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INVESTIGATION IN PERIODICITIES OF SUNSPOT AND GEOMAGNETIC STORM USING WAVELET ANALYSIS

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ABSTRACT

This investigation related to the periodicities in daily observations of sunspot concentrations and geomagnetic storms independently by applying wavelet technique for the most recent solar cycles 23, 24 and 25 and to establish which solar cycle has been more active. The periodicities of recent solar cycles are found through dividing the solar cycle by three phases that are raising phase, the maximum phase, and the declining phase. In this study, the wavelet spectrum and periodicity of geomagnetic storms from the most recent solar cycle as well as the Sunspot number were examined. To find out the periodicities and their time evolution. The Morlet wavelet technique was applied to the time sequence corresponding to fluctuation of sunspot number and geomagnetic storms. In this study, we chose to focus on geomagnetic storms and sunspots. It was observed that a severe geomagnetic storm is most likely to occur around the solar maximum, and during the declining years of the sunspot cycle, it tends to diminish at the sunspot minimum. These findings indicate the interdependence of solar magnetic storms on the number of sunspots.

Keywords: Morlet Wavelet power spectrum, Geomagnetic Storm, Sunspot Number

1. INTRODUCTION

Geomagnetic storms exhibit fluctuation over time scales ranging from a few seconds to decades, according to observations of them recorded during the current solar cycles 23, 24, and 25. For solar cycles 23 and 24, as well as the current solar cycle 25 from December 2020 to April 2023, these time scales are divided into three phases: the rising phase, the maximum phase, and the declination phase. The recent solar cycle's geomagnetic storms' periodicity was studied. The Morlet wavelet technique has been applied to the solar transient and geomagnetic storm time series to assess periodicities and their temporal evolution. The observed geomagnetic storm periodicities are better time-frequency resolved using the Morlet wave function. In the normalised wavelet scalogram of an actual time series wave elevation indicative of strong activity, the bulk of notable periodicities were found. Wavelet analysis of the times of geomagnetic storms, in general, produces the noteworthy wave oscillations in time series of solar terrestrial parameters. In various periods of the solar cycle, each period is distinct and has variable amplitude.

Sunspot number has changed throughout time scales ranging from a few seconds to decades, according to observations conducted during solar cycles 23, 24 and 25. These time frames correspond to the solar cycles 23 and 24, as well as the current solar cycle 25 from December 2020 to April 2023, which has three phases: increasing, maximum, and declining. This study looked at the Sunspot number's periodic behaviour and wavelet power over the most recent solar cycle. A time series of solar transient's sunspot number was subjected to the

Morlet wavelet technique in order to extract the periodicities and their temporal evolution. It was possible to produce a visual that showed the amplitude of any characteristic's vs scale and how this amplitude varied over time by varying the wavelet scale and translating in time (Torrence and Compo, 1998). Several studies have been carried out before on the periodic or almost periodic oscillations of solar parameters, such as interplanetary parameters like IMF (Hapgood et al., 1991).

2. DATA AND METHOD OF ANALYSIS

The NASA Goddard Space Flight Centre's website, https://omniweb.gsfc.nasa.gov, provided the daily average sunspot numbers and geomagnetic storm data are submitted to periodic examination for solar cycles 23, 24, and 25 of the Sun. The wavelet analysis can be utilised in this work to investigate individual fluctuations in power spectra (Torrence and Compo, 1998; Grinsted et al, 2004). The Morlet wavelet analysis (Morlet et al,1982, Torrence and Compo, 1998) was employed because it is best suited for detecting fluctuations in the periodicities of geophysical signals over time scales. The solar and interplanetary parameters, as well as the geomagnetic activity index, are subjected to wavelet analysis in order to identify the time variation of non-stationary power present at various periods. By adjusting the wavelet scale and translating in time, it is possible to create a picture that shows the amplitude of any features versus scale and how this amplitude varies with time (Torrence and Compo, 1998).

3. RESULT AND DISCUSSION

3.1 Spectrum Analysis of Geomagnetic Storm of Solar Cycle 23

Raising phase

The wavelet power spectrum in geomagnetic storm during the ascending phase of solar cycle 23 is shown in Figure 1. The periodicity is around 3.5 years; at the beginning of 1996, the power at the period is lower, and by the end of the raising phase in 1998, the spectrum is strong. The spectrum line ranged from 21.5 to 40 days and 24 to 42 days, respectively, and the period was found to be extremely significant for nearly the intervals of January 1996 to July 1997 and July

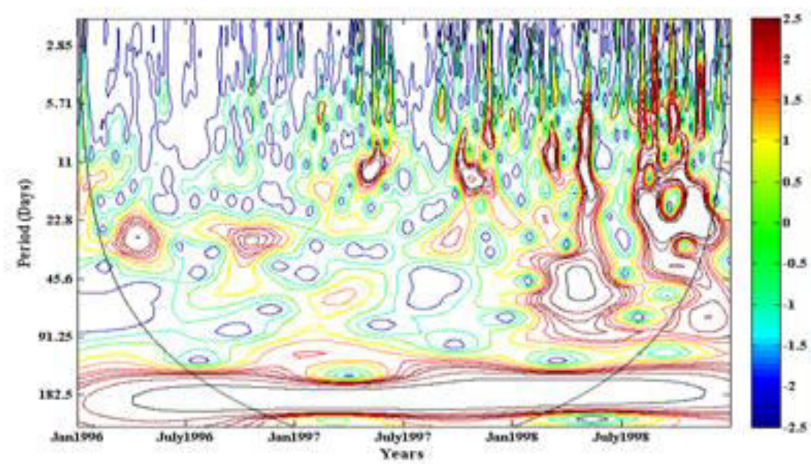

Figure 1: The wavelet spectrum of the Raising phase of Geomagnetic storm from period 1996 to 1998

