Journal of Modern Physics, 2024, 15, 2238-2255
https://www.scirp.org/journal/jmp
ISSN Online: 2153-120X
ISSN Print: 2153-1196

Statistical Study of the Occurrence of Coronal Mass Ejections (CMEs) from 1996 to 2018 (Solar Cycles 23-24)

Salfo Kaboré[1,2*], Abdoul Kader Segda[1,2], Aristide Marie Frédéric Gyébré[1,2], Frédéric Ouattara[1,2]

[1]Laboratory of Analytical Chemistry, Space and Energy Physics (L@CAPSE), Koudougou, Burkina Faso
[2]Norbert ZONGO University (UNZ), Koudougou, Burkina Faso
Email: *salfo_kabore@yahoo.fr

How to cite this paper: Kaboré, S., Segda, A.K., Gyébré, A.M.F. and Ouattara, F. (2024) Statistical Study of the Occurrence of Coronal Mass Ejections (CMEs) from 1996 to 2018 (Solar Cycles 23-24). *Journal of Modern Physics*, **15**, 2238-2255.
https://doi.org/10.4236/jmp.2024.1512091

Received: September 7, 2024
Accepted: November 11, 2024
Published: November 14, 2024

Abstract

The objective of this article was to carry out a statistical study of the occurrences of CMEs from solar cycles 23 and 24 and to deduce interpretations as a contribution to a greater understanding of heliosphere dynamics. Thus, from the statistical examination of the occurrences according to the phases it appeared that solar cycle 23 (SC23) counted 13207 occurrences of CMEs while 16510 were counted for solar cycle 24 (SC24). These occurrences of CMEs are correlated to the sunspot cycle because in each of these cycles we would note the predominance of the phase maximum (1478 for SC23 and 2338 for SC24) over the ascending phases (550 for SC23 and 1559 for the SC24) and descending (1197 for the SC23 and 1178 for the SC24) and these predominate on the minimum phase (206 for the SC23 and 834 for the SC24). However, the percentages per phase in each cycle show that SC23 was only predominant over SC24 at the maximum phase (43.08% for SC23 and 39.57% for SC24). From this correlation, some authors therefore suggest that the toroidal magnetic field would be the cause of the ejections of these CMEs. The annual statistical examination confirms the correlation with the sunspot cycle but nevertheless reveals in the descending phase of SC23 two unusual peaks in 2005 and 2007 and a drop-in sunspot activity of 42% from SC23 to SC24 while that we would note an increase in the activity of CME occurrences of 36% at SC24, thus suggesting that CMEs can occur without the toroidal magnetic field being the cause, particularly from the coronal holes. The seasonal statistical examination shows for its part that out of the total of 29717 occurrences of CMEs of the two cycles that spring (28%) was the most active than summer (25%) and summer over autumn (24%) and finally autumn over winter (23%) thus revealing that: The ascending phase of the cycle was only the most active during the winter seasons in spring and the descending phase only during the rest of the seasons. Finally, the monthly statistical examination of the occurrences of CMEs corroborates the seasonal statistical examination by the presence of two maximum peaks (May and October) and two minimum peaks (February and August).

Keywords

CMEs, Occurrence, Solar Cycle, Phase of the Solar Cycle, Seasons, Months

1. Introduction

The Sun is a sphere of magnetized plasma whose centuries-old observation reveals that its surface is marked by numerous events such as the recurrence of ejections of enormous quantities of plasma from the corona of the Sun called coronal mass CMEs. These CMEs occur in a violent manner and if they are directed [1] towards the earth, their interaction with the magnetosphere would cause magnetic storms [2] capable of disrupting communication systems, causing the appearance of northern and southern lights, disrupt pipelines, create blackouts by interrupting power lines, damage satellite solar panels as well as the artificial satellites themselves and disrupt aviation systems [3]. Also, the fact that CMEs are correlated with the sunspot cycle would lead some authors to suggest that the causes that are the toroidal magnetic fields at the origin of sunspots are also those which would be at the origin of the emissions of CMEs. But is this true or will it be necessary to put things into perspective or nuance? Are there no other sources potentially responsible for the emissions of these CMEs? These are among other questions that we ask ourselves especially when we know that the CMEs for some are coming from breaks in dipolar magnetic field lines and for others coming from coronal holes and due to the opening of the unipolar magnetic field and which are (unipolar and dipolar) components of the poloidal magnetic field. Thus, the consequences of CMEs on space weather and the terrestrial magnetosphere and their interweaving with the sunspot cycle therefore mean that the study of CMEs is essential in understanding solar and heliospheric phenomena which will make it possible to anticipate possible damage. Materials that these can cause in the terrestrial environment. This is why this present article has the main objective of contributing to more in-depth knowledge of the dynamics of CMEs, starting from a complete statistical analysis of the appearance of CMEs during solar cycles 23 and 24, which are the most recent and therefore with the best investigation tools. To do this we will first present the data and methods used, then the results and subsequently begin the discussion which will be done in terms of analyzes of the occurrences of solar cycles 23-24: 1) According to the different phases, 2) according to the years, 3) according to the seasons and the month and finish the present work with perspectives after having given the conclusion.

2. Data

Sunspot data used to determine the different phases of the solar cycle is available at https://www.sidc.be/silso/datafiles (Thanks).

3. Methodologies

3.1. Phases of the Solar Cycle

So, to determine the four phases of each of the solar cycles using the number of sunspots SN(t) or Wolf index we apply new criteria defined by [4] and used by [5] and [6] which take into account the real behavior of the Sun and also resolve the inconsistencies observed between the old classification criteria and the new data on sunspots. From these criteria the different phases of the solar cycle are broken down as follows: 1) minimum phase: $SN(t) < 0.122 \times SN_{max}$; 2) phase croissante: $0.122 \times SN_{max} \leq \mathrm{SN(t)} \leq 0.73 \times SN_{max}$; 3) phase maximale: $SN(t) > 0.73 \times SN_{max}$; 4) phase décroissante: $0.73 \times SN_{max} \geq SN(t) > SN_{Min}$ (cycle suivant).

3.2. Determining the Occurrence of CMEs

The data on CMEs used in this article are those contained in the catalog "SoHO LASCO CME CATALOG-Version 2" available on the site https://cdaw.gsfc.nasa.gov/CME_list/ (Thanks for the availability of resources).

