Opposite hemispheric asymmetries in the ionospheric F- and topside regions observed during the geomagnetic storm of 29-31 August 2004

Elvira Astafyeva[1], Irina Zakharenkova[1] and Eelco Doornbos[2]

1- *Institut de Physique du Globe de Paris, Paris Sorbonne Cité, Univ. Paris Diderot, UMR CNRS 7154, 35-39 Rue Hélène Brion, Paris 75013 France, email: astafyeva@ipgp.fr*
2- *Delft University of Technology, 2629 HS Delft, The Netherlands, email: e.n.doornbos@tudelft.nl*

ABSTRACT

By using multiple ground-based and space-borne instruments, we observed opposite hemispheric asymmetries in the ionospheric storm-time behavior in the ionospheric F- and topside region during the moderately intense magnetic storm of 29-31 August 2004 (minimum Dst excursion of -128 nT). Data from ground-based GPS-receivers and ionosondes revealed large increase in TEC and in NmF2 in the southern hemisphere, whereas in the northern hemisphere very weak or no effect were observed. On the contrary, the topside measurements indicated occurrence of a positive storm in the northern hemisphere. In the post-sunset sector (~20:30-21:30LT), the storm-time effects were observed to be stronger than that in the evening sector (17-18LT). Also, we observed signatures of the ionospheric plasma enhancement up to the height of the DMSP satellites (~840 km). We consider that such effects are linked with the storm-time behavior and redistribution of the neutral density.

1. INTRODUCTION

The ionospheric response to a geomagnetic storm which is commonly referred to as an ionospheric storm, is not yet completely understood and remains one of the primary subjects of ionospheric science (e.g., Tsurutani et al., 2004; Mannucci et al., 2005; 2014; Yizengaw et al., 2006; Foster and Coster, 2007). Ionospheric storm is known to exhibit seasonal features in the F-region (e.g., Astafyeva, 2009; de Abreu et al., 2010). The asymmetry is usually attributed to seasonal effects, as the positive phase often occurs in the winter hemisphere, while negative storm is more summer hemisphere "feature" (e.g., Prölls, 1995; Goncharenko et al., 2007; Danilov, 2013). The difference in the ionospheric response in the F-layer and in the topside ionosphere has already been observed during the super-storm of 20 November 2003 (Yizengaw et al., 2006). The authors reported that the strong downward ExB drifts pushed the ionospheric F-region down, so that the topside ionosphere and plasmasphere did not show significant storm-time alterations, while data of ground-based GPS-receivers indicated a large dayside enhancement. Pedatella et al. (2009) on the example of the geomagnetic storm of 15 December 2006 demonstrated a significant enhancement of the topside/plasmasphere TEC above ~550 km, while these effects were much less pronounced in measurements of satellite altimeters TOPEX/Jason-1. The authors suggested that the topside TEC increase was caused by soft particle precipitation. These observations demonstrate that despite numerous studies, our knowledge's of the ionospheric storm are still poor.

In this paper, we use multiple ground-based and space-borne instruments to study ionospheric response to a moderately intense geomagnetic disturbance of 29-31 August 2004. Despite being classified as a moderately intense storm, it induced sufficiently strong and interesting effects in the ionosphere (Astafyeva et al., 2015); it also caused strong GPS phase fluctuations in the auroral and equatorial regions (Zakharenkova and Astafyeva, 2015).

2. OBSERVATIONS

To study ionospheric/thermospheric behavior during the main phase of the storm of 29-31 August 2004, we use a set of the following ground-based and space-borne instruments (Fig.2a):

1) Ground-based GPS-receivers were used to obtain ionospheric total electron content (TEC) between a receiver on the ground and a GPS-satellite at an orbital altitude of ~20200 km (e.g., *Hofmann-Wellenhof*, *2001*). The slant TEC data series were further processed in absolute vertical TEC [e.g., *Zakharenkova and Astafyeva, 2015*]. TEC is measured in TEC units with 1 TECU = 10^{16} electrons/m^{-2}.

2) Ground-based ionosondes/digisondes provided data of the F2 layer peak electron density (NmF2).