1996 to June 1997, due to emergence of a solar coronal mass ejection. The data analysis shows that the 9- 20, and including 2.85 in the middle of 1997 and early 1998 are the most significant times. The scattered active region from 5.71 to 88 days, the period from January 1998 to July 1998.

First, the period was cut from 15 to 45.6 days, and then it was extended to 2.85 days. The extremely bright spectral lines and active area were initially observed in 1998, shortly after July. Either planetary wave motion or variations in solar activity could be the cause. Periodicity lasting 24–27 days was caused by the solar rotation (Rieger et al, 1984). Large amplitude Alfvénic changes in infrequent southern fields are typically connected with geomagnetic activity related to streams (Tsurutani et al. 2006; Richardson 2013).

Maximum phase

The wavelet spectrum of a time series of daily geomagnetic storm data from the peak of solar cycle 23 in 1999 to 2002 is displayed in Figure 2. The period of active prominent lines from 11- 30 almost July 1999 to January 2000 occur. The ranges are 20 - 40 and 45 - 91.25 days, respectively, for the brief time between April 1999 and November 2000, and the range is 80 - 90 days from the September 2000 to January 2001. It takes place between September 2000 and June 2001, together with the quasi-periods of 35 - 18 and 2.85-8 days. In the year 2000, there some prominent lines in these days 2.85-32. A stretch of 75- 100 days is also noted between January 2001 and the end of July 2002. There were intended spectral lines with periods ranging from 2.85 - 40 between mid-July 2001 and January 2002. When the intensity lines from 20-40 and approximately

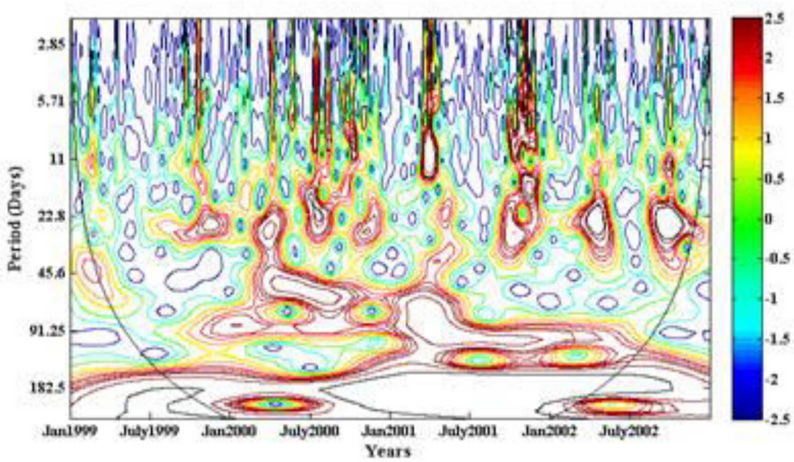

Figure 2: The wavelet spectrum of the Maximum phase of Geomagnetic storm from period 1999 to 2002

from September to December 2002, respectively, and between January and July 2002. Gonzalez and Gonzalez (1987) examined various intervals and their connection to sector structure, assigning the solar cycle to periods of 13.5 days and sunspot numbers to durations more than 1.3 years. This provides evidence for a pattern that indicates a rising cycle-to-cycle link between storm frequency and cycle size. This is to be expected, since geomagnetic activity has been used in the past to predict the size of the evolving sunspot cycle (Thompson 1993). Based on the frequency of the episodes, a number of experts have projected the likelihood of extreme storms (Riley, 2012; Tsubouchi and Omura, 2007).

Declining phase

Figure 3 shows how the wavelet power spectrum changed during the course of the 23-day solar falling phase. There are a lot of noticeable phases on the linear spectral line from 2.85 to 4 in the middle of 2003. The narrow spectral region that began 2003 with a period of 20–24 and 2004 with a period of 20 - 28. A spectral line with active days is found in the dispersed spectrum from 2.85 - 175. The fact that all of the parameters are active makes this a very active zone. The results of study that the numerous sunspot and solar flares that indicates that the intense lines from 2005 to 2006 with the ranges 11-43. The day 91.25 -100 the spectral line of the full year from 2006 to 2007, and in 2007 the period between 42-80 and 20 - 25 days in the month of April to May in the year 2007.

