I-3. *GEOMAGNETIC INDICES*

J. Virginia Lincoln[1]

1. Different Indices

1.1 Introduction

Since time variations of the earth's magnetic field have great practical importance in not only the study of geomagnetism itself, but especially in the field of solar-terrestrial relationships, there have been many indices designed to measure geomagnetic activity. The conventional reductions of geomagnetic data have been tabulations of the mean hourly values of each of the three components of the field related to a base level known in absolute units. These are published as station booklets (magnetic yearbooks) and frequently include copies of the actual magnetograms in reduced size. These are valuable tabulations for many studies in geomagnetism but are not as well suited for comparison with data in other fields of geophysics or to depict the character of magnetic activity throughout the day. The remainder of this chapter will describe different types of indices suitable

[1] Institute for Telecommunication Sciences and Aeronomy, Environmental Science Services Administration, Boulder, Colorado.

for such studies with examples of their use. The indices will be presented in the following order: *K*, *Ks*, *Kp*, *ak*, *Ak*, *ap*, *Ap*, *Q*, *R*, *C*, *Ci*, *Cp*, *C*9, *W* measure, **u** measure, $\mathbf{u}_1$ measure, and *Dst*. The rules for the selection of quiet and disturbed days will be given, as will references to the availability of tabulations of the various indices. In the following chapters of this volume, other applications of these various indices will be made.

Historically, one of the first numerical indices was that proposed by Crichton Mitchell in 1930 [Chapman and Bartels, 1940a] and used by the Association of Terrestrial Magnetism until 1939. If observatories recorded *X*, *Y*, and *Z*, the index was $X_0R_X + Y_0R_Y + Z_0R_Z$. For those recording *D*, *H*, and *Z*, the formula was $H_0R_H + Z_0R_Z$. In these two cases, the data were for the Greenwich day. Subscript zero meant the average value for the day, and the *R*'s were the absolute ranges or differences between the highest and lowest values of each element.

Another early index was prepared by Schmidt [Chapman and Bartels, 1940b]. It was based on Potsdam data beginning in 1920 and was merely $R_X + R_Y + R_Z$ for each day.

Other indices, which will not be discussed in detail, have been prepared by Chernosky and Maple [1960] and by Gjellestad and Dalseide [1963]. Chernosky uses ΔH_1, the differences of consecutive hourly values of the horizontal component in gammas per hour, and Gjellestad, based upon the early work of Birkeland, prepares mean hourly storminess values for high-latitude observatories. Her method makes use of an electronic computer.

1.2 Various Indices

1.2.1 *K index*

This is a 3-h range index designed to measure the irregular variations on the standard magnetograms. It was adopted in September 1939 by the International Association of Terrestrial Magnetism and Electricity (IATME), the organization now called the International Association for Geomagnetism and Aeronomy (IAGA). The *K* index is intended to be a measure of solar corpuscular radiation based upon the intensity of geomagnetic activity caused by the electric currents produced in the ionosphere by such radiation.

Each observatory assigns an integer from 0 to 9 to each of the 3-h intervals of the day beginning at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 Universal Time (UT or GMT). A permanent scale is adopted for each observatory. This scale defines the *K* index by giving the limits for the amplitude ranges, R, measured in units of force gamma [Bartels et al., 1939, 1957]. For each magnetic element, the difference between the highest and lowest deviation from the regular daily variation within the 3-h interval is defined as the range R. The regular daily variation is represented by a smooth curve that is determined by considering the season, sunspot cycle, and phase of the moon.

R is obtained for each of the recorded elements D, H, and Z or X, Y, and Z. The largest of the three values, or the most disturbed element, has been taken as the basis for K through 1963. However, at the IUGG Assembly at Berkeley in 1963, IAGA recommended "that from the 1st of January 1964, the Z component will not be used for the measure of the 3-h K index except by the standard Kp observatories," because the earth's induction effect caused by the anomaly within the ground is very large for the Z component (see Chap. II-3). In measuring the range R, only disturbance parameters are to be measured. This means the daily solar variation (Sq), the daily lunar variation (L), solar-flare effects, and the after-effect of the disturbance field should be eliminated (see Chap. III-1 for Sq, L and solar-flare effects).

In 1938, the K scale adopted for the standard observatory was based on data from Niemegk 52°04′N, 12°40′E as follows:

$K =$	0	1	2	3	4	5	6	7	8	9
$R =$		5	10	20	40	70	120	200	330	500 γ.

Thus, if R is smaller than 5 γ, $K = 0$; if R greater than 5 γ and less than 10 γ, $K = 1$; etc., to if R greater than 500 γ, $K = 9$. These limits gave a reasonable frequency distribution for the nine values. The lower range limit for $K = 9$ is 100 times the upper range limit for $K = 0$.

All observatories could not have the same conversion scale for range R to K index; otherwise, the auroral zone stations would have K figures many times greater than those for equatorial stations during the same storm. Thus, using 1938 data, frequency distributions were made at each station in order to assign the same number of 3-h intervals with $K = 0$, $K = 1$, etc., to each. The lower limit of R for $K = 5$ was fixed so that there were about as many indices $K = 5$ to 9 at the station as there had been at Niemegk. The lower range limit for $K = 1$ should not be less than 3 γ. The lower limit for $K = 9$ was that for the interval 0600–0900 UT on April 16, 1938, which was one of the most violently disturbed times in the history of geomagnetism. On these rules, conversion tables for each observatory were established. Typical scales for lower limits of R are given in Table 1.

TABLE 1

LOWER LIMITS OF GAMMA RANGES DEFINING *K*

Observatory	For values of *K*									
	0	1	2	3	4	5	6	7	8	9
Godhavn	0	15	30	60	120	210	360	600	1000	1500 γ
Sitka	0	10	20	40	80	140	240	400	660	1000
Huancayo	0	6	12	24	48	85	145	240	400	600
Fredericksburg	0	5	10	20	40	70	120	200	330	500
Tucson	0	4	8	16	30	50	85	140	230	350
Honolulu	0	3	6	12	24	40	70	120	200	300

As new observatories are created, IAGA recommends "that for new observatories, the lower limit for $K = 9$ should be chosen in consultation with the working group on magnetic activity indices of Commission No. 4."

From the scales presented, it can be seen that the *K* scale is quasi-logarithmic. Since the *K* index is based upon a single station, it represents regional conditions and will include such local features as the systematic diurnal variation in geomagnetic activity at its location. A possible index to express world-wide features of geomagnetic disturbance might be a straight average of the *K* indices available from all stations. This would not be satisfactory, since there is not a uniform geographic distribution of the observatories, and the local variations would not be removed by such averaging.

1.2.2 *Ks index and Kp index*

The *Kp*-planetary 3-h index was designed by Bartels [1949a, b] to measure the "planetary" variations in geomagnetic activity. *K* indices are first translated into "standardized" indices, *Ks*. These *Ks* indices are freed from local variations. *Kp* indices are then based upon the *Ks*. Twelve stations have been used for *Kp* ranging from geomagnetic latitude 63° down to 48°. These stations, in order of decreasing latitude, are Meanook (Canada) 54°37′N, 246°40′E; Sitka (Alaska, U.S.A.) 57°04′N, 224°40′E; Lerwick (Shetlands) 60°08′N, 358°49′E; Eskdalemuir (Scotland) 55°19′N, 356°48′E; Lovö (Sweden) 59°21′N, 17°50′E; Rude Skov (Denmark) 55°51′N, 12°27′E; Wingst (Germany) 53°45′N, 9°04′E; Witteveen (Netherlands) 52°49′N, 6°40′E; Hartland (England) 51°00′N, 355°31′E; Agincourt (Canada) 43° 47′N, 280°44′E; Fredericksburg (Virginia, U.S.A.) 38°12′N, 282°38′E; and Amberly (New Zealand) 43°09′S, 172°43′E.

