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

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Abstract

- Total ionospheric content (TEC) over the midlatitudinal area of Iberian Peninsula was studied using data from two locations on the west and east coasts of the peninsula.
- The data are obtained both by 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…
  - geomagnetic disturbances observed in March, June, October and December of 2015
  - solar flares and overall variations of the solar UV and XR fluxes during those months
  - a partial solar eclipse observed on March 11, 2015

Data: Total electron content (TEC)

- Vertical TEC
- 2 locations:
  - Ebro, Spain (41° N, 0.5° E)
  - Lisbon, Portugal (39° N, 9° W)
- Sources:
  - GNSS TEC data from the Royal Observatory of Belgium (ROB) – $TEC_{ROB\text{-}LIS}$ and $TEC_{ROB\text{-}EBR}$
  - GNSS TEC from SCINDA receiver in the Lisbon airport (not calibrated) – $TEC_{SCI\text{-}LIS}$
  - Ionosonde TEC provided by the Ebro Observatory – $TEC_{IONO\text{-}EBR}$
- Hourly series – see *Figure 1*
- Time interval: only March, June, October and December of 2015

TEC variations measured at different locations & by different instruments

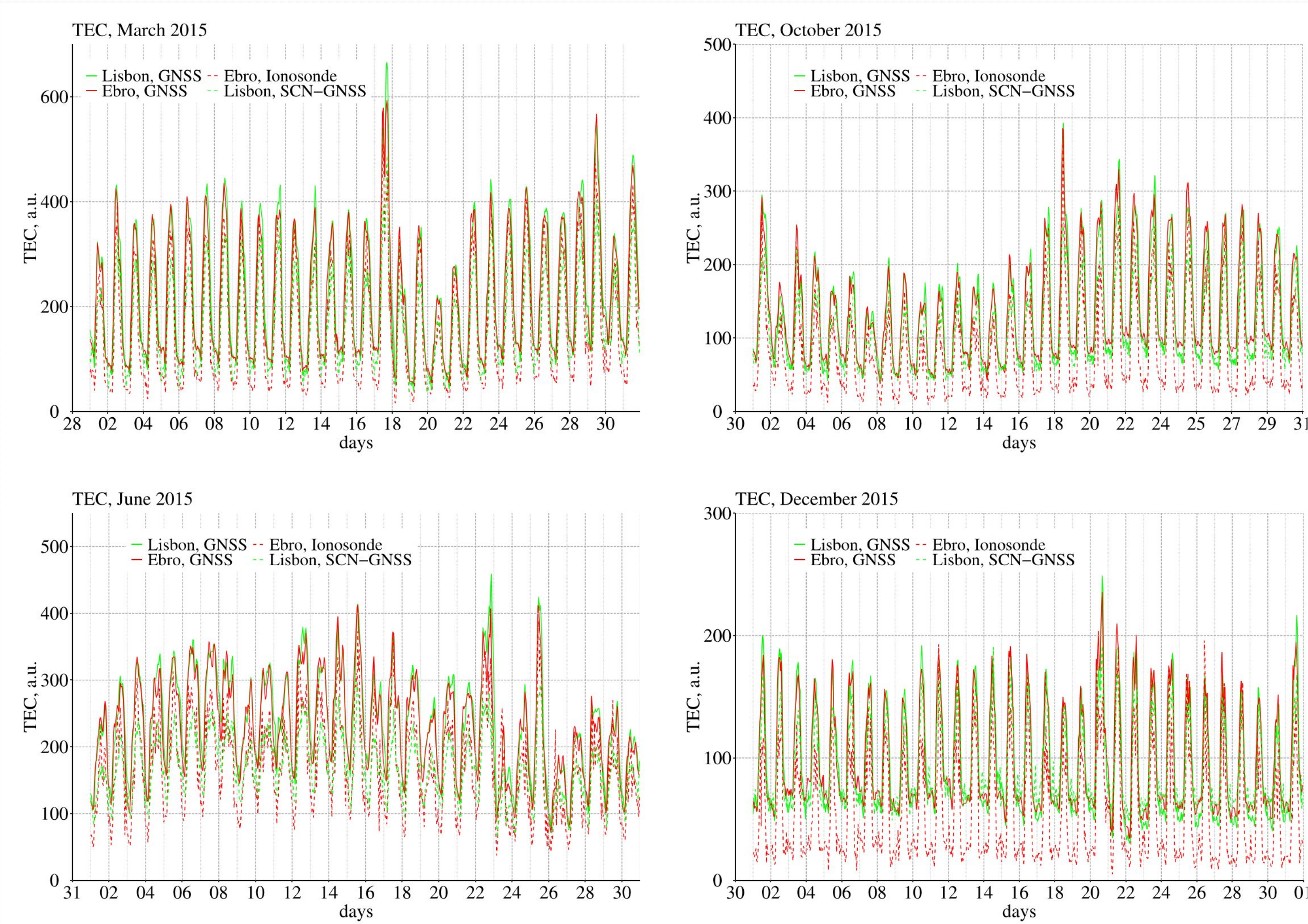


Figure 1. TEC_{Ebro} – red & TEC_{Lisbon} – green;
TEC_{GNSS} – solid lines, $TEC_{ionosonde}$ – dashed lines

Methods

- Correlation analysis
  - Similarities between series were analyzed using the correlation coefficients (*r*), and their statistical significances (*p value*)
  - Statistical significance (p value) was estimated using the Monte Carlo approach with artificial series constructed by the "phase randomization procedure" (*Ebisuzaki, 1997*).

Similarity & differences between TEC series

- The $TEC_{SCI\text{-}LIS}$ is well correlated both with other TEC_{GNSS} series (mean $r = 0.95$) and with $TEC_{ionosonde}$ (mean $r = 0.89$) – see *Table 1*
- The fact that SCI-LIS is not calibrated does not affect the results of our analysis since we used only methods insensitive to scaling and shifting of the series.

