2-1-6 Empirical Forecast of Solar Cycle

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More active solar activity tends to result in more space storms that may affect artificial satellites and other human-made technical systems. For that reason, a major challenge is predicting the magnitude of the solar cycle in space weather forecasts. This paper describes long-term forecasts of the solar cycle based on cycle length, the number of no-sunspot days during the minimum of solar activity, and geomagnetic activity during the minimum.

Keywords
Solar cycle, Sunspot number, Solar maximum, Solar minimum

1 Introduction

There have been many reports about the occurrence of artificial satellite failures due to "space storms" or disturbances in the space environment around the earth due to solar activity[1][2]. Space storms tend to occur more frequently in line with increased solar activity, thereby making prediction of the magnitude of the solar cycle in space weather forecasts a major challenge.

Figure 1 shows the yearly average sunspot number and yearly occurrence of M-class and X-class solar flares (at the top of Fig. 1), the yearly average sunspot number and yearly occurrence of solar energetic particle events (in the middle), and the yearly average sunspot number and yearly occurrence of geomagnetic disturbances (at the bottom). As shown in Fig. 1, the higher the solar activity, the more frequent the solar flares, solar energetic particle events, geomagnetic disturbances and other space storms. Moreover, the number of failures stemming from such events also rises.

Space storms have the potential to affect satellite operations, expose astronauts and aircraft crews to radiation, and disrupt HF radio communications, Global Navigation Satellite Systems (GNSS), and electric power grids[1][2]. Moreover, the higher the solar activity, the greater the atmospheric drag and orbital decay of low-earth orbiting satellites[1][2]. Maintaining a necessary orbit for operation requires the use of fuel stored onboard the satellite; therefore, the higher the solar activity, the shorter the operational service life of the satellite. The distribution of debris on the orbit also changes due to variations in atmospheric drag.

Many methods of predicting the maximum sunspot number of the solar cycle have been proposed[3][4]. Pesnell[5] classified the methods of prediction into six categories: climatological method, climatological method based on the status of activity during the solar minimum period, method based on precursory phenomena, method based on a dynamo model, spectral method, and nonlinear prediction method. The climatological method is designed to use statistical changes in previous solar activity changes for future prediction. The climatological method based on the status of activity during the minimum utilizes the most recent status of activity for predicting the next cycle. The method based on precursor phenomena uses indicators of future solar activity, as in the case of intensity of the sun's polar magnetic field during the minimum for prediction purposes. The method based on a

