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The Recurrence Tendency of Geomagnetic Activity During Solar Cycle 20

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Abstract. The equivalent recurrence number $\omega(n)$ of geomagnetic activity introduced by Bartels (1960) is a quantitative measure of the recurrence tendency during n consecutive solar rotations. Tabulated values of $\omega(n)$, for n equal to 2, 4, 8, 16, and 32, are given for the years 1971–1976 supplementing former tables (Meyer, 1965, 1973) comprising the years 1884–1970. A musical diagram of $\omega(n)$ for the years 1965–1976 provides a detailed picture of the recurrence tendency during the entire solar cycle 20.

The general course of the recurrence tendency variation, apart from superimposed arbitrary fluctuations, follows the one noticed for previous solar cycles and is especially well pronounced for the higher values of n: The recurrence tendency is lowest in the years immediately following the preceding sunspot minimum till sunspot maximum (1965–1968), it is increasing in the years after sunspot maximum (1969–1973), and is strongest in the two years before the final sunspot minimum (1974–1975), remaining still relatively high throughout 1976. In a physical interpretation the equivalent recurrence numbers $\omega(n)$ are reflecting the stability of the large-scale solar wind structure or, more specifically, of high-speed solar wind streams.

Key words: Geomagnetic activity – Recurrence tendency – Equivalent recurrence numbers.

1. Introduction

For geomagnetic activity a great variety of measures exist, the most customary ones being derived from Bartels' three-hour range index *K*. They usually underly studies of both time variations of activity and correlation with other solar or interplanetary data. Special investigations on the 27-days recurrence tendency with any of these measures have previously been carried out mainly by applying the method of superposed epochs (synchronization or Chree method), thus yielding only average results for long periods. A higher resolution of time

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variations requires a quantitative measure of the recurrence tendency itself. For this purpose J. Bartels initiated an extensive study to express the recurrence tendency numerically by means of equivalent recurrence numbers, based on the continuous series of daily character figures *C8* extending back to 1884. Preliminary results were presented by Bartels (1960) at the Helsinki Meeting of IAGA. A complete table of recurrence numbers for each solar rotation from 1884–1963/64 was published by Meyer (1965), together with a first evaluation of the calculated indices. In the same paper musical diagrams similar to those for *Kp* provided a comprehensive picture of the recurrence tendency in the course of more than seven sunspot cycles. The diagram for the years 1954–1964 (solar cycle 19) has also been shown in another paper (Meyer, 1966). Supplementary tables and diagrams for 1964–1970, 1971 have been given by Meyer (1973). The present paper contains additional data for the years 1971–1976, completing the recurrence tendency picture for the entire sunspot cycle 20.

2. The Equivalent Recurrence Number $\omega(n)$

The original concept of recurrence scaling has already been put forward by Bartels (1935; see also Chapman and Bartels, 1940) by generalizing the fundamental law of propagation of errors. The *equivalent recurrence number* $\omega(n)$ (equivalent number of repeated sets) is defined by

$$\omega(n)=m^2(n)/(m^2/n), \tag{1}$$

where m is the average standard deviation for n (long) individual sets of single values, and $m(n)$ is the standard deviation for the average set. A detailed treatment of the morphology of geophysical time series with conservation and recurrence tendencies, including the deduction of all formulas, can be found in the treatise of Meyer (1965).

For geomagnetic data, arranged as usual in lines according to solar rotations of exactly 27 days, the equivalent recurrence number $\omega(n)$ indicates how many times (among n of such consecutive sets) statistically independent sets are repeated: $\omega(n)$ being 1 means arbitrary succession without any recurrence tendency at all; $\omega(n)$ being n means perfect repetition, i.e., all n rotations show an identical day-to-day variation of activity. Thus the highest possible value for the index $\omega(n)$ is always the number n itself. Values of $\omega(n)$ between 1 and n denote positive recurrence tendency, those smaller than 1 denote negative (opposite) recurrence tendency. Starting from the daily character figures *C8* (Bartels, 1951, 1958, and supplementary tables), the equivalent recurrence numbers $\omega(n)$, for n equal to 2, 4, 8, 16, and 32, have been calculated separately for each mean (or associated) solar rotation number. The first day of the mean solar rotation is the central day of all n rotations concerned. The $\omega(n)$ data in Table 1 supplements the former tables making available a continuous series of equivalent recurrence numbers for the years 1884–1976.

