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Interrelationship among various solar activity parameters from solar cycles 21 to 24

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Abstract: *The scrutinization of the interdependence among diversified solar indices is the key incentive of this paper. The assorted solar activity parameters such as sunspot number (SSN), solar flux (SF, 10.7cm), grouped solar flares (GSF), solar flare index (SFI), coronal index (CI) for the 11-year sunspot cycles 21-24 have been examined. By employing the monthly data of the distinct solar indices SSN, SFI, GSF, CI, SF (10.7 cm) for the 11-year sunspot cycles 21-24, an intricate correlative investigation has been accomplished. Nevertheless among all the parameters, SSN has been an elite SA index depicting the potent correlation with the other indices. The correlative study demonstrates that SSN and SF are highly correlated and disparate characteristic nature of SSN for GSF and SFI. Also the current analysis shows an uninterrupted fall in the slope of regression lines between SSN and SFI as the cycle advances (from 21 to 24). Similar results are verified from the peak value of SSN and SFI. This information elucidates the basic substantial processes amenable for solar activity and their universal accord.*

Key Words: *Sunspot number / solar flux / Grouped solar flux / Solar flare index / Coronal index*

1. INTRODUCTION:

The aggregate of all fluctuating and momentary disturbances on the sun as sunspots, prominences and solar flares is called solar activity. The necessary parameter of solar activity is the Zurich or wolf sunspot number, suggested in 1848 by Rudolf wolf. This number makes it easier to explicate the physical mechanism and delivers the prolonged, sustained measure of timely variations in solar activity and is given by the formula $R_{z} = k(10g+n)$, where k is correlation factor, g the number of sunspot group and "n" the number of individual sunspots. Today the monthly and yearly recent data are made available online by different observatories like the Sunspot Index Data Center in Brussels, Belgium [Atac T et al;]. The solar activity revealed through various solar parameters for example, sunspot number (SSN), Solar Radio Flux (10.7cm) and the supplementary solar parameters comprising the entire electromagnetic spectrum from energetic X-rays and UV radiation , each depicting distinct physical conditions in solar atomosphere [Altrock RC, et al, 1999]. The nature and design of the magnetized solar plasma help to figure out the solar activities. Solar flares are massive eruptions on the sun which occur when energy stored in contorted magnetic fields (often over sunspots) is abruptly ejected. They are believed to be due to quick conversion of huge quantity of magnetic energy (accumulated into corona) depleted through magnetic reconnection. The energy explosion occurs for minutes to hours and can extend to value upto 10^{26}J (10^{33}erg). The first solar flare as a local momentary flash on the white-light perception was noticed by R.C Carrington and R. Hodgson on 1st September 1859 [Mari G et al., 2004 , Feng S, Yul, et al., 2013; Hathaway DH; 2015]. However grouped solar flare is the main flare index. The word "grouped" refers to all the investigations, conducted at various places on the identical flare event through distinct solar observatories, collected and count as one. The different flare indices such as heliographic coordinates, the start, maximum and end time of the flare, duration, apparent and correlated areas, optical significance are inferred by utilizing the information of whole investigation.

By performing different studies in the solar-terrestrial Field, the solar flare has been systematized as a key solar event influencing the earth. The solar flare parameter Q, proposed by Kleczek in 1952 to explain the H_α flare over a 24-hour duration is given by Q= i*t, I indicates the important intensity scale of flare in H_α and t -the duration of the flare in minutes. This expression is proposed to give the net energy ejected by the flares in H_α line .To determine the value of momentary activity of the sun's atmosphere; the solar flare parameter is important for that.

Though there are various solar activity parameters for example faculae, flares, coronal holes and electromagnetic radiations in several bands (10.7 cm radio flux, green corona etc), displaying the solar activity. Nevertheless the most important investigated time series in the solar physics is the sunspot number. The 11-year sunspot cycle is the most clear-cut characteristic (also called the Schwabe Cycle), depicting the long-term variation of solar activity that is far from a basic sinusoidal wave. The SSN has been utilized usually as an ideal solar parameter for numerous studies related with sun-earth interdependence [Dorman and Dorman, 1967; Pomrantz and Duggal , 1971; Rao, 1972; Webber and

Lockwood , 1989]. After the accessibility of diverse solar indices, different investigators have used unpredictably amalgamation of various indices for their analysis [Dodson et al., 1979; Mavromichalaki et al., 1988, 1990; Ahluwalia, 1998, 2003; Van Allen, 2000; Chattopdhyay et al. 2003; Usoskin et al., 2001, 2003, Hathway et al., 2002; Kane , 2005; Gupta et al ., 2006a, 20060b]. The frequently used indices are sunspot numbers (SSN), solar flux (10.5 cm), grouped solar flux (GSF), Solar flare index (SFI) coronal index (CI).