As the duration of the phases of a solar cycle is not the same, the number of CMEs recorded during a given phase would not be efficient in comparing the activities of CMEs between the phases of a solar cycle.

This is why we use the average annual occurrence per phase which is obtained by dividing the number of CMEs (of which an illustrative example of CME is given in **Figure 1** below) recorded during the phase by the duration of the phase in years, *i.e.*:

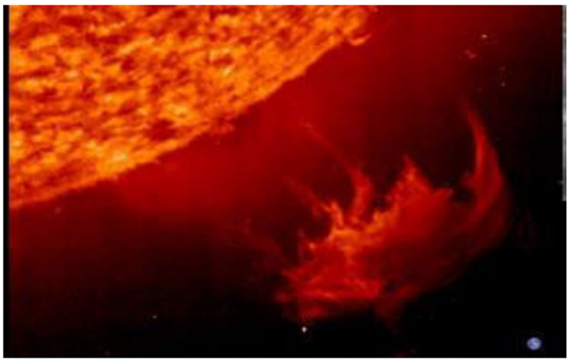

Figure 1. Image of one CME at the bottom and right (Source: SoHO Consortium, ESA, NASA).

$$\text{Occurence moy CMEs} = \frac{\text{Number of CMEs}}{\Delta t}$$

3.3. Division of the Seasons

In this scientific research work the four seasons of the year are divided as follows: spring from March 1 to May 31 (months of March, April and May); summer from June 1 to August 31 (June, July and August); autumn from September 1 to November 30 (September, October, November); winter from December 1 to February 28 (or 29) (December, January and February).

4. Results

Table 1 and **Table 2** show the results of the distribution of CME's according to solar phase and season.

Table 1. Number of CMEs per phase and their % per cycle and annual occurrence of CMEs per phase and their % per cycle.

	Period		Duration		Number of CME				Annual occurrence of CME			
	Cycle 23	Cycle 24	Cycle 23	Cycle 24	Cycle 23		Cycle 24		Cycle 23		Cycle 24	
					Number of CMEs per phase and their % per cycle				Annual occurrence of CMEs by phase and their % per cycle			
Phase minimum (1)	1996	2008-2009	1	2	206	1.56%	1668	10.10%	206	6%	834	14.11%
Ascending phase (2)	1997-1998	2010-2011	2	2	1101	8.34%	3118	18.88%	550	16.03%	1559	26.38%
Phase maximum (3)	1999-2002	2012-2014	4	3	5913	44.77%	7013	42.48%	1478	43.08%	2338	39.57%
Descending phase (4)	2003-2007	2015-2018	5	4	5987	45.33%	4711	28.54%	1197	34.89%	1178	39.57%
Bilan	1996-2007	2008-2018	12	11	13,207	100%	16 510	100%	13207	100%	16 510	100%

Table 2. Number of CMEs per season and their % per cycle and Occurrence of CMEs per season and their % per cycle.

Winter				Spring				Summer				Autumn			
Cycle 23		Cycle 24		Cycle 23		Cycle 24		Cycle 23		Cycle 24		Cycle 23		Cycle 24	
Number of CMEs per season and their % per cycle															
2782	21.06%	3963	24.00%	3 738	28.30%	4424	26.8%	3 453	26.14%	4049	24.52%	3 234	24.5%	4074	24.68%
Winter				Spring				Summer				Autumn			
Cycle 23		Cycle 24		Cycle 23		Cycle 24		Cycle 23		Cycle 24		Cycle 23		Cycle 24	
Occurrence de CMEs par saison et leur % par cycle															
232	21.07%	360	24.00%	312	28.34%	402	26.8%	288	26.16%	368	24.53%	269	24.43%	370	24.67%

5. Discussion

The sun is a star in thermonuclear fusion presenting an atmosphere where we observe the recurrence of many phenomena which testify to its activity.

In the lower part of this atmosphere called the chromosphere, chromosphere flares occur and in its upper part oriented towards interstellar space called the corona, plasma ejections or coronal mass ejections CMEs occur. All these phenomena, eruptions or CMEs result from the breakdown of the solar magnetic field, however respectively the toroidal magnetic field for the eruptions and the dipolar magnetic field for the CMEs. Thus, a flare can occur without a CME and a CME without a flare and or flares and CMEs can occur simultaneously. Also, at the North and South poles of the sun we observe cavities called coronal holes where we witness emissions of CMEs due to the unipolar magnetic field lines that open to interstellar space. The dipolar and unipolar magnetic fields constitute the two components of the poloidal magnetic field. Once the clarification has been established, the CMEs that are the subject of our article occur with a recurrence called annual occurrence that is more or less marked depending on the phases of the cycle, the years, the seasons and the months.

5.1. Annual Occurrences of CMEs According to the Phases of the Cycle: 1996-2018

According to the phases of the cycle and for example the most recent solar cycles 23 and 24 and subject of our study we observe explicitly in the tables of results, Table 1 and in Figure 2 below that on the one hand the solar cycle 24 with the exception of the descending phase was preponderant in terms of emission of CMEs than cycle 23 and on the other hand that the emissions of these CMEs would be in almost perfect correlation with the cycle of sunspots due to the number of sunspots Rz or Wolf index which increases from the phase minimum to the phase maximum peak and decreasing from this maximum peak until the end of the decreasing phase. This index or number Rz is given by the relation:

$$\mathrm{Rz} = k\left(10g + f\right) \tag{1}$$

With g which designates the number of groups of spots, f the number of

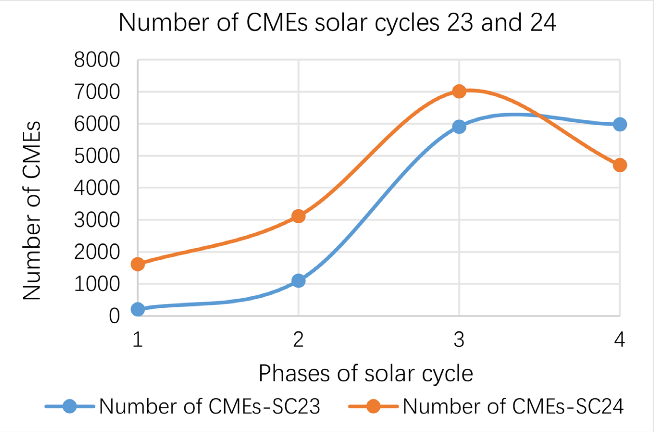

Figure 2. Number of CMEs solar cycle 23 and 24.

spots and k a corrective or normalization term which takes into account the sensitivity of the measuring devices and the observer.

