The solar quiet variation observed near the vortex focus: effect of the geomagnetic activity and vortex dynamics on the Sq extraction

Anna Morozova[1], Rania Rebbah[1], and Maria Pais[1]

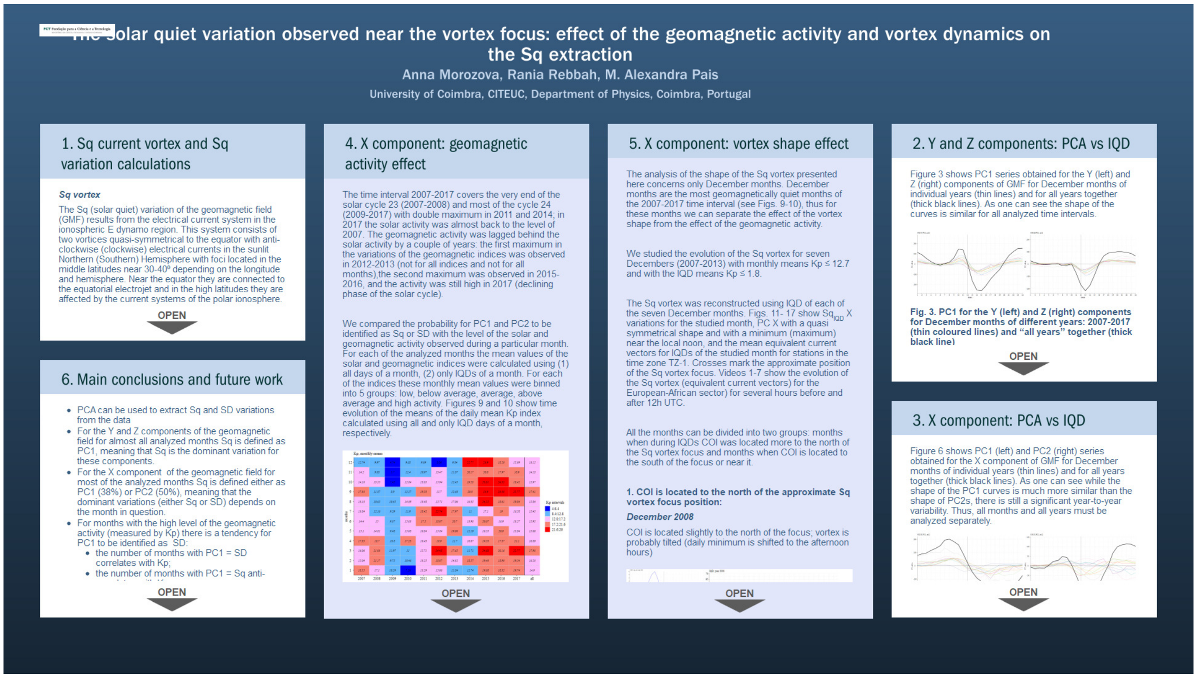
[1]University of Coimbra

November 24, 2022

Abstract

The solar quiet variation (Sq) observed at observatories near the latitude of the Sq vortex focus is difficult to assess because it is affected by both the geomagnetic activity level and the dynamics of the ionosphere and the upper atmosphere resulting in changes of the Sq ionospheric vortex shape and position. The use of only geomagnetically quiet days (QD) to calculate Sq for a given month can, to a certain extent, remove the effect of geomagnetic disturbances; however, the effect of the atmospheric dynamics still needs to be taken into account. The Sq vortex shape and position can be acquired from the horizontal vector of the geomagnetic field measured at geomagnetic observatories located in the European-African sector between 10ºN and 60ºN using vector rotation or calculating equivalent currents. Here we present results of a comparative analysis of two methods to extract Sq variations from the observations of the earth geomagnetic field. The analyzed data are measurements of the geomagnetic field done between 2007 and 2017 at the Coimbra Geomagnetic Observatory (COI, Portugal) located near 40ºN.The principal component analysis (PCA) based Sq curves are compared with the standard ones obtained using 5 international QD per month. For most of the analyzed years for the X component, the second PCA mode was identified as Sq variation whereas for the Y and Z components for all analyzed data sets the first PCA mode was identified as Sq variation. We studied differences and similarity of the PCA and IQD based Sq in relation to (1) the average geomagnetic activity level and (2) Sq vortex shape and position relatively to COI.

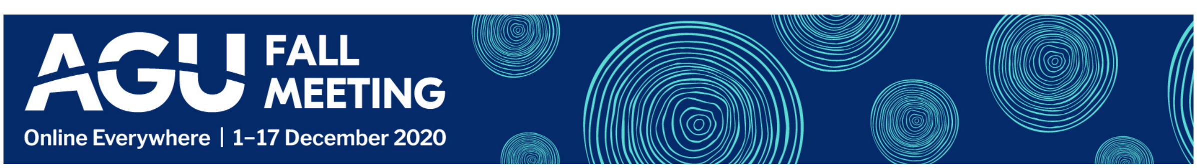
The solar quiet variation observed near the vortex focus: effect of the geomagnetic activity and vortex dynamics on the Sq extraction



Anna Morozova, Rania Rebbah, M. Alexandra Pais

University of Coimbra, CITEUC, Department of Physics, Coimbra, Portugal

PRESENTED AT:



1. SQ CURRENT VORTEX AND SQ VARIATION CALCULATIONS

Sq vortex

The Sq (solar quiet) variation of the geomagnetic field (GMF) results from the electric current system in the ionospheric E dynamo region. This system consists of two vortices quasi-symmetrical to the equator with anti-clockwise (clockwise) electric currents in the sunlit Northern (Southern) Hemisphere with foci located in the middle latitudes near 30-40º depending on the longitude and hemisphere. Near the equator they are connected to the equatorial electrojet and in the high latitudes they are affected by the current systems of the polar ionosphere. As the day progresses, the position of these vortices on the globe moves westward following the Sun.

Thus, for any given location on the planet, the geometry of the system changes along the day returning to a similar condition after one day. The character of the ground measured Sq variations of the GMF components X, Y and Z depends on the position of a geomagnetic observatory or station relative to the vortex. The change of the sign of Sq X (Bx variation) takes place around the focus latitudes. The sign of Sq Y (By variation) and Sq Z (Bz variation) changes near the equator (see *Amory-Mazaudier, 2009*).