A cycle of disturbances in the sun and its atmosphere of an average length of about 11 years is called a solar cycle. The mean number of sunspots seen on the sun's surface fluctuates from a minimum near zero to a maximum of almost a hundred. After every 11-year, the sun goes over a period of fewer, smaller sunspots, prominences and flares known as solar minimum and a period of higher, larger sunspots, prominences and flares called as solar maximum. The magnetic poles are reversed after every 11-year.

The 10.7 cm SF is available on daily basis since 1947 and monthly from Feb 1947. The Zurich sunspot number $R_{z\ is}$ available since 1749 and beyond .The SF 10.7 cm finds its application as a simple activity level indicator, as an intermediatory for rest of the solar ejections which are otherwise tedious to obtain. The rest essential parameters (solar radio flux 10.7 cm , grouped solar flare , green corona line index , sunspot area etc) are also used to explain solar activity considering a variety of database and correlation studies, it is observed that there is a strong correlation between SSN and SF even on a monthly mean basis. However, some researchers still favour adopting both of these solar parameters (monthly or yearly) to correlate them for solar -terrestrial phenomenon [Hathaway D and Robert et al., 2002].

The effect of solar variability on the heliosphere, biosphere and climate of earth is more and more evident. The green line coronal index was proposed first by Rybansky (1975). The extensive indicator , (the coronal green line index) identifies the existence of durable coronal structure and serves as a daily irradiance ejected by green corona (Fe XIV, 530.3 nm line into one steradian towards the earth) [Rybansky M et al ., 1994, Kane RP, 2015; Minarivjech M et al.,]. Altrock Rock et al have recorded CI as the index to analyze STR and is found on the irradiance of the green corona (Fe XIV, 530.3 nm) examined by ground- based coronagraphs on daily basis investigation. The maxima of CI cycle have been noticed to be risen by a factor of two.

Different tendency of regression lines carrying out solar cycle relationship between SSN and the frequency of prime flare happening after considering the more essential flares only on a yearly basis has been outlined. At a recent time, the long-term variation of various solar, interplanetary, and geomagnetic indices during the previous sunspot cycles have been noticed and is observed that SSN and SF depict same 11-year variations of fluctuating amplitude.

It is observed that the slope of the regression lines between SSN and SFI, GSF regularly declines from SC 21-24 although their correlation was completely notable. A fairly new way to examine and correlate the characteristic aspects of various solar activity indices in relation to SSN has been attempted in this paper.

2. Data sources and methods:

The majority of the solar parameter data (SSN, SF-10.7 cm, GSF, SFI and CI) have been taken from the website of NOAA (ftp;//fttp.ngdc.noaa.gov/STP/SOLAR-DATA/…html) accessible 'in public realm 'being available for decades through solar geophysical data, the monthly publication of NOAA Bouldaro Colarado, USA.

3. Running Cross correlation:

A "runnning" cross correlation technique has been employed for analyzing the short-term interdependence between SSN and flare activity parameters GSF and SFI [Usoskin IG et al ., Mishra VK, et al., 2003] in this paper. A time window of width T pivoted at time t: [t-T/2, t+ T/2] has been employed in this method. The cross-correlation coefficient r (t) is determined in the window for the data and the window after that is shifted in time with small time step $\Delta t < T$, and a next value of the cross-correlation coefficient is evaluated. Time shift of one month has been considered to determine the correlation coefficient monthly between SSN and flare activity indices [GSF and SFI] throughout the whole course of analysis. This selected value helped to correlate two contradictory concerns (1) the uncertainty of the determined r(t) are lesser for large T and (2) T should be small so that it acknowledges the accomplished sensual framework of cross-correlation function. Various time periods such as 40, 50, 60 and 70 months have been assessed to opt the period for the time window in this investigation. The observation reveals that 50-month period for the window is pertinent as it appears both contrary previous requirements.

4. Monthly moving average:

The observation of the long-term relationship for assorted solar activity parameters such as SSN, SFI and GSF have been taken into account. The monthly moving average is used to correlate the nature and distinctive aspect of different indices and has been determined to sweep away the variations of data series. This method has been studied because of its being close to first zero of the autocorrelation function and approximately one-fourth of the principal period (11-years). It solely makes the changes in the data uniform. This is attained by "moving" the average values over the time series and the information should pursue adequately linear trend and possesses a categorical rhythmical arrangement of variations.