If, however, we push the analysis further by considering only the annual occurrences or emission frequencies of these CMEs which take into account in addition the number of CMEs of the time of the phase, it appears clearer from **Figure 3** that the cycle 24 was more active than cycle 23 and both cycles correlated well with the sunspot cycle.

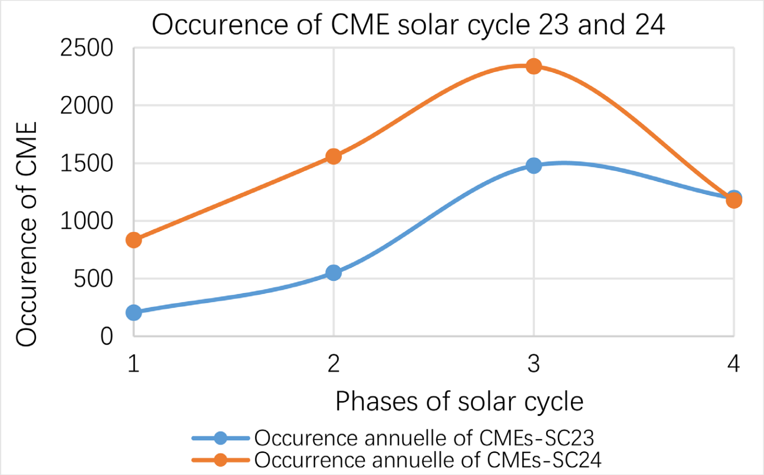

Figure 3. Occurence of CMEs solar cycle 23 and 24.

So, from these results in terms of number of CMEs emitted one could think (**Figure 2**) for cycle 23 that the descending phase was more active in ejection of CMEs as the maximum phase, which is not the case because the detailed analysis based on the annual average occurrences of CMEs emitted shows that (**Figure 3**) the maximum phase in annual average occurrence of CMEs of 1478 was more active than the descending phase of 1197. What appeared to be a bias is not and thus leads us to deduce that the gaps observed in the SoHO catalog data for 1998 (July, August and September) and 1999 (January) did not affect the results.

If we now consider the analysis in relation to the percentage per phase as shown in **Figure 4**, it comes to the conclusion in terms of the number of CMEs emitted that cycle 24 was predominant over that 23 for the minimums and growth phase and the cycle 23 on that 24 on the maximum and decay phase.

On the other hand, in terms of percentage of occurrence (**Figure 5**), we observe that the cycle 23 was only predominant over that 24 on the maximum phase thus allowing us to understand the reason according to which for certain authors cycle 23 was more active than cycle 24. Certainly, an analytical study of the occurrences of CMEs of these solar cycles by considering only the phase maximum as a determining factor could only lead to this deduction.

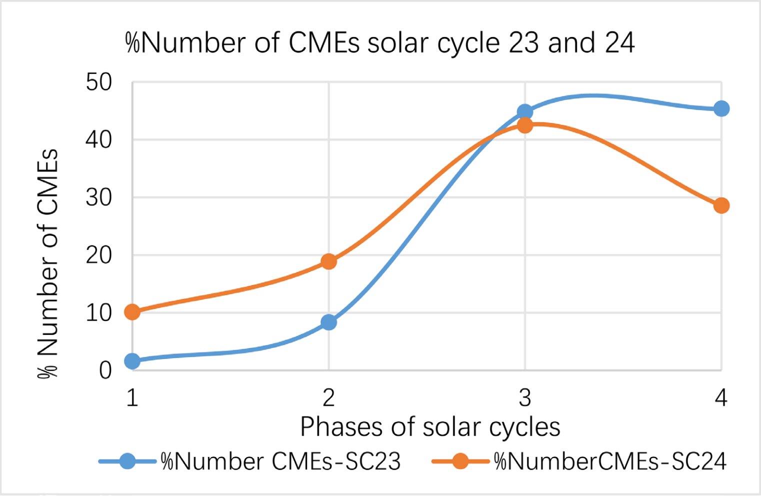

Figure 4. %Number of CMEs solar cycle 23 and 24.

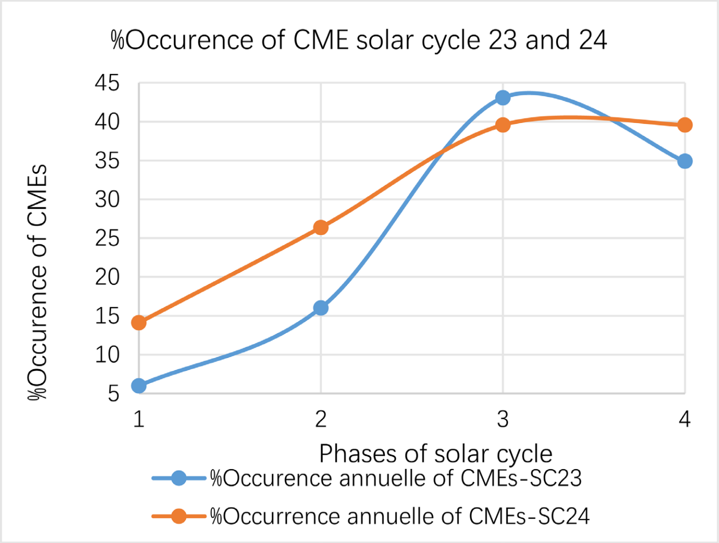

Figure 5. %Occurence of CMEs solar cycle 23 and 24.

From these annual average occurrences it appears that the daily average occurrence of CMEs detected is (a) of the order for the phase minimum of 1 CME every two days, *i.e.* on average 4 CMEs per week for solar cycle 23 and of the order of 2 during the phase minimum days for solar cycle 24; (b) of order 1 to 2 during the ascending phase for SC23 and of 4 during the ascending phase days for SC24; (c) of the order of 4 to 5 during the maximum phase for the SC23 and of 6 during the days of maximum phase for the SC24; (d) of the order of 3 to 4 during the descending phase for SC23 and of 3 during the days of the descending phase.