Ks is a continuous variable from 0.0 to 9.0 and is given in thirds of an integer. For example, the interval 1.5 to 2.5 is divided equally into thirds, designated by 2−, 2o, and 2+. For each forementioned station, conversion tables were prepared based upon data from a selected set of dates comprising, 9328 *K* figures. The tables were subdivided by season: northern winter January, February, November, December; equinoxes March, April, September, October; and northern summer May, June, July, August. By means of these tables for each observatory, the *K* index for a given 3-h interval is then converted into 3*Ks*. By definition, 3*Kp* is the simple average of these 3*Ks* values from the 12 stations.

Kp is therefore an index in 28 grades from 0o, 0+, 1−, 1o, 1+, 2−, 2o, 2+, 3−,... to 7+, 8−, 8o, 8+, 9−, 9o. The two extreme values 0o and 9o comprise actually only one-sixth of an intensity interval. 0o denotes exceptional quietness and 9o the most intense storm; both of these grades occur rarely. A change from one-third of an integer to the next third, for example, from 2− to 2o, means a noticeable increase in geomagnetic activity.

Kp, although called a planetary index and well suited for description of auroral zone disturbances as a measure of the solar wind, is not entirely satisfactory for representation of disturbance within the polar cap. A committee of IAGA is working on the development of a suitable index for polar cap studies, and caution should be exercised in the use of *Kp* for such research. The diurnal variations of *K* indices at polar cap stations are very different from those along the auroral zone or at the *Kp* selected stations.

For example, in March 1957 for the polar cap station Thule, the mean *K* indices were 3.7, 3.4, 3.6, 3.9, 4.4, 4.4, 4.5, 4.2, with the diurnal maximum occurring from 1800–2100 UT, whereas at Meanook, one of the *Kp* stations, the mean *K* indices were 2.5, 2.7, 3.4, 3.2, 3.1, 2.6, 1.8, 2.5, with diurnal minimum occurring from 1800–2100 UT.

1.2.3 *ak, Ak, ap, and Ap indices*

The preceding sections have dealt with 3-h range indices. For many applications, a daily index is desirable. Several such daily indices will be described. A possible one would be the sum of the eight *Kp* values for the day. This is not a desirable index because of the quasi-logarithmic relationship between the amplitude of the disturbance in the 3-h interval and the *Kp* index. An index based upon a linear scale is preferred. The IUGG Assembly at Brussels in 1951 requested that magnetic activity be expressed on some linear scale, and the *Ap* index was developed to fulfill that request. It is entitled the "daily equivalent planetary amplitude" [Bartels, 1957].

As an example of the inadequacy of the sum of the K's at a given station as a daily index, note that the same sum 8 is obtained from a day with K indices 1111 1111 or from a day with K indices 0000 0008. The total range for the first or quiet day would be the order of 10 γ, whereas for the second or highly disturbed day it would exceed 300 γ. It would be possible to select disturbed days by high sums, but it can be seen that low sums do not necessarily indicate quiet days.

Therefore, a system of reconversion of K indices into an equivalent range, *ak*, was developed. The center of the limiting ranges for the given grades of K defines equivalent range, *ak*, as follows in Table 2. A factor obtained

TABLE 2

EQUIVALENT RANGE *ak* FOR GIVEN K

K	0	1	2	3	4	5	6	7	8	9
ak	0	3	7	15	27	48	80	140	240	400

by dividing the lower limits for $K = 9$ at the station by 250 is used to express *ak* in the unit γ. For example, at Fredericksburg the lower limit for $K = 9$ is 500, giving the factor 2. At Fredericksburg, the middle of the $K = 3$ range or equivalent range is 30 γ. In other words, *ak* for Fredericksburg is expressed in units of 2 γ. The preceding scale is used to convert the K indices at any station into *ak* figures with only the unit γ depending upon the station. A daily index, *Ak*, or the equivalent daily amplitude, is the average of the eight daily "*ak*" values. Both *ak* and *Ak* are linear measures. Therefore, they can be combined into arithmetic means as desired. For example, *ak*'s can be averaged to determine the average equivalent amplitude of a storm period, and this might mean combining fewer than eight or up to several days' worth. Similarly, the daily index *Ak* can be averaged for selected groups of days or by the month or by the year, as desirable.

In a similar fashion, using *Kp* indices it is possible to construct *ap* indices for each 3-h interval, and the average of the eight values *ap* for a day is called the daily equivalent planetary amplitude *Ap*. The conversion table is as given in Table 3 where *ap* is an equivalent amplitude in the unit 2 γ for a standard station. Since *ap* and *Ap* are on a linear scale instead of the quasi-logarithmic scale of *Kp*, they may be combined for any combination of 3-h intervals or days for statistical studies. Therefore,

TABLE 3

EQUIVALENT RANGE *ap* FOR GIVEN *Kp*

Kp	0o	0+	1−	1o	1+	2−	2o	2+	3−	3o	3+	4−	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp	5−	5o	5+	6−	6o	6+	7−	7o	7+	8−	8o	8+	9−	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

for a daily index, *Ak* or *Ap* is strongly recommended in preference to the sum of the eight indices *K* or *Kp*.

1.2.4 *Q index*

For the International Geophysical Year (IGY), a 15-min index was proposed by Bartels and Fukushima [1956]. It was felt that a short-period index was needed for correlation with many other geophysical measurements made at such time intervals; among these are ionospheric measurements and auroral indices.

Four *Q* indices are given for each hour Universal Time. The indices are centered on 00, 15, 30, and 45 min past the hour. For example, the *Q* index for 0315 UT is based upon variations from 03 h 07 min 30 sec to 03 h 22 min 30 sec. The index at 0315 UT is thus suitable for comparison with simultaneous ionosonde records, auroral observations, or the like. Polar stations down through stations at about 58° geomagnetic latitude, or 32° polar distance, were requested to prepare these *Q* indices. During at least portions of IGY and IGC, 19 stations did so: Mawson (Australia) 67°36′S, 62°53′E; Macquarie Island (Australia) 54°30′S, 158°57′E; Yellowknife (Canada) 62°24′N, 245°36′E; Godhavn (Denmark) 69°14′N, 306°29′E; Thule (Denmark) 77°24′N, 290°50′E; Sodankyla (Finland) 67°22′N, 26°39′E; Murchison Bay (Sweden) 80°03′N, 18°18′E; Kiruna (Sweden) 67°50′N, 20°25′E; Tikhaya Bay (U.S.S.R.) 80°20′N, 52°48′E; Chelyuskin (U.S.S.R.) 77°43′N, 104°17′E; Dixon Island (U.S.S.R.) 73°30′N, 80°24′E; Tixie Bay (U.S.S.R.) 71°40′N, 128°54′E; C. Wellen (U.S.S.R.) 66°10′N, 190°10′E; Mirny (U.S.S.R.) 66°33′S, 93°00′E; Lerwick (U.K.) 60°08′N, 358°49′E; Eskdalemuir (U.K.) 55°19′N, 356°48′E; Halley Bay (U.K.) 75°31′S, 333° 24′E; College (U.S.A.) 64°52′N, 212°10′E; and Point Barrow (U.S.A.) 71°18′N, 203°14′E. Their preparation continued post the IGY at Kiruna (Sweden) and Sodankyla (Finland). At times of $Q = 4$ or greater, reductions at stations down to 50° geomagnetic latitude would be of interest. Similar to the *K* index, the *Q* index is based upon the amplitudes of the variations after the non-K variations have been eliminated. It differs from K in that the total deviation from the normal curve is measured. At polar stations, it is generally easy to determine the absolute level of the normal curve so that the absolute maximal deviations can be measured. For example, if the extreme deviations are $+200$ and $+50\,\gamma$, the K-index amplitude would be $150\,\gamma$, but the Q amplitude is $200\,\gamma$; or if the deviations were $+100$ and $-50\,\gamma$, both K and Q amplitudes would be $150\,\gamma$; or if the deviations were -50 and $-300\,\gamma$, whereas the K amplitude would be $250\,\gamma$, the Q amplitude would be $300\,\gamma$.