3) CHAMP (CHAllenging Minisatellite Payload, http://op.gfz-potsdam.de/champ), is a satellite at a near-polar near-circular orbit with inclination of 87.3° and orbital period of 91 min (*Reigber et al., 2002*). This study used data from two of the instruments on the CHAMP satellite: (1) the Planar Langmuir Probe (PLP) allowing to determine the in situ plasma density and electron temperature (McNamara et al., 2007), and (2) a dual-frequency GPS-receiver for precise orbit determination providing TEC-measurements between CHAMP and the GPS satellites (20200 km). During the event of 29-31 August 2004, CHAMP flew at a mean altitude of 385 km in the 9LT (descending) and 21LT (ascending) sectors.

4) GRACE (Gravity Recovery and Climate Experiment) is a satellite mission comprising two identical spacecraft GRACE-A and GRACE-B, separated horizontally by ~220 km; the satellites pass into a near-circular, polar orbit (inclination: 89°) with an altitude of about 500 km. Like CHAMP, the GRACE satellites carry GPS-receivers onboard, allowing to calculate the vertical TEC over the satellite. In addition, as the spacecrafts are interconnected by a K-Band ranging system using microwave to measure the exact separation distance and its rate of change, we can get the change of the electron density (Xiong et al., 2010). During the 2004 storm, the GRACE satellites were at a mean altitude of 486 km and crossed the equator at about 05LT (descending) and 17LT (ascending).

5) Data of total ion concentration (Ni in i+/cm3) were obtained with the Special Sensor for ion, Electrons and Scintillation (SSIES) onboard the Defense Meteorological Satellite Program (DMSP) F13 and F15 spacecrafts. DMSP spacecrafts are placed in a near circular, sun synchronous, polar orbit with inclination 98.8° and 98.9°. The orbital altitude is ~840-850 km, and the period is ~102 min. The ascending equator crossing time for F13 DMSP is ~18:25 LT and for F15 satellite is ~21:10 LT.

3. RESULTS

Figure 1 shows variations of interplanetary and geophysical parameters during the storm of 29-31 August 2004. A moderately intense magnetic storm was initiated by the interplanetary shock arrival at ~9 UT on 29 August 2004. The commencement of the storm can be seen at ~10:04 UT (vertical dashed line in Fig.1) as an abrupt increase of the solar wind speed from 390 km/s to 450 km/s, simultaneously with sudden changes in the solar wind ram pressure (Fig.1a). Following the storm commencement at 10:04 UT on 29 August 2004, the initial phase of the storm lasted until ~05 UT of the next day, when the IMF Bz turned southward and remained so until ~23 UT (Fig 1b, black line). Consequently, the index of geomagnetic activity SYM-H started to monotonely decrease until its minimum excursion of -128 nT at 22:50 UT (Fig.1c, black line). The maximum value 7 of the 3-hourly Kp index was reached at 21UT on 30 August 2004 (blue bars in Fig.1d). The main peculiarity of this storm is that it was accompanied by sufficiently strong and long-term substorm activity on 30-31 August, as seen from variations of the auroral electrojet (AE) (Fig.2c, gray bars), and which is due to enhanced particle precipitation in the auroral regions (Lazutin et al., 2011). Fig. 1c also shows variations of the simple Joule heating in the northern (blue curve) and southern (magenta curve) hemispheres (http://spidr.ngdc.noaa.gov/). One can see that in both hemispheres significant Joule heating started from ~17:30 and continued until 23 UT; this period corresponds to the enhancement in the