If we finally put the two cycles together, that is to say phase by phase, it appears that the number of CMEs emitted for all of these two cycles is 29,717 or 1874 (6.30%). During the phase minimum phases, 4219 (14.20%) during the ascending phases, 12,926 (43.50%) during the solar maxima and 10,698 (36%) during the descending phases. Figure 6 and Figure 7 show so clearly the preeminence of the phase maximum over the other phases followed by the ascendance of the descending and ascending phases over the phase minimum thus testify to the good correlation of these profiles with that of the sunspots.

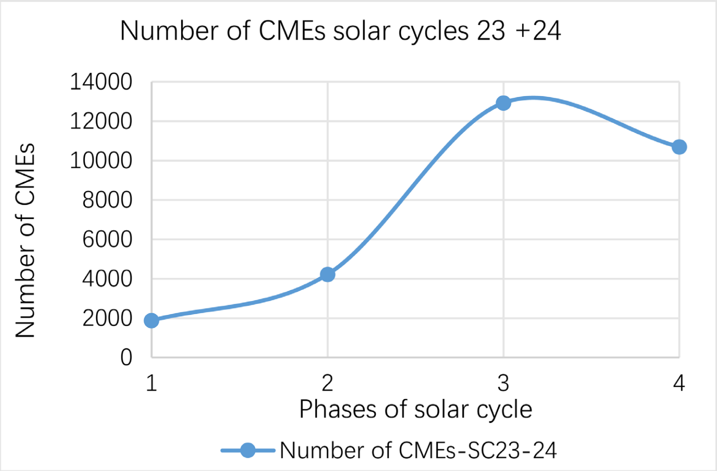

Figure 6. Number of CMEs solar cycle 23 + 24.

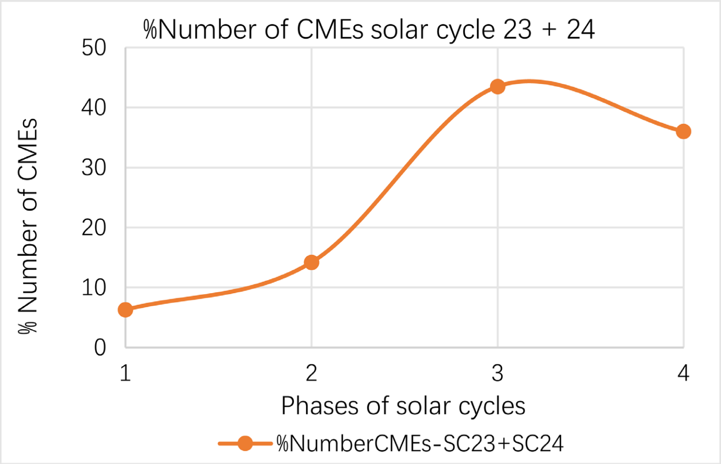

Figure 7. %Number of CMEs solar cycle 23 + 24.

As for the annual average occurrences of CMEs emitted, a total of 4716 are recorded, or 625 (13.25%) for the years of minimum phase; 1055 (22.37%) for the years of the ascending phase; 1847 for the maximum phase (39.16%) and 1189 (25.22%) for the descending phase. These results obtained with the annual average occurrences and represented by Figure 8 and Figure 9 confirm those given by the numbers and percentage of CMEs emitted.

In conclusion of the study of the occurrences of CMEs according to the phases we note that the more there are appearance of sunspots, the more the occurrences of CMEs increase and the fewer there are sunspots and the fewer there are occurrences of CMEs.

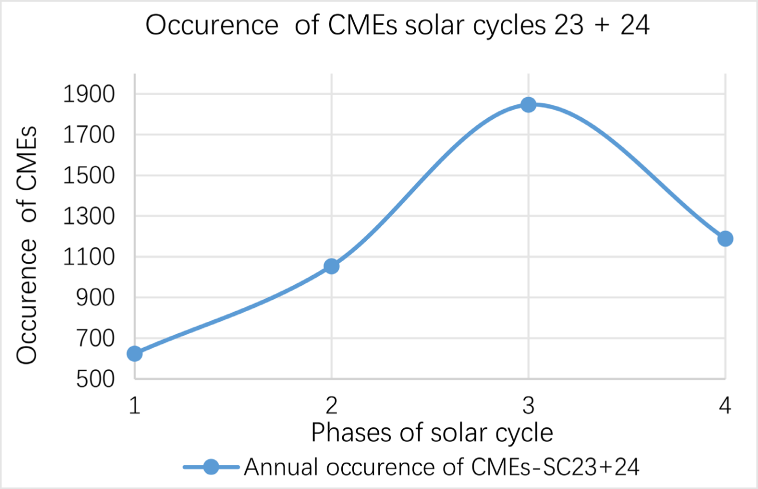

Figure 8. Occurence of CMEs solar cycle 23 and 24.

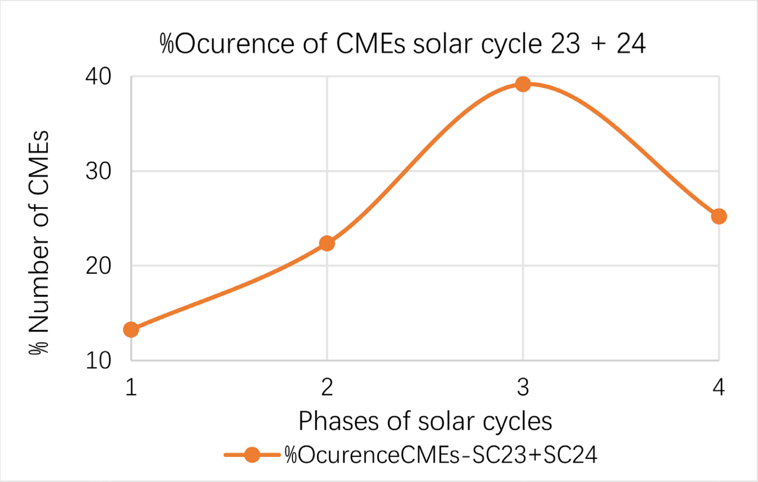

Figure 9. %Occurence of CMEs solar cycle 23 and 24.

