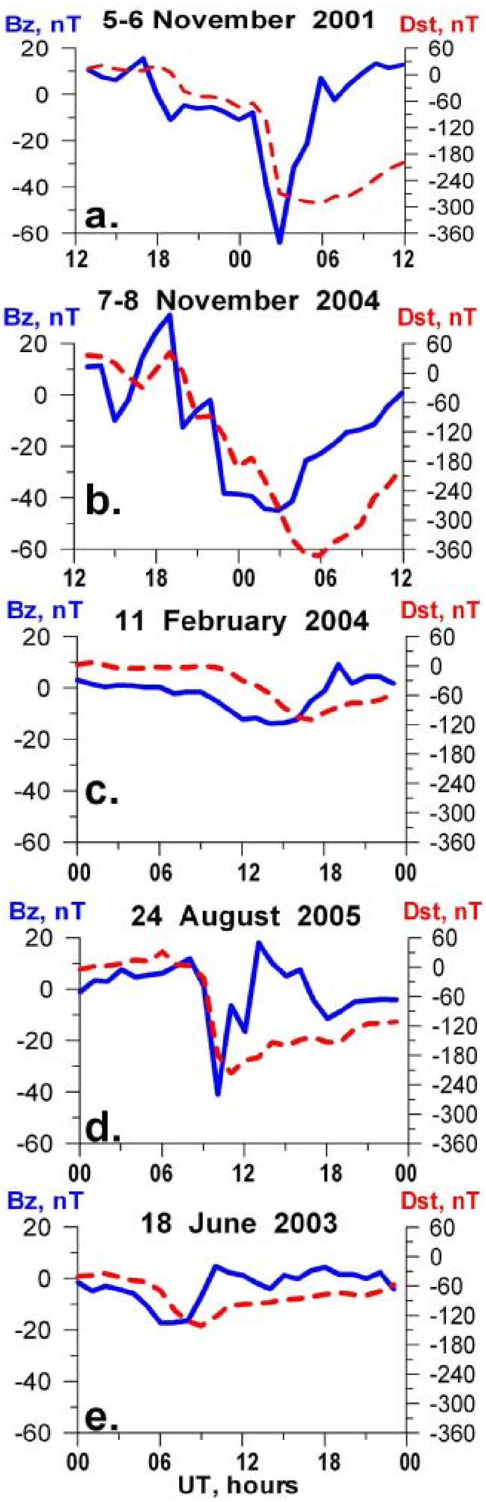

Fig. 1. Variations of the magnetic field component B_z plotted for GSM coordinates (blue continuous curves) and of the index of geomagnetic activity D_{st} (red dotted curves) during the analyzed events.

enhanced fountain effect. Whereas, TEC changes occurred in the dusk sector can be much stronger since at dusk the eastward penetration electric field may add to the eastward electric field because of the neutral dynamo (Basu et al., 2007).

The obtained here results are in good agreement with previous observations of the SFE (Tsurutani et al., 2004, 2008; Mannucci et al., 2005; Astafyeva, 2009).

2.2 Storm of 7–8 November 2004

Figure 1b shows variations of the index of geomagnetic activity D_{st} and of IMF B_z on 7–8 November. The B_z turns southward first at ~14:00 UT, then reaches +30 nT at 18:00–19:00 UT. From 20:00 UT B_z turns sharply southward again and remains deeply negative of −40 nT for next 10 h, attaining its maximum negative value of −44 nT by 01:00–02:00 UT of 8 November 2004 (Fig. 1b, Table 2). The D_{st} index went sharply down from 23:00 UT and the minimum value of −380 nT was reached by 05:00–06:00 UT.

In order to estimate the quiet-time TEC values, we plotted TEC changes that occurred ~24 h before the storm within the same longitudinal sectors, i.e. at ~04:00 UT (D_{st}=7 nT) and at ~06:00 UT (D_{st}=10 nT) on 7 November 2004 (Fig. 3a and b, respectively). As seen from Fig. 2a, b, the EIA had a singular peak structure with maximum TEC value of ~40–45 TECU in the dusk sector (the Jason-1 measurements, below 1336 km). Similar TEC values (~50 TECU) were observed in the afternoon sector above ~400 km (from the CHAMP observations). At the same time, the TEC above 715 km was ~20 TECU.

At the main phase of the geomagnetic storm on 8 November 2004, the TEC above ~400 km in the early afternoon sector (~14:30 LT) increased to 125 TECU that is more than 2 times greater than during geomagnetically quiet period. Concurrently, the two crests of the EIA were formed with their positions at ±18–20° MLAT (Fig. 3b, f, blue crosses). Two hours later the crests moved back equatorward for ~5° of latitude, the maximum TEC decreased to 110 TECU and the ratio of the EIA crest-to-trough level decreased as well (Fig. 3c, g, blue crosses).

Even greater storm-time TEC modifications were observed in the evening sector by the Jason-1 satellite altimeter (~18:30 LT). The TEC levels below 1336 km reached 130 TECU (the northern EIA crest) and 170 TECU (the southern crest), whereas in the EIA trough the TEC was ~22 TECU (Fig. 3c, g, red triangles).

