AGU100 ADVANCING EARTH AND SPACE SCIENCE

Space Weather

RESEARCH ARTICLE
10.1029/2018SW002080

Key Points:
- A new calibration of sunspot number must be used in solar cycle predictions
- The climatological average is used to assess other predictions
- Other simple predictions are not very accurate or useful

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Citation:
Pesnell, W. D. (2018). Effects of version 2 of the International Sunspot Number on naïve predictions of Solar Cycle 25. *Space Weather*, *16*. https://doi.org/10.1029/2018SW002080

Received 16 SEP 2018
Accepted 15 NOV 2018
Accepted article online 23 NOV 2018

Effects of Version 2 of the International Sunspot Number on Naïve Predictions of Solar Cycle 25

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Abstract The recalibration of the International Sunspot Number brings new challenges to predictions of Solar Cycle 25. One is that the list of extrema for the original series is no longer usable because the values of all maxima and minima are different for the new version of the sunspot number. Timings of extrema are less sensitive to the recalibration but are a natural result of the calculation. Predictions of Solar Cycle 25 published before 2016 must be converted to the new version of the sunspot number. Any prediction method that looks across the entire time span will have to be reconsidered because values in the nineteenth century were corrected by a larger factor than those in the twentieth century. We report a list of solar maxima and minima values and timings based on the recalibrated sunspot number. Naïve forecasts that depend only on the current values of the time series are common in economic studies. Several naïve predictions of Solar Cycle 25, the climatological average (180 ± 60), two versions of the inertial forecast, and two versions of the even-odd forecast, are derived from that table. The climatological average forecast is the baseline for more accurate predictions and the initial forecast in assimilative models of the Sun. It also provides the error estimate for Monte Carlo techniques that anticipate the long-term effects on the terrestrial environment. The other four predictions are shown to be statistically insignificant.

Plain Language Summary We use predictions of the next sunspot cycle to plan satellite missions. The simplest prediction is the average of all previous peaks in the sunspot number. A new version of the sunspot number has been released, and this average must be recalculated. The new value predicts a peak sunspot number of 180 in Solar Cycle 25.

1. Introduction to Solar Cycle Predictions

Long-term predictions of solar activity are an essential part of space weather forecasts. Two of the main sources of space weather effects at the Earth tend to track the sunspot number, solar flares (e.g., Temmer et al., 2001), and coronal mass ejections (Wang & Colaninno, 2014). A third source, high-speed streams from coronal holes, is not as well correlated with sunspot number, especially during the decline from solar maximum. This requires that a second quantity, such as a geomagnetic index, also be predicted. However, long-term predictions of the geomagnetic indices can be created from the predictions of sunspot number and a stochastic component (Naasz et al., 2008).

Satellite operators need to plan their missions years, if not decades, in advance. As a result, forecasters are asking for usable predictions of upcoming solar cycle(s) long before the anticipated maxima and leading to the development of many types of solar cycle predictions. Up through Solar Cycle 24, all solar cycle amplitude predictions had been made or reported using the International Sunspot Number, R_Z. On 1 July 2015 the Solar Influences Data Center (SIDC) began serving version 2 of the International Sunspot Number, S_N. It reconciled numerous inconsistencies in earlier calibrations of R_Z, such as R_Z being too small in the nineteenth century, that can be repaired by comparing the raw observations and deducing biases among the observers or by comparison with the geomagnetic measurements (Clette et al., 2014; Pevtsov et al., 2014; Svalgaard, 2012).

