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Distribution of the activity of the Sun during an average solar cycle

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Abstract. The paper offers a look at distribution of solar activity during an average solar cycle. Activity profiles in solar cycles from 13 to 17 and from 18 to 22 were studied based on the relative sunspot numbers. The average values for both groups of cycles were derived after the standardization to the maximum monthly value. Obtained values differed minimally, allowing us to derive a uniform distribution of activity for the entire review period from 1890 to 1996. The derived model of the distribution of activity in an average solar cycle allows us to predict the maximum value of an activity cycle with an advance of approximately 5 years based only on the value obtained in the first year of the cycle. This can be of use for, e.g., the planning of long-term human activities in outer space.
Key words: solar cycle – distribution of activity

1. Introduction

The relationship between various phenomena in the Solar System and solar activity has been often studied, e.g., climate changes on the Earth, changes in the intensity of the velocity and density of the particles of the solar wind, sudden changes in brightness of comets, or atmospheric storms on Jupiter (e.g. A'Hearn, 1965; Friis-Christensen and Lassen, 1991; Clarke et al., 2009). And although, for example, the relationship between cometary activity and changes of solar activity ranks amongst the most studied questions in the field, the problem as a whole has not been satisfactorily addressed yet. Many authors have approached the problem and their conclusions cover a wide range of opinions from clearly positive analyzes providing explicit correlations between different indices of solar activity and the activity of comets (Beyer (1969)), up to the statement that the activity of comets is mainly caused by internal processes in cometary nuclei and effects of the solar activity play no, or only a negligible role (Kresák (1974)). Equally vague is correlation to climate changes on the Earth, although a connection of the breakdown in solar activity during the 17th century, called "the Maunder Minimum", and a long cold period on the Earth, called "the Little Ice Age", was proposed as early as 40 years ago (Eddy, 1976).

Context is very complex, but the reason is also the lack of models of solar activity, which would describe the distribution of activity during a solar cycle and allows some comparison. To provide exact distribution of activities in the "average" solar cycle is very difficult, if not impossible, since there are practically no two cycles with the same values at maximum and the same activity profile. In Figure 1, taken from *http://sidc.be/silco*, there are clearly visible differences among distributions of activity during solar cycles 19 to 24. When looking at activity in an average solar cycle, we must ignore the details and examine only the basic characteristics. Nevertheless, the creation of such average cycle, though greatly simplified, is very useful for many comparisons. Creating such a model may not have any significance for the study of the Sun itself, so this issue has not attracted sufficient attention yet.

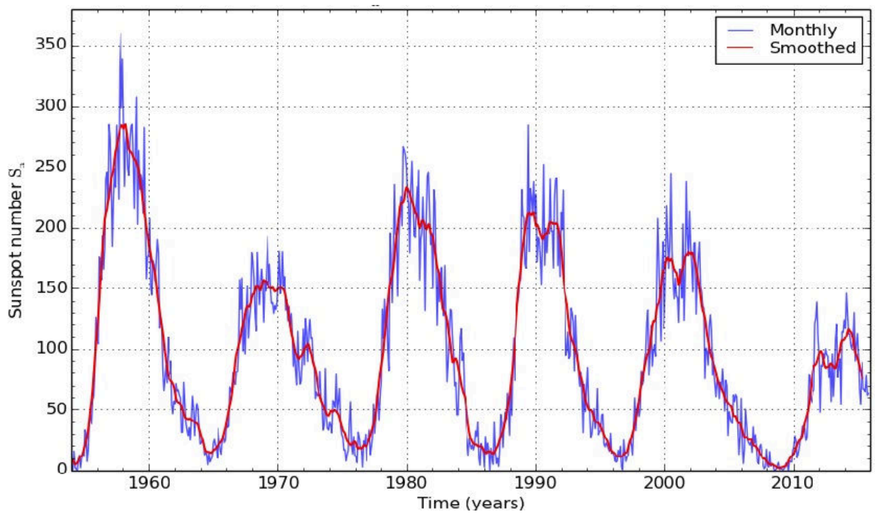

Figure 1. Sunspot numbers - monthly mean and 13-month smoothed numbers. Taken from SILSO graphics (http://sidc.be/silco) Royal Observatory of Belgium, 2015 December 1.