- Series from different locations are well correlated: mean $r = 0.93$
- TEC_{GNSS} are well correlated with $TEC_{ionosonde}$: mean $r = 0.95$
- TEC_{GNSS} is systematically higher than $TEC_{ionosonde}$ by ~3-5 TECU, probably because…
  - $TEC_{ionosonde}$ is the TEC without plasmaspheric contribution
  - ROB data are interpolation of the actual observations to a regular grid

Correlation coefficients between different TEC series

Series	month	$TEC_{ROB-LIS}$	$TEC_{IONO-EBR}$	$TEC_{SCI-LIS}$
$TEC_{ROB-EBR}$	March June October December	0.99 0.96 0.97 0.96	**0.97** **0.90** **0.96** **0.93**	0.94 0.91 0.94 0.93
$TEC_{ROB-LIS}$	March June October December		0.96 0.87 0.94 0.89	**0.95** **0.95** **0.97** **0.95**
$TEC_{IONO-EBR}$	March June October December			0.93 0.86 0.89 0.88

Table 1. all *p values* ≤ 0.05;
r for different data sources but for the same location are in **bold**

Methods

- TEC series are decomposed using the principal component analysis (PCA)

- Each of $TEC_{ROB\text{-}LIS}$, $TEC_{ROB\text{-}EBR}$, $TEC_{SCI\text{-}LIS}$ and $TEC_{IONO\text{-}EBR}$ series with 1 h time resolution was analyzed separately during each of the month-long time intervals

Principal components analysis (PCA)

- Input data ⇒ covariance matrix ⇒ eigenvalues & eigenvectors.
- Eigenvalues ⇒ explained variances of the extracted modes
- Eigenvectors ⇒ principal components (PC) & empirical orthogonal functions (EOF).
- $PC_{\#} + EOF_{\#} = mode\#$

- PCA input matrix:
  - each column contains 24 observations (every 1 h)
  - number of columns = number of days in a month
- PCs = TEC daily variations of different types
  - see *Figures 2 & 3* for PC1 & PC2
- EOFs = amplitudes of daily variations for each of the analyzed days
  - see *Figures 5 & 6* for EOF1 & EOF2

TEC Mode 1

- Regular daily variations due to the changes of the insolation – *Figure 2*
- Explains:
  - 93-95% of the TEC variations for March
  - 77-86% of the TEC variations for June
  - 92-95% of the TEC variations for October
  - 87-94% of the TEC variations for December
- TEC series are well correlated between each other (mean *r* = 0.95) – see Table 2
- Series from different locations are well correlated: mean *r* = 0.97
- TEC_{GNSS} are well correlated with $TEC_{ionosonde}$: mean r = 0.95

PC1 (daily TEC variations)

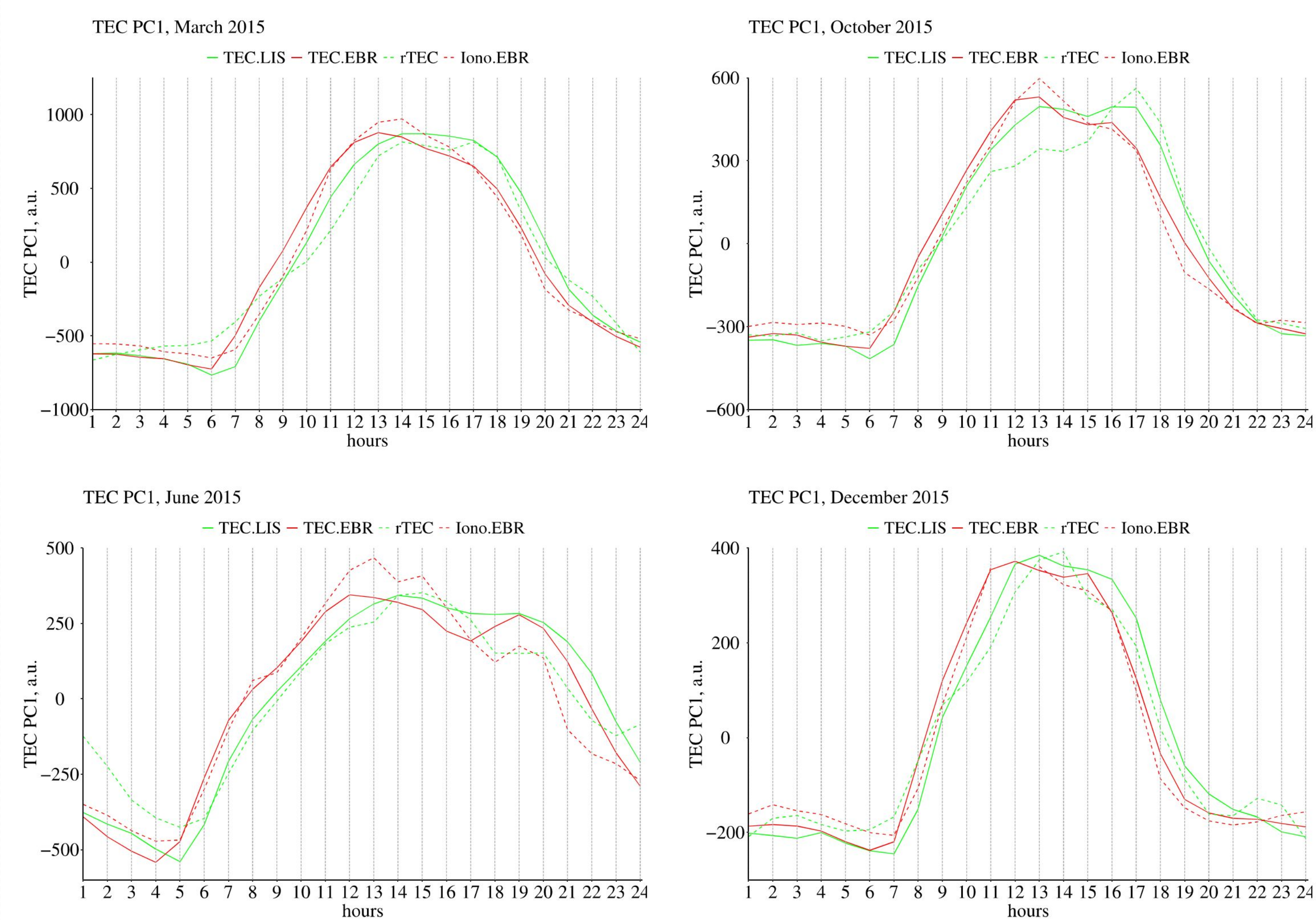


Figure 2. TEC_{Ebro} – red & TEC_{Lisbon} – green;
TEC_{GNSS} – solid lines, $TEC_{ionosonde}$ – dashed lines