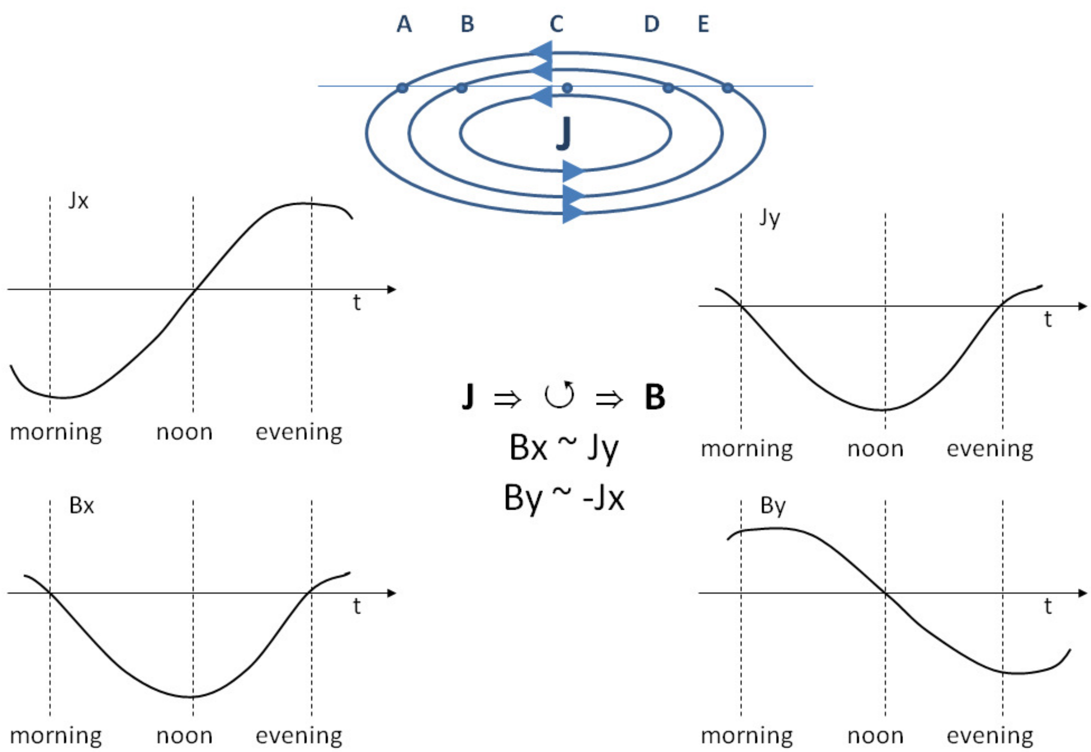


Fig. 1. Sq variations of the electric current (J) and magnetic field (B) components X and Y in the Northern Hemisphere for a station located to the north of the vortex's focus. Arrows show direction of the current J in the Northern Hemisphere.

Fig. 1 shows variations of the geomagnetic field (B) components X and Y generated by an ideal current vortex (J) in the Northern Hemisphere for a station located to the north of the vortex's focus. The Sq X variation is symmetrical around the local noon, while Sq Y is anti-symmetrical. In reality the shape of the Sq current cortex can be far from the ideal circle or oval: the vortex can, e.g., be tilted (resulting in, e.g, a shift of the daily minimum of Sq X to the afternoon hours, see *Amory-Mazaudier, 2009*), stretched or compressed. The shape of the vortex affects mostly Sq X variation measured by the ground stations, whereas the shape of the Sq Y and Sq Z variations changes only slightly.

Methods

There are many sources for the day-to-day variability of Sq: shape and position of the vortex, geomagnetic activity, tides and waves in the upper atmosphere.

The standard method to obtain Sq from the ground observations of GMF consists in the selection of days with lowest level of the GMF perturbations (so called "quiet days", typically, 5 days per a calendar month) and averaging of the observed daily GMF variations observed at a particular geomagnetic observatory or stations over selected days. These days can be selected using the data of an individual observatory (local quiet days) or using the data from a number of selected observatories (international quiet days – IQD, hereafter Sq_{IQD}).

Another way to estimate Sq is to apply a decomposition method to the GMF data: the wavelet analysis (*Maslova et al., 2010*), the empirical mode decomposition (*Piersanti et al., 2017*) or the principal component analysis (PCA; *Xu and Kamide, 2004*). On the other hand, the shape of the vortex can be deduced from the data using, for example, the spherical harmonic analysis (SHA, *Takeda, 1982*) to calculate the equivalent electric current or can be reconstructed as equivalent electric current vectors (horizontal component of the J field) from the observed horizontal GMF vector (*Stening et al., 2005*).

In this work we used **PCA** to extract the main modes of the GMF variability and to compare them with $\mathbf{Sq_{IQD}}$, and computed the equivalent vectors to deduce the shape of the Sq vortex for particular time intervals.

The similarity of the analyzed series was estimated 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**) considers 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.

Data

The GMF data for PCA are the hourly measurements of the X, Y and Z component at the *Coimbra Geomagnetic Observatory* in Portugal (**COI**, 40º 13' N, 8º 25.3' W, 99 m a.s.l.). The vectors of the electric current were constructed using hourly measurements at a number of European and African observatories – see Fig. 2. All Sq variations were calculated in LT. Please note that for the COI location LT = UTC.

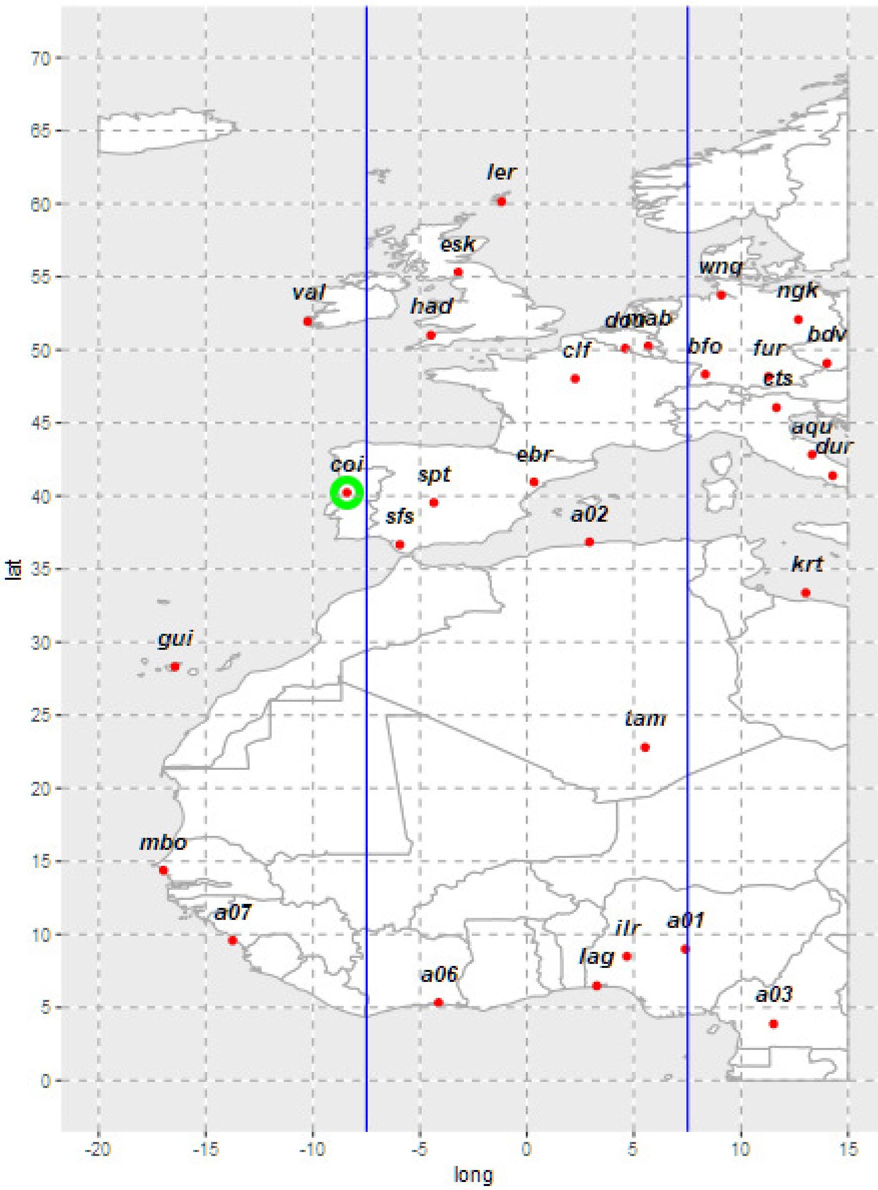


Fig. 2. Geomagnetic observatories for the European-African sector used in this study. Position of COI is marked by a green circle. Vertical blue lines divide the area into three time zones (from left to right: TZ-1, TZ0, TZ+1).

The data analyzed cover the period from 2007 to 2017. The **Sq** variations were calculated individually for each year for each of the months (11 years x 12 months = 132 data sets) and using the data for each of the months for all 11 years together (12 more data sets, marked as "all years"). The **SD** (solar distrubed) variation was estimated from the COI data as a difference between the monthly mean of the daily variation and Sq, separately for each of the analyzed months and for each of the components.