Table 1. Equivalent recurrence numbers $\omega(n)$ for geomagnetic activity during 1971–1976

Year	Assoc. Rot.-No.	Rot.-No.	$\omega(2)$	Rot.-No.	$\omega(4)$	Rot.-No.	$\omega(8)$	Rot.-No.	$\omega(16)$	Rot.-No.	$\omega(32)$
1971	1880	1879+80	1.15	1878−81	1.56	1876−83	1.42	1872−87	1.67	1864−95	2.18
	1881	1880+81	1.69	1879−82	1.79	1877−84	1.68	1873−88	1.60	1865−96	1.94
	1882	1881+82	1.37	1880−83	2.14	1878−85	2.64	1874−89	1.86	1866−97	1.95
	1883	1882+83	1.48	1881−84	1.94	1879−86	2.60	1875−90	1.67	1867−98	1.96
	1884	1883+84	1.14	1882−85	1.81	1880−87	2.67	1876−91	1.96	1868−99	1.79
	1885	1884+85	1.08	1883−86	1.57	1881−88	2.06	1877−92	1.75	1869−00	1.81
	1886	1885+86	1.21	1884−87	1.29	1882−89	1.65	1878−93	2.12	1870−01	1.84
	1887	1886+87	1.10	1885−88	1.32	1883−90	1.27	1879−94	2.02	1871−02	1.81
	1888	1887+88	1.42	1886−89	1.58	1884−91	1.58	1880−95	1.90	1872−03	1.92
	1889	1888+89	1.30	1887−90	1.58	1885−92	1.75	1881−96	1.39	1873−04	1.65
	1890	1889+90	1.19	1888−91	1.54	1886−93	2.18	1882−97	1.24	1874−05	1.54
	1891	1890+91	1.16	1889−92	1.45	1887−94	2.46	1883−98	1.32	1875−06	1.51
	1892	1891+92	1.27	1890−93	1.67	1888−95	2.20	1884−99	1.23	1876−07	1.43
	1893	1892+93	1.07	1891−94	1.68	1889−96	1.40	1885−00	1.30	1877−08	1.51
1972	1894	1893+94	1.26	1892−95	1.39	1890−97	1.35	1886−01	1.39	1878−09	1.66
	1895	1894+95	1.12	1893−96	0.89	1891−98	1.44	1887−02	1.61	1879−10	1.62
	1896	1895+96	1.04	1894−97	1.03	1892−99	1.12	1888−03	1.71	1880−11	1.87
	1897	1896+97	1.34	1895−98	1.69	1893−00	1.12	1889−04	1.52	1881−12	1.91
	1898	1897+98	1.50	1896−99	1.36	1894−01	1.07	1890−05	1.41	1882−13	1.87
	1899	1898+99	0.84	1897−00	0.93	1895−02	1.17	1891−06	1.28	1883−14	1.74
	1900	1899+00	0.67	1898−01	0.79	1896−03	1.02	1892−07	1.11	1884−15	1.80
	1901	1900+01	1.35	1899−02	0.75	1897−04	0.84	1893−08	1.28	1885−16	1.65
