North-South asymmetry in the ionosphere and seismic activity

T.L. Gulyaeva¹, F. Arikan², M. Hernandez-Pajares³ and I.S. Veselovsky⁴,⁵

¹IZMIRAN, Moscow, 142190 Troitsk, Russia
gulyaeva@izmiran.ru

²Department of EEE, Hacettepe University, Beytepe, Ankara 06800, Turkey
arikan@hacettepe.edu.tr

³Universitat Politècnica de Catalunya (UPC) Barcelona, Spain
manuel@ma4.upc.edu

⁴Skobeltsy Institute of Nuclear Physics, Moscow State University, Moscow, Russia
veselov@dec1.sinp.msu.ru

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Abstract.

[1] A retrospective study of the North-South asymmetry (NSA) during the solstices is made using the different geospace parameters in the North and South magnetic hemispheres. The NSA features are investigated using Total Electron Content, TEC, and Global Electron Content, GEC, produced from global ionospheric maps, GIM-TEC for 1999-2013, the Ionospheric Electron Content, IEC, measured by Topex-Jason-1,2 (T/J) satellites for 2001-2012, the F2 layer critical frequency and peak height measured onboard of ISIS1,2 and IK19 satellites during 1969-1982, and the earthquakes M5+ occurrence for 1999-2013. NSA is observed with GEC and IEC for the years of observation with asymmetry index, AI, showing January>July excess from 0.02 to 0.25. The coincident pattern of January-to-July asymmetry ratio of TEC and IEC co-located along the magnetic longitude sector of 270°±5°E in the Pacific ocean is obtained varying with local time and magnetic latitude. The sea/land differences in the F2 layer peak electron density, NmF2, and the peak height, hmF2, gathered with topside sounding data exhibit tilted ionosphere along the seashores with denser electron population at greater peak heights over the sea. The topside peak electron density NmF2, TEC, IEC and the hemisphere part of GEC are dominant in the South hemisphere which resembles the pattern for seismic activity with dominant earthquake occurrence in the South magnetic hemisphere. Though the study is made for the NSA during solstices in the ionosphere the conclusions seem valid for other aspects of seismic-ionospheric associations with tectonic plate boundaries representing zones of enhanced risk for space weather.

1. Introduction.

[2] The North-South asymmetry (NSA) in the neutral upper atmosphere and ionosphere has been extensively studied with the ground-based and topside sounders, the satellite drag data, the total height-integrated electron content, TEC, TOPEX/JASON ionospheric electron content, IEC, the FORMOSAT/COSMIC electron density, the CHAMP and GRACE observations of electron density, thermospheric mass density and neutral thermospheric wind and models [Buonsanto, 1986; Jee et al., 2004; Mendillo et al., 2005; Illes-Almar and Almar, 2006; Rishbeth and Muller-Wodarg, 2006; Rishbeth, 2006; Zhao et.al, 2007; Hocke, 2008; Zeng et al., 2008; Bencze, 2009; Liu et al., 2009; Lee et al. 2013; Balan et al., 2013; Xiong et al., 2013; Förster and Cnossen, 2013; Qian et al., 2013]. The geomagnetic effect in neutral composition has brought evidence of the existence of NSA of total neutral density and an appropriate asymmetry term was incorporated into the CIRA’86 and NRLMSIS-E-00 models [Illes-Almar and Almar, 2006; Förster and Cnossen, 2013]. With the ionosonde data it is found that the F2 layer annual asymmetry with greater electron density in January than in July exists at noon and at midnight, at all latitudes from equatorial to sub-auroral, and tends to be greater at solar minimum than solar
maximum [Rishbeth and Muller-Wodarg, 2006]. The annual asymmetry can only be separated from the seasonal anomaly (winter noon NmF2 exceeding the summer noon value) by combining data from opposite seasons in the two hemispheres. Rishbeth and Muller-Wodarg [2006] admit that the asymmetry is “hemispheric” – a difference between hemispheres rather than between solstices. Since the ionosphere is sensitive to dynamic forces such as the neutral wind and electric field and its configuration depends on the magnetic field forcing the electrons along the magnetic field lines our analysis is provided for the North and South magnetic hemispheres using the data separated by geomagnetic equator.