Correlation coefficients between different $TEC_{Mode\ 1}$ series

Series	month	$TEC_{ROB-LIS}$	$TEC_{IONO-EBR}$	$TEC_{SCI-LIS}$
$TEC_{ROB-EBR}$	March June October December	0.97 0.97 0.98 0.96	**0.98** **0.94** **0.98** **0.97**	0.95 0.92 0.94 0.96
$TEC_{ROB-LIS}$	March June October December		0.97 0.91 0.96 0.93	**0.98** **0.96** **0.98** **0.97**
$TEC_{IONO-EBR}$	March June October December			0.95 0.92 0.90 0.94

Table 2. all *p values* ≤ 0.05;
r for different data sources but for the same location are in **bold**

TEC Mode 2

- Relatively shallow minimum of TEC around the noon and a maximum of TEC in the late afternoon (19-21 h) – *Figure 3*
- Explains
  - 2.4-2.9% of the TEC variations for March
  - 6.1-8.4% of the TEC variations for June
  - 1.5-3.0% of the TEC variations for October
  - 2.5-3.7% of the TEC variations for December
- TEC series are relatively well correlated between each other (mean r = 0.71) – see *Table 3*
- Series from different locations are relatively well correlated: mean r = 0.74
- TEC_{GNSS} are moderately correlated with $TEC_{ionosonde}$: mean r = 0.60

PC2

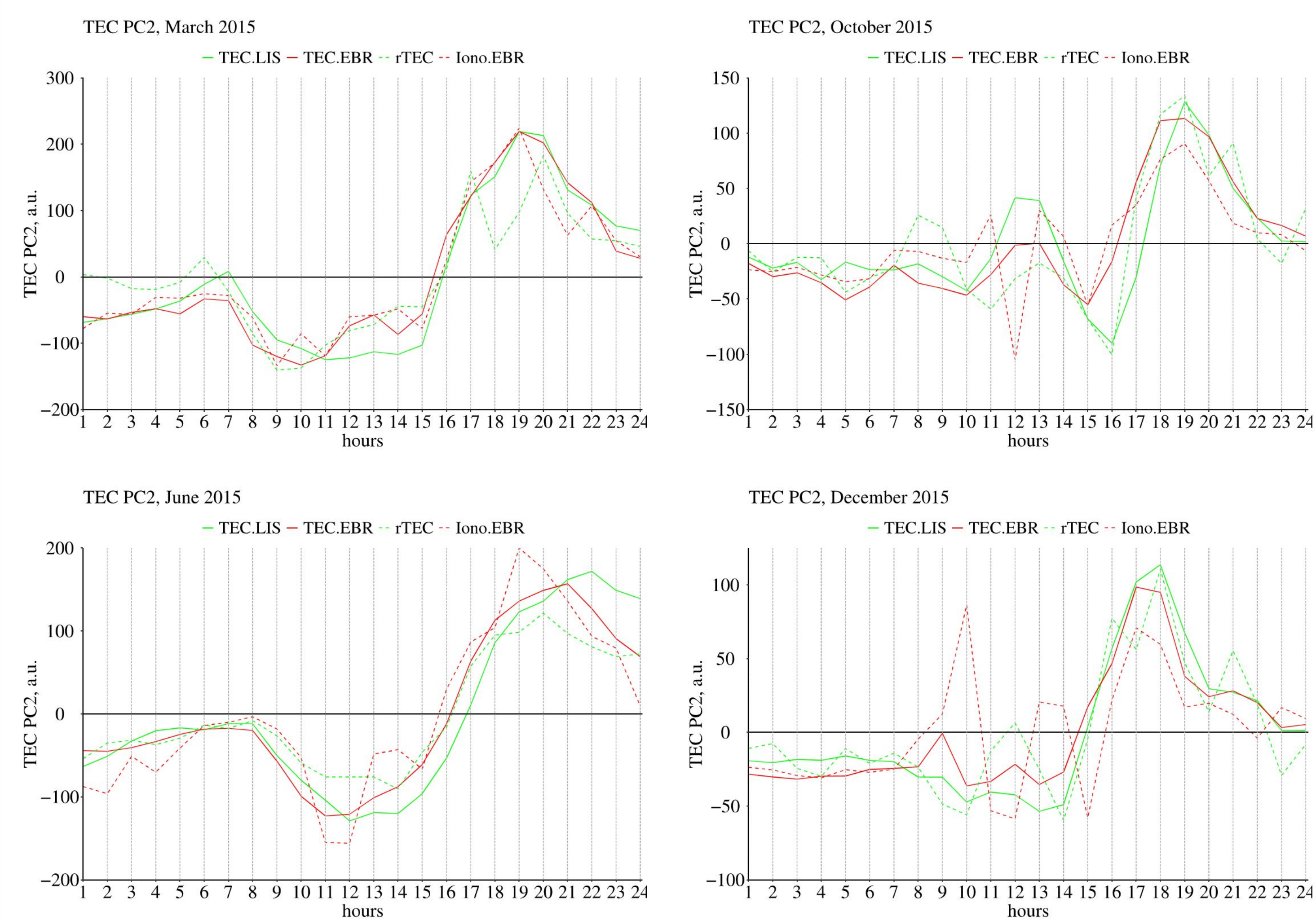


Figure 3. TEC_{Ebro} – red & TEC_{Lisbon} – green;
TEC_{GNSS} – solid lines, $TEC_{ionosonde}$ – dashed lines

Correlation coefficients between different $TEC_{Mode\ 2}$ series

Series	month	$TEC_{ROB-LIS}$	$TEC_{IONO-EBR}$	$TEC_{SCI-LIS}$
$TEC_{ROB-EBR}$	March June October December	0.94 0.91 0.73 0.93	**0.91** **0.81** **0.6** **0.35**	0.78 0.94 0.80 0.74
$TEC_{ROB-LIS}$	March June October December		0.89 0.69 0.34 0.28	**0.80** **0.91** **0.69** **0.81**
$TEC_{IONO-EBR}$	March June October December			0.74 0.84 0.49 0.11

Table 3. all *p values* ≤ 0.05;
r for different data sources but for the same location are in **bold**

