



# Nocturnal variability of total electron content (TEC) at Koudougou (Burkina Faso) during three geomagnetic storms of solar cycle 24: implications for equatorial ionospheric irregularities

Kiswendsida Théophile GUISSOU, Allain Doua GNABAHOU, Sagedo SAWADOGO, Frédéric  
5 OUATTARA <sup>1</sup>

<sup>1</sup>Laboratoire de chimie analytique, de physique spatiale et énergétique (LACAPSE), Koudougou, Burkina Faso

*Correspondence to:* Kiswendsida Théophile GUISSOU (guissoutheo@gmail.com)

**Abstract.** This study analyses the nocturnal variability of GPS-derived total electron content (TEC) at Koudougou, Burkina Faso (12°15'N, 2°20'W), during three geomagnetic storms with Sudden Storm Commencement (SSC) that occurred during  
10 solar cycle 24 (22 June 2015, 14 July 2012 and 8 October 2013). The objective is to identify the geophysical conditions favourable to the generation or suppression of equatorial ionospheric irregularities. In this work, nocturnal variability is quantified by the hourly nocturnal standard deviation  $\sigma_{\text{TEC}}$  (20:00–05:00 LT) and by the relative perturbation  $\delta\text{TEC}$  (%). The reference TEC is constructed from the median of five geomagnetically quiet days ( $K_p < 2$ ) of the month of each storm. A Superposed Epoch Analysis (SEA) is applied to the three events aligned at  $T = 0$ , corresponding to the SSC time. The  
15 storms of 22 June 2015 ( $\text{SYM-H}_{\text{min}} = -198.8$  nT) and 14 July 2012 ( $\text{SYM-H}_{\text{min}} = -114.2$  nT) are dominated by the negative phase ( $\delta\text{TEC}$  reaching  $-91.4\%$  and  $-99.5\%$  respectively), with  $\sigma_{\text{TEC}}$  classified as moderate to reduce during the main phase (3.38 and 3.79 TECU), characteristic of the disturbance Dynamo. In contrast, the storm of 8 October 2013 ( $\text{SYM-H}_{\text{min}} = -64$  nT) exhibits a prolonged positive phase ( $\delta\text{TEC}_{\text{max}} = +77.6\%$ , 16 hours of positive phase) and an intense  $\sigma_{\text{TEC}}$  over the three analysed nights (5.0 to 7.9 TECU), the signature of a dominant Prompt Penetration Electric  
20 Field (PPEF). SEA of the three events reveals a transition from a brief median positive phase ( $T = -21\text{h}$ ,  $+29.7\%$ ) to a prolonged median negative phase ( $T = +1\text{h}$  to  $+34\text{h}$ , minimum  $-80.3\%$  at  $T = +32\text{h}$ ). These results quantitatively highlight, over the West African sector, the generation/suppression duality of nocturnal ionospheric irregularities during disturbed periods, illustrating the antagonistic role of PPEF and the disturbance Dynamo.

Keywords: nocturnal TEC; ionospheric irregularities; geomagnetic storm;  $\sigma_{\text{TEC}}$ ;  $\delta\text{TEC}$

## 25 1 Introduction

The equatorial ionosphere is the site of numerous plasma instabilities after sunset, the most well-known being equatorial Spread-F or Equatorial Plasma Bubbles (EPBs). These electron-depleted structures, linked to the Rayleigh-Taylor instability developing at the base of the ionospheric F layer, cause rapid fluctuations in total electron content (TEC) and severely degrade the performance of GNSS systems and HF communications (Kintner et al., 2007; Basu et al., 2001). The dynamics



30 of these irregularities are strongly controlled by equatorial electric fields and the vertical  $E \times B$  drift, which is particularly sensitive to geomagnetic conditions.

The variability of the equatorial ionosphere during geomagnetic storm periods constitutes a major scientific and technological challenge due to its impact on satellite navigation systems (GNSS) and radio communications. Equatorial ionospheric irregularities such as Equatorial Plasma Bubbles are strongly modulated by equatorial electric fields, which are themselves influenced by the electrodynamic processes associated with geomagnetic storms, notably the Prompt Penetration Electric Field (PPEF) and the disturbance dynamo (Blanc & Richmond, 1980; Scherliess & Fejer, 1997; Fejer et al., 2008).  
35 However, these two mechanisms can produce opposite effects on F-layer dynamics and on the generation of ionospheric irregularities, making the equatorial ionospheric response complex and still insufficiently understood, particularly at night.

This problem is even more pronounced in the African sector due to the low density of the observation network (Yizengaw et al., 2013; Amory-Mazaudier et al., 2017). However, work carried out at Niamey (Ouattara & Fleury, 2011) and at African equatorial latitudes during solar cycle 24 (Jimoh et al., 2020) has demonstrated strong nocturnal TEC variability during disturbed periods, without systematically characterising the PPEF and disturbance Dynamo signatures. Furthermore, Yizengaw et al. (2013) showed that the magnetic declination of the African sector confers specific behaviour on the African equatorial electrojet, potentially modulating PPEF transmission differently compared to the American or Asian sectors  
45 (Abdu et al., 2009; Nishioka et al., 2008).

In this context, it appears necessary to quantitatively analyse the nocturnal TEC variability in the West African sector to better understand the equatorial ionospheric response to geomagnetic storms and identify the geophysical conditions favourable either to the generation or to the suppression of ionospheric irregularities. The GPS station of Koudougou ( $12^{\circ}15'N$ ,  $2^{\circ}20'W$ , Burkina Faso), located near the African magnetic equator and under the direct influence of the equatorial electrojet, offers a geophysically particularly suitable position for studying the consequences of these electrodynamic processes. The present study therefore analyses the nocturnal GPS-TEC variability during three SSC geomagnetic storms of solar cycle 24 (22 June 2015, 14 July 2012 and 8 October 2013). The nocturnal TEC standard deviation ( $\sigma_{TEC}$ ) is used as a proxy indicator of equatorial ionospheric irregularities, an approach already used in several previous studies (Ouattara & Fleury, 2011; Jimoh et al., 2020) and adapted to the temporal resolution of the data.  
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55 The objective of this work is to characterise the nocturnal TEC response at Koudougou during geomagnetic storms, identify the dominant signature mechanism (PPEF and disturbance Dynamo) during an SSC geomagnetic storm, and to explain the physical factors likely to account for the differences in behaviour observed between these events.