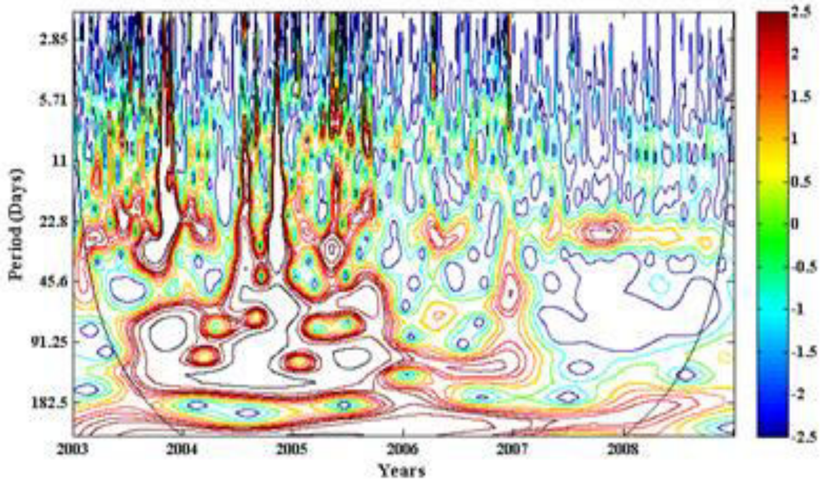

Figure 3: The wavelet spectrum of the Declining phase of Geomagnetic storm from period 2003 to 2008

As the solar active patches quickly form or disappear, their location on the solar surface may change longitudinally (Kane, 2003). Baranyi and Ludmany (2003) state that the rotation rate rises when the sun goes from its maximum to its minimum and falls with latitude. Verma and Joshi (1994) suggested that this periodicity could be the time scale at which coronal hole areas accumulate enough energy to produce high-velocity stream events.

3.2. Spectrum Analysis of Sunspot Number of Solar Cycle 23

Raising phase

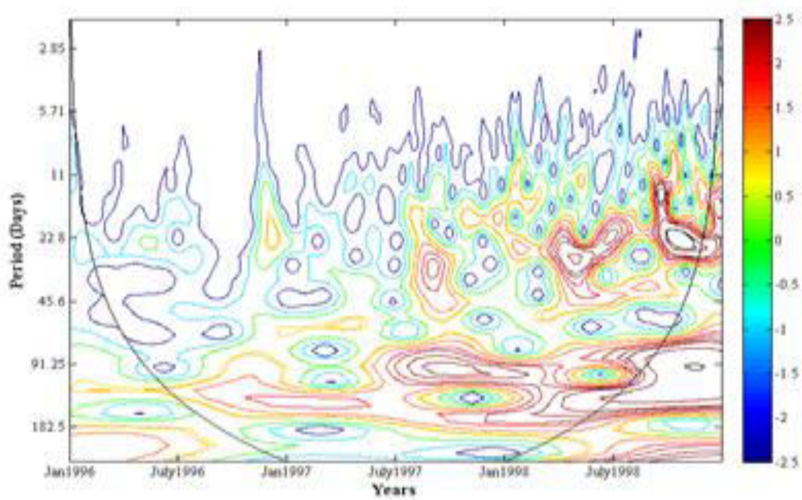

Figure 4: The wavelet spectrum of the raising phase of Sunspot number from period 1996 to 1998.

A series of daily sunspot counts were subjected to wavelet analysis, and the results are shown in Figure 4. Between August 1996 and June 1998, the duration of the active spectral line was between 80 - 170 days. From August 1996 to June 1996, July 1997 to March 1998, and August.

A 1997 to February 1998, the days that the active lines between 120 -150, 80 - 100, and 160 -170 are considered to be between the period of days 80-170. The age range that was investigated is therefore between 3.5 years. At the end of the phase, the increasing phase becomes stronger. The energy contribution for cycles in this region that exhibit continuous irregular fluctuation has shifted to high value frequencies. At the end of 1997, the 30 - 50 lines were the most noticeable ones at the spectrum's boundary. From early March 1998 to the end of July 1998, the short time spans 19-45.6 and 11-35 days roughly, and the day 11 -35 the spectral line generally from September to December 1998. Periodicity less than 10 days is also shown by the solar parameters used in the current investigation. The wavelet spectrum of sunspots, which provides ensure on periodicities throughout this phase, played a significant role in understanding the physical processes of the Sun, as seen by the growing spectral line due to magnetic activity.

Maximum phase

The greatest phase of the sunspot number for solar cycle 23 is shown in Figure 5 as a wavelet power spectrum. The spectral line was initially spread out across a period of 10-45.6 days, from the beginning of the maximum phase in January 1999 to early December 2000. It had 91.25 days between the middle of 1999 and January 2001, which brought the active spectrum closer to day 50. The days fluctuated from 91.25 to 100 in a brief period from September 2000 to July 2001. From February 2001 to July 2001 and from July 2001 to July 2002, there were active spectral lines in the range 11- 91.25. The less intense contour red lines intervals from March 2002 to October 2002 were 13- 48, and the entire month of July 2002. Sunspot activity of declining phase start as the maximum phase comes to be end.