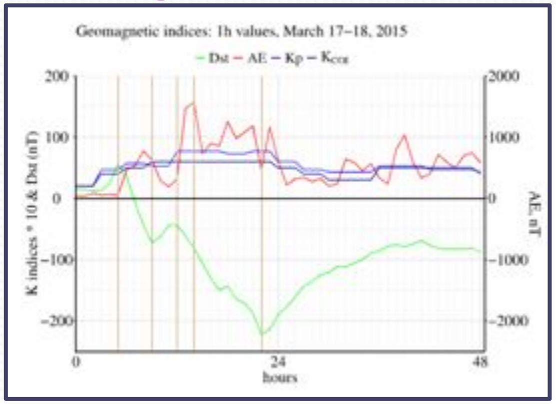
Data: Space weather parameters

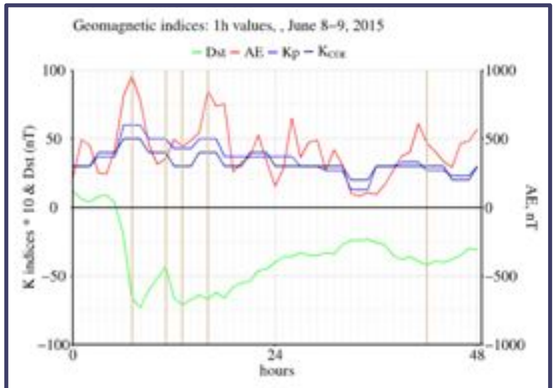
- Geomagnetic field:
  - Dst
  - Kp
  - K_{COI} (local K-index based on the data of the Coimbra (Portugal) geomagnetic observatory
  - AE (auroral electrojet index)
- UV and XR solar flux:
  - UV: Mg II composite series – a proxy for the spectral solar irradiance variability in the spectral range from UV to EUV (*Snow et al., 2014*)
  - UV: F10.7 index (*OMNI database*)
  - XR: Solar EUV Experiment (SEE) for the NASA TIMED mission at the wavelength 0.5 nm (*LISIRD database*)
- Number of solar flares of classes C, M and X per day and their daily sum (*NGDC database*)
- Hourly and daily mean series

Geomagnetic storms and disturbances of 2015

- Only disturbances with Dst ≤ -50 nT (see *Figure 4*):
  - -50 nT ≤ Dst < -100 nT – “moderate disturbances”
    - June 8-9 (Dst = -73 nT)
    - October 18-19 (Dst = -48 nT)
    - December 14-15 (Dst = -47 nT)
  - Dst ≤ -100 nT – “storms”
    - March 17-18 (Dst = -223 nT) – strongest storm of 24^{th} solar cycle
    - June 22-26 (Dst = -204 nT) – second strongest storm of 24^{th} solar cycle
    - October 7-8 (Dst = -124 nT)
    - December 20-21 (Dst = -155 nT)

Variations of the geomagnetic indices during geomagnetic disturbances





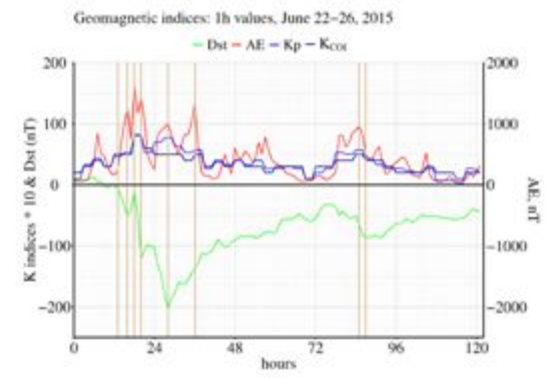
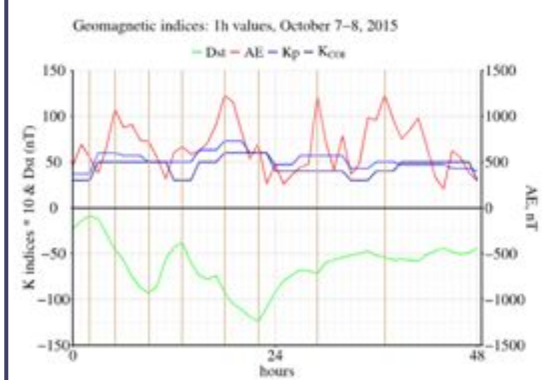
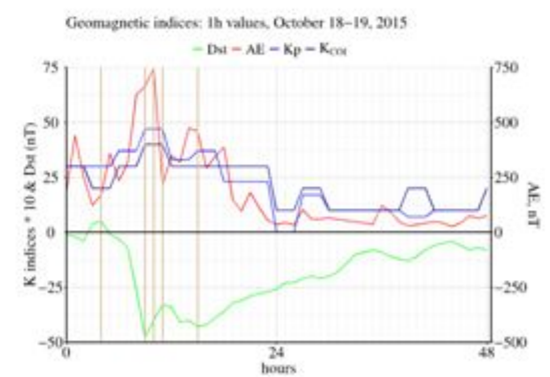
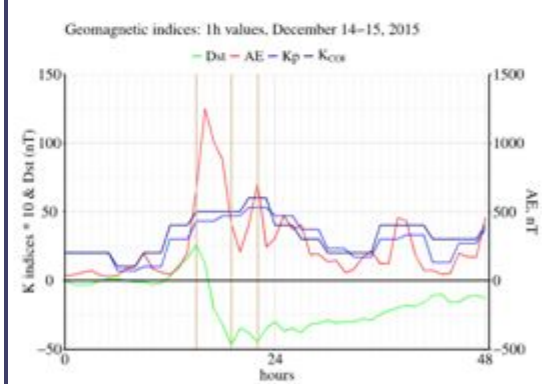


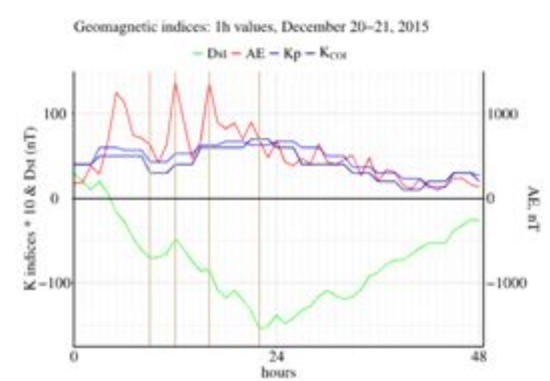
Figure 4. Kp and K_{COI} – blue,
AE – red,
Dst – green

