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Prediction of the Amplitude and Main Characteristics of Solar Cycle 25

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Abstract

In this note, we estimate the maximum amplitude for the Solar Cycle 25. We use the curvature technique presented for earlier cycles by Verdes and coworkers. We further extrapolate the location of the solar maximum number of Sunspots, of which the prediction made is about 115 in the year 2025 and identify the arrival to the minimum in the year 2031, forecasting the main characteristics for the current Solar Cycle 25 and list a short comparison with a few other predictions.

Keywords

Solar Corona Manifestations in the Evolution of the Solar Cycle (Sun Spots), Mathematical Techniques and Tools Used to Evaluate a Function's Fundamental Properties, Sun Spots Since the Start of Their Recording Near Year 1774 of This Era

1. Introduction

This Report closely follows the work by Uzal, Piacentini, and Verdes [1] (from now on referred to as UPV) in predicting the number of sunspots maximum and their date as well as the date at the end of the Solar Cycle 25 and at the start of the Solar Cycle 26 at its defining minimum. It is worth mentioning that the predictions of the solar cycle often tend to be quite different, as can be seen in [2]. In particular, the forecasting of the intensity of the 24 solar cycle maximum, obtained by UPV of the maximum Sunspot number equal to 78, was a prediction that was quite reasonable and, within that work, was estimated at one sigma uncertainty of the measured Sunspot number of 116 (as given in SISLO:

https://www.swpc.noaa.gov/products/predicted-sunspot-number-and-radio-flux). The curvature method developed in UPV [1] then is no more than a numerical search technique attempting to maximize the chance of success in locating the time and intensity of the Solar Maximum based on ideas pioneered by Waldmeier around the earlier 1930s [3], see also, e.g., Garg *et al.*, 2019 [4].

We perform a numerical evaluation of a smoothed Sunspot number as a function of time, using as input the monthly Sunspot list since 1740 (to near present, March 2023), obtained thanks to world-wide-web public access site provided by the WDC-SILSO service (https://www.sidc.be/SILSO/home).

The next section (Section 2) describes the numerical approach based on available algorithms instead of their personal development, as in our guiding technique by UPV [1]. Section 3 presents our conclusions.

2. Method and Results

In our evaluation of the fastest ascent of Sunspots when past the solar minimum of the new cycle, we proceed to identify the curvature numerically of the smoothed Sunspot number, *i.e.*, the location of the fastest ascent with a technique described wholly in the Appendix and available from the numerical tools in the literature of which we provide in detail the one we used in our work and which distinguish this tool from those employed by Uzal, Piacentini and Verdes (see [1]) and which being self-developed are in general less simple to apply.

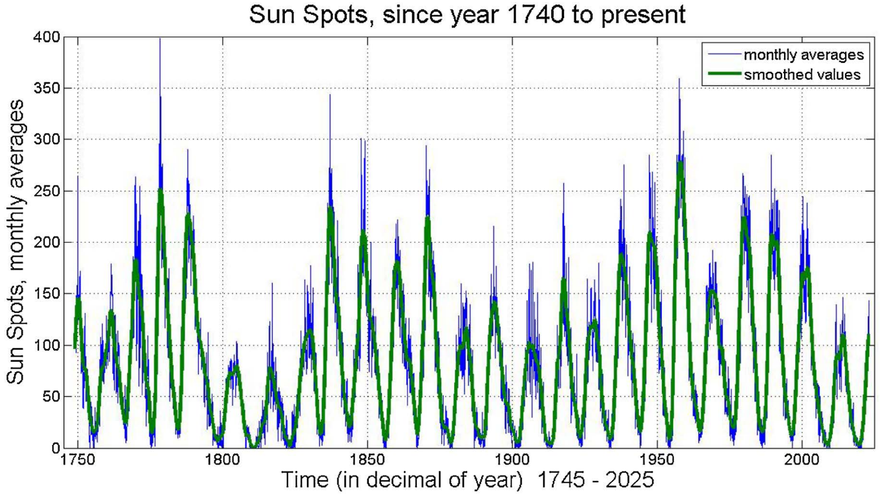


Figure 1. Solar sunspot number from the year 1740 to March 2023 plotted with a scale that extends until the start of the year 2025. The complete series is indicated in blue and the smoothed series is running monthly and averaged using the neighboring 12-month values (in green). Reference of Sunspot number data: WDC-SILSO service (https://www.sidc.be/SILSO/home).