The greatest TEC changes occurred around 06:00 UT when the TEC value reached 160 TECU within the both EIA crests and the trough TEC fell below 20 TECU. At the same time, the crests were located at ~±30° MLAT. These phenomena are known to be the indicators of the penetration of the eastward electric field at middle and low latitudes which lead to enhance of the fountain effect (Vlasov et al., 2003). Obviously, this storm caused essential altitudinal ionosphere redistribution: TEC above ~400 km in the afternoon sector

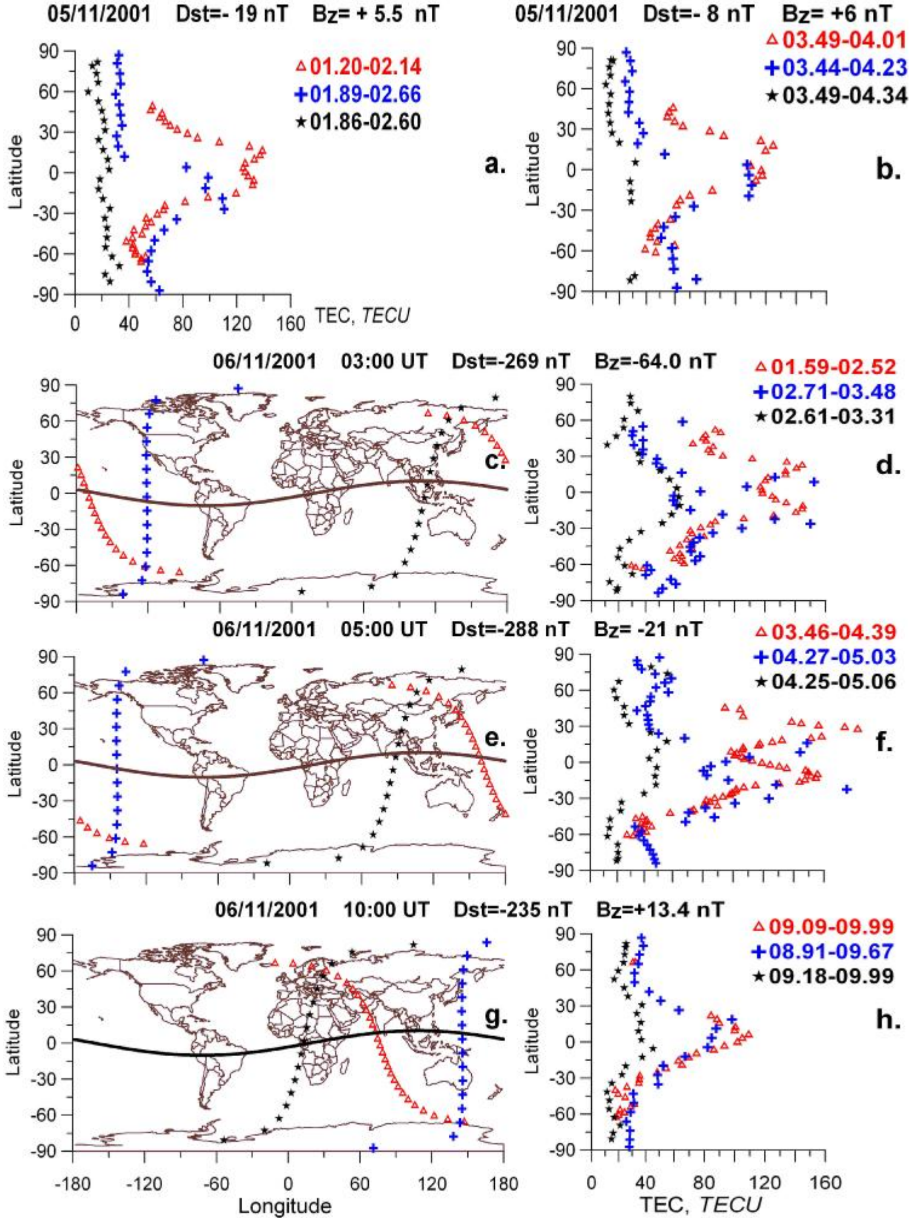

Fig. 2. TEC changes occurred on 5 November 2001 (represent quiet day, panels **a**, **b**) and during geomagnetic storm on 6 November 2001 (**e**–**h**). TEC measurements were performed by TOPEX (below 1336 km, triangles), CHAMP (above 350 km, crosses) and SAC-C satellites (above 715 km, stars). The trajectories of the satellites are indicated on panels **(c)**, **(e)**, **(g)**, the passes on panels(a) and (b) correspond to the trajectories depicted on panels (c) and (e), respectively. UT of each satellite pass and D_{st} and B_z values are written on panels. The satellites pass near the following sectors: TOPEX ∼15:00 LT, CHAMP ∼19:00 LT, SAC-C ∼10:30 LT. Solid line on panels (c), (e), (g) shows position of the geomagnetic equator.

two times exceeded the undisturbed level and TEC value below 1336 km increased 4 times compared to the day before the storm. However, the SAC-C measurements (black stars in Fig. 3, ∼10:20 LT) did not show TEC changes at $h>715$ km as it was in the case of the previously described storm of November 2001 or during the intense geomagnetic storms of 21–22 October 2001, 7–8 September 2002 and 20 November 2003 (Astafyeva, 2009), when TEC value 2–3 times exceeded the undisturbed level. Apparently, the dayside ionosphere uplift was observed by the CHAMP and Jason-1 satellites but not by SAC-C. Possible explanation of this feature can be as follows: during this storm the SFE itself was not as "stretched" longitudinally as during the other intense storms, so that the SAC-C passing along the sector ∼10:20 LT did not register TEC enhancements above 715 km.

