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Solar events and seasonal variation of foF2 at Korhogo station from 1992 to 2002

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In this paper we report the effect of solar events (CMEs and solar winds) on foF2 diurnal profiles at Korhogo Station (Long 8.427° W; Lat: 9.336° N; dip: -1.88°) from 1992 to 2002. We reviewed on seasons and all the four geomagnetic activity classes (Quiet activity, recurrent activity, Shock activity, and Fluctuating activity). The results show that (1) Coronal Mass Ejections (CMEs) and high-speed solar winds affect trough around midday on foF2 profiles during winter and spring when fluctuating solar winds have no effect on this characteristic. (2) In autumn, CMEs and solar winds do not affect the nighttime peak, but in winter CMEs, high-stream solar winds and fluctuating solar winds affect this characteristic of foF2 profile. In spring, only storms generated by CMEs and fluctuating solar winds have an effect on the nighttime peak. (3) Most of the time, the ionospheric storms observed at Korhogo station are positive storms and the CMEs always cause stronger positive storms compared to the solar winds effects. We assume that, these storms are mainly related to the combination of the phenomena of rapid penetration eastward electric and equatorward neutral winds during daytime but at nighttime they are mainly related to neutral winds alone.

Key words: Geomagnetic activity, trough, peak, positive storm, negative storm.

INTRODUCTION

A geomagnetic storm is an intense and temporal disturbance of the Earth's magnetosphere caused mainly by solar events such as solar winds and Coronal Mass Ejections (CMEs). These disturbances induce currents in the magnetosphere and the ionosphere which provoke transient variation of the Earth's magnetic field known as geomagnetic activity (Simon and Legrand, 1989). This phenomenon is one of the indirect consequences of solar winds - magnetosphere and Coronal Mass Ejections (CMEs) - magnetosphere interactions. Many authors (Simon and Legrand, 1989; Richardson and Cane, 2000; Richardson et al., 2002; Ouattara F, 2009; Zerbo et al., 2012; Zerbo et al., 2013) have reported on the geomagnetic activity divided into four classes according to solar events: (1) quiet activity caused by slow solar wind coming from solar

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heliosheet; (2) recurrent activity due to high speed solar wind coming from solar coronal hole; (3) shock activity provoked by Coronal Mass Ejections (CMEs) and (4) fluctuating activity due to wind stream coming from the fluctuation of solar heliosheet. Recent works have investigated on the effects of solar activity on the critical frequency foF2 profiles in equatorial regions. Ouattara and Zerbo (2011) analysed the effect of solar events on foF2 and hmF2 variations at Ouagadougou Station and showed that severe storms induce equinoctial anomaly in foF2, shock activity causes vernal equinoctial asymmetry in foF2, and fluctuating wind streams produce autumnal equinoctial asymmetry in foF2 and vernal equinoctial asymmetry in hmF2. Ouattara and Amory-Mazaudier (2012) found that at Ouagadougou Station (Lat: 12.4°N; long: 358.5°E; dip: 1.43°), shock and recurrent activities tend to enhance or diminish the morning or afternoon maximum of the F2 layer critical frequency. In more recent investigations, Hussein et al. (2014) have studied the impact of CMEs on foF2 at Puerto Rico (Long. - 67.2°; Lat. 18.5°) and Eglin AFB (Long. -86.7°; Lat. 30.4) stations during the period 1996-2013 and found that the energetic, massive and fast CMEs can affect foF2 more efficiently. Gyébré et al. (2018) found that shock activity only produces positive storms during solar maximum and decreasing phases at Ouagadougou Station. Sawadogo et al. (2018) found that at this station, recurrent activity produces at daytime positive storm for all solar cycle phases. In the present paper, we focus our investigation on the impact of geomagnetic activity on foF2 seasonal variations at Korhogo Station (Long 8.427° W; Lat: 9.336° N; dip: -1.88°) during the period 1992-2002, in order to learn more about the effect of solar events (CMEs and solar winds) on foF2 diurnal profiles at equatorial latitudes and then contribute to the improvement of model used to predict ionospheric parameters data.

