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Variability of the electric field of magnetospheric convection in recurrent activity during the solar cycle 24

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This paper employs a statistical approach to investigate the diurnal variability of the magnetospheric convective electric field (MCEF) during recurrent activity, considering the phases of solar cycle 24. This study reveals that the magnetosphere exhibits greater dynamism during the maximum and descending phases on recurrent days. The diurnal variability of the MCEF on days of recurrent geomagnetic activity indicates the following trends: (a) An increasing trend followed by a decreasing trend at the phase minimum of the solar cycle; (b) A decreasing trend followed by an increasing trend during the ascending phase and the phase maximum, and (c) five trends during the descending phase. From the minimum phase of the solar cycle to the falling phase, the daily mean values of the MCEF are 0.07428018, 0.10682778, 0.14172194, and 0.11505584 mV/m, respectively. Night-time magnetic reconnections with a southern interplanetary magnetic field (IMF) occur at the phase maximum of the solar cycle and during all-phase periods. Daytime magnetic reconnections occur during the ascending phase at 0700 UT and during the descending phase at 1000 UT.

Key words: Magnetospheric convection electric field, recurrent activity, phases of the solar cycle, magnetic reconnections, interplanetary magnetic field.

INTRODUCTION

The hot plasma in the solar corona is not gravitationally bound, and a stream of ionized matter, known as the solar wind, continually escapes from the solar atmosphere (Parker, 1959). There are two types of solar wind: the slow solar wind and the fast solar wind. Fast solar winds originate from coronal holes and have speeds in excess of 450 km/s, up to 1,000 km/s. These fast solar wind regimes tend to recur over periods of 27 days, linked to the solar rotation of the large-scale magnetic field. This phenomenon is the source of recurrent geomagnetic storms. Slow solar winds come from other regions of the solar corona, particularly from structures called large jets, and have maximum speeds estimated at 450 km/s. Solar winds continually escape in all directions

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from the surface of the Sun, bathing the entire solar system.

As it approaches the Earth, the solar wind, which is low-density, collisionless, magnetized plasma, interacts with the Earth's magnetic field, distorting it and confining it to a cavity in the solar wind. This cavity, created by the interaction between the solar wind and the Earth's magnetic field (Chapman and Ferraro, 1931), was named the Earth's magnetosphere by Gold (1959). The part of the magnetosphere directly exposed to the solar wind (solar direction or day side) prevents the flow of ionized matter from entering the Earth's environment and can only be compressed. As a result, the magnetopause, the region where the magnetosphere meets interplanetary space, is only 7 to 10 times the Earth's radius. On the other hand, the anti-solar part of the magnetosphere located in the Earth's shadow (night side) does not receive the solar wind head-on and can stretch into a long tail to a distance of around 100 times the Earth's radius (Ness, 1965). It is important to remember that the Earth's magnetosphere forms a veritable shield against the charged energetic particles of the devastating solar wind, which, if not slowed down by a shock wave upstream of the magnetosphere and deflected by the geomagnetic field, would diffuse freely towards the Earth.

Based on several essential facts, such as the contribution of shock waves to the geomagnetic activity now known as shock activity, the values of the geomagnetic activity index established by Mayaud (1968, 1971, 1972), the dates of the Sudden Storm Commencement (SSC), and the correlation between the values of the aa index and the solar wind (Svalgaard, 1977), Legrand and Simon (1989) studied and classified geomagnetic activity into four classes: calm day activity, shock day activity, recurrent day activity, and fluctuating day activity. Quiet-day activity is caused by the slow solar winds coming from the heliosheet and blowing continuously past the magnetosphere. Recurrent activity is caused by fast solar winds originating from coronal holes and shows an uninterrupted evolution over several Bartel rotations. Shock activity is caused by coronal mass ejections accompanied by fast solar winds. Fluctuating activity is caused by fluctuating winds (moderate and fast) due to the fluctuation of the neutral plate. The fast solar winds cause disturbances in the geomagnetic field known as recurrent activity (Legrand and Simon, 1989; Zerbo et al., 2012; Richardson and Cane, 2002).

The interaction between the solar wind and the magnetosphere can occur either through viscosity or through reconnection between the lines of the two magnetic fields. It is essential to note that the most advanced theory explaining the solar wind-magnetosphere interaction process was proposed by Dungey (1961), involving reconnection between the interplanetary magnetic field (IMF) lines, oriented either north or south, and the terrestrial magnetic field lines, naturally north-oriented. A small portion of the solar electric field is frozen in the solar wind. During the coupling of the solar wind and the magnetosphere, a fraction of the Ey component of this field is transmitted to the terrestrial magnetosphere (Revah and Bauer, 1982; Wu et al., 1981). This field, transmitted to the magnetosphere, has a general direction from dawn to dusk and is known as the magnetospheric convection electric field (MCEF), responsible for magnetospheric convection, the transport of the plasma sheet from the tail of the magnetosphere towards the Earth.