The red curve in **Figure 2** shows the value of the derivative and we proceed to smooth it in the same way that we did with the smoothing of the Sunspots number, using the algorithm MATLAB "filtfilt". The value is adjusted to an approximate reproduction in its intensity to all maxima in the Solar Cycle, since the start of the eighteenth century. In this case, the adjustment factor has been ~6.25, which is, as the figure shows, the one used for the black curve (Adjusted Curvature). It is quite consistent with the observed maximum average intensity in the number of sunspots, with an uncertainty that we indicate when we solely consider the last 4 Solar Cycles.

Figure 2 shows the smoothed sunspots number, the first curvature evaluation and the smoothed curvature used to predict for Solar Cycle 25, the maxima for the Sunspots number, adjusted to the already known Sunspots maxima (from 1745 to Solar Cycle 24 included).

With our knowledge of the maximum for the Solar Cycle 24, the curvature technique used agrees better (40% larger sunspot number than in the base work for the present predictions of Uzal, Piacentini, Verdes, 2012) for the Sunspot number for the Solar Cycle 25, as **Figure 2** shows, evaluated at the solar minimum with the method of the adjusted curvature over the whole 25 Solar Cycles of the "modern era." We conservatively extrapolate the location in the starting time of the next Solar cycle 26 to be the year (2020.3 + 11.5 = 2031.8), *i.e.* considering the uncertainty in the model calculation, for some time between years 2031 and 2032.

With a smoothed curvature of 0.1 and with the help of **Figure 4** in the work of UPV [1], we evaluate an estimated occurrence of the maximum in about (5.0 ± 0.5) years after the start of this Solar Cycle in 2020. For the error of the prediction, we consider the deviation of the difference between the previous 4 cycles, obtained in the present approach of well-reproduced values. The complete information is presented in **Table 1**, where we compare the present results for the maximum and time interval of the present Solar Cycle 25 with the information provided in the Space Weather Prediction Center/NOAA pages [5] (at https://www.swpc.noaa.gov/products/predicted-sunspot-number-and-radio-flux).

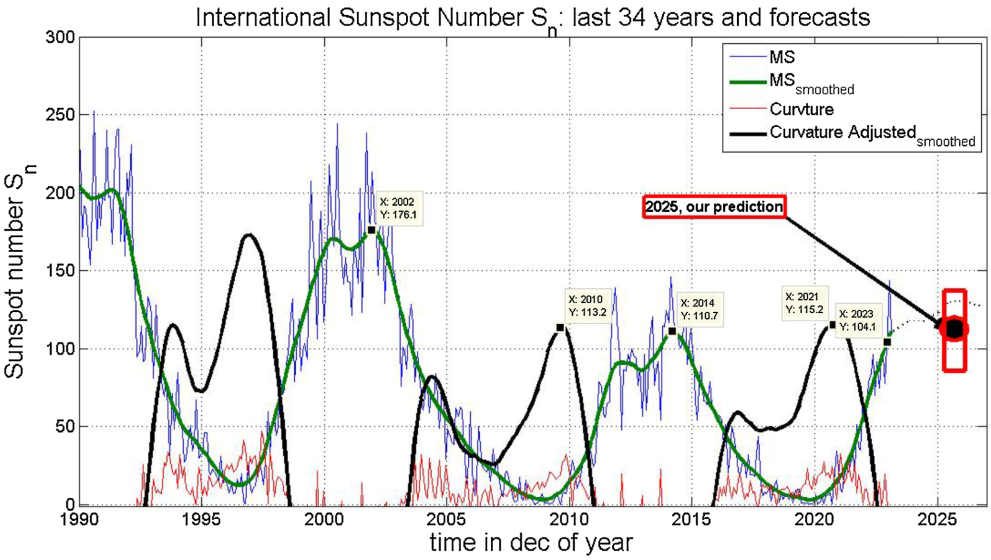


Figure 2. Identification with the curvature of the forecasted intensity of the number of Sunspots in Solar cycle 25. As is clearly seen in the independent variable, time ends at the start of the year 2025, even if the data displayed only extends up to March 2023.

At the current time, it seems that our prediction is somewhat short of the possible values that take place and may be possible around the time which is predicted for the occurrence of the Solar Maximum of Cycle 25.