Such results are in agreement with results of previous work such as those of [7]-[10] according to which the activity of CMEs varies in phase with the stained activity and many others on the phase maximum such as [11] for example for whom the high rate of solar flares observed during solar maximum years seems to be linked to the weakness of the polar fields. Also, for certain authors such as ([1] [8] [12]) the temporal evolution of the activities of the poloidal fields for CMEs and toroidal for sunspots are approximately in phase opposition and amplitude ratio ½. As an example, at minimum phase the toroidal magnetic field is weak and the poloidal or dipolar field strong and therefore less subject to ruptures and thus justifying that there is less occurrence of CMEs.

Finally, being correlated to the sunspot cycle we can therefore suggest that these occurrences of CMEs will also be to a lesser extent (because at the level of the coronal holes CMEs can occur) of good correlation with the Carrington diagram also called butterfly diagram or Spoerer law of sunspot cycles. Thus we can deduce the latitudinal variation of the occurrences of CMEs as shown in **Figure 10**, showing that of sunspots.

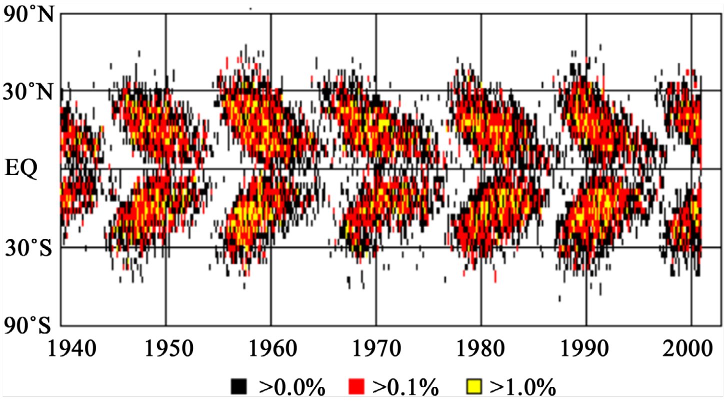

Figure 10. Latitudinal variation in sunspot appearance (NASA).

If the study of the occurrences of CMEs according to phases showed the good correlation of these occurrences with the sunspot cycle, would the same be true of the study of CMEs according to years?

5.2. Annual Occurrences of CMEs from 1996 to 2018

Figure 11 below shows the occurrences of CMEs and the number of sunspots Rz as a function of the years. It appears from the analysis of this figure that for the study period, the average annual occurrence of CMEs is 1292, or around 3 to 4 CMEs detected per day.

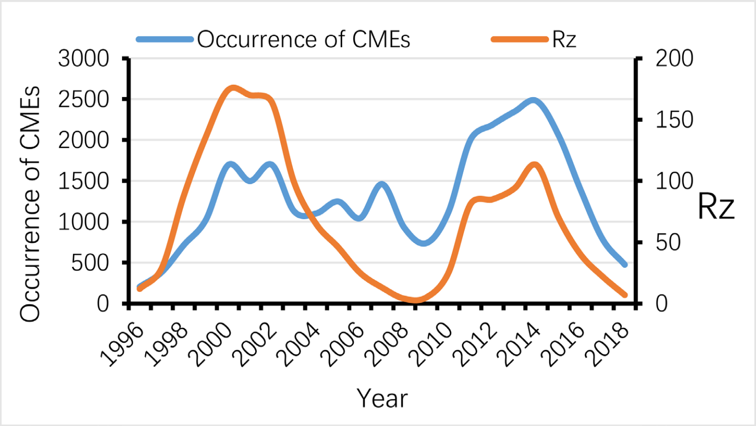

Figure 11. Annual occurrence of CMEs and annual number of sunpot Rz at 1996 to 2018.

Figure 11 also reveals on the one hand the existence of CME peaks during the years of maximum solar activity (in 2000, 2002, 2014) and the years of descending phases (2005; 2007); and on the other hand, the existence of troughs during solar minima (1996, 2008-2009). Better analysis of the same figure shows that during the entire period concerned by the statistical study of the occurrence of CMEs, the year 2014, the year belonging to the solar maximum of solar cycle 24 with 2478 CMEs recorded, is that for the in which the annual occurrence of CMEs recorded is maximum while the year 1996 with 206 CMEs recorded is the year for which the annual occurrence of CMEs is minimal. It appears from the observation of **Figure 11** that with the exception of the period 2004-2007 where two unusual peaks were recorded in 2005 and 2007, years belonging to the descending phase of the solar cycle 23, the annual occurrence of CMEs varies in phase with that of the Rz sunspots. This result clearly confirms previous results such as those of [13] [14], for whom the rate of appearance of CMEs essentially follows the solar activity cycle. This observation also agrees with those of [15] [16] for whom the occurrence rates of CMEs generally follow the solar activity indices.

It also emerges from the analysis of **Figure 11** that regardless of the phase of the solar cycle, the average annual number of sunspots is 85 for solar cycle 23 and 50 for solar cycle 24, *i.e.* a decrease in the order of 42%. Conversely, it appears that the average annual occurrence of CMEs of cycle 23 is lower than the average annual occurrence of CMEs of cycle 24; *i.e.* 1101 for solar cycle 23 against 1500 for solar cycle 24, which corresponds to an annual increase of around 36%. So, although the average number of spots annual solar emissions of cycle 24 are relatively low compared to that of the previous cycle, it appears that there is a general increase in coronal mass ejections during said cycle.

Thus, the peaks of CME rebounds observed during the descending phase of cycle 23 in 2005 and 2007 and the increase in the annual occurrence of CMEs during solar cycle 24 (2008-2018) compared to cycle 23 (1996-2007) while the annual number of sunspots follows the opposite trend would therefore lead to put into perspective the interpretation of certain authors for whom the toroidal magnetic field at the origin of the appearances of sunspots would also be the cause of the CME emissions. Also, if it was an unusual increase in the toroidal magnetic field as suggested by others, we would also observe the unusual peaks of increase in sunspots in cycle 23 in the descending phase and an increase in activity sunspots in cycle 24. As this is not the case, we can therefore consider that CMEs can occur without the toroidal magnetic field being the real cause because these CMEs are essentially due to breaks in the magnetic field lines dipolar which connects the two poles at the crown and at the opening of the magnetic field lines unipolar at the coronal holes. This is all the truer especially since we know from the Carrington or butterfly diagram that sunspots originate towards latitudes of 45˚ then progress towards the solar equator at latitudes of 5˚ at the end of the descending phase. Thus, we suggest that the CME peaks observed at the descending phase of cycle 23 are due to the CMEs emitted at the level of the coronal holes. For cycle 24, taking into account that the number of sunspots and the occurrences are in phase despite the drop-in sunspot activity, leads us to suggest that the solar flares due to ruptures of the toroidal magnetic field were accompanied by emissions of CMEs due to breaks in the dipolar magnetic field lines. The emissions of CMEs in this case due to the coronal holes are not perceptible given their relatively lower number than that of the CMEs generated by the rupture of the dipole lines. However, it is only a question of number and occurrence, so the correlation with the sunspot cycle is all the truer due to the fact that the toroidal magnetic field is of great intensity compared to the poloidal field, *i.e.* 3000 Gauss against 10 Gauss. If it were a question of CME intensity, we would certainly observe that the drop-in sunspot activity would also lead to a drop in CME intensity.