The magnetosphere is a dynamic region that never seems to reach a state of equilibrium. Its dynamics are strongly influenced by the parameters of the solar wind and geomagnetic activity. Therefore, it undergoes continuous variations in the thrust of the solar wind and its magnetism, along with a series of internal processes that destabilize it, causing sudden, almost daily reconfigurations (Mottez, 2018).

This study conducts a statistical analysis of the variability of the MCEF intensity during periods of recurrent activity, considering the phases of solar cycle 24. This analysis is performed in reference to the phenomena of reconnection between geomagnetic and interplanetary field lines. The objective is to contribute to a better understanding of the dynamics of the magnetosphere in general, and specifically during periods of recurrent geomagnetic activity.

DATA AND METHODOLOGY

Determination of recurring days

For this study, days during which the Earth was under the influence of fast solar winds (responsible for recurrent activity) were selected using the criteria defined by Zerbo et al. (2012) and taking into account the speed of the solar wind. Data from eleven-pixel diagrams constructed from geomagnetic data taken from the ISGI website were used. Recurrent days are days with a daily mean value of Aa>20 nT repeated over at least two Bartels rotations. A condition on the daily mean speed: V>450 km/s was also imposed.

Figure 1 shows the pixel diagram for 2008, illustrating three groups of recurring activity days: (a) group 1: 16 y to 19 January; 12 to 15 February; 10 to 13 March; and 6 to 9 April; (b) group 2: 28 February to 01 March; 26 to 28 March and (c) group 3: 15 to 17 April; 12 to 14 July.

Determining the different phases of the solar cycle

To determine the different phases of solar cycle 24, the values of the solar index Rz and adopting the criteria defined by Ouattara and Amory Mazaudier (2009) and used by Guibula et al. (2019), Sandwidi et al. (2020), Kaboré et al. (2021) and Gyébré et al. (2022) were used. According to this method, the different phases of the solar cycle are defined as follows: (a) minimum phase: number of sunspots Rz less than 20 ($Rz < 20$); (b) ascending phase: number of sunspots between 20 and 100 ($20 \leq Rz \leq 100$); (c) maximum phase: number of sunspots greater than 100 ($Rz > 100$); and (d) descending phase: number of sunspots between 100 and 20 ($100 \geq Rz \geq 20$). It is important to note that the values of the solar index Rz used to determine the solar phases can be accessed via the Omniweb site, whose URL is http://omniweb.gsfc.nasa.gov/. The different phases of the solar cycle 24 thus identified by