5. Results and Discussions:

To observe the Solar and Terrestrial Relationship (STR), the sunspot number (SSN) of long-term solar activity is considered as a predictable index in the field. Furthermore a large number of other solar parameters for example GSF, SF (10.7 cm) , coronal index help to check out the determined value and distinctive aspect of long-term variation of 11-year sunspot cycles, especially from ionospheric examination .The solar data being acquirable through different web sites, it is suitable to examine the relationships between such parameters and the most appropriate solar parameter for several STR studies is figured out. We have been taking into account the monthly average values of the solar parameters for research described in previous section.

SSN and SF relationship:

In this work, it has been observed that SSN and SF display a strong correlation which is found to be ~ 0.981,~ 0.986, ~0.976 and ~ 0.944 for the solar cycles 21 to 24 respectively shown in figure 8. So it is clear that for STR investigations, either SSN or SF parameters are considered sufficient enough for depicting identical conclusions. After checking out the correlation coefficient (≥0.96) is stronger with the advancement of solar cycles 21 to 23 except that of solar cycle 24 (a lower activity cycle as compared to others) as displayed in table-1.

Sunspots and Solar Flare indices:

We have performed the monthly moving average to check out the momentary variations of the data series to contrast the subjective nature and changes in several solar parameters. Fig-1 shows the monthly moving average of SSN, GSF and SFI. The disagreement in the peak value as obviously visible and ceaselessly declining from SC 21 (peak value for SC 21 is higher) while it is otherwise in cycles 22 and 23. For SC 21 to 23, there is a decline in the dissimilarity between the peak of SSN and SFI, and for SC 21, it is higher. There could be two reasons for the higher peak difference between GSF and SFI for SC in contrast to other cycles. Either due to inadequacy of more essential flare occurrences or the large duration of flares during the given cycle exhibiting irregular relationship between SSN and SFI.

Table 1. The correlation coefficient for solar cycles 21 to 24

Solar cycle	SSN-SF	SSN-GSF	SSN-SFI	SSN-CI
SC 21	0.981	0.963	0.903	0.908
SC 22	0.986	0.922	0.917	0.991
SC 23	0.976	0.900	0.778	0.975
SC 24	0.944	NA	0.566	NA

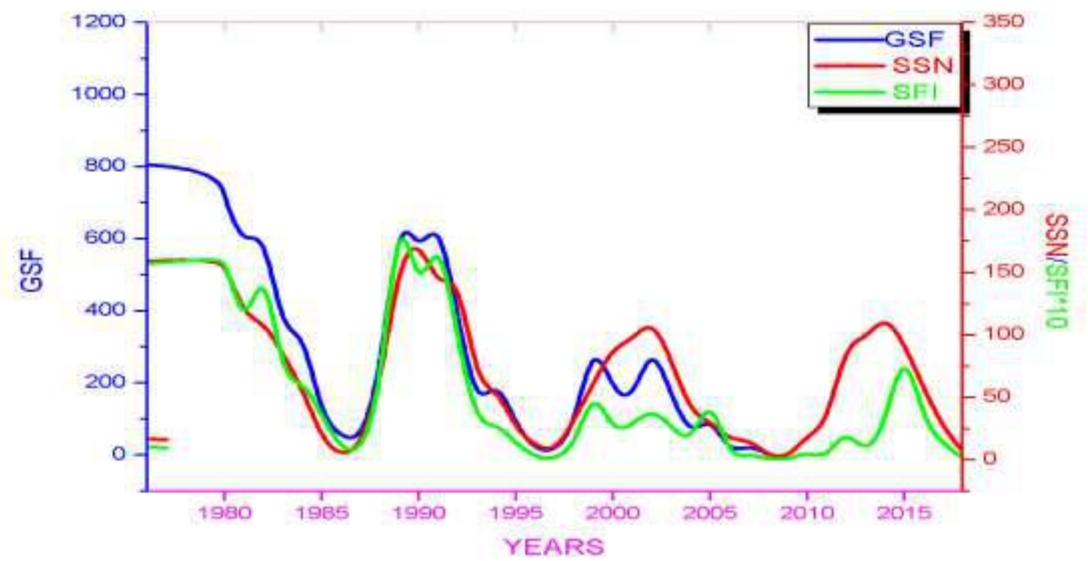

Fig. 1 shows the monthly values of SSN,,SFI and GSF during the period of 1976 to 2018.There is an obvious difference in the peak value of SSN, GSF and SFI.