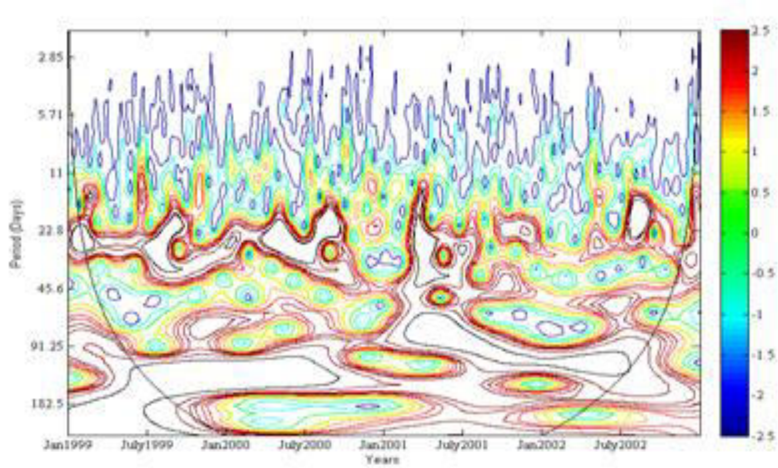

Figure 5: The wavelet spectrum of the Maximum phase of Sunspot number from period 1999 to 2002.

The Wavelet Sunspot counts were zero in 1996, the first year of solar cycle 23, and then progressively climbed over time, peaking at about 300 in the years 2000 to 2002 before decreasing once more to zero in 2008, the last year of solar cycle 23, according to studies by (Poudel et al, 2020). The Sun was approaching its maximum phase and had complex sunspots throughout the 13.5 period, which was identified during active phase (Pap et al., 1990).

Declining phase

The wavelet power spectrum of a sunspot number in its declining phase from 2003 to 2008 is shown in Figure 6. Between the beginning of 2003 and the beginning of 2006, a sporadic period of varying length ranging from 22.8 to 175 days is usually found in the starting phase. A notable periodicity from 15-175 days is present. The time period between 11-25 and the day 11 appears between 2005 and the beginning of 2006. A period signal with a duration of 88 to 185 days develops between the middle of May 2005 and April 2007. In the middle of 2006, a quasi-period of 20 - 28 days arises, and day 28 appears in 2007. The existence of periodicities due to active region alone with coronal holes on the sun associated with diminished solar activity revealed the characteristics of the Sun.

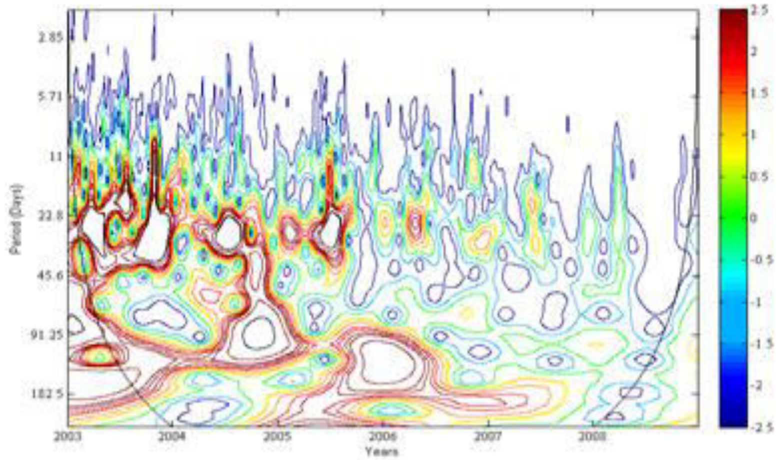

Figure 6: The wavelet spectrum of the declining phase of Sunspot number from period 2003 to 2008.

During the declining phase of the sunspot cycle, recurrent streams were more prominent than during the ascending phase or maximum (Feynman, 1983). Gonzalez and Gonzalez (1987) examined a range of intervals and their connection to sector structure, attributing to sunspot counts and the solar cycle, respectively, lengths greater than 1.3 years and less than 13.5 days.

3.3 Spectrum Analysis of Geomagnetic Storm of Solar Cycle 24

Raising phase

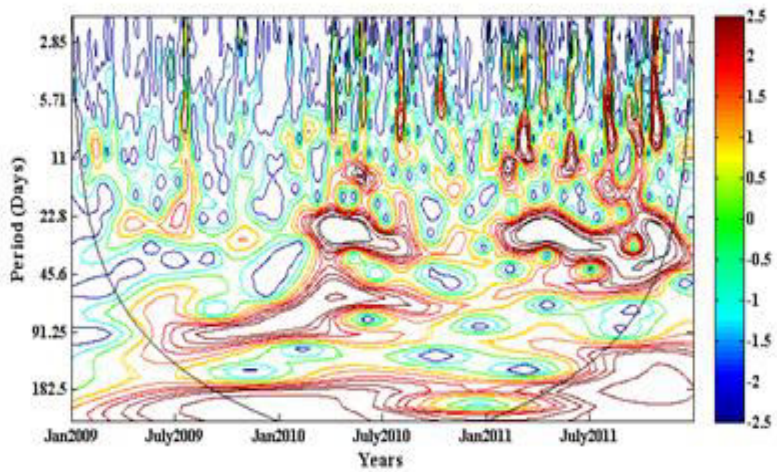

Figure 7: The wavelet spectrum of the raising phase of Geomagnetic storm from period 2009 to 2011.