To analyze the effect of the solar and geomagnetic activity we used the following indices: for the solar activity – the daily means of the sunspot numbers (**R**) and the **F10.7** index; for the geomagnetic activity – the daily means of the **Dst**, **Kp** and **ap**, and **AE** indices.

6. MAIN CONCLUSIONS AND FUTURE WORK

- PCA can be used to extract Sq and SD variations from the data
- For the Y and Z components of the geomagnetic field for almost all analyzed months Sq is defined as PC1, meaning that Sq is the dominant variation for these components.
- For the X component of the geomagnetic field for most of the analyzed months Sq is defined either as PC1 (38%) or PC2 (50%), meaning that the dominant variations (either Sq or SD) depends on the month in question.
- For months with the high level of the geomagnetic activity (measured by Kp) there is a tendency for PC1 to be identified as SD:
  - the number of months with PC1 = SD correlates with Kp;
  - the number of months with PC1 = Sq anti-correlates with Kp.
- The variation of the shape and position of the focus of the Sq current vortex can be deduced from the ground measurements of GMF:
  - the shape of Sq X variation at COI depends on the COI position relative to the Sq vortex focus and the deformation of the vortex shape;
  - typically, the tilt of the vortex axis results in a shift of the daily minimum of Sq X to the afternoon hours;
  - although the shape of Sq_{IQD} X could change, for the all analyzed cases there is always a PC (PC1 or PC2) that is quasi-symmetrical relative to the local noon with a minimum (maximum) near or soon after the local noon.

In future we plan:

- to study the seasonal variations of the Sq vortex shape and position and the effect of the geomagnetic activity;
- to study in detail the effect of the Sq vortex shape on the Sq X variation observed at the ground level;
- to compare the equivalent vortices reconstructed by the vectors and using SHA or its analogues.

4. X COMPONENT: GEOMAGNETIC ACTIVITY EFFECT

The time interval 2007-2017 covers the very end of the solar cycle 23 (2007-2008) and most of the cycle 24 (2009-2017) with double maximum in 2011 and 2014; in 2017 the solar activity was almost back to the level of 2007. The geomagnetic activity was lagged behind the solar activity by a couple of years: the first maximum in the variations of the geomagnetic indices was observed in 2012-2013 (not for all indices and not for all months),the second maximum was observed in 2015-2016, and the activity was still high in 2017 (declining phase of the solar cycle).

We compared the probability for PC1 and PC2 to be identified as Sq or SD with the level of the solar and geomagnetic activity observed during a particular month. For each of the analyzed months the mean values of the solar and geomagnetic indices were calculated using (1) all days of a month, (2) only IQDs of a month. For each of the indices these monthly mean values were binned into 5 groups: low, below average, average, above average and high activity. Figures 9 and 10 show time evolution of the means of the daily mean Kp index calculated using all and only IQD days of a month, respectively.

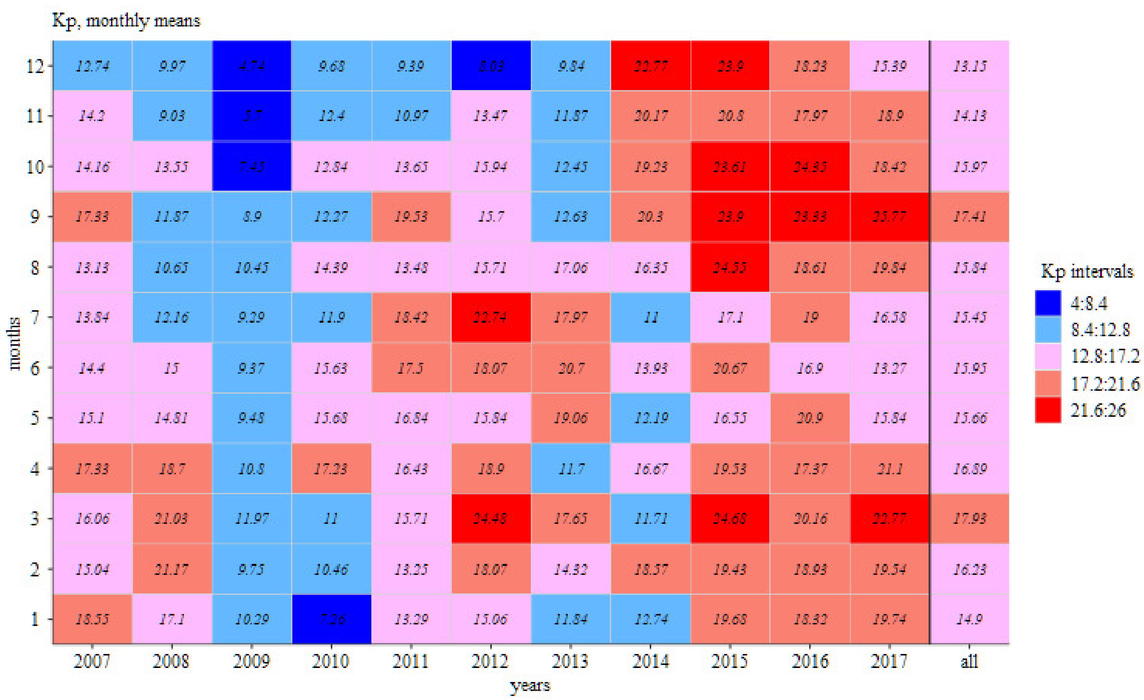


Fig. 9. Geomagnetic activity level for individual months defined as means of the daily mean Kp for all days of a month. Numbers show the mean Kp values.

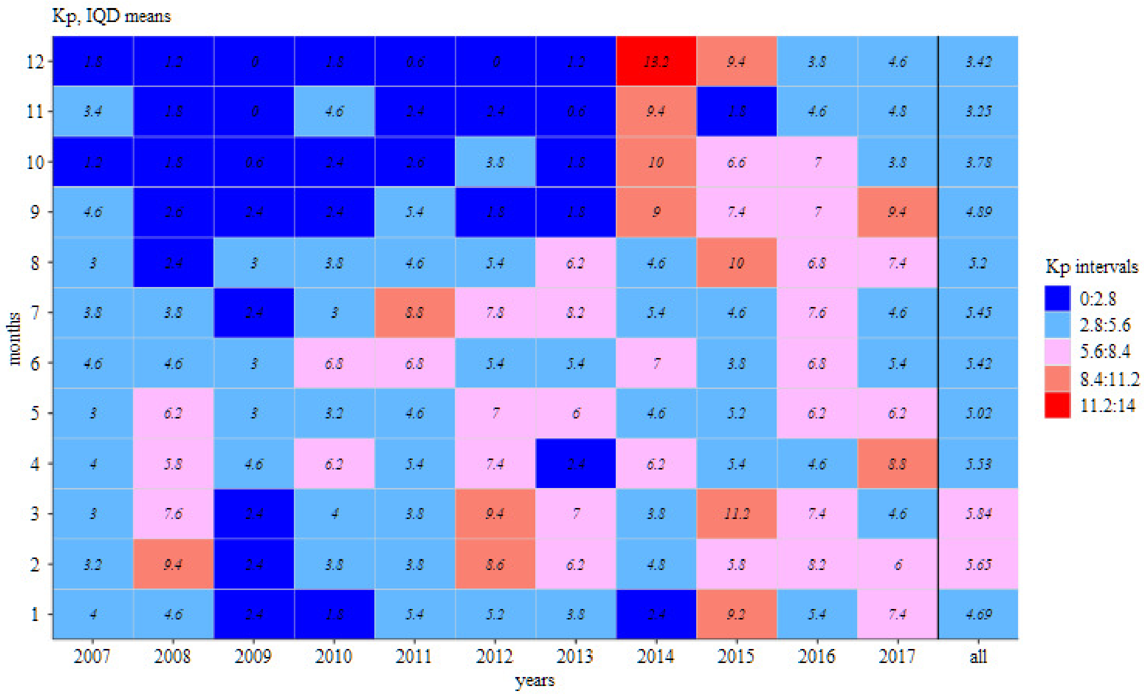


Fig. 10. Geomagnetic activity level for individual months defined as means of the daily mean Kp for IQDs only. Numbers show the mean Kp values.