[3] An obvious possible cause of the annual asymmetry is the January/July variation of 3.5% in Sun-Earth distance, though the resulting 7% variation in the flux of solar ionizing radiation is insufficient to account for the reported annual January/July difference of 10-20% in NmF2 [Buonsanto, 1986]. The displacement of the geomagnetic field axis from the geographic axis and the change in Sun-Earth distance are supposed as the primary causes of the annual asymmetry [Zeng et al., 2008; Förster and Cnossen, 2013] but Qian et al. [2013] report that the causes of the annual and semiannual variations in NmF2 are not fully understood. After considering possible explanations of NSA, Rishbeth and Muller-Wodarg [2006] conclude that dynamical influences of the lower atmosphere (below about 30 km), not included in their computations, are the most likely cause of the asymmetry. This idea was further expanded by Rishbeth [2006] where it has been suggested that phenomena such as storms, earthquakes and volcanic explosions may produce F2-layer anomalies. Following this conclusion, we extend the present study for evaluation of the annual asymmetry with Global Electron Content, GEC, and Topex/Jason1,2 ionospheric electron content, IEC, compare results with the F2 layer peak parameters gathered with the topside sounder onboard of ISIS1,2 and IK19 satellites, and make retrospective analysis of the earthquake occurrence of Richter magnitude M5+ in the North and South magnetic hemispheres as a possible contributor to the annual asymmetry of the ionosphere.

[4] The production of Global Ionospheric Maps (GIM) with global coverage and routine operation of Global Positioning System (GPS) derived vertical total electron content (TEC) induced extensive studies of global characteristics of the ionosphere and plasmasphere [Iijima et al., 1999; Zhao et al., 2007; Hocke, 2008; Afraimovich et al., 2006, 2008; Astafyeva et al., 2008; She et al., 2008; Liu et al., 2009, 2011; Scharroo et al., 2010; Lean et al., 2012; Li et al., 2013; Lee et al., 2013; Gulyaeva et al., 2013; Gulyaeva and Veselovsky, 2012, 2014]. The advantage of the global mean TEC and Global Electron Content parameters is that they can capture the overall ionospheric features and greatly depress local noises in the ionosphere [Astafyeva et al., 2008]. The North-South asymmetry index, AI [Rishbeth and Muller-Wodarg, 2006] is evaluated in Section 2 with GEC data for 1999-2013.

[5] Evaluation of NSA using the global plasmaspheric total electron content (pTEC) with the ionospheric TEC (iTEC) simultaneously measured by Jason-1 satellite during the declining phase of solar cycle 23 brought straightforward evidence on their hemispheric asymmetry for solstices under moderate and low solar activity [Lee et al., 2013]. It is shown that the plasmaspheric contribution to the nighttime ionosphere does not increase with solar activity and the largest contribution occurs during June solstice. There is an annual variation (i.e., December→June) in the plasmasphere maximizing in American sector (-100° to -30° in geographic longitude) unlike the annual variation in the ionosphere, which exists regardless of longitude. The ratio of December to June in the equatorial plasmaspheric TEC is approximately 1.5 to 2.0, depending on local time and solar activity; it is larger at night and for low solar activity than during the day and for high solar activity, respectively. The Topex/Jason1,2 data of ionospheric electron content, IEC, are used in Sections 2 and 3 as the most reliable source of information for investigations of NSA in the ionosphere over the oceans.

[6] Comparisons of GPS derived TEC representing the combination of the ionospheric and plasmaspheric TEC measured by ground based receivers with the ionospheric electron content, IEC, measured onboard of Topex-Jason-1,2 satellites over the sea is only possible using TEC extracted (interpolated) from the Global Ionospheric Map, GIM (Hernandez-Pajares et al., 2009).
In selecting these data for the present study the displacement of the magnetic equator and geographic equator should be taken into account which produces large North–South difference in the effective magnetic meridional neutral wind velocity, which is the main cause of the ionospheric asymmetry [Balan et al., 2013]. To make a reliable comparison of TEC with IEC, the TEC data co-located with IEC measurements along the T/J orbit over the Pacific ocean are extracted from GIM-TEC at the magnetic longitude sector of 270°±5°E (geographic longitudes sector from 180 to 215°E) where the magnetic equator crosses the geographic equator providing opportunity to ignore the impact of the difference of the gravitational field and geomagnetic field on the ionosphere structure and dynamics. The annual anomaly at selected sector is investigated in Section 3.

