Variations of TEC over Iberian Peninsula in 2015: geomagnetic storms, solar flares, solar eclipse

A. L. Morozova, T. V. Barlyaeva, and T. Barata

CITEUC, University of Coimbra, Almas de Freire, Sta. Clara, Coimbra, 3040-004, Portugal.

Corresponding author: Anna L. Morozova (annamorozovauc@gmail.com)

Key Points:

• Variations of TEC over the Iberian Peninsula is analyzed during space weather events of 2015: geomagnetic storms, solar flares and eclipse
• Most of the analyzed geomagnetic storms caused positive-negative ionospheric storms; half of them had secondary peaks during the first day
• Daily maximum of TEC depends on the level of the solar UV and XR fluxes and total number of flares; it is decreases during the eclipse
Abstract

The total ionospheric content (TEC) over the midlatitudinal area (Iberian Peninsula) was studied using data from two locations (on the west and east coasts) obtained both by the GNSS receivers and an ionosonde. The principal component analysis applied to the TEC data allowed us to extract two main modes. The variations of these modes as well as the original TEC data were studied in relations to four strongest geomagnetic storms of 2015, three geomagnetic disturbances of lower amplitude observed during the same months as the storms. Seven of eight analyzed geomagnetic events were associated with positive-negative ionospheric storms (seen both in TEC daily cycle amplitude and in the Mode 1). Four out of eight analyzed geomagnetic events were associated with variations of the Mode 2 that can be described as the appearance of the second daily peak on the 1st day of the storm and a deep in TEC variations on the 2nd day. Besides, the effect of solar flares and the solar UV and XR fluxes on TEC variations during four months of 2015 and an effect on TEC of a partial solar eclipse observed on March 20, 2015 were studied. These events were found to affect only the amplitude of the daily cycle (Mode 1).

1 Introduction

Modern society, industry and science use GNSS-based technologies more and more often (operations of the unmanned air-born, floating and land vehicles, GNSS-assisted landing procedures for commercial aviation, GNSS positioning for rescue operations, etc.). The quality of the GNSS signal and therefore the reliability of the GNSS-based technological solutions depend on the conditions in the upper part of the Earth atmosphere – the partially ionized layer called ionosphere.

The main sources for the data on the ionospheric conditions are ionosondes installed at specific locations (e.g., the only ionosonde on Iberian Peninsula belongs to the Ebro Observatory in Spain) and networks of GNSS receivers. The ionosondes allows obtaining the information about the altitude and maximal concentrations of electrons for different ionospheric layers (D, E, F1 and F2) and, consequently, to estimate a so called ionospheric total electron content without plasmaspheric contribution (iTEC). However, the number of ionosondes is limited; they provide information for a certain area and with limited time resolution. On the other hand, the territories of heavily populated areas like the continental Europe are well covered by networks of GNSS receivers. These networks allow to monitor ionospheric conditions with high precision and to develop empirical models to predict ionospheric response to different external forcings: solar flares, geomagnetic storms and, e.g., events associated with gravity waves propagation like sudden stratospheric warming events or solar eclipses.

There are two widely used parameters characterizing ionospheric conditions that can be obtained from the GNSS data: the total electron content (TEC) and scintillation indices (e.g., S3). TEC data are often used [Astafyeva et al., 2017; Goncharenko et al., 2013; Li et al., 2019] to analyze and simulate ionospheric disturbances caused by space weather or atmospheric events. In general, TEC response to space weather events consists of either changes of the amplitude and the shape of the regular daily TEC variations or a phenomenon called traveling ionospheric disturbances (TID) which are observed on a shorter time and space scales. In particular it was shown that at middle latitudes ionospheric conditions (TEC, TID and scintillation events) varies during strong geomagnetic storms of recent years [Astafyeva et al., 2015; Aa et al., 2018; Shim et al., 2018]. These variations can be a reason for perturbation of the GNSS signal causing a degradation of the signal and decrease of the precision of the positioning in the affected area.
The ionospheric response to different events can be obtained both from the analysis of the ionospheric data and from simulation using semi-empirical and physical models. Besides, the results of the data analysis are often used to develop regional empirical models allowing prediction of ionospheric response to different forcings, e.g., geomagnetic storms. The advantage of the regional models [e.g., Petry et al., 2014; Mukhtarov et al. 2017; Hu and Zhang, 2018; Tsagouri, et al., 2018; Tebabal et al., 2019] over the global ones is in their better reflection of specific local behavior of the ionosphere. In particular, the method called principal component analysis (PCA) showed good potential for the analysis and modeling of ionospheric regular variations and disturbances [Chen et al., 2015; Li et al., 2019; Morozova et al., 2019].

In this paper we present results of the analysis of the TEC data calculated for a mid-latitudinal region both from the ionosonde measurements and from the data of GNSS receivers. The main goal of this study was to detect main features of the mid-latitudinal response to such space weather events like geomagnetic disturbances (both strong and weak with a threshold at Dst = -100 nT), solar flares and overall variations of the solar UV and XR fluxes, and such rare events like solar eclipse.

The paper is organized as follows. Section 1 gives an introduction to the problem. Sections 2 and 3 describe, respectfully, the data in use and the methods. Section 4 presents short description of main space weather events of 2015 and ionospheric responses to them observed in other regions. Section 5 gives the comparison of different TEC data series used for the analysis. Section 6 presents the results of our analysis of TEC variations associated with selected events. Section 7 gives summary and conclusion.

2 Data

2.1 Total electron content

Three sources for the vertical total electron content (TEC) data were used in this work. The TEC series are obtained for one of two locations on the Iberian Peninsula (IP): Lisbon (Portugal) and Ebro (Spain). Thus our analysis of the ionospheric response to the space weather events is limited by the midlatitudinal region of IP.

First data set is the GNSS TEC data from the ROB data base and are publicly available as vertical TEC maps in the IONEX format in a grid of 0.5° x 0.5° with 15min time resolution [see also Bergeot et al., 2014]. Accordingly to the information from the ROB web site, the vertical TEC is estimated in near real-time from the GPS data of the EUREF Permanent Network (EPN). The vertical TEC maps are produced from the slant TEC of each satellite-receiver pair as projections in the vertical TEC at the ionospheric piercing points using an ionospheric single thin layer shell approximation located at 450 km and interpolated to a grid using a spline interpolation. For this analysis the TEC data for the grid points most close to Lisbon (39°N, 9°W) and Ebro (41°N, 0.5°E) were used, hereafter TEC_LIS-ROB and TEC_EBR-ROB, respectively. The TEC_ROB series were averaged to obtain 1h time resolution.

Another series, hereafter TEC_LIS-sci, is the GNSS TEC measured by the SCINDA receiver installed in 2015 in the Lisbon airport in the frame of the ESA Small ARTES Apps project “SWAIR – Space weather impact on GNSS service for Air Navigation” and C4G – Collaboration for Geosciences. The data are originally of 1 min time resolution were averaged to have the 1h time resolution. The calibration procedure was not performed during the installation of this.
receiver. To validate the non-calibrated TEC$_{LIS-sci}$ we present in Section 5 the comparison of the TEC$_{LIS-sci}$ series with the calibrated series obtained from ROB database.

Third data source is the ionospheric total electron content (iTEC$_{EBR}$) values provided by the Ebro Observatory, Spain (40.8°N, 0.5°E, 50 m asl). The instrument currently installed at the Ebro Observatory is the DPS-4D ionospheric sounder and the measured parameter is $f_{0}F2$. The altitude profiles of electron density are calculated from the ionograms, and the integration of these electron profiles up to 1000 km height gives the values of iTEC. The iTEC$_{EBR}$ data are of 1h time resolution.

2.2 Space weather data

Four parameters were used to analyze the geomagnetic field variations. The global $Dst$ index database has 1h time resolution and the global $Kp$ index has 3h time resolution. The local K-index ($K_{COI}$) was calculated from the horizontal component of the geomagnetic field measured at the Coimbra Magnetic Observatory (IAGA code COI) located in Coimbra, Portugal (40.22°N, 8.42°W, 99 m asl). The fourth index is the AE index.