A uniform scale is used for all stations to convert the upper limit of the amplitude variation to Q. The Q index is based upon the most disturbed of the two horizontal components. The vertical component Z is not used. By restricting the measurements to the horizontal components, the Q index is related to the intensity of the ionospheric currents above the station and not to the intensity of a line current along the auroral zone. Table 4 gives the upper limit of the amplitude in terms of Q.

TABLE 4

UPPER GAMMA LIMIT DEFINING Q

Q	0	1	2	3	4	5	6	7	8	9	10	11
Upper limit	10	20	40	80	140	240	400	660	1000	1500	2200	inf. γ

1.2.5 *Hourly R index*

The Q index defined in the preceding section takes a great deal of effort to prepare, and few stations have attempted it. Still another index has been prepared at many polar and high-latitude stations to give a finer time resolution than the 3-h K indices but not as fine time resolution as the 15-min Q index. This is the hourly R index recommended for stations at geomagnetic latitudes higher than about 65°. This index is the absolute hourly range in tens of γ for each horizontal component. IAGA has invited observatories to participate in the preparation of R indices beginning January 1, 1964.

1.2.6 *C, Ci, Cp, and C9 indices*

The C index is a daily character figure for a single observatory. The observatory merely rates the magnetogram for the 24-h Greenwich day as 0 if very quiet, as 1 if moderately disturbed, or as 2 if severely disturbed.

This is a subjective index defining geomagnetic activity in a limited general fashion. During the same period of time, observatories do not give the same percentages of $C = 0$ or $C = 2$. Because of this fact, a daily world-wide index can be formed by taking the arithmetic mean of the individual C indices reported by all of the collaborating observatories [Bartels, 1957]. This index can range from 0.0 to 2.0 and is called *Ci*, the daily international character figure. *Ci* values are available back to 1884, although the scheme was developed in 1906. For time-series studies, the *Ci* indices are important, since they form the longest available homogeneous series of values covering several solar cycles.

An index analogous to *Ci* is the daily index *Cp* based upon the day's *Kp* indices. First *Kp* are converted to *ap*. The daily sum of the eight *ap* for each day is then converted to *Cp* by the scale as shown in Table 5. The ranges for *Cp* were defined by making the frequency distributions of *Ci* and *Cp* in the 10 years 1940 to 1949 practically the same. Since then, although obtained by entirely different definitions, *Ci* and *Cp* have rarely differed by more than 0.2.

TABLE 5

UPPER LIMIT OF DAILY SUM OF EIGHT *ap* DEFINING *Cp*

Upper limit of sum	22	34	44	55	66	78	90	104	120	139	164	190	228
Cp	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
Upper limit of sum	273	320	379	453	561	729	1119	1399	1699	1999	2399	3199	3200
Cp	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5

For graphical purposes, it is convenient to express the geomagnetic activity on a given day by a single digit. This can be done by *C*9, which contracts either *Ci* of *Cp* as in Table 6.

TABLE 6

Ci OR *Cp* RANGES DEFINING *C*9

Ci	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.5	1.9	2.0
or	to	to	to	to	to	to	to	to		to
Cp	0.1	0.3	0.5	0.7	0.9	1.1	1.4	1.8		2.5
*C*9	0	1	2	3	4	5	6	7	8	9

1.2.7 *Selected quiet and disturbed days*

For many studies, a selection of quiet or disturbed days is necessary. Such selections are prepared monthly by IAGA [1961]. The criteria are based upon *Kp*. The days are ordered according to three systems: (1) the sum of the eight values of *Kp*, (2) the sum of the squares of the eight *Kp*, and (3) the greatest of the eight values of *Kp*. The average of the three-order numbers is taken. The days with the highest mean-order numbers are the five disturbed. The days with the lowest-order numbers are the 10 quiet days, and within them are designated the five quietest days.

It is obvious that days selected in this way will not represent equal disturbance or equal quiet, since they depend upon the actual percentage of disturbance and quiet within the month in question. In some months, the disturbed days will be relatively quiet, whereas in others some of the 10 selected quiet days may be relatively disturbed. Because of this limitation, IAGA has a committee active in study of the selection of days by some means that would rate days in groups representing the same level of geomagnetic activity. Some examples of indices for a quiet and a disturbed day are shown in Table 7.

TABLE 7

INDICES ON A QUIET VERSUS A DISTURBED DAY

Quiet: October 12, 1955, Cheltenham, Maryland									
K_{Ch}	0	0	0	0	0	0	0	0	Sum = 0
a_{Ch}	0	0	0	0	0	0	0	0	Sum = 0
A_{Ch}	0	C_{Ch} = 0							
Kp	0o	0o	0+	0o	0o	0o	0o	0+	Sum = 1−
ap	0	0	2	0	0	0	0	0	Sum = 4
Ap	0	*Cp* = 0.0	*Ci* = 0.0	*C*9 = 0					
Disturbed: November 13, 1960, Fredericksburg, Virginia									
K_{Fr}	8	8	9	9	9	8	7	5	Sum = 63
a_{Fr}	240	240	400	400	400	240	140	48	Sum = 2108
A_{Fr}	263.5	C_{Fr}	2						
Kp	9−	9−	9o	9o	9−	8+	8o	6+	Sum = 67−
ap	300	300	400	400	300	236	207	94	Sum = 2237
Ap	280	*Cp* = 2.3	*Ci* = 2.0	*C*9 = 9					

1.2.8 *W measure*

This measure of geomagnetic activity is based upon the amplitude of the quiet solar daily variation, *Sq* [Bartels, 1946]. Chapter III-1 will consider *Sq* in detail. The *W* measure is intended to be a measure of solar wave radiation effects and is an index of the intensity of the equatorial electrojet (see Chap. III-2). It is thought to be related to the solar radiation absorbed in the lower ionospheric layers ionized at the time of solar flares. The *W* measure has been derived from the daily range of the solar diurnal geomagnetic variation *Sq* in the horizontal intensity *H* at Huancayo, Peru. The excess of the average *H* from 0900–1400 75th West Mean Time (WMT) over the average from 0000–0500 75 WMT is corrected for noncyclic change and for the lunar diurnal variation (see Chap. III-1). This index is difficult to compute because of the need to compute the lunar influence on the daily amplitude. Monthly mean values are normally limited to the average on the 10 international quiet days of the month in order to eliminate possible SD variations (see Chap. IV-3 for *SD*). The index correlates well with sunspot number.