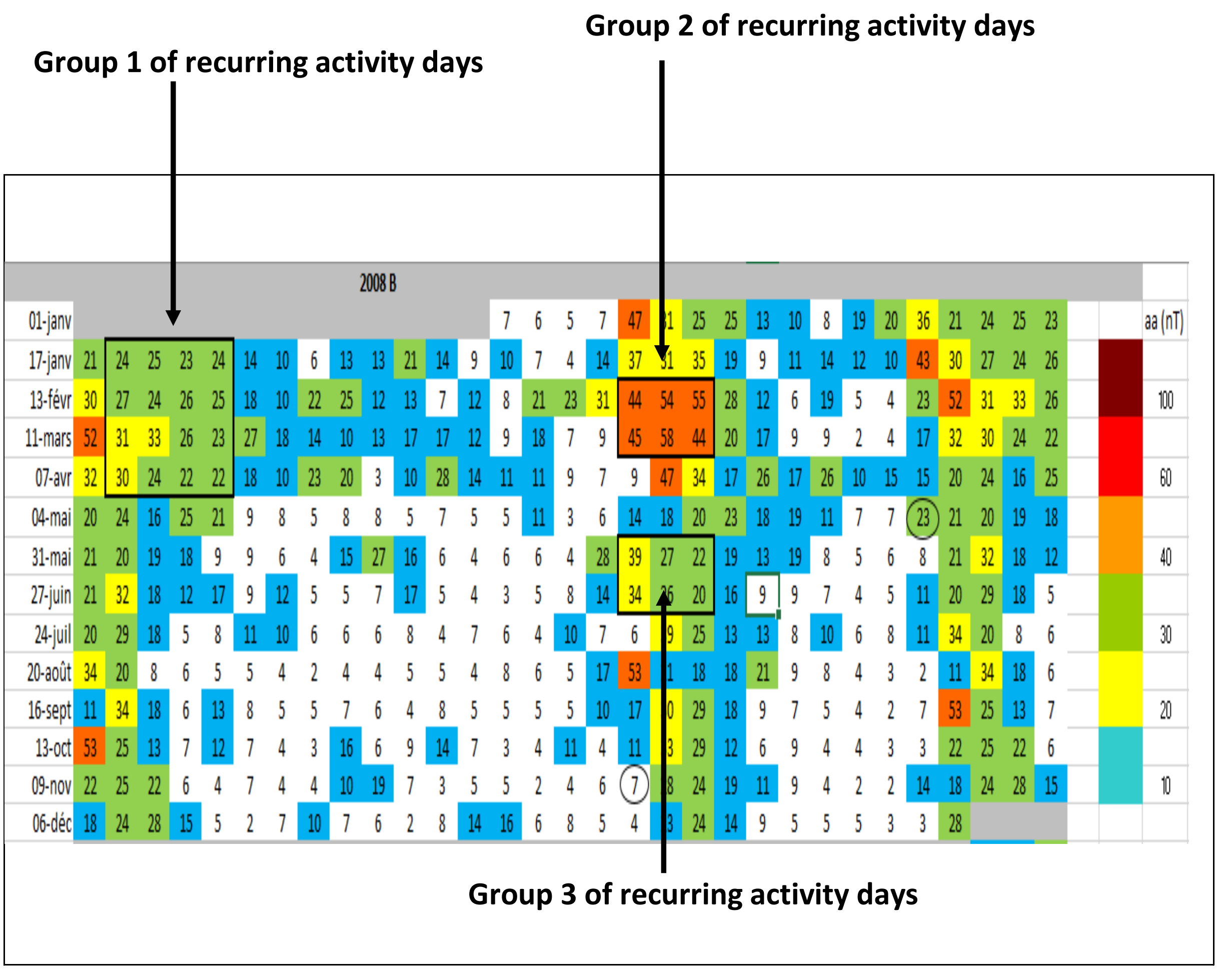

Figure 1. Pixel diagram of the year 2008, showing a few days of recurring geomagnetic activity.

Table 1. Breakdown of the solar cycle by year.

Phase	Minimum	Ascending	Maximum	Descending
Years	2008-2009	2010-2011	2012-2014	2015-2018

applying the aforementioned criteria are shown in Table 1.

Determination of the MCEF

The period of investigation into the variability of the MCEF on days of recurrent geomagnetic activity covers solar cycle 24, an 11-year cycle that began in 2008 and ended in 2018. As data from *in situ* measurements of the magnetospheric convection electric field were not available, the correlation relationship between the Ey component of the electric field frozen in the solar wind and the magnetospheric convection electric field E_M were used. This relationship was established by Wu et al. (1981) and validated by Revah and Bauer (1982):

$$E_M = 0.13E_y + 0.09$$

with a correlation coefficient of 0.97. It is important to point out that the data for the Ey component (mV/m) of the electric field frozen in the solar wind, a fraction of which is transmitted to the magnetosphere during the solar wind-magnetosphere interaction that was used in this article, are available on the OMNIWEB website http://omniweb.gsfc.nasa.gov/form/dx1.html.

RESULTS AND DISCUSSION

Diurnal variability of the MCEF without phase distinction

Figure 2 shows the hourly mean variability of the MCEF over all the recurrent days, without distinction of phase. The curve shows four trends: two decreasing trends observed from 0000 to 0300 UT and from 1200 to 1800

