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Recent history of solar activity

Lessons and advances in flare forecasting

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Abstract. There is a general interest in the forecasting of natural phenomena. Some of them can cause some effect, perturbation, damage or offer risk. That is the case of space phenomena, whose effects range from slight perturbations on the Earth environment up to the blackout of strategic technological services/systems. On last case the impacts extend from the human activities till risk. Solar energetic phenomena, particularly solar flares and coronal mass ejection (CME), can deeply impact the environment and technological systems, depending on their intensity and characteristics. As flares are radiation, propagate through interplanetary space and arrive the Earth in a little more than 8 minutes. So, there is no gap in time available as a purpose to mitigate their terrestrial effects. With the intend to avoid or minimize those effects the better alternative would be forecasting flare occurrence by a 1-2 days anticipation, what is not possible yet. However, we can learn from the history of solar activity data which allow us to obtain some level of forecasting about those phenomena. Related to this, a survey on the data basis of solar flares as well as activity indexes has been done including solar cycles 23, 24, and 25. That to search for any kind of previous signature related to a future flare occurrence. For the mentioned period, we present the history of some activity indexes and what can be learned in terms of forecasting the future flare occurrence. Results indicate magnetic configuration of a significant portion ($10-25\%$) of flaring active regions change in a scale within 24 hour on flare day. Also, the relationship between peak flare as well background flux levels allow us to estimate the stronger x-ray flare on a day.

Resumo.

Keywords. Sun: flares – Sun: activity – Sun: general

1. Introduction

By September 1st, 1859, in a parallel observation of a sunspot group Carrington and Hodgson suddenly observed a strong brightness. That discovery became known as a solar flare since then. In 2025, the forecast of a flare keeps uncertain, mainly related to determination of the exact moment a flare will occur, and to its peak flux too. Up to the 21st century turning, solar flare forecast research concentrated on traditional data processing. Since then, and mainly in the last 10-20 years, the most of works related to that use an approach based either on one or a couple of machine learning/deep learning techniques (MLT/DLT), isolated or in combination, for a comparison of flare forecasting methods see (Leka 2019). A work on flare intensity prediction has been carried out by (Jiao 2020). Some works go through some specific data-driven model (Han 2023), and applied to some kind of data set.

Other approaches with an operational bias have been a deep flare net model by Nishizuka (2021), and tranformer-based framework (Abduallah 2023). (Bringewald & Parisot 2025; **?**) made a significant progress, as well (Newman 2025), who used SDO/HMI data combined with a multiple machine learning model. (Gradvohl 2021) claim the forecast can have improvement by optimization using hyperparametric search, atribute selection, unbalanced data handling, and properly deal with the relationship between accuracy and time scale forecasting. One example using deep convolution neural network and one-against-rest approach originated by (Zhang 2024), and other works also using statistical precursors are in literature (Volvach 2025; Chen 2023). However, even an approach using no MLT but exploring the data set by a certain extended way can generate some advance and significative result.

Here, we explore several solar activity information and indexes from the cycles 23rd, 24th, and 25th - current one - on SWPC-NOAA data basis. We focused on those observed M-class and X-class solar flares taking into account for what has been observed in terms of corresponding active region Mt. Wilson and McIntosh magnetic classifications a couple of days before as well as the day after the flare. The purpose is to search for in the data basis a previous signature of a flare occurrence, and also a checking of the accuracy on some activity information or index. In reference to the signature search, it gives a robustness to the flare forecasting making use of it. By the other side, inaccuracy on some or various of those indexes can indicate us that its determination or measurement has to be revised and improved. We present the findings by this extended survey which points to at least two important remarks: a necessary revision on the determining and publishing of active region magnetic classificatioln, and the possibility to estimate the strongest flare of a day.

In relation to M/X flares, we also explore the X-ray (GOES, 0.1-0.8 nm sensor) flux values, both the background flux prior the flare as well as the flare peak flux along 23rd, 24th and 25th cycles. The purpose is searching for some new information which can give us new insight about the flare forecasting.