	1902	1901+02	0.96	1900−03	1.84	1898−05	0.98	1894−09	1.18	1886−17	1.57
	1903	1902+03	1.47	1901−04	1.49	1899−06	1.11	1895−10	1.13	1887−18	1.69
	1904	1903+04	0.91	1902−05	1.26	1900−07	1.42	1896−11	1.23	1888−19	1.54
	1905	1904+05	1.19	1903−06	1.23	1901−08	1.38	1897−12	1.52	1889−20	1.42
	1906	1905+06	1.41	1904−07	1.38	1902−09	1.27	1898−13	1.88	1890−21	1.37
1973	1907	1906+07	1.29	1905−08	1.56	1903−10	1.33	1899−14	1.84	1891−22	1.19
	1908	1907+08	1.37	1906−09	1.56	1904−11	1.82	1900−15	2.02	1892−23	1.13
	1909	1908+09	1.44	1907−10	2.07	1905−12	2.01	1901−16	1.90	1893−24	0.99
	1910	1909+10	1.49	1908−11	2.36	1906−13	2.53	1902−17	1.72	1894−25	1.05
	1911	1910+11	1.64	1909−12	2.27	1907−14	2.33	1903−18	1.32	1895−26	1.09
	1912	1911+12	1.41	1910−13	1.91	1908−15	2.19	1904−19	1.30	1896−27	0.99
	1913	1912+13	1.54	1911−14	1.56	1909−16	1.80	1905−20	1.17	1897−28	1.22
	1914	1913+14	1.09	1912−15	1.53	1910−17	1.37	1906−21	1.24	1898−29	1.56
	1915	1914+15	1.23	1913−16	1.65	1911−18	1.03	1907−22	1.24	1899−30	1.72
	1916	1915+16	1.48	1914−17	1.91	1912−19	1.29	1908−23	1.12	1900−31	1.84
	1917	1916+17	1.37	1915−18	1.58	1913−20	1.18	1909−24	1.35	1901−32	1.96
	1918	1917+18	1.29	1916−19	1.73	1914−21	1.52	1910−25	1.53	1902−33	1.70
	1919	1918+19	1.41	1917−20	1.81	1915−22	1.67	1911−26	1.98	1903−34	1.97
	1920	1919+20	1.17	1918−21	1.93	1916−23	1.72	1912−27	2.38	1904−35	2.25
1974	1921	1920+21	1.53	1919−22	2.04	1917−24	2.47	1913−28	2.73	1905−36	2.26
	1922	1921+22	1.39	1920−23	2.05	1918−25	2.73	1914−29	3.22	1906−37	2.43
	1923	1922+23	1.36	1921−24	1.90	1919−26	3.39	1915−30	3.31	1907−38	2.88
	1924	1923+24	1.09	1922−25	2.42	1920−27	3.39	1916−31	3.99	1908−39	3.50
	1925	1924+25	1.76	1923−26	2.20	1921−28	3.55	1917−32	4.85	1909 40	3.94
	1926	1925+26	1.48	1924−27	2.08	1922−29	3.41	1918−33	5.14	1910−41	4.15
	1927	1926+27	1.51	1925−28	2.32	1923−30	3.09	1919−34	5.48	1911−42	4.65