Then, the time evolution of the number of months with a PC identified as Sq or SD was compared with the time evolution of the monthly means series of the solar and geomagnetic indices. It was found that the solar activity has low influence on the identification of a PC as Sq or SD. Among the geomagnetic activity indices, the highest influence was found for the Kp and ap indices. Therefore, here we present only the results obtained for Kp.

It was found that the number of months with PC1 identified as SD increases with the increase of the mean Kp level ($r = 0.71$, p value = 0.03) and, correspondingly, the number of months with PC1 identified as Sq anti-correlates with Kp ($r = -0.71$, p value = 0.01).

The autumn-winter months are more frequently the months with PC1 = SD, whereas the spring-summer months are more frequently the months with PC1 = Sq. On the other hand, there is no significant correlation between the Kp and the number of months with PC1 = Sq or PC1 = SD on the seasonal time scale, probably because Kp has rather semiannual variability than annual.

In case of the PC2 identification neither strong correlation with Kp ($r = 0.27$) nor particular seasonal patterns were found.

5. X COMPONENT: VORTEX SHAPE EFFECT

The analysis of the shape of the Sq vortex presented here concerns only December months. December months are the most geomagnetically quiet months of the 2007-2017 time interval (see Figs. 9-10), thus for these months we can separate the effect of the vortex shape from the effect of the geomagnetic activity.

We studied the evolution of the Sq vortex for seven Decembers (2007-2013) with monthly means Kp ≤ 12.7 and with the IQD means Kp ≤ 1.8.

The Sq vortex was reconstructed using IQD of each of the seven December months. Figs. 11- 17 show Sq_{IQD} X variations for the studied month, PC X with a quasi symmetrical shape and with a minimum (maximum) near the local noon, and the mean equivalent current vectors for IQDs of the studied month for stations in the time zone TZ-1. Crosses mark the approximate position of the Sq vortex focus. Videos 1-7 show the evolution of the Sq vortex (equivalent current vectors) for the European-African sector) for several hours before and after 12h UTC.

All the months can be divided into two groups: months when during IQDs COI was located more to the north of the Sq vortex focus and months when COI is located to the south of the focus or near it.

1. COI is located to the north of the approximate Sq vortex focus position:

December 2008

COI is located slightly to the north of the focus; vortex is probably tilted (daily minimum is shifted to the afternoon hours)

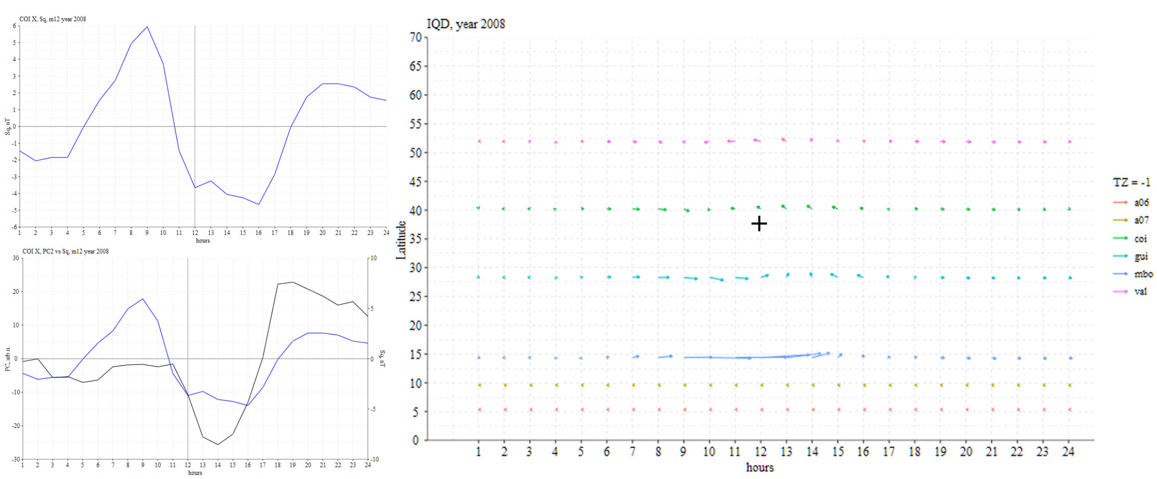


Fig. 11. December 2008: Sq (left, blue lines) and PC2 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the north of the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 1.8.

[VIDEO] https://www.youtube.com/embed/CIdye_9Scps?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 1. Equivalent current vectors in the European-African sector for IQD of December 2008 between 09:30 UTC and 15:30 UTC

December 2010

COI is located clearly to the north of the focus; vortex is symmetrical

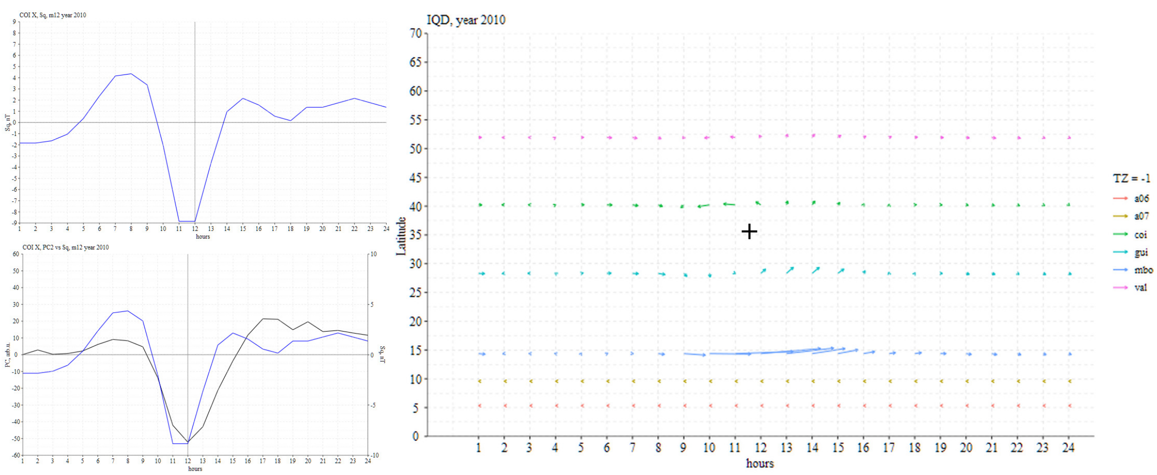


Fig. 12. December 2010: Sq (left, blue lines) and PC2 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the north of the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 1.8.