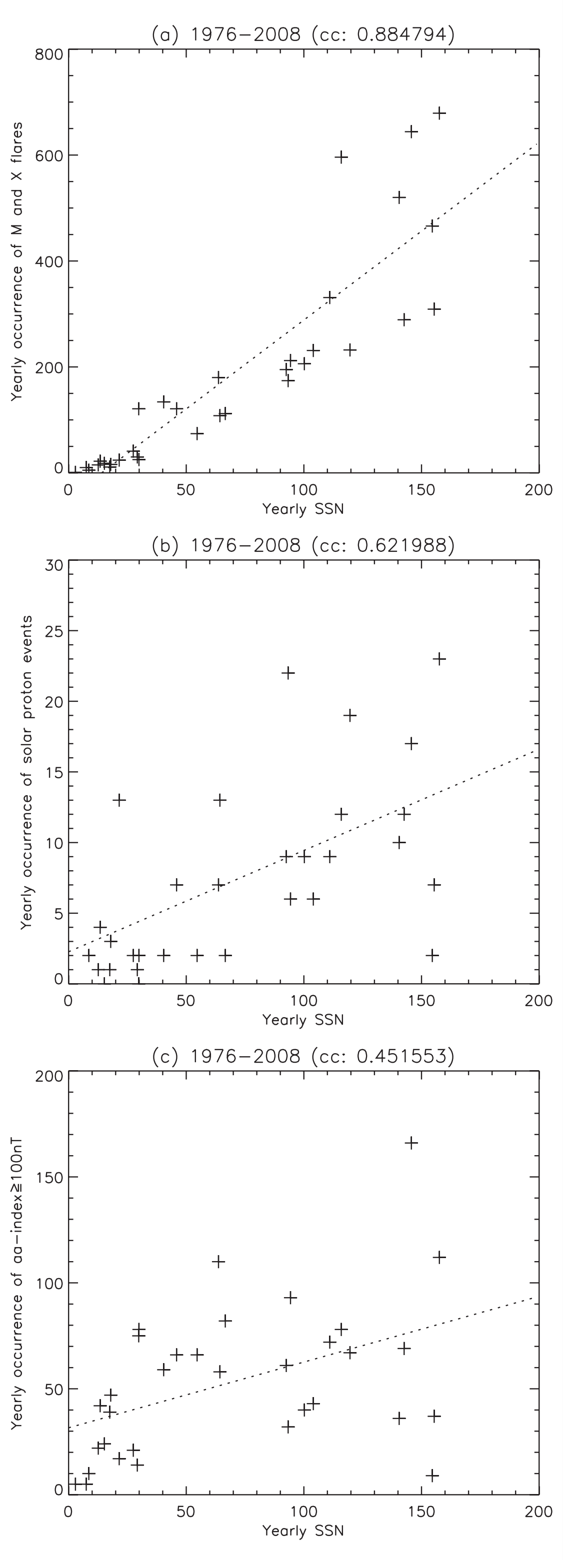

Fig.1 *The yearly average sunspot number and yearly occurrence of M-class/X-class solar flares (top); yearly average sunspot number and yearly occurrence of solar energetic particle events (middle); yearly average sunspot number and yearly occurrence of geomagnetic disturbances (bottom)*

dynamo model is used to make predictions by considering the physical model that drives solar activity. This method was first used to predict solar cycle 24[6]. The spectral method is used to make predictions based on time series analysis as in the case of Fourier analysis. The nonlinear prediction method is used to make predictions based on a nonlinear statistical model as in the case of a neural network. The predicted maximum sunspot number of solar cycle 24 shows a great difference (42 to 185) depending on the method of prediction employed. This clearly shows that solar cycle predictions must be further studied in the future.

This paper describes predictions made using a statistical method regarding the maximum sunspot number of the solar cycle based on length of the solar cycle, the number of no-sunspot days during the minimum, and geomagnetic activity during the minimum, along with predictions of the maximum of solar cycle 24 based on such prediction methods.

2 Data

With regard to correlation with the maximum sunspot number and the length of the solar cycle, number of no-sunspot days during the minimum, the rise time of the solar cycle, and other aspects, statistical analysis was conducted based on daily values (from January 1849 to December 2009), yearly average, monthly average, and 13-month moving average of sunspot numbers as provided by the SIDC-Team, World Data Center for the Sunspot Index, at the Royal Observatory of Belgium. Regarding correlation between the maximum sunspot number and geomagnetic activity during the minimum, analysis was conducted by using the geomagnetic aa-index supplied by the National Geophysical Data Center (NGDC) of the National Atmospheric and Oceanic Administration (NOAA). The aa-index represents geomagnetic activity based on geomagnetic observation data obtained at two locations (in Britain and Australia). Because there is approximately 140 years' worth of data, this index is advantageous in that it allows for longer-term statistical analysis than other geomagnetic indices.

3 Length of the solar cycle and solar activity of the next cycle

Figure 2 shows the length of each solar cycle. From this figure, one can see that each solar cycle lasts approximately 11 years on average, but a closer look at each cycle reveals a variance from 9 to 13 years. From an analysis of past solar activity by using carbon-14 (isotope), Miyahara et al[7] demonstrated that during the Maunder Minimum, the length of solar cycle was longer at 13 to 15 years. This suggests that a relation exists between solar cycle length and solar activity. Statistical analysis was therefore conducted of solar cycle length and solar activity of the next cycle[8].

Figure 3 gives a plot of the solar cycle length and the maximum sunspot number (at the top), and a plot of the solar cycle length and rise time of the next cycle (at the bottom). As is evident in Fig. 3, a negative correlation exists between the solar cycle length and the maximum sunspot number of the next cycle. On the other hand, a positive correlation exists between the solar cycle length and the rise time of the next cycle. Equations 1 and 2 yield the results of fitting the data indicated in Fig. 3 by using the least square method.

