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Classification and Study of Solar Flares: A Comprehensive Analysis Spanning 1990–2022

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Abstract: The surface of the sun constantly bellows, fluctuates and twists due to its varying magnetic field activity. Due to the release of magnetic energy associated with the sunspots an intense burst of radiation coming out is known as solar flare. Flares are caused by the release of magnetic energy of 10^{29} to 10^{33} erg in the solar atmosphere with the duration of few seconds to minutes. In this article, we have shown a data collection of solar flare (number of flare, flare index and their classification in different cases) and its analysis by graphical representation. We have also studied the statistical analysis by calculating the correlation coefficient between yearly sunspot numbers and different class of flares during period 1997 – 2022. It can be clearly seen from the data observations that the flares occurs most during the solar maximum and least at solar minimum.

Keywords: Solar Flares, Sunspot Activity, Magnetic Field, Solar Maximum and Minimum, Radiation Bursts, Solar Dynamics.

1. Introduction

Our Sun is the nearest star and the largest object in the solar system. The sun is made of plasma consisting of mostly super-heated hydrogen and helium gas that is in constant fluid motion within the interior and on the Sun’s surface. The Sun is continuously emitting radiations. The activity of sun is mostly due to the variation in magnetic field that is why it is called magnetic active star [1]. Solar flares are giant explosions on the Sun that send energy, light and high speed particles into space. When the solar activity is increases magnetic energy can build up in the corona or outer atmosphere of the Sun and eventually lead to relatively sudden release of this magnetic energy. This process can temporarily increase the brightness of the Sun. During the solar flare, magnetic energy of 10^{29} to 10^{33} ergs is released by means of magnetic reconnection [2]. The radiation contains frequencies throughout the spectrum but most of the flares are not in visible region [3]. The frequency of occurrence of solar flares varies from several per day when the Sun is particularly “active” to less than one every week the Sun is “quiet”, following the 11-year cycle (the solar cycle). Smaller flares are more frequent than larger ones. These flares often associated with solar magnetic storms known as Coronal Mass Ejections (CMEs).

The first recorded observation of a solar flare was made by Richard Christopher Carrington on September 1, 1859 at his private observatory at Redhill, outside London [4]. The estimates of the storm strength (Dst) is range from -0.80 to -1.75 µT. Hudson's 2021 study estimated that the radiation from the Carrington flare likely carried about 4×10^{32} ergs of energy, which is about as much as 10 billion 1-megaton nuclear bombs. He also estimated that the event's CME likely carried about 3×10^{32} ergs of kinetic energy [5].

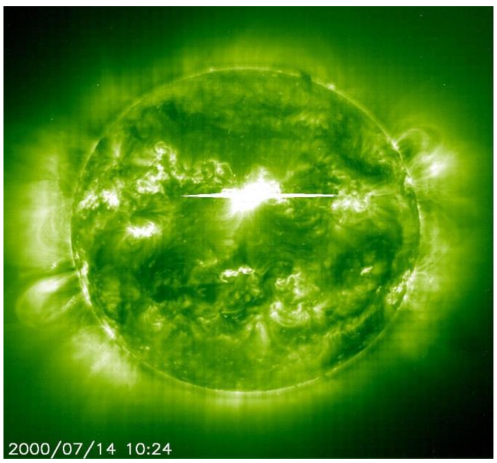


Figure 1 This SOHO animation of the July 14th X-class solar flare was recorded by the spacecraft's Extreme-ultraviolet Imaging Telescope at 195 angstroms.

2. Formation of solar flare

Solar flare is caused by magnetic reconnection phenomenon. Magnetic reconnection is process where magnetic field lines are broken and rejoined in highly conducting plasma. In this magnetic energy is converted to kinetic energy, thermal energy, and particle acceleration. When magnetic field lines on the sun come together they can realign into a new configuration. They can produce tremendous amounts of energy, powering gigantic explosions in the sun's atmosphere.