2. Data set selection and processing

As a purpose to make the mentioned survey we selected data from solar indexes data basis, specially from the Space Weather Prediction Center from National Oceanic and Atmospheric Administration (SWPC-NOAA). Also, a local data basis has been built to become the work quicker. Selected indexes used are: M-class and X-class flare daily listing, time series of the X-ray flux recorded daily by the 0.1-0.8 nm GOES detector, and

Mt. Wilson and McIntosh magnetic classification of those flaring active regions.

Related to those M and X flares, we have taken for each one both background flux immediately before the flares and their peak flux. Based on these data a plot of the peak flux versus the background flux for each M and X flares has been obtained for each of the cycles 23rd, 24th, and the actual, 25th, one.

This plot shows there are different thresholds of M and X flares occurrence, so that below them no flare of the corresponding class was observed. Also, in the figure it is possible to visualize for each background flux the measured strongest flare peak.

In a comparison with the previous figure it becomes evident the M and X flare thresholds differ from those measured for the previous cycle although are within the same order of magnitude. Yet, the measured strongest flare peaks in this case are distinct and lower compared to the previous cycle.

About the magnetic configuration of flaring active regions, we used the two classifications, Mt. Wilson and McIntosh. Related to the method used to determine the magnetic class of each active region, it is an average of measurements coming from several observatories along a full day, and the corresponding information is published at the end of that day. So, up to the end of the next day, that is the available magnetic classification. Therefore, on practice that classification obtained on the previous day. All these aspects are analyzed in the next section.

3. Results and analysis

A search on solar indexes data basis, related to soft X-ray flux whether background prior flares or peak flare values has been analyzed. The period of analysis extends from beggining of 23rd solar cycle up to present days which corresponds to approximately half of the 25th cycle. Then, the period extends from 1996 August up to 2025 November. The purpose is to search for whether some association between the background flux just before flare beggining and the flare peak flux focusing on those M-class and X-class flares, and analyzing each day of each cycle. All this analysis having on mind the solar cycle presents a cyclic behavior with a minimum and maximum periods.

The data volume is large including 29 years and 3 months. It must be emphasized the criterion we have stablished and used for a flare be accounted for is, exclusively, if it began after the flux decay of the previous flare has risen to the 1/e level of its peak flux. According this criterium some flares recorded on the SWPC flares list has been discarded, which account for about $\leq 5\%$. During the cited period we have two full solar cycles - 23rd and 24th - and aproximately half of the actual (25th) cycle. In respect to the amount of flares, cycle 23 recorded around 1550 of them, being 1422 M-class, and 125 X-class. Along the cycle 24, the Sun generated almost half of the flares recorded in previous one, with 711 M flares and 49 X flares. At last, the 25th solar cycle till the 2025 December, 10th, recorded 1614 M flares and 91 X flares. In a comparison of the activity among the three cycles, last is the most active.

In Fig. 1 we can see a plot of flare peak flux versus background flux on X-ray (GOES, 0.1-0.8 nm) just before the flare for the 25th cycle. In this figure is clear there are different M-class and X-class flares minimum flux thresholds below those no M/X flare has been observed. In the case of M and X flares, till mentioned date, no one has been observed respectively below $3.0\times10^{-8} W.m^{-2}$ and $5.0\times10^{-7} W.m^{-2}$. In addition, from the plot it is clear that up to beggining of 2025 December no flare stronger than X9.1 has been observed on the solar disk visible since the Earth. The brown and green dashed lines are upper and lower limits of M/X flares, which indicate regions where no flare has been recorded yet. The plot in Fig. 2 exhibits the same for 24th cycle.

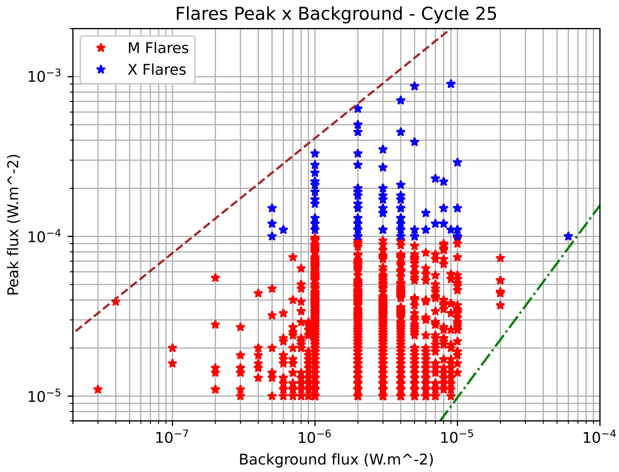

FIGURE 1: Peak flux values recorded daily for each M-flares (red stars) and X-flares (blue stars) versus background flux just before flare observed along the 25th solar cycle.

