

Fluctuating Geomagnetic Activity: Occurrences and Response of the Magnetospheric Convective Electric Field (MCEF) during the Solar Cycle 24

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Abstract

In this paper, we use a statistical approach to study the distribution of days of geomagnetic activity caused by the fluctuation of the Sun's neutral plate as a function of solar phases and season during solar cycle 24. We also examine the daily response of the magnetospheric convective electric field (MCEF) to the geomagnetic disturbance caused by these days of fluctuating activity. A comparison of the different responses of the MCEF to the three main classes of geomagnetic activity disturbance is also made. A study of the occurrences of fluctuating days shows that: 1) the descending phase is the most active, with an annual occurrence of 50%, followed by the maximum phase (28%), the ascending phase (19%) and finally the ascending phase (15%); 2) spring is the most active season, with an occurrence of 25.55%, followed by autumn (25.25%), summer (24.75%) and winter (24.45%). Irrespective of the phase and time of year, one day in four the Earth's magnetosphere is under the impact of the fluctuating solar winds responsible for the fluctuating geomagnetic activity. From the minimum phase of the solar cycle to the waning phase, the daily mean values of the MCEF are 0.08448182 mV/m, 0.1134496 mV/m, 0.11846218 mV/m and 0.1178042 mV/m, respectively. The average daily intensities of the MCEF are 0.116947784 mV/m in spring, 0.10854571 mV/m in summer, 0.12374118 mV/m in autumn and 0.10678156 mV/m in winter. Irrespective of solar phase and season, the average daily intensity of the MCEF on fluctuating days is 0.10854945 mV/m. A comparison of the results of this study with previous work on cycle 24 shows that of the three classes of disturbed geomagnetic activity, fluctuating geomagnetic activity is the one that

disturbs the magnetospheric convection electric field the least.

Keywords

Fluctuating Activity, Distribution, Season, Solar Cycle, Magnetospheric Convective Electric Field

1. Introduction

Geomagnetic activity is the set of rapid variations in the Earth's magnetic field. These variations are a consequence of solar activity and are an estimate of the effects of solar activity on the Earth's magnetic field. The rapid variations in the Earth's magnetic field concern the component produced by the electric currents circulating in the magnetosphere, respectively at the equator and in the auroral regions ([1]). It is important to remember that before 1989, two classes of geomagnetic activity were known: quiet geomagnetic activity and disturbed geomagnetic activity. [2] refined the class of disturbed activity and extracted three new classes. The identification of the different classes of disturbed geomagnetic activity is based on the contribution of shock waves to geomagnetic activity, now known as shock activity, the values of the geomagnetic activity index aa established by [3] [4] [5], the dates of SSCs (Sudden Storm Commencement) and the linear correlation between the values of the aa index and the solar wind ([6]). This classification leads to the distinction of four classes of geomagnetic activity: calm, recurrent, shock and fluctuating.

- Quiet activity: quiet day activity is caused by slow solar winds (<450 km/s).
- These winds originate in the heliosheet and blow continuously beyond the magnetosphere. Days of calm activity correspond to days when the daily average value of the geomagnetic index aa is less than 20 nT ($Aa < 20$ nT).
- Recurrent activity: this is caused by fast solar winds from coronal holes that exhibit an uninterrupted evolution over several Barthel rotations. Days of recurrent activity correspond to days with indices $A Aa \geq 40$ nT and extended over one or more Bartels rotations and without SSC in the main phase.
- Shock activity: this is caused by coronal mass ejections (CMEs). The days of shock activity correspond to the dates of non-recurrent SSCs (without repetition) at the start of the activity and for which the Aa indices remain above 40 nT over one, two or three days.
- Fluctuating activity: days of fluctuating activity include all days that do not fall into any of the above three categories. The source of this activity, which is the subject of this investigation, is the fluctuations observed in the flow of moderate and fast solar winds caused by the fluctuation of the Sun's neutral plate.

It is well known that the Earth's magnetosphere acts as a shield, a bulwark, preventing charged energetic particles from the Sun from penetrating the Earth's environment. However, when solar winds reach the Earth, their interaction with the

Earth's magnetosphere can cause magnetic storms ([7]), damage satellites in orbit and irradiate astronauts in their path, be dangerous for passengers on transpolar flights, cause problems for telecommunications and power grids and disrupt air traffic control ([8]).