## 2 Data and methodology

### 2.1 GPS-TEC data

60 The vertical total electron content (VTEC) data come from the GPS receiver at Koudougou (dip:  $+8.24^{\circ}$ ), installed in December 2008 within the framework of the International Heliophysical Year (IHY) with the support of ENST-Bretagne.



This station is part of the equatorial SCINDA network. It provides data in RINEX format processed to estimate VTEC with a temporal resolution of 1 hour. VTEC is expressed in TECU (1 TECU =  $10^{16}$  electrons/m<sup>2</sup>). Koudougou is in West Africa at geographic coordinates 12°15'N, 2°20'W. Its magnetic latitude, calculated with the IGRF-13 model, is approximately 2°N, placing it in the immediate vicinity of the foot of the northern crest of the equatorial ionisation anomaly (EIA). The station is under the direct influence of the African equatorial electrojet, conferring on this position a high sensitivity to variations in the equatorial vertical E×B drift.

## 2.2 Geomagnetic indices and solar wind

The geomagnetic indices Dst, Kp and SYM-H, as well as solar wind parameters including the Bz component of the interplanetary magnetic field (IMF), are obtained from the NASA Goddard Space Flight Center high-resolution OMNI database (<https://omniweb.gsfc.nasa.gov>). These parameters are used to characterise the geomagnetic and interplanetary conditions associated with the studied events, identify the phases of geomagnetic storms, and analyse the electrodynamic mechanisms responsible for ionospheric disturbances, in particular the PPEF and the disturbance dynamo. The geomagnetically quiet days used for constructing the reference TEC were selected from the International Service of Geomagnetic Indices (ISGI) database based on the criterion  $Kp < 2$ .

## 2.3 Storm selection

Two classifications are used in this work to interpret the geomagnetic and interplanetary conditions associated with the studied events. The first concerns the classification of geomagnetic storm intensity based on the SYM-H index according to the criteria of Loewe and Prölss (1997). The second concerns the classification of the IMF Bz component intensity according to Gonzalez et al. (1994), which allows evaluation of the magnetosphere-ionosphere coupling efficiency and the expected intensity of the PPEF.

Table 1: Classification of the SYM-H index according to Loewe & Prölss (1997) criteria

Storm class	SYM-H
Weak	$-30 \geq \text{SYM-H} > -50$
Moderate	$-50 \geq \text{SYM-H} > -100$
Intense	$-100 \geq \text{SYM-H} > -200$
Very intense	$\text{SYM-H} \leq -200$

Table 2: Classification of southward IMF Bz intensity. <sup>1</sup> After Gonzalez et al. (1994). <sup>2</sup> Ionospheric implications after Fejer et al. (2008) and Scherliess & Fejer (1997)."

Bz (nT)	Intensity <sup>1</sup>	Minimum duration	Ionospheric implication <sup>2</sup>
0 to -5 nT	Weak	-	Limited magnetosphere-ionosphere coupling



-5 to -10 nT	Moderate	$\geq 3$ hours	Observable prompt penetration electric field (PPEF)
-10 to -20 nT	Strong	$\geq 2$ hours	Intense PPEF, positive TEC phase likely
< -20 nT	Very strong	$\geq 2$ hours	Extreme PPEF, intense geomagnetic storm

In this work, three geomagnetic storms were selected based on precise criteria: (1) availability of continuous TEC data over a period including 24 hours before the SSC and 48 hours after it; (2) triggering characterised by an SSC; (3) minimum storm intensity defined by a Dst index drop below -40 nT. Based on these criteria, the following solar cycle 24 storms were selected: 22 June 2015, 14 July 2012 and 8 October 2013.

#### 2.4 Reference TEC and $\delta$ TEC perturbation

For each storm, an hourly reference TEC,  $TEC\_Q(h)$ , is calculated to isolate the variations induced by the geomagnetic event from the quiet background conditions. This reference TEC is calculated from the median of the five quietest days of the month in which the storm occurred:

$$TEC\_Q(h) = \text{Median} [TEC(h, j-5), \dots, TEC(h, j-1)] \quad (1)$$

The quiet days retained for each storm are: 22 June 2015: 2, 3, 4, 5 and 6 June 2015; 14 July 2012: 13, 18, 19, 26 and 27 July 2012; 8 October 2013: 19, 20, 21, 24 and 25 October 2013. The relative TEC perturbation  $\delta$ TEC(h,t) is then calculated hour by hour:

$$\delta TEC(h,t) = [TEC\_D(h,t) - TEC\_Q(h)] / TEC\_Q(h) \times 100 \quad (2)$$

A value  $\delta$ TEC(h,t) > +20% indicates a positive phase (electron enhancement, typically associated with the PPEF), while  $\delta$ TEC(h,t) < -20% indicates a negative phase (depletion, associated with the disturbance Dynamo or atmospheric composition changes [O/N<sub>2</sub>]). These thresholds are consistent with those used in the literature for nocturnal TEC studies during disturbed periods (Balan et al., 2010; Jimoh et al., 2020).