In short, the analysis of the CMEs as a function of the years always shows the good correlation of the occurrences of the CMEs with the sunspot cycle but reveals to us

that the CMEs emitted by the coronal holes will only be noticeable during the period of decline in sunspot activity, that is to say from the peak of the phase maximum until the end of the descending phase. The analysis according to the years thus done, what will it reveal about the analysis of the occurrences of CMEs according to the seasons?

5.3. Occurrence of CMEs Depending on the Season from 1996 to 2018

The seasons which are winter (1), spring (2), summer (3) and autumn (4) have the same duration then the variability curves of the number of CMEs and the occurrences of the seasons will be same profiles and consequently the resulting analyzes will also be. It therefore appears necessary to us that a representation option, either in terms of number or occurrence, will be sufficient and for more details we could refer to **Table 2** above in the results section. Thus, starting from the occurrences as shown in **Figure 12**, it clearly appears that solar cycle 24 in each season and in terms of occurrences prevails over solar cycle 23 and that of the two cycles 23 and 24 spring was the season the most active preceded by summer, autumn and finally winter.

However, if we look only at **Figure 13** giving the percentage of occurrences of each season it appears that cycle 24 was only predominant over cycle 23 in winter and cycle 23 over cycle 24 over the other three seasons.

Likewise, the observation of the different curves also shows us that the occurrences of CMEs are correlated with the sunspot cycle and that the cycle is only quasi-symmetrical. If the sunspot cycle were perfectly symmetrical as in the example of the curves parabolic of the form $Ax^2 + Bx +$

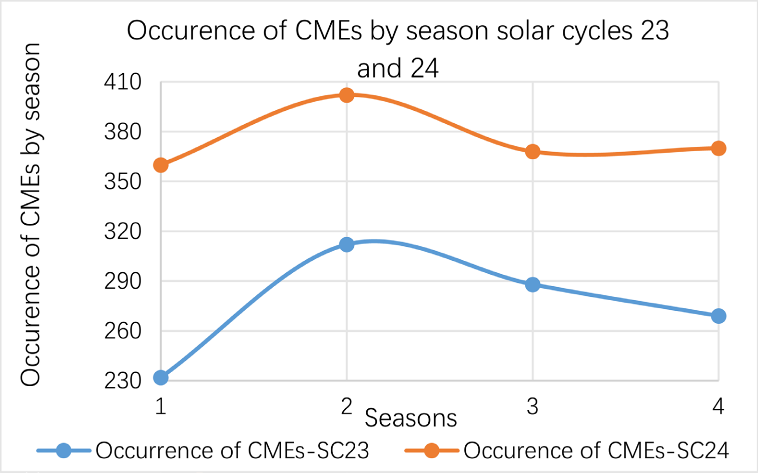

Figure 12. Seasonal occurrence of CMEs of solar cycle 23 and 24.

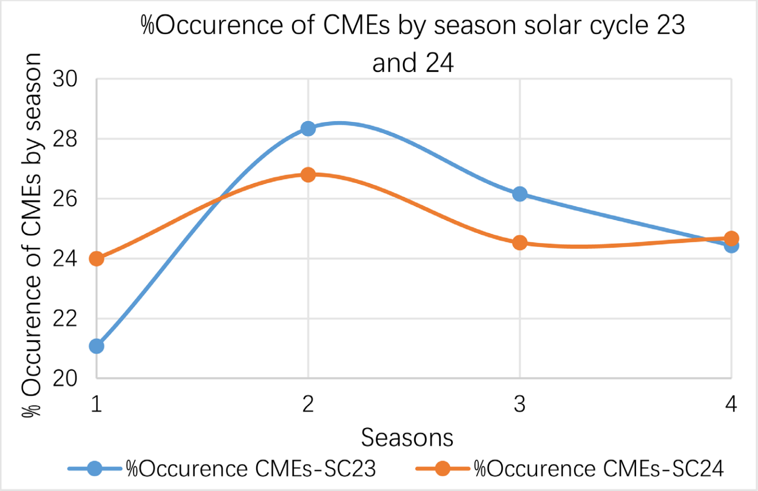

Figure 13. % of seasonal occurrence of CMEs of solar cycle 23 and 24.

C with A, B and C constants and x the variable, we would obtain for each season 25% in terms of percentage of occurrence, *i.e.* perfect equality between the seasons. Which is not the case. We obtained in winter 21.07% for SC23 and 24% for SC24, in spring 28.34% for SC23 and 26.8% for SC24, in summer 26.16% for SC23 and 24.53% for SC24 and finally in autumn 24.43% for SC23 and 24.67% for SC24. Furthermore, these different curves show that it is during the seasons from winter to spring that the ascending phase was the most predominant in terms of occurrence of CMEs over the descending phase and the descending phase more active in terms of occurrences of CMEs on the ascending phase only during the spring, summer and autumn seasons. This is justified by the fact that during the ascending phase the activity of the sun is increasingly increasing, suggesting that autumn will predominate over summer, summer over spring and finally spring predominating over winter. During the descending phase, the opposite occurs because the activity of the sun is increasingly decreasing.

Thus, winter will be predominant over spring, spring over summer and summer over autumn. Finally, according to the butterfly or Carrington diagram, the sun will be more active in winter and spring in its progression of the Latitudes 45˚ towards 10˚ corresponding to the period from minimum to maximum phase. The sun also more active from spring to autumn and latitudes of 10˚ towards the equator of the sun corresponding to the period of the maximum until the end of the waning phase.