Figure 7 shows the wavelet spectrum of the geomagnetic storm's rising phase from 2009 to 2011 across a time span of a few days to two years. The strength of sunspot number fluctuations for intervals shorter than 0.25 years demonstrates a fairly apparent progression with solar cycle. During the increasing phase of solar cycle 24, the duration of 27 days that corresponds to the solar rotation period is observed to be prominent. However, this time frame is 75 to 100 days long time frame for this is July 2009 to November 2010. For a brief period from the beginning of March 2010 to the end of August 2010, the period between 22.3 - 30 days is discovered. The 9-day periodicity was brought on by the active centres' longitudinal extension brought on by the subharmonics of the solar rotation. Because of the longitudinal expansion of two coronal holes in the northern polar solar hemisphere, most solar and geomagnetic variables have a 14-day periodicity, but only at certain particular intervals. According to Rieger *et al.* (1984), the solar rotation was the cause of the periodicities of 24–27 days. The very active periodicities ranged from days 2.85 to 11 days from February 2010 to December 2011.

Maximum phase

The figures 8 show a wavelet power spectrum of geomagnetic storm during the 24 solar maximum periods for each time range. In a few chosen times, the wavelet power is greater. During the first stage of the 24 solar maximum, periods such as 97-150 and 22.8- 45.6 days are significantly more intense, with roughly 53 days of periodicities being more prominent from January 2012 to December 2013 and 22.8 days of periodicities being more prominent from January 2013 to December 2013. Starting at 24 maxima, the observatory found periodicities of 38-50, 20-38 between February and April 2012. Due to halo CME with high concentration the observatory also found periodicities 38-45.6 and 13-38 between July and November 2012, and 7, 10 days in July and March 2012. In the remaining days of February 2013, the periodicities of 3-10 days are prevalent. It has been noted that the spectral power peaks every 53 days or so. The spectral lines are shown for

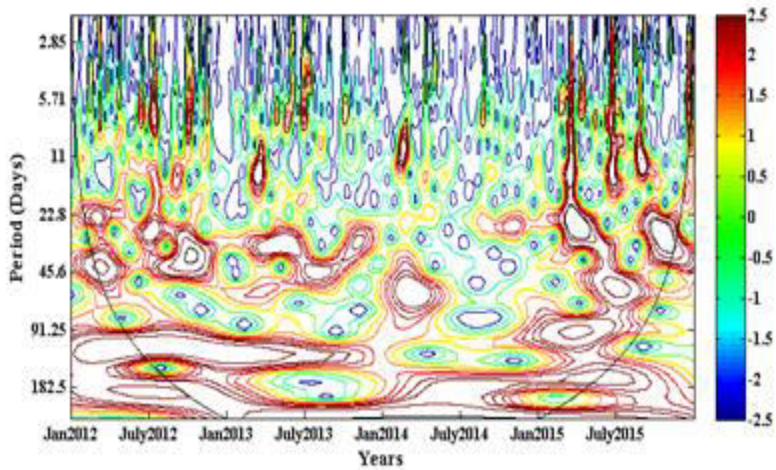

Figure 8: The wavelet spectrum of the maximum phase of Geomagnetic storm from period 2012 to 2015.

the time span from 35 to 91.25, which approximately equals 56.25 days, from January 2014 to June 2014. In the middle of the spectrum, the periodicities are limited to a small range of periods. From September 2014 to September 2015, there are no active spectral lines in the periodicities from 93 to 98. The periods 45.6-85 and 22.8-45.6 are active in 2015. The solar maximum peak is where the 22.8 - 45.6 days of periods are concentrated, while active narrow spectral lines can be observed at 9-18 days.

Declining phase

In the declining phase of solar cycle 24 from 2016 to 2019, the wavelet spectrum of a geomagnetic storm is shown in Figure 9. The 3.5 years of periodicity took place during the time of decline. In the wavelet spectrum's high frequency range, oscillations around 14^{th} days and 27^{th} days may be seen both the solar rotation and the fluctuation in the solar magnetic field and have a periodicity respectively. The decreasing phase of the solar cycle is when both periodicities are observed to be strongest. Between March 2016 and March 2017, this solar cycle's phase, which has quasi periods of 50 to 91.25 days, is present. The period between 45.6 - 11 is a very active region in the spectrum as a result of the solar wind shock wave. The nearly 24 - 30 days of periodicity appears between the middle of March 2016 and the end of June 2016. In a short-term periodicity of

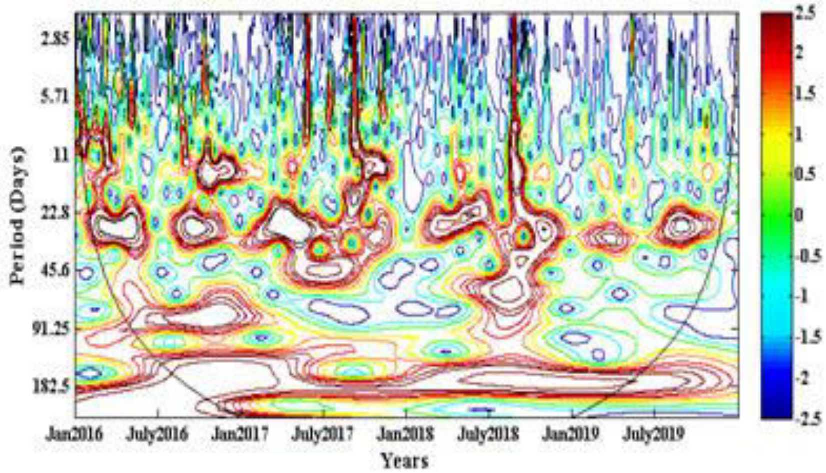

Figure 9: The wavelet spectrum of the declining phase of Geomagnetic storm from period 2016 to 2019.