It is important to remember that the continuous movement of the solar wind around the magnetosphere generates an electric field through the dynamo effect. This field is directed globally from the dawn side to the dusk side and is called the magnetospheric convection electric field (MCEF). This field is responsible for magnetospheric dynamics and is particularly responsible for transporting the plasma sheet from the tail of the magnetosphere (night side) towards Earth.

Previous studies have specifically addressed the diurnal temporal variation of the MCEF during quiet and shock geomagnetic activities as a function of the different solar phases ([9] [10]), and during recurrent activities ([11] [12]) during the different phases of the solar cycle.

In the present study, we investigate the occurrence of fluctuating days and their impact on the dynamics of the magnetospheric convection electric field (MCEF) as a function of solar phase and season during solar cycle 24, the last complete solar cycle for which the best data acquisition instruments have been used. The main objective of this research work is to contribute to a better understanding of the impact of geomagnetic activity on the disturbance of magnetospheric convection. For this study, Sections 2 and 3 present the data and methods used, respectively. The results and discussions are presented in Section 4. We end this manuscript with a conclusion that not only summarises all our important results, but also sets out the limitations and various perspectives of the present research.

2. Data

In this work, the following data were used:

1) daily hourly values of the E_y component [mV/m] of the solar electric field frozen in the solar wind obtained from

<https://omniweb.gsfc.nasa.gov/form/dx1.html>

2) the annual sunspot number $SN(t)$ from: <https://www.sidc.be/SILSO/datafiles>

3) the three-hourly mean values of the geomagnetic index A_a taken from:

http://isgi.unistra.fr/data_download.php

4) dates of sudden storm onset (SSC) from

http://isgi.unistra.fr/data_download.php

3. Methodology

3.1. Method for Determining Different Days of Fluctuating Geomagnetic Activities

To identify days of fluctuating activity, we first constructed pixel diagrams for 2008 to 2018 by applying the criteria defined by [13]. Pixel diagrams were established by [2], improved by [14] and used by [15]-[18] among others. From these pixel diagrams, we identify the days corresponding to quiet activity and the recur-

rent activity and shock classes. For a given year, once the days concerned by these three classes have been determined, the remaining days, *i.e.* those that do not appear in the first three classes mentioned above, are the days of fluctuating geomagnetic activity, resulting from the fluctuation of the Sun’s neutral plate ([16]). **Figure 1**, which shows the pixel diagram for 2016, illustrates examples of days with calm activity, shock activity, days with recurrent activity and a class of days with fluctuating activity (5-6 March 2016 and 2-3 April).

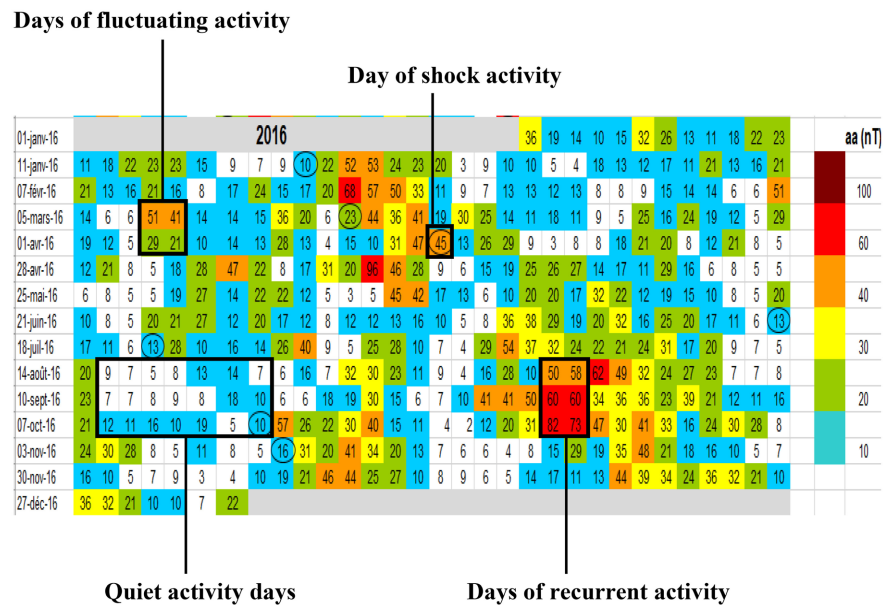


Figure 1. Pixel diagram for 2016 showing the four classes of geomagnetic activity.