[VIDEO] https://www.youtube.com/embed/lMTsiB1h4gA?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 2. Equivalent current vectors in the European-African sector for IQD of December 2010 between 09:30 UTC and 15:30 UTC

December 2011

COI is located slightly to the north of the focus; vortex is probably tilted (daily minimum is shifted to the afternoon hours)

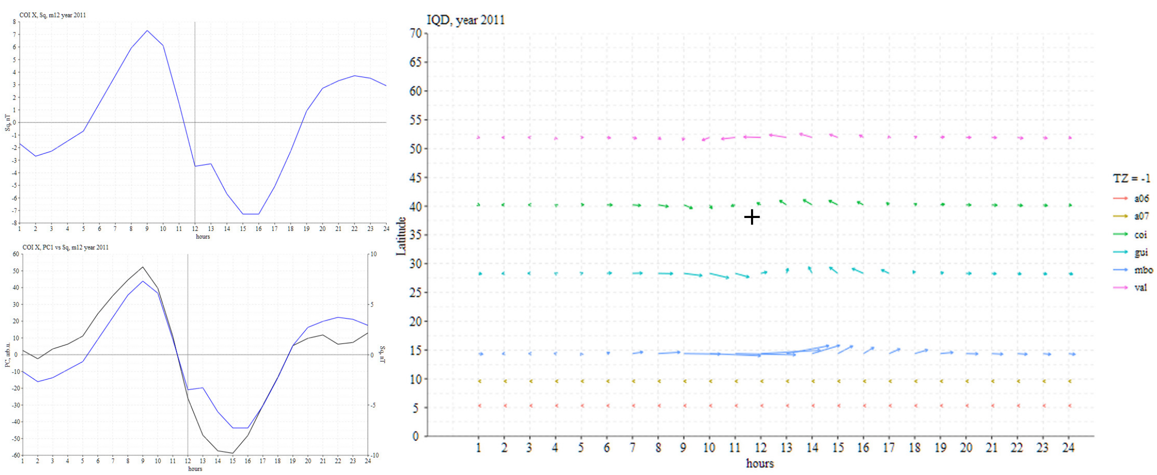


Fig. 13. December 2011: Sq (left, blue lines) and PC1 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the north of the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 0.6.

[VIDEO] https://www.youtube.com/embed/NHRZJ4wUTiU?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 3. Equivalent current vectors in the European-African sector for IQD of December 2011 between 09:30 UTC and 15:30 UTC

December 2013

COI is located slightly to the north of the focus; vortex is probably slightly tilted (daily minimum is shifted to the afternoon hours)

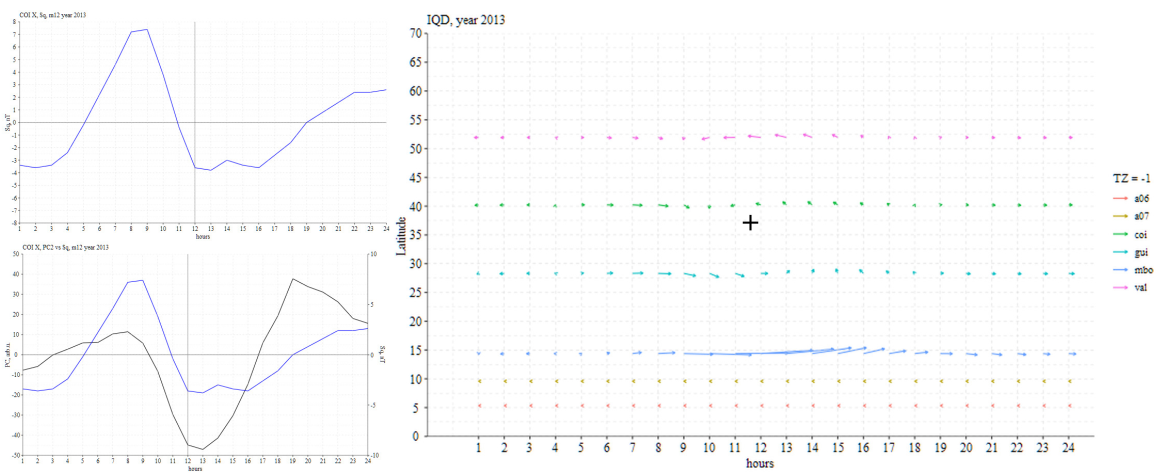


Fig. 14. December 2013: Sq (left, blue lines) and PC2 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the north of the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 1.2.

[VIDEO] https://www.youtube.com/embed/oQfMPr5x5TU?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 4. Equivalent current vectors in the European-African sector for IQD of December 2013 between 09:30 UTC and 15:30 UTC

2. COI is located to the south of or under the approximate Sq vortex focus position:

December 2007

COI is located clearly to the south of the focus; vortex is probably deformed (additional minima/maxima)

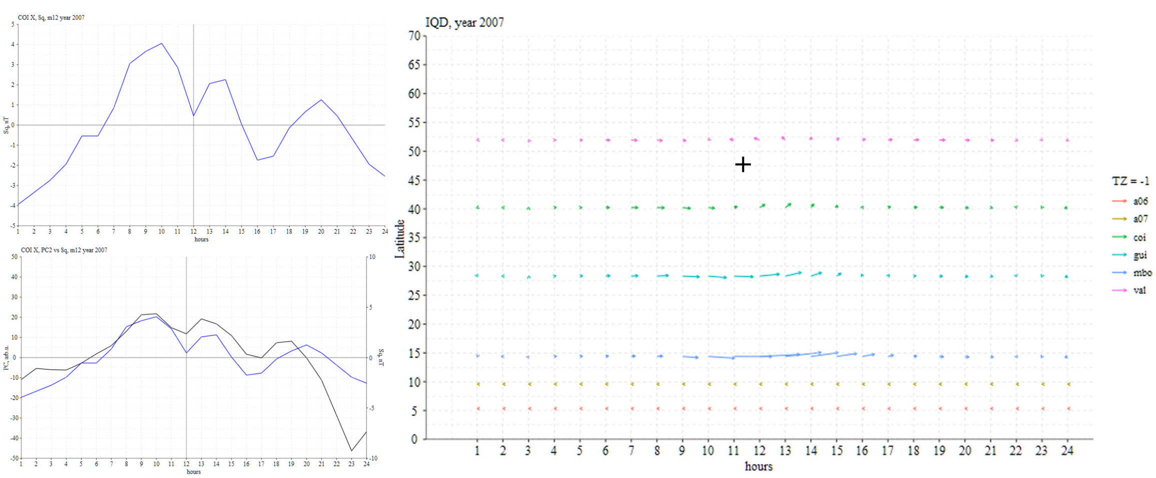


Fig. 15. December 2007: Sq (left, blue lines) and PC2 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the south of the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 1.8.

[VIDEO] https://www.youtube.com/embed/4f-nsmB3sYg?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 5. Equivalent current vectors in the European-African sector for IQD of December 2007 between 09:30 UTC and 15:30 UTC

December 2009

COI is located slightly to the south of the focus; vortex is probably tilted (daily minimum is shifted to the afternoon hours)

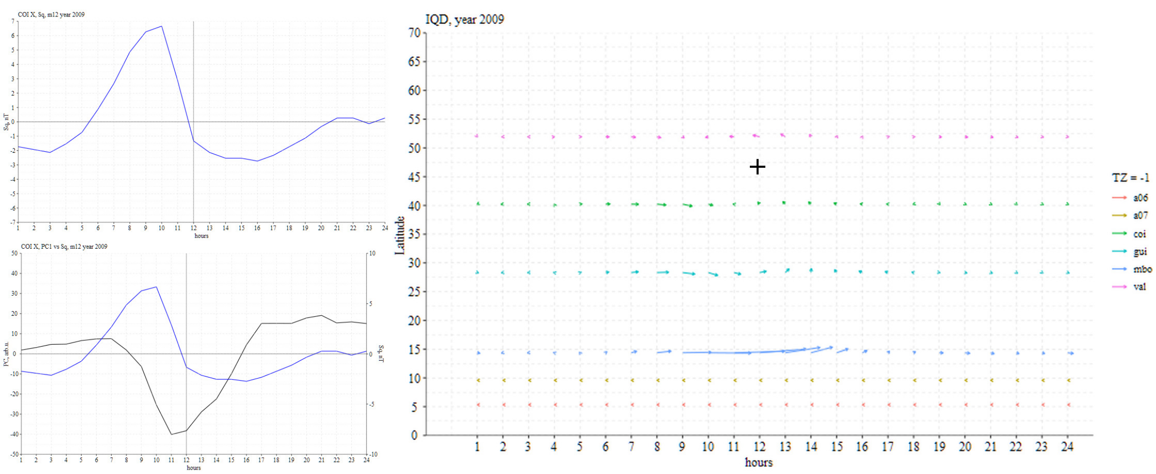


Fig. 16. December 2009: Sq (left, blue lines) and PC2 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the south of/under the vortex focus (approx. marked by the cross). Mean $Kp_{IQD} = 0$.