Generally except for the maxima, the GSF and SSN series accompany each other and depict higher correlation during rising and declining phase and feeble during maxima and minima as is obvious from fig-5. The cross plots drawn between SSN and GSF for SCs 21 to 24 are shown in fig-1 and is obvious that correlation coefficient is weaker as compared to correlation between SSN and SF and is ~ 0.900 (lower) or higher with the largest value ~ 0.96 for SC 21. The correlation coefficient is nearly same for SCs 21 and 22 (~0.96 and ~0.93 *and* ~ 0.90 for 23) as shown in table-1. Furthermore it has been noticed, by using the statistical value of SSN-GSF, that regression lines are remarkably contrasting

From each other and the slope of regression line is found uninterruptedly declining and approaches to X-axis shown in figure 2. The regression line for SC 21 implies that for SSN (~ 100), GSF is more (~ 564) where as for SC 23 , SSN being the same , GSF is considerably low (~ 329) also clear from the above observation of the from fig- 2.

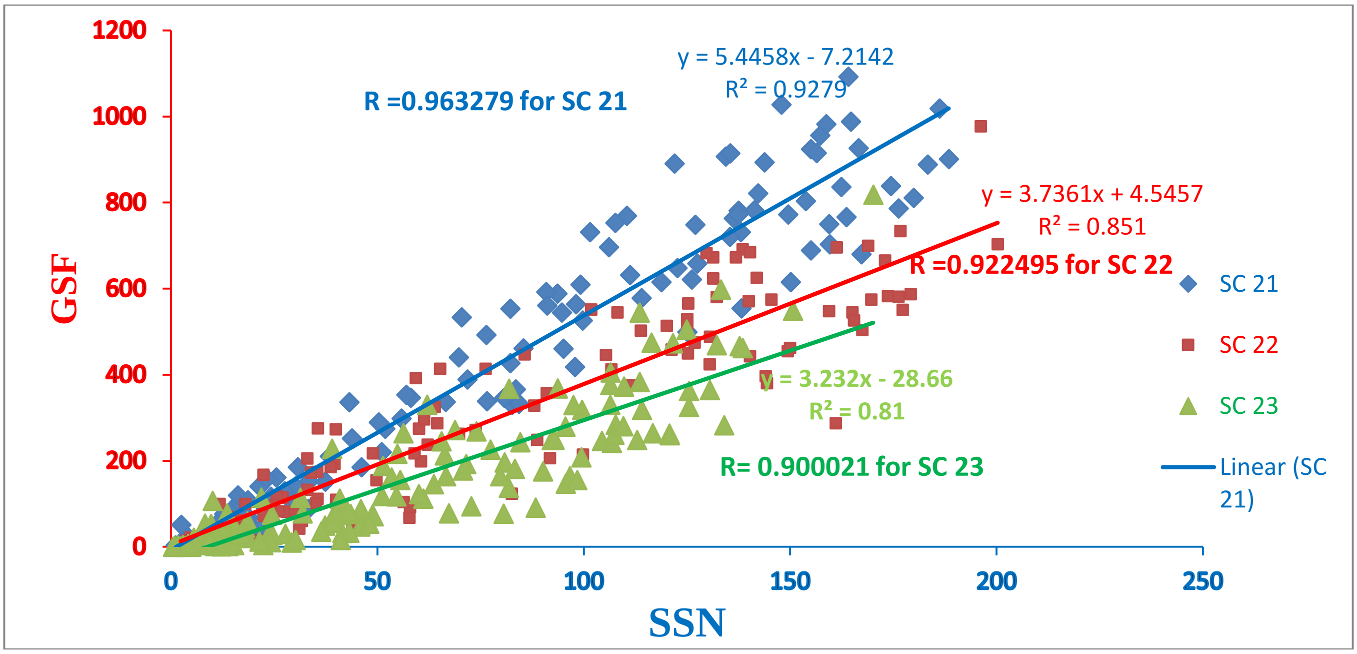

Fig. 2. The above figure displays the cross plots between SSN and GSF for the solar cycles 21 to 23 and the different trend of regression lines tending towards x-axis.

Table 2. **Total and average value of SSN, SFI and SF for solar cycle 21-24.**

Solar cycle	Total value of GSF	Avg. value of GSF	Total value of SFI	Avg. value of SFI	Total value of SF	Avg. value of SF
SC 21	538835	423.89	1156.7	8.76	16934.15	133.33
SC 22	3583.7	298.63	844.36	7.03	16025.18	133.54
SC 23	21765	151.14	459.36	3.19	17705.51	118.84
SC 24	NA	NA	294.81	2.45	13885.57	96.42

The mean value of GSF for solar cycle 21 to 23 has been shown to be ceaselessly falling and this proves the above observation shown in table-2. However it is obvious from the slope of trend line in fig. 3, the GSF value in comparison to SSN (GSF and SSN ratio) falls regularly for solar cycle 21 to 23. During the minima of solar cycle 22 (1986), the value of GSF was abnormally large (=51 in relation to SSN =2.5), which has not been examined in the minima of rest of the solar cycles. So a requirement of further research is important to probe why during the solar minimum such a large value of GSF is obtained.