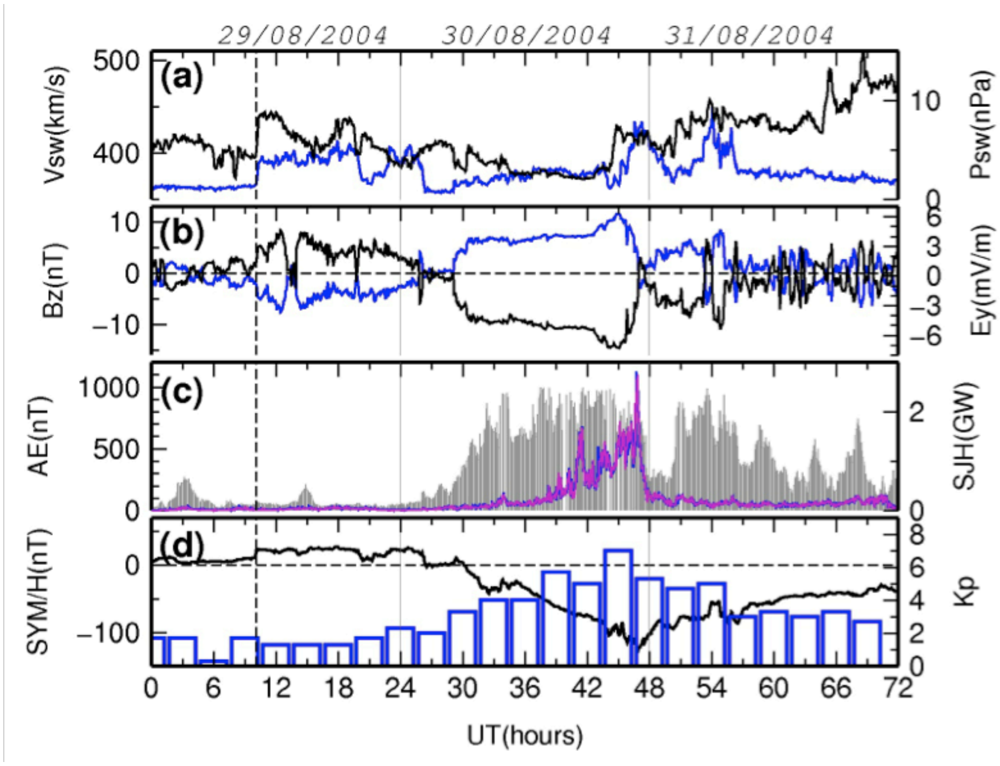

Figure 1. Interplanetary and geomagnetic variations during the geomagnetic storm of 29–31 August 2004. **(a)** Solar wind speed (Vsw, black curve) and solar wind ram pressure (Psw, blue curve). **(b)** IMF Bz component (Bz, black curve) and Ey component (blue curve) of the interplanetary electric field; **(c)** Geomagnetic auroral electrojet index (AE, gray bars) and the simple Joule heating over the northern and southern poles (SJH, blue and magenta curves, respectively). **(d)** Index of geomagnetic activity SYM-H (black curve) and planetary index Kp (blue bars).

IMF Bz negative component. In this paper, we will focus on this period of time.

The ionosondes data, a strong hemispheric asymmetry is observed in both American and African-European sectors (Fig.2b,c): during the main phase of the storm, a strong positive storm in seen in the southern hemisphere, while in the northern hemisphere small negative storm no storm-time change is detected. These effects continued during the next day of 31 August, i.e. during the recovery phase. TEC-data from ground-based GPS-receivers show similar storm-time behavior (Fig.2d-e): first TEC increase of 50-200% occurred during the main phase at low-latitudes. Also in the vTEC data, we observed a strong asymmetry between northern and southern hemispheres, and this effect continued until ~6-8 UT of the next day (Fig. 3a,b), while in the northern hemisphere the effects of the storm were much less pronounced. From these simultaneous observations, we can conclude that the observed positive storm in SH occurred in the ionospheric F-layer, whereas the observations in NH may indicate on somewhat opposite effects in the ionospheric response above the ionospheric F-layer, i.e. in the topside ionosphere.

Indeed, in the data of the vTEC above the height of the GRACE satellite of 485 km