[VIDEO] https://www.youtube.com/embed/JSj258Uy75E?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 6. Equivalent current vectors in the European-African sector for IQD of December 2009 between 09:30 UTC and 15:30 UTC

December 2012

COI is located slightly to the south of the focus; vortex is probably tilted (daily minimum is shifted to the afternoon hours)

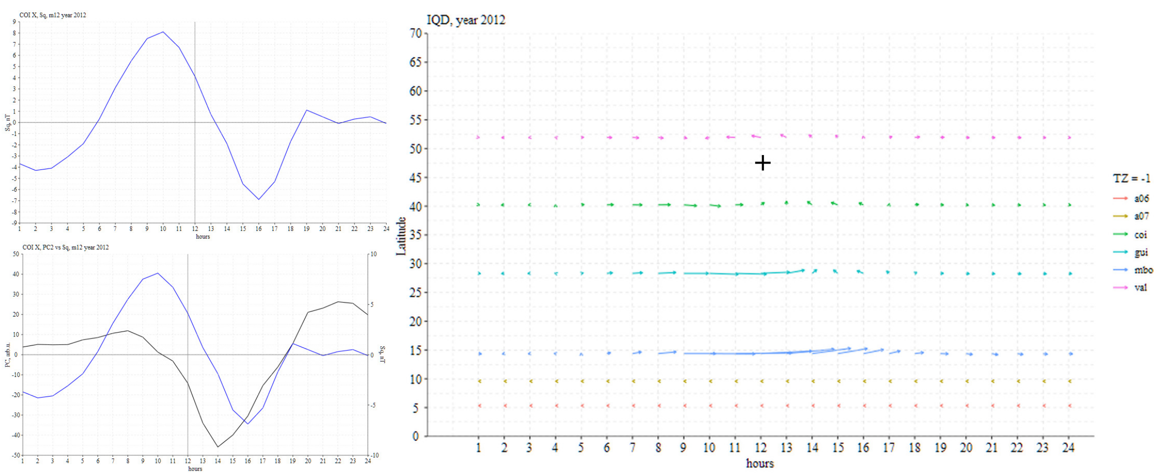


Fig. 17. December 2012: Sq (left, blue lines) and PC1 (bottom left, black line) for the X component and the equivalent current vectors for TZ-1 for IQD (right). COI is located to the south of/under the vortex focus (approx. marked by the cross). Mean Kp_{IQD} = 0.

[VIDEO] https://www.youtube.com/embed/JOE77UOHCwU?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 7. Equivalent current vectors in the European-African sector for IQD of December 2012 between 09:30 UTC and 15:30 UTC

In all analyzed cases there is a PC X (PC1 for 2 cases and PC2 for 5 cases out of 7) with a quasi-symmetrical shape with a minimum (maximum for 2007) near the noon-early afternoon hours.

The low number of the analyzed cases (7) does not allow to make a conclusion on how the shape of the vortex and position of the station relative to its focus affect the PCA results. Future studies are needed.

2. Y AND Z COMPONENTS: PCA VS IQD

Figure 3 shows PC1 series obtained for the Y (left) and Z (right) components of GMF for December months of individual years (thin lines) and for all years together (thick black lines). As one can see the shape of the curves is similar for all analyzed time intervals.

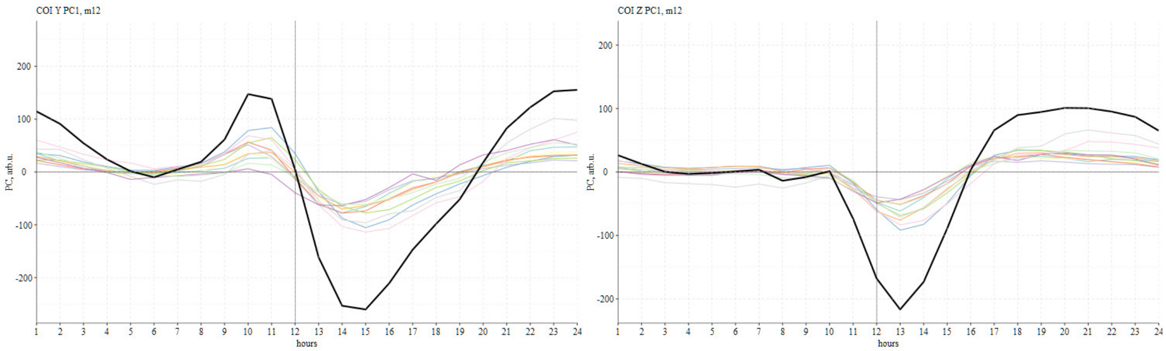


Fig. 3. PC1 for the Y (left) and Z (right) components for December months of different years: 2007-2017 (thin coloured lines) and “all years” together (thick black line)

The comparison of PC1s to the corresponding Sq and SD variations shows that for all except 1 case for the Y component and for all cases for the Z component, PC1 is identified as Sq with very high correlation coefficients – see Figs. 4-5.

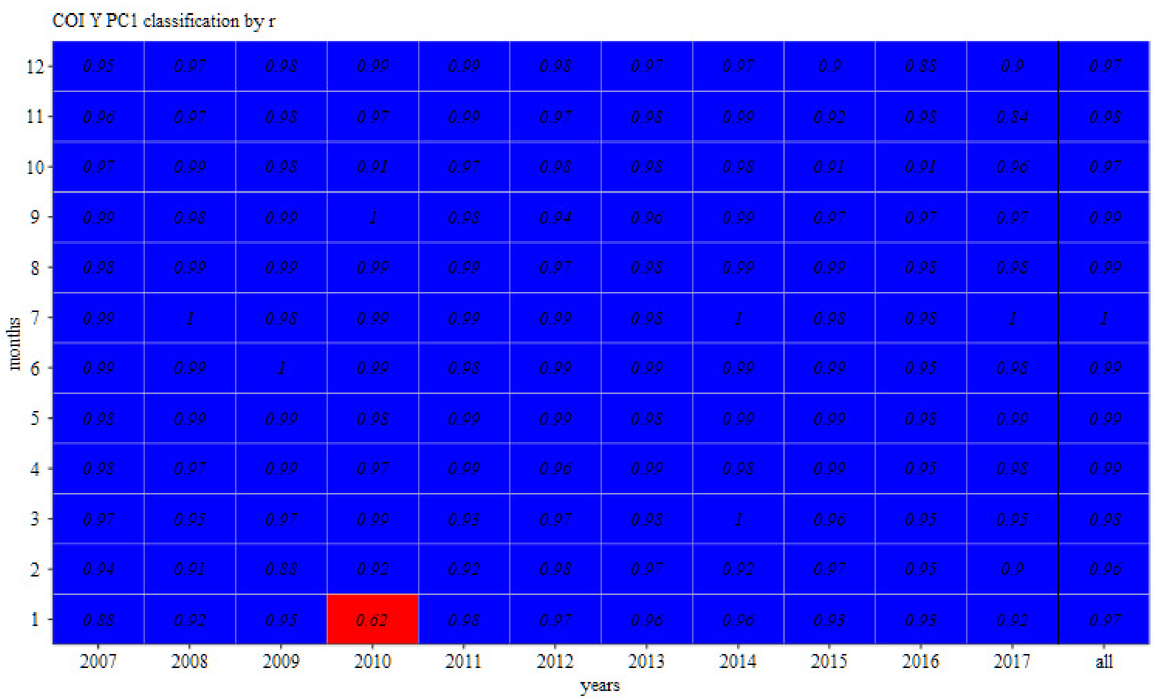


Fig. 4. Identification of PC1 for the Y component as Sq or SD using correlation coefficients (black numbers). Blue tiles mark PC1 = Sq; red tile mark PC1 = SD.