only 4 days, the active days are only 4-8 with different lengths between them, starting in August

2016 and ending in December 2016. The same applies to the period from 10 to 18 days in September 2016 to November 2016. The spectral lines are narrow active zones when they are dispersed approaching 2.85 days. Although there are some active regions here, overall activity is extremely low. The number of days in the year 2017 ranges from 22.8 to 50. These spectral lines are spread to 20 - 45.6 days and have a periodicity of 19 - 42 active days from February to June 2018 and 70.2 to 91.25 active days from April to October 2018. There is a scattered peak of approximately 9-22.8 days between the middle of 2017 and the middle of 2018. The high periodicity due to the corotating high speed streams and halo CME which causes the strong active geomagnetic storm. So, the activity of geomagnetic storm is varied with time, the 15 - 30 periods are essentially from January 2019 to March 2019 and July 2019 to October 2019.

Ram and Ashok (2022) about the geomagnetic storms that occurred between October 12 and October 14 and also about the differences in the properties of the interplanetary solar wind that they discovered using OMNI data from the geomagnetic event that occurred from October 12 to October 14. This image shows the geomagnetic storm in a moderate state. The geomagnetic storms that occurred between September 6 and 8, 2017, demonstrate the storm's strength. And the cause of it is the infiltration of solar particles with high energy into the earth's magnetosphere.

3.4 Spectrum Analysis of Sunspot Number of Solar Cycle 24

Raising phase

The raising phase of wavelet power spectrum in sunspot number from 2009 to 2011 be seen in this figure 10. The solar rotation period corresponds to the maximum phase of solar cycle 24, which is 27 days long. It is shown that the long time period between 15-25 days and 11 days exists from February 2011 to April 2011 and May 2011 to July 2011. Additionally, there are quasi-periods of 40-50 and 150–180 days in the periods from March 2011 to October 2011 and from September 2010 to April 2011. The periodicity varies with length between 11 to 14, and in September 2011 only a small patch of active sunspots is seen. The existence of active region of sunspot in power spectrum due to the changes in the Sun’s magnetic field lines. The Solar Cycle 24, which is at a lower activity level and its climbs throughout the ascending phase.

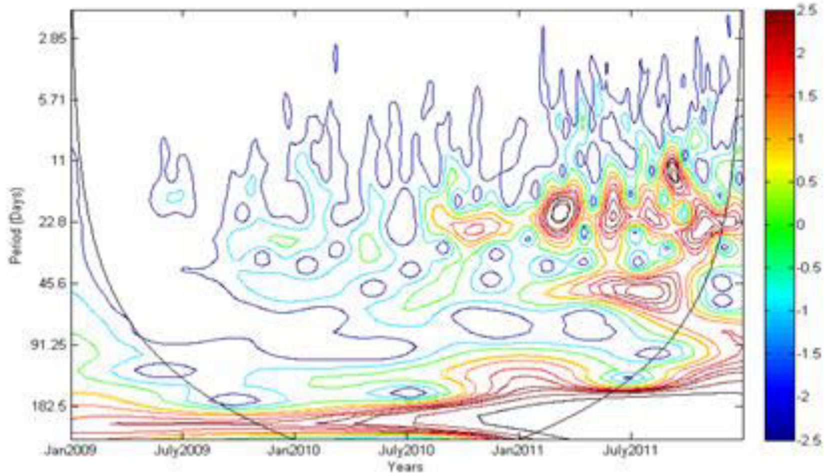

Figure 10: The wavelet spectrum of the rising phase of Sunspot number from period 2009 to 2011.

Tong, Xu, et al. (2007) also predicted figures for solar cycle 24's sunspot number of 112, which are displayed, prior to 2011–2012. The amplitude of solar cycle 24 is smaller than that of cycles 21, 22, and 23, which is in line with research conducted by Binod Adhikari et al. (2019), Duhau, S. (2003) and Wang, J. L et al. (2002).

Maximum phase

The Wavelet Power Spectrum of Maximum Phase in Sunspot Number from 2012 to 2015 shown in figure11. The scattered periodicity, which has a length of 18 to 100 days, initially emerges in February 2012 and lasts until April of the following year. The spectrum is visible during the years of 2012 and 2014. Between March and the end of roughly August 2015, a number of other quasi-periods with lengths between 20 and 40 days have been discovered. A scattered peak of spectral lines from 13 to 45.6 is visible from August to October 2015. Between 11 and 22.8 days, a minor pair of spectral lines emerge between July 2013 and December 2014. Grinsted et al., (2004) the study prove that the spectral power was comparatively weak at high frequencies or for brief periods of time. However, at scale factors (i.e., periods) of roughly 16 to 64 days, between September 2012