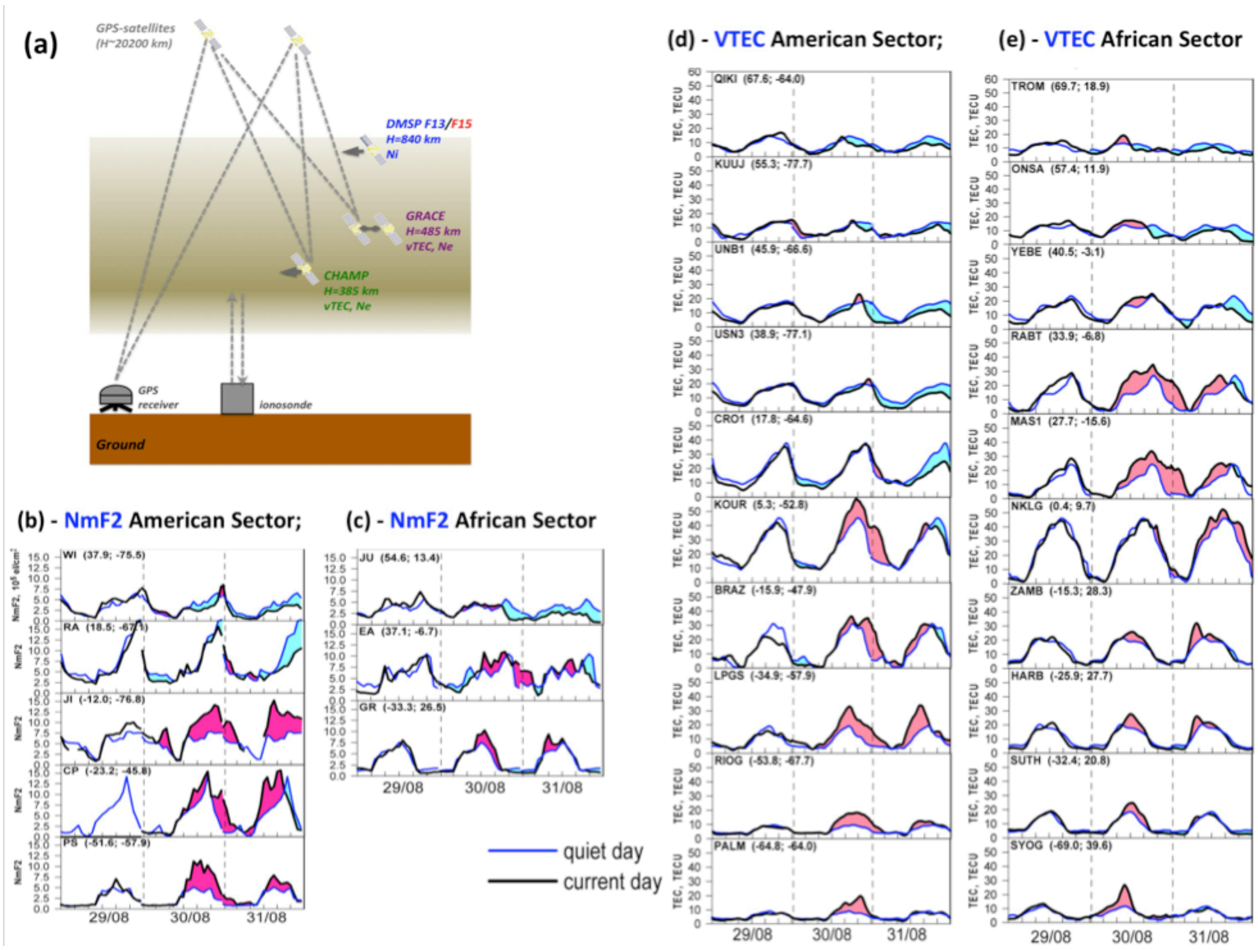

Figure 2. (a) A scheme of ground-based and space-borne instruments used in the study; **(b-c)** Variations of NmF2 measured by digisondes in the American and European-African longitudinal sectors during the 29-31 August 2004 magnetic storm (black curves) as compared to quiet day 28 August (blue curves)**; (d-e)** Vertical TEC-variations as calculated from data of ground-based GPS-receivers located in American **(d)** and European-African **(e)** sectors. The names and the geographic coordinates of the GPS-receivers and ionosondes are indicated in panels **(b-e)**.

(~17LT sector), signatures of the positive ionospheric storm at low-latitudes were observed (Fig.3, 2 and 3 column of panels). The equatorial and low-latitude TEC 1.5-2 times exceeded the quiet-time levels. From 18UT, we observe a growth of TEC at high latitudes of the SH, and from 22UT TEC in the mid-latitudes of the SH increase as well. Similar behavior can be concluded from variations of the electron density Ne at the orbital height of the GRACE satellite (Fig. 3, third column of panels from the left). One can see a small storm-time enhancement of the Ne throughout the main phase of the storm, and we also observe 2-peak structure of the EIA. Starting from ~17UT, we notice hemispheric asymmetry, when the northern EIA crest showed a larger peak of density, and an increase of Ne can be seen at high and middle latitudes of the NH. Development and traveling of high-latitude traveling ionospheric disturbances (TID) is also clear from the panels as small high-latitude increases.

In the post-sunset sector (~21LT), the overall storm-time TEC increase was observed to be stronger (Fig.3, 4th and 5^{th} column of panels), which can be explained by the storm-time reinforcement of the ionospheric fountain effect from ~19UT on 30 August to ~1UT on 31 August. Also, In the same manner as in the evening sector, we observed higher TEC and Ne values in the NH than in the SH. The Ni data from two DMSP satellites also confirm that the storm-time density increase in the post-sunset sector was stronger than that in the evening sector.