DATA AND METHODS

In this study, we use foF2 data recorded at Korhogo Station (Long 8.427° W; Lat: 9.336° N; dip: -1.88°) in Ivory Coast (RCI) and provided by Brest Télécom (France) to analyze the impact of geomagnetic activity on foF2 seasonal variations.

Seasons are classified as follows: winter (December, January and February); spring (March, April, May); summer (June, July, August) and autumn (September, October and November).

Solar events are investigated through geomagnetic activity classified by Simon and Legrand (1989), Ouattara and Amory-Mazaudier (2009) using a pixel diagram. A pixel diagram is a table displaying geomagnetic index aa as a function of solar rotation (~27 days). Figure 1 is an example of pixel diagram for the year 1994. In this figure, circles correspond to the dates of sudden storm commencement (SSC) and values are the daily average of aa values. According to the criteria fixed by Simon and Legrand (1989) we have four classes: (1) quiet activity is given by the days of index Aa < 20 nT (white and blue colors), (2) recurrent activity is given by the days with index Aa ≥ 40 nT on at least one Bartel's rotation without magnetic storm (ssc); (3) shock activity days correspond to the dates of SSCs where Aa ≥ 40 nT during one, two or three days; (4) fluctuating activity corresponds to all days not included in the other three previous classes.

In this paper, we present two analyses: (1) qualitative analysis and (2) quantitative analysis. The qualitative analysis consists on a morphological comparison between the foF2 seasonal profiles during quiet activity and those of the other geomagnetic activities (recurrent, shock, and fluctuating) in order to point out possible effects of geomagnetic activity on foF2 profiles. Then, we compare the mean values of foF2 during quiet geomagnetic conditions with those during active solar events (fluctuating, recurrent and shock days) in order to identify the effect of geomagnetic activity on foF2 seasonal variations. If the hourly mean values of foF2 during storms time are greater/less than those of the quiet time, then a positive/negative storm was reported (Buonsanto, 1999; Zhao et al., 2005; Tsurutani et al., 2004). For this we use the error bars placed on foF2 profiles. Error bars are obtained by the relation:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \bar{X})^2} \tag{1}$$

Where X and $\bar{X}$ are respectively value and mean value of foF2; N is the total number of available data. Quantitative analysis permits determination of the storm strength. For this, we use according to Vijaya et al. (2011) and Sawadogo et al. (2018), the storm time deviation ΔX, defined as follow:

$$\Delta X = X1 - X2 \tag{2}$$

Where $X1$, $X2$ are the hourly values of foF2 respectively during storm time and quiet time. ΔX denotes the storm time deviation of foF2. According to these authors, the storm strength is the maximum positive value of ΔX for the positive storm and the maximum negative value of ΔX for the negative storm.

The relationship between the local time and the universal time is given by the expression (3)

$$\mathrm{LT} = UT + \frac{\varphi}{15}\dots \tag{3}$$

Where LT, UT and ψ are respectively local time, universal time and longitude.

Our study covers the period from 1992 to 2002. This period corresponds to the data available at the Korhogo Station (Long 8.427° W; Lat: 9.336° N; dip: -1.88°).