1.2.9 **u** *measure*

The **u** measure was developed by Bartels [Chapman and Bartels, 1940c]. It is a type of ring current measure, since it includes the postperturbation effects of a storm as well as the direct storm effects. At a given station, the difference of the mean value of horizontal intensity for one day from the value for the preceding day is taken without regard to sign. This difference is expressed in units of 10 γ. An equatorial value of **u** is found by multiplying the station's **u** value by $1/\sin\theta \cos\Psi$, where Ψ is the angle between the direction of horizontal force at the station and the great circle passing through the station and the magnetic-axis poles, and θ is the magnetic colatitude or north-polar distance. Tables of **u** measures have been published based upon averages of the values from one up to six stations. Data from Huancayo, Peru, as well as other equatorial stations are normally used. The **u** measure is not considered suitable for day-to-day analyses but rather for monthly or annual mean studies.

1.2.10 $\mathbf{u}_1$ *measure*

The monthly mean **u** measure can be heavily influenced by the occurrence of a very severe storm within the month. Therefore, the $\mathbf{u}_1$ measure was derived to reduce such storm effects. Its scale was adjusted to have a frequency distribution similar to that of sunspot numbers [Chapman and Bartels, 1940d]. The conversion scale is as shown in Table 8. These values form a continuous graph if more detailed conversations are desired.

TABLE 8

CONVERSION SCALE FOR $\mathbf{u}_1$ FROM $\mathbf{u}$

$\mathbf{u}$	0.3	0.5	0.7	0.9	1.2	1.5	1.8	2.1	2.7	3.6
$\mathbf{u}_1$	0	20	40	57	79	96	108	118	132	140.

1.2.11 *Equatorial Dst*

For all of the indices discussed in this chapter, with the exception of the W, $\mathbf{u}$, and $\mathbf{u}_1$ measures, the effects of the ring current shown by the decrease of horizontal force, H, in the equatorial and temperate latitudes all over the world during storms have been ignored. This ring current effect can be measured by the quantity known as *Dst*, which will be discussed in detail in Chaps. IV-3 and V-3. Given an instant of time, *Dst* is the average of the storm variation over all longitudes. *Dst* may be obtained for a specified latitude. Although it is often computed as a function of storm time by measuring from the onset of the storm, it may be determined continuously as a function of Universal Time regardless of geomagnetic activity levels.

Sugiura [1963] has computed hourly equatorial *Dst* values for the IGY from a group of stations spreading from 9.5° to 33.3° geomagnetic latitude. The stations are Hermanus (South Africa) 34°25′S, 19°14′E; Alibag (India) 18°38′N, 72°52′E; Kakioka (Japan) 36°14′N, 140°11′E; Apia (Samoa) 13°48′S, 188°14′E; Honolulu (Hawaii, U.S.A.) 21°18′N, 201°54′E; San Juan (Puerto Rico) 18°23′N, 293°53′E; Pilar (Argentina) 31°40′S, 296°07′E; and M'Bour (Senegal) 14°24′N, 343°03′E. The station selections were based upon several rules. No stations near the auroral zones or the magnetic equator were used. The stations were distributed in longitude as uniformly as possible and were chosen from both northern and southern hemispheres. Reliable hourly H values were readily available.

Kertz [1958] has prepared 3-h values of *Dst* in units of 3 γ for the IGY, and these, together with Sugiura's hourly values, are published in the Annals of the International Geophysical Year.

Dst values correlate in gross features with *ap* indices. However, after the start of a geomagnetic storm, *Dst* recovers more slowly, indicating that the ring current dies away less rapidly than the polar disturbance. At the

IUGG Assembly at Berkeley in 1963, the following resolution was made: "The IAGA recognizes that for the studies of the secular variations, magnetic storms, *Sq*, and other geomagnetic variations the determination of *Dst* is of great importance and that in space research and in the studies of the relationships between geomagnetic variations and other geophysical phenomena, data giving the *Dst* variations are frequently required. The IAGA therefore, recommends the publication of the hourly values and a graphical representation of the equatorial *Dst* variation on a regular basis with shortest possible delay from the time of observation and invites the cooperation of interested organizations."

Dst hourly values will no doubt replace the **u** and $\mathbf{u}_1$ measures. Availability of these older measures will be outlined in the next section. The National Aeronautics and Space Administration of the U.S.A. has planned to continue preparation of the hourly *Dst*.

1.3 Availability of Tabulations of Indices

The International Union of Geodesy and Geophysics IAGA (formerly IATME) Bulletin No. 12 series is the best single source of data on indices. These are annual volumes entitled "Geomagnetic Data (year) Indices *K* and *C*, Rapid Variations," by J. Bartels, A. Romaña, and J. Veldkamp. They are distributed by North-Holland Publishing Company, Amsterdam. The data are provided by the committee on Characterization of Magnetic Disturbances of the IAGA. Since 1954, these publications have been prepared by the "Permanent Service of Geomagnetic Indices" in the Federation of Astronomical and Geophysical Services of the International Council of Scientific Unions. The contents are the individual station's daily *K* and *C* indices, *Ci*, selected days, storm sudden commencements, bays and pulsations, sudden impulses, minor disturbances, solar-flare effects, *Kp*, *Ap*, *Cp*, 27-day recurrence diagrams, and special lists and notes from time to time such as the monthly mean *Ci* for 1900–1957 are published in No. 12 1. Table 9 references the tables and diagrams for *Kp*, *Ap*, and *Cp* in these bulletins.

IAGA Bulletin No. 18 is a most valuable reference, since it contains all the *Kp*, *Ap*, and *Cp* indices for the years 1932–1961. It was prepared by J. Bartels and is distributed by the North-Holland Publishing Company, Amsterdam.

Selected data are published monthly in the Journal of Geophysical Research. These are *Kp*, *Ap*, *Ci*, *Cp*, and selected days on a monthly basis.