The data on the solar wind properties were obtained from the OMNI data base. In this study we used following parameters: interplanetary magnetic field (IMF) components: scalar B, Bx, By and Bz GSM (nT), solar wind flow speed (km/sec), proton density, (n/cm$^3$) and flow pressure (nPa).

To parameterize the variations of the solar UV radiation we used two proxies. The first one is the Mg II composite series [Snow et al., 2014], a proxy for the spectral solar irradiance variability in the spectral range from UV to EUV based on the measurements of the emission core of the Mg II doublet (280 nm). The second proxy is the $F10.7$ index from the OMNI data base. Both Mg II and $F10.7$ series have 1d time resolution.

As a proxy for the variations of the solar XR flux we used the data measured by the Solar EUV Experiment (SEE) for the NASA TIMED mission ($XR_{TIMED}$) at the wavelength 0.5 nm with time resolution of 1d. Please note that for the plots the UV and XR irradiance proxies were scaled individually for better visualization.

The information about the solar flares observed during the analyzed time interval was obtained through the NOAA National Geophysical Data Center (NGDC). The daily numbers of solar flares of classes C, M and X separately as well as the total daily number of such flares (N) were calculated.

3 Methods

All series used in the presented work were averaged or interpolated to obtain series with 1h and 1d time resolution. There was a number of small gaps in the series linearly interpolated.

The analysis of the TEC series obtained from different sources was performed using the principal component analysis (PCA). PCA is a widely used method to extract independent spatial-temporal modes of variability (principal components, PC, for time series and empirical orthogonal functions, EOF, for, e.g., spatial patterns) when a number of series of the same parameter from, e.g., different stations is used. The input data set is used to construct a covariance matrix and calculate corresponding eigenvalues and eigenvectors. The eigenvectors are used to calculate principal components (PC) and empirical orthogonal functions (EOF). The
combination of a PC and corresponding EOFs is called a “mode” and the eigenvalues allow to estimate the explained variances ($f$) of the extracted modes. The PCs are orthogonal and conventionally non-dimensional. The full descriptions of the method can be found in (e.g.) Bjornsson and Venegas [1997], Hannachi et al. [2007] and Shlens [2009].

Each of the TEC series obtained at different locations and by different instruments ($TEC_{LIS-ROB}$, $TEC_{LIS-sci}$, $TEC_{EBR-ROB}$, and $iTEC_{EBR}$) with 1h time resolution was analyzed separately during each one month time interval. The PCA input matrices were constructed in a way that each column contains 24 observations (every 1h) for a specific day. Thus, PCA allows us to obtain daily variations of different types as PCs and the amplitudes of those daily variations for each day of a month as corresponding EOFs.

Similarities between the variations of the TEC and space weather parameters were analyzed using the correlation coefficients, $r$, that test linear relations between analyzed variables. The significance of the correlation coefficients was estimated using the Monte Carlo approach with artificial series constructed by the “phase randomization procedure” [Ebisuzaki, 1997]. The obtained statistical significance ($p$ value) takes into account the probability of a random series to have the same or higher absolute value of $r$ as in the case of a tested pair of the original series.

4 Description of significant space weather events of 2015

In this work we consider variations of the ionospheric and space weather parameters during four months of 2015: March, June, October and December. These months were selected as containing main space weather events of 2015.

First of all, major geomagnetic storms with Dst < -200 nT occurred in March and June 2015 (strongest and second strongest geomagnetic storms of 24th solar cycle), other two strong geomagnetic storms with Dst $\leq$ -125 nT were observed in October and December of this year. Three of these four storms were associated with coronal mass ejections (CME). Also, in June, October and December geomagnetic disturbances with Dst > -50 nT took place.

Two X-class flares were observed in 2015: one on March 11 (X2.2, at 16:11 UT) and another on May 5 (X2.7, at 22:05 UT). Since the last event took place during the night hours in the analyzed region it was excluded from the analysis.

Another interesting event that took place in 2015 is the partial eclipse observed in Europe on March 20. Even so it mostly affected the north-west part of the Europe, on the territory of the Iberian Peninsula the maximal obscuration was ~60% at ~09:00 UT.

The variations of the geomagnetic indices, the solar UV and XR fluxes, number of solar flares of type C and higher as well as parameters of the solar wind ($p$, $n$ and $v$) and the interplanetary magnetic field components for 2015 are shown in Fig. S1 (1h time resolution) and S2 (daily means) in the Supporting Information (SI). Below we present brief description of these events and their effects on the ionosphere observed in different regions. The summary of the events is presented in Table 1 and more detailed information can be found in Table S1 in SI.
4.1 Geomagnetic storms

4.1.1 March 17-18

Geomagnetic storm of 17-18 of March 2015 (GS1, see Table 1 and Fig. 1, and also Figs. S1 and S3 in SI) is still considered to be the strongest storm of 24th solar cycle with Dst < -220 nT and Kp = 8. This storm and its effect on the ionosphere is thoroughly analyzed by many authors [see, e.g., Astafyeva et al., 2015; Liu et al., 2015; Nava et al., 2016; Fagundes et al., 2016; Liu and Shen, 2017; Piersanti et al., 2017; Balasis et al., 2018; Paul et al., 2018], so here we present only brief description. The storm was triggered by two flares of C type on March 14 and 15 which, most probably were sources for two halo CME that arrived at 1 AU around 04:30 UT and around 18:00 UT, respectively, on March 17 [Liu et al., 2015]. These interacting CME caused sharp increase of the solar wind speed and pressure resulting in the sudden storm commencement (SSC) at ~04:30 UT on March 17 [Astafyeva et al., 2015]. The storm was developed in two steps [Liu et al., 2015; Balasis et al., 2018]: the Dst deeps were caused by the southward Bz component first in the sheath region behind the shock between 04:00 UT and 09:00 UT, and second within the interplanetary CME between 12:00 UT and 24:00 UT. Recovery phase of the storm started on March 18 and lasted for several days. Dst is remained below -50 nT to the end of March.

The Earth’s ionosphere responded to this storm by an increase of TEC during the main phase (“positive ionospheric storm”) on March 17 which was followed by a decrease of TEC (“negative ionospheric storm”) during March 18-19 [Astafyeva et al., 2015; Fagundes et al., 2016; Liu and Shen, 2017]. For Chinese middle latitudes the decrease of TEC relative to the undisturbed level was ~60-70% [Liu and Shen, 2017]. In the European-African sector the positive storm on March 17 was observed only in the Northern Hemisphere [Astafyeva et al., 2015]; and the daily TEC variations at 30-40º N are characterized by the second peak around 16-20 h LT [Astafyeva et al., 2015; Nava et al., 2016]. The main mechanism behind the ionospheric perturbation during this time intervals is, most probably, the prompt penetration of electric field (PPEF) [Nava et al., 2016; Fagundes et al., 2016; Paul et al., 2018].

4.1.2 June 22-25

The geomagnetic storm on June 22 (GS2, see Table 1 and Figs. 2, and also Figs. S1 and S3 in SI) to the moment is considered as the second strongest storm of 24th cycle and thoroughly described in, e.g., Liu et al. [2015], Astafyeva et al. [2016], Astafyeva et al. [2017], Piersanti et al. [2017], Singh and Sripathi [2017], Astafyeva et al. [2018], Ngwira et al. [2018], Paul et al. [2018], and Pazos et al. [2019]. This storm, similarly to the one in March, was related to the arrival of two CME associated with two solar flares (M-class) on June 18 and 21. The first CME arrived at 1 AU around 16:04 UT of June 21 and followed by a sequence of shocks around 05:04 UT and 18:08 UT on June 22 and around 13:07 UT on June 24 [Balasis et al., 2018]. The storm started on 18:33 UT with SSC and reached its maximum with Dst = -204 nT (and Kp = 8) at 04:30 UT on June 23. It was accompanied by the intense auroral activity [Astafyeva et al., 2016] and has three steps of development [Balasis et al., 2018]. On June 23 the recovery stage began but was partly disrupted by a small CME arrived on June 25 and resulted in another small deep of Dst [Pazos et al., 2019] on December 26.