As the activity of CMEs impacts the dynamics of the ionosphere [17], [18] and the magnetosphere [19] then the previous result is indirectly aligning with previous results such as those of [20]-[22] for whom the temporal variability of ionospheric parameters such as the total electronic content (TEC), the critical frequency of the F2 sublayer of the ionosphere (foF2) depend on the season. Also, it is important to note that our results on the rates of occurrence of CMEs detected during each of the four seasons indirectly and largely confirm previous results such as those of [23] for whom the fastest CMEs affect the ionosphere more effectively in spring and summer, then in autumn and winter.

If this is the case for the seasons, what will it be for the months which are components integrated into the seasons?

5.4. Occurrence of CMEs Depending on the Month from 1996 to 2018

This monthly analysis would simply like to give the details on the months as shown in **Figure 14** because the overall trend is already observed in the analyzes according to the seasons.

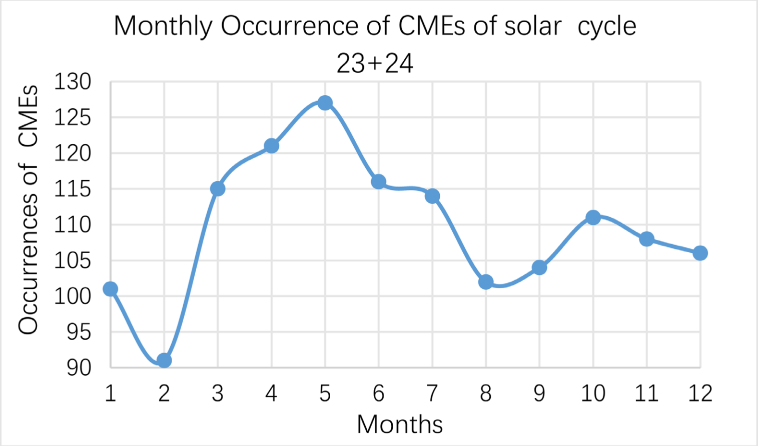

Figure 14. Monthly occurrence of CMEs of solar cycle 23 + 24.

To this end, the observation of **Figure 14** reveals respectively on the one hand the existence of two peaks of maxima and on the other hand of two peaks of minima. The two maximum peaks are one observed in the month of May (127) and the other in the month of October (111) with an asymmetry in favor of the month of May. For the minimum peaks, one is observed in the month of February (91) and the other in the month of August (104). Thus, the periods of decline observed from January to February, then from May to August and finally from October to December would indicate to us the periods where the descending phase of the cycle was the most active of the cycle. Thus, according to the Carrington or butterfly diagram of latitudes of 10˚ towards the equator of the sun. On the other hand, the periods of growth observed from February to May and from August to October are the periods where the ascending phase was the most active in the cycle. So according to the Carrington or butterfly diagram of latitudes from 45˚ to 10˚ from the sun. Such an observation well corroborates what we observed in the seasonal analyses.

6. Conclusion

In conclusion of the study of the occurrences of CMEs from solar cycles 23 and 24, it appears that the more the number of sunspots increases and the more the occurrences of CMEs increase and the fewer there are sunspots and the fewer there are occurrences of CMEs. Thus, from this observation it is deduced from the analysis according to the phases that the occurrences of CMEs are correlated to the sunspot cycle and therefore on the one hand for certain authors that these occurrences are governed by the toroidal magnetic field and that therefore on the other hand their latitudinal variations are also correlated with that of the sunspots observed in the butterfly or Carrington diagram. The study of occurrences according to the years, however, puts things into perspective and considers that CMEs, although well correlated with the sunspot cycle, can occur without the toroidal magnetic field being the real cause. In fact, CMEs are essentially due to breaks in the lines of dipolar magnetic field that connects the two poles at the coronal level and the opening of the unipolar magnetic field lines at the coronal holes. The seasonal analysis shows us that the occurrences of CMEs are correlated with the sunspot cycle and that the cycle is only quasi-symmetrical due to the relative predominance of certain seasons over others. Thus, it appeared as a consequence of this fact that it was during the seasons from winter to spring that the ascending phase was the most predominant in occurrence of CMEs over the descending phase and the descending phase more active in terms of occurrences of CMEs on the ascending phase during the spring, summer and fall seasons. The seasonal analyzes will be corroborated by the monthly analyzes which showed the existence of two maximum peaks in May and October and two minimum peaks in February and August. Thus, the periods of decay observed would indicate to us the periods where the descending phase of the cycle was the most active of the cycle and thus according to the Carrington or butterfly diagram of latitudes of 10˚ towards the equator of the sun. On the other hand, the growth periods observed are the periods where the ascending phase was the most active of the cycle and thus according to the Carrington or butterfly diagram of latitudes from 45˚ to 10˚ from the sun.

7. Limits and Perspectives

7.1. Somes Limitations

The main limitations of our research are linked not only to our relatively small sample (two solar cycles analyzed), but also to the fact that all the data on CMEs used come from a single source, that of CDAW from SoHO LASCO CME CATALOG-Version 2. These limits make it difficult to generalize our results to other solar cycles. Research covering several solar cycles and using CME data from several sources, such as those from the CME catalogs of CACTus, SEEDS, ARTEMIS and CORIMP, would produce results whose generalization would be much more unanimously accepted.

7.2. Perspectives

Finally, as perspectives, in our next research on coronal mass ejections: 1) we are looking for a possible link between the increase in the occurrence of CMEs and that of average temperatures observed on a planetary scale in recent years through a cross-analysis of meteorological and solar data, 2) we will study the evolution of some physical properties of CMEs capable of moving towards the Earth, namely the size and apparent speed of CMEs, the shape of CMEs (CMEs in rope of flow, loop CMEs, jet CMEs, etc.), the distribution of the apparent hemispherical positions of the CMEs over their lifetime.

Acknowledgments

The authors thank the National Geophysical Data Center (NGDC) and NASA’s ACE data center for the CME data. The authors also thank the Sunspot Index and Long-term Solar Observations (WDC-SILSO, Royal Observatory of Belgium) for the availability of sunspot number data. The authors would also like to thank the reviewers for their detailed comments, their constructive remarks and suggestions which helped to improve the article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Simon, P.A. and Legrand, J.P. (1989) Solar Cycle and Geomagnetic Activity: A Review for Geophysicists. Part II. The Solar Sources of Geomagnetic Activity and Their Links with Sunspot Cycle Activity. *Annales Geophysicae*, **7**, 579-594.