TABLE 9

AVAILABILITY OF INDICES IN IAGA BULLETIN 12 SERIES

Year	*Kp* indices tables		*Kp* diagrams		Frequencies of *Kp*		Stormy intervals		Quiet intervals	
	Bull.	pp.	Bull.	pp.	Bull.	p.	Bull.	p.	Bull.	p.
1932/33	12 d	48–50	12 d	52–53	12 c	131	12 c	135	—	—
1932	12 l	222–227	12 l	258–259	12 l	252	12 l	255	12 l	255
1933	12 l	228–233	12 l	260–261	12 l	252	12 l	255	12 l	256
1934	12 l	234–239	12 l	262–263	12 l	253	12 l	255	12 l	256
1935	12 l	240–245	12 l	264–265	12 l	253	12 l	255	12 l	257
1936	12 l	236–251	12 l	266–267	12 l	254	12 l	255	12 l	257
1937	12 g	97–98	12 g	113–114	12 g	112	12 g	111	12 k	154
1938	12 g	99–100	12 g	114–116	12 g	112	12 g	111	12 k	154
1939	12 g	101–102	12 g	116–117	12 g	112	12 g	111	12 k	154
1940	12 c	104–105	12 c	114–115	12 c	131	12 c	135	12 k	154
1941	12 c	106–107	12 c	116–117	12 c	131	12 c	135	12 k	155
1942	12 c	108–109	12 c	118–119	12 c	131	12 c	135	12 k	155
1943	12 c	110–111	12 c	120–121	12 c	132	12 c	135	12 k	155
1944	12 c	112–113	12 c	122–123	12 c	132	12 c	135	12 k	155
1945	12 i	106–107	12 c	124–125	12 c	132	12 c	135	12 k	156
1946	12 i	108–109	12 c	126–127	12 c	132	12 c	135	12 k	156
1947	12 i	110–111	12 i	102–103	12 c	133	12 c	136	12 k	156
1948	12 i	112–113	12 i	104–105	12 c	133	12 c	136	12 c	137
1949	12 c	102–103	12 c	128–129	12 c	133	12 c	136	12 c	137
1950	12 e	104–105	12 e	106–107	12 c	133	12 c	136	12 f	105
1951	12 f	86–87	12 f	88–89	12 f	98	12 f	105	12 f	105
1952	12 g	103–108	12 g	118–119	12 g	112	12 g	111	12 g	110
1953	12 h	80–85	12 h	88–89	12 h	86	12 h	87	12 h	87
1954	12 i	78–83	12 i	114–115	12 i	84	12 i	87	12 i	87
1955	12 j	114–119	12 j	122–123	12 j	120	12 j	121	12 j	121
1956	12 k	147–152	12 k	158–159	12 k	153	12 k	153	12 k	156
1957	12 l	210–215	12 l	218–219	12 l	216	12 l	217	12 l	217

Table 9 (*continued*)

Year	*Ap* daily values		*Ap* monthly ar annual mea	
	Bull.	pp.	Bull.	p.
1932/33	12 f	91	12 f	97
1932	12 l	222–227	12 l	254
1933	12 l	228–233	12 l	254
1934	12 l	234–239	12 l	254
1935	12 l	240–245	12 l	254
1936	12 l	246–151	12 l	254
1937	12 g	109	12 g	110
1938	12 g	109	12 g	110
1939	12 g	109	12 g	110
1940	12 f	91	12 f	97
1941	12 f	92	12 f	97
1942	12 f	92	12 f	97
1943	12 f	93	12 f	97
1944	12 f	93	12 f	97
1945	12 f	94	12 f	97
1946	12 f	94	12 f	97
1947	12 f	95	12 f	97
1948	12 f	95	12 f	97
1949	12 f	96	12 f	97
1950	12 f	96	12 f	97
1951	12 f	97	12 f	97
1952	12 g	103–108	12 g	110
1953	12 h	80–85	12 h	86
1954	12 i	78–83	12 i	84
1955	12 j	114–119	12 j	120
1956	12 k	147–152	12 k	153
1957	12 l	210–215	12 l	216

Table 9 (*continued*)

Year	*Ap* daily values		*Ap* monthly and annual means		*Cp* daily values		*Cp* monthly and annual means	
	Bull.	pp.	Bull.	p.	Bull.	pp.	Bull.	p.
1932/33	12 f	91	12 f	97	12 e	112	12 e	120
1932	12 l	222–227	12 l	254	12 l	222–227	12 l	254
1933	12 l	228–233	12 l	254	12 l	228–233	12 l	254
1934	12 l	234–239	12 l	254	12 l	234–239	12 l	254
1935	12 l	240–245	12 l	254	12 l	240–245	12 l	254
1936	12 l	246–151	12 l	254	12 l	246–251	12 l	254
1937	12 g	109	12 g	110	12 i	85	12 i	86
1938	12 g	109	12 g	110	12 i	85	12 i	86
1939	12 g	109	12 g	110	12 i	85	12 i	86
1940	12 f	91	12 f	97	12 e	113	12 e	120
1941	12 f	92	12 f	97	12 e	113–114	12 e	120
1942	12 f	92	12 f	97	12 e	114	12 e	120
1943	12 f	93	12 f	97	12 e	115	12 e	120
1944	12 f	93	12 f	97	12 e	115–116	12 e	120
1945	12 f	94	12 f	97	12 e	116	12 e	120
1946	12 f	94	12 f	97	12 e	117	12 e	120
1947	12 f	95	12 f	97	12 e	117–118	12 e	120
1948	12 f	95	12 f	97	12 e	118	12 e	120
1949	12 f	96	12 f	97	12 e	119	12 e	120
1950	12 f	96	12 f	97	12 e	119	12 e	120
1951	12 f	97	12 f	97	12 i	86	12 i	86
1952	12 g	103–108	12 g	110	12 g	103–108	12 i	86
1953	12 h	80–85	12 h	86	12 h	80–85	12 i	86
1954	12 i	78–83	12 i	84	12 i	78–83	12 i	86
1955	12 j	114–119	12 j	120	12 j	114–119	12 j	120
1956	12 k	147–152	12 k	153	12 k	147–152	12 k	153
1957	12 l	210–215	12 l	216	12 l	210–215	12 l	216

Information on principal geomagnetic storms, sudden storm commencements, sudden impulses, and solar-flare effects were published on a quarterly basis until January 1967. Similar data also appeared in that journal's predecessor, the Quarterly of Terrestrial Magnetism and Atmospheric Electricity.

The Fredericksburg K indices are given in the Journal of Geophysical Research. British observatories K indices are published in the Journal of Atmospheric and Terrestrial Physics. The Institute for Telecommunication Sciences and Aeronomy, Environmental Science Services Administration, Boulder, Colorado, U.S.A. publishes Kp, Ap, Ci, selected days, preliminary sudden commencements and principal magnetic storms monthly in the IER-FB "Solar-Geophysical Data" reports available on an exchange basis through the World Data Center A—Upper Atmosphere Geophysics, Environmental Science Services Administration, Boulder, Colorado 80302, U.S.A., but also available through the Superintendent of Documents, Government Printing Office, Washington, D.C., U.S.A., 20402, at a nominal cost.

The Handbook of Geophysics of the U.S. Air Force published by the McMillan Company, New York, 1960 presents tables of monthly and annual mean Ci indices for 1884–1956 and daily Ci indices for 1931–1951.

In *Terrest. Magn. Atmosph. Elec.*, *37*, 1932 on page 9 will be found monthly and annual means in units of 10 γ of $\mathbf{u}$ measures from 1872–1930 and on page 11 annual means at half-yearly epochs from 1835–1871. The monthly means in units of γ for $\mathbf{u}$ for 1872–1949 are also published in Landolt-Börnstein, Zahlenwerte and Funktionen, Band 3, *Astronomie und Geophysik*, p. 761 (Berlin, 1952, Springer-Verlag) and monthly means for 1940–1945 in units of 10 γ are in *Terrest. Magn. Atmosph. Elec.*, *51*, 71, 1946. For the $\mathbf{u}_1$ measures, both monthly and annual means for 1872–1930 can be found on page 15 in *Terrest. Magn. Atmosph. Elec.*, *37*, 1932 and annual means by half-yearly epochs on page 16.