Solar Cycle 24 was a below-average amplitude, peaking at an annual sunspot number of about 80 in R_Z. A set of 105 predictions of the amplitude of Solar Cycle 24 ranged from zero to unprecedented levels of solar activity (Pesnell, 2016). The unweighted average of that compilation of predictions anticipated the amplitude of the annual-averaged sunspot number for Solar Cycle 24 as $\langle R_{Z,24} \rangle = 106 \pm 31$, slightly lower than the average value of previous cycles, but higher than the actual amplitude. There were peaks in the daily- and

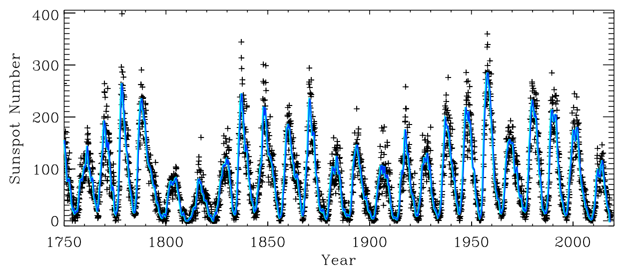

Figure 1. Version 2 of the International Sunspot Number as a function of time since 1750. The solid blue line is the 13-month running average of the values (sampled monthly) and the "+" symbols show the monthly values.

monthly-averaged sunspot number in the Northern Hemisphere in 2011 and in the Southern Hemisphere in 2014, another complication in the prediction of the amplitude that we do not consider here.

At least 13 predictions of the amplitude of Solar Cycle 25 already exist. Some were from before 2016 and use R_Z (Dumitrache, 2011; Helal & Galal, 2013; Javaraiah, 2015; Kakad, 2011; Lampropoulos et al., 2016; Li et al., 2015; Miao et al., 2015; Yoshida, 2014; Zachilas & Gkana, 2015). Others report their results with S_N (Gkana & Zachilas, 2016; Pesnell & Schatten, 2018) or as fractions of previous activity (De Jager & Duhau, 2012; Shepherd et al., 2014). The Solar Cycle 25 prediction of Helal and Galal (2013) used R_Z to derive a correlation between the number of spotless days and the rise time. But Pesnell (2012) showed that the number of spotless days in S_N was a more accurate precursor. Because R_Z is no longer officially produced, this lack of consistency in what is reported in a prediction complicates the comparison and use of those predictions.

Dynamo models rarely predict the sunspot number. They often report the factor by which the next cycle will increase (Cameron et al., 2016; Hathaway & Upton, 2016) or decrease (Upton & Hathaway, 2018) over the current one. Therefore, they are less sensitive to the nominal values of S_N—unless they calibrated the model on the sunspot number.

Naïve forecasts use information from the near past without further adjustment or attempting to determine causality. They provide an easily calculated benchmark to compare with more sophisticated predictions. Naïve predictions are used by businesses as well as scientists. Examples include saying that tomorrow's weather will be the same as today's and next month's sales of winter coats will be the same as this month's. Both of these forecasts may ignore possible trends and seasonal effects but provide the information needed to judge other forecasts.

We will describe the impact of S_N on several simple solar cycle predictions. A brief description of S_N will be presented, followed by a table of extrema to be used in solar cycle predictions. Five naïve predictions that can be derived from that table will then be discussed.

2. The New Calibration of the International Sunspot Number

The sunspot number is a unique reference for solar dynamo models, climate studies, and solar activity predictions as well as a direct proxy of magnetic flux emergence (Stenflo, 2012). The original International Sunspot Number (R_Z, also called version 1) was measured, derived, and recorded for over 300 years. It was created in 1849 by R. Wolf of the Zurich Observatory as an index that combined the total number of observed spots (S) and the number of groups of spots (G) : $R_Z = 10G + S$. Observer-dependent correction factors were introduced, as successive observers became the curators of the data series. Since 1981, R_Z has been produced at the World Data Center for Sunspot Index and Long-term Solar Observations in Brussels using a worldwide network of over 85 stations. Daily values of R_Z exist since 1818, monthly means since 1749, and annual averages since 1700. The time dependences of the 13-month running mean, sampled at monthly intervals, and the monthly-averaged S_N are shown in Figure 1.

The reliability of R_Z had long been questioned because a reanalysis of the data gave differing long-term trends (Hoyt & Schatten, 1998a, 1998b). From 2011 to 2015 a community effort led to the first recalibration of the entire series (Clette et al., 2014; Pevtsov et al., 2014; Svalgaard, 2012). Version 2 of the International Sunspot Number (S_N) has been produced since 1 July 2015 and is the recommended version of the International Sunspot Number.