3.2. Methods for Determining the Different Phases of Solar Cycles

To determine the four phases of each solar cycle, we use the sunspot number $SN(t)$ or Wolf index, and we apply the new criteria defined by [19] and used by [20]-[22]. These criteria define the different phases of the solar cycle as follows:

- 1) minimum phase: $SN(t) < 0.122 \times SN_{max}$;
- 2) ascending phase: $0.122 \times SN_{max} \leq SN(t) \leq 0.73 \times SN_{max}$;
- 3) phase maximum: $SN(t) > 0.73 \times SN_{max}$;
- 4) descending phase: $0.73 \times SN_{max} \geq SN(t) > SN_{Min}$ (following cycle).

By applying these criteria, different phases of the solar cycle 24 are identified as shown in **Table 1**.

Table 1. Illustration of the different phases of solar cycles 24 (extracted from [19]).

Cycle	Extension period	Average Duration (years)	Minimum phase	Ascending Phase	Maximum Phase	Descending Phase
24	2008-2018	11	2008-2009	2010-2011	2012-2014	2015-2018

3.3. Seasons Are Divided up

In this work, the four seasons of the year are divided as follows: spring from 1

March to 31 May (March, April and May); summer from 1 June to 31 August (June, July and August); autumn from 1 September to 30 November (September, October, November) and winter from 1 December to 28 (or 29) February (December, January and February).

3.4. Determination of the Intensity of the Magnetospheric Convection Electric Field

To determine the daily mean EM intensity (Equation (2)) of the magnetospheric convective electric field (MCEF) controlling the circulation of solar wind particles responsible for the fluctuating geomagnetic activity in the Earth's magnetosphere, we use the relationship (1) which links the daily data of the E_y component and the MCEF. This relationship was established by [23] and validated by [24]

$$\text{MCEF} = 0.13E_y + 0.09 \quad (1)$$

$$E_M = |\text{MCEF}| \quad (2)$$

4. Results and Discussion

4.1. Distribution of Fluctuating Activity as a Function of Solar Phases

Figure 2 and Figure 3 show, respectively, the percentages of fluctuating days recorded for each phase and the average annual percentages of fluctuating days for each solar phase. From 2008 to 2018, covering the period of solar cycle 24, 1002 fluctuating days were recorded, *i.e.* an average of 91 fluctuating days per year. The distribution by solar phase gives 100 days of fluctuating geomagnetic activity (10%) during the minimum phase, 125 days (12%) during the ascending phase, 277 days (28%) during the maximum phase of the solar cycle and 500 days (50%) during the descending phase. These results show that, of the four solar phases, fluctuating days are more frequent during the descending phase and less frequent during the phase minimum, and that the number of fluctuating days during the phase maximum is higher than during the ascending phase of the solar cycle 24. These observations are confirmed by an analysis based on the average annual occurrences of fluctuating days. This analysis shows that in terms of annual occurrence of fluctuating days, the descending phase was the most active (38%), followed by the maximum phase (28%), the ascending phase (19%) and finally the minimum phase (15%). In fine, the above results show that: 1) of the four solar phases, fluctuating days are more frequent in years of descending phases and less frequent in years of minimum solar activity, 2) fluctuating days are more frequent in years of solar maximum than in years of ascending phases and 3) one day in four the Earth's magnetosphere is under the impact of fluctuating solar winds responsible for fluctuating geomagnetic activity. These results show that the fluctuating activity is not uniform and varies according to the solar phase. These different results also suggest that: 1) the fluctuation of the Sun's neutral plate is more pronounced during the waning phase and less pronounced during the minimum solar activity, 2) the frequency of fluctuating activity does not strictly follow sun-

spot activity. Since sunspot activity is governed by the toroidal component of the solar magnetic field ([25]) and solar wind activity, particularly that of the fluctuating winds responsible for fluctuating geomagnetic activity, is governed by the poloidal component of the solar magnetic field ([15] [26]), fluctuating activity would then be governed both by the toroidal component of the solar field and by the open component of the solar field. Better still, the previous results suggest that the action of the closed component of the solar field is predominant on the fluctuation of the neutral blade during the descending phase and minimal during the phase of minimum solar activity.