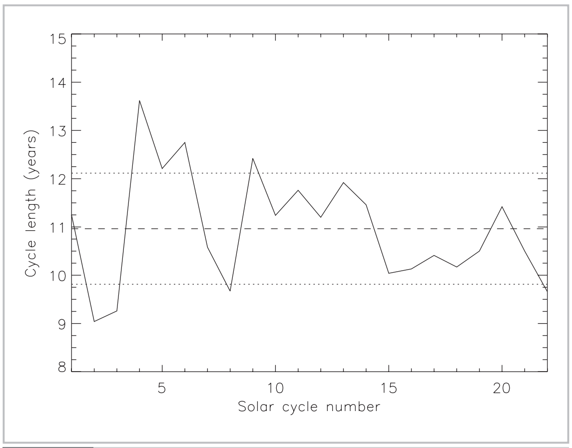

Fig.2 Length of each solar cycle

$$[\text{Maximum sunspot number of the next cycle}] = -22.92 \times [\text{length of the solar cycle}] + 366.58 \quad (1)$$

$$[\text{Rise time of the next cycle}] = 0.63 \times [\text{length of the solar cycle}] - 2.72 \quad (2)$$

4 Number of no-sunspot days during the solar minimum and solar activity of the next cycle

Table 1 shows the 1st to 10th years in and after 1849 in ascending order of years having the greatest number of no-sunspot days. There were many no-sunspot days in the year 2008 (corresponding to the minimum of solar cycle 23), thereby indicating considerably low solar

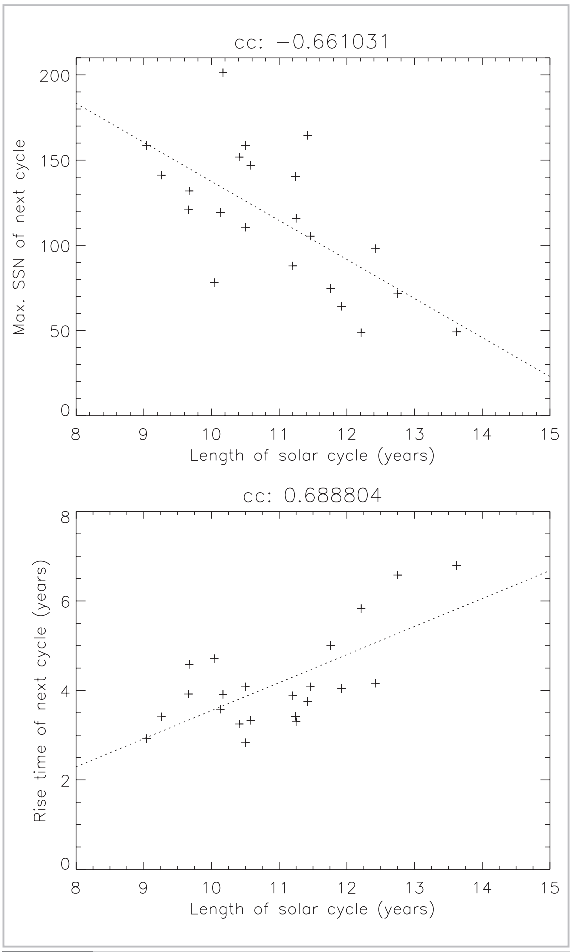

Fig.3 A plot of solar cycle length and maximum sunspot number of the next cycle (top); a plot of solar cycle length and rise time of the next cycle (bottom)

Table 1 Number of no-sunspot days per year in and after 1849

No.	Year	Number of no-sunspot days per year (days/year)	Cycle number
1	1913	311	14
2	1901	287	13
3	1878	280	11
4	2008	265	23
5	2009	262	
6	1856	261	10
7	1902	257	13
8	1912	254	14
9	1954	241	18
10	1933	240	16