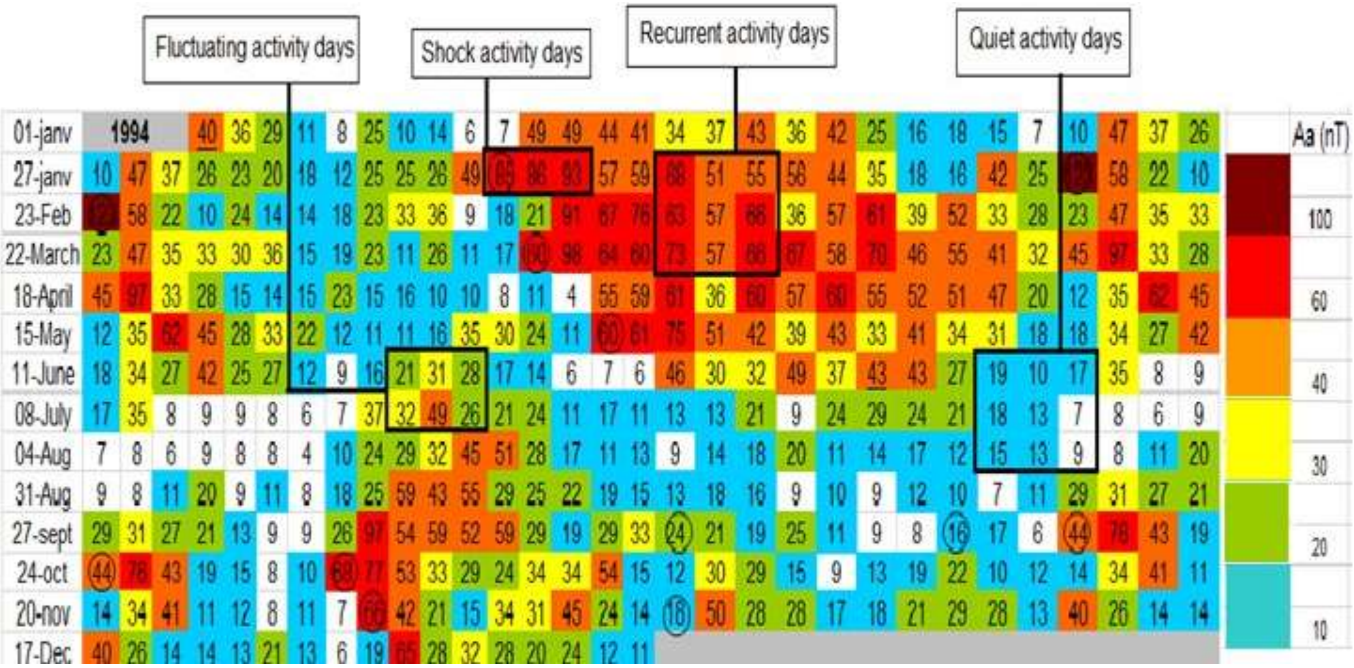
RESULTS AND DISCUSSION

Occurrence of geomagnetic class of activities

Table 1 gives the number of days corresponding to the manifestation of each type of geomagnetic activity between 1992 and 2002 per seasons. We note that the period is characterized by a predominance of quiet activity (1780 days) and fluctuating activity (991 days). This observation, which is in agreement with Zerbo et al. (2012), indicates a less intense solar activity during the period 1992-2002.

foF2 seasonal variations and geomagnetic activity signature

Figure 2a to d are respectively devoted to foF2 variations



01-janv	1994			40	36	29	11	8	25	10	14	6	7	49	49	44	41	34	37	43	36	42	25	16	18	15	7	10	47	37	26
27-janv	10	47	37	26	23	20	18	12	25	25	26	49	85	86	83	57	59	88	51	55	56	44	35	18	16	42	25	[illegible]	58	22	10
23-Feb	[illegible]	58	22	10	24	14	14	18	23	33	36	9	18	21	91	87	76	83	57	88	36	57	61	39	52	33	28	23	47	35	33
22-March	23	47	35	33	30	36	15	19	23	11	26	11	17	(100)	98	84	80	73	57	88	87	58	70	46	55	41	32	45	97	33	28
18-April	45	97	33	28	15	14	15	23	15	16	10	10	8	11	4	55	59	61	36	60	57	68	55	52	51	47	20	12	35	62	45
15-May	12	35	62	45	28	33	22	12	11	11	16	35	30	24	11	(60)	61	75	51	42	39	43	33	41	34	31	18	18	34	27	42
11-June	18	34	27	42	25	27	12	9	16	21	31	28	17	14	6	7	6	46	30	32	49	37	43	43	27	19	10	17	35	8	9
08-July	17	35	8	9	9	8	6	7	37	32	49	26	21	24	11	17	11	13	13	21	9	24	29	24	21	18	13	7	8	6	9
04-Aug	7	8	6	9	8	8	4	10	24	29	32	45	51	28	17	11	13	9	14	18	20	11	14	17	12	15	13	9	8	11	20
31-Aug	9	8	11	20	9	11	8	18	25	59	43	55	29	25	22	19	15	13	18	16	9	10	9	12	10	7	11	29	31	27	21
27-sept	29	31	27	21	13	9	9	26	97	54	59	52	59	29	19	29	33	㉔	21	19	25	11	9	8	⑯	17	6	㊹	78	43	19
24-oct	㊹	78	43	19	15	8	10	(68)	77	53	33	29	24	34	34	54	15	12	30	29	15	9	13	19	22	10	12	14	34	41	11
20-nov	14	34	41	11	12	8	11	7	(66)	42	21	15	34	31	45	24	14	⑱	50	28	28	17	18	21	29	28	13	40	26	14	14
17-Dec	40	26	14	14	13	21	13	6	19	65	28	32	28	20	24	12	11														