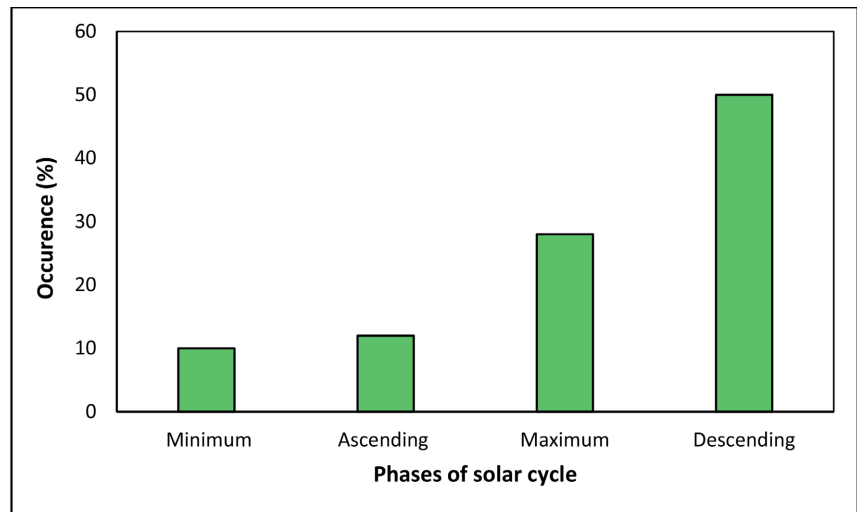


Figure 2. Percentage of fluctuating days per solar phase.

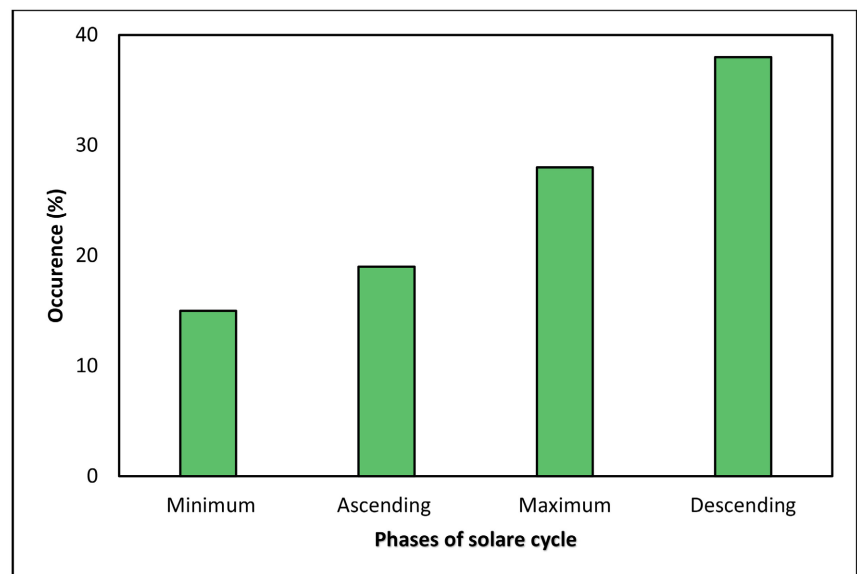


Figure 3. Annual percentage of fluctuating days per solar phase.

4.2. Distribution of Activity Fluctuates with the Seasons

The average seasonal occurrences of fluctuating days recorded are shown in **Fig-**

Figure 4. From 2008 to 2018, *i.e.* for the entire period of investigation, the numbers and percentages of fluctuating days by season are 256 (25.55%) in spring, 248 (24.75%) in summer, 253 (25.25%) in autumn and 245 (24.45%) in winter. On average, over the course of a year, the Earth's magnetosphere is disturbed by fluctuating solar winds for just over 23 days in spring, 22 days in summer, 23 days in autumn and 22 days in winter. The slight differences in the contribution of fluctuating activity by season are justified by the fact that the sunspot activity that governs fluctuating activity is not perfectly symmetrical ([22]). Thus, on the basis of occurrences, as shown in **Figure 4**, it is clear that during solar cycle 24, spring was the most active season, followed by autumn, summer and finally winter. These different results suggest that: 1) fluctuating geomagnetic activity affects the Earth's magnetosphere more effectively in spring than in autumn, then in summer and less so in winter, 2) fluctuating activity varies in phase with sunspot activity but is not symmetrical with it. It is also important to note that our results on the rates of occurrence of fluctuating days during each of the four seasons suggest that the fluctuating solar winds responsible for fluctuating geomagnetic activity disturb the magnetosphere more in spring than in summer, then in autumn and winter.