Table 2 Number of consecutive no-sunspot days in and after 1849

No.	Start date of consecutive no-sunspot days	Number of consecutive no-sunspot days (days)	Cycle number
1	1913/04/08	92	14
2	1901/03/11	69	13
3	1879/02/16	54	12
4	1855/08/14	49	9
5	1902/03/17	49	14
6	1878/04/04	47	11
7	1878/09/14	45	11
8	1902/01/16	45	13
9	1912/01/21	43	14
10	1996/09/13	42	23
11	1856/04/22	41	10
12	1901/11/26	40	13
13	1913/07/15	39	14
14	1924/01/06	39	16
15	1855/12/12	38	9
16	1866/12/29	38	10
17	1876/05/17	37	11
18	1878/07/27	37	11
19	1933/11/05	36	17
20	1944/04/18	36	18
21	1867/04/20	35	10
22	2009/07/31	32	
23	1900/11/25	31	13
24	1912/07/12	31	14
25	1933/12/12	31	17
26	2008/07/21	31	23

activity. Table 2 shows the 1st to 10th years in ascending order of the number of consecutive no-sunspot days in and after 1849. From this table, one can see some cases during the previous cycle where no sunspots were observed for approximately 10 consecutive months. Recent years witnessed a time when no sunspots were observed for 42 consecutive

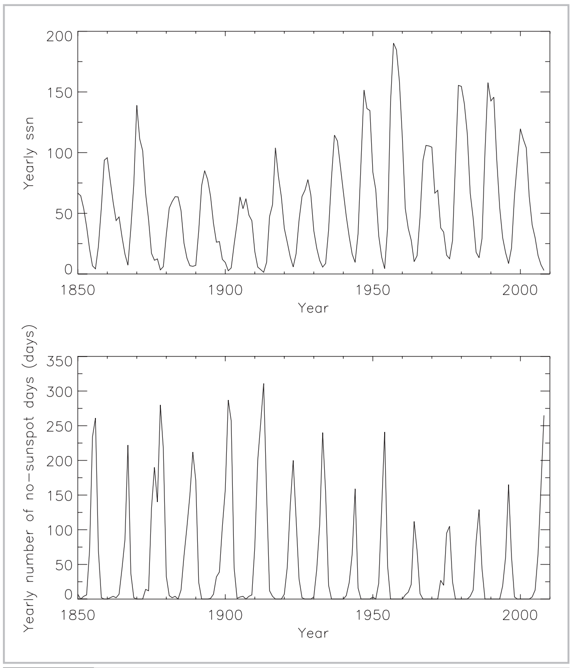

Fig.4 Yearly average of sunspot number (top); number of no-sunspot days per year (bottom)

days during the minimum of solar cycle 22. Moreover, no sunspots were observed for 31 consecutive days from July 21, 2008, and for 32 consecutive days from July 31, 2009.

Figure 4 is a plot of the yearly average sunspot number (at the top) and a plot of the number of no-sunspot days per year (at the bottom). As shown in Fig. 4, near the minimum of the solar cycle, one can see a rise in the number of no-sunspot days, which varies according to the cycle. One can also see in Fig. 4 that several recent past cycles had fewer no-sunspot days per year near the minimum than in previous cycles. A positive correlation is known to exist between the sunspot number during the minimum and the maximum sunspot number of the next cycle[9]. The number of no-sunspot days during the minimum and solar activity of the next cycle was then subjected to statistical processing.

Figure 5 shows a plot of the number of no-sunspot days during the year immediately prior to the minimum and the maximum sunspot numbers of the next cycle (at the top), and a plot of the number of no-sunspot days during the year immediately prior to the mini-