The SFI and GSF explain clearly the happenings of dynamic flare outcome over sun's atmosphere through the center of the core. The scattered graph has been drawn between SSN and SFI for solar cycles 21 to 24 (SFI data available upto 2018). There is an uninterrupted decline in the regression line and approaches to X-axis for solar cycles 21 to 24 demonstrated in fig-4.

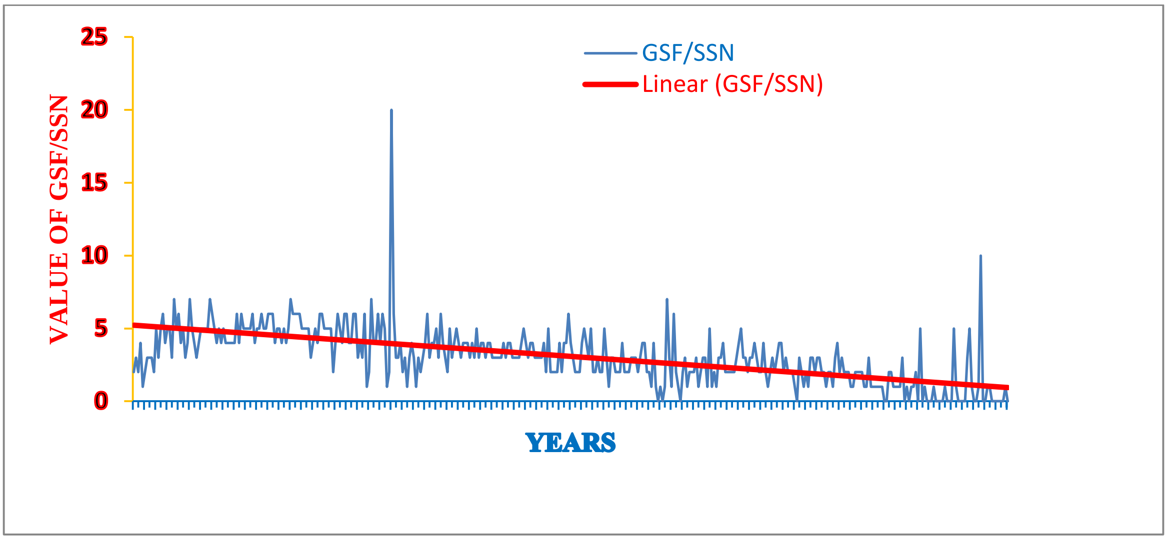

Fig. 3 The decreasing trend of GSF/SSN ratio with respect to time, is analyzed throughout the investigation period from SC 21 to 23.

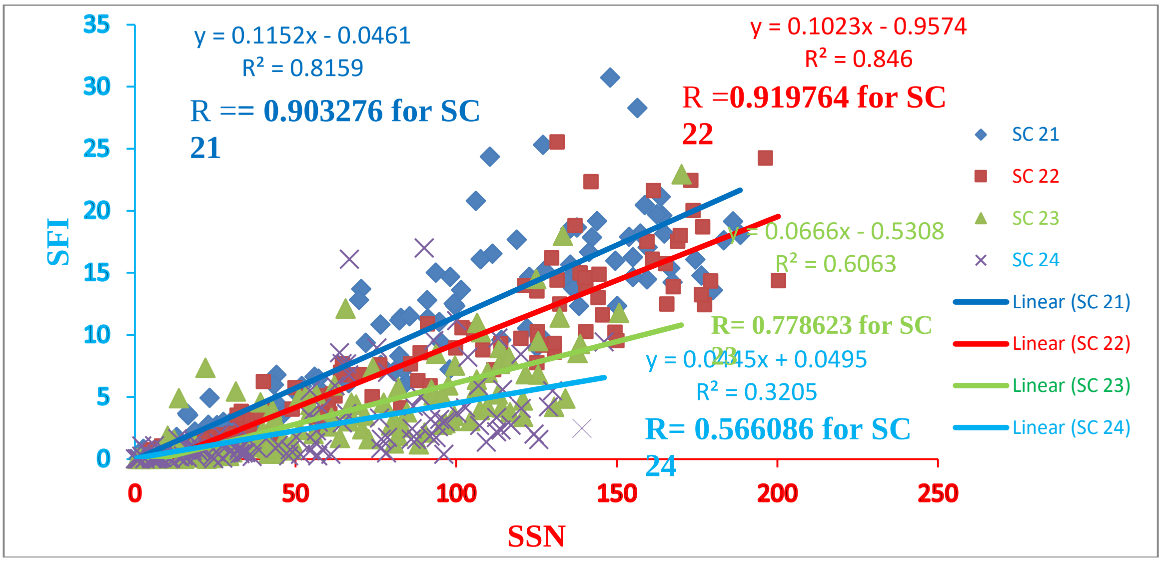

Fig. 4. The cross plots between SSN and SFI for the solar cycles 21 to 24. The regression lines show an uninterrupted trend towards x-axis from SCs 21 to 24.