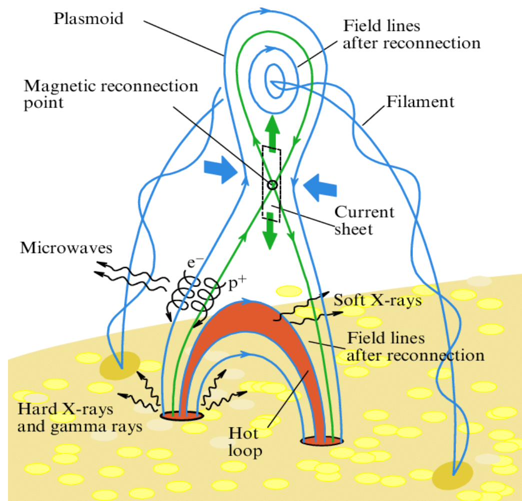


Figure 2 An illustrated model of magnetic reconnection on the Sun.

During solar flare, magnetic reconnection will dissipate magnetic energy which will cause particle acceleration and release of huge amount of emissions. The process of magnetic reconnection was first postulated by Giovanelli (1946) [6]. The concept of magnetic reconnection was first introduced in 1950 in the Phd thesis of James Dungey to explain the coupling of mass, energy and momentum from the solar wind into earth's magnetosphere [7] and was published for the first time on the open literature in his seminal paper in 1961 [8].

3. Classification of solar flare

3.1 *Soft X-ray classification*

In modern classification system as it uses the letters A,B,C,M or X, according to the peak flux in watts per square metre (W/m^2) of soft X-rays with wavelength 0.1 to 0.8 nanometres (1 to 8 angstroms), as measured by the GOES spacecraft in geosynchronous orbit.

(a) **Table 1:** X-ray classification

Class	Range (0.1 - 0.8nm) (W/m^2)
A	$<10^{-7}$
B	$10^{-7} – 10^{-6}$
C	$10^{-6} – 10^{-5}$
M	10^{-5} -10^{-4}
X	$>10^{-4}$

(b) **Table 2:** H – alpha classification

3.2 *Magnetic topology classification*

(a) Simple-Loop (Confined Flare)

Most flares and sub-flares are of this type. It is a small flare, in which essentially a single magnetic loop or flux tube brightens in X-rays and remains apparently unchanged in shape and position throughout the event [9]. They consist of single loop, typically 10,000 km high, with a temperature of 2×10^7 K and density of $10^{17} – 10^{18}$ m^{-3} [10].

(b) Two-Ribbon (Ejective Flare)

All major flares are of this type. Two ribbon flares are much larger than a compact flare and takes place near a Solar prominence, a loop of plasma confined between two magnetic field lines [9]. They take the form of an arcade of hot loops which rises at 20 km/s or more in the initial stages and at only 0.5 km/s later on, reaching an altitude of 1,00,000 km. The summit density and temperature are about 10^{17} m^{-3} and 2×10^7K at first, falling to $10^{16}m^{-3}$ and 5×10^6K after a few hours [10].

4. Solar cycle

The rise and fall in number and surface area of sunspots vary in a cycle that lasts about 11 years. The appearance of sunspots occurs initially in clusters about midway between the Sun's equator and the poles. The sunspot number increases over the next few until it reaches a peak of 100 of more sunspots. The number of sunspots begins to decrease after the peak and it reaches a minimum. During the sunspot cycle the solar pole gets flip — north becomes south and south becomes north. It happens approximately in every 11 years. Solar minimum is the start of the solar cycle.

Classification	Corrected area (millionths of hemisphere)
S	< 100
1	100–250
2	250–600
3	600–1200
4	> 1200

Solar cycle can be tracked by the counting the number of sunspots. The pair of sunspots of the consecutive cycles have opposite polarities. The entire solar magnetic field gets reverses itself from one solar cycle to the next. The poles reverse back again to their original magnetic configuration making the full solar cycle actually a 22-year phenomenon. Solar flares & CMEs are such solar eruption on the Sun also increases during the sunspot cycle. A physics-based prediction relying on the data-driven solar dynamo and solar surface flux transport models by Bhowmik and Nandy (2018) seems to have predicted the strength of the solar polar field at the current minima correctly and forecasts a weak but not insignificant solar cycle 25 similar to or slightly stronger than cycle 24 [11].