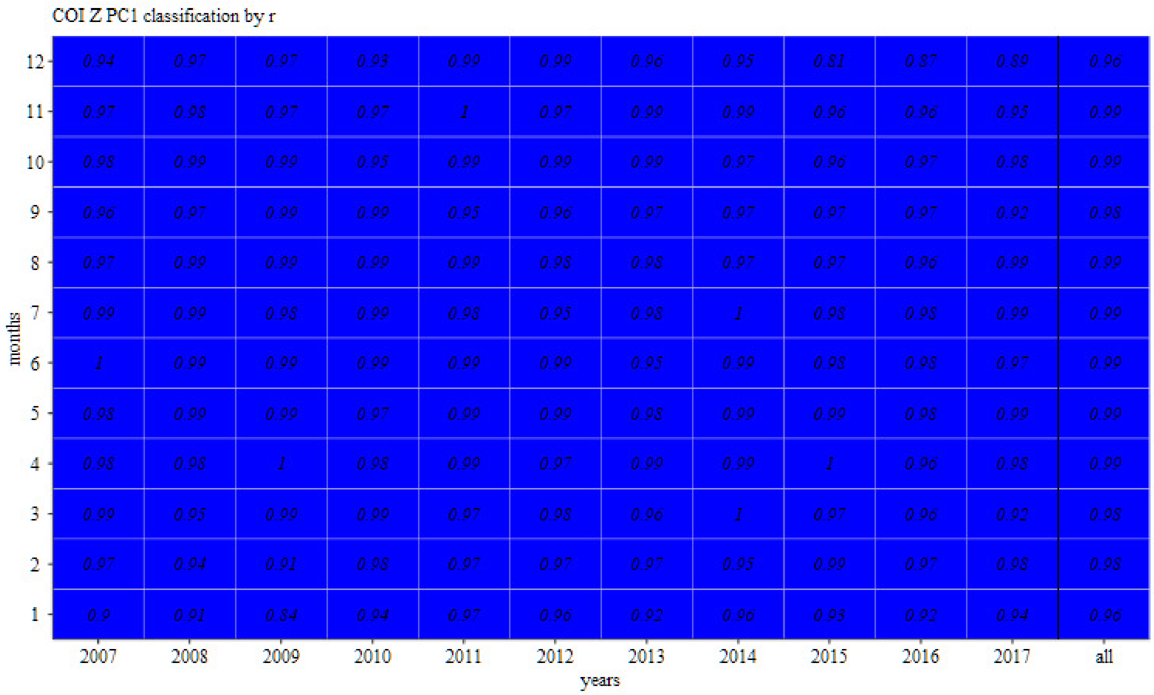


Fig. 5. Identification of PC1 for the Z component as Sq using correlation coefficients (black numbers). Blue tiles mark PC1 = Sq.

Thus, PCA is a reliable tool to extract Sq from the GMF observations of the Y and Z components. PC1 is defined as Sq for almost all series (1 exception for 144 analyzed series for Y and no exception for Z).

3. X COMPONENT: PCA VS IQD

Figure 6 shows PC1 (left) and PC2 (right) series obtained for the X component of GMF for December months of individual years (thin lines) and for all years together (thick black lines). As one can see while the shape of the PC1 curves is much more similar than the shape of PC2s, there is still a significant year-to-year variability. Thus, all months and all years must be analyzed separately.

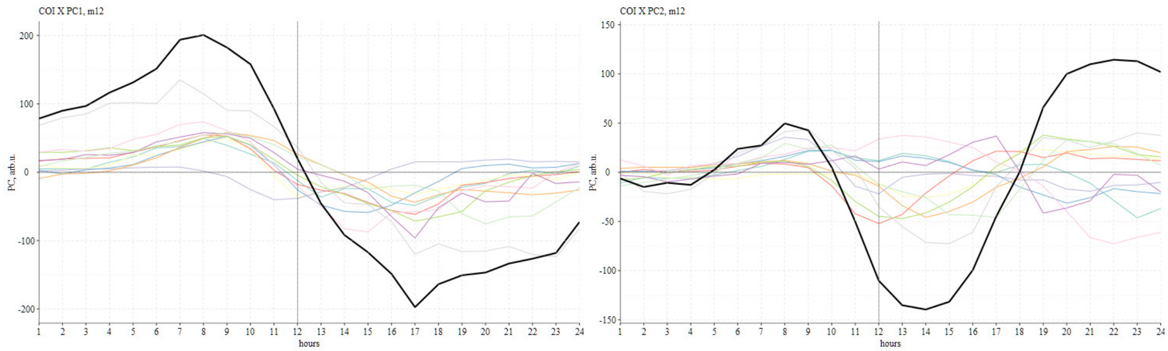


Fig. 6. PC1 (left) and PC2 (right) for the X component for December months of different years.

The correlation analysis of PC1s and PC2s vs corresponding Sq and SD shows that in some cases PC1 or PC2 can be identified as SD with high correlation coefficients (see red tiles in Figs. 7-8) and in others they can be identified as Sq (blue tile in Figs. 7-8). In several cases it was impossible to identify PC1 or PC2 neither as Sq nor as SD.

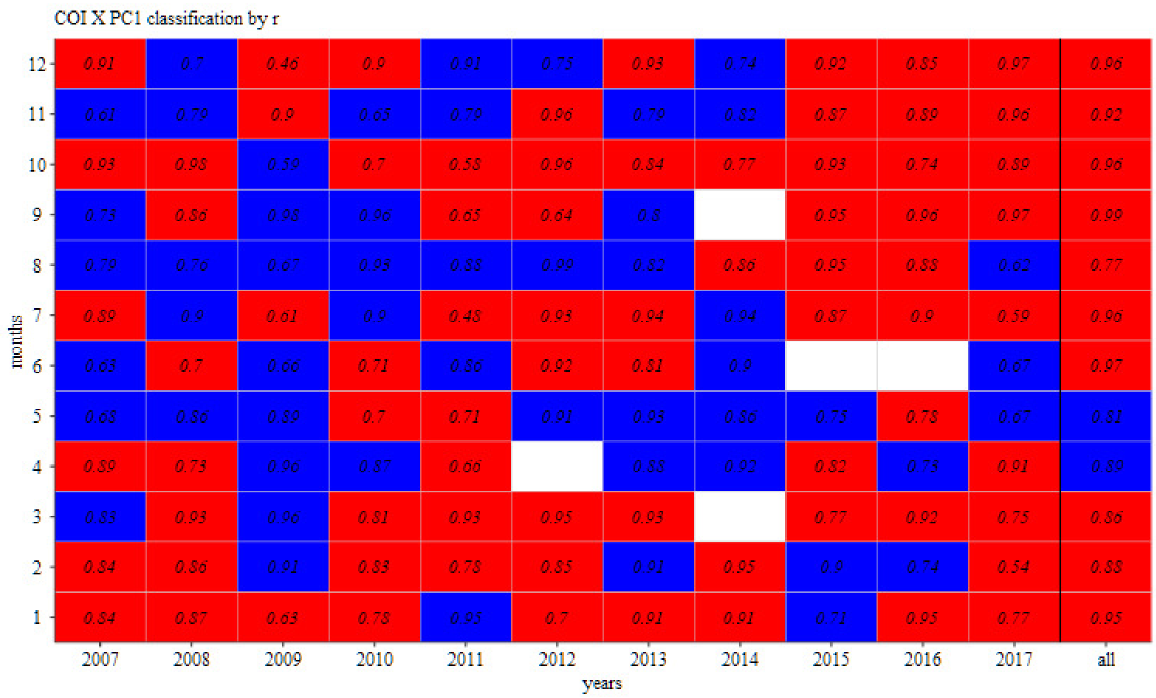


Fig. 7. Identification of PC1 for the X component as Sq or SD using correlation coefficients (black numbers). Blue tiles mark PC1 = Sq; red tiles mark PC1 = SD; white tiles mark non-identified cases.