#### 2.5 Nocturnal variability index $\sigma\_TEC$

In this study, the main indicator of equatorial ionospheric irregularities is the nocturnal TEC standard deviation ( $\sigma\_TEC$ ), calculated over the nocturnal window 20:00–05:00 LT, corresponding to 10 hourly values (N = 10). This indicator quantifies the rapid TEC variability during the night, which is directly linked to the presence of irregularities such as Equatorial Plasma Bubbles. The standard deviation is calculated according to the classical sample formula:

$$\sigma\_TEC = \sqrt{\{ (1/(N-1)) \times \Sigma [TEC\_D(h_i) - \overline{TEC\_night}]^2 \}} \quad (3)$$

The following standard thresholds are adopted for result interpretation:  $\sigma\_TEC < 2$  TECU: quiet night (stable ionosphere);  $2 \leq \sigma\_TEC < 5$  TECU: moderate irregularities (increased ionospheric activity);  $\sigma\_TEC \geq 5$  TECU: intense irregularities (significant ionospheric disturbances).



## 2.6 Superposed Epoch Analysis (SEA)

To identify the typical nocturnal TEC responses to geomagnetic storms, this study uses Superposed Epoch Analysis (SEA).

115 This method aligns all events on a common temporal axis  $T$ , where  $T = 0$  corresponds to the exact SSC time. At each time step  $T$ , the median of the relative TEC perturbations ( $\delta\text{TEC}$ ) is calculated for the three studied storms:

$$\langle \delta\text{TEC} \rangle(T) = \text{median} \{ \delta\text{TEC}_i(T), i = 1, 2, 3 \} \quad (4)$$

The 25th and 75th percentiles are also calculated to estimate the dispersion of responses. The analysis window extends from  $T = -24\text{h}$  to  $T = +48\text{h}$ , capturing the background ionospheric state, the immediate PPEF effects and the delayed responses

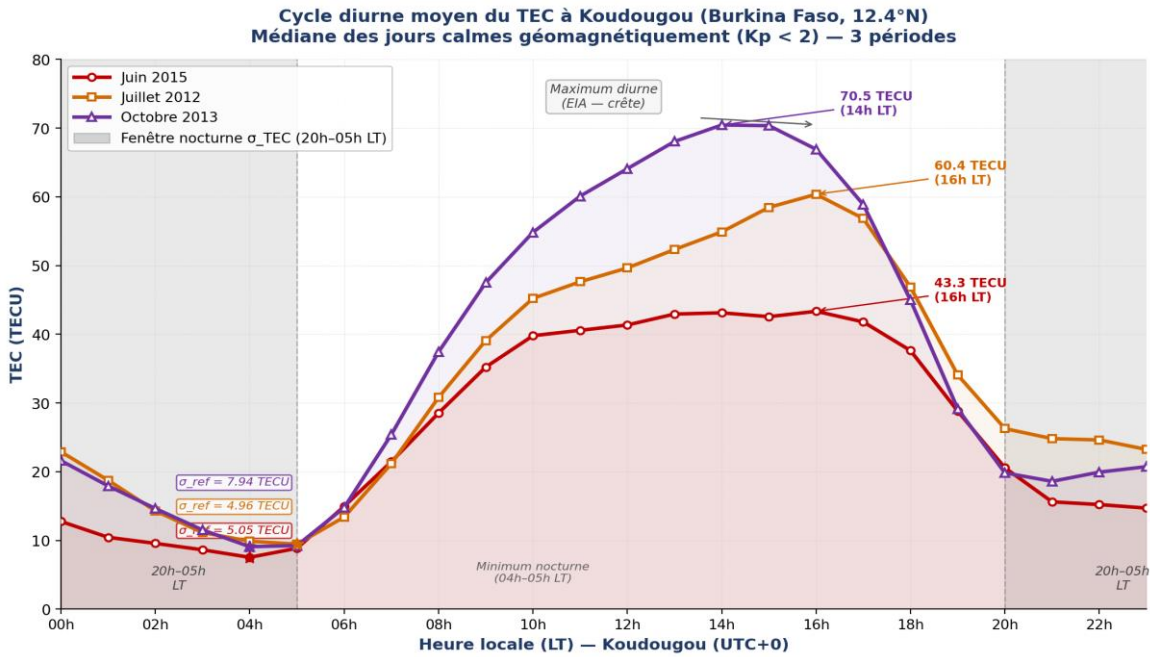
120 associated with the disturbance dynamo.

## 3 Results

### 3.1 Quiet TEC analysis at Koudougou GPS station

Before analysing TEC during disturbed periods, it is crucial to first study TEC under quiet conditions in order to establish a baseline reference that accounts for natural diurnal, nocturnal and seasonal variability. Analysis of Figures 1 and 2  
125 characterises the daily and nocturnal TEC variability under quiet conditions ( $K_p < 2$ ) for the three studied periods: June 2015, July 2012 and October 2013.

Figure 1 shows the overall diurnal cycle and the nocturnal minimum, essential for situating TEC in its daily context. The nocturnal window (20:00–05:00 LT) is indicated in light grey, and the nocturnal TEC minimum is located around 04:00–05:00 LT. TEC reaches its diurnal maximum between 14:00 and 16:00 LT: 43.3 TECU for June 2015 (maximum at 16:00  
130 LT), 60.4 TECU for July 2012 (maximum at 16:00 LT), and 70.5 TECU for October 2013 (maximum at 14:00 LT). These maxima correspond to the period of intense photo-ionisation and reflect the influence of the northern EIA crest. The reference nocturnal variability standard deviation  $\sigma_{\text{TEC}}$ , calculated on the night preceding the SSC ( $J-1$ ), is 4.96 TECU for July 2012, 5.05 TECU for June 2015 and 7.94 TECU for October 2013, indicating that the Koudougou station presents strong nocturnal irregularity activity even during geomagnetically quiet periods.