[7] The retrospective analysis of behavior of the F2 layer peak height, hmF2, over the land and seashores [Bencze, 2009] reveals that taking into account both the field-aligned and the electro-dynamical drift, northward (eastward) tidal winds and southward (westward) tidal winds would create downward and upward drifts, respectively, in the Northern Hemisphere but southward (eastward) and northward (westward) tidal winds in the Southern Hemisphere. An upward drift is accompanied by an increase and a downward drift is accompanied by a decrease of hmF2. It has been suggested that because of the thermal driven origin of the non-migrating tides, the distribution of hmF2 may also be connected with ocean currents warming or cooling the neighborhood of the coastline. The effect of ocean currents would create downward drift due to cooling at the western coastlines of the continents but upward drift at the eastern coastlines as a result of the warming. This has been shown by comparing the distribution of hmF2 trends with the map of ocean currents. The corresponding hmF2 trends may develop because of changes in the land/sea warming ratio [Sutton, 2007], where the land-surface air temperature increases faster than the sea-surface air temperature. These considerations are also valid for the sea-dominant global land/sea asymmetry in the F2 layer peak electron density, Nmf2 (foF2 critical frequency) and peak height, hmF2, measured onboard of ISIS1,2 and IK19 satellites during 1969-1982 [Gulyaeva, 2010]. Investigations of the topside sounding data of foF2 and hmF2 are extended here for effects of NSA in Section 4.

[8] Recent investigations indicate relations of TEC and other ionosphere parameters changes with seismic activity in the lithosphere before, during and after earthquakes [Gokhberg et al., 1983; Chen et al., 2004; Liu et al., 2004, 2014; Pulinets and Boyarchuk, 2004; Rishbeth, 2006; Zhao et al., 2008; Astafyeva et al., 2009; Karatay et al., 2010; Namgaladze et al., 2012; Afraimovich et al., 2013; Komjathy et al., 2013; Le et al., 2013; Pohunkov et al., 2013; Freund, 2013; Pulinets and Davidenko, 2014]. Though it is difficult to distinguish between pure seismic precursors in the ionosphere from geomagnetic storms effects [Karatay et al., 2010] the post-earthquake phenomena are well observed and found over the local areas of high seismic activity providing opportunity to make both temporal and spatial earthquake-ionosphere associations [Rishbeth, 2006]. This is confirmed, e.g., with radio frequency mass spectrometer onboard the spacecraft Meteor-M at the orbit altitude near 820 km which detected presence of abnormally high relative concentration of light ions of hydrogen and helium (exceeding normal concentration of the species up to 6 times) over the local areas of high seismic activity before and during more than two weeks after the devastating earthquake [Pohunkov et al., 2013]. The speed of the earthquake-induced acoustic gravitational wave propagation through the ionosphere of near 990 m/s has been detected with GPS network, which is close to the sound speed at ionospheric heights, and the effects are registered at the ionospheric point at a distance up to 2000 km away from the epicenter [Astafieva et al., 2009]. Signatures of seismic precursors have been detected with electron density Ne and electron temperature Te measured onboard of DEMETER at 630 km altitudes for a spatial distribution from few degrees to almost twenty degrees equatorward from the epicenter [Liu et al., 2014]. Though an earthquake affects the surrounding space within the restricted area the prolonged impact and frequency of occurrence of the earthquakes may have cumulative effects on the ionosphere structure and variability. Special consideration is given in Section 5 for the North-South asymmetry of the earthquake occurrence.
and their possible impact on the relevant ionosphere asymmetry. Section 6 sums up the conclusions derived.

2. North-South asymmetry of Global Electron Content and Topex/Jason IEC.

[9] The Global Positioning System (GPS) provides information on slant Total Electron Content (STEC), which is the total number of electrons in a cylinder with a cross section of 1 m² with its axis along a ray path from a satellite to receiver. The slant STEC is transformed to vertical TEC at the sub-ionospheric piercing point from which the global ionospheric maps, GIM-TEC, are generated in a continuous operational way by several Data Analysis Centers since 1998, covering the period more than the entire solar cycle [Manucci et al., 1998; Hernandez-Pajares et al., 2009]. The hourly and two-hourly files used in the present study are provided by Jet Propulsion Laboratory and by Universitat Politècnica de Catalunya. When an input IONEX file is available only with 2h UT resolution, the linear interpolation in time is applied to bring GIM-TEC for 1h UT resolution.