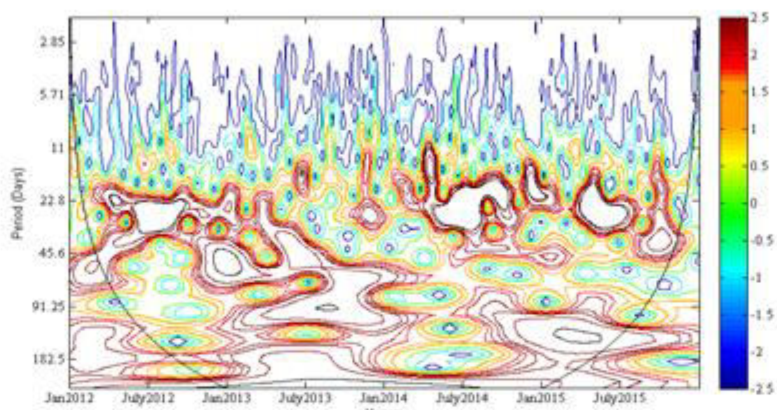

Figure 11: The wavelet power spectrum of the maximum phase of Sunspot number from period 2012 to 2015.

and May 2015, it is not hard to locate several distinct dual-patches of noticeably higher shapes. For the number of sunspots, large oscillations in the time flow are found to have a periodicity of approximately 27 days. The other tiny peaks cannot be dismissed as a coincidence because of multiple testing. Poudel et.al, (2020) In his study, fewer sunspot counts were observed at the beginning of solar cycle 24, which increased to over 100 between 2012 and 2014 before counting zero once more by the end of 2019, marking the conclusion of solar cycle 24.

Declining phase

This periodicity is shown to be strongest for solar variables around the sunspot maximum and for heliosphere variables in the late declining phase of the solar cycle (Mursula and Zieger, 1996, 1998). Mursula and Zieger (1996) likewise observed the strongest 13.5-day periodic intervals in heliospheric and geomagnetic variables during the late falling phase of the solar cycle. Both

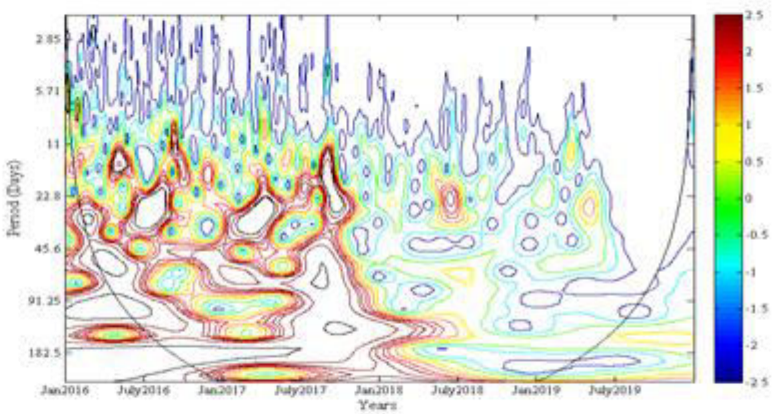

Figure 12: The wavelet power spectrum of the declining phase of Sunspot number from period 2016 to 2019

Nayar et al. (2001) and Rangarajan and Iyemori (1997) reported that the solar geomagnetic properties exhibited a 27-day periodicity. Although the recurrence duration of a solar cycle is always 27 days, as observed by Bogart (1982), the rotational time varies from cycle to cycle. Both Hugrs and Kesteven (1981) and Mursula and Zieger (1996) observed that the geomagnetic activity throughout the preceding three cycles and the solar flux of 10.7 cm show strong patterns with a period of around 25 days.

3.5 Spectrum Analysis of Geomagnetic Storm of Solar Cycle 25

Raising phase

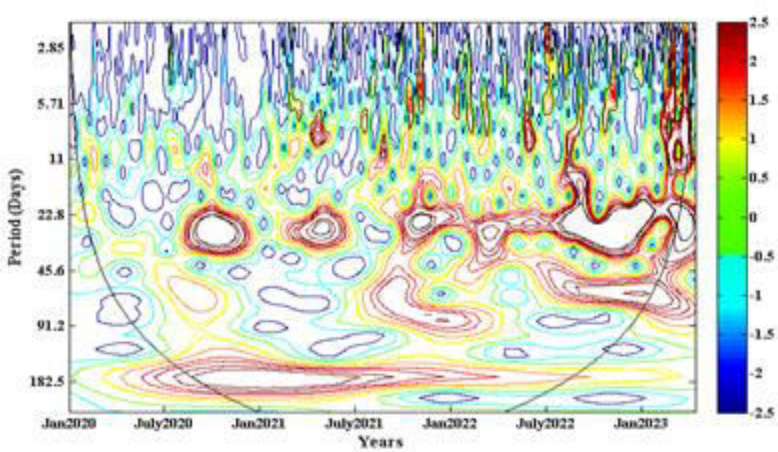

Figure 13: The wavelet power spectrum of the raising phase of Geomagnetic storm from period 2020 to 2023.