[2] Martinić, K., Dumbović, M., Temmer, M., Veronig, A. and Vršnak, B. (2022) Determination of Coronal Mass Ejection Orientation and Consequences for Their Propagation. *Astronomy & Astrophysics*, **661**, A155. https://doi.org/10.1051/0004-6361/202243433

[3] Zhang, J., Dere, K.P., Howard, R.A. and Bothmer, V. (2003) Identification of Solar Sources of Major Geomagnetic Storms between 1996 and 2000. *The Astrophysical Journal*, **582**, 520-533. https://doi.org/10.1086/344611

[4] Sawadogo, S., Gnabahou, D.A., Pahima, T. and Ouattara, F. (2024) Solar Activity: Towards a Standard Classification of Solar Phases from Cycle 1 to Cycle 24. *Advances in Space Research*, **73**, 1041-1049. https://doi.org/10.1016/j.asr.2023.11.011

[5] Chafik, B., El Malki, M., Miskane, F. and Nebdi, H. (2024) Study of Geomagnetic Activity according to kp Index and Its Variability in Relation to Sunspots over the Last Five Solar Cycles. *International Journal on* "*Technical and Physical Problems of Engineering*" (*IJTPE*), **16**, 331-341.

[6] Ouédraogo, P., Guibula, K., Diabaté, A., Fleury, R. and Ouattara, F. (2024) Study of Regular Variations in Vertical Total Electron Content (VTEC) from 2013 to 2021 at Station BF01 in Ouagadougou. *Current Journal of Applied Science and Technology*, **43**, 103-117. https://doi.org/10.9734/cjast/2024/v43i74410

[7] Cyr, O.C., Howard, R.A., Sheeley, N.R., Plunkett, S.P., Michels, D.J., Paswaters, S.E., *et al*. (2000) Properties of Coronal Mass Ejections: SOHO LASCO Observations from January 1996 to June 1998. *Journal of Geophysical Research*: *Space Physics*, **105**, 18169-18185. https://doi.org/10.1029/1999ja000381

[8] Ouattara, F. (2009) Solar Magnetic Fields Components: Phases, Profiles and Their Relationship. *Journal of Science*, **9**, 9-16.

[9] Poletto, G. (2013) Sources of Solar Wind over the Solar Activity Cycle. *Journal of Advanced Research*, **4**, 215-220. https://doi.org/10.1016/j.jare.2012.08.007

[10] Mitsakou, E. and Moussas, X. (2014) Statistical Study of ICMEs and Their Sheaths during Solar Cycle 23 (1996-2008). *Solar Physics*, **289**, 3137-3157. https://doi.org/10.1007/s11207-014-0505-y

[11] Luhmann, J.G., Li, Y., Liu, Y., Jian, L., Russell, C.T., Kilpua, E. and Hoeksema, J.T. (2011) Heliospheric Space Weather at the Start of Cycle 24. *American Geophysical Union*, *Fall Meeting* 2011, San Francisco, 5-9 December 2011.

[12] Legrand, J.P. and Simon, P.A. (1989) Solar Cycle and Geomagnetic Activity: A Review for Geophysicists, Part I. The Contributions to Geomagnetic Activity of Shock Waves and of the Solar Wind. *Annales Geophysicae*, **7**, 565-578.

[13] Webb, D.F. and Howard, R.A. (1994) The Solar Cycle Variation of Coronal Mass Ejections and the Solar Wind Mass Flux. *Journal of Geophysical Research*: *Space Physics*, **99**, 4201-4220. https://doi.org/10.1029/93ja02742

[14] Raychaudhuri, P. (2004) Variability of Coronal Mass Ejections. *Proceedings of the International Astronomical Union*, **2004**, 211-212. https://doi.org/10.1017/s1743921305000529

[15] Robbrecht, E., Berghmans, D. and Van der Linden, R.A.M. (2009) Automated Lasco CME Catalog for Solar Cycle 23: ARE CMEs Scale Invariant? *The Astrophysical Journal*, **691**, 1222-1234. https://doi.org/10.1088/0004-637x/691/2/1222

[16] Webb, D.F. and Howard, T.A. (2012) Coronal Mass Ejections: Observations. *Living Reviews in Solar Physics*, **9**, Article No. 3. https://doi.org/10.12942/lrsp-2012-3

[17] Idosa, C. and Shogile, K. (2023) Variations of Ionospheric TEC Due to Coronal Mass Ejections and Geomagnetic Storm over New Zealand. *New Astronomy*, **99**, Article

ID: 101961. https://doi.org/10.1016/j.newast.2022.101961

[18] Aristide Marie Frederic, G., Salfo, K., Abidina, D. and Frederic, O. (2022) Seasonal Effect on Fof2 Variability During One-Day-Shock at Ouagadougou Station During Solar Cycles 20, 21 and 22. *International Journal of Advanced Research*, **10**, 608-616. https://doi.org/10.21474/ijar01/15706

[19] Kabore, S. and Ouattara, F. (2018) Magnetosphere Convection Electric Field (MCEF) Time Variation from 1964 to 2009: Investigation on the Signatures of the Geoeffectiveness Coronal Mass Ejections. *International Journal of Physical Sciences*, **13**, 273-281. https://doi.org/10.5897/ijps2018.4759

[20] Farid, H.M., Mawad, R., Ghamry, E. and Yoshikawa, A. (2020) The Impact of Coronal Mass Ejections on the Seasonal Variation of the Ionospheric Critical Frequency f_0F2. *Universe*, **6**, Article 200. https://doi.org/10.3390/universe6110200

[21] Seyoum, A., Gopalswamy, N., Nigussie, M. and Mezgebe, N. (2019) The Impact of Cmes on the Critical Frequency of F2-Layer Ionosphere (foF2). *Proceedings of the International Astronomical Union*, **15**, 400-402. https://doi.org/10.1017/s1743921320003579

[22] Seemala, G.K., Katual, I., Kapil, C. and Vichare, G. (2023) Seasonal and Solar Activity Dependence of TEC over Bharati Station, Antarctica. *Polar Science*, **38**, Article ID: 101001. https://doi.org/10.1016/j.polar.2023.101001

[23] Farid, H.M., Mawad, R., Yousef, M. and Yousef, S. (2015) The Impacts of CMEs on the Ionospheric Critical Frequency foF2. *Elixir Space Science*, **80**, 31067-31070.