[10] The Global Electron Content, GEC, product of GIM-TEC, represents the total number of electrons in the near-Earth space taking into account the sphere space volume from the bottom of the ionosphere to the GPS orbit at altitude of 20,200 km over the Earth [Afraimovich et al., 2006, 2008; Astafyeva et al., 2008; Gulyaeva and Veselovsky, 2012, 2014]. Hourly, daily and monthly GEC have been calculated from global GIM-TEC maps on a latitude/longitude grid (2.5ºx5º) converting 5184 TEC values per map to Ne(h) profiles with IRI-Plas code [Gulyaeva et al., 2013; Gulyaeva and Veselovsky, 2012, 2014]. More than 6.0×10^8 Ne(h) profiles for 1999-2013 were used for GEC production and analysis. As an example, daily GEC values produced from hourly UPC and JPL maps for 2012 are plotted in Figure 1. Close proximity of GEC produced from the both GIM-TECs is obtained clearly demonstrating annual anomaly of GEC with its excess for January (December) over July (June) data.

[11] The North and South hemisphere parts of GEC (denoted further as half-GEC) are calculated from JPL GIM-TEC maps separating the data for the North and South magnetic hemispheres over the Earth’s surface on the both sides of the magnetic equator. Results are plotted in Figure 2 for the monthly North and South parts of GEC and the total GEC for 1999-2013. NSA (January > July) is clearly seen for all years in all three curves with the greater South amplitude due to the lower June-July values than the North one. These data are used for estimate of January-to-July ratio, Rjj, and the Asymmetry Index, AI.

[12] We define the GEC annual Asymmetry Index, AI, similar to its derivation for the F2 layer peak electron density, NmF2 [Rishbeth and Muller-Wodarg, 2006]:

\[
AI = \frac{GEC_{jan} - GEC_{jul}}{GEC_{jan} + GEC_{jul}} \tag{1}
\]

We also quantify the ratio of January-to-July parameter Y as a measure of the annual asymmetry:

\[
R_{jj} = \frac{Y_{jan}}{Y_{jul}} \tag{2}
\]

where Y = TEC, IEC, NmF2, or hmF2. The AI is positive if the January/July ratio Rjj > 1 and negative if it is less than 1. A ratio Rjj = 1.1 corresponds approximately to an asymmetry index AI = 0.05. Table 1 shows January-to-July ratio, Rjj, and the asymmetry index, AI, for GEC and its North and South counterparts along with the annual sunspot number, SSN. Total global AI and the South results are always positive which means a permanent presence of NSA in the data. The AI in the North hemisphere is negative at the ascending phase of the solar cycle near solar maximum when greater July (summer) than January (winter) GEC occurs. While a winter anomaly can occur (AI > 1) with noon peak electron density greater than the summer noon NmF2 but the noon characteristics are smoothed out in GEC which is composed for Universal
Time, UT, hourly bins from mixed day and night TECs. The reverse $R_{ij} < 1$ near the solar maximum is smoothed away when averaging results for several years of a solar cycle so that the total average $R_{ij} > 1$ and NSA with January>July values are seen in the last line of Table 1 and in Figure 3a where the monthly mean GEC in the North and South magnetic hemispheres and global GEC are averaged for the period of T/J observations of the ionospheric electron content, IEC, during 2001-2012.

[13] The GIM-TEC maps (a source of GEC) may be less reliable over the oceans in view of rare GPS receiver network only on seashores and islands which involves more assumptions / interpolations imposed on GIM mapping techniques. For this reason we include in our analysis estimate of the NSA with the Topex/Jason1,2 ionospheric electron content, IEC, gathered for a period of 2001-2012. The Topex/Jason altimeter provides the ionospheric IEC measurements over the oceans at altitudes below 1,336 km (Topex/Jason orbit) which do not include the plasmasphere contribution present in GPS-TEC [Jee et al., 2004; Lee et al., 2013], so an allowance for GPS-TEC exceeding Topex/Jason IEC should be kept in mind when comparing these two data sources. Monthly average IEC over the oceans in the North and South magnetic hemispheres and global mean IEC are plotted in Figure 3b. Figure 3a,b demonstrates the congruent patterns of annual variation of GEC and IEC notwithstanding that GEC is based on height integrated TEC through the ionosphere and plasmasphere over the both land and sea while T/J IEC is measured below 1336 km in the ionosphere only over the sea surface. The NSA with January (December) > July (June) proportions are seen in all curves of Figure 3a,b. The ratio of January-to-July for North, South and global results is equal to $R_{ij} = 1.12, 1.74,$ and $1.48$ with GEC data, respectively, and $R_{ij} = 1.06, 1.84,$ and $1.41$ with T/J data. Hence, average NSA shows the global ionosphere plasma population in January dominated more than by 40% over July with this difference few times greater in the South hemisphere than in the North hemisphere. Analysis of NSA variation with local time and magnetic latitude is presented in the next Section using GPS-derived TEC and T/J IEC data.