Table 1 (Continued)

Year	Assoc. Rot.-No.	Rot.-No.	$\omega(2)$	Rot.-No.	$\omega(4)$	Rot.-No.	$\omega(8)$	Rot.-No.	$\omega(16)$	Rot.-No.	$\omega(32)$
	1928	1927+28	1.60	1926−29	2.91	1924−31	3.37	1920−35	5.40	1912−43	4.94
	1929	1928+29	1.74	1927−30	2.69	1925−32	3.77	1921−36	4.95	1913−44	4.74
	1930	1929+30	1.49	1928−31	2.65	1926−33	4.13	1922−37	4.52	1914−45	4.65
	1931	1930+31	1.52	1929−32	2.54	1927−34	4.03	1923−38	4.75	1915−46	4.75
	1932	1931+32	1.47	1930−33	2.46	1928−35	3.95	1924−39	5.00	1916−47	4.84
	1933	1932+33	1.37	1931−34	2.69	1929−36	3.25	1925−40	4.74	1917−48	5.09
	1934	1933+34	1.80	1932−35	2.40	1930−37	3.14	1926−41	4.55	1918−49	4.91
1975	1935	1934+35	1.50	1933−36	1.98	1931−38	3.33	1927−42	4.54	1919−50	4.78
	1936	1935+36	1.44	1934−37	2.10	1932−39	3.11	1928−43	4.39	1920−51	4.47
	1937	1936+37	1.43	1935−38	2.39	1933−40	2.94	1929−44	4.08	1921−52	4.07
	1938	1937+38	1.56	1936−39	2.05	1934−41	2.85	1930−45	3.70	1922−53	3.61
	1939	1938+39	1.24	1937−40	1.91	1935−42	2.89	1931−46	3.56	1923−54	3.47
	1940	1939+40	1.37	1938−41	1.75	1936−43	2.30	1932−47	3.15	1924−55	3.43
	1941	1940+41	1.57	1939−42	1.89	1937−44	1.87	1933−48	2.83	1925−56	3.60
	1942	1941+42	0.96	1940−43	1.36	1938−45	1.80	1934−49	2.73	1926−57	3.73
	1943	1942+43	1.25	1941−44	1.45	1939−46	2.41	1935−50	2.84	1927−58	3.49
	1944	1943+44	1.56	1942−45	1.85	1940−47	2.20	1936−51	2.71	1928−59	3.31
	1945	1944+45	1.34	1943−46	2.07	1941−48	2.48	1937−52	2.55	1929−60	3.47
	1946	1945+46	1.10	1944−47	1.67	1942−49	2.61	1938−53	2.46	1930−61	3.11
	1947	1946+47	1.27	1945−48	1.79	1943−50	2.37	1939−54	2.43	1931−62	2.84
1976	1948	1947+48	1.42	1946−49	2.14	1944−51	2.16	1940−55	2.27	1932−63	2.73
	1949	1948+49	1.54	1947−50	2.14	1945−52	2.20	1941−56	2.42	1933−64	2.79
	1950	1949+50	1.52	1948−51	2.34	1946−53	2.45	1942−57	2.41	1934−65	2.60
	1951	1950+51	1.59	1949−52	2.30	1947−54	2.04	1943−58	2.41	1935−66	2.64
	1952	1951+52	1.36	1950−53	1.86	1948−55	2.23	1944−59	2.51	1936−67	2.49
	1953	1952+53	0.97	1951−54	1.52	1949−56	1.93	1945−60	2.64	1937−68	2.26
	1954	1953+54	1.70	1952−55	1.32	1950−57	1.80	1946−61	2.46	1938−69	2.17
	1955	1954+55	1.07	1953−56	1.88	1951−58	1.81	1947−62	2.18		
	1956	1955+56	1.41	1954−57	1.84	1952−59	2.18	1948−63	2.18		
	1957	1956+57	1.36	1955−58	1.96	1953−60	3.02	1949−64	2.13		
	1958	1957+58	1.22	1956−59	1.78	1954−61	2.63	1950−65	2.03		
	1959	1958+59	1.29	1957−60	2.01	1955−62	2.45	1951−66	1.91		
	1960	1959+60	1.45	1958−61	1.57	1956−63	1.92	1952−67	2.13		
	1961	1960+61	1.15	1959−62	1.52	1957−64	1.98	1953−68	2.13		

The physical significance of the equivalent recurrence number $\omega(n)$ can easily be derived from its relation to the mean correlation coefficients r_τ ($\tau=1, 2, \ldots, n-1$) between the n solar rotations:

$$\omega(n)=1+2\frac{n-1}{n}r_1+2\frac{n-2}{n}r_2+\cdots+\frac{2}{n}r_{n-1}. \tag{2}$$

It shows that, for a higher value of n, e.g., n equal to 16 or 32, $\omega(n)$ is determined to a considerable amount by the number of non-vanishing correlation coefficients: $\omega(n)$ increases with increasing number of solar rotations connected by positive correlation, and vice-versa. Thus the indices $\omega(16)$ and $\omega(32)$ are essentially determined by the mean duration of the activity sequences in the time-pattern of geomagnetic activity. They can be interpreted as a relative measure of the *average life-time* of all disturbance-causing solar *M*-regions within the 16 or 32 rotations considered. Since the solar wind is the transmitting medium for the geomagnetic activity originating primarily from solar activity, the equivalent recurrence numbers may also be conceived as a measure for the degree of *stability* of the large-scale solar wind structure.