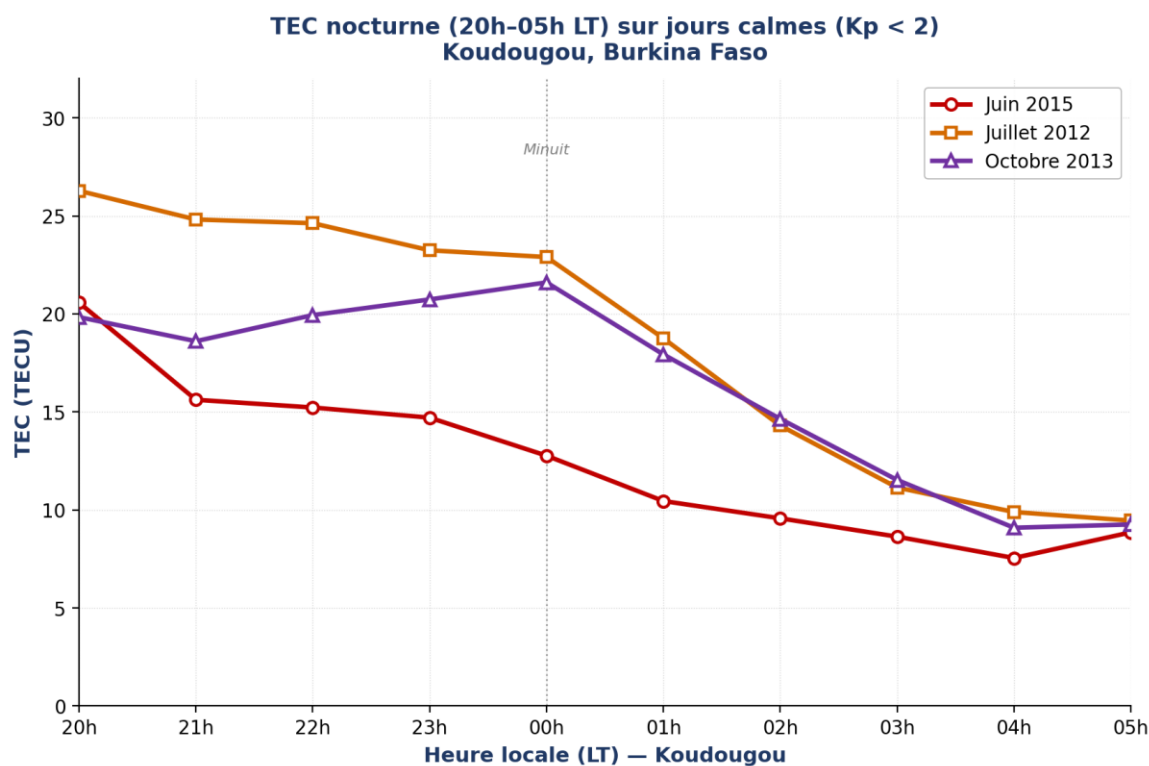


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Figure 1: Overall daily variability of quiet TEC medians at Koudougou.

Figure 2 details the hourly nocturnal TEC variability for the three quiet periods, focusing on the 20:00–05:00 LT range. Nocturnal TEC values progressively decrease from 20:00 LT towards the minimum around 04:00–05:00 LT. TEC is slightly higher for July 2012, and October 2013 compared to June 2015, indicating seasonal and possibly solar variability. These

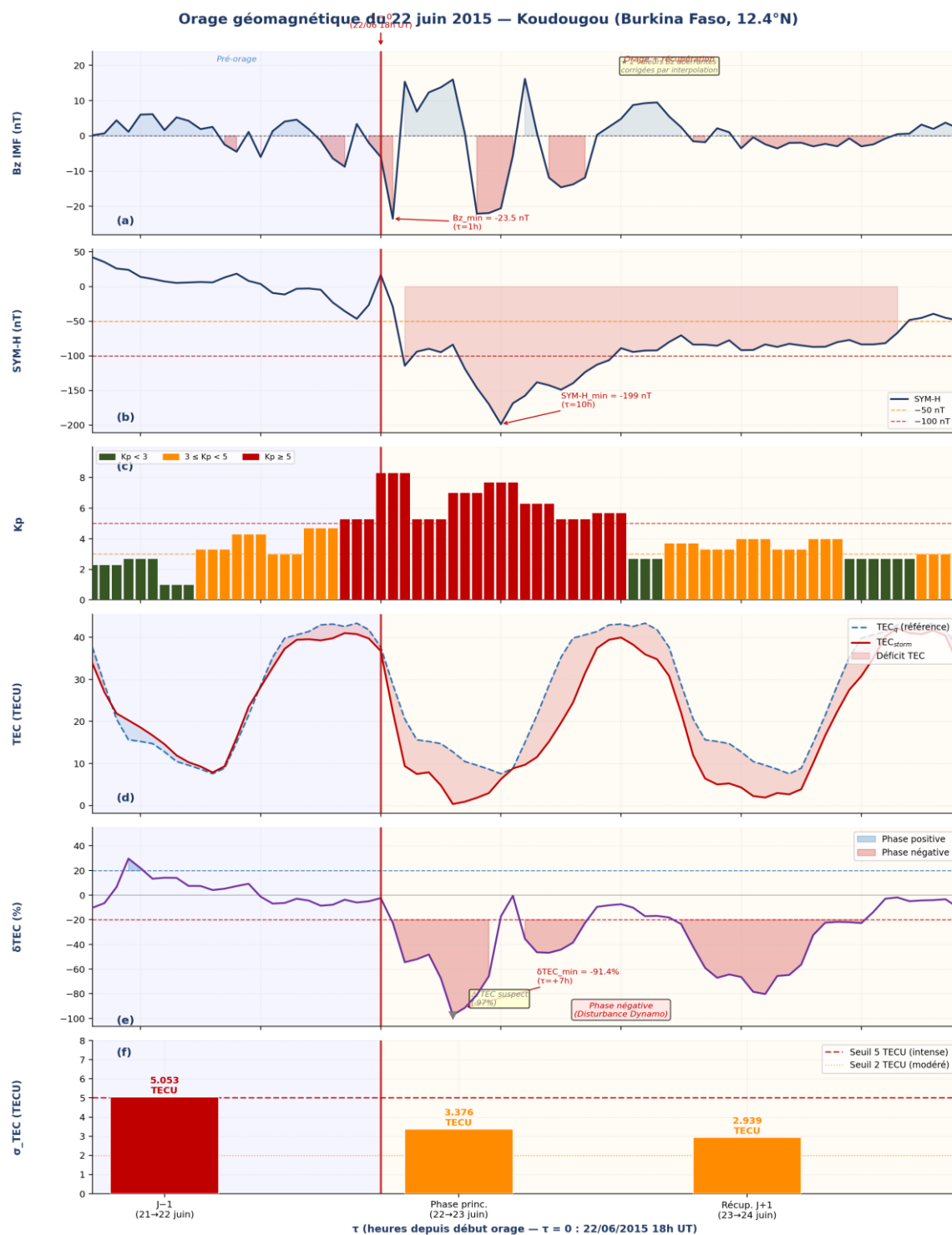
140 curves serve as quiet reference for each storm to calculate the relative perturbation  $\delta\text{TEC}$ .