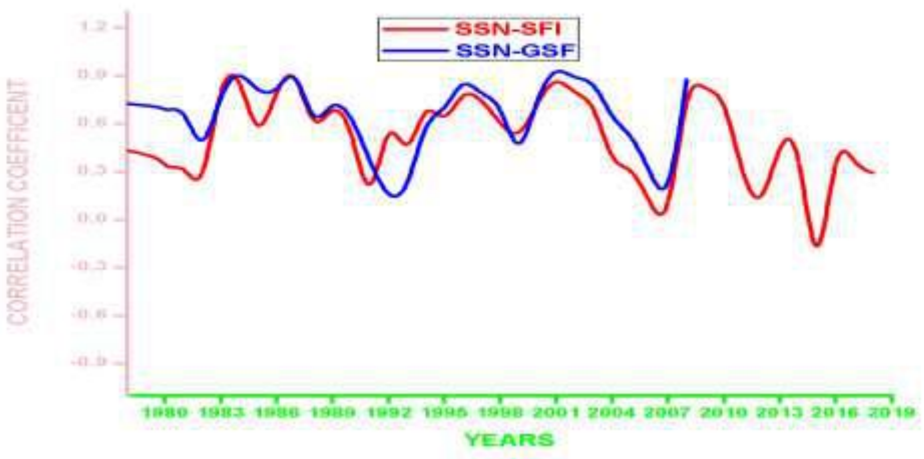

Fig 5.The monthly running cross-correlation function between SSN and GSF during the period 1976-2008 and SSN-SFI for the period 1967-2018.

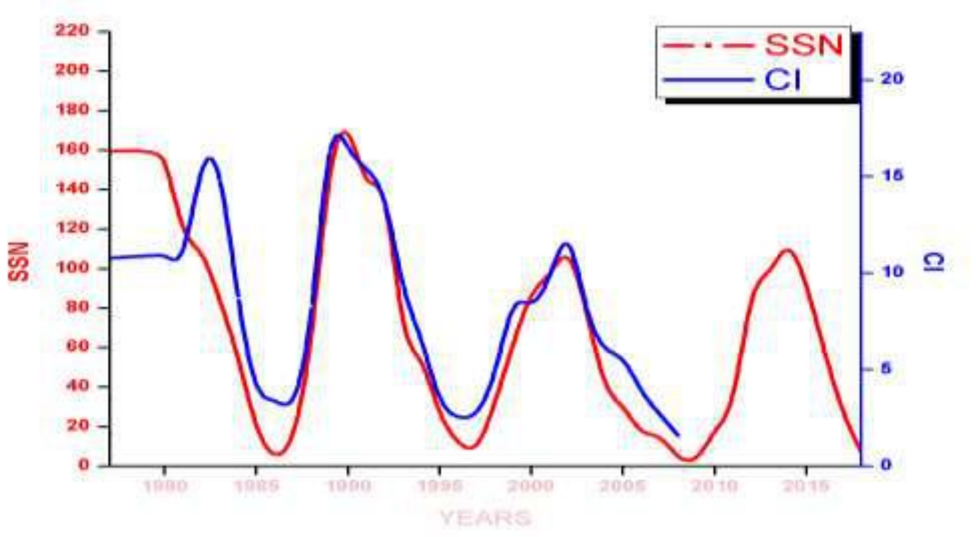

Fig. 6 The monthly cross-plots between SSN-CI during the period 1976-2018.