Rectangles mark geomagnetic storms with Dst < -100 nT









Classification of ionospheric storms

- Positive ionospheric storm:
  - amplitude of the daily TEC variation increases during 1st (maybe even 2nd) day(s) of a geomagnetic disturbance
- Negative ionospheric storm:
  - amplitude of the daily TEC variation decreases during 1st (maybe even 2nd) day(s) of a geomagnetic disturbance
- Positive-negative ionospheric storm:
  - amplitude of the daily TEC variation increases during 1st day and decreases during 2nd day of a geomagnetic disturbance

TEC and $TEC_{Mode\ 1}$ response to geomagnetic disturbances

- The types of the ionospheric storm defined from the TEC and $TEC_{Mode\ 1}$ series are the same
- The analysis of Mode 1 allows easy classification of an ionospheric storm:
  - if the amplitude of the Mode 1 (= EOF1) increases during 1-2 days of the ionospheric storm ⇒ positive ionospheric storm
  - if the amplitude of the Mode 1 (= EOF1) decreases during 1-2 days of the ionospheric storm ⇒ negative ionospheric storm
  - if the amplitude of the Mode 1 (= EOF1) increases during 1st day and decreases during 2nd day of the ionospheric storm ⇒ positive-negative ionospheric storm

- EOF1 – see *Figure 5*

EOF1 (daily TEC variations)

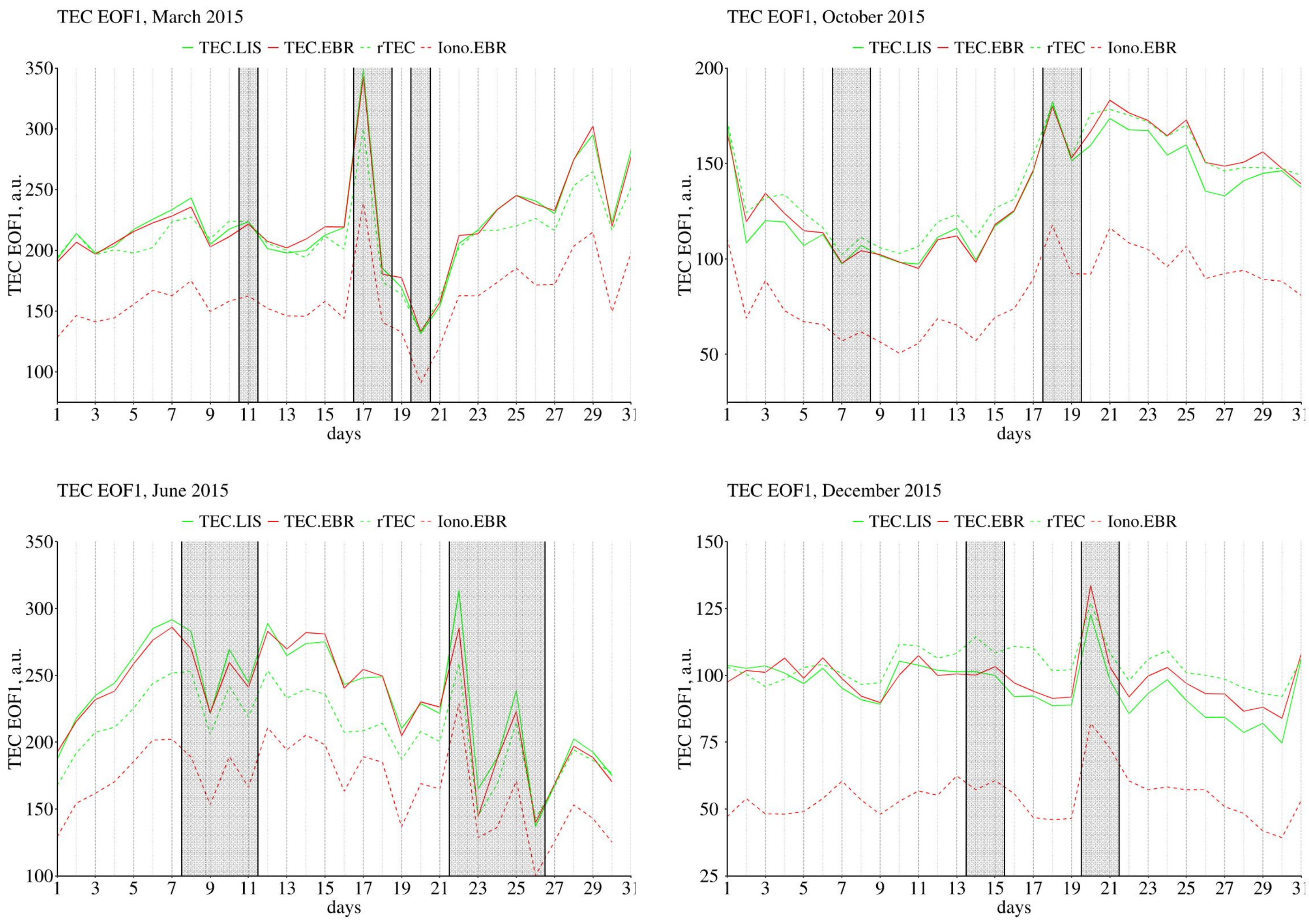


Figure 5. TEC_{Ebro} – red & TEC_{Lisbon} – green;
TEC_{GNSS} – solid lines, $TEC_{ionosonde}$ – dashed lines;
Shaded areas mark analyzed events

TEC and TEC$_{Mode 1}$ response to geomagnetic disturbances

- 4 strong geomagnetic storms of 2015:
  - **March 17-18 – positive-negative ionospheric storm**
  - **June 22-26 – positive-negative ionospheric storm**
  - October 7-8 – negative ionospheric storm
  - **December 20-21 – positive-negative ionospheric storm** (concurs with two C-class flares on December 21)
- 3 moderate geomagnetic disturbances of 2015:
  - **June 8-9 – positive-negative ionospheric storm**
  - **October 18-19 – positive-negative ionospheric storm**
  - December 14-15 – no ionospheric response