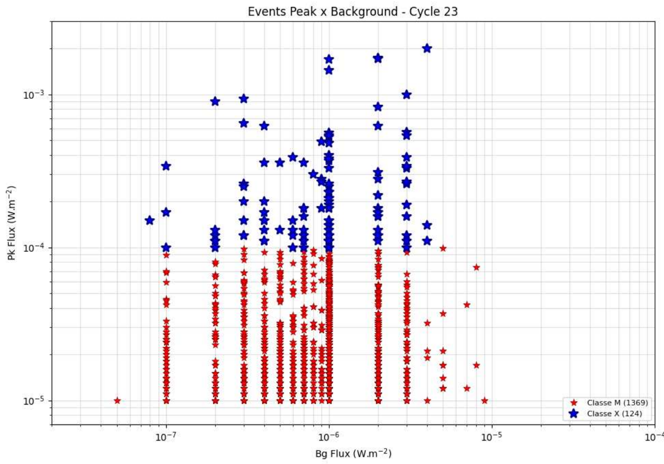

FIGURE 2: Peak flux values recorded daily for each M-flares (red stars) and X-flares (blue stars) versus background flux just before flare observed along the 23th solar cycle.

Based on these and up to now we can estimate the maximum flux of a flare in a day for any background flux. For instance, taking the background flux level of $3.0\times10^{-6} W.m^{-2}$ we estimate the strongest flare of the day could be approximately a X10 ($1.0\times10^{-3} W.m^{-2}$). However, it must be emphasized we are around half of the 25th cycle. Despite this is an estimate only, it can be used as a kind of flare class forecasting.

We have the same as in the previous figure now for the 23rd solar cycle in Fig. 3. Again we can see different X-ray flux thresholds of M-class and X-class flares. No M-flares was recorded below $5.0\times10^{-8} W.m^{-2}$. In case of X-flares $8.0\times10^{-8} W.m^{-2}$ marked the lower limit below which no X-flare was observed. Also, in that cycle the strongest flare was X19.7 corresponding to $\simeq 2.0\times10^{-3} W.m^{-2}$.

The 24th cycle presented considerably lower activity than other two as cited above. A comparison among these cycles indicates that no M-flares was observed for a X-ray background flux below $5.0\times10^{-8} W.m^{-2}$. In case of X-flares this lower threshold

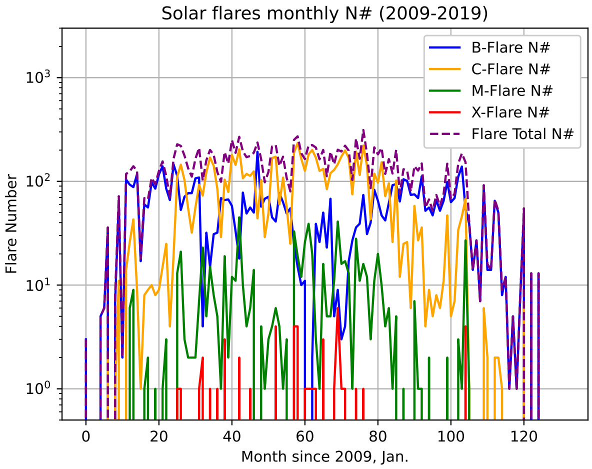

FIGURE 3: Accumulated monthly B, C, M and X class flare number observed along the 24th solar cycle.