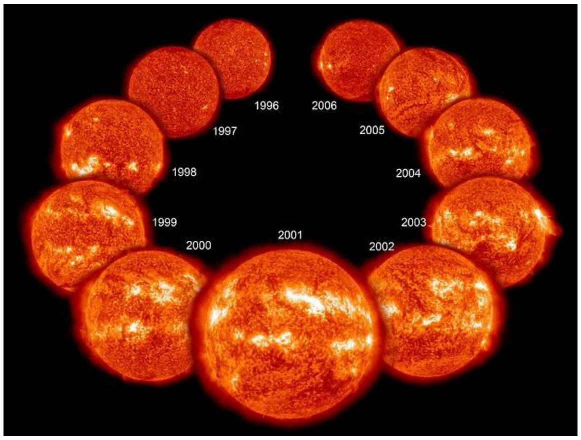


Figure 3 Eleven years in the life of the Sun, spanning most of solar cycle 23, as it progressed from solar minimum (upper left) to maximum conditions and back to minimum (upper right) again, seen as a collage of ten full-disk images of the lower corona. *Credit: NASA*

5. Data Collection

A data for solar flares obtained from time period, 1997 - 2022. These data taken from Space Weather Live organization/Belgium through the website (www.spaceweatherlive.com). Only considerable magnitudes selected in order to reduce the irregular fluctuations. The solar flares data had quantified by converting symbols in to magnitudes according to the table1.

Table 3: Total number of solar flares (C, M and X-class) for years 1997 – 2022.

Years	C – Flare	M – Flare	X – Flare	Total Flare	Total Peak Flux (μwatt/m^2)	Yearly Sunspot Numbers
1997	287	20	3	310	787	28.9
1998	1198	96	14	1308	3558	88.3
1999	1860	170	13	2043	4860	136.3
2000	2254	215	17	2486	6104	173.9
2001	2090	312	21	2423	7310	170.4
2002	2319	210	12	2549	5619	163.6
2003	1315	162	20	1496	4935	99.3
2004	912	122	12	1041	3332	65.3
2005	577	95	18	690	3327	45.8
2006	150	10	4	164	650	24.7
2007	73	10	-	83	173	12.6
2008	8	1	-	9	18	4.2
2009	28	-	-	28	28	4.8
2010	170	23	-	193	400	24.9
2011	1199	111	8	1318	3109	80.8
2012	1329	127	7	1463	3299	84.5
2013	1357	99	12	1468	3547	94.0
2014	1776	207	16	1999	5446	113.3

2015	1368	125	2	1495	2818	69.8
2016	320	15	-	335	470	39.8
2017	237	39	4	280	1027	21.7
2018	13	-	-	13	13	7.0
2019	32	-	-	32	32	3.6
2020	81	2	-	83	101	8.8
2021	398	27	2	427	868	29.6
2022	2036	178	7	2221	4516	83.2

Table 4: Solar flare index (yearly mean), northern and southern solar flare index (yearly mean) calculated for the years 1990 – 2021.

Years	Solar Flare Index	Northern Hemisphere flare index	Southern Hemisphere flare index	Years	Solar Flare Index	Northern Hemisphere flare index	Southern Hemisphere flare index
1990	12.2	6.43	5.74	2006	0.54	0.01	0.53
1991	15.16	5.57	9.58	2007	0.47	0.05	0.42
1992	7.74	2.71	5.02	2008	0.03	0	0.02
1993	4.23	1.99	2.29	2009	0.02	0.01	0.01
1994	1.58	0.7	0.87	2010	0.39	0.26	0.12
1995	0.86	0.3	0.56	2011	2.36	1.67	0.69
1996	0.42	0.07	0.35	2012	2.8	1.25	1.55
1997	1.01	0.54	0.46	2013	2.04	0.84	1.2
1998	4	2.1	1.9	2014	6.34	1.62	4.72
1999	6.39	3.82	2.57	2015	3.03	1.26	1.77
2000	7.61	4.64	2.96	2016	0.67	0.55	0.12
2001	6.8	3.27	3.53	2017	1.22	0.44	0.78
2002	4.56	1.75	2.81	2018	0.04	0.02	0.02
2003	3.46	1.37	2.09	2019	0.08	0.08	0
2004	1.6	0.97	0.63	2020	0.28	0.11	0.17
2005	1.91	0.87	1.04	2021	0.7	0.32	0.38