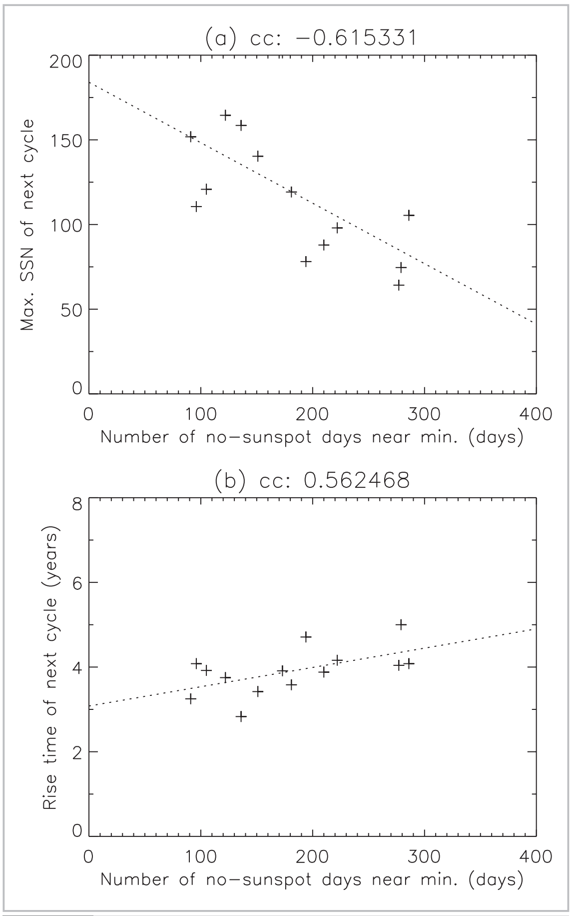

Fig.5 A plot of the number of no-sunspot days during the minimum and the maximum sunspot number of the next cycle (top); a plot of the number of no-sunspot days during the minimum and the rise time of the next cycle (bottom)

mum and the rise time of the next cycle (at the bottom). As is evident from Fig. 5, a positive correlation exists between the number of no-sunspot days during the year immediately prior to the minimum and the maximum sunspot number of the next cycle, and that a negative correlation exists between the number of no-sunspot days during the year immediately prior to the minimum and the rise time of the next cycle. Equations 3 and 4 yield the results of fitting the data indicated in Fig. 5 by using the least square method.

[Maximum sunspot number of the next cycle] =
 −0.36 × [Number of no-sunspot days during the minimum] + 184.01 (3)

[Rise time of the next cycle] =
 0.0046 × [Number of no-sunspot days during the minimum] + 3.08 (4)

5 Geomagnetic activity during the solar minimum and solar activity of the next cycle

Geomagnetic activity during the minimum period of solar activity is known to be a good indicator of solar activity in the next cycle. Ohl[10] discovered that the geomagnetic aa-index during the minimum of solar activity has a positive correlation with the maximum sunspot number of the next cycle. Feynman[11] divided the long-term changes in the aa-index into components R and I, examined their relation with solar activity, and then demonstrated that the peak value of component I has a good positive correlation with the maximum sunspot number of the next cycle. Here, component R is due to geomagnetic disturbance stemming from sporadic solar activity such as coronal mass ejection (CME), while component I is due to recurrent geomagnetic disturbance due to fast solar wind from a coronal hole.

This paper used the aa-indices in and after 1868 and regarded the average of aa-indices during the year immediately prior to the minimum of solar activity as an indicator of geomagnetic activity of the solar minimum. Figure 6 is a plot of the average of aa-indices during the year before the minimum and the maximum sunspot number of the next cycle (at the top), and a plot of the average of aa-indices during the year before the minimum and the rise time of the next cycle (at the bottom). As is evident from Fig. 6, a positive correlation exists between the average of aa-indices during the year before the minimum and the maximum sunspot number of the next cycle, while a negative correlation exists between the average of aa-indices and the rise time of the next cycle. Equations 5 and 6 yield the results of fitting the data indicated in Fig. 6 by using the least square method.