5. DISCUSSION AND CONCLUSIONS

By use of multi-instrumental approach, we have studied ionospheric response to the moderately intense geomagnetic storm of 29-31 August 2004. With the minimum Dst excursion of -128 n, this storm was far from the strongest in solar cycle 23, but it provoked sufficiently strong ionospheric effects:

1) A positive storm in vertical TEC (vTEC) and NmF2 started to develop at low-latitudes with the beginning of the main phase and persisted until the recovery phase. The large dayside low-latitude enhancement was also seen in the topside ionosphere, as shown by the GRACE and CHAMP satellites, and reached as high as 840 km of altitude, as seen in data of the F13 and F15 DMSP satellite.

2) Data of ground-based GPS-receivers and ionosondes revealed a strong positive storm in the ionospheric F-layer in the southern hemisphere (SH) in the American and European-African sectors; at the same time, in data from the northern hemisphere (NH), we observed no or a very small and short-term positive effect, followed by larger negative deviations during the main phase of the storm.

3) The satellites' data covered the topside region and detected opposite asymmetry than it was observed in the F-layer, i.e. larger vTEC and electron density (Ne) values in the NH, and no or small storm-time enhancement in the SH. This phenomenon was observed in both late afternoon (17-18LT) and post-sunset (~20:30-21:30 LT) sectors, and it was also shown to reach at least 840 km of height.