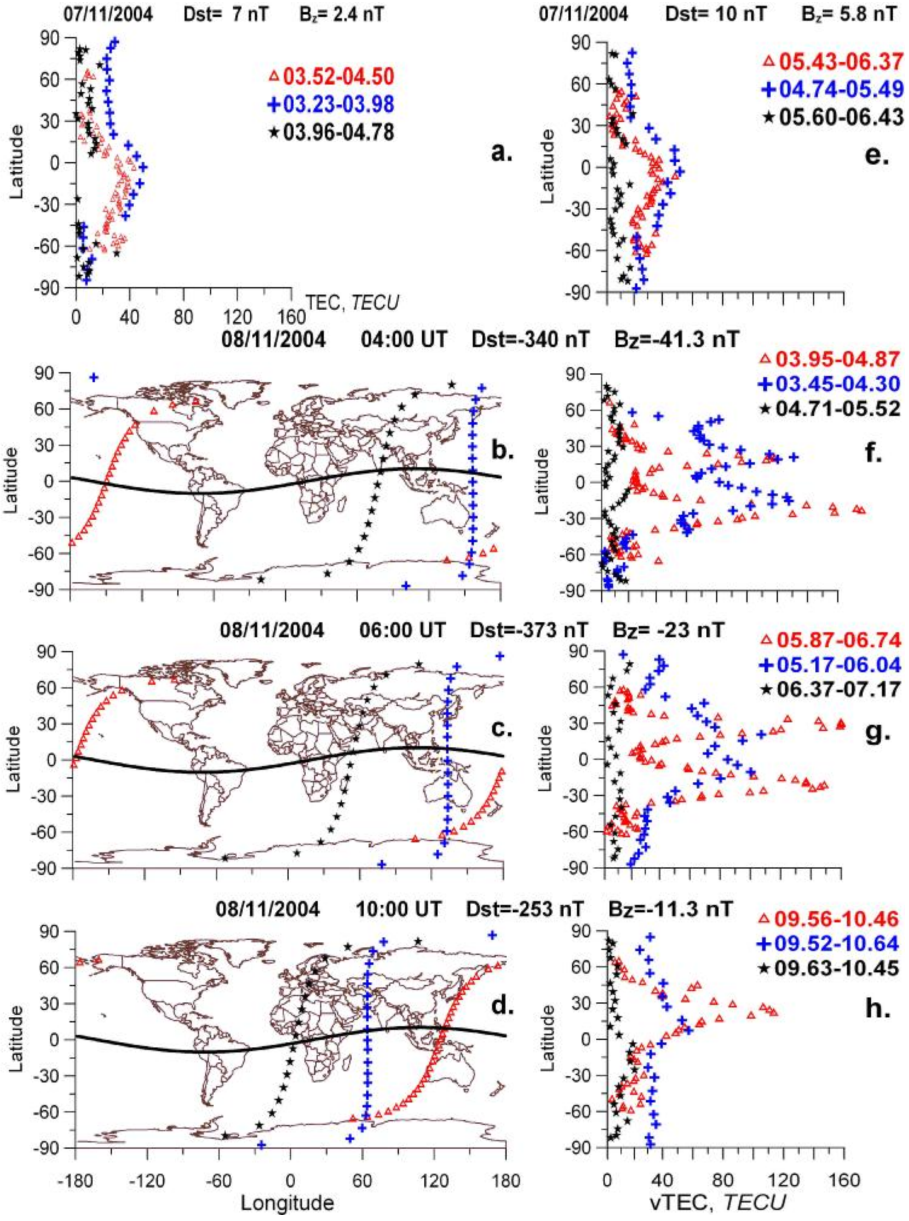

Fig. 3. The same as in Fig. 2 but for quiet day 7 November 2004 **(a)**, **(b)** and geomagnetic storm on 8 November 2004 **(e–h)** and Jason-1 measurements (red triangles). The time when the satellites cross the equator is: Jason-1 ~18:30 LT, CHAMP ~14:30 LT, SAC-C ~10:20 LT.

At the recovering phase of the storm, the TEC below 1336 km decreased to 120 TECU and the crests moved back equatorward (Fig. 3g, h, red triangles). At the same time, the TEC above ~400 km went down to ~60 TECU, i.e. close to the undisturbed level (Fig. 3a, b).

2.3 Storm of 11 February 2004

The B_z turned southward at 10:00 UT on 11 February 2004 and remained below −10 nT for at least next 6 h. The minimum value of B_z=−13.9 nT was reached at 13:00–14:00 UT. The certain D_{st} value went sharply down from 17:00 UT and reached its maximum negative value of −110 nT by 17:00 UT (Fig. 1c, Table 2).

During this event TEC was measured in the early afternoon sector (Jason-1, ~13:40 LT), in the afternoon sector (CHAMP, ~15:30 LT) and in the fore-noon sector (SAC-C, ~10:30 LT).

The quiet day (10 February 2004) TEC is shown in Fig. 4a, b. The corresponding traces of the satellites are shown in Fig. 4c and e. The geometry of the Jason-1 passes did not allow estimating the equatorial TEC. At the same time, the value of the mid-latitude TEC below ~1336 km was