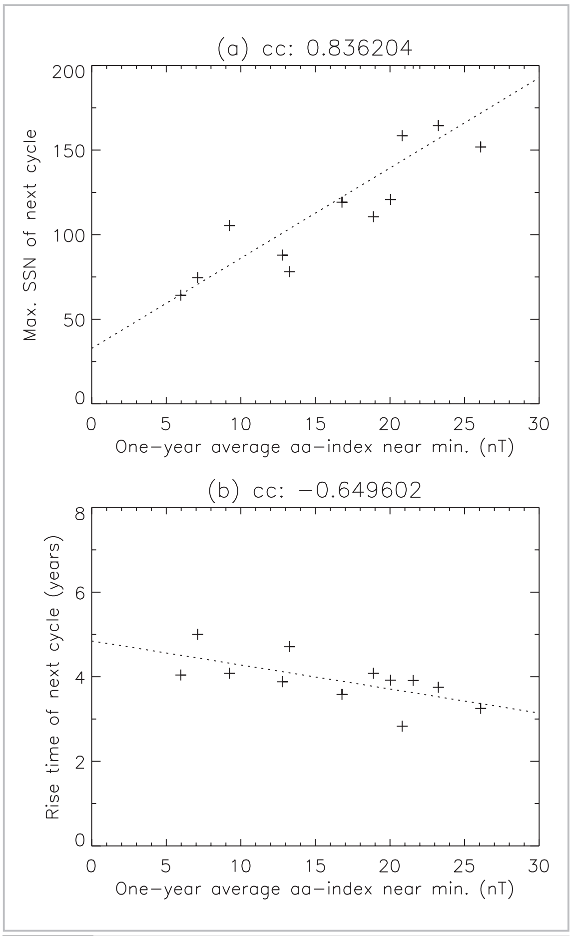

Fig.6 A plot of the average of aa-indices during the minimum and the maximum sunspot number of the next cycle (top); a plot of the average of aa-indices during the minimum and the rise time of the next cycle (bottom)

[Maximum sunspot number of the next cycle] = 5.33 × [One-year average of aa-indices during the year before the minimum] + 32.75 (5)

[Rise time of the next cycle] = −0.057 × [One-year average of the aa-indices during the year before the minimum] + 4.85 (6)

6 Prediction of solar cycle 24

The “Solar Cycle 24 Prediction Panel” was organized by NOAA and NASA to predict solar cycle 24[12]. Regarding the maximum of solar cycle 24, this panel announced two predictions in March 2007: the maximum sunspot number would reach 140 in October 2011, and the maximum sunspot number would reach 90 in August 2012. Given the low solar activity in 2008, however, this panel revised its previously announced predictions, and in May 2009 predicted that the activity of solar cycle 24 would be smaller than average, and that the maximum would be such that the maximum sunspot number would be 90 in May 2013. At that time, the panel stated that the minimum of solar cycle 23 was in December 2008.

Table 3 Predictions of the timing of the maximum and the maximum sunspot number of solar cycle 24

Method of prediction	Timing of the maximum of Cycle 24	Maximum sunspot number of Cycle 24
Prediction based on the number of no-sunspot days during the minimum	March, 2013	89
Prediction based on geomagnetic activity (based on the aa-index) during the minimum	March, 2013	110
Prediction based on length of the solar cycle	February, 2014	78
Prediction based on a consensus by the Solar Cycle 24 Prediction Panel	May, 2013	90

Table 3 shows the time of the maximum of solar cycle 24 from Equations 1 to 6 and the predictions of the maximum sunspot number, together with predictions made by the Solar Cycle 24 Prediction Panel. The prediction values presented in Table 3 are the result of calculations based on the assumption that the minimum of solar cycle 23 was December 2008, and indicate that the maximum sunspot number of solar cycle 24 would become smaller than the maximum sunspot number (120.8) of solar cycle 23. The low solar activity and low geomagnetic activity during the minimum period of solar cycle 23 suggest low solar activity of solar cycle 24, and that the timing of the maximum would be late. However, solar activity during the minimum of solar cycle 18 was considerably low, though the maximum sunspot number of solar cycle 19 was 241, the highest recorded during a previous solar cycle.

7 Conclusion

Current methods of predicting the activity of future solar cycle are mainly based on a statistical method, and predicting solar activity in the next cycle remains difficult. Past studies indicate that solar activity and geomagnetic activity during the minimum can be good indicators of solar activity of the next cycle. A sunspot group having the reverse magnetic field polarity of solar cycle 23 began to appear at high latitudes around the beginning of 2008, but the number of no-sunspot days totaled 265 in 2008 and 262 in 2009, thus indicating a lower condition of solar activity.

The low solar activity and low geomagnetic activity during the minimum of solar cycle 23 suggests that solar cycle 24 would be one with lower activity. Predictions made in this paper also include that the time of the minimum of solar cycle 24 will be around 2013, and yield a result whereby the maximum sunspot number will be smaller than that of solar cycle 23. One important future challenge regarding predictions of the solar cycle is to develop a prediction model based on a physical model that drives the cycle of solar activity.

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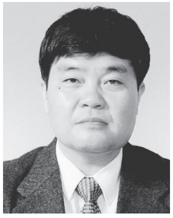

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