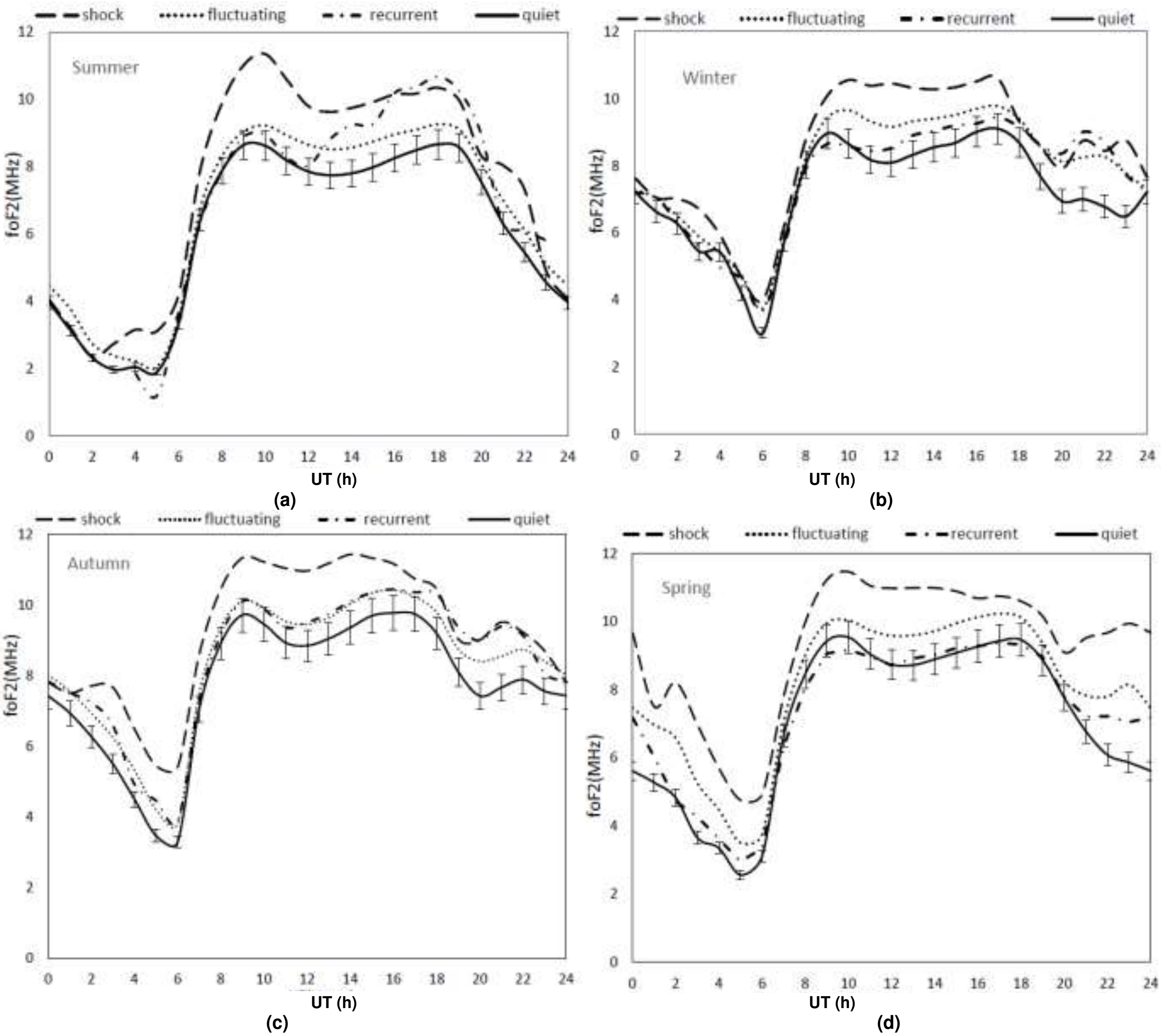
Figure 1. Example of pixel diagram showing quiet, recurrent, fluctuating and shock activities for year 1994.