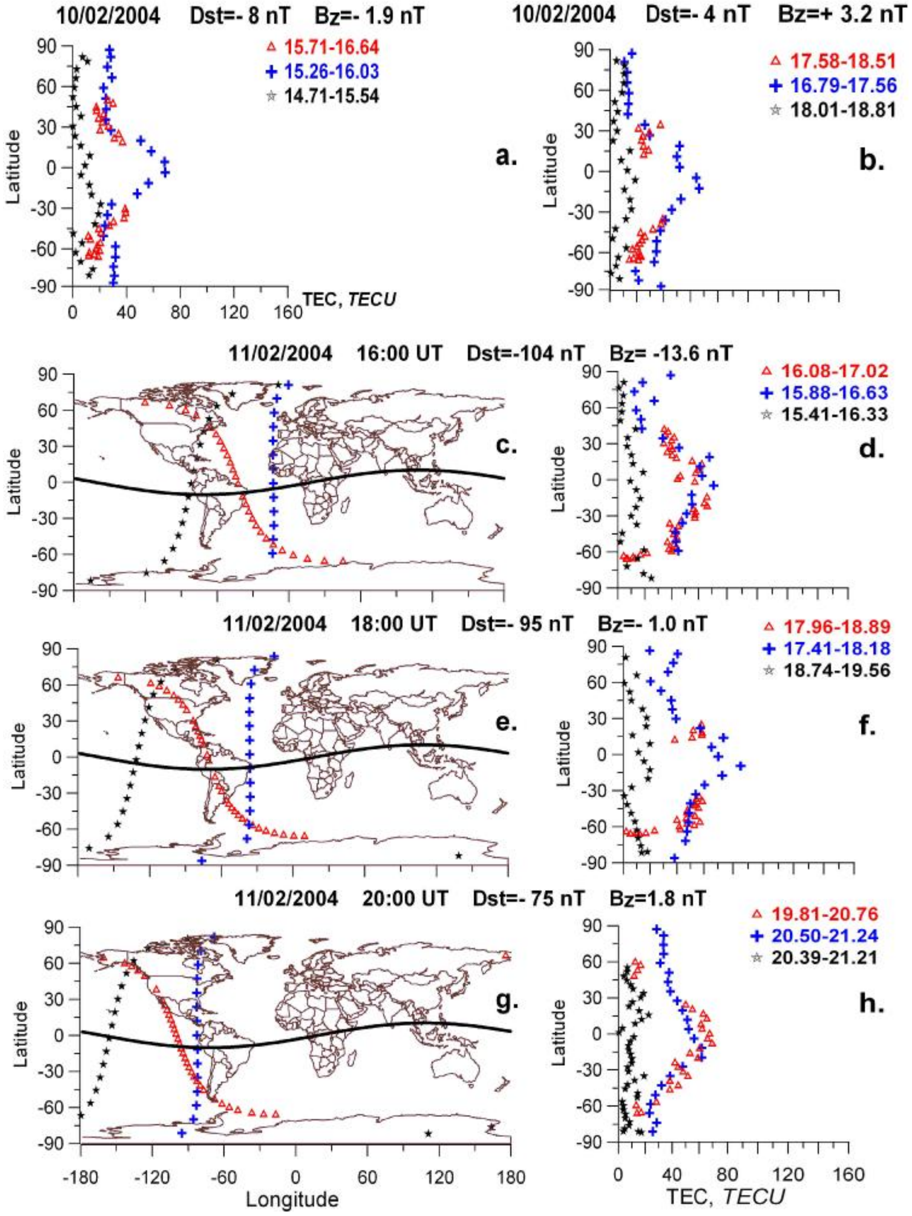

Fig. 4. The same as in Fig. 3 but for quiet day 10 February 2004 **(a)**, **(b)** and the geomagnetic storm on 11 February 2004 **(c–h)**. The satellites pass near the following sectors: Jason-1 ∼13:40 LT, CHAMP ∼15:30 LT, SAC-C ∼10:30 LT.

∼40 TECU that was equal to the TEC above ∼400 km. According to the CHAMP records, the EIA had a form of singular peak (Fig. 4a) and quasi-singular peak (Fig. 4b) with TEC level no more than 70 TECU (Fig. 4a, b, blue crosses). The quiet-time TEC above ∼715 km did not exceed 20 TECU.

During the main phase of geomagnetic storm of 11 February 2004, the two EIA crests became more pronounced and moved to ±15–18° MLAT (Fig. 4c, d). Simultaneously, the equatorial afternoon TEC increased to 70–72 TECU (the CHAMP and Jason-1 measurements). By 18:00 UT, TEC above ∼400 km increased to 85 TECU though the EIA crests remained at the same position as at 16:00 UT. Since the Jason-1 passed over the land, there is a data gap during this period of time. However, Fig. 4e, f shows good agreement in the mid-latitude TEC values above ∼400 km and below ∼1336 km (∼60 TECU).

During the recovering phase of the storm the crests of the EIA moved equatorward combining into a singular equatorial peak with concurrent decrease of TEC value to ∼60-70 TECU (CHAMP and Jason-1 measurements; Fig. 4g, h).

As shown in Fig. 4 (d, f, h), the value of TEC above ∼715 km remained unchangeable ∼20–22 TECU for more than 8 h of observations. It should be noted, that in this longitudinal sector (∼10:30 LT) the ionosphere uplift above the SAC-C was observed during a series of intense storms that occurred in 2001–2003 (Tsurutani et al., 2004; Astafyeva, 2009). Taking into consideration the fact that the satellite observations during this storm did not reveal significant redistribution of the mid- and low-latitude TEC that is peculiar to the SFE, it is possible to assume that the effect did not occur during this storm.

2.4 Storm of 24 August 2005

The B_z IMF firstly dropped down to −17.9 nT at 09:00 UT and went further down to its minimum value of −38.3 nT by 10:00 UT. Within next 2 h B_z remained below −15–18 nT. Such IMF negative B_z caused an intense geomagnetic storm with a minimum D_{st} of −220 nT that was reached at 11:00 UT. Further variations of B_z at 18:00 UT to −17 nT led to a subsequent D_{st} decrease from −130 nT to −150 nT around 18:00–19:00 UT (Fig. 1d, Table 2). In this paper the attention will be focused on TEC changes occurred from 10:00 to 16:00 UT.