Further, we notice that **Figure 2** offers the possibility for the understanding/interpretation of a one-to-one correspondence of the fastest ascending method proposed in **Figure 2** in the work by Waldmeier [3] with ours. In our method, we identify the tricky-find region of fastest ascending at the beginning of the newer cycle, which as mathematics teaches, is given by the maximum in the curvature (2^{nd} derivative in our case of the smooth sunspots number processed as we indicate in the Appendix, see also [1]) as a first step for the forecasting of the number of sunspots at maximum of the newer cycle. The next step discussed is a one-parameter adjustment to the historically known sunspot cycles from 1745 to the latest solar cycle.

Table 1 lists, in alphabetic order by authors, several studies that are very limited versions of a much larger list of predictions, as can be seen, for example, in the work of Su *et al.* [6].

It must be pointed out that in its recent publication of the prediction of the

Table 1. Comparison of the present results for the start, end, maximum (and date) of occurrence of the present Solar Cycle 25 with other references. A more detailed table can be seen in Table 5 of the article by Su *et al.* (2023) [6].

Reference	Start of Solar Cycle 25	End of Solar Cycle 25	Maximum value (and date of occurrence) of Solar Cycle 25
Abdel-Fattah *et al.* (2013) [7]			90.7 (2022)
Helal and Galal (2013) [8]			118.2
McIntosh *et al.* (2020) [9]			233
NOAA [5] and NWS	July 2019-September 2020		95-130 (2023-2026)
Okoh *et al.* (2018) [10]	March 2020	April 2031	122.1 (January 2025)
Riley P (2023) [11]			~ 130 (December 2024)
SWPC/NOAA*	December 2019		114.6 (July 2025)
Su *et al.* (2023) [6]			133.9 (February 2024)
Yoshida (2014) [12]			115.2
Present results	*2020*	*June 2031*	*115 (2025)*

*Retrieved from SWPC/NOAA web page (https://www.swpc.noaa.gov/products/predicted-sunspot-number-and-radio-flux) the day, July 12, 2023. See also SCP-SWPC (Solar Cycle Progression—Space Weather Prediction Center)/NOAA (https://www.swpc.noaa.gov/products/solar-cycle-progression).

evolution of Solar Cycle 25 Sunspot number, Riley [11], illustrates the high uncertainty present when the whole data-set since the Modern era records exist, on the evolution and the uncertainty of the identification of the possible maximum. Riley's work [11] emphasizes the problems present and clarifies the scatter in the prediction of the solar maximum occurrence and the value of the number of maximal smooth Sunspots, as well as the occurrence and duration of the cycle. Nevertheless, he also arrives at a prediction for the Solar Cycle 25 of value ~130 in December 2024 (see **Table 1**).

3. Conclusions

In contradistinction to Riley [11], our predictions are obtained in the straightforward manner presented in Chapter 2.

The results of our analysis predict, as indicated in **Table 1**, the following values for the maximum intensity of the already begun solar cycle of 115 ± 20 sunspots in the year 2025, and the extension of the cycle to the year 2031 when the solar minimum is in this study predicted to take place, marking the beginning of the Solar Cycle 26.

Further, we count with the backing of, in our view, the quite reasonable predictions by the same method for the Solar Cycle 24 in [1]. Hence, once more, we expect to reach an equally good prediction of the Solar Cycle 25 maximum intensity and its extension to the following minimum. It is worth mentioning that this approach, at least for the current prediction(s) for Solar Cycle 25, arrives at a value that agrees well with those predicted by SWPC/NOAA, and Yoshida, see **Table 1**. An advantage of their method is that although their uncertainty appears larger than ours, it can arrive at a prediction well before our approach, which as we explained requires data information well after the solar minimum is reached.

It is notable that a comparison between two of the most recent progressions in the solar cycle for any estimation of the solar maximum is live testimony in **Figure 3** to the risk of extrapolating.