3. TEC and IEC along the magnetic meridian of 270°

[14] To put TEC and IEC in the relevant conditions over the sea surface (T/J regime of observations), we extract total electron content TEC co-located with IEC measurements from GIM-TEC for the period of T/J database from July, 2001, to December, 2012. The both TEC and IEC data are extracted in the magnetic longitude sector of 270°±5°E (geographic longitudes between 180° and 215°E) over the Pacific ocean shown in Figure 4. This sector is selected because there is a minimum displacement of the magnetic equator with the geographic equator providing opportunity to ignore the impact of the difference of the gravitational field and geomagnetic field on the ionosphere structure and dynamics. Our selection belongs to the most significant longitudinal variation of T/J IEC which was found in the South Pacific region by Jee et al. [2004]. While the overall T/J data are spatially limited in the North hemisphere because of the huge land mass structure therein, this shortcoming is excluded using the data bins which are completely located over the sea in the both hemispheres (Figure 4).

[15] Patterns of the IEC latitudinal profile along the 270° magnetic meridian averaged for 2001-2012 are presented in Figure 5a (5b) at midnight (noon) for 4 months: January (North winter, South summer), March and October (equinox), July (North summer, South winter). Comparing curves for January and July, the noon curves display $R_{ij} > 1$ for all latitudes (January>July) but alternate results of $R_{ij} \geq 1$ varying with magnetic latitude zones by night (the zones are shown in Figure 4). In particular, NSA with January>July is observed by night in the zones 1S, 2S and 0N but January<July elsewhere.

[16] Latitudinal profiles of $R_{ij}$ along 270° magnetic meridian are plotted in Figure 6a (noon) and 6b (midnight). The both parameters show congruent NSA variation of $R_{ij} > 1$ by day with peaks at Mlat = ± 20° and Mlat = ± 50° and minima at Mlat = 0°, ±40°, < -60° and >60°. As concerns the midnight values, $R_{ij} > 1$ (annual anomaly) is observed only in the South hemisphere at Mlat <
-15° with peaks at Mlat = -50° and -20° and minima at Mlat < -60° and Mlat = -35° while $R_{jj} < 1$ (July > January) at Mlat > -15°.

[17] Local time variation of ratio $R_{jj}$ at the magnetic meridian of 270° also shows identical variation with both TEC and IEC data (Figure 6c). The annual anomaly ($R_{jj} > 1$) persists for the most of local time except for $t = 6h$ and $9h$ in the morning and $16h$ to $21h$ in the evening sector. Maximum of $R_{jj}$ is observed at noon, $t = 12h$, and towards the midnight $t = 22h$ the latter is obliged to the dominant $R_{jj} > 1$ in the South hemisphere. The close resemblance of January-to-July ratio of TEC and IEC confirm that the ionosphere contribution in GPS-derived TEC is prevailing compared with the plasmasphere part at least over the oceans (Lee et al., 2013). We proceed to evaluation of NSA with the F2 layer peak parameters derived from the topside sounding data which provide global coverage over the sea and land thus allowing to make comparisons between the ionosphere over the both areas.

4. Contribution of Sea-Land ionosphere differences to N-S asymmetry

[18] The first separation of the topside sounder data for the F2 layer peak electron density, NmF2 (critical frequency, foF2) and the peak height, hmF2, over the land and sea was carried out with the data collected onboard of the International Satellites for Ionospheric Studies, ISIS1, ISIS2, Intercosmos-19 and COSMOS-1809 satellites for the period of 1969–1987 [Gulyaeva, 2010]. The results of dominating NmF2 and hmF2 at sea as compared to land are obtained therein and reproduced here in Figure 7a,b. The global annual variation of foF2 is shown in Fig. 7a at low solar activity, LSA (upper panel) and high solar activity, HSA (bottom panel), from the topside (ISIS) data and ITU-R (CCIR, 1990) maps averaged over the sea (left panel) and land (right panel). Similar results for the peak height, hmF2, are plotted in Figure 7b. January-to-July ratio $R_{jj}$ (Eqn.2) according to results in Figure 7a,b is given in Table 2. The NSA (January>July) is present for both NmF2 and hmF2 only over the sea, $R_{jj} > 1$, and the asymmetry ratio $R_{jj}$ is greater for sea than for land. NSA is very low, $R_{jj} = 1.01$, in hmF2 over the sea and it is opposite, $R_{jj} < 1$, with July>January over the land. What is remarkable that the sea-land differences derived with topside sounder data are reproduced also (Figure 7a,b) with ITU-R (former CCIR) maps based on ionosonde observations [CCIR, 1990]. The limitations of these maps are due to the poor geographical coverage afforded by the measurements, with most of the ground-based ionosondes located unevenly in industrial areas on the land and large ocean areas not sampled. The sea-land differences in the F2 peak electron density and peak height observed throughout a year deserve special investigations. By now we can conclude that the excess of both the peak height and peak electron density over sea implies tilted ionosphere towards the land along the seashores with denser plasma population located at the greater peak height over the sea. Hence, the GPS-derived TEC measured near seashore should gain an extra check for the signal coming from satellites over the land and over the sea areas to mitigate sea-land differences in the ionosphere.