The ionospheric response to this storm also consisted of the positive (June 22) and negative (June 23-24) ionospheric storms observed in all latitudinal sectors. In the middle
latitudes of the European-African sector TEC increased (relative to the undisturbed level) in the evening of June 22, pre-sunset hours end even after the sunset [Astafyeva et al., 2017]. On June 23 TEC started to decrease on both dayside and nightside of the Earth [Astafyeva et al., 2017], and dual peaks in TEC diurnal variation were observed at the middle and low latitudes of the Northern Hemisphere [Paul et al., 2018]. The main proposed mechanism for the ionospheric response to the geomagnetic storm was again PPEF [Astafyeva et al., 2016; Ngwira et al., 2018; Paul et al., 2018] and the disturbance dynamo electric field (DDEF) on June 23 [Paul et al., 2018].

4.1.3 October 7-8

On October 7-8 a storm with Dst = -124 nT and Kp = 6 was registered (GS4, see Table 1 and Figs. 3, and also Figs. S1 and S3 in SI). This storm was not associated with any CME and was probably caused by a coronal hole high-speed streams [Matsui et al., 2016; Pazos et al., 2019]. No significant ionospheric response to this storm was observed in the Earth ionosphere.

4.1.4 December 19-20

The last storm of 2015 started in the evening of December 19 and lasted until December 22 (GS3, see Table 1 and Figs. 4, and also Figs. S1 and S3 in SI). The minimum Dst of -155 nT with Kp = 6 was observed on the night from December 20 to December 21. This was a two-step storm [Balasis et al., 2018] caused by CME arrived around 15:38 UT on December 19 and related to a flare on December 16 [Balasis et al., 2018] with auroral activity over the Europe [Cherniak and Zakharenkova, 2018]. Detailed description of this storm can be found, e.g, in Loucks et al. [2017], Balasis et al. [2018], Cherniak and Zakharenkova [2018] and Paul et al. [2018].

During this time interval the positive ionospheric storm was observed in the middle latitudes of the Asian sector on December 20-21 [Paul et al., 2018] without the consequent negative phase. In the European region large-scale traveling ionospheric disturbances (LSTID) were observed on December 19-21 propagating during the main phase of the geomagnetic storm from European high latitudes to middle latitudes (35-40° N) [Cherniak and Zakharenkova, 2018].

4.2 Solar flares

On March 11, 2015 an X2.1-class solar flare (XF, see Table 1 and Table S1 in SI) was observed between 16:11 UT and 16:29 UT. Even so that the X-class flares are expected to increase ionization in the ionospheric D, E, and F regions, this particular flare being of short durations (few minutes) did not have significant effect on TEC values, at least in the Brazilian sector [de Abreu et al., 2019].

During all four analyzed months there were series of solar flares of the C and M classes (see bar plots in Figs. 1-4, middle left and S1-2, top left). On the whole, the increased number of flares resulted in the elevated level of the UV (F10.7 and Mg II indices) and XR (XR\textsubscript{TIMED}) solar fluxes (see step lines in Figs. 1-4, middle left and S1-2, top left). Correlation coefficients between the daily means of F10.7, Mg II and XR\textsubscript{TIMED} and the total daily number of the flares (C, M and X classes) are between 0.24 and 0.71 with higher and statistically more significant ($p$ values $\leq 0.05$) for the XR flux proxy.
4.3 Solar eclipse

In the morning hours of March 20, 2015 a partial solar eclipse was observed in Europe with ~60% obscuration around 9:00 UT for the IP region. A solar eclipse may cause substantial reduction of the ion production due to photoionisation and relative decrease of TEC values. Since the eclipse on March 20 happened during a geomagnetically quiet day (the storm of March 17 was in the recovering phase), the observed ionospheric disturbances can be associated solely with the eclipse. The ionospheric response in the European middle latitudes consisted of a decrease of TEC (relatively to the normal level) between 8 and 12 h LT [Verhulst et al., 2016; Stankov et al., 2017] with overall lower TEC values for the whole day of March 20: ~10-20% lower over most of the European region and ~30% lower in its south-west part [Verhulst et al., 2016; Stankov et al., 2017]. Also, LSTID were observed during the eclipse time with prevailing north-east direction over the region from 45° to 50° N and from 2° W to 8° E [Panasenko et al., 2019]. These LSTIDs were caused by local heating/cooling processes occurring during the eclipse [Panasenko et al., 2019] and gravity waves consequently generated in the atmosphere [Verhulst et al., 2016; Panasenko et al., 2019].

5 Comparison of TEC series from different locations and instruments

In this work we used series of TEC obtained for two different locations over IP (Lisbon and Ebro) and series obtained by different instruments (GNSS receivers and ionosonde). Therefore, before further analysis we want to discuss similarities and differences of these series during analyzed time intervals.

The correlation coefficients between the studied series are shown in Table 2 and the individual series are shown in Fig. S4 in SI for all four studied months. All correlation coefficients have \( p \) values \( \leq 0.05 \). As one can see, the series from different locations are well correlated (mean for four months \( r = 0.93 \)). There is also good agreement between the TEC values measured by the GNSS receivers and the ionosonde: mean \( r = 0.95 \). There is a systematic difference between the ROB and ionosonde series: the GNSS-based TEC values are higher than the iTEC series by ~30-50 TECU, which, to our mind reflect both the difference between iTEC and TEC values and the fact that the ROB data are interpolation to the regular grid of the actual observations.

The \( TEC_{LIS-sci} \) series is well correlated both with other GNSS-based TEC series (mean \( r = 0.95 \)) and with iTEC (mean \( r = 0.89 \)). The fact that \( TEC_{LIS-sci} \) is not calibrated does not affect the results of our analysis since we used only methods insensitive to scaling and shifting of the series. Please note also that for the plots \( TEC_{LIS-sci} \) was scaled to achieve better visualization.

Since the TEC series are highly correlated we calculated a mean TEC series using the normalized (varying between -1 and 1) individual TEC series. This mean TEC series was used further for visualization of TEC variations (see Figs. 1-4, top left, black lines).

The individual TEC series for each of the analyzed months were submitted to PCA as described in Section 3. Here we will discuss only first two modes of PCA, Mode 1 and Mode 2, respectfully. Each mode consists of corresponding PC (variations of TEC during a day) and EOF (amplitude of the PC for a specific day of a month).

The percentage of the variation of the original series that is explained by each mode for each month is in Table 3. Overall, first two PCA modes explain 90-95% of the variations of the original series with Mode 1 explaining 82-94%. The PCs for both modes and for all TEC series
are presented in Fig. S5 and S6 (in SI), respectively, and the mean PCs are shown in Fig. 5. Corresponding EOF1 and EOF2 are shown in Fig. S7 and S8 (in SI) with shaded areas marking event analyzed in Section 6.

As one can see, PC of the Mode 1 represents daily TEC variations caused by the regular changes of the insolation through a day. Daily minimum is observed during the local night and the daily maximum is around the afternoon hours. Thus it is expected that the TEC Mode 1 series are highly correlated between the locations and instruments for all four analyzed months (see correlation coefficients in Table 2). This daily cycle is the main reason of high correlation coefficients between the TEC series.

The Mode 2 of TEC series is defined as PC2/EOF2 for March and June of 2015 for all TEC series and for October and December of 2015 for the GNSS TEC series, whereas for the iTEC series for October and December of 2015 this mode rather consists of PC3/EOF3. The Mode 2 represents daily TEC variations with a relatively shallow minimum around the noon and a maximum in the late afternoon (19-21 h) and explains 2.1-7.3% of the variations of the original series. The correlation coefficients between Mode 2 series from different locations and instruments are shown in Table 2. The variations associated with the Mode 2 are relatively well correlated between the locations and instruments (mean r = 0.71). Please note that for October and especially for December 2015 the iTEC Mode 2 shows lower correlation with other (GNSS TEC) series, probably, because for these months the variations associated with this mode for the iTEC series are distributed between modes PC3/EOF3 (more) and PC2/EOF2 (less).

The mean TEC Mode 1 and Mode 2 series are shown in Figs. 1-4 (tope left, grey line, and top right, black line, respectfully) are constructed in the same way as the mean TEC series.