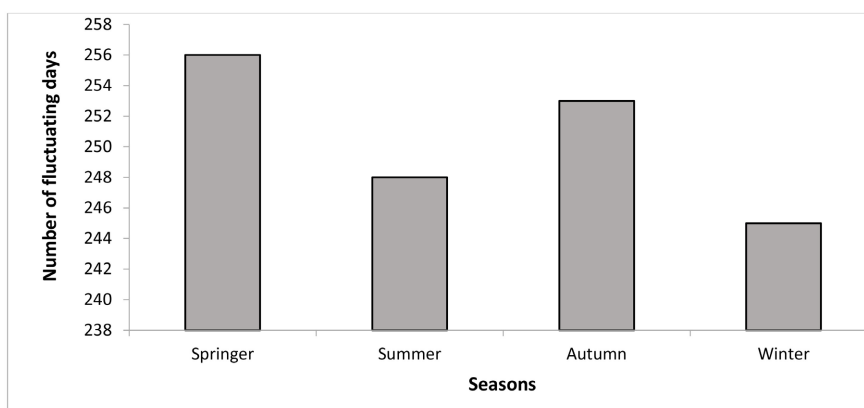


Figure 4. Number of fluctuating days per season.

4.3. Average Daily MCEF Intensities on Days That Fluctuate According to Solar Phases

Figure 5 shows the daily hourly mean values of the MCEF for each of the four phases of solar cycle 24 during a period of fluctuating geomagnetic activity. From the minimum phase of the solar cycle to the falling phase, the daily mean values of the MCEF are 0.08448182 mV/m, 0.1134496 mV/m, 0.11846218 mV/m and 0.1178042 mV/m, respectively. Analysis of this figure shows that the response of the MCEF during days of fluctuating geomagnetic activity depends on the sunspot cycle. Specifically, the daily mean hourly intensity of the MCEF is at its minimum during the minimum phase and at its maximum during the phase of maximum solar activity. The daily mean intensity of the MCEF on days of fluctuating activity during the waning phase, therefore, outweighs that during the ascending phase. The high occurrence of fluctuating solar winds in the waning phase (the frequent

disturbance of the Earth's magnetosphere by fluctuating solar winds during the waning phase) could partly explain this result. These results show that 1) fluctuating geomagnetic activity affects magnetospheric convection more effectively in the maximum phase than in the descending phase of solar activity, and then in the ascending phase than in the minimum phase of solar activity, 2) the impact of fluctuating activity on magnetospheric convection varies in phase with stained activity and is therefore governed by the toroidal component of the solar magnetic field and 3) the response of the MCEF to the fluctuating disturbance is not symmetrical with respect to stained activity.

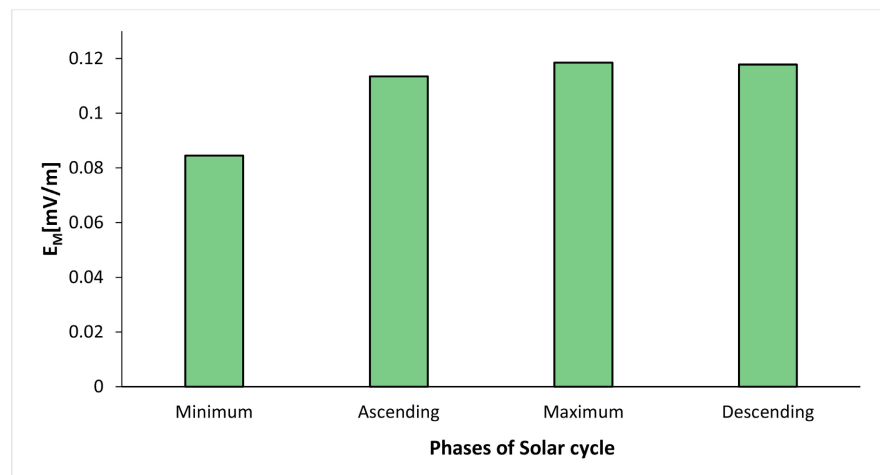


Figure 5. Average daily MCEF values on days that fluctuate according to solar phases.