Table 1. Number of days per seasons for each geomagnetic activity.

Season	Quiet days	Fluctuating days	Shock days	Recurrent days
Autumn	419	273	40	24
Summer	515	202	7	5
Winter	452	235	21	14
Spring	394	281	24	37

in summer, winter, autumn and spring respectively. One can observe that all profiles present trough around midday except in winter (Figure 2b) and spring (Figure 2d) where during shock activity the profiles do not exhibit this characteristic. Moreover, during these seasons, the midday trough is less pronounced during recurrent activity compared to quiet day. These observations show that coronal mass ejections (shock activity) and high-speed solar winds (recurrent activity) affect the midday trough on foF2 diurnal profiles during winter and spring. However, fluctuating solar winds (fluctuating activity) have no effect on this characteristic of the foF2 diurnal profiles. These observations extend those made by Ouattara and Amory-Mazaudier (2012) on seasonal variations of foF2 in equatorial regions. According to Fejer, (1981) and Farley et al. (1986), trough on the foF2 profile around midday expresses the signature of the vertical E×B drift. Thus, from previous observations we can hypothesize that in winter and spring, CMEs and high-speed solar winds have an influence on the EXB drift whereas fluctuating solar winds have no effect on this phenomenon.

At nighttime, there is no night peak in foF2 profiles during summer (Figure 2a) in opposite to autumn profiles (Figure 2c). During winter (Figure 2b), disturbed activities (shock, recurrent and fluctuating) profiles present night peak (2000-2300 UT). In spring (Figure 2d) nighttime peak appears only during shock and fluctuating activities. The observations showed that (1) in autumn, solar events (CMEs and solar winds) do not affect nighttime peak on foF2 diurnal profiles; (2) in winter, the magnetic storm generated by all solar events (CMEs, high-speed winds and fluctuating solar wind) affects nighttime peak; (3) in spring, only storm generated by CMEs and fluctuating solar wind affect this characteristic of foF2 diurnal profiles. Considering that nighttime peak on foF2 profiles expresses the signature of reversal of zonal electric field in equatorial latitude (Farley et al., 1986; Scherliess and Fejer, 1997; Vincent, 1998) and taking into account the origin of geomagnetic activities defined by Simon and Legrand (1989), we suggest that in the autumn, CMEs, high-speed solar



(a) (b) (c) (d)

Figure 2. foF2 profiles in a) summer, b) winter, c) autumn and d) spring during the manifestation of all geomagnetic activities.

winds and fluctuating solar winds might not have an effect on reversal of zonal electric field at evening. But during winter the solar events could affect this phenomenon. In spring, only CMEs and fluctuating solar winds might affect the reversal of zonal electric field at evening.