[19] We should keep in mind that 63% (37%) of the total Earth’s surface is covered by sea (land), this disproportion of sea (land) surface is equal to 55% (45%) in the North magnetic hemisphere and is much greater, 71% (29%) in the South magnetic hemisphere. Using the same database of the ISIS1, ISIS2 and IK19 topside sounding, we compare the annual variation calculated from combined land-sea surface foF2 and hmF2 in the North and South magnetic hemispheres for the period of observations 1969-1982. The results are plotted in Figure 8a (foF2) and Figure 8b (hmF2). The median values of foF2 for the South hemisphere (dashed curve) exceed by 10% to 20% those for the North hemisphere (solid curve) throughout the year. The excess of hmF2 in the North hemisphere over the South hemisphere values is greatest during January and December solstice, it is reduced during the equinoxes and disappears for June-July solstice. The theory of the sea-land differences in the ionosphere is not fully understood [Bencze, 2009] while the earthquake-ionosphere associations are much better investigated [Rishbeth, 2006; Freund, 2013; Pulinets and Davidenko, 2014]. So we proceed to analysis of seismic
activity as a possible source of the annual (hemispheric) asymmetry in NmF2, IEC, TEC and GEC according to hypothesis of [Rishbeth, 2006].

5. Contribution of seismic activity to N-S asymmetry.
[20] Impact of seismic activity on the atmosphere and ionosphere has a long record of investigations (the reader is addressed to references in paragraph [8] of Introduction and references therein). Vertical surface displacements related with earthquake generate shock acoustic waves in the neutral atmosphere which propagate upwards with their amplitude increased with height through the decreasing atmospheric density. At the ionosphere heights the acoustic waves generate disturbances due to interaction between the neutral and charged particles [Afraimovich et al., 2013]. In our study we use global Catalogue of the Advanced National Seismic System (ANSS) provided by the Northern California Earthquake Data Center (NCED). The composite Catalogue of earthquakes created by ANSS is a world-wide earthquake catalog which is created by merging the master earthquake catalogs from contributing ANSS member institutions and then removing duplicate events, or non-unique solutions for the same event. We use monthly and annual data sets of events with magnitude greater or equal to M5.0 (denoted by M5+) from the Catalogue for a period from 1999 to 2013 corresponding to the total period of available GIM-TEC and GEC parameters. We separated the monthly lists of earthquakes for those occurring in the North and South magnetic hemispheres with their coordinates above or below the magnetic equator.
[21] The monthly earthquake number for the North hemisphere (points and median solid line) and South hemisphere (crosses and median dashed line) are plotted in Figure 9. The median (rather than average) is selected to exclude contribution of extreme events such as those for Tohoku earthquake in March 2011 (circle point). There are 60-70 events per month on an average in the North hemisphere and 80-100 events in the South hemisphere. While most of publications on earthquake-ionosphere associations refer to investigation of the individual earthquake or series of events, the total set of events allows conclude that there are more earthquakes occurring in the South hemisphere than in the North hemisphere. This conclusion remind on the similar proportion with greater electron density, ionospheric electron content, IEC, TEC and half-GEC in the South hemisphere than in the North hemisphere.
[22] The reason behind the greater earthquakes occurrence in the South hemisphere than in the North hemisphere is the greater length of the tectonic plates boundaries in the South magnetic hemisphere than in the North one: the South and North parts of the total length comprise 53% and 47%, respectively. It is illustrated in Figure 10 where the global distribution of the earthquakes (bold dots) and the tectonic plate boundaries (weak points) are shown above and below the magnetic equator for January and July 1999-2013. The both sets for two months are shown on the same map because location/monthly occurrence for earthquakes in these months are overlapping (see monthly occurrence in Figure 9). Hence, one could expect an enhanced number of earthquakes occurrence in the South magnetic hemisphere which, however, got less public awareness because of their location on the uninhabited ocean territory. We have presented analysis of a seismic activity just as the events occurrence. The more difficult problem might be taking into account temporal and spatial extent of pre-event and post-event effects. One could expect that these effects taken into account would facilitate the conclusions on seismic activity contributing to the annual asymmetry in the ionosphere.