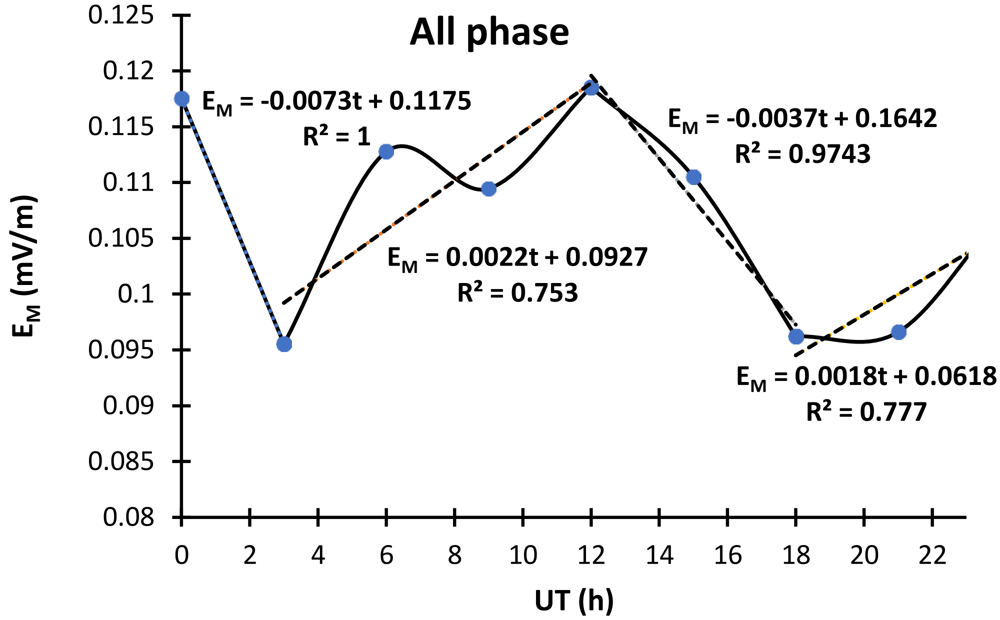

Figure 2. MCEF variability regardless of solar cycle phase.

UT and two increasing trends observed from 0300 to 1200 UT, and from 1800 and 2400 UT.

The decreasing trends observed during the night and the following night indicates a weakening of the convection. This weakening could be explained by a change in direction of the Bz component of the IMF from south to north. According to Dungey (1961), when the IMF is directed northwards, the interplanetary magnetic field lines and the geomagnetic field lines are parallel and any reconnection in the front of the magnetosphere is impossible. The energy accumulated inside the magnetosphere dissipates (Kelley et al., 1979). This dissipation of energy and matter leads to a decrease in the MCEF, reflecting a reduction in magnetospheric convection. It is important to note that this interpretation corroborates those of Kaboré et al. (2019) and Kelley (2012), for whom magnetospheric convection weakens when the MFI tilts from south to north.

The two observed increasing phases indicate a rise in the MCEF. These phases result from the tilting of the IMF from the South-North direction to the North-South direction. According to Kelley et al. (1979), this change in direction influences magnetospheric convection. The periods of increased hourly mean values of MCEF intensity could thus be attributed to a reconnection between the southward IMF lines and those of the Earth's magnetic field. Paulo et al. (2019) have noted that a north-south orientation of the IMF favors magnetic reconnection, leading to an intensification of the magnetospheric electric field. Similar results have been reported by several authors (Siqueira et al., 2011; Kaboré and Ouattara, 2018; Inza et al., 2022).

Additionally, Nishimura et al. (2009) and Poudel et al. (2019) have demonstrated that MCEF is sensitive to changes in the direction of the Bz component of the IMF. Furthermore, other studies (Kelley et al., 1979; Nishimura et al., 2009; Partamies et al., 2011; Kabore et al., 2019; Inza et al., 2022) have observed that reconnection with a southern IMF is associated with an increase in MCEF. Consequently, the two increasing phases symbolize the maintenance of the IMF in a southerly direction, promoting night-time reconnections at 0400 and 1800 UT, explaining the observed rise in MCEF values.

It is crucial to highlight that night-time reconnection aligns with Dungey's (1961) reconnection theory, wherein magnetic field lines open on the day side and close again on the night side at the second neutral point. This process results in the accumulation of energy in the magnetospheric tail, causing trapped particles to move towards the Earth. This explains the increase in magnetospheric convection and, consequently, the rise in the mean values of the electric field responsible for it.

According to Kaboré and Ouattara (2018), on days of shock activity caused by geoeffective ICMEs, the hourly mean value of the MCEF varies between a minimum value of 0.137 mV/m and a maximum value of 0.217 mV/m. However, on days of recurrent activity, the hourly mean MCEF value ranged from a minimum of 0.095534848 mV/m to a maximum of 0.118527778 mV/m. A comparison with earlier study by Kaboré and Ouattara (2018) shows that the hourly mean values of the MCEF on days of recurrent activity are lower than those for shock activity. This would be explained by lower values of the frozen electric field in the solar wind during