**Figure 2: Nocturnal variability of quiet TEC medians at Koudougou.**

### 3.2 Storm of 22 June 2015: dominance of the negative phase

Figure 3 presents the geomagnetic parameters and TEC variability for the storm of 22 June 2015 (SSC at 18:00 UT), over the window  $T = -24h$  to  $+48h$ . Panel (a) shows a drop in  $B_z$  from the first hour ( $T = +1h$ ) with a value of  $-23.5$  nT, favouring magnetosphere-ionosphere reconnection and the triggering of a PPEF. Panel (b) shows that the SYM-H index crosses the  $-50$  nT threshold at  $T = +2h$  and reaches its minimum of  $-198.8$  nT at  $T = +10h$ , classifying this storm as very intense according to Loewe and Pröls (1997). Panel (c) confirms a  $K_p$  value of 8.3 at  $T = 0h$ , remaining  $\geq 5$  for 24 hours. Panel (e) shows a brief positive phase ( $+29.7\%$  at  $T = -21h$ ) followed by a dominant negative phase of 31 hours, with a minimum of  $-91.4\%$  at  $T = +7h$ , corresponding to the night of 22–23 June. Panel (f) presents the nocturnal  $\sigma_{TEC}$ : intense before the SSC (5.05 TECU), it becomes moderate during the SSC night (3.38 TECU) and continues decreasing after (2.94 TECU), consistent with suppression of ionospheric irregularities by the disturbance dynamo.

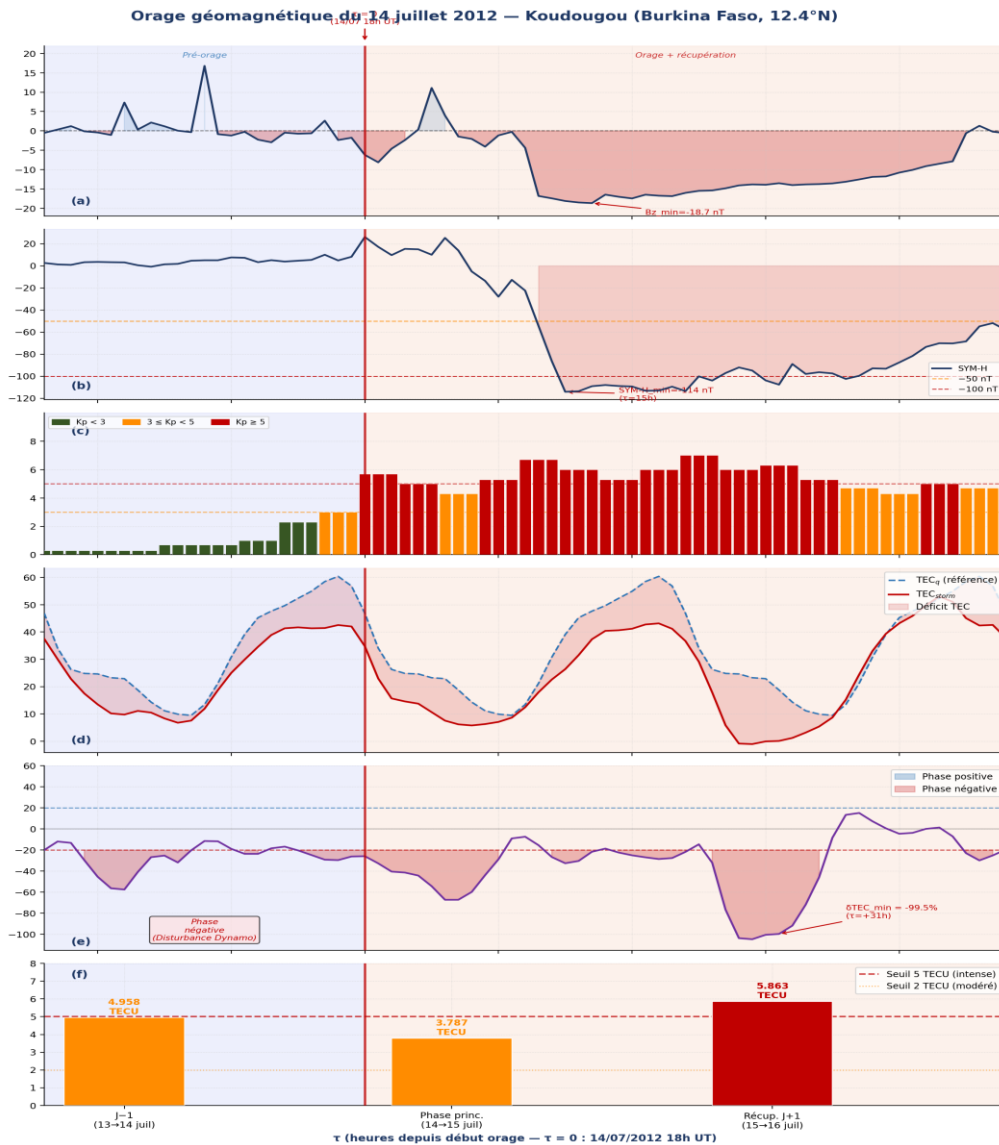


155 **Figure 3: Variability of solar wind parameters (IMF Bz component), geomagnetic indices (SYM-H, Kp) and ionospheric parameters (TEC,  $\delta TEC$ ,  $\sigma_{TEC}$ ) during the storm of 22 June 2015 at Koudougou.**