6. Conclusion.
[23] The North and South hemisphere parts of GEC (half-GEC) are calculated from JPL GIM-TEC maps for 1999-2013 using TEC at two sub-sets of cells in the North and South hemispheres separated by the magnetic equator. The analysis is made as well with independent data of the Ionospheric Electron Content, IEC, measured by Topex-Jason-1,2 (T/J) satellites for 2001-2012. The North-South Asymmetry, NSA (January > July) is obtained with the overall GEC and half-GEC in the South hemisphere while it occurs in the North hemisphere for the most of time.
except for an opposite ratio (January<July) during the years approaching the solar maximum. The average results for the total period, 2001-2012 (T/J IEC database) confirm NSA (January>July) with GEC and IEC for the globe and the both hemispheres: NSA has greater amplitude in the South hemisphere where the June-July (local winter) values of GEC and IEC have less magnitude than at the same months in the North hemisphere (local summer). The average NSA shows the global ionosphere plasma population in January dominated more than by 40% over July data with this difference much greater in the South hemisphere than in the North hemisphere.

[24] To make a comparison of TEC and IEC under relevant conditions over the sea (regime of T/J IEC observations) a special analysis is performed with TEC and IEC data at the magnetic sector of 270°±5°, selecting TEC co-located with T/J measurements of IEC by interpolation from GIM-TEC maps. This sector is located completely over the sea surface at crossing the geographic and geomagnetic equator. Evaluating the data independent of the difference between the gravitational and magnetic fields. Though absolute values of GIM-TEC include both ionosphere and plasmasphere contribution below 20,200 km (GPS orbit) while T/J IEC consists only from the ionosphere electron content below 1,336 km (T/J orbit) these differences doesn’t affect a relative ratio $R_{jj}$ (Eqn.2) with each kind of data. The close congruence of January-to-July ratio of TEC and IEC is obtained at 270° magnetic meridian. In particular, $R_{jj}$ variation with magnetic latitude shows $R_{jj} > 1$ by day with peaks at Mlat = ±20° and Mlat = ±50° and minima at Mlat = 0°, ±40°, < -60° and >60°. As concerns the midnight values, $R_{jj} > 1$ (annual anomaly) is observed only in the South hemisphere at Mlat < -15° with peaks at Mlat = -50° and -20° and minima at Mlat < -60° and Mlat = -35° while $R_{jj} < 1$ (July > January) at Mlat > -15°. The local time variation of $R_{jj}$ shows persisting annual anomaly ($R_{jj} > 1$) for the most of local time except for $t = 6h$ and 9h in the morning and 16h to 21h in the evening sector. Maximum of $R_{jj}$ is observed at noon, $t = 12h$, and towards the midnight $t = 22h$ when the dominant $R_{jj} > 1$ exists in the South hemisphere. The close resemblance of January-to-July ratio of TEC and IEC confirm that the ionosphere contribution in GPS-derived TEC is prevailing compared with the plasmasphere part, in particular, over the oceans.

[25] The next important conclusion is obtained demonstrating that the ionosphere around the peak of the F2 layer is tilted at the seashore from the denser peak electron concentration, NmF2, at the greater peak altitude, hmF2, over the sea, towards the land where the both NmF2 and hmF2 are reduced. This conclusion is based on analysis of the topside sounder critical frequency, foF2, and peak height, hmF2, gathered onboard of ISIS1, ISIS2, Intercosmos-19 and COSMOS-1809 satellites for the period of 1969–1987. When these sea-land combined topside sounder critical parameters are separated for the North and South magnetic hemispheres, the dominant NmF2 (related with foF2) is obtained in the South hemisphere throughout a year; however, the excess of hmF2 in the North hemisphere over the South hemisphere values is greatest during January and December solstices, it is reduced during the equinoxes and disappears for June-July solstice. The NSA (January>July) is present for both NmF2 and hmF2 only over the sea, $R_{jj} > 1$, and the asymmetry ratio $R_{jj}$ is greater for sea than for land. NSA is very low, $R_{jj} = 1.01$, in hmF2 over the sea and it is opposite, $R_{jj} < 1$, with July>January over the land.