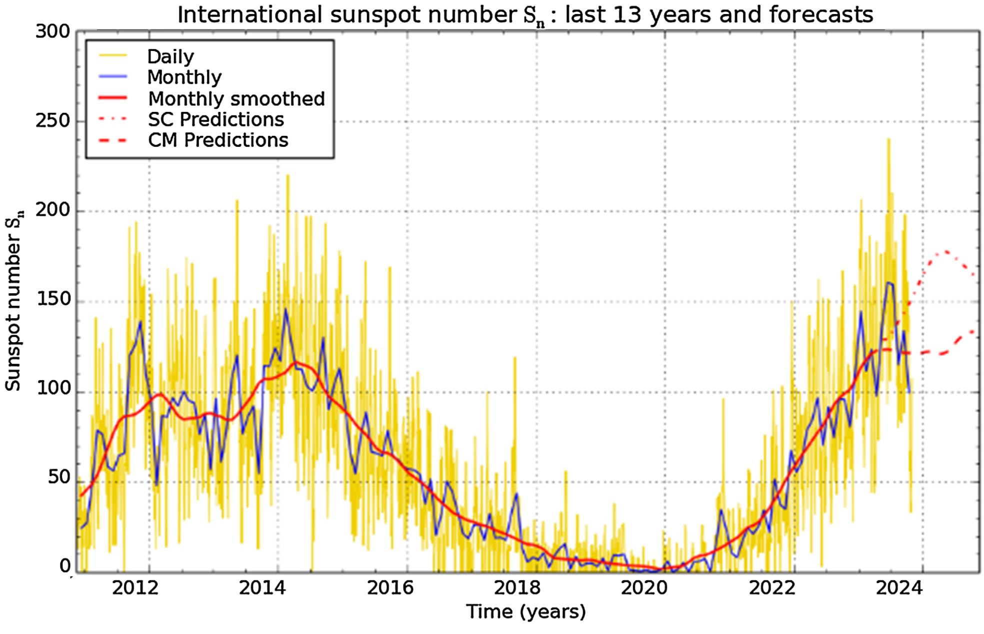
Extrapolation, mean, and the two-standard sigma (deviations) shown on the right side of the following **Figure 4** is derived by making use of the 14 double peaks in the observation of the sunspots started in the year 1749 to the recently ended (year 2020) "24th eleven years solar cycle."

In the process for the determination of standard deviation, we aligned in time all monthly averages of the solar maxima holding a double peak and took its average as well as the standard deviation normalized to zero in the following way:

Mean Sunspots value (mean_j) for each one of the "j" fourteen double peak maxima ($1 \le j \le 14$):

$$\text{mean}_j(\text{time}_{\text{Extrapolated}}) = \Sigma_i\,[\text{Sunspot}_i(\text{monthly}) - \text{Sunspot}_{i+1}(\text{monthly})] \text{ for } 1 \le i \le 54.$$

Notice that the right side shows a time dependence, which is in months and inspired by cycle 24 maximum extension, **Figure 3** and **Figure 4**, with its about two and half years extension, which is the same as our designed extrapolation to



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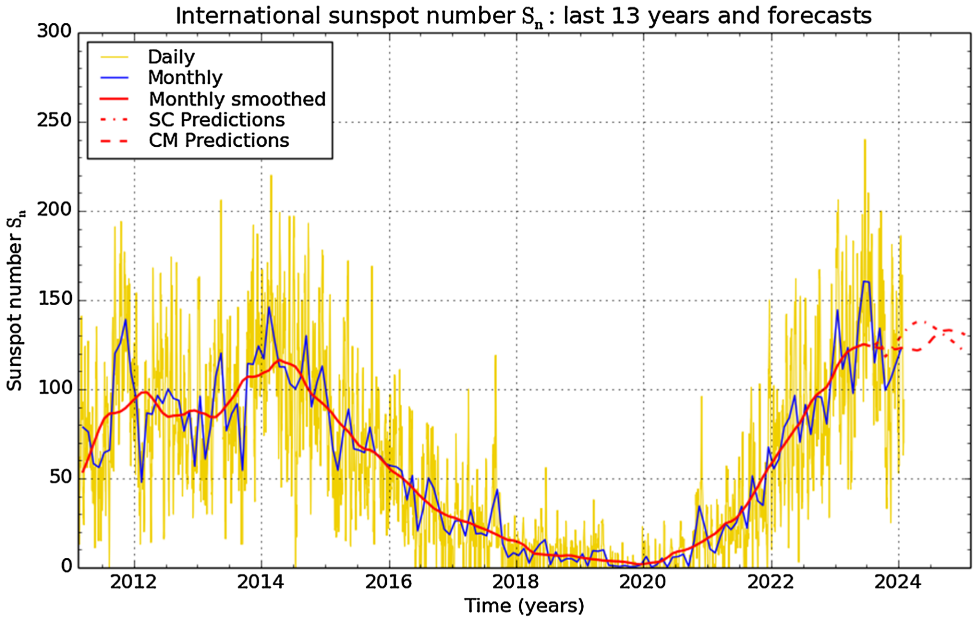