The latter interpretation can also be applied to $\omega(8)$. However, regarding $\omega(2)$ and $\omega(4)$ attention has to be paid to the superimposed semiannual wave (Meyer, 1965, 1966, 1973) which clearly is an effect of terrestrial or magnetospheric modulation (see also Damaske, 1977). The appearance of a semiannual wave also in the recurrence tendency, i.e., in the persistence of geomagnetic activity sets, is probably due to the method of calculating $\omega(n)$, using linear deviations from quasi-logarithmic character figures. If $\omega(2)$ and $\omega(4)$ are to indicate the stability of the solar wind structure, the semiannual wave has to be eliminated in a way analogous to the one suggested already for activity indices (Roosen, 1966; Meyer, 1973).

The equivalent recurrence numbers $\omega(n)$ have proved to be a useful tool for recurrence studies of geomagnetic activity (e.g., see Siebert, 1971). Beyond, they are regarded as an adequate basis for detailed correlation studies with solar wind and interplanetary field data.

3. Results for Solar Cycle 20

The musical diagram for $\omega(n)$ ($n=2$, 4, 8, 16, and 32) shown in Figure 1, supplementing also former diagrams (Meyer, 1965, 1966, and 1973) gives a synoptic picture of the recurrence tendency variations during solar cycle 20 (years 1965–1976). The first index in a year is always associated with the first rotation belonging fully to that year. It refers to the period from $n/2$ rotations before to $(n/2)-1$ rotations after the associated (mean) rotation number. In practice, the associated rotation number can be read either from the table of $\omega(n)$ or from the semi-graphic table of *C9*. Sunspot minimum and maximum are particularly marked by the triangles above the musical charts. In order to facilitate the recognition of recurrence tendency decrease at or soon after sunspot minimum, the beginning of solar cycle 21, beyond the minimum of March 1976, is also shown. The base line for the single indices meets the value of $\omega(n)=1$, corresponding to the absence of any recurrence tendency (accidental sequences of solar rotations). Indices plotted upward denote positive, those plotted downward denote negative (opposite) recurrence tendency. The key shows values at intervals of 0.5. The scale itself is continuous.

As is immediately apparent from the diagram, the recurrence tendency was strongest in 1974 and 1975, i.e., in the two years preceding sunspot minimum, remaining relatively high throughout 1976. But it is also perceptible, with varying intensity, in the years immediately following the sunspot maximum year of 1968. In the interval from 1965 to about 1968 (i.e., the years after the 1964