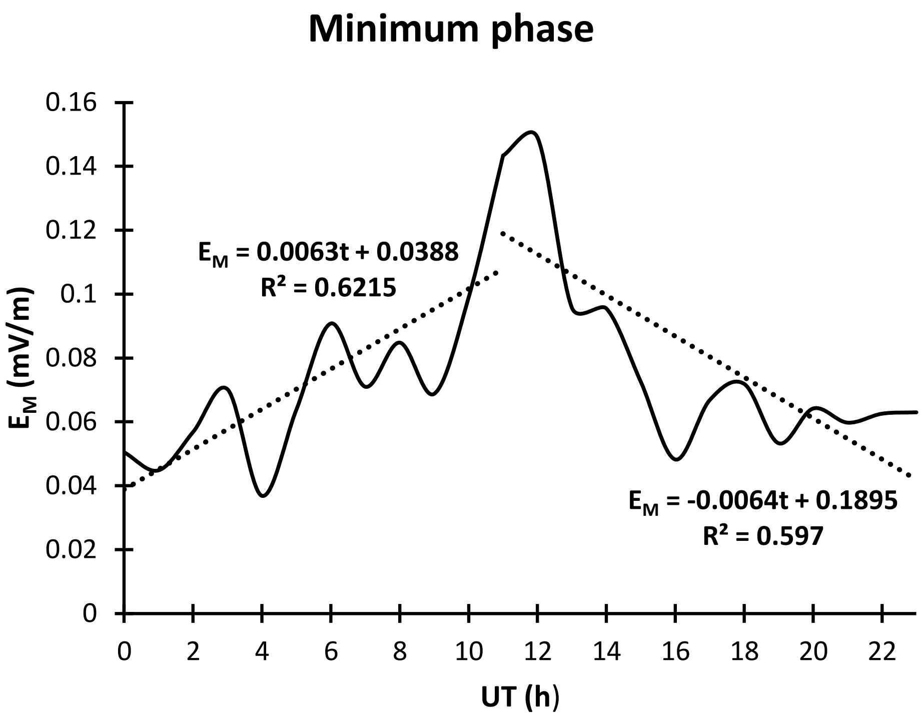

Figure 3. Variability of the MCEF during the phase minimum of the solar cycle 24.

periods of recurrent activity and shows that the intensity of the magnetospheric disturbance is dependent on the solar source responsible for the geomagnetic activity. So compared with days of shock activity during days of recurrent activity, the Earth's magnetosphere is less disturbed.

Diurnal variability of the MCEF during the phase minimum of the solar cycle

Figure 3 shows the day/night variability of the MCEF during the minimum of solar cycle 24. During the phase minimum of solar cycle 24, the MCEF shows two trends: an increasing trend observed from 0000 UT to 1200 UT, at which point it reaches a maximum value of 0.149 mV/m, and a decreasing trend after 1200 UT. The lowest MCEF intensity value of 0.036 mV/m was recorded at 0400 UT. After 1800 UT, the field remained relatively stable until 2400 UT. The hourly mean intensity of the electric field responsible for magnetospheric convection therefore increases until 1200 UT. This increase therefore corresponds to a phase characterized by a southerly direction of the north-south component of the interplanetary magnetic field frozen in the solar wind. Twelve hours Universal Time (1200 UT) is the time at which magnetospheric convection begins to weaken. This weakening of magnetospheric convection continues until 2400 UT. Between 1200 and 1800 UT, the energy that entered the magnetosphere during reconnection on the day side is dissipated. From 1800 to 2400 UT, there are slight variations in MCEF values: during periods of recurrent geomagnetic activity, at the phase minimum of the solar cycle between 1800 and 2400 UT, the magnetosphere appears to be in a stable state of convection, albeit with sporadic increases. Previous studies such as those by Kabore and Ouattara (2018) have shown that during the solar minimum in periods of shock activity, the MCEF was characterised by an increase after 1200 UT. The opposite was observed during days of recurrent activity. This finding suggests that the dynamics of the magnetosphere depend on the solar sources responsible for geomagnetic activities.

Diurnal variability of the MCEF during the ascending phase of the solar cycle

Figure 4 shows the day/night variability of the MCEF during the ascending phase of solar cycle 24. During the rising phase, the convection electric field shows two trends: a decreasing phase between 0000 UT and 0700 UT, at which time it reaches its minimum of 0.016 mV/m, and an increasing phase between 0700 UT and 2300 UT. The maximum value reached is 0.16 mV/m. This shows an increase in magnetospheric convection from 0700 UT. This increase in the hourly mean intensity of the MCEF is the consequence of a reconnection of the magnetosphere on the day side which occurred at 0700 UT. According to Dungey (1961), a reconnection between the Earth's