The quiet day (23 August 2005) TEC is shown in Fig. 5a, b. Measurements by the Jason-1 in the dusk sector (crossing the equator at ∼19:40 LT) showed that the TEC below 1336 km equaled to 20–30 TECU. In the noon sector (∼12:00 LT) CHAMP recorded weakly pronounced EIA with a singular TEC peak of ∼50 TEC. The TEC above the SAC-C satellite, which passed in the forenoon sector (∼10:30 LT), was ∼10–20 TECU.

Figure 5c–f shows that despite the drastic and long-term B_z impact the TEC response to the storm of 24 August 2005 was not as well pronounced as during the storm of November 2004. CHAMP detected that the noon TEC above ∼400 km increased to 60 TECU at 12:00 UT, and the EIA was a single-peak structured (Fig. 5c, d). At 14:00 UT there was a rise in the near-equatorial TEC to ∼40 TECU extending from −40 MLAT to +40 MLAT (Fig. 5e, f). By 16:00 UT the observed singular peak retains its maximum TEC value around 40 TECU but rearranges to be less extended latitudinally (Fig. 5g, h, blue crosses).

At the same time, the Jason-1 observations around the evening sector clearly revealed the southern peak of the EIA with TEC value of ∼70 TECU located ∼−15° MLAT at the time of the D_{st} minimum (Fig. 5c, d, red triangles). Unfortunately, it was not possible to observe TEC changes in the Northern Hemisphere since the altimeter passed over the land and there is a data gap. Within next 2 h the TEC below ∼1336 km decayed till 30 TECU (Fig. 5e, f) and kept this value at least till 16:00 UT (Fig. 5g, h).

The SAC-C satellite that crossed the equator at ∼10:30 LT did not show any significant variations of TEC. The maximum TEC value above ∼715 km was observed around 12:00 UT (∼25 TECU, Fig. 5c, d).

Thus, the satellite TEC measurements showed small dayside TEC enhancements in response to the geomagnetic storm of 24 August 2004. The maximum TEC value of ∼70 TECU was observed in the southern EIA crest in the dusk sector during the minimum of the D_{st}, whereas during undisturbed conditions the TEC amounted to ∼20–30 TECU. At the same time, the position of the crest was close to the normal (∼−15° MLAT). It should be noted though, that at the initial phase of the storm the anomaly consisted of only a singular peak. Therefore, this storm appeared to cause formation of the dual anomaly peaks in the evening sector. However, this effect lasted no more than 2 h.

2.5 Storm of 18 June 2003

The IMF B_z first turned southward at 01:00 UT, then intensified to −16.7 nT at 06:00 UT and remained below −15 nT till 10:00 UT. Within next hour the IMF B_z increased to positive values (Fig. 1e, Table 2). The following D_{st} sudden drop started at 07:00 UT till the minimum of −141 nT by 09:00 UT. From 11:00 UT the D_{st} started to increase as well.

Use of the satellite measurements made it possible to assess storm-time TEC changes in the afternoon sector (Jason-1, ∼14:20 LT) and in the early afternoon sector (CHAMP, ∼13:00 LT). Unfortunately, data from the SAC-C satellite for the time of observations were not available.

The period ∼24 h prior to the storm commencement can be characterized as a period of medium geomagnetic activity, with decrease of IMF B_z to −8.7 nT at 07:00 UT and to −4.9 nT at 09:00 UT. Such changes of IMF caused the changes of the index of geomagnetic activity D_{st} down to −71–76 nT at 07:00–09:00 UT. As seen from observations by Jason-1 and CHAMP, the distribution of the mid-latitude and equatorial TEC below ∼1336 km is similar to the one above ∼400 km (Fig. 6a, b), with maximum TEC of 70–80 TECU.

During the geomagnetic storm of 18 June 2003 the maximum value of TEC did not exceed 85 TECU (Fig. 6d, f), that is close to the maximum TEC value under medium magnetic activity (Fig. 6a, b). However, during the storm, the two EIA crests were formed at ∼±12–15° MLAT that is close to their normal position. Within next 2 h the crests seemed to move more towards each other, maintaining a maximum TEC value of 78–80 TECU (Fig. 6e, f).

By 12:00 UT both the Jason-1 and CHAMP recorded a single-peak structure in the near-equatorial region, with TEC value no more than 40–42 TECU. Note, that the Jason-1 satellite altimeter data for TEC below ∼1336 km show good agreement between its values and those of the CHAMP TEC measurements for TEC above ∼400 km.

Thus, during the storm of 18 June 2003 there was observed appearance of the dual anomaly peaks with concurrent increase of the near-equatorial TEC up to 80 TECU. However, the peaks do not travel far from each other, i.e. were located within their normal position. Such storm-time changes