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Figure 3. Above, shows in Panels (Top) and (Bottom) the two very recent predictions and extrapolations from the SILSO center interval prediction from **Figure 2** in a format similar to the ones shown in the panels of the previous figure.

include two peaks at maximum for solar cycle 25 and for which our predictions are made on the maximum number of Sunspots and their time of occurrence within a yearly average (*i.e.* ≥180 days).

First, we evaluated using a monthly time dependence for an interval of 55 months (1 ≤ i ≤ 54) from the start of the 1st downturn of average monthly sunspot number (Sunspot [monthly]), and then we normalize its value to zero at the start

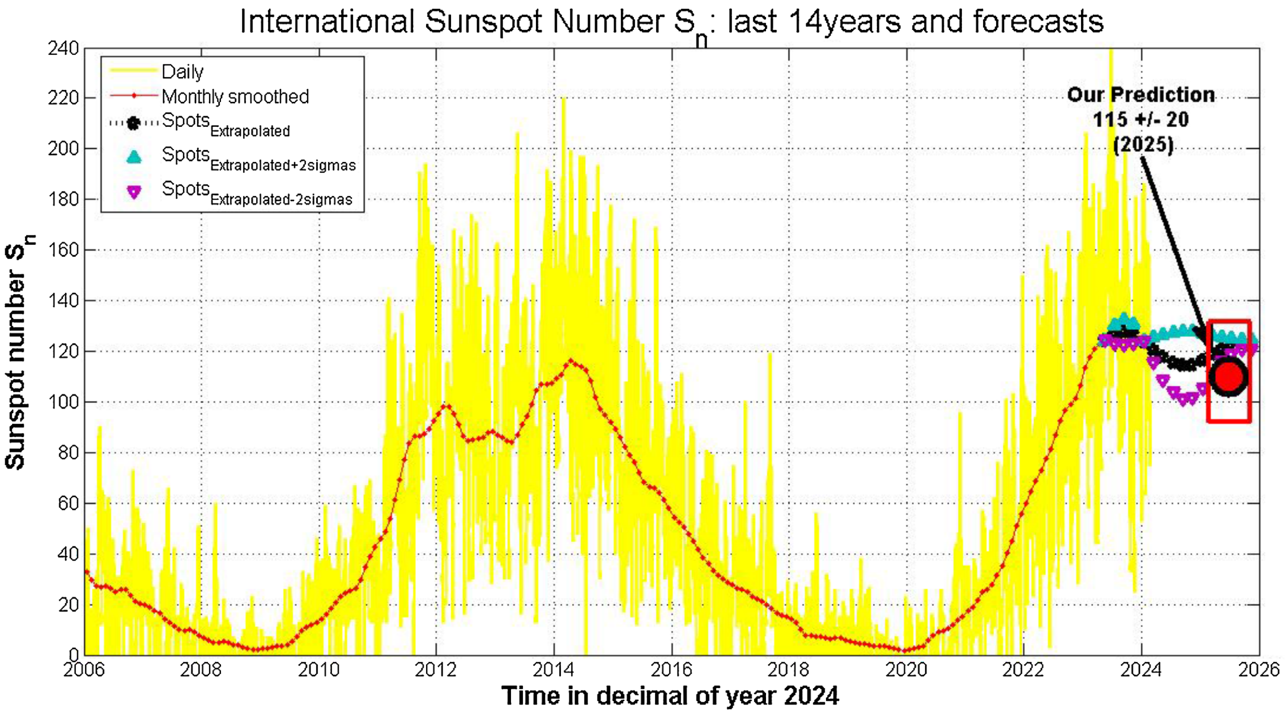

Figure 4. A more extended interval than in **Figure 3**, with an extrapolated prediction with two standard deviations based on all fourteen earlier solar cycles with double peaks (Double arrow shows the two-sigma uncertainty). As indicated in the inset description from top to bottom: (yellow line) daily sunspots, (thick red dot-line) Sunspot monthly smooth number, previously introduced, And the bottom last lines are three extrapolated values which include the two sigma deviations as explained in the body of the text.

of the counting as is illustrated in the above equation.