$TEC_{Mode\ 2}$ response to geomagnetic disturbances

- $TEC_{Mode\ 2}$ is characterized by…
  - a second daily peak

    or
  - a sharp deep in the TEC variations during the afternoon hours

- EOF2 – see *Figure 6*

EOF2

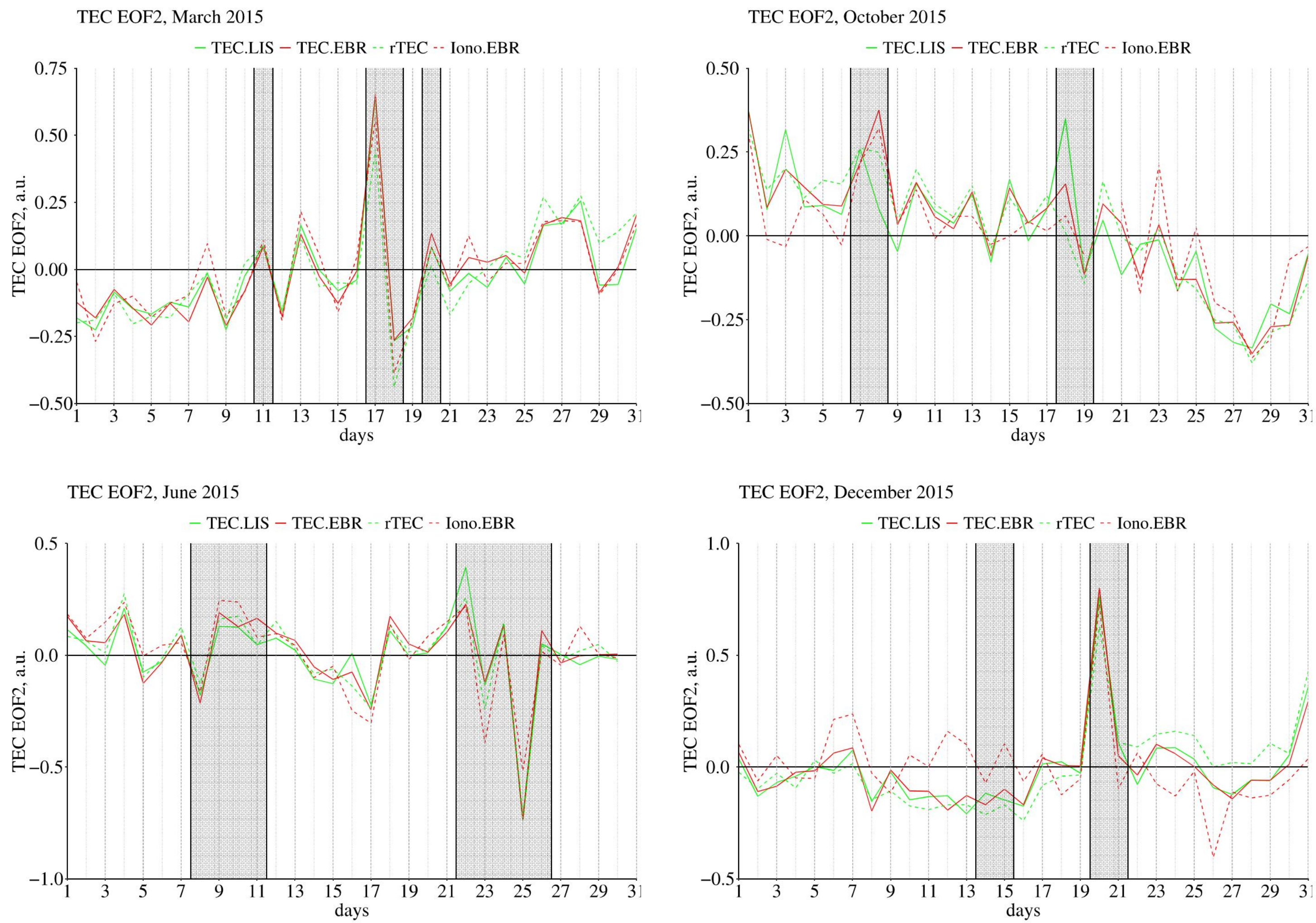


Figure 6. TEC_{Ebro} – red & TEC_{Lisbon} – green;
TEC_{GNSS} – solid lines, $TEC_{ionosonde}$ – dashed lines;
Shaded areas mark analyzed events

Changes of EOF2 sign during first 2 days during geomagnetic disturbances

- 4 strong geomagnetic storms of 2015:
  - **March 17-18** – +/–
  - **June 22-26** – +/–
  - October 7-8 – +/+
  - **December 20-21** – **+/–(~0)**

- 3 moderate geomagnetic disturbances of 2015:
  - June 8-9 – –/+
  - **October 18-19** – +/–
  - December 14-15 – –/–

Correlation coefficients: TEC EOF1 & EOF2 vs geomagnetic indices

EOF1

Series	March *lag = 1 d*	June *lag = 1 d*	October *lag = 1 d*	December *lag = 0 d*
Dst	**0.56 (<0.01)**	**0.51 (0.05)**	**0.75 (0.14)**	-0.63 (<0.01)
Kp	-0.43 (0.05)	-0.35 (0.18)	-0.64 (0.17)	**0.76 (<0.01)**
K_{COI}	-0.42 (0.07)	-0.38 (0.07)	-0.66 (0.18)	**0.71 (<0.01)**
AE	**-0.55 (<0.01)**	-0.35 (0.16)	**-0.74 (0.09)**	**0.77 (<0.01)**

EOF2

Series	March *lag = 1 d*	June *lag = 2 d*	October *lag = 0 d*	December *lag = 0 d*
Dst	0.34 (0.10)	**0.42 (<0.01)**	-0.62 (0.07)	-0.52 (<0.01)
Kp	-0.35 (0.09)	**-0.4 (<0.01)**	**0.69 (<0.01)**	0.61 (<0.01)
K_{COI}	-0.32 (0.12)	-0.37 (<0.01)	**0.70 (<0.01)**	0.57 (<0.01)
AE	**-0.44 (0.02)**	-0.37 (0.06)	**0.71 (<0.01)**	**0.72 (<0.01)**

Table 4. only $|r| \geq 0.2$ and *p value* ≤ 0.2 (in round parentheses) are shown;
highest in absolute values *r* for each month are in **bold**
r are calculated with a lag (geomagnetic indices lead)