The largest change is the renormalization of new version that makes S_N 40–70% larger than R_Z. This increase is particularly problematic when predicting the next solar cycle because the renormalization changes with time. The largest change was to drop the 0.6 normalization, effectively multiplying the entire series by $1/0.6 \approx 1.67$. After 1947 the scaling factor changes from 1.67 to 1.42. Details of these and other changes are in Clette and Lefèvre (2016). The R_Z data set was the basis of the many predictions of the amplitudes of Solar Cycles 21–24 (Pesnell, 2016). A recalibration of such a well-analyzed data set requires any existing prediction algorithm be thoroughly reconsidered for Solar Cycle 25.

Table 1
Solar Minimum and Maximum Timings and Amplitudes of S_N

Solar	Minimum		Maximum		Times (years)		
Cycle	Date	S_N	Date	S_N	Rise	Fall	Min-Min
1	1755.204	14.0	1761.455	144.1	6.251	5.000	11.251
2	1766.455	18.6	1769.707	193.0	3.252	5.748	9.000
3	1775.455	12.0	1778.371	264.3	2.916	6.337	9.253
4	1784.708	15.9	1788.124	235.3	3.416	10.164	13.580
5	1798.288	5.3	1805.123	82.0	6.835	5.835	12.670
6	1810.958	0.0	1816.373	81.2	5.415	6.998	12.413
7	1823.371	0.2	1829.874	119.2	6.503	4.000	10.503
8	1833.874	12.2	1837.204	244.9	3.330	6.334	9.664
9	1843.538	17.6	1848.124	219.9	4.586	7.834	12.420
10	1855.958	6.0	1860.124	186.2	4.166	7.080	11.246
11	1867.204	9.9	1870.623	234.0	3.419	8.335	11.754
12	1878.958	3.7	1883.958	124.4	5.000	6.246	11.246
13	1890.204	8.3	1894.042	146.5	3.838	8.000	11.838
14	1902.042	4.5	1906.123	107.1	4.081	7.500	11.581
15	1913.623	2.5	1917.623	175.7	4.000	6.000	10.000
16	1923.623	9.4	1928.290	130.2	4.667	5.417	10.084
17	1933.707	5.8	1937.288	198.6	3.581	6.836	10.417
18	1944.124	12.9	1947.371	218.7	3.247	6.917	10.164
19	1954.288	5.1	1958.204	285.0	3.916	6.587	10.503
20	1964.791	14.3	1968.874	156.6	4.083	7.332	11.415
21	1976.206	17.8	1979.958	232.9	3.752	6.749	10.501
22	1986.707	13.5	1989.874	212.5	3.167	6.750	9.917
23	1996.624	11.2	2001.874	180.3	5.250	7.084	12.334
24	2008.958	2.2	2014.288	116.4	5.330	—	—
Mean Values		9.29		178.7	4.33	6.74	11.03
Standard Deviation		5.70		57.76	1.11	1.24	1.18
Median		9.65		183.3	4.08	6.75	11.25

More quantitative data covers much shorter periods of time. F10.7 is available for 70 years, less than 25% of the length of the sunspot number record. Even over that short period of time, the relationship between F10.7 and R_Z appeared to be drifting (Livingston et al., 2012; Pesnell, 2014). The differences include the phasing of the peak activity of a sunspot cycle as well as a trend toward R_Z being smaller than the equivalent F10.7 in the current epoch. Some of this discrepancy was resolved with S_N (Clette et al., 2014). Due to the use of F10.7 in models of planetary thermospheres and ionospheres to calculate the effects of satellite drag and ionospheric scintillation, F10.7 has been used in solar cycle predictions (Pesnell & Schatten, 2018). Measurements of the extreme ultraviolet spectral irradiance, the actual energy input into the thermosphere and ionosphere, have become more regular since the launch of the Solar Extreme ultraviolet Experiment on NASA's Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED/SEE) and the Extreme ultraviolet Variability Experiment on NASA's Solar Dynamics Observatory (SDO/EVE) but still only cover the last 20 years. That is only one 22-year solar cycle and is not long enough to use in most prediction algorithms.