Analysis with error bars shows the daytime positive storms ($foF2_{shock}$ > $foF2_{quiet}$) during shock activity at all seasons (Figures 2a to d). During recurrent activity, the daytime positive storm ($foF2_{recurrent}$ > $foF2_{quiet}$) appears only in summer (Figure 2) between 1200 and 1900 UT. But in the other seasons, the daytime ionization during recurrent activity is 5% closed to that of quiet activity, reflecting the absence of an ionospheric storm. During fluctuating activity, at daytime, there are the positive storms ($foF2_{fluctuating}$ > $foF2_{quiet}$) in summer (Figure 2a) and spring (Figure 2d). But during autumn (Figure 2c) and winter (Figure 2b), ionization is not affected at daytime (0800-1900 UT). At nighttime (2000-0000 UT), error bars show that ionization is most important during perturbed activities compared to quiet activities for all seasons (Figures 2a to d). The negative storms are only observed in summer between 0400-0600 UT during recurrent activity. Then, using the error bars, we can assume that the majority of ionospheric storms observed at the Korhogo Station during geomagnetic storms are

Table 2. ΔX values during days and night through different geomagnetic activities.

Season	Period	Geomagnetic activities		
		Fluctuating	Recurrent	Shock
Autumn	Daytime	0.79	2	2.72
	Nighttime	0.69	1.67	1.87
Summer	Daytime	1.14	0.57	2.35
	Nighttime	1.49	2	2.26
Winter	Daytime	0.67	1.12	2.13
	Nighttime	0.98	1.72	2.16
Spring	Daytime	0.87	0.39	2.26
	Nighttime	1.84	1.55	4.05

positive storms. This result is in agreement with Adeniyi (1986) and Mikhailov et al. (1994).

Table 2 gives the maximum positive value of ΔX. Based on the values of ΔX (Table 2), which are always higher during shock activity compared to those of the other geomagnetic activities, it appears that during all seasons, the positive storms are always stronger during shock activity than during the recurrent activity ($\Delta X_{-shock} > \Delta X_{-recurrent}$) and fluctuating activity ($\Delta X_{-shock} > \Delta X_{-fluctuating}$). As the shock activity is related to the shock waves caused by coronal mass ejections (CMEs) and the other disturbed activities are related to solar winds (Simon and Legrand, 1989), our results indicate that at the considered station, the ionospheric disturbances due to CMEs are more intense than those caused by solar winds for the period covered by our investigations.

The values in Table 2 also show that for all seasons except summer, positive storms are stronger at nighttime than daytime ($\Delta X_{strom\text{-}nighttime} > \Delta X_{strom\text{-}daytime}$) during fluctuating and recurrent activities. During shock activity, this trend is observed in autumn and spring. ΔX values in summer indicate that positive storms are stronger during daytime than nighttime for all activities. According to Balan et al. (2009), the direct effects of storm-time equatorward neutral wind can be the main driver of positive ionospheric storms at low-mid latitude. These authors also indicate that the equatorward wind without the penetrating eastward electric field (PEEF) can result in stronger positive ionospheric storms than with PEEF. With this previous investigation and our comparison between $\Delta X_{strom\text{-}nighttime}$ and $\Delta X_{strom\text{-}daytime}$ (Table 2), it can be assumed that, in general, at the considered station, the positive storms observed during the geomagnetic storms are mainly related to the combination of the equatorward neutral wind and the PEEF at daytime and related to the equatorial neutral wind also at nighttime.

Conclusion

We have outlined some ideas about the seasonal signature of solar events on foF2 variations at Korhogo ionosonde station:

i) CMEs and solar wind affect midday trough on foF2 diurnal profiles in winter and spring. But the fluctuating solar winds have no significant effect on this characteristic during all seasons.

ii) In autumn, CMEs and solar winds do not affect the nighttime peak on foF2 diurnal profiles. But in winter, the magnetic storm generated by all solar events (CMEs, high-speed winds and fluctuating solar wind) seems to favor the appearance of night peaks on foF2 profiles. In spring, only storms generated by CMEs and fluctuating solar wind have an effect on this phenomenon.

iii) Most of the time, the ionospheric storms observed at Korhogo Station are positive and the CMEs always cause stronger positive storms than the solar winds. We think that these storms are mainly related to the combination of the phenomena of rapid penetration of eastward electric field and equatorward neutral wind during the daytime but at nighttime they are mainly related to neutral winds.

CONFLICT OF INTERESTS

The authors have not declared any conflicts of interests.

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