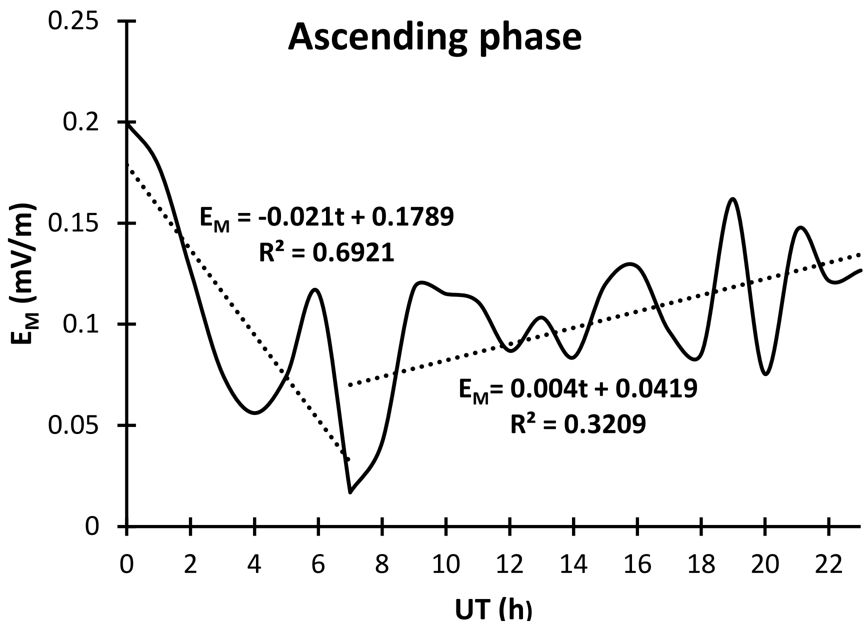

Figure 4. MCEF variability during the ascending phase of the solar cycle 24.

magnetic field lines and those of the interplanetary magnetic field with an IMF generates a strong injection of energy into the magnetosphere. This massive inflow would then explain the intensification of convection observed. The decrease in the MCEF between 0000 UT and 0700 UT could be explained by a closed magnetosphere associated with a Bz component of the IMF that is maintained in a northerly direction. Similar variability has been observed during solar minimum in periods of shock activity caused by geoeffective ICMEs (Kaboré et al., 2018); as well as during the quiet period (Kaboré et al. 2019). During days of recurrent geomagnetic activity, this type of variation was observed but during the ascending phase of the solar cycle. This would suggest that the effects of the fast solar winds responsible for recurrent activity on the magnetosphere during the ascending phase are similar to those of the slow solar winds during quiet periods and to those of the fast solar winds that accompany the ejection of geoeffective coronal masses at phase minimum.

The MCEF variability curve also shows that on days of recurrent activity, during the solar ascent phase, magnetospheric convection intensifies during the day and most of the night and gradually weakens from 0000 UT until the morning hours (0800 UT).

Diurnal variability of the MCEF during phase maximum of the solar cycle

Figure 5 shows the diurnal variability of the MCEF during phase maximum of solar cycle 24 in days of recurrent geomagnetic activity. During the maximum phase of the solar cycle, the MCEF variability curve follows two trends: (a) a generally decreasing trend observed from 0000 to 1700 UT, at which time the curve reaches its minimum with a value of about 0.0752 mV/m; (b) an increasing trend from 1700 UT onwards. The maximum value reached by the MCEF is around 0.1992 mV/m. Such an increase observed from 1700 UT could be the signature of a magnetic reconnection at the level of the lobes of the Earth's magnetosphere with the IMF, which was initially oriented north, and the geomagnetic field lines. It may also be due to a viscous interaction between the particles of the solar wind and those of the magnetopause, the region at the boundary of the magnetosphere with interplanetary space (Axford and Hines, 1961). In days of recurrent activity, at solar maximum, magnetospheric convection intensifies at night and gradually weakens during the day.

Diurnal variability of the MCEF during the waning phase of the solar cycle

Figure 6 shows the variability of the MCEF during the downward phase of the solar cycle 24. During the descending phase, the MCEF shows five trends, including three decreasing trends and two increasing trends. The decreasing trends are observed between 0000 and 0500 UT, 0700 and 1000 UT, and 1400 and 2400 UT. The two increasing trends are observed between 0500 and 0600 UT and 1000 and 1400 UT. The highest value of the hourly mean intensity of the MCEF is reached at 0600 UT and is 0.1449 mV/m and the minimum value is 0.0813 mV/m. At 1000 UT, the IMF