6 Ionospheric responses in middle latitudes to significant space weather events of 2015

6.1 Geomagnetic storm effects

6.1.1 March 17-18

Figure 1 shows variations of the solar, solar wind, IMF and geomagnetic parameters (see also Fig. S3) together with TEC, TEC Mode 1 and Mode 2 (see also Fig. 6, middle) for March 2015. As one can see, the main geomagnetic disturbance that took place on March 17-18 (DOY 76-77) coincides with the increase of the TEC daily cycle amplitude on March 17 and decrease of one on the following day, March 18, see black lines in Fig. 1 (top left) and 6 (middle left). The TEC variations observed over IP are in an agreement with ones observed for this geomagnetic storm by other researchers: the positive ionospheric storm on March 17 with double peak and the negative one on March 18 (see Section 4.1.1).

The TEC variations described above are reflected in the changes of the amplitude of the Mode 1 (see grey lines in Fig. 1, top left and 6, middle left): the amplitude of the daily cycle (or Mode 1) on March 18 is about half of the amplitude on the previous day and smaller then the amplitudes for other days of the month (except March 20, see Section 6.3). As one can see in Fig. 1 (top right) and 6 (middle right), the variations of the Mode 2 (which can be seen in TEC variations as a peak or a deep in the afternoon hours) have maximal amplitudes (for this month) on March 17-18 and are almost 2-3 times higher than for other days. Mode 2 is responsible for the 2nd peak on March 17. Also the sign of the EOF2 (the amplitude of PC2, see Fig. S8) for this mode is opposite on March 17 and 18. On March 17 the EOF is positive and the Mode 2 is...
responsible for a second peak observed around 16-18 h (compare Fig. 6 middle left and right). On contrary, on March 18 this EOF has negative values resulting in a sharp deep after the noon (38 h from the midnight of March 17) and, also in an offset of the daily maximum to the morning hours (~10 h).

6.1.2 June 22-25

Figures 2 and S3 show variations of the space weather parameters together with TEC, TEC Mode 1 and Mode 2 (see also Fig. 7, top and S9, top) for June 2015. The main 2-phases geomagnetic storm took place on June 22-26, however on June 8-11 there was also a very weak geomagnetic disturbance (2-phases as well) with Dst = -73 nT. Similar to the March event, the amplitude of the TEC daily cycle over IP significantly increases on June 22 (DOY 173) and, again, on June 25 (DOY 177), during the 2nd Dst deep. On the following days (June 23 and 26, respectively) the amplitude of the daily cycle decreased. These variations are reflected in the variations of the amplitude of the Mode 1 (see Figs. 2 and 7, top left). Similar behavior but with smaller amplitude difference was also observed during the weak disturbance on June 8-11 (Fig. 2, and S9, top left). The Mode 2 of the TEC variations shows more complex behavior. Similar to the March event, its amplitude is high and the EOF (see Figs. S7 and S8) is positive on the 1st day of the main storm (June 22, DOY 173) and negative on the 2nd day of the main storm (June 23, DOY 174). On contrary, for the 2nd Dst deep on June 25 (DOY 177), as well as for the weak disturbance on June 8-11 (GD1), the amplitude of the Mode 2 is high but the EOF2 is negative changing to almost zero but positive on the following day (see Figs. 2, 7 and S9, top right). Please note, that for June 25-26 and 8-11 the Dst index did not reached -100 nT threshold.

6.1.3 October 7-8

Figures 3, S3 and 7 (middle) show variation of the TEC as well as the other parameters in October 2015. The main storm of the month took place on October 7-8 (Dst < -100 nT) also small disturbances were observed on first days of the month (not analyzed here) and on October 18 (GD2, Dst > -50 nT). The variations of TEC during the storm of October 7-8 (DOY 280-281) can be identified as a negative storm: the amplitude of the daily TEC cycle on the 1st day of the storm was lower than during previous and following days (see Figures 3, top left and 7, middle left). This is also seen in the variations of the Mode 1. Another feature of TEC variations during this storm is that the Mode 2 increased on both days of the storm causing a second peak in TEC daily cycle on October 7 and an offset of the daily maximum on October 8 (see Figures 3, top right and 7, middle right).

6.1.4 December 19-20

The variations of TEC, and geomagnetic (see also Fig. S3), solar wind and IMF parameters in December 2015 are shown in Figs. 4, 7 (bottom). The storm on December 20-21 was characterized by the increase of the amplitude of the TEC daily variations, as well as the Mode 1, on the 1st day (positive storm). On the 2nd day the amplitude of the daily variations were still high but lower than on the 1st day. Probably this ionospheric storm can be classified as a positive-negative storm as well, and the relatively high amplitude of the TEC variations on the 2nd day is related to the two C-class flares that were observed on December 21 (see Fig. 4, middle left). The Mode 2 variations were significantly amplified only on the 1st day of the storm. The small geomagnetic disturbance on December 14-15 (GD3) seems to have no effect on the TEC variations (see Fig. S9, bottom in SI).
6.1.5 Summary

The detailed information about the variations of geomagnetic indices and TEC modes during analyzed events is shown in Table S1 (see SI) and the vertical lines on Fig. 6, 7, and S3 and S9 mark particular episodes listed in Table S1. This information is also summarized in Table 1.

Among four strongest geomagnetic storms of 2015 (GS1-GS3) only one (in October) was characterized by just the negative ionospheric storm (TEC decreased during the storm day and recovered to the normal value on the next). Two geomagnetic storms (in March and June) caused ionospheric disturbances that can be classified as positive-negative storms: TEC amplitudes increased during the 1st day of the storm and decreased on the 2nd. Lastly, the geomagnetic storm in December resulted in the ionospheric storm that either positive or positive-negative: most probably, on the 2nd day of the storm there was a combined effect of the geomagnetic variations and a C-class solar flares. The types of the ionospheric storm defined by the original TEC values and by their Mode 1 are the same. Thus, the analysis of the Mode 1 (or EOF1), which represents the daily TEC cycle, allows easy classification of an ionospheric storm.

Besides the overall increase or decrease of the amplitude of the TEC variations described by the Mode 1, there is another prominent feature of the TEC variations that was extracted from the data as the PCA Mode 2. The Mode 2 which is associated with appearance of a second daily peak or a sharp deep during the afternoon hours. This mode also has geomagnetic storm-associated variations which are more prominent for the March and June storms. During these geomagnetic storms the Mode 2 was shown to increase on the 1st day of the storm (causing second daily peak in TEC). This behavior is seen for all four storms of 2015. On the 2nd day of the storms in March and June the Mode 2 was also high in amplitude but of the opposite sign causing sharp decrease of the TEC in the afternoon hours. During the storm in October this mode was also significant in amplitude but of the same sign as for the previous days (resulting, however, not in second peak but in the offset of the daily peak to the afternoon hours). During the storm in December the amplitude of the Mode 2 on the 2nd day was negligible.

The geomagnetic disturbances with lower amplitudes (GD1-GD3), the disturbances in June (GD1) and October (GD2) caused ionospheric disturbances that can be also classified as positive-negative (accordingly to the variations of TEC and Mode 1). The amplitude of Mode 2 was high on the 1st day of the disturbances with positive EOF2 for GD2 and negative one for GD1. On the 2nd day of both disturbances the EOF2s changed sign to opposite. The GD3 in December showed no effect on the ionospheric TEC variations.

6.2 Solar flare effects

Figure 1 (middle left) shows variations of the solar UV and XR fluxes and number of solar flares together with TEC, TEC Mode 1 and Mode 2 (top) for March 2015 and the TEC variation on March 11 are shown in Fig. 6 (top). As one can see, the X-flare on March 11 (XF event in Tables 1 and S1) had very weak effect on the TEC variations over IP: there is weak increase of TEC at 17 h (first hourly measurements after the flare). Neither Mode 1 nor Mode 2 show particular response to this flare.