TEC response to geomagnetic disturbances: Summary

- Amplitude of the TEC daily variations (TEC and $TEC_{Mode\ 1}$):
  - 3 out of 4 geomagnetic storms of 2015 with Dst < -100 nT resulted in the positive-negative ionospheric storms
  - 2 out of 3 geomagnetic disturbances of 2015 with Dst < -50 nT resulted in the positive-negative ionospheric storms

- Appearance of the second daily maximum/afternoon deep ($TEC_{Mode\ 2}$):
  - 3 out of 4 geomagnetic storms of 2015 with Dst < -100 nT showed second maximum of TEC during 1st day and an afternoon deep during 2nd day of the storm
  - 1 out of 3 geomagnetic disturbances of 2015 with Dst < -50 nT showed second maximum of TEC during 1st day and an afternoon deep during 2nd day of the storm

- Both EOF1 and EOF2 correlate with geomagnetic activity variations – see *Table 4*

Solar flares and UV & XR solar flux variations in 2015

- Solar flares
  - X2.1 solar flare on March 11, 16:11 UT
  - Significant numbe of flares of classes C and M during every analyzed month

- Monthly variations of the solar UV and XR fluxes are affected by…
  - mean level of the solar activity
  - number of flares

- Daily numbers of solar flares and variations of the solar UV & XR fluxes are shown in *Figure 7* for March, June, October and December of 2015.

Solar flares and UV & XR solar flux

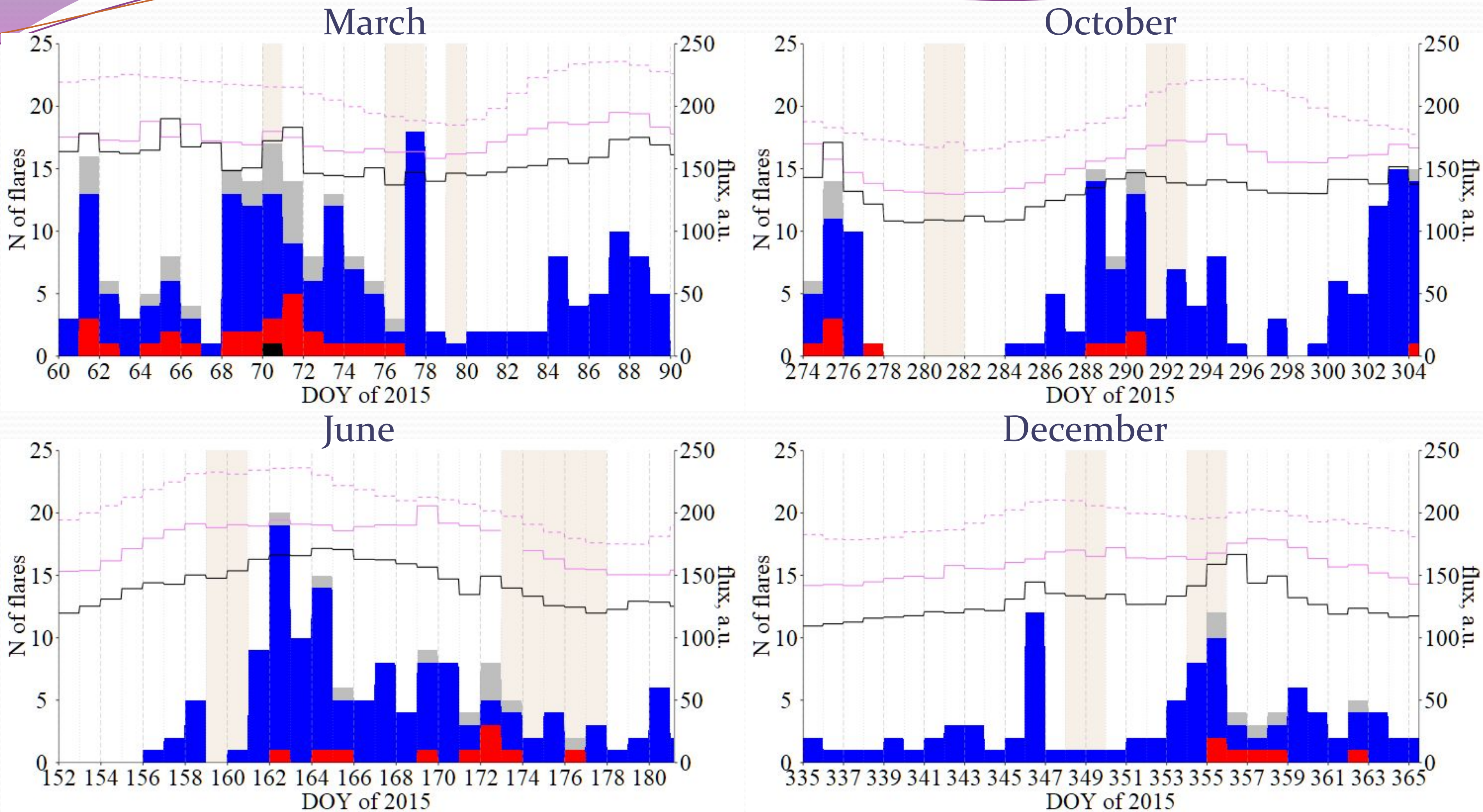


Figure 7. solar UV (violet step lines) and XR (black step lines) fluxes;
solar flares: C – blue bars, M – red bars, C – black bars;
shaded areas mark analyzed events