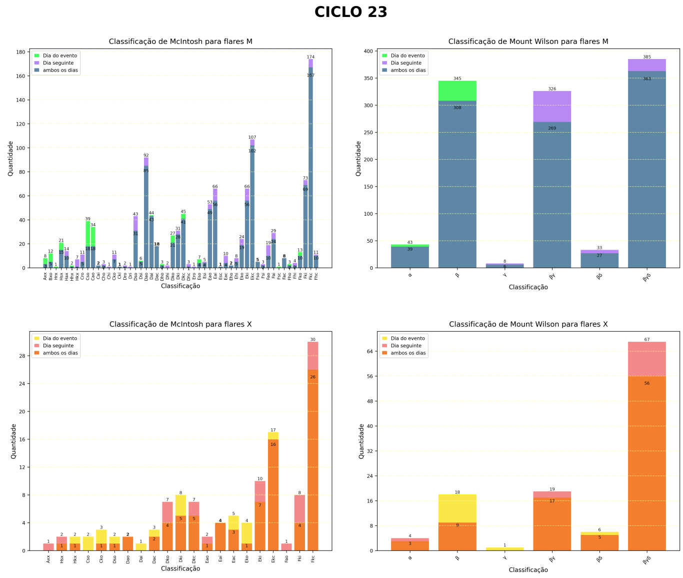

FIGURE 4: Magnetic classifications of flaring active regions - Mt. Wilson, McIntosh - along the 23rd cycle. A period of 5-6 days is analyzed been 3-4 of them prior the flare, that of flare day, and the day after. Top figures correspond to M-class while botton ones to X-class flares.

was $8.0\times10^{-8}W.m^{-2}$. Those plots indicates also the flare peak flux can be observed for each background flux in the range from the lower to the higher limits.

We have also made a plot of the monthly accumulated number of flares for the 24th cycle, since B-flares up to X-flares as exhibited in Fig. 4.

It is clear the dominance of B class flares in the first and last 1-1.5 years of the cycle. The contribution of M class and mainly C class flares gradually increases along the intermediate period. By the end of these first 2-3 years C class flares overpass B class flares, and the amount of M class flares increase to tens by month. When the rising phase of the cycle is at half way to maximum, those X class flares show up occasionally during most active periods of the cycle, with a slight increasing as the maximum and beggining of decay phases occur.

In reference to flaring active regions magnetic classification, a 3-4 days before the flare occurrence, the flare day, and day after were analyzed. That analysis suggested the magnetic classification became more complex in the day after the flare for a significant (10-20%) fraction of the active regions in comparison with the flare day. It must be emphasized, the determination of the referred magnetic classification is an average of measurements from several observatories obtained during one day and published at the turn to the next day, as cited above. In practice, this information available for some day, in true corresponds to that of the previous day. So, it must be taking into account for the information of the day after which in reality corresponds to the one of the flare.

Following, the evolution of magnetic classification in the pointed period is presented in the form of bar plots on Fig. 4 for both magnetic classifications - Mt. Wilson, and McInstosh - separately for those active regions responsible for M-class and X-class flares along the full 23rd solar cycle. In the figure, upper frames show M-flares active region magnetic configuration while lower ones show the X-flare. Right figures show Mt. Wilson classification and left ones the McIntosh classification. For the last, darker color marks magnetic classification repetition from flare day to day after, green correspond to decrease of magnetic complexity and violet its increase. For Mt. Wilson classification red mark magnetic complexity repetition from flare day to day after, while and light red correspond respectively to the decrease and increase of magnetic complexity.

It can be seen in upper figures that a significant ($\simeq 15-20\%$) fraction of active regions change - mainly increase or even decrease - the magnetic complexity from the flare day to the day after on both classifications.

A similar plot for the cycle 25 up to November 2025 is exhibited in Fig. 5. In this case, the significant fraction of active regions which changed the magnetic classification along the flare day, evidenced at the day after grew to about 60% for M- and X-flares on the McIntosh classification. In respect to Mt. Wilson classification of active regions same is true for X-flares but a lower (25%) fraction of M-flares changed - increased or decreased magnetic complexity - from flare day up to the day after.