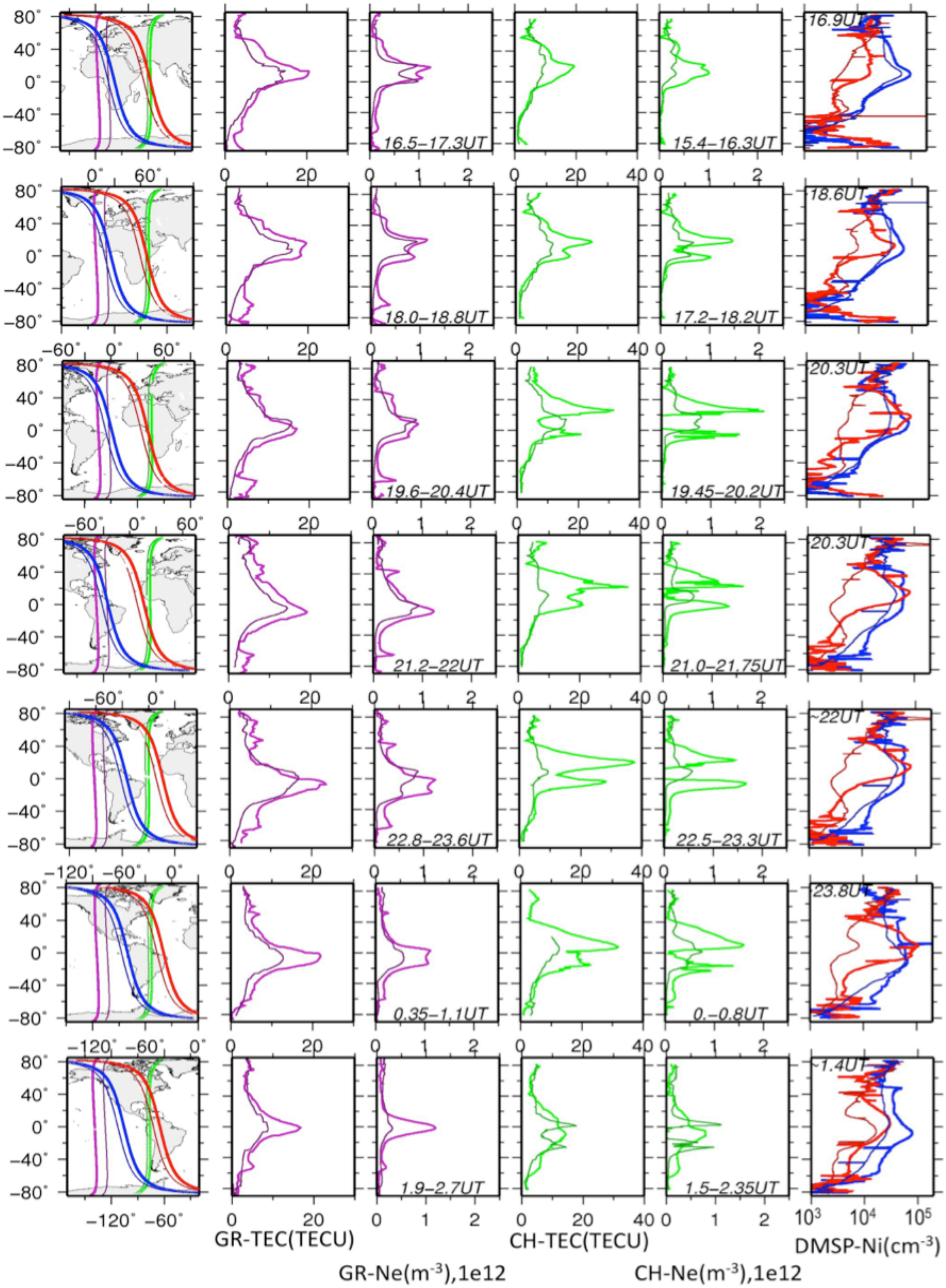

Figure 3. Vertical TEC (GRACE- magenta curves, CHAMP-green curves), electron density observations (GRACE and CHAMP) and ion density (DMSP F13 – blue curves, DMSP F15 –red curves) are compared with the quiet day 28 August (gray, dark green, dark blue and dark red curves, respectively). The trajectories for all the satellites are shown on the left panels. GRACE crosses the equator at ~17LT, CHAMP at ~21 LT, DMSP F13 at 18:30LT and DMSP F15 at 21:10 LT.

The observed opposite hemispheric asymmetry in the ionospheric storm-time behavior at different heights is a very interesting feature. The north-south asymmetry in the ionospheric response in the F-region has been already observed during a number of geomagnetic storms (e.g., Astafyeva, 2009; de Abreu et al., 2010); it is usually attributed to seasonal effects, as it is known that positive phase often occurs in the winter hemisphere, while negative storm is more summer hemisphere "feature" (e.g., Prölls, 1995; Goncharenko et al., 2007; Danilov, 2013). In our case, we observe opposite asymmetries in the F-layer and in the topside ionosphere/plasmasphere, which can signify different drivers for these two altitudinal regions. The low-latitude and SH positive storms in the F-layer (increases in NmF2 and TEC) are usually attributed to either a downwelling of neutral atomic oxygen as a result of the storm-time induced thermospheric circulation, or to uplifting of the F2-layer because of the vertical drift (*Prolls, 1995; Danilov*, 2013). In addition, plasma fluxes from plasmasphere can also make a possible cause of the positive ionospheric storm in the F-layer. The NH positive storm in the topside ionosphere seemed to respond to storm-time alterations in the neutral density that were much stronger over the northern polar and the NH high-latitude regions (Astafyeva et al., 2015). One other explanation of the opposite hemispheric asymmetries can be the fact that the ionospheric plasma can be either uplifted or pushed down during a storm, so that the topside sounders could detect increase or decrease of plasma as compared to the quiet-time levels. This is in line with the DMSP observations that clearly show larger uplift in the northern hemisphere.

4) In the post-sunset sector, we observed a strong storm-time reinforcement of the equatorial ionization anomaly (EIA), also known as a super-fountain effect (e.g., Tsurutani et al., 2004; Astafyeva, 2009). At the end of the main phase of the storm, about an hour after a further intensification of the IMF Bz component, TEC and Ne within the crests of the post-sunset EIA increased up to 250-400%; this effect further strengthened during the next 4-5 hours and lasted until the beginning of the recovery phase. DMSP observations showed a rise of the ionospheric plasma to at least 840 km. We consider that in addition to the storm-time eastward pre-reversal enhancement electric field, the storm-time increased thermospheric density could produce that effect on the ionosphere in the post-sunset sector (Astafyeva et al., 2015).

ACKNOWLEDGEMENTS

This work is supported by the European Research Council under the European Union's Seventh Framework Program (ERC Grant Agreement n.307998). We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service, and the SPIDR services (http://spidr.ngdc.noaa.gov) for the data of the simple Joule heating rate. We thank the GFZ Potsdam for providing data of CHAMP satellite through the ISDC data centre, and the Center for Space Sciences at the University of Texas at Dallas and the US Air Force for providing the DMSP thermal plasma data, the International GNSS Service (IGS) for GPS data and products, and the UML DIDBase (http://umlcar.uml.edu/ DIDBase/). We acknowledge the PO.DAAC (Physical Oceanography Distributed Active Archive Center, ftp://podaac.jpl.nasa.gov) for the data of GPS-receivers and K-band measurements from the GRACE satellites.