On the other side, on the time scale of a month there is dependence between the number of solar flares (C, M and X classes), solar UV and XR fluxes and the amplitude of the daily TEC cycle and the amplitude of Mode 1 (EOF1). This is clearly seen from comparison of top left and
middle left panels of Figs. 1-4 (see also Fig. S7 in SI). The correlation coefficients between the 
EOF1s, and the solar UV and XR proxies and the number of flares are \( r = 0.4-0.89 \) (depending 
on the month). The overall increase of the flares number and/or solar UV and XR fluxes results 
in the increase of the amplitude of the daily TEC cycle and, consequently, EOF1.

6.3 Solar eclipse effects

The data used in this study are of at least 1h time resolution, thus we cannot make a 
detailed analysis of TEC variations during the partial eclipse on March 20 (SE event in Tables 1 
and S1). However, we still can see the ionospheric response over IP to the eclipse: as one can see 
in Fig. 6 (bottom), the amplitude of the daily TEC cycle (and the amplitude of the Mode 1) is 
almost half of the amplitude on the previous day. Also, around 09:00 UT there is a sharp 
deviation from the steady growth of TEC during morning hours. This deviation is related, most 
probably, to the maximum of the obscuration observed in the IP region around this time.

5 Conclusions

In this work we analyzed variations of the total electron content (TEC) over the mid-
latitudinal area of Iberian Peninsula during main space weather events of 2015: four geomagnetic 
storms with Dst < -100 nT happened in March, June, October and December 2015, X-class solar 
flare and a partial solar eclipse that took place in March. We compared variations of TEC 
observed during geomagnetic storms in June, October and December to ones associated with 
smaller geomagnetic disturbances (Dst > -100 nT) observed during the same months. We also 
analyzed variations of TEC in relation to the daily total number of solar flares (C, M and X 
classes) and the solar UV and XR fluxes.

The TEC data were obtained for two locations on the Iberian Peninsula: Lisbon 
(Portugal) on the west coast and Ebro (Spain) on the north-east coast of the peninsula and have 
1h time resolution. Two types of TEC were used in the study: TEC calculated from the GNSS 
receivers and the ionospheric TEC (iTEC) obtained from the ionosonde at the Ebro Observatory.

All four TEC series are in good agreement. The new data series, the non-calibrated TEC 
from the SCINDA GNSS receiver installed in 2015 in the Lisbon airport area, is found to be well 
correlated with other series which allowed us to use it for the analysis.

The TEC series were submitted to the principal component analysis allowing to extract 
two main modes that together explain > 90% of the TEC variability. The 1\textsuperscript{st} mode (Mode 1) 
represent daily TEC cycle and the 2\textsuperscript{nd} mode (Mode 2) is associated with either 2\textsuperscript{nd} daily peak or a 
sharp deep in the afternoon hours (19-21 h).

In the mid-latitudinal region of IP most of the analyzed geomagnetic storms (on March 
17-18, June 8-11 and 23-27, and December 21-22) during their 1\textsuperscript{st} days were accompanied by the 
positive ionospheric storms. During the 2\textsuperscript{nd} day of the geomagnetic storms in March and June the 
negative ionospheric storms were observed over IP, whereas for December storm the amplitude 
of the TEC daily cycle was still elevated, probably due to the overlapping effect of a series of 
solar flares (M and C classes) on December 20-24. Corresponding variations are seen in the 
Mode 1. Similar changes in TEC and Mode 1 were observed during the small geomagnetic 
disturbances in June and October. The geomagnetic storm on October 7-8 was accompanied by 
the negative ionospheric storm, and a geomagnetic disturbance in December 14-15 had no effect 
on the ionosphere over Iberian Peninsula.
The Mode 2 of the TEC variations during the storms on March 17-18, June 23-27 and December 21-22 increased in amplitude with positive EOF2 values on the 1st day of the storm and negative (or almost zero in case of December storm) EOF2 values on the 2nd day. Opposite changes of the EOF2 sign were observed for a weak disturbance on June 8-11; and for the storm on October 7-8 the Mode 2 increased with positive EOF2 values during both days of the storm.

The X-class solar flare on March 11 had no significant effect on the TEC variations, however, the overall increase/decrease of the flares number as well as changes of the solar UV and XR fluxes during analyzed months resulted in the increase/decrease of the amplitude of the TEC daily cycle (and therefore Mode 1). No relation between the amplitude of the Mode 2 associated with the solar UV and XR fluxes was found.

The partial solar eclipse (~60% around 09:00 UT on March 20 over the Iberian Peninsula) was seen in the analyzed TEC data both as a decrease of the amplitude of the daily cycle (seen also in Mode 1 variations) and as a sharp deviation from the regular daily cycle observed around 9 h. No response to this event in the variations of the Mode 2 was found.

To our knowledge this is the first study applying this method to the analysis of TEC variations over the Iberian Peninsula region for specific space weather events.
Acknowledgments, Samples, and Data

CITEUC is funded by National Funds through FCT - Foundation for Science and Technology (project: UID/MULTI/00611/2019) and FEDER – European Regional Development Fund through COMPETE 2020 – Operational Programme Competitiveness and Internationalization (project: POCI-01-0145-FEDER-006922)

This research was supported through the project “SWAIR - Space weather impact on GNSS service for Air Navigation”, ESA Small ARTES Apps, https://goo.gl/YN2iJf

The GNSS solutions were computed using resources provided by C4G – Collaboration for Geosciences (POCI-01-0145-FEDER-022151).

We acknowledge the mission scientists and principal investigators who provided the data used in this research:

We acknowledge the use of the Dst index from the Kyoto World Data Center http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html.

Geomagnetic data measured by the GAO UC are available by request (pribeiro@ci.uc.pt).

We acknowledge the use of the Kp index from the GFZ German Research Centre for Geosciences https://www.gfz-potsdam.de/en/kp-index/.

The solar wind data are from the SPDF OMNIWeb database. The OMNI data were obtained from the GSFC/SPDF OMNIWeb interface at https://omniweb.gsfc.nasa.gov, see also King and Papitashvili [2004] for more details.

The F10.7 index was also obtained from the OMNI data base at https://omniweb.gsfc.nasa.gov/form/dx1.html.

The Mg II data are from Institute of Environmental Physics, University of Bremen http://www.iup.uni-bremen.de/gome/gomemgii.html, see also Snow et al. [2014] for more information.

The data on the variations of the solar XR flux are from the LASP Interactive Solar Irradiance Data Center (LISRD, http://lasp.colorado.edu/lisird/). LISIRD provides a uniform access interface to a comprehensive set of Solar Spectral Irradiance (SSI) measurements and models from the soft X-ray (XUV) up to the near infrared (NIR), as well as Total Solar Irradiance (TSI). The XR_{TIMED} data are from the Solar EUV Experiment (SEE) measures the solar ultraviolet full-disk irradiance for the NASA TIMED mission. Level 3 data represent daily averages and are filtered to remove flares available at http://lasp.colorado.edu/lisird/data/timed_see_ssi_l3/.

The X-ray Flare dataset was prepared by and made available through the NOAA National Geophysical Data Center (NGDC). The data about the solar flares for 2015 are from https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/goes-xrs-report_2015_modifiedreplacedmissingrows.txt.

The TEC_{ROB} data sets are from the Royal Observatory of Belgium (ROB) data base and are publicly available in IONEX format at ftp://gnss.oma.be/gnss/products/IONEX/, see also Bergeot et al. [2014] for more information.

We also wish to thank the Ebro Observatory and Dr. Germán Solé for the provision of ionosonde data.
References

Aa, E., Huang, W., Liu, S., Ridley, A., Zou, S., Shi, L., Chen, Y., Shen, H., Yuan, T., Li, J. and Wang, T., 2018. Midlatitude plasma bubbles over China and adjacent areas during a magnetic storm on 8 September 2017. Space Weather, 16(3), pp.321-331.

Astafyeva, E., Zakharenkova, I. and Alken, P., 2016. Prompt penetration electric fields and the extreme topside ionospheric response to the June 22–23, 2015 geomagnetic storm as seen by the Swarm constellation. Earth, Planets and Space, 68(1), p.152.

Astafyeva, E., Zakharenkova, I. and Förster, M., 2015. Ionospheric response to the 2015 St. Patrick's Day storm: A global multi-instrumental overview. Journal of Geophysical Research: Space Physics, 120(7), pp.9023-9037.