The results of the present study also show that, irrespective of the phases of the solar cycle, the daily mean value of the intensity of the MCEF is 0.10854945 mV/m. Previous results such as those of [10] show that 1) the daily mean values of the MCEF intensity during periods of shock activity caused by interplanetary coronal mass ejections during the ascending, maximum and descending solar phases are 0.26399935 mV/m; 0.2961038 mV/m and 0.28652747 mV/m and 2) the intensity of the daily mean value of the MCEF during periods of shock activity and quiet activity irrespective of the phase are 0.28221020 mV/m and 0.0703175 mV/m respectively. In addition, the work of [12] have shown that 1) the daily mean values of the MCEF intensity in periods of recurrent geomagnetic activity from the phase minimum to the falling phase are respectively 0.07428018 mV/m; 0.10682778 mV/m, 0.141721944 mV/m; 0.11505584 mV/m and 2) the intensity of the daily mean value of the MCEF in periods of recurrent activity irrespective of phase is 0.1094471436 mV/m. A comparison of the results of our study with those of the previous work mentioned above shows that, of the three classes of disturbed geomagnetic activity identified by [2]: 1) fluctuating geomagnetic activity is that which generates a moderate disturbance of the magnetospheric convective electric field, while 2) shock activity is that for which the disturbance generated on the Earth's magnetosphere is the strongest, and 3) the intensity of the MCEF increases

with the geomagnetic index Aa. Thus, the Earth's magnetospheric convection is more dynamic during periods of shock activity, then during periods of recurrent activity, then during days of fluctuating activity, and less so during periods of magnetic calm. These results are indirectly in line with those of [27]-[29], for whom the interplanetary coronal mass ejections (ICMEs) at the origin of shock geomagnetic activity are the main drivers of space weather events. These results are also in line with those of [30] for whom geomagnetic storms induced by ICMEs: 1) are the most geo-effective, 2) are characterised by the strongest ring currents and 3) transfer more energy into the inner magnetosphere than storms induced by co-rotating interaction regions (CIRs).

4.4. Daily Hourly Mean Intensities of the MCEF during Periods of Fluctuating Geomagnetic Activity under a Seasonal Prism

Figure 6 shows the mean daily MCEF values for each season under conditions of fluctuating geomagnetic activity. The mean daily MCEF intensities are 0.116947784 mV/m in spring, 0.10854571 mV/m in summer, 0.12374118 mV/m in autumn and 0.10678156 mV/m in winter. Irrespective of solar phase and season, the average daily intensity of the MCEF on fluctuating days is 0.10854945 mV/m. Analysis of these results shows that MCEF intensity is lowest in winter and highest in autumn. It is higher in spring than in summer. These results show that the response of magnetospheric convection during periods of fluctuating activity depends on the Earth's relative position to the Sun, *i.e.* the time of year. In particular, fluctuating geomagnetic activity affects magnetospheric convection more effectively in autumn than in spring, summer and winter. Due to the coupling of the geo-spatial regions neutral atmosphere-ionosphere-terrestrial magnetosphere due to the precipitation of energetic charged particles and the aligned currents over high latitudes ([31]), the differences in MCEF intensity observed during the seasons could therefore be explained by physical phenomena such as: 1) semi-annual oscillations in the lower and middle atmosphere ([32]) and 2) the semi-annual variation in thermospheric neutral density and molecular atomic composition ([33]). In other words, the change in the ionisation rate in the ionosphere caused by the seasonal variation in the Sun-Earth distance coupled with the magnetosphere-Earth ionosphere coupling ([34] [35]) would be one of the major physical phenomena that could explain the differentiated seasonal variability of the MCEF. The displacement of the geomagnetic field axis relative to the geographic axis ([36]) could also be an underlying physical phenomenon that explains the observed results.

The study of the occurrence of fluctuating days and their impact on the seasonal variability of the MCEF shows that there is a seasonal asymmetry. This seasonal asymmetry could be explained by three major physical mechanisms: 1) the axial mechanism ([37]) for which the peak in temporal occurrence corresponds to the maximum solar angle B0 ([38]); 2) the equinoctial mechanism ([6]) for which the peak in temporal occurrence corresponds to the minimum solar declination ([38]) and 3) the Russell-McPherron mechanism ([39]) for which the temporal occur-

rences are due to those of the maximum of the solar angle P . It is important to remember that angle B_0 corresponds to the heliographic latitude of the Earth and angle P is the angle corresponding to the extreme northern position of the solar rotation axis measured eastwards from the northern point of the solar disc ([40]). It is also important to note that the axial mechanism is also used to explain seasonal variations in solar wind speed ([41]).