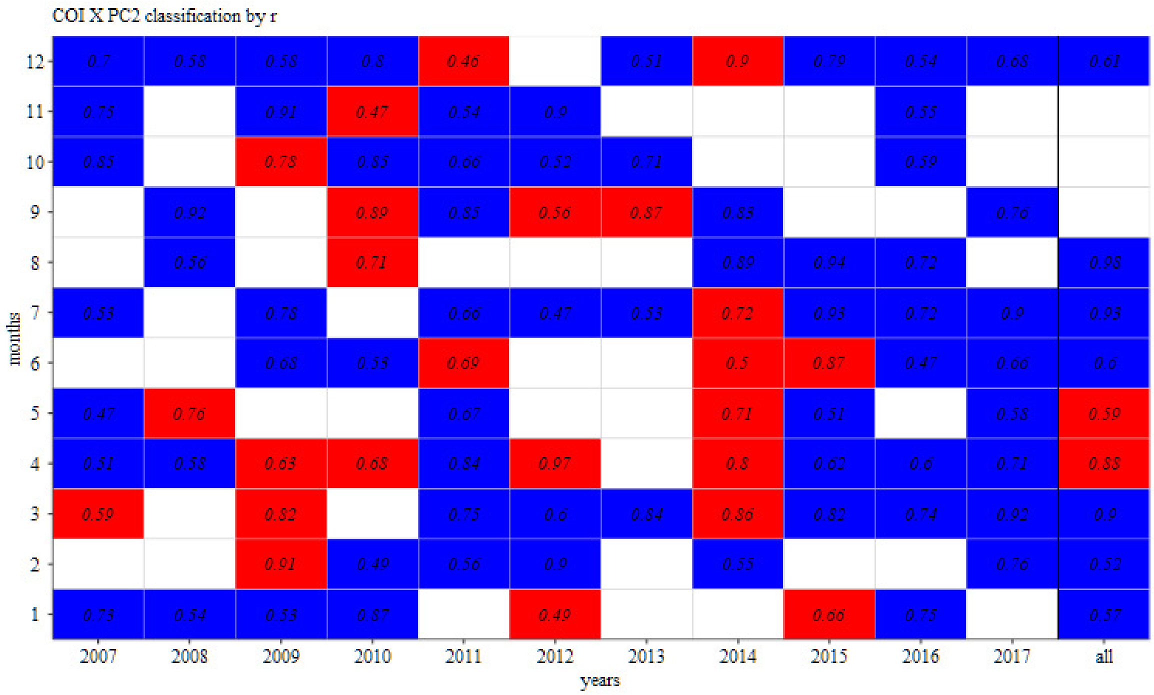


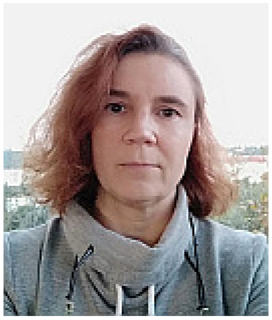
Fig. 8. Identification of PC2 for the X component as Sq or SD using correlation coefficients (black numbers). Blue tiles mark PC2 = Sq; red tiles mark PC2 = SD; white tiles mark non-identified cases.

Overall, 54 out of 144 PC1s (38%) were identified as SD and 72 out of 144 PC2s (50%) were identified as Sq. Please note that the double identification (both PC1 and PC2 can be identified as either SD or Sq) is possible.

Thus, PCA can be used to extract Sq from the GMF observations of the X component, however there is no simple rule to identify PCs as Sq or SD. There is a tendency for PC2 to be identified as Sq and the identification of the PC1 has a pattern discussed further in Section. 4

AUTHOR INFORMATION

Dr. Anna L. Morozova



annamorozovauc@gmail.com

ORCID iD: 0000-0002-8552-8052

Reseacher at the Center for Earth and Space Research of the University of Coimbra (CITEUC), University of Coimbra, Coimbra, Portugal

She is the author of 22 papers in peer review journals. The main areas of scientific activities are: Solar-Terrestrial Physics; Solar physics; Atmosphere physics; Ionosphere physics; Statistical data analysis; Geophysical data homogenization.

Rania Rebbah

rebbah6rania@gmail.com

ORCID ID : 0000-0003-2483-8898

Research fellow at CITEUC, UC, Portugal and a PhD student at Mining and Geo-Resources Engineering at the University of Porto, Portugal.

She published 1 journal article and has 1 section(s) of books. Her current research interest is on Mining and Environmental Engineering, Statistical data analysis, Geophysics and Solar-Terrestrial physics.

M. Alexandra Pais

pais@fis.uc.pt

ABSTRACT

Abstract

The solar quiet variation (Sq) observed at observatories near the latitude of the Sq vortex focus is difficult to assess because it is affected by both the geomagnetic activity level and the dynamics of the ionosphere and the upper atmosphere resulting in changes of the Sq ionospheric vortex shape and position. The use of only geomagnetically quiet days (QD) to calculate Sq for a given month can, to a certain extent, remove the effect of geomagnetic disturbances; however, the effect of the atmospheric dynamics still needs to be taken into account.

The Sq vortex shape and position can be acquired from the horizontal vector of the geomagnetic field measured at geomagnetic observatories located in the European-African sector between 10ºN and 60ºN using vector rotation or calculating equivalent currents.

Here we present results of a comparative analysis of two methods to extract Sq variations from the observations of the earth geomagnetic field. The analyzed data are measurements of the geomagnetic field done between 2007 and 2017 at the Coimbra Geomagnetic Observatory (COI, Portugal) located near 40ºN.The principal component analysis (PCA) based Sq curves are compared with the standard ones obtained using 5 international QD per month. For most of the analyzed years for the X component, the second PCA mode was identified as Sq variation whereas for the Y and Z components for all analyzed data sets the first PCA mode was identified as Sq variation.

We studied differences and similarity of the PCA and IQD based Sq in relation to (1) the average geomagnetic activity level and (2) Sq vortex shape and position relatively to COI.

Acknowledgement

This study is funded by national funds through FCT (Foundation for Science and Technology, I.P.), under the project MAG-GIC: PTDC/CTA-GEO/31744/2017.

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).

REFERENCES

Amory-Mazaudier, C., 2009, Electric current systems in the earth’s environment. Nigerian Journal of Space Research, 8, pp.178-255.

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.

Maslova, I., P. Kokoszka, J. Sojka, and L. Zhu, 2010, Estimation of Sq variation by means of multiresolution and principal component analyses. Journal of Atmospheric and Solar-Terrestrial Physics, 72, 7-8, 625-632.

Piersanti, M., T. Alberti, A. Bemporad, F. Berrilli, R. Bruno, V. Capparelli, V. Carbone, C. Cesaroni, G. Consolini, A. Cristaldi, and A. Del Corpo, 2017, Comprehensive analysis of the geoeffective solar event of 21 June 2015: Effects on the magnetosphere, plasmasphere, and ionosphere systems. Solar Physics, 292(11), p.169.

Stening, R., T. Reztsova, and L.H. Minh, 2005, Day-to-day changes in the latitudes of the foci of the Sq current system and their relation to equatorial electrojet strength. Journal of Geophysical Research: Space Physics, 110(A10), A10308, doi:10.1029/2005JA011219.

Takeda, M., 1982, Three dimensional ionospheric currents and field aligned currents generated by asymmetrical dynamo action in the ionosphere. Journal of Atmospheric and Terrestrial Physics, 44(2), 187–193. doi:10.1016/0021-9169(82)90122-2

Xu, W.Y. and Y. Kamide, 2004, Decomposition of daily geomagnetic variations by using method of natural orthogonal component. Journal of Geophysical Research: Space Physics, 109(A5).