Table 5: The maximum values of solar flares with their location calculated for years (1996 – 2022).

Years	Class	Sunspot Region	Location	X (arcsecs)	Y (arcsecs)
29/11/1996	M1	07999	S05W35	229"	-15"
06/11/1997	X9.4	08100	S20W66	812"	-346"
18/08/1998	X4.9	08297	N32W80	789"	480"
14/10/1999	X1.8	08731	N11E23	-363"	91"
14/7/2000	X5.7	09077	N17W11	173"	208"
02/04/2001	X20+	09393	N16W70	861"	221"

23/07/2002	X4.8	10039	S12E54	-755"	-266"
04/11/2003	X28+	10486	S17W89	907"	-277"
16/07/2004	X3.6	10649	S10E26	-411"	-268"
07/09/2005	X17+	10805	S12W73	889"	-229"
05/12/2006	X9	10926	S10W57	786"	-227"
04/06/2007	M8.9	10960	S09E36	-553"	-242"
25/03/2008	M1.7	10987	S08E09	-147"	-247"
18/12/2009	C7.6	11035	N30W46	593"	401"
12/02/2010	M8.3	11046	N23E01	-15"	263"
09/08/2011	X6.9	11263	N18W82	893"	275"
07/03/2012	X5.4	11429	N17E15	-235"	169"
05/11/2013	X3.3	11890	S09E36	-563"	-203"
25/02/2014	X4.9	11990	S15E65	-849"	-199"
05/05/2015	X2.7	12338	N04E28	-447"	120"
23/07/2016	M7.6	12565	N04W89	941"	64"
06/09/2017	X9.3	12673	S09W42	630"	-236"
07/02/2018	C8.1	12699	S08E39	-608"	-50"
06/05/2019	C9.9	12740	N08E81	-619"	177"
29/11/2020	M4.4	12786	S18E03	-48"	-317"
03/07/2021	X1.59	12838	N24W91	861"	383"
20/04/2022	X2.25	12992	S28W911	842"	-447"

6. Data Analysis

The statistical analysis of the data collection of total number of solar flares (C, M and X-class) for years 1997 – 2022.

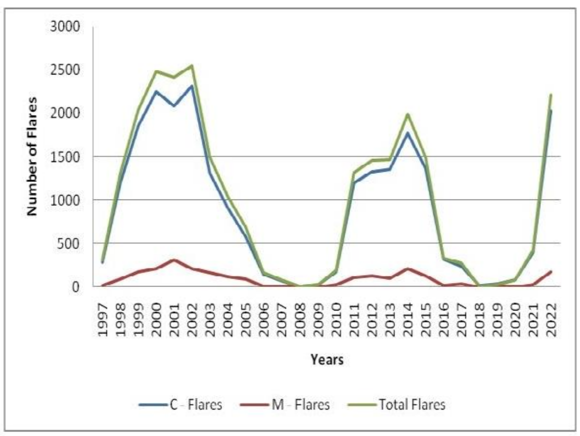


Figure 4 Total flares, C- and M– class vs years (1997 – 2022).