REFERENCES

Astafyeva, E.I. (2009), Dayside ionospheric uplift during strong geomagnetic storms as detected by the CHAMP, SAC-C, TOPEX and Jason-1 satellites. *Advances in Space Research*, 43, 1749-1756, DOI:10.1016/j.asr.2008.09.036.

Astafyeva, E., I. Zakharenkova and E. Doornbos (2015). Opposite hemispheric asymmetries during the ionospheric storm of 29-31 August 2004. *J. Geophys. Res. - Space Physics*, V.120, 697-714, doi:10.1002/2014JA020710.

Danilov, A. D. (2013). Ionospheric F-Region Response to Geomagnetic Disturbances. *Adv. Sp. Res.* 52 (3), 343–366. doi:10.1016/j.asr.2013.04.019.

de Abreu, A.J., P.R. Fagundes, Y. Sahai, R. de Jesus, J.A. Bittencourt, C. Brunini, M. Gende, V.G. Pillat et al. (2010), Hemispheric asymmetries in the ionospheric response observed in the American sector during an intense geomagnetic storm, *J. Geophys. Res.*, 115, A12312, doi:10.1029/2010JA015661.

Foster, J. C. and Coster, A. J. (2007) Conjugate localized enhancement of total electron content at low latitudes in the American sector, *J. Atmos. Solar-Terr. Phys*., 69, 1241–1252.

Goncharenko, L.P., Foster, J.C., Coster, A.J., Huang, C., Aponte, N., Paxton, L.J. Observations of a positive storm phase on September 10, 2005. *J. Atmos. Solar-Terr. Phys.* 69, 1253–1272, 2007.

Hofmann-Wellenhof, B. (2001), Global Positioning System: Theory and Practice, Springer, New-York.

Lazutin, L.L., M.I. Panasyuk, and N. Hasebe (2011). Acceleration and Losses of energetic protons and electrons during magnetic storm on August 30-31, 2004. *Cosmic Research*, 49 (1), 38-44.

Mannucci, A.J., Tsurutani, B.T., Iijima, B.A., Komjathy, A., Saito, A., Gonzalez, W.D., Guarnieri, F.L., Kozyra, J.U., Skoug, R. (2005) Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 “Halloween Storms”. *Geophys. Res. Lett.* 32, 12, doi:10.1029/2004GL021467.

Mannucci, A.J., G. Crowley, B.T. Tsurutani, O.P. Verkhoglyadova, A. Komjathy, P. Stephens. (2014) Interplanetary Magnetic Field By Control of Prompt Total Electron Content Increases During Superstorms*, J. Atm. Solar-Terr. Phy*s, doi :10.106/j.jastp.2014.01.001.

Pedatella, N. M., J. Lei, K. M. Larson, and J. M. Forbes (2009), Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect, *J. Geophys. Res.,* 114, A12313, doi:10.1029/2009JA014568.

Prölls, G. (1995), Ionospheric F-region storms, in: Volland, H. (Ed.), Handbook of Atmospheric Electrodynamics, vol 2, CRC Press/Boca Raton, pp. 195–248.

Tsurutani, B., Mannucci, A., Iijima, B., Abdu, M.A., Sobral, J.H.A., Gonzalez, W., Guarneri, F., Tsuda, T. (2004), et al. Global dayside ionospheric uplift and enhancement associated with interplanetary electric fields. *J. Geophys. Res*. 109, A08302.

Xiong, C., J. Park, H. Lühr, C. Stolle, and S.Y. Ma. (2010) Comparing plasma bubble occurrence rates at CHAMP and GRACE altitudes during high and low solar activity. *Ann. Geophys*., 28, 1647-1658, doi :10.5194/angeo-28-1647-2010.

Yizengaw, E., M. B. Moldwin, A. Komjathy, and A. J. Mannucci (2006), Unusual topside ionospheric density response to the November 2003 superstorm, *J. Geophys. Res*., 111, A02308, doi:10.1029/2005JA011433.

Zakharenkova, I. and E.Astafyeva (2015). Topside ionospheric irregularities as seen from multi-satellite observations. *J. Geophys. Res. - Space Physics*, V.120, 807-824, doi:10.1002/2014JA020330.