Astafyeva, E., Zakharenkova, I., Hozumi, K., Alken, P., Coïsson, P., Hairston, M.R. and Coley, W.R., 2018. Study of the Equatorial and Low-Latitude Electrodynamic and Ionospheric Disturbances During the 22–23 June 2015 Geomagnetic Storm Using Ground-Based and Spaceborne Techniques. Journal of Geophysical Research: Space Physics, 123(3), pp.2424-2440.

Astafyeva, E., Zakharenkova, I., Huba, J.D., Doornbos, E. and Van den IJssel, J., 2017. Global ionospheric and thermospheric effects of the June 2015 geomagnetic disturbances: Multi-instrumental observations and modeling. Journal of Geophysical Research: Space Physics, 122(11), pp.11716-11742.

Balasis, G., Daglis, I.A., Contoyiannis, Y., Potirakis, S.M., Papadimitriou, C., Melis, N.S., Giannakis, O., Papaioannou, A., Anastasiadis, A. and Kontoes, C., 2018. Observation of Intermittency-Induced Critical Dynamics in Geomagnetic Field Time Series Prior to the Intense Magnetic Storms of March, June, and December 2015. Journal of Geophysical Research: Space Physics, 123(6), pp.4594-4613.

Bergeot N., J.-M. Chevalier, C. Bruyninx, E. Pottiaux, W. Aerts, Q. Baire, J. Legrand, P. Defraigne and W. Huang (2014), Near real-time ionospheric monitoring over Europe at the Royal Observatory of Belgium using GNSS data, J. Space Weather Space Clim., 4, A31, doi: 10.1051/swsc/2014028.

Bjornsson, H., and S. A. Venegas (1997), A manual for EOF and SVD analyses of climatic data, McGill University, CCGCR Report 97-1.

Chen, Z., Zhang, S.R., Coster, A.J. and Fang, G., 2015. EOF analysis and modeling of GPS TEC climatology over North America. Journal of Geophysical Research: Space Physics, 120(4), pp.3118-3129.

Cherniak, I. and Zakharenkova, I., 2018. Large-scale traveling ionospheric disturbances origin and propagation: Case study of the December 2015 geomagnetic storm. Space Weather, 16(9), pp.1377-1395.

de Abreu, A.J., Roberto, M., Alves, M.A., Abalde, J.R., Nogueira, P.A.B., Venkatesh, K., Fagundes, P.R., de Jesus, R., Gende, M. and Martin, I.M., 2019. Effects of X2-class solar flare events on ionospheric GPS-TEC and radio waves over Brazilian sector. Advances in Space Research, 63(11), pp.3586-3605.
Ebisuzaki, W. (1997), A method to estimate the statistical significance of a correlation when the data are serially correlated, J. Clim., 10 (9), 2147-2153.

Fagundes, P.R., Cardoso, F.A., Fejer, B.G., Venkatesh, K., Ribeiro, B.A.G. and Pillat, V.G., 2016. Positive and negative GPS-TEC ionospheric storm effects during the extreme space weather event of March 2015 over the Brazilian sector. Journal of Geophysical Research: Space Physics, 121(6), pp.5613-5625.

Goncharenko, L., Chau, J.L., Condor, P., Coster, A. and Benkevitch, L., 2013. Ionospheric effects of sudden stratospheric warming during moderate-to-high solar activity: Case study of January 2013. Geophysical Research Letters, 40(19), pp.4982-4986.

Hannachi, A., I.T. Jolliffe, and D.B. Stephenson (2007), Empirical orthogonal functions and related techniques in atmospheric science: A review, Int. J. Climatol., 27 (9), 1119-1152.

Hu, A. and Zhang, K., 2018. Using Bidirectional Long Short-Term Memory Method for the Height of F2 Peak Forecasting from Ionosonde Measurements in the Australian Region. Remote Sensing, 10(10), p.1658.

King J.H. and N.E. Papitashvili (2004), Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data, J. Geophys. Res., 110( A2), A02209, doi: 10.1029/2004JA010649.

Li, S., Zhou, H., Xu, J., Wang, Z., Li, L. and Zheng, Y., 2019. Modeling and analysis of ionosphere TEC over China and adjacent areas based on EOF method. Advances in Space Research, 64(2), pp.400-414.

Liu, G. and Shen, H., 2017. A severe negative response of the ionosphere to the intense geomagnetic storm on March 17, 2015 observed at mid-and low-latitude stations in the China zone. Advances in Space Research, 59(9), pp.2301-2312.

Liu, Y.D., Hu, H., Wang, R., Yang, Z., Zhu, B., Liu, Y.A., Luhmann, J.G. and Richardson, J.D., 2015. Plasma and magnetic field characteristics of solar coronal mass ejections in relation to geomagnetic storm intensity and variability. The Astrophysical Journal Letters, 809(2), p.L34.

Loucks, D., Palo, S., Pilinski, M., Crowley, G., Azeem, I. and Hampton, D., 2017. High-latitude GPS phase scintillation from E region electron density gradients during the 20–21 December 2015 geomagnetic storm. Journal of Geophysical Research: Space Physics, 122(7), pp.7473-7490.

Matsui, H., Erickson, P.J., Foster, J.C., Torbert, R.B., Argall, M.R., Anderson, B.J., Blake, J.B., Cohen, I.J., Ergun, R.E., Farrugia, C.J. and Khotyaintsev, Y.V., 2016. Dipolarization in the inner magnetosphere during a geomagnetic storm on 7 October 2015. Geophysical Research Letters, 43(18), pp.9397-9405.

Morozova, A.L., P.Ribeiro, J.J.Blanco, T.V.Barlyaeva,2019. Temperature and pressure variability in mid-latitude low atmosphere and stratosphere-ionosphere coupling, Advances in Space Research, JASR14522, 10.1016/j.asr.2019.10.039, https://www.sciencedirect.com/science/article/pii/S0273117719307896.
Mukhtarov, P., Andonov, B. and Pancheva, D., 2018. Empirical model of TEC response to geomagnetic and solar forcing over Balkan Peninsula. Journal of Atmospheric and Solar-Terrestrial Physics, 167, pp.80-95.

Nava, B., Rodríguez-Zuluaga, J., Alazo-Cuartas, K., Kashcheyev, A., Migoya-Orué, Y., Radicella, S.M., Amory-Mazaudier, C. and Fleury, R., 2016. Middle- and low-latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm. Journal of Geophysical Research: Space Physics, 121(4), pp.3421-3438.

Ngwira, C.M., Habarulema, J.B., Astafyeva, E., Yizengaw, E., Jonah, O.F., Crowley, G., Gisler, A. and Coffey, V., Dynamic response of ionospheric plasma density to the geomagnetic storm of 22-23 June 2015. Journal of Geophysical Research: Space Physics, doi:10.1002/2018JA026172

Panasenko, S.V., Otsuka, Y., Van de Kamp, M., Chernogor, L.F., Shinbori, A., Tsugawa, T. and Nishioka, M., 2019. Observation and characterization of traveling ionospheric disturbances induced by solar eclipse of 20 March 2015 using incoherent scatter radars and GPS networks. Journal of Atmospheric and Solar-Terrestrial Physics, 191, doi: 10.1016/j.jastp.2019.05.015.

Paul, B., De, B.K. and Guha, A., 2018. Latitudinal variation of F-region ionospheric response during three strongest geomagnetic storms of 2015. Acta Geodaetica et Geophysica, 53(4), pp.579-606.

Pazos, M., Mendoza, B., Sierra, P., Andrade, E., Rodríguez, D., Mendoza, V. and Garduño, R., 2019. Analysis of the effects of geomagnetic storms in the Schumann Resonance station data in Mexico. Journal of Atmospheric and Solar-Terrestrial Physics, p.105091.

Petry, A., de Souza, J.R., de Campos Velho, H.F., Pereira, A.G. and Bailey, G.J., 2014. First results of operational ionospheric dynamics prediction for the Brazilian Space Weather program. Advances in Space Research, 54(1), pp.22-36.