The change of magnetic complexity for a so significant fraction of the flaring active regions from flare day to the day after indicates the magnetic field of active regions has a dynamic behavior on scales within 24 hour or less. Also, it suggests the proccess of determination and mainly publishing of the magnetic classification of flaring active regions at the end of each day has to be reviewed. That is due the magnetic classification information was obtained along the previous day. So, we suggest the determination and publishing of magnetic field information must be either on real time or done on regular intervals along the day.

4. Discussion and conclusion

A survey of solar activity indexes and information on SWPC-NOAA data basis for solar cycles 23rd, 24th, and 25th data basis has been done. It emphasizes M and X class flares x-ray (0.1-0.8 nm, GOES) flux values, both the background flux immediately prior flare, and the flare peak flux. Also, we studied the magnetic classification corresponding to the flaring active regions from 3-4 days before the flare, flare day, and day after.

A monthly cumulative flare number for the 24th cycle showed the weaker B-class flare dominated on those first and last 2 years of the cycle been overpassed by C-class flares in the intermediate period within which M-class flares grew by 1-2 orders of

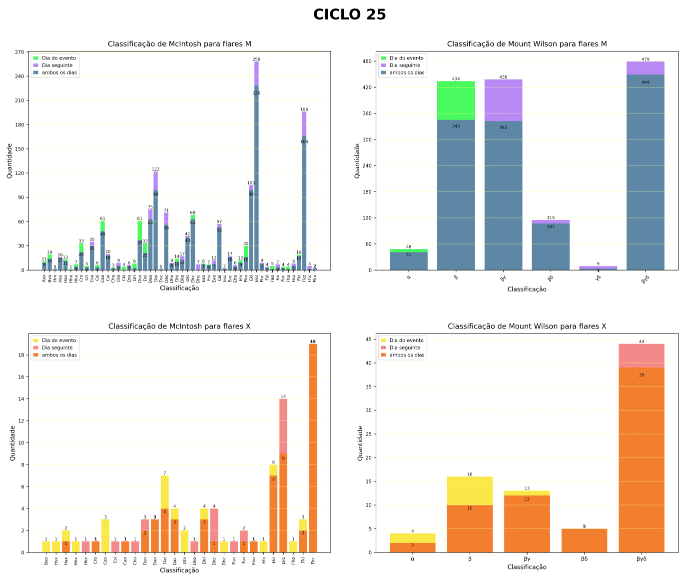

Figure 5: Magnetic classifications of flaring active regions - Mt. Wilson, McIntosh - on the 25th cycle up to the 2025, November. Also, analysis from 3-4 days prior the flare, on flare day, and the day after. Yet, top figures correspond to M-flares while botton ones to X-flares.

magnitude and X-class flare show up occasionally. Flares classes distribution changed from cycle to cycle depending on their intensity.

Those plots of flare peak flux versus background flux prior flare for each cycle showed that there exist a minimum flux threshold below which no flare was observed. Different thresholds were observed for M-flares and X-flares. Different M and X flare thresholds were observed in a comparison among the cycles studied, although they remain within one order of magnitude. The same comparison showed a distinction among flares recorded on each cycle with the 23rd one been that generated the most strong flares, highlight is due to the X45 flare observed on 2003 November, 4th at 20 UT. A composition of the 3 cycles allow us a statistics of strongest flares observed for each background flux value. As an example, taking the background of $3.0{\times}10^{-6} W.m^{-2}$ we estimate the corresponding strongest flare approximately a X10 ($1.0{\times}10^{-3} W.m^{-2}$).

In respect to the study of magnetic classification evolution from a couple of days prior flare up to the day after flare, taking into account for the 3 cycles, we obtained a significant fraction ($10 - 25\%$) of the flare producing active regions changed its magnetic classification from flare day to the day after so on Mt. Wilson as on McIntosh classifications. This indicates a significant portion of active regions present a dynamical evolution in a scale within 24 hour or less. Finally, we strongly suggest a revision of this so as to either publish the active regions magnetic classification in real time or several times along a day.

As a future extension to this work, we plan a comparison with those results will be obtained from the use of machine learning techniques (MLT) applied to same data basis. We expect this will give us additional insights and information which will probably decrease the uncertainty on solar flare forecasting.

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