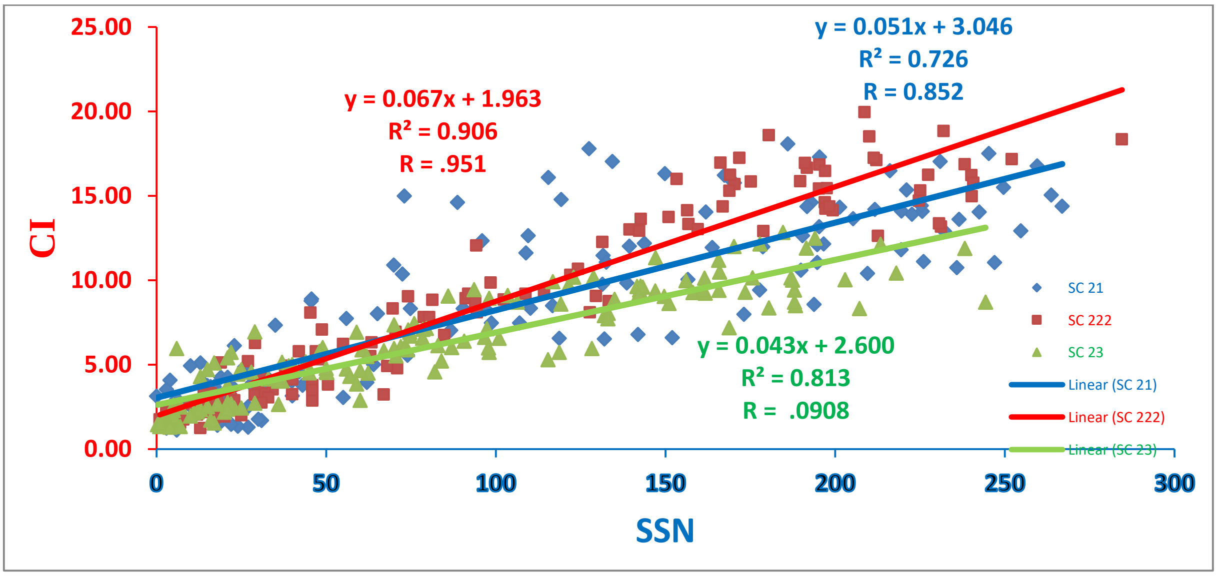

Fig. 7 shows the regression line between SSN and CI for the solar cycles 21- 23.

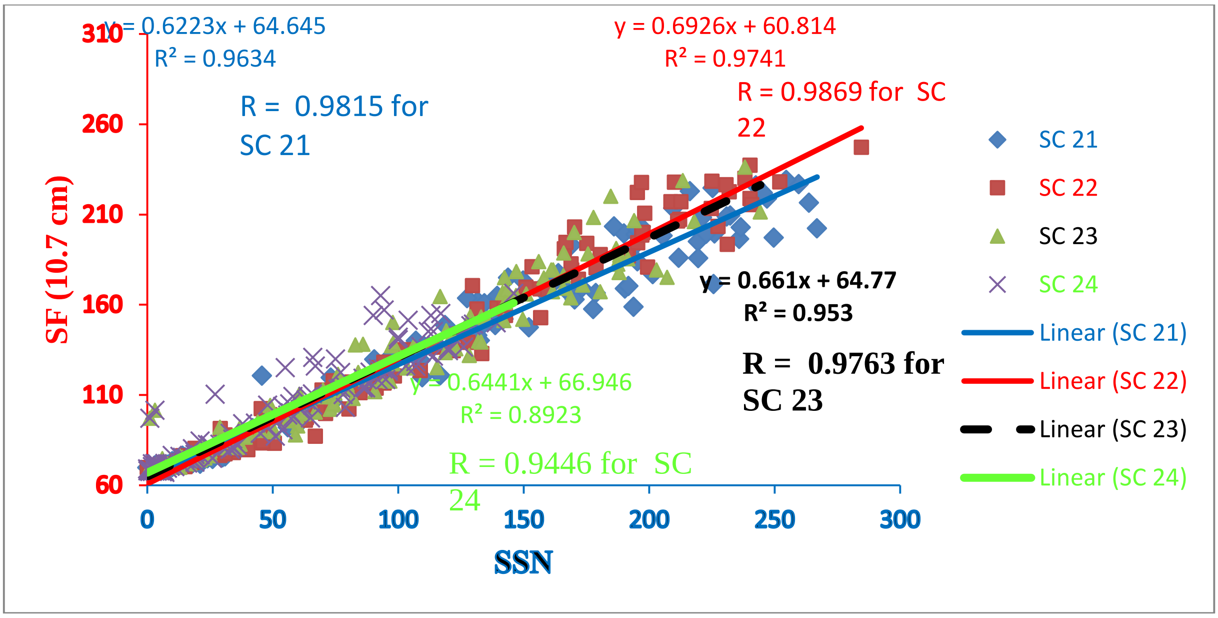

Fig. 8 The regression lines between SSN and SF.