Piersanti, M., Cesaroni, C., Spogli, L. and Alberti, T., 2017. Does TEC react to a sudden impulse as a whole? The 2015 Saint Patrick’s day storm event. Advances in Space Research, 60(8), pp.1807-1816.

Shim, J.S., Tsagouri, I., Goncharenko, L., Rastaetter, L., Kuznetsova, M., Bilitza, D., Codrescu, M., Coster, A.J., Solomon, S.C., Fedrizzi, M. and Förster, M., 2018. Validation of ionospheric specifications during geomagnetic storms: TEC and foF2 during the 2013 March storm event. Space Weather, 16(11), pp.1686-1701.

Shlens, J. (2009), A tutorial on principal component analysis, Systems Neurobiology Laboratory, University of California at San Diego, version 3.01, 2009, On-line: http://snl.salk.edu/~shlens/pca.pdf

Singh, R. and Sripathi, S., 2017. Ionospheric response to 22–23 June 2015 storm as investigated using ground-based ionosondes and GPS receivers over India. Journal of Geophysical Research: Space Physics, 122(11).

Snow, M., M. Weber, J. Machol, R. Viereck, and E. Richard, (2014), Comparison of Magnesium II core-to-wing ratio observations during solar minimum 23/24, J. Space Weather Space Clim., 4, A04, doi:10.1051/swsc/2014001.
Stankov, S.M., Bergeot, N., Berghmans, D., Bolsée, D., Bruyninx, C., Chevalier, J.M., Clette, F., De Backer, H., De Keyser, J., D’Huys, E. and Dominique, M., 2017. Multi-instrument observations of the solar eclipse on 20 March 2015 and its effects on the ionosphere over Belgium and Europe. Journal of Space Weather and Space Climate, 7, p.A19.

Tebabal, A., Radicella, S.M., Damtie, B., Migoya-Orue, Y., Nigussie, M. and Nava, B., 2019. Feed forward neural network based ionospheric model for the East African region. Journal of Atmospheric and Solar-Terrestrial Physics.

Tsagouri, I., Koutroumbas, K. and Elias, P., 2018. A new short-term forecasting model for the total electron content storm time disturbances. Journal of Space Weather and Space Climate, 8, p.A33.

Verhulst, T.G., Sapundjiev, D. and Stankov, S.M., 2016. High-resolution ionospheric observations and modeling over Belgium during the solar eclipse of 20 March 2015 including first results of ionospheric tilt and plasma drift measurements. Advances in Space Research, 57(11), pp.2407-2419.
Figure 1. Variations of normalized mean series of TEC and TEC Mode 1 (top left), and TEC Mode 2 (top right), solar UV flux and flares number (middle left), solar wind parameters (middle right), geomagnetic indices (bottom left) and IMF components (bottom right) in March 2015. Days with specific events are marked by shading: DOY 70 (March, 11) – solar X flare; DOY 76-77 (March, 17-18) – geomagnetic storm; DOY 79 (March, 20) – solar eclipse.
Figure 2. Variations of normalized mean series of TEC and TEC Mode 1 (top left), and TEC Mode 2 (top right), solar UV flux and flares number (middle left), solar wind parameters (middle right), geomagnetic indices (bottom left) and IMF components (bottom right) in June 2015. Days of geomagnetic storm DOY 173-176 (June 22-25) are marked by shading.
Figure 3. Variations of normalized mean series of TEC and TEC Mode 1 (top left), and TEC Mode 2 (top right), solar UV flux and flares number (middle left), solar wind parameters (middle right), geomagnetic indices (bottom left) and IMF components (bottom right) in October 2015. Days of geomagnetic storm DOY 280-281 (October 7-8) are marked by shading.
Figure 4. Variations of normalized mean series of TEC and TEC Mode 1 (top left), and TEC Mode 2 (top right), solar UV flux and flares number (middle left), solar wind parameters (middle right), geomagnetic indices (bottom left) and IMF components (bottom right) in December 2015. Days of geomagnetic storm DOY 354-355 (December 20-21) are marked by shading.
Figure 5. Mean TEC PC1 (top) and PC2 for March (green solid), June (red dashed), October (orange dotted) and December (blue dot-dashed).
Figure 6. Left: Variations of normalized mean series of TEC (black) and TEC Mode 1 (grey) during events of March 2015: top – DOY 70 (March, 11) a solar X flare; middle – DOY 76-77 (March, 17-18) a geomagnetic storm; bottom – DOY 79 (March, 20) a solar eclipse. Right: Same for TEC Mode 2. Vertical lines mark events listed in Tables 1 and S1.
Figure 7. Left: Variations of normalized mean series of TEC (black) and TEC Mode 1 (grey) during geomagnetic storms: top – DOY173-177 (June, 22-26); middle – DOY280-281 (October 7-8); bottom – DOY354-355 (December 20-21). Right: Same for TEC Mode 2. Vertical lines mark peaks(deeps) of Dst and/or AE listed in Tables 1 and S1.
Table 1. List of analyzed event of 2015. Mode 1: “+” – increase of the amplitude (positive ionospheric storm), “−” – decrease of the amplitude (negative ionospheric storm), “0” – no effect. The positive-negative ionospheric storms are marked by bold. Mode 2: “+” – increased amplitude, positive EOF2, “−” – negative EOF2, “0” – very small in amplitude. The ionospheric storms having 2nd daily peak during the 1st day and a deep on the 2nd day are marked by bold.

| Name     | Date       | DOY | Dst     | Mode1 1st day | Mode1 2nd day | Mode2 1st day | Mode2 2nd day |
|----------|------------|-----|---------|--------------|--------------|--------------|--------------|
| Geomagnetic storms |            |     |         |              |              |              |              |
| GS1      | March 17-18| 76-77 | -223 nT| +            | −            | +            | −            |
| GD1      | June 8-9   | 159-160 | -73 nT| +            | −            | −            | +            |
| GS2      | June 22-26 | 173-177 | -204 nT| +            | −            | +            | −            |
| GS4      | October 7-8| 280-281 | -124 nT| −            | +            | +            | +            |
| GD2      | October 18-19| 291-292 | -48 nT| +            | −            | +            | −            |
| GD3      | December 14-15| 348-349 | -47 nT| 0            | 0            | −            | −            |
| GS3      | December 20-21| 354-355 | -155 nT| +            | −            | +            | − (0)        |
| Solar flare |            |     |         |              |              |              |              |
| XF       | March 11   | 70  | X2.1    | 0            | 0            |              |              |
| Solar eclipse |        |     |         |              |              |              |              |
| SE       | March 20   | 79  | 60%     | −            |              | 0            |              |
Table 2. Correlation coefficients between different TEC series for months of 2015 (M – March, J – June, O – October, D – December) and their means. All p values $\leq 0.05$. Correlation coefficients for the series from different data sources but for the same location are in bold.

| month | TEC       | ROB-EBR | IONO-EBR | SCI-LIS |
|-------|-----------|---------|----------|---------|
|       | individual | mean    | individual | mean   | individual | mean |
| M     | 0.99      | 0.97    | 0.97      | 0.94    |
| J     | 0.96      | 0.97    | 0.90      | 0.94    |
| O     | 0.97      | 0.96    | 0.96      | 0.94    |
| D     | 0.96      | 0.93    | 0.93      | 0.93    |
|       |           |         |           |         |
| M     | 0.96      | 0.87    | 0.92      | 0.95    |
| J     | 0.94      | 0.96    | 0.96      | 0.96    |
| O     | 0.89      | 0.89    | 0.89      | 0.89    |
| D     | 0.89      | 0.89    | 0.89      | 0.89    |
| Mode 1 |         |         |           |         |
| M     | 0.97      | 0.98    | 0.98      | 0.95    |
| J     | 0.97      | 0.94    | 0.94      | 0.92    |
| O     | 0.98      | 0.98    | 0.98      | 0.94    |
| D     | 0.96      | 0.97    | 0.97      | 0.96    |
| Mode 2 |         |         |           |         |
| M     | 0.94      | 0.91    | 0.91      | 0.78    |
| J     | 0.91      | 0.81    | 0.81      | 0.94    |
| O     | 0.73      | 0.6     | 0.6       | 0.80    |
| D     | 0.93      | 0.35    | 0.35      | 0.74    |
Table 3. Fraction of the original TEC series variability explained by two first PCA modes.

|     | March   | June    | October | December | mean  |
|-----|---------|---------|---------|----------|-------|
| PC1 | 93-95%  | 77-86%  | 92-95%  | 87-94%   | 90.5% |
| PC2 | 2.4-2.9%| 6.1-8.4%| 1.5-3.0%| 2.5-3.7% | 3.8%  |
Supporting Information for

Variations of TEC over Iberian Peninsula in 2015: geomagnetic storms, solar flares, solar eclipse

A. L. Morozova, T. V. Barlyaeva, and T. Barata

CITEUC, University of Coimbra, Almas de Freire, Sta. Clara, Coimbra, 3040-004, Portugal

Contents of this file
- Figures S1 to S9
- Table S1

Additional Supporting Information (Files uploaded separately)

Data Set S1: Output files from the SCINDA receiver installed in 2015 in the Lisbon airport (ds01.txt)

Introduction

This file provides complementary information to topics discussed in the main article.