Then we proceed to add all the normalized to zero Sunspot at the start for the extrapolation, *i.e.*, the fourteen known cases of the above "mean_j" for the double maxima $1 \le j \le 14$ totaling the 14 cases that were evaluated after that the usual standard deviation. Then we proceeded to plot in **Figure 4** the two years extrapolated mean and its two standard deviations to achieve a sense of the possible location of the 1st and 2nd maximum. In this way, we identified that our prediction, with its uncertainty, would likely be within the range expected in 2025 of the mean average maximum Sunspot number. In this way, we interpreted that our forecasting appears reasonable, with a reduced number of assumptions, which is useful for its use in the future with reasonable accessibility to the non-specialist in need of useful maxima intensity predictions for the upcoming solar cycle maximum using the common technique provided by the number of sunspots. In our case, we used the available monthly smoothed sunspot numbers from the first stage of our calculations, illustrated in detail in **Figure 1** and **Figure 2** and thoroughly discussed in the Appendix. The error bar is just a plain estimate, standard in probabilities, which provides affirmation to the fact that we understand that the error in the estimates is from the outset present.

Note added on proof: (A work by Bhowmik and Nandy, 2018 came to our knowledge with a prediction similar to ours on the maximum average intensity of the sunspots for the current Solar Cycle 25, see [13]).

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We thank WDC-SILSO for maintaining open public access to the sunspot data from the modern-era observations, which is the key to the present investigation. Further, we thank the SWPC/NOAA US agency for its friendly access to solar cycle evolution and the associated information. One of us (DBB) thanks his father for the love of his whole life. We are grateful to our colleague Cristina Mandrini for bringing to our attention a thorough revision work focused on the smoothed solar maximum, which contains an analysis of a very large number of predictions for the Solar Cycles 24 and 25 by the invited review work presented by Nandy, 2021, see [14].

Conflicts of Interest

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

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Appendix

As well as UPV work [1], it is worth mentioning the earlier work by Verdes *et al.*, [15].

To evaluate numerically the smoothed Sunspot number and its curvature we use algorithms readily available in MATLAB version R2022a, Update 6 (9.12.0.2170939), 64 bit (maci 64), upgrade on Jan 17, 2023. ***Figure 1*** *presents the complete series of Sunspots (in blue), and its smoothing with running monthly averaged using the neighbour 12 month values. The key MATLAB algorithm is "filtfilt" in its smoothing mode, whose syntax we proceed to explain next because it is valid in the description of* ***Figure 1****. The three arguments are illustrated in the example:*

Smoothed function = filtfilt(ones(1, set_number)/set_number, function).

The function "ones" takes the place of the first two arguments of the function-algorithm "filtfilt." "ones (1, set_number)" when divided by the quantity "set_number" warrants the preservation of the mean value of the function to smooth. The filtering algorithm "filtfilt" further benefits the preservation of the mean location on the independent variable as well as the preservation of zeroth phase shift. In addition, the set number equals the contiguous number of values of the function of position "j" between its beginning value, as a function of the independent variable also of index "j". In this case, the independent variable is the time from the start of the analyzed data in 1745 and extending until its end in 2023, with a value every week. The function is the sunspot number observed for the week "j", counted since the start of the data set in the eighteenth century. The thick line in the plot, as explained at the start of paragraph, gives the smoothed Sunspots values. In this way its smoothed number is at each "j" value. Boundary effects due to the application of the algorithm are solely of relevance in the neighborhood of the starting values, from j = 1 to 6, and ending values from N – 6 < j < N (with N = 3890).

With this proven technique, we evaluate the curvature (2nd derivative) of the smoothed function, which for detailed purposes is plotted in **Figure 2**, focused only on the interval starting in 1990 and ending in 2023. There, we proceed to smooth the curvature and adjust it to be consistent in its value with the Solar Maximum value, the same as was done in the work by UPV [1]. In this way, we obtain the mean (average) prediction for the Solar Cycle 25 maximum in the smoothed amplitude. For the 2nd derivative, we use the MATLAB function "diff", which has the syntax:

2nd derivative = diff(y, x, n)

n = order of the derivative (n = 2 in the case of the evaluation we perform in this work)

x = independent variable

y = variable, which derivative evaluates "diff" with respect to the independent variable "x".