For the W measure, monthly means for March 1922—October 1939 were published in *Terrest. Magn. Atmosph. Elec.*, *51*, 184, 1946. Two-monthly means starting with March–April 1922 through November–December 1947 appear in Landolt-Börnstein, Zahlenwerte und Funktionen, Band 3, *Astronomie und Geophysik*, p. 752 (Berlin, 1952, Springer-Verlag).

Ci indices in 27-day recurrence sequences for 1906–1931 are in *Terrest. Magn. Atmosph. Elec.*, *37*, 42, 1932.

World Data Centers were established during the International Geophysical Year and are depositories for data from July 1957 onward. The data archived are mean hourly scalings, normal magnetograms, tellurigrams,

rapid-run magnetograms
records, C and K sheets,
The archives are availab
data may be obtained fo
centers are as follows:

A. World Data Cente
Geomagnetism I
Coast and Geod
Rockville, Mary

B. World Data Cente
Molodezhnaya 3
Moscow B-296,

C1. World Data Cente
Meteorological I
Charlottenlund,

C2. World Data Cente
Geophysical Inst
Kyoto Universit
Kyoto, Japan

The Permanent Services

Meteorologisch Institüt
De Bilt, Holland

Geophysikalisches Insti
Herzberger Landstra
20 (b) Göttingen
Federal Republic of

Commission IV Morph
Observatorio del Eb
Apartado 9
Tortosa, Spain

rapid-run magnetograms and tellurigrams, very rapid and ultra-rapid records, C and K sheets, K indices and *sfe*'s, Q indices, and special events. The archives are available to all research scientists. Copies of any of the data may be obtained for the cost of reproduction. The addresses of these centers are as follows:

A. World Data Center A
Geomagnetism Division
Coast and Geodetic Survey, ESSA
Rockville, Maryland 20852, U.S.A.

B. World Data Center B2
Molodezhnaya 3
Moscow B-296, U.S.S.R.

C1. World Data Center C1
Meteorological Institute
Charlottenlund, Denmark

C2. World Data Center C2
Geophysical Institute
Kyoto University
Kyoto, Japan

The Permanent Services for Geomagnetism are as follows:

Meteorologisch Institüt
De Bilt, Holland

Geophysikalisches Institut
Herzberger Landstrasse 180
20 (b) Göttingen
Federal Republic of Germany

Commission IV Morphology of Rapid Variations
Observatorio del Ebro
Apartado 9
Tortosa, Spain

2. Correlations between Geomagnetic Indices and Parameters of Other Phenomena (Application of Geomagnetic Indices)

2.1 Solar Phenomena and Geomagnetic Activity

Several periodicities in addition to the diurnal variations can be found in geomagnetic indices. Chapman and Bartels [1940c, d] clearly demonstrated the 11-year solar cycle periodicity as shown by the **u** and $\mathbf{u}_1$ measures (see Fig. 1). The correlation is best for annual means but can also be seen

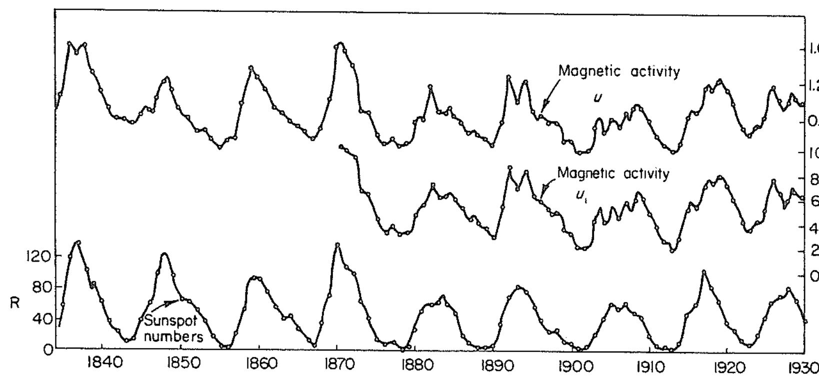


Fig. 1. Geomagnetic activity indices **u**, $\mathbf{u}_1$, and sunspot numbers R, 1834–1930 (after Chapman and Bartels [1940a]).

in the monthly means. Using the 1872–1930 data, the correlation coefficients were 0.869 between the annual mean **u** measure and sunspot number, 0.884 between annual mean $\mathbf{u}_1$ and sunspot number, and 0.654 between monthly means for the latter. There is a lag of the geomagnetic activity compared to the sunspot activity. On the descending part of the sunspot cycle, $\mathbf{u}_1$ corresponds to sunspot number values about 20 higher than on the ascending part.

Kp indices exhibit systematic changes with sunspot cycle if analyzed by frequency distributions. Bartels [1963] made a complete analysis of the 1932–1961 *Kp* and *Ap* indices and extended the distributions through 1963, as shown in Fig. 2. It will be noted that the most severe disturbances, $Kp = 8$ or 9, occur only in the years around sunspot maximum. The disturbed figures, $Kp = 4$ to 9, maximize on the falling part of the sunspot cycle. Minima in disturbance as shown by mean *Ap* or the $Kp = 4$ to 9 distribution occur at the time of sunspot minimum and the year after. The same general fact is shown by the maxima in the $Kp = 0$ and 1 for sunspot minimum and the following year.

In the years just preceding minima, the mean level of disturbance is high. This is also the time for the well-established patterns of 27-day recur-

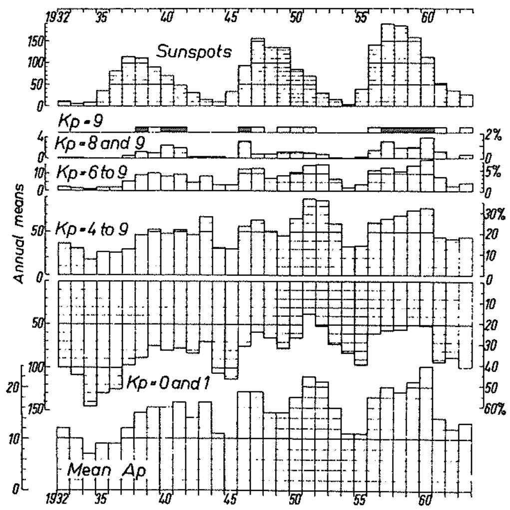
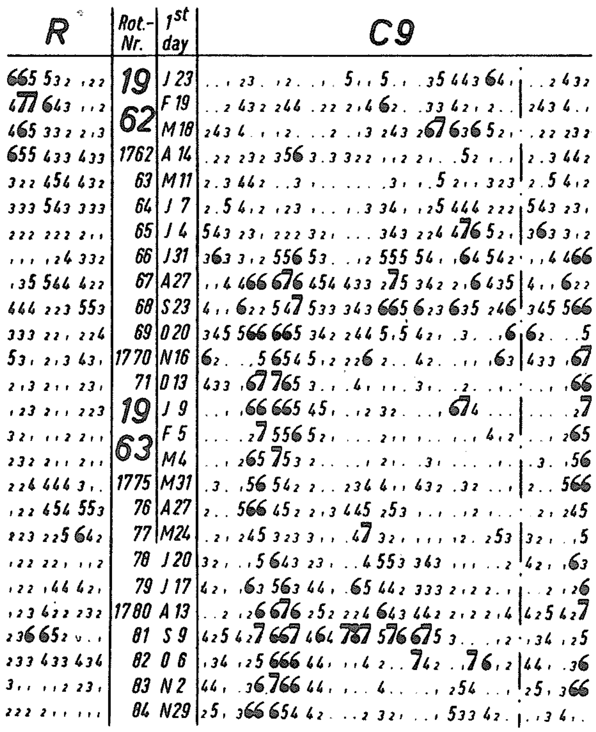


FIG. 2. Distributions of Kp and mean Ap throughout solar cycles, 1932–1963, prepared by Bartels.

rence related to the average rotation period of the sun. Figure 3 is a demonstration of this tendency. The figure is again from Bartels. Disturbance is indicated by the degree of blackness for the figures. It will be noted that as R, the sunspot number, becomes smaller, a well-established sequence of disturbed values of $C9$ persists from the middle of 1962 through 1963 during the first part of the 27 day cycle. In the next section of this chapter, the 1963 portion will be repeated in the form of the so-called musical note diagrams of Kp.