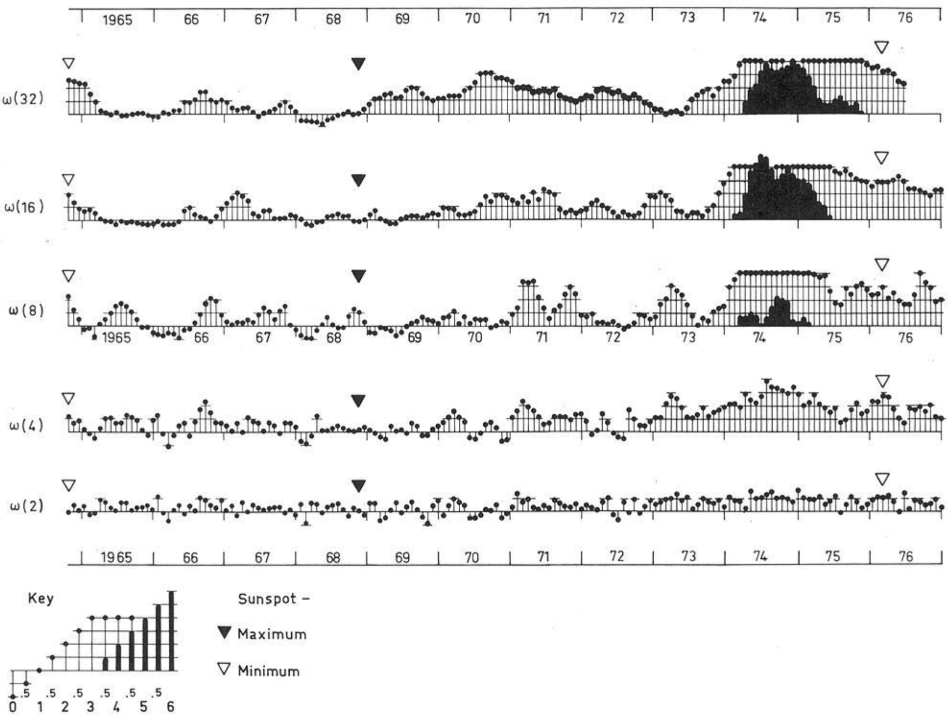

Fig. 1. Equivalent recurrence numbers $\omega(n)$ for the years 1965–1976 (solar rotations 1796–1961)

minimum till sunspot maximum) the recurrence tendency was less pronounced, though still existing on the average.

In its essential characteristics the systematic variation of the recurrence indices $\omega(n)$ during solar cycle 20 corresponds to the average variation of recurrence tendency in the course of a sunspot cycle found, for example, using the superposed epochs method (Bartels, 1948). On the other hand, quite an unusual aspect of solar cycle 20 has been noted concerning variations of geomagnetic activity itself (e.g., Gosling et al., 1977). The maximum activity occurred exceptionally late, not earlier than 1973–1975: i.e., 5–7 years after sunspot maximum, whereas the usual lag is 1–2 years. Furthermore, the activity maximum nearly coincided with the period of extremely high recurrence tendency, while the maximum recurrence tendency usually appears for declining or even minimum activity. This suggests that geomagnetic activity and its recurrence tendency are not as closely correlated as previously supposed by the results from other solar cycles.

As solar cycle 20 is the first cycle for which direct solar wind measurements for longer periods are available, some of the inferences from geomagnetic activity analysis can immediately be related to results of interplanetary data evaluation, though still tentatively in many respects. Recurrence tendencies in the earth passage of interplanetary magnetic sector boundaries as well as in well-defined high-speed wind streams have been reported by Sawyer (1976). Comparing both he finds that the recurrence interval for the latter has a clearly narrower frequency distribution centered at 27.0 days, i.e., at exactly the same period obtained on the average for geomagnetic activity recurrences. (For sector boundaries the average recurrence interval turns out to be half a day longer). Thus the results of Sawyer are quite in favour of a close correlation between recurrent geomagnetic activity and high-speed solar wind streams.

Further evidence for this view has been given by Gosling et al. (1976) who have plotted the occurrence of all high-speed streams observed from 1962 to 1974 in a 27-day format to emphasize recurrent features. A merely qualitative judgement already shows the distinct difference in the recurrence pattern of different years, i.e.: a rather poor stability in years of high solar activity (1965–1967), an increasing stability on the declining branch of the solar cycle (1970–1973), and the most stable streams appearing in 1974. This is in good agreement with a corresponding variation of the recurrence tendency of geomagnetic activity. Gosling et al. (1976) confirm their results in a more quantitative manner by means of yearly and half-yearly autocorrelation curves. The resolution, however, is not nearly as high as it is for the equivalent recurrence numbers $\omega(n)$. A definite relation between geomagnetic activity and high-speed solar wind streams would, at the same time, identify Bartels' hypothetic M-regions as the coronal holes in which the streams most probably originate (for a review see Zirker, 1977). A detailed analysis of this relation will have to imply systematic correlations between individual streams and activity sequences after eliminating any effects of superimposed magnetospheric modulation. An investigation on this topic is being planned.

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