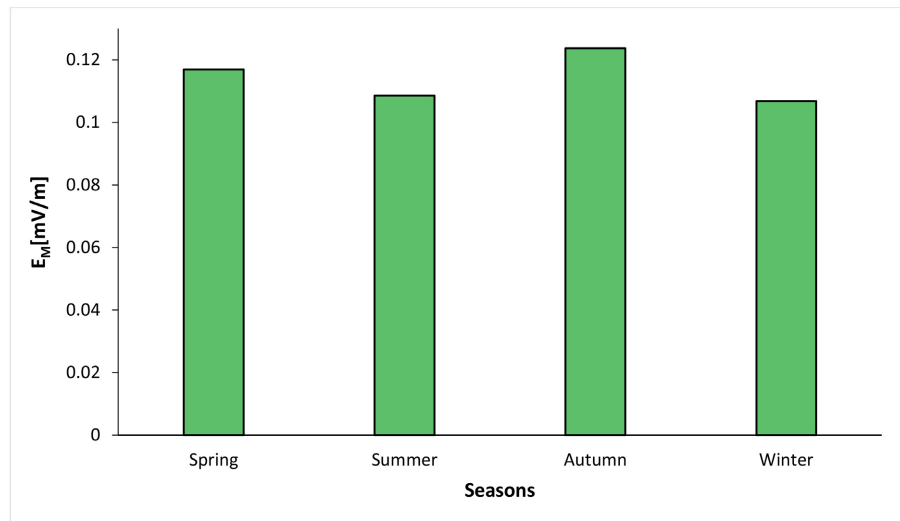


Figure 6. Average daily MCEF values on days that fluctuate with the seasons.

5. Conclusions

In this paper, we use a statistical approach to study the distribution of days of fluctuating activity as a function of solar phase and season during solar cycle 24. We also examine the response of the magnetospheric convective electric field to the geomagnetic disturbance caused by fluctuating solar winds. Our study shows that the occurrence of fluctuating days and the response of magnetospheric convection to geomagnetic activity vary as a function of the stained activity and the season.

On average, the annual occurrences of fluctuating days, from the minimum phase to the descending phase, are 15%, 19%, 28% and 50% respectively. By season, the frequency of fluctuating days is 25.55% in spring, 24.75% in summer, 25.25% in autumn and 24.45% in winter.

The intensity of the MCEF response follows sunspot activity, but is not symmetrical with respect to sunspot activity: it is at its maximum during maximum solar activity, at its minimum during minimum solar activity, and is higher in the descending phase than in the ascending phase.

The study of the seasonal disturbance of the MCEF revealed that the daily average intensities of the MCEF are: 1) maximum in autumn and minimum in winter and 2) higher in spring than in summer. Furthermore, a comparison of the results of this study with previous work shows that 1) of the three classes of disturbed geomagnetic activity identified by Legrand and Simon (1989), fluctuating

geomagnetic activity causes the least disturbance to the magnetospheric convective electric field and shock activity causes the greatest disturbance, 2) the hourly mean intensities on fluctuating days are greater than those on calm days 3) the MCEF response increases with the geomagnetic activity index Aa.

This study has shed light on the distribution of fluctuating days and their impact on the perturbation of MCEF intensity. The study also helped us to better understand the impact of each class of geomagnetic activity disturbed on the daily mean values of the MCEF. However, we have to admit that our work has some shortcomings in that it covers only one solar cycle, cycle 24. An investigation covering a longer period (1966 to 2018 solar cycle 20 to 24) could lead to more edifying results. Extending the study over several solar cycles would also make it possible to see whether the results observed for solar cycle 24, which is a relatively short cycle (10 years), hold true for longer and more intense solar cycles. Furthermore, a comparative study on the distributions and impact of the disturbances caused by each of the three disturbed classes identified by Legrand and Simon (1989) covering the period 1966 (year of the first measurements on solar wind data) to 2018 (date marking the end of the last complete solar cycle) and taking into account, among other things, the impact of the season, solar activity, solar wind parameters, pre-existing conditions on the flank of the magnetosphere just before the impact of the fluctuating activity on it would allow a better understanding of the comparative dynamics of the MCEF during geomagnetic disturbances.

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Conflicts of Interest

The authors of the article declare no conflict of interest.

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