[26] Since the theory of the sea-land differences in the ionosphere is not fully understood we have made investigation of the earthquake-ionosphere associations using the earthquakes M5+ data for 1999-2013 (the total period of GIM-TEC and its product GEC database). While most of publications on earthquake-ionosphere associations refer to investigation of the individual earthquake or series of events, the total set of events allows conclude that there are more earthquakes occurring in the South hemisphere (80 to 100 events per month on an average) than in the North hemisphere (60-70 events). The North/South difference in the earthquake occurrence is associated with the greater length of the tectonic plate boundaries (the sites of enhanced risk of seismic activity) in the South magnetic hemisphere than in the North one: the South and North parts of the total length comprise 53% and 47%, respectively. Thus we relate the North-South asymmetry in the ionosphere with greater peak electron density, ionospheric
electron content, IEC, TEC and half-GEC in the South hemisphere than in the North hemisphere with seismic activity also dominant in the South magnetic hemisphere. The future studies taking into account temporal and spatial extent of precursors and post-earthquake effects will shed light on actual extent of their impact on the ionosphere. One could expect that these effects taken into account would facilitate the conclusions on seismic activity contributing to the annual asymmetry in the ionosphere. Though the study is made for the NSA during solstices in the ionosphere, the conclusions seem valid for other aspects of seismic-ionospheric associations with tectonic plate boundaries representing zones of enhanced risk for space weather.

ACKNOWLEDGEMENTS

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REFERENCES


Figure Captions.

Fig. 1. Close proximity of daily average GEC values produced from hourly UPC and JPL GIM-TEC maps for 2012.

Fig. 2. Monthly mean half-GEC in North magnetic hemisphere and South magnetic hemisphere and global GEC based on GIM-TEC during 1999-2013.

Fig. 3. Congruent annual variation of GEC and IEC in the North and South magnetic hemispheres and global means for the period of Topex/Jason, T/J, observations, 2001-2012: (a) Global electron content, GEC, based on GIM-TEC; (b) T/J derived the ionospheric electron content over the oceans, IEC.

Fig. 4. Location of the magnetic longitude sector of 270°±5°E (geographic longitudes between 180 and 215°E) over the Pacific ocean selected for the analysis of GIM-TEC-based TEC and T/J IEC.

Fig. 5. Magnetic latitude T/J IEC profiles averaged for 2001-2012 at 270° magnetic meridian for January, March, July and October: (a) midnight, (b) noon.

Fig. 6. January/July ratio, $R_{jj}$, for GPS-based TEC and T/J IEC at 270° magnetic meridian: (a) noon magnetic latitude profile; (b) midnight magnetic latitude profile; c) local time profile.

Fig. 7. Annual variation of average topside sounder measurements over the sea (left column) and land (right column) for low solar activity (LSA, upper panel) and high solar activity (HAS, lower panel): (a) the F2 layer critical frequency, foF2; (b) the F2 layer peak height, hmF2. Predictions by ITU-R (CCIR) are provided for a comparison (reproduced from Figures 6 to 9 by Gulyaeva [2010]).

Fig. 8. Annual global mean variation of ISIS1,2 and IK19 topside sounding in the North and South magnetic hemispheres for the period of observations 1969-1982: (a) foF2; (b) hmF2.

Fig. 9. The monthly earthquake M5+ occurrence in the North magnetic hemisphere (points and median solid line) and South hemisphere (crosses and median dashed line) observed during 1999-2013. Extreme monthly events number for March, 2013, including Tohoku earthquake.

Fig. 10. Global distribution of earthquakes M5+ (bold dots) for January and July 1999-2013 and tectonic plates boundaries of the Earth (weak points). Magnetic equator – dashed line.
Table 1. The January/July ratio, $R_{jj}$, and Asymmetry Index, $AI$, of global electron content, GEC and its components in North and South magnetic hemispheres, and annual mean sunspot number, SSN.

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<td>$R_{jj}$</td>
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Table 2. January-to-July ratio $R_{jj}$ of mean NmF2 and hmF2 over the sea and land measured by ISIS1,2 and IK-19 satellites.

<table>
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<th>Solar maximum $R_{jj}$ (NmF2)</th>
<th>Solar minimum $R_{jj}$ (hmF2)</th>
<th>Solar maximum $R_{jj}$ (hmF2)</th>
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Fig. 1

Fig. 2.
Fig. 3a

GEC, 2001-2012

Fig. 3b

Topex/Jason IEC, 2001-2012
Fig. 6a,b

TEC@Mlat270, 2002-2009

Fig. 6c

TEC@Mlat270, 2002-2009
Fig. 7a

Fig. 7b
Fig. 8a

Fig. 8b