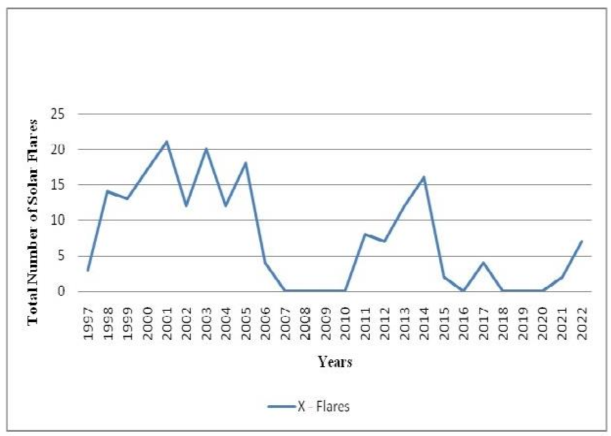


Figure 5 X – class flares vs years (1997 – 2022).

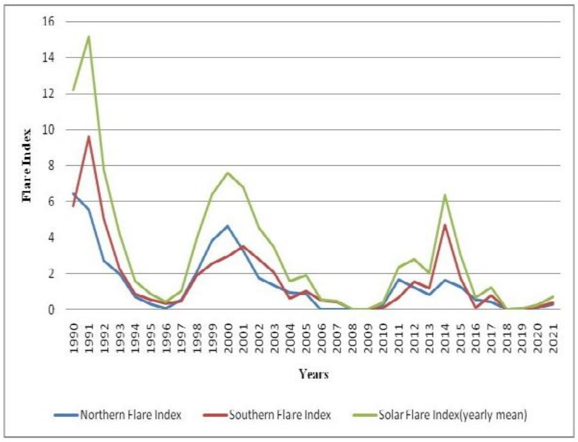


Figure 6 Solar flare index, northern flare index and southern flare index verses years.

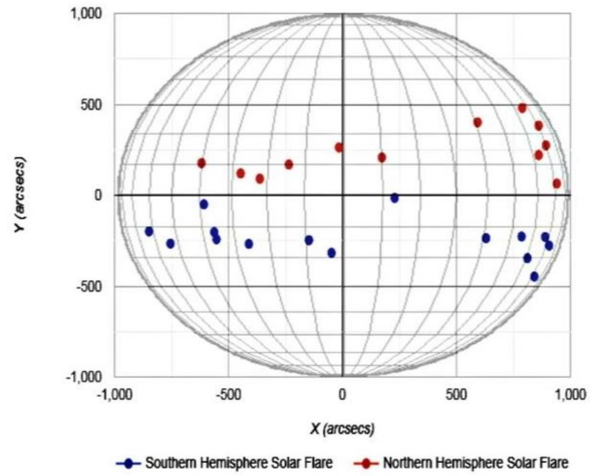
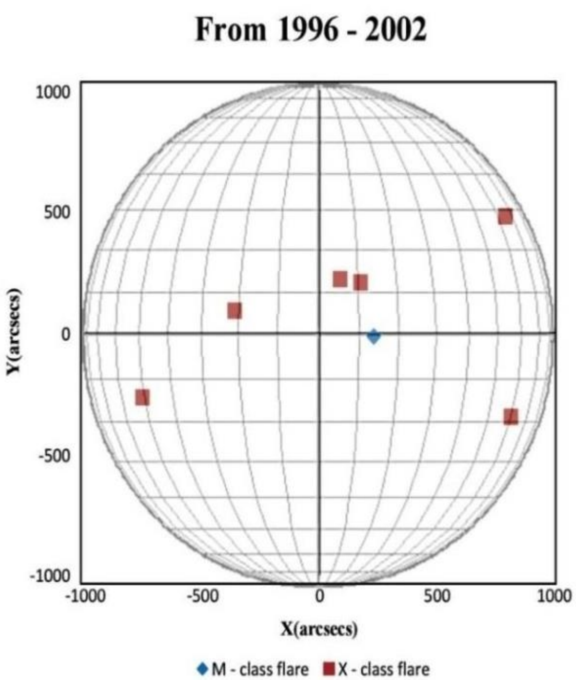
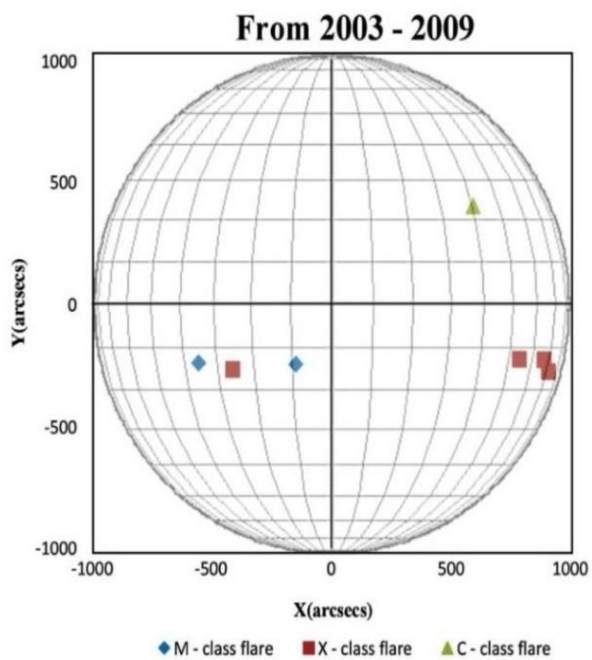