Correlation coefficients: TEC EOF1 vs solar UV & XR fluxes

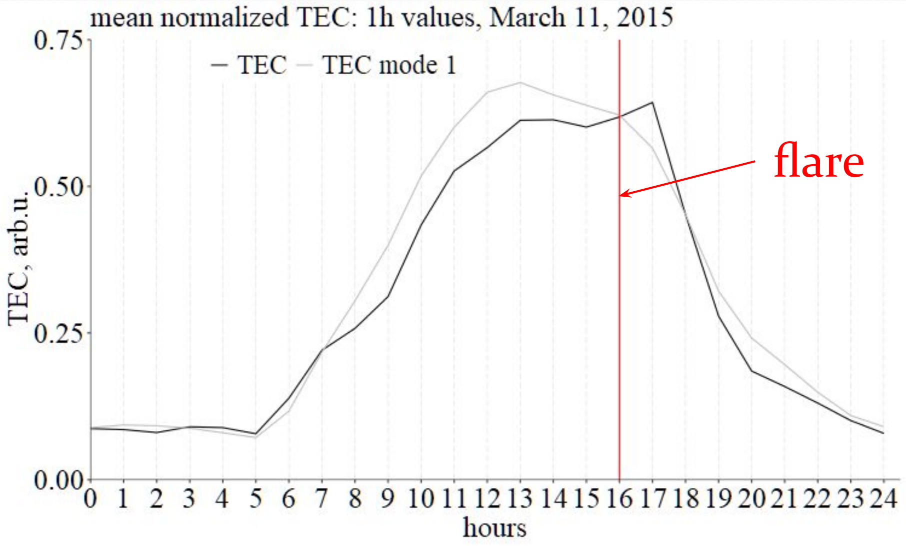
Series	March	June	October	December
UV: F10.7	**0.49 (0.01)**	0.69	**0.84 (0.02)**	
UV: Mg II	**0.45 (0.02)**	**0.74 (0.01)**	**0.87 (0.05)**	0.26
XR	0.2	0.69 (0.09)	0.59 (0.15)	0.34

Table 5. only $|r| \geq 0.2$ and *p value* ≤ 0.2 (in round parentheses) are shown; highest in absolute values *r* for each month are in **bold**

NB : *r* for EOF2 are low and statistically non-significant

TEC response to solar flares and UV&XR fluxes: Summary

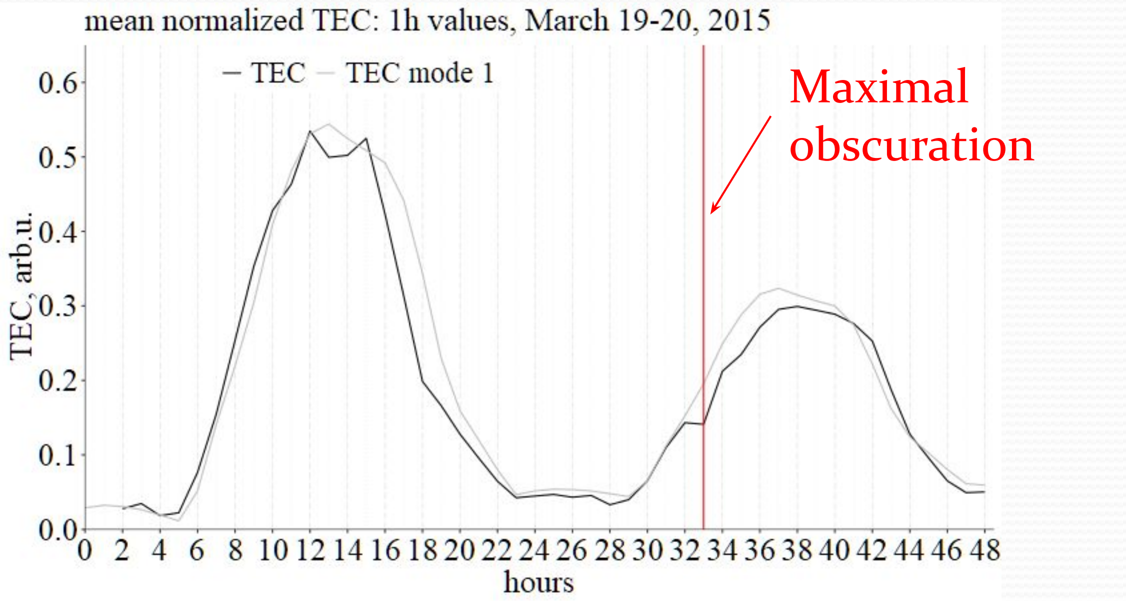
- The flare on March 11 being of short durations (few minutes) had no significant effect on TEC values
  - there is weak increase of TEC at 17 h;
  - neither $TEC_{Mode\ 1}$ nor $TEC_{Mode\ 2}$ responds to this flare



- More flares ⇒ more UV& XR ⇒ EOF1 increases
- Only EOF1 (= amplitude of the TEC daily variations) correlates with variations of the solar UV & XR fluxes – see *Table 5*

Partial solar eclipse on March 20, 2015

- Maximal obscuration at Iberian Peninsula ~60% at 09:00 UT
- EOF1 (= amplitude of Mode 1) on March 20 ≈ ½ EOF1 on March 19
- Around 09:00 UT there is a sharp deviation from the steady growth of TEC during morning hours



TEC response to flares and solar irradiance: Summary

- The X2.1 solar flare on March 11 had no significant effect on TEC
- The overall increase/decrease of the flares number as well as changes of the solar UV & XR fluxes during analyzed months resulted in the increase/decrease of the amplitude of the TEC daily cycle (= EOF1)
- No relation between EOF2 associated with the solar UV & XR fluxes

- The partial solar eclipse (~60% around 09:00 UT on March 20) affects the amplitude of the daily cycle (= EOF1)
- There is also sharp deviation from the regular daily cycle observed around 09:00 UT
- No response to this event in the variations of Mode 2 was found.

Final Conclusions

- Five of seven analyzed geomagnetic storms were associated with positive-negative ionospheric storms
- This response can be indentified analyzing both the amplitude of the TEC daily cycle and the amplitude of the Mode 1 (= EOF1).
- Four out of seven analyzed geomagnetic storms were associated with variations of Mode 2 (=EOF2) 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.

- Only amplitude of the daily TEC cycle (= amplitude of Mode 1 = EOF1) responds to…
  - solar flares and overall variations of the solar UV & XR fluxes
  - a partial solar eclipse was observed in March 2015

Results of this study are available as a preprint (*Morozova et al., 2020)* and under review in *Space Weather.*

Data sources

- The SCI-LIS TEC data are available at Barlyaeva, T., Barata, T., Morozova, A., 2020. Datasets of ionospheric parameters provided by SCINDA GNSS receiver from Lisbon airport area, Mendeley Data, v1 http://dx.doi.org/10.17632/kkytn5d8yc.1
- The TEC ROB-LIS and ROB-EBR 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 (TEC IONO-EBR).
- 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 OGAUC 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/.

Data sources

- 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.

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- 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