There is also a semiannual wave in geomagnetic activity with disturbances peaking at March–April and September–October (see Fig. 4). Although it exists throughout the sunspot cycle, the equinoctial peaks are accentuated in the years of minimum and just before minimum. In some individual years, the normal semiannual wave can be swamped by very severe disturbances in other months, such as by the July 1959, November 1960, and July 1961 storms.

Shapiro and Ward [1960] demonstrated this semiannual wave clearly in computations of the daily averages of the Ci, international character figures



Symbol		.	2	3	4	5	6	7	8	▮
R =	0	1–15	16–30	31–45	46–60	61–80	81–100	101–130	131–170	171–
C9 =	0	1	2	3	4	5	6	7	8	9
Cp =	0.0–0.1	0.2–0.3	0.4–0.5	0.6–0.7	0.8–0.9	1.0–1.1	1.2–1.4	1.5–1.8	1.9	2.0–2.5
Ap =	0–4	5–7	8–10	11–13	14–17	18–24	25–40	41–91	92–140	141–400

FIG. 3. 27-day recurrence tendency by character figures $C9$ and sunspot numbers R, 1962–1963, prepared by Bartels.

for the period 1884–1955. By use of Student's t test, the few observed departures of the daily averages of Ci from a smooth semiannual variation were determined to be statistical sampling fluctuations.

Ward [1960] studied the power spectra of the indices Ci, Kp, and Ap. All were found to be similar. In addition to the semiannual and 27-day periodicities, the spectra showed 14-, 9-, 7-, $5\frac{1}{2}$-, and $4\frac{1}{2}$-day variations. These are approximately 27/2-, 27/3-, 27/4-, 27/5-, and 27/6-day variations.

Few systematic differences were found between the times of sunspot maxima and minima. The percentage contributions to the total variance did differ among the different periods studied. The *Kp* data were for April 1951 to March 1956 and for April 1941 to March 1951. *Ci* and *Ap* for April

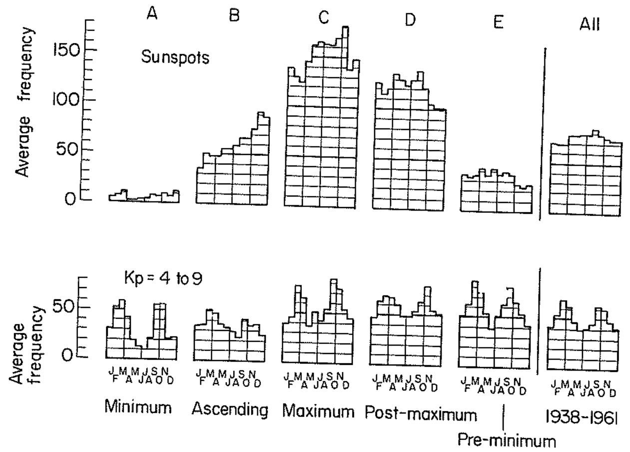


FIG. 4. Semiannual wave with maximum disturbance at equinoxes at various phases of sunspot cycle (after Bartels [1963]).

1941 to March 1946 were used. Also, *Ci* was used for January 1905 to December 1909, July 1914 to June 1919, and January 1920 to December 1924.

The latitudinal distribution of geomagnetic activity was studied by Whitham et al. [1960] at 16 Canadian stations spread from 85.7° to 54.3° geomagnetic north and located within 20° of 302°E geomagnetic longitude. The hourly range index of *H* in gammas was used to measure the irregular activity during August, September, and December 1957 and June 1958. The auroral region showed a pronounced maximum of intensity in all seasons. A bifurcation of the zone was evident in summer and during the equinox, and this bifurcation was enhanced if only disturbed days were used. The main maximum occurred at 66.6° geomagnetic latitude close to the zone of maximum auroral frequency, which is at about 67° geomagnetic latitude. The secondary maximum was at 61.9°. A maximum of geomagnetic activity was always present at Alert, 85.7° geomagnetic latitude. During summer it was enhanced. The inner zone had a narrow maximum using data from Thule and Godhavn, together with Alert. Equinoctial activity increased more to the north and south of the main auroral zone than in the zone itself compared to winter. In summer, a large increase in activity was present only in the polar cap. During winter, the daytime peak in activity found in the north of the auroral zone and inside the polar cap moved south, whereas the nighttime peak found throughout the auroral zone and to its south moved north. The time of maximum of the daytime activity was later as geomagnetic latitude increased. It was about 6 h local time at 67° and about 14 h local time at 86°. The nighttime maximum was within a few hours of local midnight at all latitudes.

In a pair of papers, Nicholson and Wulf [1961a, b] studied the 10 quiet-day and the five disturbed-day variations by Local Time and Universal Time during 1940–1948 of K indices from Alibag (18°38′N, 72°51′E), Watheroo (30°19′S, 115°53′E), Honolulu (21°18′N, 201°54′E), Tucson (32°15′N, 249°10′E), San Juan (18°23′N, 293°53′E), and San Fernando (36°28′N, 353°48′E). All of these stations are at rather low latitude but fairly evenly distributed in longitude. The quiet-day analysis Local Time component had a minimum at 3 h, maximum from 9 to 15 h, and secondary minimum at 18 h for the average of all years. There was no pronounced seasonal change, but there was a possible solar cycle effect in that from 1940 to 1948 there was a consistent change in form. The Universal Time component had less regular monthly behavior with smaller amplitude. The yearly average of this component had a minimum at 3 h and maximum at 21 h. The disturbed-day analysis Local-Time component yearly average had its minimum between 6 and 9 h and its maximum near 21 h. There was a pronounced change in amplitude over the individual years but again small seasonal change, as in the quiet-day study. On the other hand, the Universal Time component had an amplitude similar to the Local Time component but had a pronounced seasonal change as well. The yearly average for all years combined showed a maximum indicative of more disturbance between 9 and 12 h and minimum or less disturbance between 0 and 3 h. From year to year, there was a large random variability.

G. Rourke of the Research and Advanced Development Division, AVCO Corporation, Wilmington, Massachusetts, U.S.A. has done detailed analyses of the Antarctic magnetic activity indices collected during the International Geophysical Year.