### 3.3 Storm of 14 July 2012: total suppression of the positive phase

Figure 4 presents the geomagnetic parameters and TEC variability during the storm of 14 July 2012 (SSC at 18:00 UT).  $B_z$  remains negatively dominant over the entire analysis window, with a minimum of  $-18.7$  nT.  $SYM-H$  reaches its minimum of  $-114.2$  nT at  $T = +15$ h, classifying this event as an intense storm according to Gonzalez et al. (1994).  $K_p$  maintains values between 5 and 7 for more than 30 consecutive hours. This storm is distinguished by the total absence of a positive phase:  $\delta TEC$  is negative from  $T = -21$ h and remains in the negative phase throughout the window, with a minimum of  $-99.5\%$  at  $T = +31$ h. The  $\sigma_{TEC}$  shows a slight decrease during the main phase (3.79 TECU), then a remarkable recovery to 5.86 TECU during J+1 recovery, suggesting a progressive return of the ascending  $E \times B$  drift after the weakening of the disturbance Dynamo.



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**Figure 4: Variability of solar wind parameters (IMF Bz component), geomagnetic indices (SYM-H, Kp) and ionospheric parameters (TEC,  $\delta$ TEC,  $\sigma_{TEC}$ ) during the storm of 14 July 2012 at Koudougou.**

### 3.4 Storm of 8 October 2013: dominance of the PPEF

Figure 5 presents the geomagnetic parameters and TEC variability for the storm of 8 October 2013 (SSC at 20:00 UT). Bz is moderately negative (minimum of  $-3.8$  nT at  $T = -9$ h). SYM-H reaches its minimum of  $-64$  nT at  $T = +4$ h, classifying this event as a moderate storm ( $-100$  nT  $<$  SYM-H  $\leq -50$  nT) according to Gonzalez et al. (1994). Unlike the two previous storms, storm TEC exceeds the reference over almost the entire analysis window, with a particularly marked excess between  $T = +10$ h and  $T = +40$ h. This storm is radically distinguished by a dominant and prolonged positive phase:  $\delta$ TEC is positive

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from  $T = -22\text{h}$  to  $T = +35\text{h}$ , with a maximum of  $+77.6\%$  at  $T = +31\text{h}$ . The  $\sigma_{\text{TEC}}$  is intense over all three nights: 7.94  
 175 TECU before the storm, 5.78 TECU during the main phase and 5.04 TECU during J+1 recovery, reflecting persistent intense  
 ionospheric irregularity activity, the signature of a dominant PPEF.