Figure 7 Distribution of maximum value of solar flare of each year from year 1996 - 2022 with their location corresponding to Table 5.





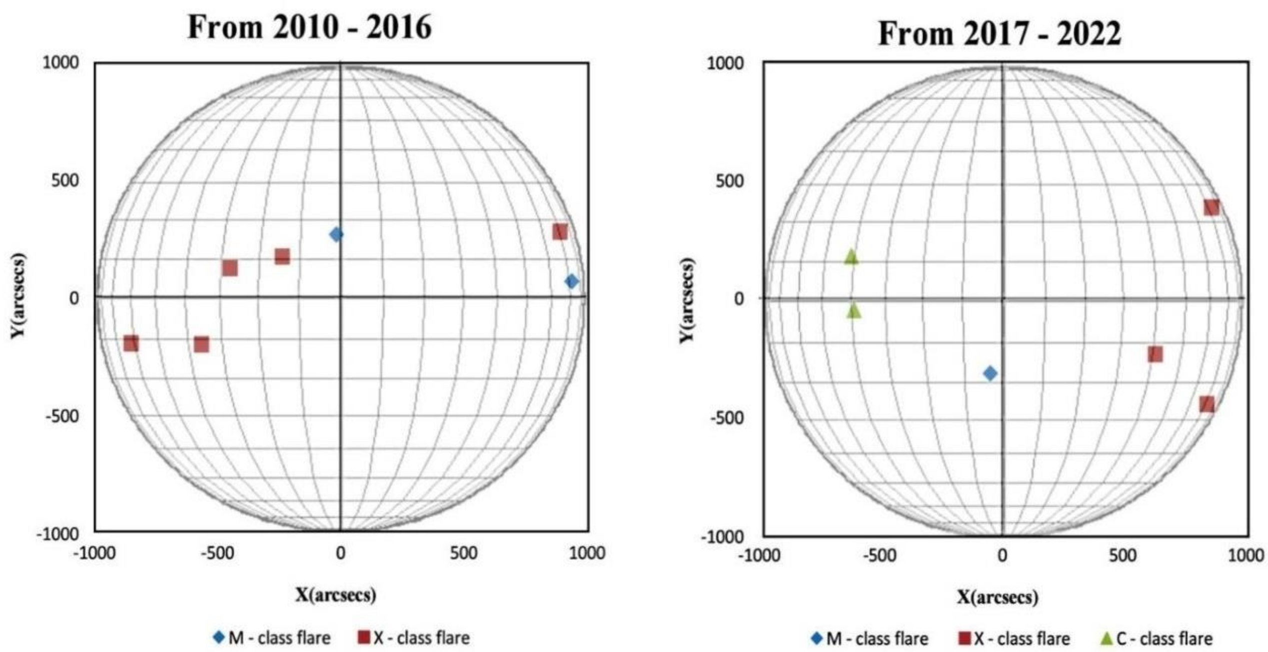
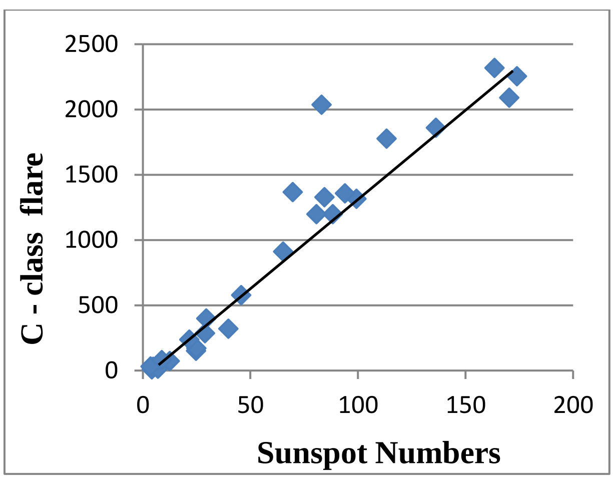