The wavelet power spectrum of an increasing geomagnetic storm in solar cycle 25 from 2020 to 2023 is shown in Figure 13. A series of oscillations with various amplitudes of 24-40 days occur between August 2020 and early January 2021, as well as a regular fluctuation of 24-38 days between February 2021 and early July 2021. Most people may see the quasi spectrum between 5.71-11 days. The length of the period corresponding to the solar rotation fluctuates between August 2021 and April 2022, ranging from 42.6 to 91.2 days. For nearly two years, roughly from the middle of September 2021 to the middle of September 2022 to the beginning of April 2023, the scattered peak of between 40 - 85 days is observed sporadically by the existence of active region along with the high-speed coronal mass ejection (Gopalswamy et.al, 2020). In this result the distribution of sky-plane speeds of 91 CMEs observed during SCs23, 24, and part of SC 25 that caused intense storms.

The 27-day cycle makes it possible to forecast the daily levels of geomagnetic activity with reasonable accuracy. When the pattern was strong, the forecast was more accurate (Hapgood, 1993). It has long been known that the Earth's magnetosphere interacts with fast-moving solar wind streams that co-rotate with the Sun to create recurrent geomagnetic activity that lasts about 27 days (Wilcox and Ness, 1965). They also projected solar cycle 25 using these inferred regressions. Their research revealed that solar cycle 25 would peak in April–June 2023 at an amplitude of 33.4 - 112.3, and that the next minimum would occur in December 2018–January 2019. Furthermore, they speculated that cycle 25 may be one of the weakest.

3.6 Spectrum Analysis of Sunspot Number of Solar Cycle 25

Raising phase

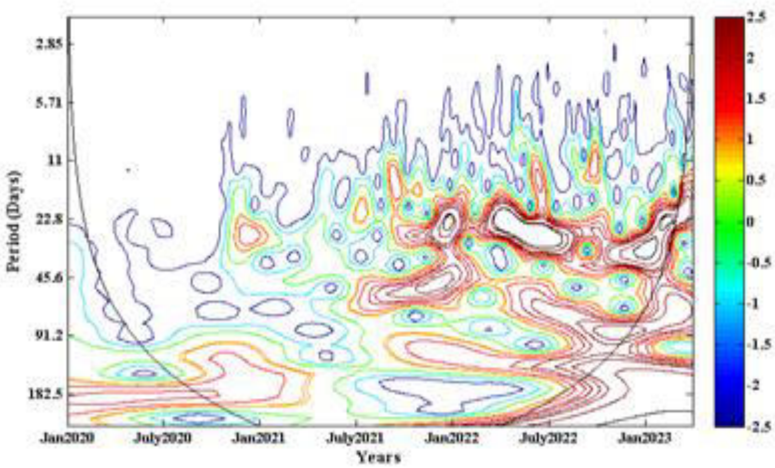

Figure 14: The wavelet spectrum of the raising phase of Sunspot number from period 2020 to 2023.

Figure 14 shows the solar cycle 25 rising phase power spectrum for the sunspot number data from 2020 to 2023. By the end of 2020, variable periods ranging from 22.8 to 30 days have been identified. a quasi-period with a variable amplitude of the day 25 and 100 - 182.5 days in July 2020, as well as between October 2020 and April 2021. Since this area is more active, the scattered contours with a variable duration of 11-160 days are edge-affected on the right side from June 2021 to April 2023. The high periodicities due to solar wind velocity. Periods longer than 53 days may have started because of activity in the concentrated magnetic fields found in sunspots, not in more diffuse field regions (Ozguc and Atac, 1994).

Hathaway & Upton (2016) and Gopalswamy et al. (2018) predicted that cycle 25 will have moderate amplitudes, while Cameron, Jiang & Schüssler (2016) hypothesised that cycle 25 would be somewhat stronger than the current one. Predictions of a comparable or larger cycle 25 are in line with the results of this study when compared to the present cycle 24.

4. CONCLUSION

Morlet wavelet spectral approaches were utilised to identify significant period in the spectrum of Geomagnetic storm and Sunspot observed by NASA Goddard Space Flight Center's website throughout recent solar cycles. The dominant line in the time series of solar activity geomagnetic storm and sunspot were observed to have solar cycle. During the recent solar cycle raising phase of a geomagnetic storm, short term periodicities were more apparent in solar cycle 23 than in solar cycles 24 and 25. When comparing Solar Cycles 24 and 25, the active zone in the wavelet spectrum of the raising phase of Solar Cycle 25 is larger. This revealed that regional variation affects the periodicities in high during the solar cycle 23 geomagnetic storm increasing phase. For the maximum phase, solar cycle 23 has a higher periodicity than solar cycle 24, however for the declining phases, solar cycle 24 has a higher periodicity than solar cycle 23. From the result the Sunspot number raising phases of solar cycles 23, 24, and 25, the raising phase of Solar Cycle 23 has a lot of prominent lines with high intensity from the beginning of the increasing phase, but the raising phase of Solar Cycle 24 has fewer prominent lines than 23. When Solar Cycles 24 and 25 are compared, the active zone in the wavelet spectrum of the rising phase of Solar Cycle 25 is greater. According to the observations, the periodicity of solar cycle 23 is greater at the maximum and decreasing phases than that of solar cycle 24. This research looks at the periodicity of the wavelet spectrum during the rising phase of solar cycle 25. They calculated the greatest number of sunspots for 2021, and solar cycle 25 is higher than solar cycle 24 in this periodic study of rising phase of geomagnetic storm and sunspot.

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