3. Extrema of the Revised Sunspot Number

The basic statistics of the data set are required for any attempt to predict the sunspot number. Examples of such statistics include the timing and amplitude of extrema that are required to calculate the standard predictions and their uncertainties. A table (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/cycle-data/table_cycle-dates_maximum-minimum.txt) of solar cycle extrema hosted at NOAA's National Geophysical Data Center (now called the National Center for Environmental Information for Space Weather) fulfilled this purpose for many years (NOAA, 2013). With the arrival

Table 2
Naïve Predictions of Solar Cycle 25, SIDC Values

		Pred. S_N		Correlation	
Name	Summary	Flywheel[a]	Fit[b]	r	r_c(95%)
Average	$\langle N \rangle \rightarrow N+1$	180 ± 60			
Inertial	$N \rightarrow N+1$	115 ± 70	105 ± 30	0.259	0.404
Even-odd	$N-1 \rightarrow N+1$	180 ± 85	180 ± 30	-0.0802	0.413

Note. SIDC = Solar Influences Data Center.
[a]Solar Cycle $N+1$ = Solar Cycle N or Solar Cycle $N+1$ = Solar Cycle $N-1$. [b]Linear fit between Solar Cycle $N+1$ and Solar Cycle N or Solar Cycle $N+1$ and Solar Cycle $N-1$.

of version 2, this table must be recalculated. The timing and amplitude of solar maximum are changed throughout the data set, and these values should now be used in the solar cycle prediction algorithms.

Table 1 lists the dates and values of solar minima and maxima for Solar Cycles 1–24. Minimum and maximum were found by a simple peak-bagging algorithm of the 13-month running average S_N. An extrema had to be greater (or less) than the surrounding 24 months to be listed in the table. Although this algorithm produced unique times of maximum, there are several minima with ties. In those cases the last point was selected. The time elapsed from minimum to maximum (rise time) and from maximum to minimum (fall time) are shown along with the minimum-to-minimum time (the length of each sunspot cycle). The average, standard deviation (σ), and median of appropriate columns are listed at the bottom of the table. Two other statistical measures were calculated. The skewness of the maximum values is −0.043, indicating a symmetric distribution, while the kurtosis is −1.19, indicating a flat (platykurtic) distribution. The latter statistic indicates that the maximum values do not form a normal distribution.

Compared with the similar table using R_Z, the average length of a sunspot cycle has decreased from 11.1 to 11.03 years while the standard deviation decreased from 1.5 to 1.2 years. While changes in the timing of most minima and maxima are small, several recent maxima shifted to later times when the Locarno variable sunspot sizes were removed (Clette et al., 2014), affecting both the rise and fall times but leaving the length unchanged.

The average amplitude of a cycle has increased by 61%, from 113 to 179, and the standard deviation of the amplitude (σ_0) increased by 44% from 40 to 58. Most of these increases are due to the removal of the traditional observer scaling factor of 0.6. While comparisons of other quantities, such as rise and fall times, can be made, the length and amplitude are the most critical to solar cycle predictions.

4. Naïve Predictions of Solar Cycle 25

There are several naïve predictions of the upcoming sunspot cycle that can be calculated with this information. They would be included in the climatology and recent climatology categories of Pesnell (2016) if those categories were to be adopted for predictions of Solar Cycle 25.

4.1. Climatology Forecasts

Climatological, or statistical, forecasts determine the future of a system from the statistical properties of the past. An example is that S_{25} will be the average of all observed maxima. Using the rows at the bottom of Table 1, this is $S_{\mathrm{N,ave}} = 180 \pm 60$, which is listed in Table 2. This also provides an error estimate for judging the predictions ($\sigma_0 = 60$). As is common in solar cycle predictions, predictions and uncertainties are rounded to the nearest multiple of five.