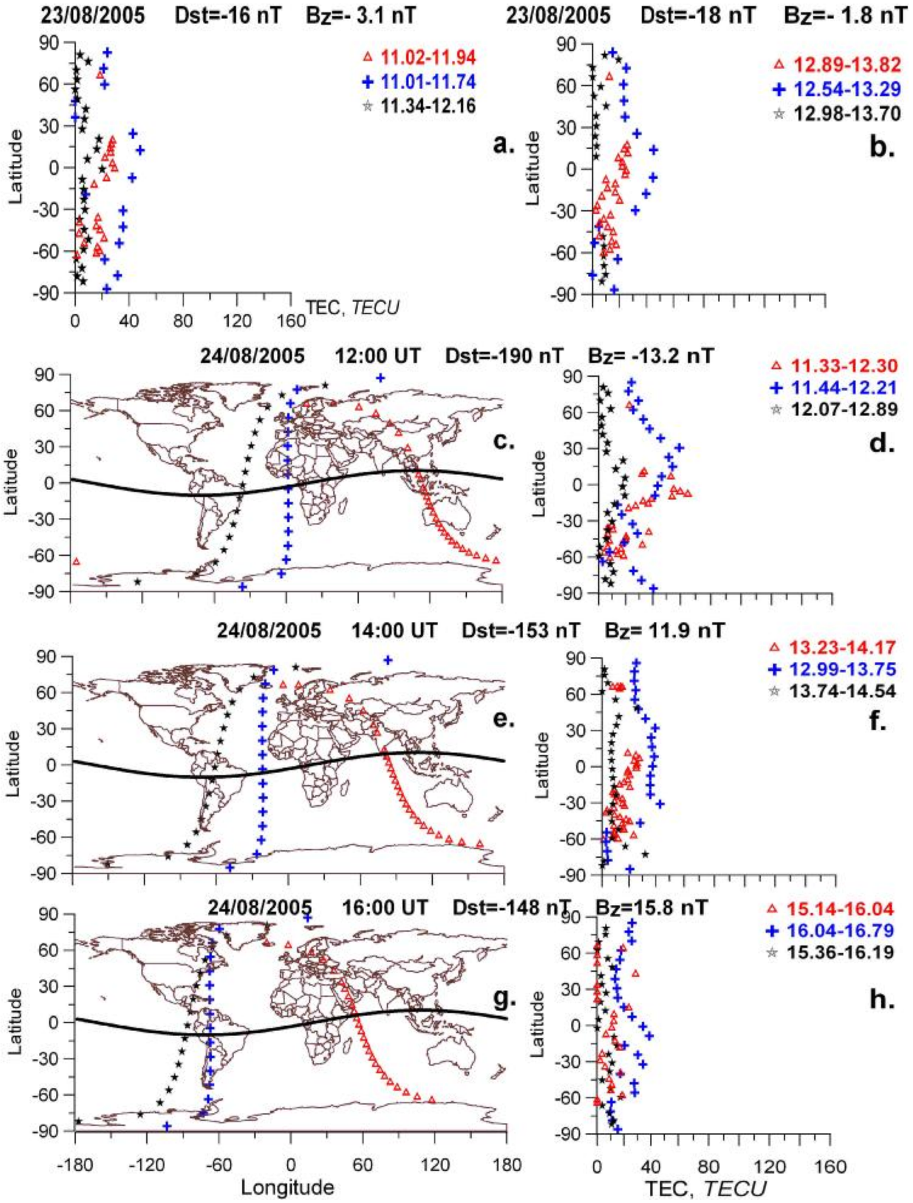

Fig. 5. The same as in Fig. 3 but for quiet day 23 August 2005 **(a)**, **(b)** and the geomagnetic storm on 24 August 2005 **(c–h)**. The satellites pass near the following sectors: Jason-1 ∼19:30 LT, CHAMP ∼12:00 LT, SAC-C ∼10:30 LT.

occurred at the main phase of the storm and they damp by the time when the D_{st} index tends to increase.

3 Discussion and conclusions

Use of data of satellite altimeters TOPEX or Jason-1 and measurements from GPS receivers onboard CHAMP and SAC-C satellites made it possible to examine TEC response to five intense geomagnetic storms ($D_{st}<-120$ nT) that occurred in 2001–2005. Since the satellites passed over different longitudinal sectors and measured TEC in different range of altitudes, it was possible to obtain information about altitudinal and longitudinal ionosphere redistribution during geomagnetic storms.

Severe enhancements of the equatorial and mid-latitude TEC above ∼430 km (up to ∼350%) with concurrent traveling of the EIA crests for a distance of 10–15° of latitude were observed during two of the five events analyzed here. This phenomenon, known as the dayside ionosphere uplift, or the "daytime super-fountain effect", occurred after sudden drop in IMF B_z and consequent penetration of electric fields to the low-latitude ionosphere. The SFE weakened after the B_z value increased and turned northward. Our results on the SFE are in good agreement with previous observations