The correlation coefficient for solar cycles 21, 22, 23 and 24 are 0.904, 0.919 (highest), 0.779 and 0.567 respectively. It is thus obvious that cc is stronger for SCs 21 and 22 (≥ 0.90) and 24 yields the lowest, 0.567 (data available upto 2018) as displayed in table-1. Next eye catching characteristic is that the net value of SFI uninterruptedly declines from solar cycle 21 to 24. So our investigation verifies that there is a ceaseless fall in the flare activity in relation to SSN shown table 2. SFI bears the highest value for SC 21 (~12.51), smallest for SC 23 (~7.54) for the same value of SSN (~100) as seen in fig-4.

However after determining the monthly running cross correlation between SSN-GSF and SSN-SFI, for the entire research period, it is apparent that along the rising and declining phase fig-5, the SSN-GSF correlation is stronger. Furthermore the minimum value of cross-correlation coefficient has been acquired during the maxima of solar cycle or shortly after it (i.e. , 1980, 1988, and 1998) consecutively for solar cycle 21-23. By virtue of this outcome, different conclusions about local solar disturbances during the maximum activity period has been verified. There is an unbroken decline in the peak differences during the maximas (fig-1). With the advancement of cycle the correlation between SSN and solar flare activity parameters (GSF and SFI) is stronger verifying the above results. And for SCs 21-23, the cc between SSN and SFI depict same results.

SSN and CI relationship:

To extend our investigation, we have taken another index called CI. It is the peripheral –extremely hot and diluted- layer of solar atmosphere with electron density 108 cm^{-3}, the most excellent measure of the solar activity in the emission corona. Fig -6 shows a plot between the monthly average value of SSN and CI. It is observed that SSN and CI bear immediate relationship for long- term variation. We have also investigated notable differences in amplitude and nature of odd-even CI cycles in congruence with the SSN and the odd cycles (21,23) depict identical behavior and even solar cycles exhibit same behavior by virtue of peak difference, thus proving the odd-even imbalance shown in fig-6. Table-1 shows cc between SSN and CI. Fig-7 demonstrates the identical trends in the regression lines for odd (21 and 23 and even (22) SCs. Solar cycle 23 has a unique regression line different from others (21, 22).

6. CONCLUSION:

This study has revealed notable differences in the nature and amplitude of odd-even solar cycles [Wilson RM et al., 1988, Mursula K et al.,2001; Yoshida A. et al ;2014; Durney BR, 2000].This is due to non-linear interaction which displays study tool for cycle's amplitude and is higher for even SCs in contrast to odd ones. To best identify the 22-year SC is by virtue of its alternate magnetic field polarities of the bipolar sunspot groups in the neighbouring 11-year cycles .They can also be indicated by the solar corona magnetic fields topography also when deduced from the undeviating field measurement at solar photospheric level. This study concentrates on the nature of long-term variation dependence on the solar output and flare activity. A strong correlation between SSN-SF exists if and only if GSF and SFI are also highly correlated with SSN for both photospheric and chromospheric phenomena. Majority of the researchers are analyzing the physical structure to probe the relationship among fluctuations of solar parameters in the various phases of 22-year of magnetic cycle acknowledged by the 11- year periodic observation. These outcomes deliver a proposal to figure out the regional solar disturbances as regards to general level activity.

From the discussion based on the statistically and numerically determined value, following conclusion is drawn:

1. There is a strong correlation between SSN and SF (≥ 0.978) for SCs 21 to 23 and 0.944 for SC 24. If correlation coefficient is ≥0.95 for any correlative analysis, any one of the two parameters can be used to observe the solar Terrestrial-correspondence.
2. It is found that cc between SSN and SF is stronger as compared to SSN and GSF. Its value is ~0.94 (lowest) for vsolar cycle 24 and high (0.987) for solar cycle 22. SSN and GSF have almost same value for SC 21 and 22 (~0.96 and 0.92) and 0.90 for SC 23. However there is a considerable fluctuation in the slope of regression lines which tends to lower side on the cross plots depicting that there is is an unbroken reduction trend as the cycle advances (21 to 23). For the confirmation of our result, the net determined value of GSF is continuously reducing from SC 21 to 23. Similar trend happening for GSF in relation to SSN (GSF/SSN) for the entire study further confirms the result derived above.
3. SSN and SFI are strongly correlated during SCs 21 and 22 with cc ≥ 0.90 and 0.778 for SC 23 and for solar cycle 24 it is the lowest ~0.566.The regression lines however show considerable difference and their slope decreases from SC 21 to 24 as it advances.
4. It is observed that peak value is higher for even cycles in contrast to odd ones. The correlation between SSN and CI is higher for SC 22 (0.98). Also it is found that the trends of regression lines between SSN and GSF for odd and even SCs are almost same but the SC 23 depicts a specific nature in contrast to other SCs due to its less activity

From the above statistical investigation and discussion, it is concluded that there is a continuous reduction in the flare activity from solar cycle 21 to 24.

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