Estimates of timing information can be derived in a similar way. The average sunspot cycle lasts 11.0 years with a standard deviation of 1.2 years. The average time from minimum to maximum is 64% of the time from maximum to minimum. Using this idea, the average fall time in Table 1 indicates that solar minimum will be at 2021.03 and, from the rise time, the maximum of Solar Cycle 25 will be at 2025.36. Both of these estimates also have uncertainties of ± 1.2 year.

The ratio of $S_{\mathrm{N,ave}}$ to the average used in the Solar Cycle 24 predictions, $R_{Z,\mathrm{ave}} = 115 \pm 40$ (Pesnell, 2012), is 1.56, close to the averaged renormalization of S_N.

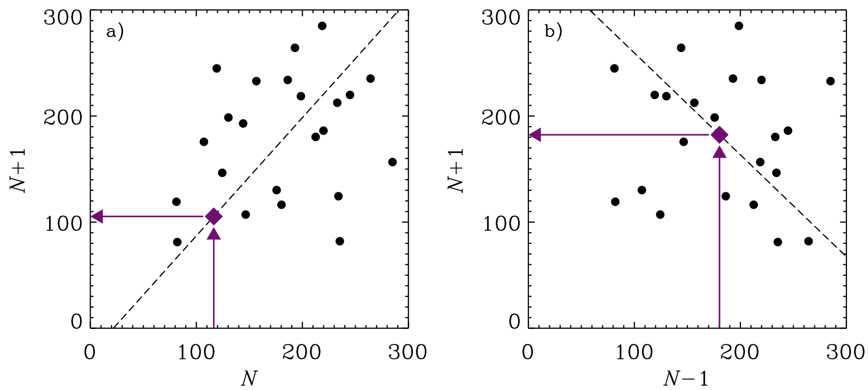

Figure 2. Correlation diagrams showing the fits for the Inertial and Even-odd predictions. The left panel shows the amplitude of the next solar cycle vs. the current cycle for the 23 cycles in the V2 sunspot numbers. The right panel shows the amplitude of the next solar cycle vs. the previous cycle for the 22 usable cycles in the V2 sunspot numbers. The round symbols are the values from Table 1 and the diamonds show the predicted amplitude of Solar Cycle 25 based on the linear fit through the data evaluated with either S_{24} (left) or S_{23} (right). In both panels the arrows illustrate the process, tracing from the previous cycle (N or $N-1$) to the fit line and then onto to the predicted value.

4.2. Recent Climatology Forecasts

Climatological methods will often fail when the average behavior does not represent the future behavior. This can be anticipated by using other naïve forecasts, such as seasonally adjusted forecast methods. Recent climatology forecasts use the behavior in the recent past, defined here as including data since Solar Cycle 18 (about 1955) or later. Examples include the *inertial* (or persistence) forecast, $S_{25} = S_{24}$, which is used as a base forecast in weather and business forecasting, and the *even-odd cycle* forecast, $S_{25} = S_{23}$, which resembles a naïve seasonal forecast used in economics. Neither forecast has trend information.

These forecasts were calculated for S_{25} using the information in Table 1 and two algorithms, flywheel and linear regression, and are also listed in Table 2. The flywheel algorithm evaluates the error by calculating the standard deviation of the forecast and actual values over the numbered Solar Cycles in Table 1. If the sunspot number were a random fluctuation about a mean, then the standard deviation of these predictions would be $\sqrt{2}\sigma_0$. If the sunspot number were a random walk in time, then the inertial forecast would be an optimal forecast; the deviation of the actual value from the forecast value would be σ_0. The standard deviation for the flywheel inertial forecast is greater than σ_0 but less than $\sqrt{2}\sigma_0$, indicating the sunspot number is neither type of random variable. The uncertainty of the even-odd forecast is consistent with that method of prediction working with a random variable.

Because the flywheel method does not provide any statistical insight into the prediction, linear regression fits were also used to calculate these predictions. The data points and fits for the inertial and even-odd predictions are shown in Figure 2. The fits were derived using errors of five in both variables. The fit for $N \rightarrow N+1$ is

$$S_{N+1} = -24.3 + 1.11 S_N, \tag{1}$$

while the fit for $N-1 \rightarrow N+1$ is

$$S_{N+1} = 355 - 0.961 S_{N-1}. \tag{2}$$

Both predictions agree with the flywheel predictions within the error bars.