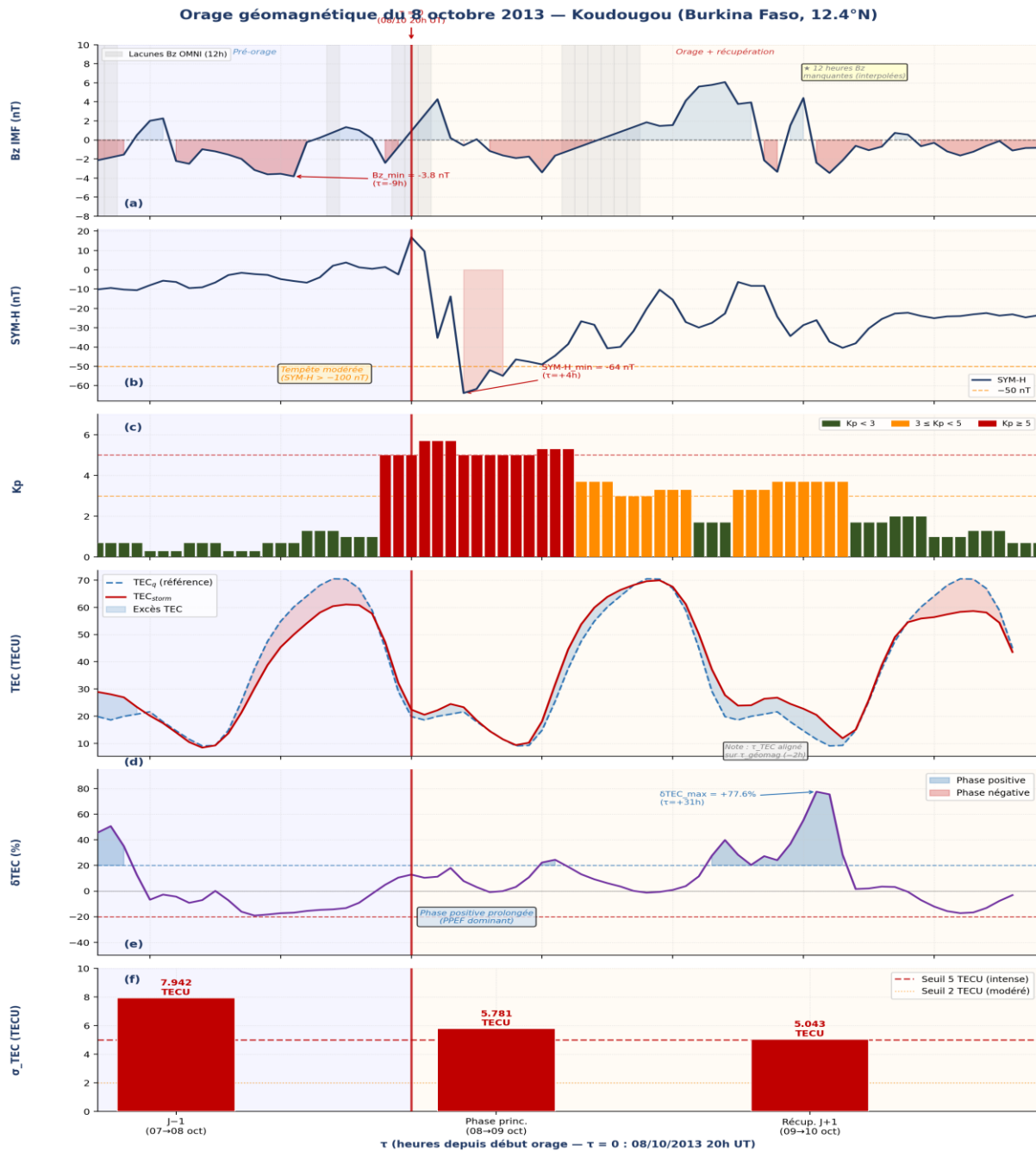


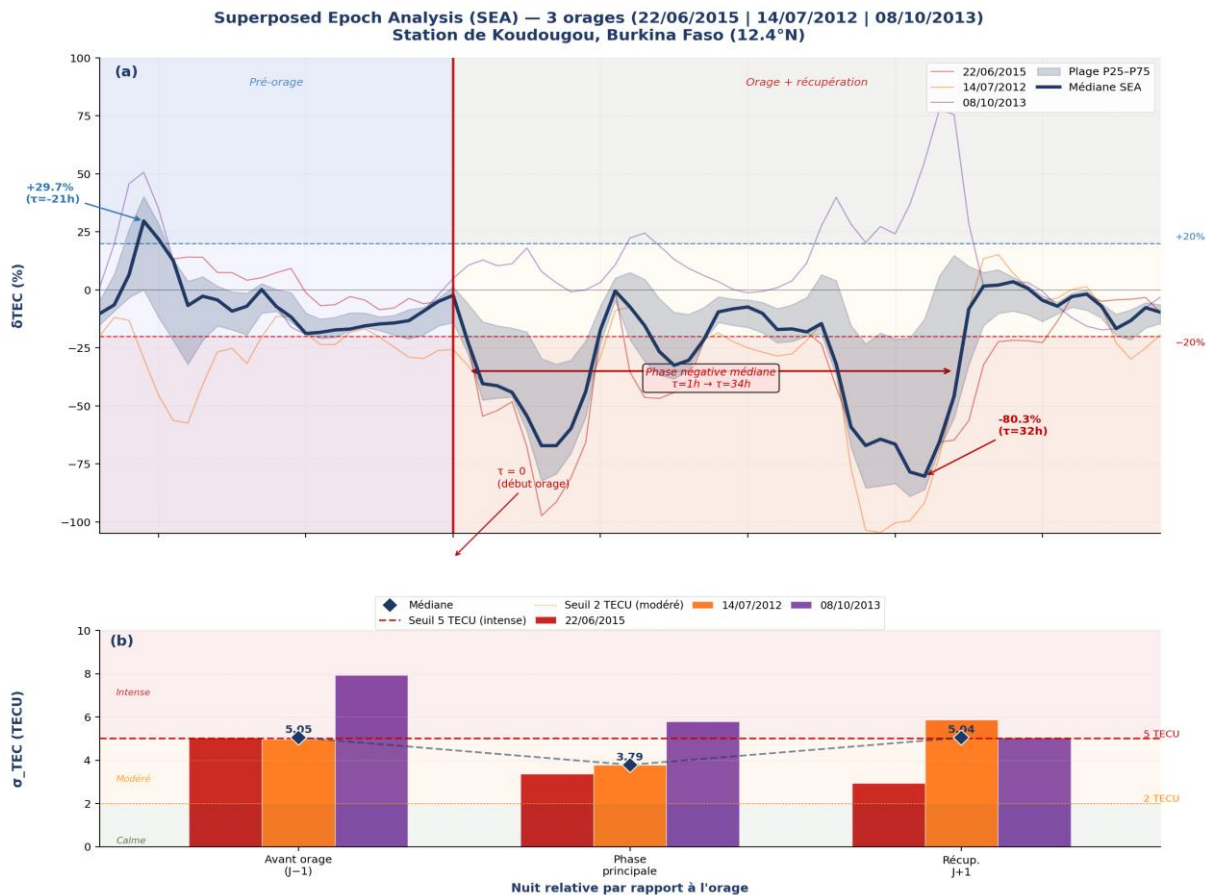
Figure 5: Variability of solar wind parameters (IMF Bz component), geomagnetic indices (SYM-H, Kp) and ionospheric parameters (TEC,  $\delta\text{TEC}$ ,  $\sigma_{\text{TEC}}$ ) during the storm of 8 October 2013 at Koudougou.



### 180 3.5 Superposed Epoch Analysis (SEA) of the three storms

Figure 6 presents the SEA results applied to the three geomagnetic storms (22/06/2015, 14/07/2012 and 08/10/2013) at the Koudougou station. Panel (a) shows the median  $\delta\text{TEC}(T)$  curve (thick black line) with the interquartile range P25–P75 (grey area) and individual curves for the three events. The median reveals a two-stage characteristic signature: a brief positive phase at  $T = -21\text{h}$  (+29.7%), mainly driven by the October 2013 storm (purple curve), followed by a median negative phase from  $T = +1\text{h}$  to  $T = +34\text{h}$ , with a median minimum of  $-80.3\%$  at  $T = +32\text{h}$ . The wide P25–P75 range reflects strong inter-event dispersion, explained by the antagonistic behaviour of the October 2013 storm (dominant positive phase) against the June 2015 and July 2012 storms (deep negative phases), confirming that the three events belong to two distinct electrodynamic regimes (PPEF vs. disturbance Dynamo). Panel (b) presents the median nocturnal  $\sigma_{\text{TEC}}$  by relative night: 5.05 TECU before the storm, 3.79 TECU during the main phase and 5.04 TECU during recovery, illustrating the transient suppression of ionospheric irregularities by the disturbance Dynamo.