2. Phases of the solar cycles

The division of each solar cycle into 10 parts was the first step of our analysis. The times of minima (i. e. onsets) of solar cycles were taken from Waldmeier (1961), McKinnon and Waldmeier (1987) and Hathaway (2010). The data are given with the precision of one month - we have counted the beginnings of cycles from the middle of the month concerned.

In this analysis, each individual solar cycle (counting from minima to minima) was divided into 10 equidistant parts which were grouped into four periods: parts 10 and 1 represent the minimum of the cycle, parts 2, 3 and 4 the ascend-

Table 1. Phases of solar cycles 13 to 22. Abbreviations: c – cycle, b – begining, d - duration in years.

c	b	d	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
13	1890.2	11.9	1891.4	1892.6	1893.8	1895.0	1896.2	1897.3	1898.5	1899.7	1900.9
14	1902.1	11.5	1903.2	1904.4	1905.6	1906.7	1907.8	1909.0	1910.2	1911.3	1912.5
15	1913.6	10.0	1914.6	1915.6	1916.6	1917.6	1918.6	1919.6	1920.6	1921.6	1922.6
16	1923.6	10.1	1924.6	1925.6	1926.6	1927.6	1928.6	1929.7	1930.7	1931.7	1932.7
17	1933.7	10.4	1934.7	1935.8	1936.8	1937.9	1938.9	1939.9	1941.0	1942.0	1943.1
18	1944.1	10.2	1945.1	1946.1	1947.2	1948.2	1949.2	1950.2	1951.2	1952.3	1953.3
19	1954.3	10.5	1955.4	1956.4	1957.4	1958.5	1959.6	1960.6	1961.6	1962.7	1963.8
20	1964.8	11.7	1966.0	1967.1	1968.3	1969.5	1970.6	1971.8	1973.0	1974.2	1975.3
21	1976.5	10.2	1977.5	1978.5	1979.6	1980.6	1981.6	1982.6	1983.6	1984.7	1985.7
22	1986.7	9.7	1987.7	1988.6	1989.6	1990.6	1991.6	1992.5	1993.5	1994.5	1995.4
23	1996.4										

ing branch of the cycle, parts 5 and 6 the maximum of the cycle and parts 7, 8 and 9 the descending branch of the cycle.

3. Average solar cycle

Solar activity was studied based on relative sunspots number. Although there are plenty of modern indices describing the activity of the sun better (e.g. Minarovjech et al., 2011), only the Wolf number allows us to compare data from a long period of time. Data for 10 cycles from 1890 to 1996 were analysed in order to obtain a more meaningful distribution of activity in the solar cycle. The average length of the cycle in the period under study was 10.6 years, from maximum 11.9 years in cycle 13 to minimum 9.7 years in cycle 22.

Table 2. Variations of the averaged Wolf number in dependence on the phase of solar cycles (divided into ten intervals).

cycle/part	1	2	3	4	5	6	7	8	9	10
13	20.7	97.2	136.8	131.6	101.7	65.0	42.3	30.8	17.0	4.6
14	10.3	49.2	87.4	105.7	96.8	82.4	69.6	24.0	6.0	4.3
15	7.9	53.7	95.1	127.0	158.3	127.7	75.4	52.6	31.3	10.2
16	18.0	43.9	105.2	120.1	123.2	108.3	80.3	44.0	23.2	12.6
17	11.1	40.5	117.2	195.2	182.1	155.0	109.7	79.2	48.7	26.0
18	18.0	59.2	163.4	208.1	205.4	179.0	109.9	83.9	39.4	13.5
19	14.4	109.8	227.7	281.8	252.1	180.9	110.5	59.1	44.6	16.9
20	21.2	73.5	134.1	157.5	149.4	105.0	98.5	52.0	41.6	22.4
21	23.2	84.1	174.2	230.6	200.1	190.0	126.7	75.0	22.5	14.3
22	23.9	75.4	186.9	201.6	204.9	172.2	103.3	53.8	38.2	15.4

As the input data we used monthly values of the Wolf number for solar cycles 13 to 22, which are very well covered by observations (Table 2). The

Table 3. Normalized to the maximum value in the cycle.