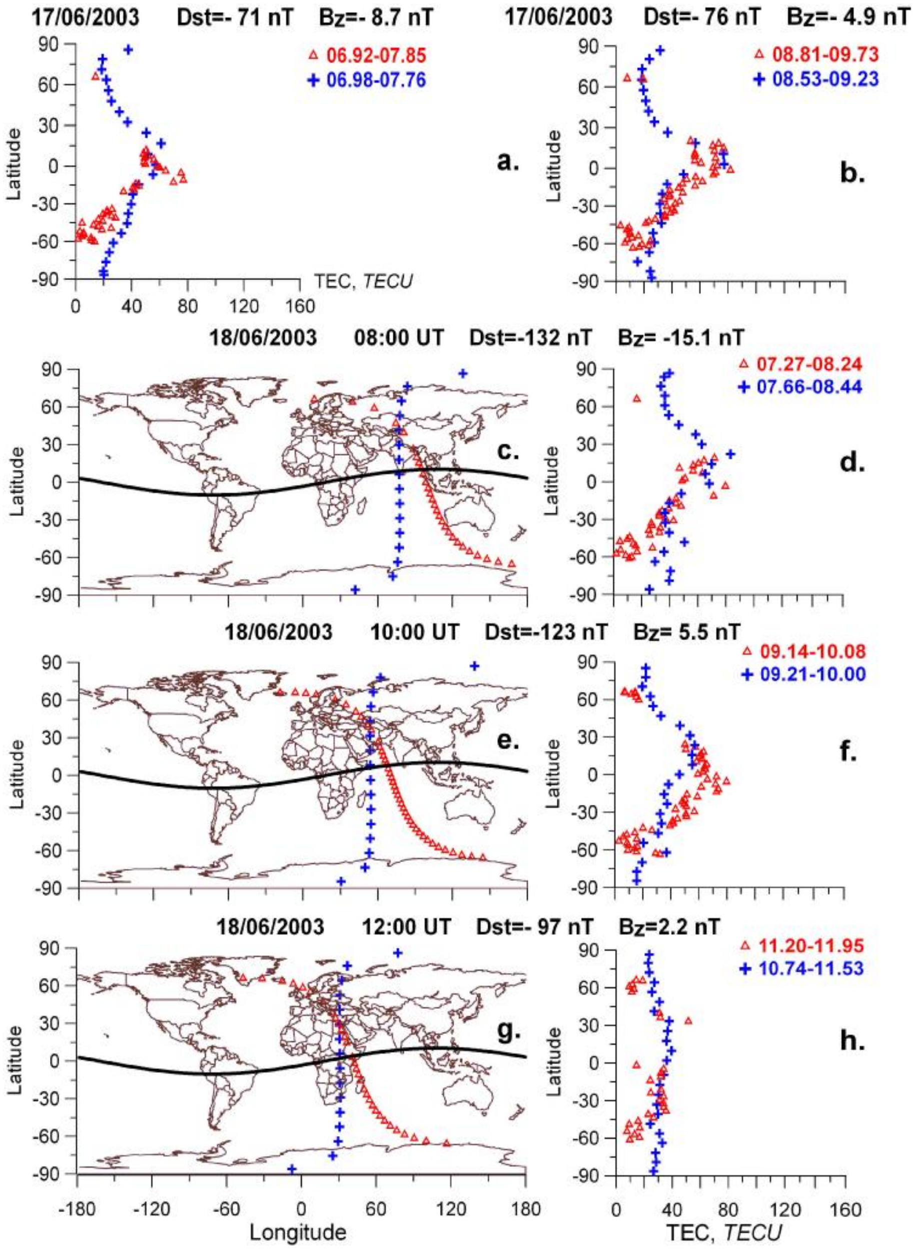

Fig. 6. The same as in Fig. 3 but for 17 June 2003 **(a)**, **(b)** and the geomagnetic storm on 18 June 2003 **(c–h)**. The satellites pass near the following sectors: Jason-1 ~14:20 LT, CHAMP ~13:00 LT. No data of the SAC-C satellite were available.

(Vlasov et al., 2003; Tsurutani et al., 2004, 2008; Mannucci et al., 2005; Basu et al., 2007; Astafyeva, 2009).

It should be noted that during the storm of 7–8 November 2004 the TEC value above the SAC-C satellite remained unchangeable, unlike it was during the storm of 5–6 November 2001, when TEC above 715 km 2–3 times exceeded the quiet-time TEC level. This could be possibly explained by less longitudinal extension of the dayside storm-time effects than it was during the storm of 2001, so that the SAC-C that passed in the forenoon sector (~10:20 LT) could not observe the effect. This conclusion is proved by the observations of some strong evidences of the SFE during the storm of November 2004, such as poleward displacements of the EIA crests and severe increase of the equatorial TEC along with a ratio of crest-to-trough TEC (Vlasov et al., 2003; Mannucci et al., 2005; Basu et al., 2007).

It is known that the EIA develops in the before noon sector, is intensified in the afternoon and starts to diminish after sunset. For a number of events, satellite observations clearly show that the dayside storm-time TEC enhancement extends at least from 10:30 LT to 19:30 LT (Tsurutani et al., 2004; Astafyeva, 2009). The dayside ionosphere uplift above 715 km was recorded by the SAC-C satellite in the ∼10:30 LT sector during a series of intense geomagnetic storms (Tsurutani, 2004; Astafyeva, 2009). Thus, the results presented in this study are helpful in assessing a longitudinal distribution of the ionosphere uplift which, in some cases, apparently does not reach the 10:20 LT sector.

Other important feature resultant from this study is that the drastic dayside TEC enhancements along with other SFE signatures were not observed during three of the five geomagnetic storms analysed here. Let us try to figure out possible reasons of that. As it was mentioned before, the primary cause of geomagnetic storms and the dayside ionosphere uplift are dawn-to-dusk electric fields associated with the passage of southward directed IMF B_z. Generally speaking, the electric field is determined by two factors: the solar wind velocity and the southward IMF. It has been empirically shown that intense storms with a peak $D_{st}<-100$ nT are primarily caused by large $B_z<-10$ nT with duration greater than 3 h (Gonzalez and Tsurutani, 1987). In addition, the electric fields seem to be modulated by the solar wind ram pressure, so that solar wind density, besides B_z IMF and solar wind velocity, plays an important role in the ring current intensification (Smith et al., 1986; Gonzalez et al., 1994). However, it was previously shown that the amplitude of the storms has a little dependence on the strength of the shocks (Gonzalez and Tsurutani, 1987).