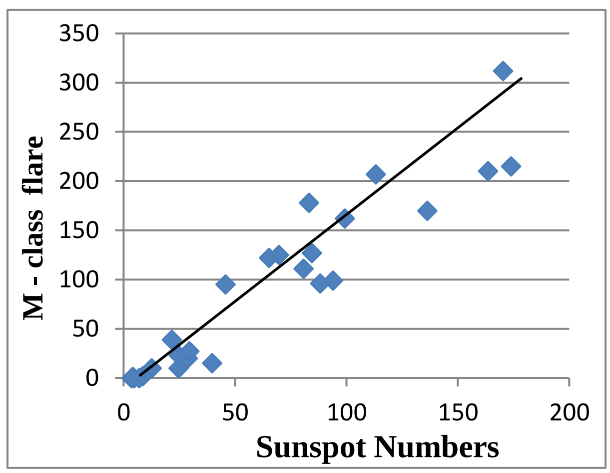
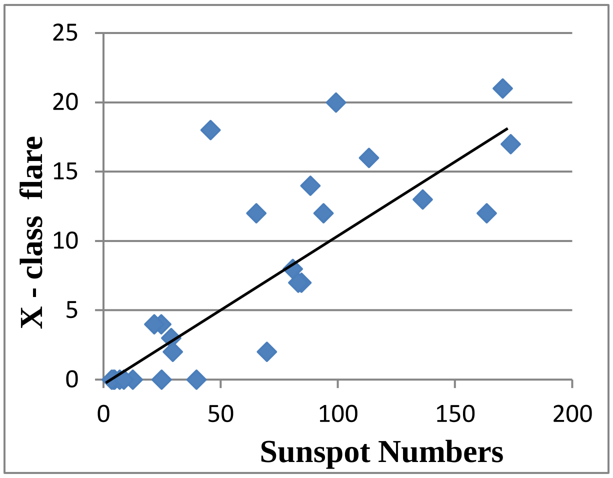


Figure 8 Distribution of maximum value of solar flare of each year with their location corresponding to Table 5.