The negative slope of the even-odd forecast is surprising, but a negative slope was found using three common methods of calculating the slope of the linear regression line: allowing for errors in the y variable, errors in x, and errors in both, which is used here. The calculated correlation coefficient (r) is listed in the fifth column of Table 2. The low value of r, the large scatter of the data points in both panels of Figure 2, and the reduction in formal error between the flywheel and fit methods led to an examination of the significance of the correlation.

This significance was evaluated by comparing the critical correlation coefficient (r_c) with r. Here r_c is defined so that if $r > r_c$, there is a 95% chance that the correlation is usable as a forecast (or that there is a 5% chance of the correlation coming from a set of random values). Values of r_c are a function of the number of degrees of freedom in the data and the desired significance (Bevington & Robinson, 1992, section C.3). They are available in tables (Bevington & Robinson, 1992, Table C.3) or by direct calculation. The needed values of r_c for a significance of 95% (r_c[95%]) are listed in the final column of Table 2. The correlation coefficients for both predictions fail this test of significance, meaning the forecasts are not usable.

Because the values of maximum do not form a normally distributed variable, two other statistical tests were performed, the Spearman rank-order correlation coefficient (r_S) and Kendall's Tau (τ_K). The inertial forecast had $r_S = 0.224$ with a significance of 0.304, where a larger significance means the correlation is more likely due to chance, and $\tau_K = 0.154$ with a significance of 0.303. The even-odd forecast had $r_S = -0.160$ (0.478) and $\tau_K = -0.117$ (0.446). Every correlation shows that the even-odd forecast has a negative relationship. In all four cases the significance is greater than 0.05, and we conclude that these tests show these marginal correlations are likely due to chance.

4.3. Solar Cycle 24 Predictions

Climatological average, inertial, and even-odd predictions for Solar Cycle 24 were described by Pesnell (2012). Using R_Z (version 1) units, they were 115 ± 40, 120 ± 45, and 150 ± 54, respectively. Compared with $S_{24} = 80$, we see that the first two agreed with the actual measurement to some degree (the difference between prediction and actual was less than σ_0), but the even-odd prediction disagreed by $1.5\sigma_0$. This shows that $S_{\rm ave}$ is a good benchmark prediction of the solar cycle amplitude.

5. Conclusions

Preparing for an onslaught of amplitude predictions for Solar Cycle 25, we have presented a list of extrema of S_N, version 2 of the International Sunspot Number. The values in Table 1 are intended to supersede earlier tables using R_Z (version 1). The timings of the calculated extrema are consistent with the earlier values while the values of maximum and minimum differ due to the global renormalization and the cycle-to-cycle changes used to produce S_N.

Using those values, we presented a variety of naïve predictions for Solar Cycle 25: five predictions of the amplitude, a prediction of the timing of the next solar minimum, and the timing of the maximum in Solar Cycle 25. Four of the amplitude predictions were then shown to be statistically insignificant.

The climatological average of $S_{25} = 180 \pm 60$ can be used as the basis of comparison for all predictions published before the next maximum. Another prediction would be considered to produce useful information if its magnitude and error show that it varies significantly from the climatological average (Pesnell, 2008). It is also important that predictions of the amplitude of Solar Cycle 25 be reported in version 2 of the International Sunspot Number. If another solar activity index must be used, then a conversion to S_N should be part of the report. Linear correlations for that purpose can be found in Pesnell and Schatten (2018).

Acknowledgments
This work was supported by NASA's *Solar Dynamics Observatory*. Version 2 of the International Sunspot Number, both monthly averages and monthly samples from a 13-month running average, was obtained from the Solar Influences Data Center (SIDC) website as http://www.sidc.be/silso/DATA/SN_ms_tot_V2.0.csv and http://www.sidc.be/silso/DATA/SN_m_tot_V2.0.csv, respectively.

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