In connection with that, first of all, the chosen for the study events can be characterized by the IMF $B_z<-12$–15 nT that lasted for more than 3 h. Second of all, it was found that among the five analyzed here storms, four were associated with a jump in values of solar wind velocity and density (i.e., appeared to be the interplanetary shocks) and were originated from M5.6–X1.3 solar flares (the parameters are not shown here but can be accessed via http://umtof.umd.edu/pm/). During the 11 February 2004 event the solar wind density increased suddenly for ∼100%, whereas no sharp changes in the wind velocity were recorded. Thus, even the values of parameters of solar wind are important for the development of geomagnetic storms, they seem not to be decisive for the ionosphere storms occurrence.

Besides the electric fields, associated with B_z variations, the equatorial plasma distribution is controlled by the neutral winds. The equatorward winds force the arisen by the vertical $\boldsymbol{E}\times\boldsymbol{B}$ drift plasma particles against gravity (Kelley et al., 1989; Fuller-Rowell et al., 1997) and, as a result, lead to the total accumulation of plasma within the crests of the EIA and to increase of the mid-latitude plasma. Under quiet geomagnetic conditions the neutral gas flows extensively out of the area of the pressure enhanced by the solar heat (∼16:00–17:00 LT). The wind is directed mostly poleward during daytime and equatorward during night-time. By solstice time such area of the enhanced pressure moves to the summer hemisphere, so the wind flows mostly from the summer hemisphere to the winter hemisphere through equator. Apparently, the distribution of the neutral winds can be one of the reasons for appearance of stronger storm-time ionosphere effects (and the SFE) during equinox time, in the same way as it is the cause of much higher background TEC values during equinox time compared to solstice (e.g., Afraimovich et al., 2008). However, during geomagnetic storms the winds distribution changes significantly because of the increased Joule heating and particle energy injection in the auroral zone. The heat source drives the global wind surges from both polar regions to low latitudes and to the opposite hemisphere, so that the storm-induced thermospheric winds overcome the seasonal winds. The energy input into the high-latitude ionosphere can be evaluated by the Auroral Electrojet (AE) index. Table 2 (last column) presents data of the AE index for the moment of the main phase of the storms discussed in this paper (the data are available from http://swdcwww.kugi.kyoto-u.ac.jp/aedir). The AE index enhanced up to a very high values (∼2000 nT) during the storms of November 2001, November 2004 and August 2005, and up to ∼1000–1200 nT during less intensive storms of June 2003 and February 2004. Evidently, the analyzed events are characterized by different values of the energy that generated storm-time wind and dynamo electric field disturbances and this could lead to difference in the ionosphere response.

Other important fact that should be taken into account is solar energy input to upper-atmosphere of the Earth, which can be evaluated by the 10.7 cm solar radio flux (Table 2). It is known that the intensity of solar radiation varies during the solar cycle, providing the maximum input during the maximum of solar activity. In turn, global TEC alters following the variations of solar flux and has its maximum at solar maximum conditions (e.g., Afraimovich et al., 2008). Besides, global TEC has semi-annual variations with maximums during equinox time, caused by the global circulation of the thermosphere. As a result, maximums of the background ionization can be expected in March–April and September–October of the years 1999–2001. Thus, the storm of November 2001 occurred during the period of solar maximum (F10.7=186), while the other four correspond to periods with lower solar energy input (F10.7<130).

Finally, the development of drastic changes in the ionosphere can depend on the time of a storm onset. Ionosphere storm-time effects were noticed to be much stronger when the main phase of geomagnetic storms corresponds to dusk conditions in the Atlantic region (Basu et al., 2007; Foster and Coster, 2007). The reason for that is possibly in enhanced conductivity gradient caused by energetic particle precipitation in the South Atlantic magnetic Anomaly (SAMA) region. Near geomagnetic equator, under normal conditions the neutral wind dynamo develops enhanced zonal electric fields across the terminator because of the conductivity gradient. Then, at dusk the eastward penetration electric field may add to the eastward electric field because of the neutral wind dynamo. The resultant electric field is responsible for a large uplift of the ionosphere near the terminator.

Combination of all these facts can create a preferred longitude sector for the build-up of enhanced TEC.

Note, that the events, examined in this paper vary in time by a storm commence (Fig. 1 and Table 2). The most severe changes in TEC were observed during the storms of November 2001 and November 2004, started at 03:00 UT and 03:00–05:00 UT, respectively. Previously, similar effects were also observed during the Bastille Day storm of 15–16 July 2000 (e.g., Vlasov et al., 2003) with the D_{st} minimum at 21:00 UT, the two "Halloween" storms of 29–30 October 2003 (e.g., Mannucci et al., 2005) – both ~22:00 UT and during the storms of 21 October 2001, 7–8 September 2002 and 20 November 2003, with a maximum negative D_{st} excursion around 19:00 UT (Astafyeva, 2009). From these examples one can conclude that for this time there is no an unambiguous answer to the question of the "preferred" longitude sector for the enhanced ionosphere storm-time effects.

Thus, all the mentioned issues seem to be responsible for the formation and occurrence of ionosphere superstorm effects and can be the cause of non-occurrence of the ionosphere super-storm effects during storms of 18 June 2003, 11 February 2004 and 24 August 2005. Apparently, a storm-enhanced zonal electric field itself is not sufficient to produce such significant alterations in the ionosphere as the SFE. The whole effect is determined by a combination of many factors within the global magnetosphere-ionosphere-thermosphere coupling and within the framework of this study it seems difficult to estimate the precise quantitative contribution of each of the possible reasons, responsible for different character of the ionization redistribution during geomagnetic storms. Apparently, these effects require additional experimental and model studies and the present study would be a useful contribution in better understanding of the ionosphere super-storms development.

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