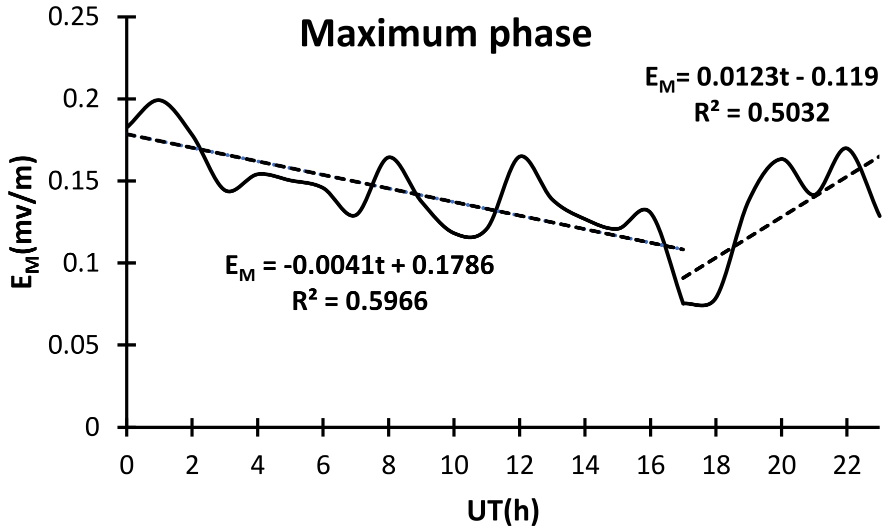

Figure 5. Variability of the MCEF during the phase maximum of the solar cycle 24.

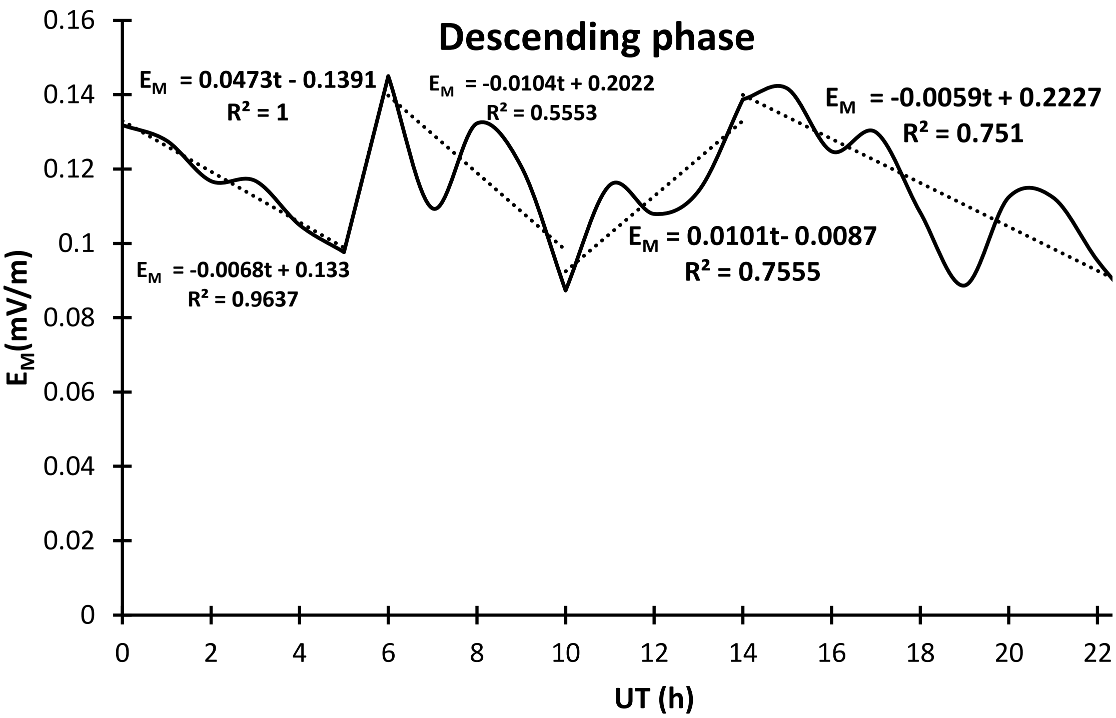

Figure 6. Variability of the MCEF during the waning phase of the solar cycle 24.

reconnects during the day and remains south-facing until 1400 UT. After 1400 UT, a weakening of the convection was noticed. This weakening of the convection can be interpreted by an absence of magnetic reconnections both at night and in the lobes of the magnetosphere. This weakening can also be interpreted as the consequence of a lack of viscous interaction between particles in the solar wind and those in the Earth's magnetosphere (Axford and Hines, 1961).

Of the four phases of the solar cycle, the descending phase is the one with the most trends: overall, the Earth's magnetosphere is much more dynamic and recurrent activity is more marked during the descending phase than during the other three phases of the solar cycle.