cycle/part	1	2	3	4	5	6	7	8	9	10	Sum
13	15	71	100	96	74	48	31	23	12	3	
14	10	47	83	100	92	78	66	23	6	4	
15	5	34	60	80	100	81	48	33	20	6	
16	15	36	85	97	100	88	65	36	19	10	
17	6	21	60	100	93	79	56	41	25	13	
average	10	42	78	95	92	75	53	31	16	7	499
18	9	28	79	100	99	86	53	40	19	6	
19	5	39	81	100	89	64	39	21	16	6	
20	13	47	85	100	95	67	63	33	26	14	
21	10	36	76	100	87	82	55	33	10	6	
22	12	37	91	98	100	84	50	26	19	8	
average	10	37	82	100	94	77	52	31	18	8	508

data were normalized to the maximum value for each cycle (equal to 100) and they are shown in the rows of Table 3. One can see that, e.g., cycles 19 and 20, differing in maxima by a ratio of two, have very similar normalized behavior. The normalized values were used to determine average values (separately for cycles 13 to 17 and separately for cycles 18 to 22). Interestingly, the sum of these two files, each containing 5 cycles vary only by 2% (499 versus 508).

Table 4. The average value of the proportion of activities attributable to a part of the cycle.

cycle/part	1	2	3	4	5	6	7	8	9	10
13-17	2	8	16	19	18	15	11	6	3	1
18-22	2	7	16	20	18	15	10	6	4	2
sum 13-22	2	8	16	19	18	15	10	6	3	2

We obtained even a better agreement by comparing how much of the activity in the percentage is connected with individual parts of the cycle. The average values for data sets 13-17 and 18-22 are either within the precision of the same or differ by not more than 1%. In order to compare both distributions to each other, we calculated a correlation coefficient R. The value of R is 0.9942, the value of the coefficient of determination R^2 is 0.9884. Obtained coefficients confirmed the almost total agreement between the two sets of values. Due to presented results, the last line of Table 4 could be considered as a model of the average distribution of activity in the solar activity cycle (Fig. 2).

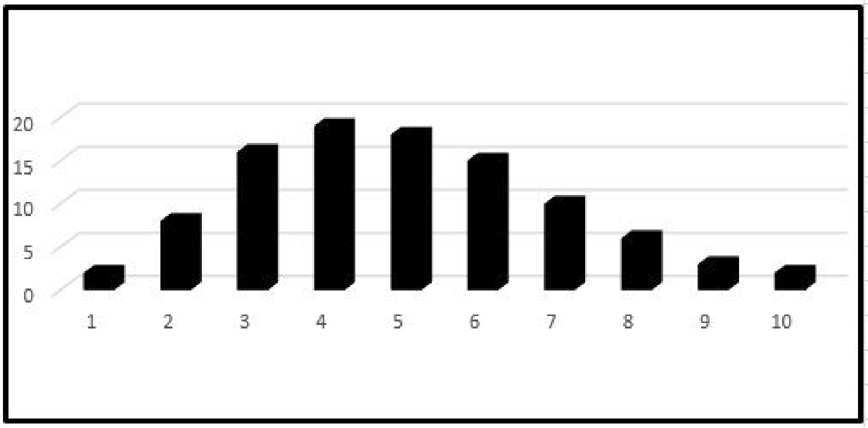

Figure 2. The average solar cycle. The x-axis shows ten parts of the solar cycle from the minimum to the subsequent minimum. The y-axis shows the ratio of activity attributable to the relevant part of the cycle as a percentage of the sum of activities for the whole cycle.

4. Conclusion

The distribution of solar activity during an average solar cycle was derived based on the sunspot numbers for solar cycles from 13 to 22. One can for example see that monthly values at the peak of the cycle are approximately 9 times higher than the monthly values in the first tenth of the onset cycle. This conclusion can be used to predict the values of the peak activity cycle of approximately 3 to 5 years before its maximum. This can be of use for, e.g., the planning of long-term human activities in outer space. The asymmetry of the cycle with a sharper and shorter onset of activity from minimum to maximum and the gradual fading-out of activities from maximum to minimum is also obvious. The ability to easily forecast the height of the cycle is only a byproduct of this article. There are plenty of sophisticated forecasting methods of the solar activity based on examination of physical processes and parameters, for example Clette at al. (2014) and references therein.

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