Figures S1-S2 present variations of the solar, solar wind, interplanetary magnetic field and geomagnetic parameters for 2015 with data of 1h and 1d time resolution, respectfully.

Figure S3 shows variations of geomagnetic indices during geomagnetic storms (GS1-GS4) geomagnetic disturbances (GD1-GD3) discussed in the main text.

Figure S4 presents variations of the TEC series from different instruments/locations for the four analyzed months.

Figures S5-S6 and S7-S8 show variations of the PC1-PC2 and EOF1-EOF2, respectfully, for the four TEC series during four analyzed months.

Figure S9 presents variations of the TEC, Mode 1 and Mode 2 for the geomagnetic disturbances (GD1-GD3) discussed in the main text.

Table S1 contains the detailed information about the events analyzed in the main text: the data, time of main features observed during an event, the behavior of the Mode 1 and Mode 2. For each of the geomagnetic storms and disturbances time of main and secondary deeps and intermediate peaks of Dst and peaks of AE are presented.
Figure S1. Variations of the solar UV flux and flares number (top left), solar wind parameters (top right), geomagnetic indices (bottom left) and IMF components (bottom right) in 2015. Days with specific events analyzed in the paper are marked by shading.
Figure S2. Same as Figure S1 but for daily mean series.
Figure S3. Variations of the Dst, Kp, K_{COI} and AE geomagnetic indices during the geomagnetic storms (GS1-GS4, left) and disturbances (GD1-GD3, right) in March, June, October and December 2015 (top to bottom).
Figure S4. TEC variations measured at different locations (Ebro in red and Lisbon in green) and by different instruments (GNSS TEC as solid lines, ionosonde iTEC as dashed lines) for four months of 2015: March (top left), June (bottom left), October (top right) and December (bottom right).
**Figure S5.** TEC PC1 variations for series measured at different locations (Ebro in red and Lisbon in green) and by different instruments (GNSS TEC as solid lines, ionosonde iTEC as dashed lines) for four months of 2015: March (top left), June (bottom left), October (top right) and December (bottom right).
Figure S6. Same as Figure S5 but for PC2.
Figure S7. TEC EOF1 variations for series measured at different locations (Ebro in red and Lisbon in green) and by different instruments (GNSS TEC as solid lines, ionosonde iTEC as dashed lines) for four months of 2015: March (top left), June (bottom left), October (top right) and December (bottom right). Shaded areas mark analyzed events.
Figure S8. Same as Figure S7 but for EOF2.
Figure S9. Left: Variations of normalized mean series of TEC (black) and TEC Mode 1 (grey) during geomagnetic disturbances: top – DOY159-160 (June 8-9); middle – DOY291-292 (October 14-15); bottom – DOY348-349 (December 14). Right: Same for TEC Mode 2. Vertical lines mark peaks (deeps) of Dst and/or AE listed in Table S1.
Table S1. List of analyzed event of 2015 with characteristic parameters of the Dst and AE indices for geomagnetic storms and starting time of the eclipse and the X flare. Mode 1: “+” – increase of the amplitude (positive ionospheric storm), “−” – decrease of the amplitude (negative ionospheric storm), “o” – no effect. Mode 2: “+” – increased amplitude, positive EOF2, “−” – negative EOF2, “o” – very small in amplitude.

| Name | Date       | DOY | Parameter and time | Mode1 | Mode2 |
|------|------------|-----|--------------------|-------|-------|
|      |            |     | Dst (nT) or AE     | 1st day | 2nd day | 1st day | 2nd day |
| Geomagnetic storms | | | | | | |
| GS1  | March 17-18 | 76-77 | 17.03.2015 05:00 UT | + | – | + | – |
|      |            |     | +56 nT             |       |       |       |       |
|      |            |     | -73 nT             | 09:00 UT |       |       |       |
|      |            |     | -44 nT             | 12:00 UT |       |       |       |
|      |            |     | 1570               | 14:00 UT |       |       |       |
|      |            |     | -223 nT            | 22:00 UT |       |       |       |
|      |            |     | -73 nT             | 08.06.2015 08:00 UT |       |       |       |
| GD1  | June 8-9   | 159-160 | 22.06.2015 13:00 UT | + | – | + | – |
|      |            |     | -6 nT              | 16:00 UT |       |       |       |
|      |            |     | -51 nT             | 18:00 UT |       |       |       |
|      |            |     | -8 nT              | 20:00 UT |       |       |       |
|      |            |     | -121 nT            | 23.06.2015 04:00 UT |       |       |       |
|      |            |     | -204 nT            | 1346   |       |       |       |
|      |            |     | -93 nT             | 967    |       |       |       |
|      |            |     | -38 nT             | 1227   |       |       |       |
|      |            |     | -86 nT             | 07.10.2015 02:00 UT |       |       |       |
|      |            |     | 1080               | 13:00 UT |       |       |       |
|      |            |     | 1030               | 15:00 UT |       |       |       |
|      |            |     | -124 nT            | 22:00 UT |       |       |       |
|      |            |     | 1233               | 08.10.2015 05:00 UT |       |       |       |
|      |            |     | 1231               | 13:00 UT |       |       |       |
| Name             | Date           | DOY    | Parameter and time          | Mode1 1st day | Mode2 1st day | Mode1 2nd day | Mode2 2nd day |
|------------------|----------------|--------|----------------------------|---------------|---------------|---------------|---------------|
| Geomagnetic storms |                |        | Dst (nT) or AE              |               |               |               |               |
| GD2              | October 18-19  | 291-292| 5 nT 18.10.2015 04:00 UT    | +             | –             | +             | –             |
|                  |                |        | -48 nT 09:00 UT             | –             | –             | +             | –             |
|                  |                |        | 745 10:00 UT                |               |               |               |               |
|                  |                |        | -33 nT 11:00 UT             |               |               |               |               |
|                  |                |        | -43 nT 15:00 UT             |               |               |               |               |
| GD3              | December 14-15 | 348-349| +26 nT 14.12.2015 15:00 UT  | 0             | 0             | –             | –             |
|                  |                |        | 1250 16:00 UT               |               |               |               |               |
|                  |                |        | -47 nT 19:00 UT             |               |               |               |               |
|                  |                |        | 709 22:00 UT                |               |               |               |               |
| GS4              | December 20-21 | 354-355| -71 nT 20.12.2015 09:00 UT  | +             | –             | +             | –(0)          |
|                  |                |        | 1396 12:00 UT               |               |               |               |               |
|                  |                |        | 1375 16:00 UT               |               |               |               |               |
|                  |                |        | -155 nT 22:00 UT            |               |               |               |               |
| Solar flare      |                |        | Class                       |               |               |               |               |
| XF               | March 11       | 70     | X2.1 11.03.2015 16:11 UT    | 0             |               |               |               |
| Solar eclipse    |                |        | Max obscuration             |               |               |               |               |
| SE               | March 20       | 79     | 60% 20.03.2015 09:00 UT     | –             |               |               | 0             |