190 suppression of ionospheric irregularities by the disturbance Dynamo.



**Figure 6: Results of the Superposed Epoch Analysis (SEA) of the three geomagnetic storms ( $T = -24\text{h}$  to  $+48\text{h}$ ,  $T = 0$  = start of the main phase).**



#### 4 Discussion

195 The results obtained at Koudougou contribute to the current debate on the duality between generation and suppression of equatorial ionospheric irregularities during geomagnetic storm periods, a debate already well documented in other longitude sectors but still poorly constrained over the West African sector.

The strong dominance of the negative  $\delta\text{TEC}$  phase observed during the storms of 22 June 2015 ( $-91.4\%$  over 31 hours) and 14 July 2012 ( $-99.5\%$  over 49 hours), accompanied by a decrease in  $\sigma_{\text{TEC}}$  during the main phase, is consistent with the  
200 results of Fejer et al. (2008). These authors, using ROCSAT-1 plasma drift data over the American sector, showed that the disturbance Dynamo generates a westward-directed nocturnal electric field persisting several tens of hours after the SSC during intense storms. Scherliess & Fejer (1997) established a positive correlation between the amplitude of this disturbing electric field and storm intensity ( $\text{Dst}_{\text{min}}$ ), which allows interpretation of the more marked suppression observed in June 2015 ( $\text{SYM-H}_{\text{min}} = -198.8$  nT) compared to July 2012 ( $\text{SYM-H}_{\text{min}} = -114.2$  nT). Similarly, Tulasi Ram et al. (2014)  
205 reported systematic suppression of nocturnal plasma irregularities during the recovery phases of intense storms over the Asian sector, attributed to the disturbance Dynamo mechanism. Our results thus extend these observations to the West African sector.

In contrast, the behaviour of the 8 October 2013 storm reveals a different electrodynamic regime. The prolonged positive  $\delta\text{TEC}$  phase ( $\delta\text{TEC}_{\text{max}} = +77.6\%$  over 16 hours), associated with high  $\sigma_{\text{TEC}}$  values over three consecutive nights (5.78  
210 to 7.94 TECU), presents characteristics similar to those described by Abdu et al. (2009) in Brazil, who showed that during moderate storms with nocturnal SSC, the PPEF can act in phase with the post-sunset  $E \times B$  drift, thereby promoting intensification of equatorial irregularities (EPBs). Furthermore, Nishioka et al. (2008), using a global network of GPS receivers, demonstrated that moderate storms associated with a strongly negative IMF  $B_z$  can be more effective at triggering plasma irregularities than more intense storms, in which the disturbance Dynamo effect tends to counterbalance that of the  
215 PPEF. This interpretation precisely corresponds to the difference observed between the October 2013 event (moderate storm dominated by the PPEF) and the more intense 2015 and 2012 storms (dominated by the disturbance Dynamo).

Finally, the specificity of the West African sector must be emphasised. Yizengaw et al. (2013) showed, in a comparative study between the African and American sectors, that the African equatorial electrodynamic response is characterised by greater variability, partly linked to the near-zero magnetic declination that influences equatorial electrojet efficiency.  
220 Ouattara & Fleury (2011), using GPS-TEC data at Niamey, demonstrated strong nocturnal TEC variability under disturbed conditions without explicitly distinguishing PPEF and disturbance Dynamo regimes. Our study provides a complementary contribution by proposing a quantitative characterisation of these two regimes using the nocturnal  $\sigma_{\text{TEC}}$  and  $\delta\text{TEC}$  parameters.



## 5 Conclusion

225 This study has presented a quantitative analysis of nocturnal GPS-TEC variability at Koudougou (Burkina Faso, 12°15'N) during three SSC geomagnetic storms of solar cycle 24, using the nocturnal standard deviation  $\sigma_{\text{TEC}}$  and the relative perturbation  $\delta\text{TEC}$  (%) as indicators. The study reveals the PPEF / disturbance Dynamo duality: the storms of 22 June 2015 (SYM-H<sub>min</sub> = -198.8 nT) and 14 July 2012 (SYM-H<sub>min</sub> = -114.2 nT) are dominated by the disturbance Dynamo (dominant negative phase and  $\sigma_{\text{TEC}}$  moderate to reduced during the main phase); the storm of 8 October 2013 (SYM-  
230 H<sub>min</sub> = -63.8 nT) is dominated by the PPEF (16 hours in positive phase,  $\delta\text{TEC}$  = +77.6%, intense  $\sigma_{\text{TEC}}$  over three nights). The SEA reveals across the three events a brief median positive phase (T = -21h to -20h, +29.7%), followed by a prolonged median negative phase (T = +1h to +34h, minimum -80.3%), illustrating the temporal succession of PPEF and disturbance Dynamo.

## Code and data availability

235 GPS-TEC data come from the SCINDA network. Geomagnetic indices and solar wind parameters are available from the OMNI database (<https://omniweb.gsfc.nasa.gov>). [Complete according to the journal data availability policy]

## Author contributions

The authors used Claude (Anthropic, version Sonnet) as an AI-assisted tool for language editing, figure generation (Python/matplotlib) and bibliographic suggestions. All scientific data, analyses, interpretations and conclusions are the sole  
240 responsibility of the authors, who reviewed and validated all AI-assisted content.

## Competing interests

The authors declare that they have no conflict of interest.

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