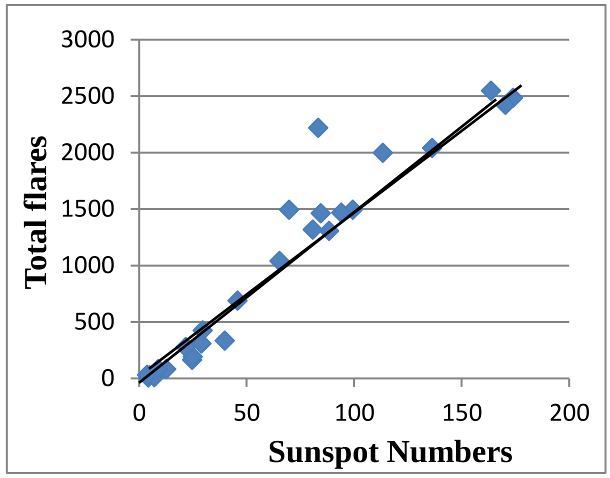
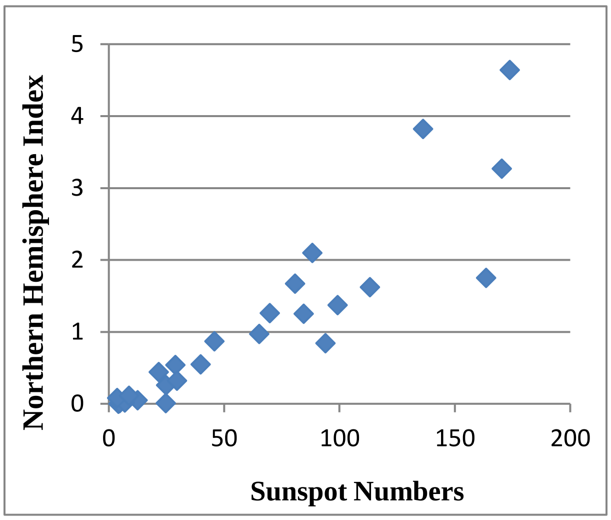


Figure 9 Annual correlation between sunspot numbers and solar flares during period 1997 – 2022.



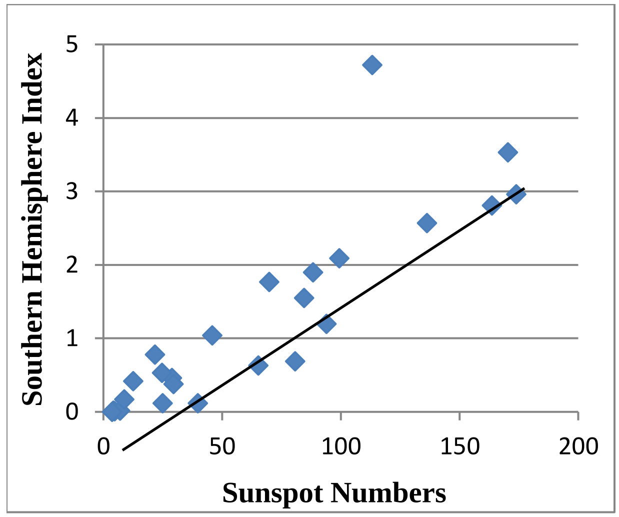


Figure 10 Annual correlation between sunspot numbers and northern and southern hemisphere index during period 1997 – 2021.

7. Result and conclusion

Solar flares produce high energy particles and radiation that are dangerous to living organisms. However, on the surface of the Earth, we are well protected from the effects of solar flares by the Earth's magnetic field and atmosphere. The most dangerous emissions from the flares are energetic charged particles (primarily high – energy proton) and electromagnetic radiation (primarily x – rays).

It can be seen from the above data analysis that number of flares are most in solar maximum i.e. in 2002, which is 2549. And they are least in number in solar minimum i.e. in 2008, which is 9. Solar cycle 23 reached its solar maximum during the years 2000 – 2002 and in year 2000 the northern flare index is 4.64 and whereas southern is 2.96. Solar cycle 24 reached its solar maximum in year 2014 and the northern flare index is 1.62 and whereas southern flare index is

4.72. From above results it can be seen that pole of the Sun gets flip – north becomes south and south becomes north. We have gone through the study of correlation coefficient with the occurrence of different kinds of flares with the yearly mean sunspot numbers. We found that there is a positive correlation between sunspot numbers and C-class, M-class, X-class and Total solar flares. The correlation coefficient were stronger for C-class (0.96), M-class (0.93) and Total flares (0.96) and moderate (0.67) for X-class during period 1997-2022, respectively. The correlation coefficient for sunspot numbers with northern hemisphere index is 0.90 while for the southern hemisphere it is 0.87 during the period 1997-2021.

The shifting of solar flare data with respect to the north hemisphere is more persistent and smooth as compare to the south hemisphere solar flare data. The climatic variability with respect to the north hemisphere is more predictable than the south hemisphere. The study will be useful to understand and predict the climatic change on the earth's hemispheres as well as for the space weather.

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