It was noted that the variability of the MCEF during disturbed periods depends on the nature of the

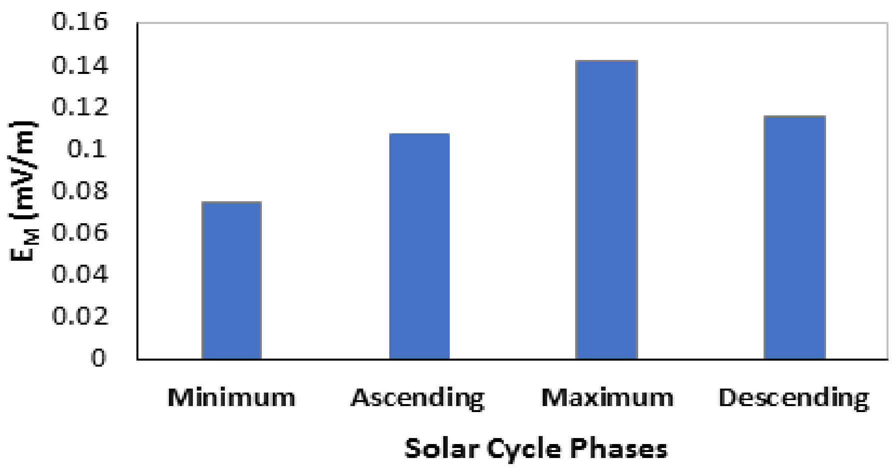

Figure 7. Histogram showing average MCEF values for each phase of the solar cycle 24.

geomagnetic activity. Indeed, a comparison with previous studies (Kaboré et al., 2019) shows that the variability of the MCEF as a function of the different phases of the solar cycle on days of recurrent activity is different from that of the MCEF on days of shock activity caused by geoeffective ICMEs. This difference is easily explained by the fact that the fast solar winds responsible for recurrent activity and the geoeffective ICMEs responsible for shock activity differ in parameters such as density, the interplanetary magnetic field and the intensity of the electric field frozen in the solar wind, but also by the dependence of their preponderance during certain solar phases on others.

Daily mean values of the MCEF during the phases of the solar cycle

Figure 7 shows the histogram of mean MCEF values during the phases of solar cycle 24 in days of recurrent geomagnetic activity. The daily mean hourly MCEF values on days of recurrent activity increase from solar minimum to phase maximum. These results show that during periods of recurrent activity the daily mean value of the MCEF varies in phase with the stained activity. However, it was noted that the daily mean value of the MCEF on days of recurrent activity during the falling phase is higher than that during the rising phase. Better still, the average MCEF values during the descending phase represented 52% of the MCEF intensity during the two phases as a whole. These results: (a) corroborate those of Gnanou et al. (2022) for whom the contribution of the mean value of the MCEF in the ascending phase represents only 48% of the mean value of the MCEF for the two phases as a whole; (b) show that the activity of magnetospheric convection is not symmetrical with respect to the sunspot cycle and (c) that the recurrent activity is more marked during the descending phase of the solar cycle than during the ascending phase. This latter observation is in line with those of Ouattara and Amory Mazaudier (2009) and Zerbo et al. (2012), for whom recurrent activity is more pronounced during the waning phase of the solar cycle. The high mean values of the MCEF observed at phase maximum on days of recurrent activity corroborate previous results such as those of Vijaya Lekshmi et al. (2011), for whom magnetic storms, which are markers of magnetospheric disturbance and therefore of disturbances on recurrent days, are more frequent at solar maximum and more intense during the waning phase.

Conclusion

This article examines the diurnal variability of the magnetospheric convection electric field as a function of the phases of solar cycle 24, particularly during periods of recurrent activity. It reveals that the daily mean value of the MCEF varies in relation to geomagnetic activity and the phase of the solar cycle. Specifically, the daily mean value of the MCEF is minimal during the minimum phase of the solar cycle and maximal during the maximum phase. This finding is significant as it suggests a strong correlation between sunspot activity and magnetospheric convection.

Furthermore, the study demonstrates that the daily mean value of the MCEF during the ascending phase differs from that during the descending phase. This result indicates that, during periods of recurrent activity, magnetospheric convection is not symmetrical with respect to sunspot activity.

The investigation also reveals that, in all-phase periods, the diurnal variability of the MCEF on recurring days exhibits four trends, starting the day with a northerly MFI and concluding with a night-time reconnection. During all-phase periods, at the phase minimum, the MFI shifts from south to north at 1200 UT, resulting in a decrease in the hourly mean values of the MCEF.

From the phase minimum to the phase maximum, the MCEF displays two trends: an increasing phase followed by a decreasing phase at the phase minimum and a decreasing phase followed by an increasing phase during the ascending phase and at the phase maximum. During the descending phase, the MCEF shows five trends, starting and ending the day with a lack of magnetic reconnection between the geomagnetic field lines and those of the MCEF.

This study highlights that, during periods of recurrent geomagnetic activity, the magnetosphere exhibits increased dynamism during the maximum and descending phases of the solar cycle.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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