One of the exciting results of the Mariner 2 space probe data came from the solar wind analyses of Snyder et al. [1963] (see Fig. 30 in Chap. V-2). They found a continuous large plasma outflow from the direction of the sun. Its day-to-day variations were well correlated with Kp ($r = 0.73 \pm 0.04$ for the entire period August 29, 1962 through January 3, 1963). The data fit the equation v (km/s) $= 8.44 \Sigma Kp + 330$, where v and ΣKp are daily values. This indicates that the minimum plasma velocity that produces disturbances in the geomagnetic field is 330 km/s. In addition, a very strong 27-day recurrence tendency was present in the plasma velocity data corresponding to the M region storms of the period. It appears thus that M regions[2] are emitters of high-velocity plasma (see sect. 8 in Chap. V-2). No dependence of plasma velocity on solar distance was detected between 1.0 and 0.8 a.u.

Dessler and Fejer [1963] believe, on the other hand, that Kp, rather than being a measure of the strength of the solar wind, is actually a measure of the fluctuations of the sum of the plasma plus magnetic pressure acting on the outer boundary of the magnetosphere (see Chap. V-3). M-region disturbances are not caused by a simple solar wind sweeping past the earth every 27 days, but by a sheet of turbulence and irregularities in the solar wind. This could be caused by a longitudinal gradient in coronal heating and could last as long as the coronal heat source does. The sheet of turbulence is generated by the collision of a region of high solar-wind velocity with a low-velocity region. Their arguments are based on the facts that the solar wind is continuous with velocity of at least 100 km/s, the geomagnetic field contains a plasma, and the magnetopause is stable. They give the following expression:

$$Kp = fn\left[\frac{d}{dt}\left(\varrho_s v_s^2 + \frac{B_s^2}{\mu_0}\right)\right]$$

where ϱ_s and v_s are the solar-wind mass density and velocity, B_s is the solar magnetic field strength, and μ_0 is the *mks* unit of vacuum permeability.

Relationships between event type of solar phenomena and geomagnetic activity will be discussed in sect. 3 of this chapter.

2.2 Ionospheric Indices

Ionospheric disturbances will be developed in Chap. IV-1, but attention should be called to the fact that there is close correlation between geomagnetic and ionospheric effects. Matsushita [1959] did a comprehensive analysis of the variations of the maximum electron number density in the $F2$ layer of the ionosphere during the 109 SC geomagnetic storms of 1946–

[2] M regions were first named by J. Bartels in a paper "Terrestrial-Magnetic Activity and Its Relation to Solar Phenomena" in *Terrest. Magn. Atmosph. Elec.*, *38*, 57, 1932. M regions were proposed to explain 27-day recurrence sequences that could not be identified with sunspots or other solar phenomena but that inferred the existence on the sun of certain restricted areas responsible for geomagnetic disturbances.

1955. The geomagnetic storm selections were based upon the *Ap* values reached following the *SC*'s. Storms were considered strong if *Ap* exceeded 50 or weak if *Ap* did not exceed 50. Thirty-eight ionospheric stations from 60.4°N to 60.4°S geomagnetic latitude were used. They were grouped into eight zones: 60.4°–55.5°, 55.4°–50.5°, 50.4°–45.5°, 45.4°–40.5°, 40.4°–29.5°, 29.4°–20.5°, 20.4°–9.5°, and +9.4°– –9.4°. Storm-time variations *Dst* and disturbance daily variations *DS* during each 6-h interval were obtained. As shown in Fig. 5, at the highest latitudes the *Dst* variation was character-

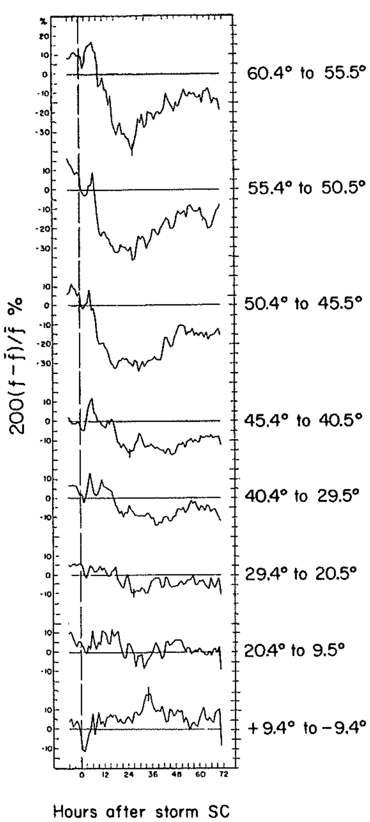


FIG. 5. *Dst* variation against storm time for strong storms by latitude groupings for maximum electron density of the *F*2 layer (after Matsushita [1959]).

ized by an initial short increase followed by a large decrease whose amplitude was greatest in the summer season. In the equatorial zone, the *Dst* had an initial decrease followed by an increase, and no seasonal effect was noticed. At the middle latitudes, the *Dst* variation was similar to the high latitudes in summer and to the equatorial region in winter. If *Dst* was averaged over all seasons, the variation for middle latitudes was relatively flat. The diurnal component of the *DS* variation was clockwise except in the equatorial region. The maximum amplitude of the mean *DS* variation decreased from high to lower latitudes, with an increase again at the equatorial region.

Many other workers, Appleton, Piggott, Martyn, and Rishbeth among them, have studied ionospheric storms (see Chap. IV-1).

2.3 Meteorological Phenomena and Geomagnetic Activity

In studies of meteorological phenomena, it is difficult to formulate measures of the large-scale atmospheric circulation patterns that might be expected to correlate with geomagnetic activity indices. Several workers have made attempts at such analyses, and in a few cases the results are promising enough to encourage further efforts. MacDonald and Roberts [1960] demonstrated an association between large troughs at the 300-mb level in 1956–1957, 1957–1958, and 1958–1959 winters which formed in the Gulf of Alaska-Aleutian Islands area on the second, third, and fourth days after the start of significant corpuscular radiation by key dates chosen as the day on which isolated *SC* storms began at Cheltenham, Maryland, U.S.A. or as the first day of successive days on which a strong auroral display was reported at the University of Saskatchewan, Saskatoon, Canada. Twitchell [1963] noted an increase in the 500-mb trough index obtained from the intensity of moving 500-mb troughs circumventing the northern hemisphere at approximately 7 and 14 days after *SC*'s.

More significant relationships have been shown between atmospheric phenomena and geomagnetic indices by Jacchia [1959, 1961]. The secular accelerations of satellite 1958 Delta 1 had strong correlation with *Kp* at the time of great geomagnetic disturbances. The cases of July 4–16 and August 30–September 11, 1958 were used as illustrations. In the latter paper, it was found that geomagnetic storms of comparable intensity give rise to larger drag perturbations when the background drag of the satellite is lower, either because of lower solar flux or because of greater angular distance of the perigee from the diurnal bulge. The observed atmospheric perturbations can be given by assuming the temperature of the upper atmosphere is augmented by an amount ΔT proportional to the geomagnetic planetary index *ap*; $\Delta T = 1.5° \times ap$.

3. Forecast of Geomagnetic Storms and Radio Disturbance

Many administrations prepare forecasts of high-frequency radio propagation disturbance based upon the expectation of geomagnetic storms. These forecasts are based for the most part upon statistical solar-terrestrial relationships. With the advent of satellites and space probes, there is now the possibility of detecting solar plasma streams while they are in the space between sun and earth; predictions in the future may well be based upon

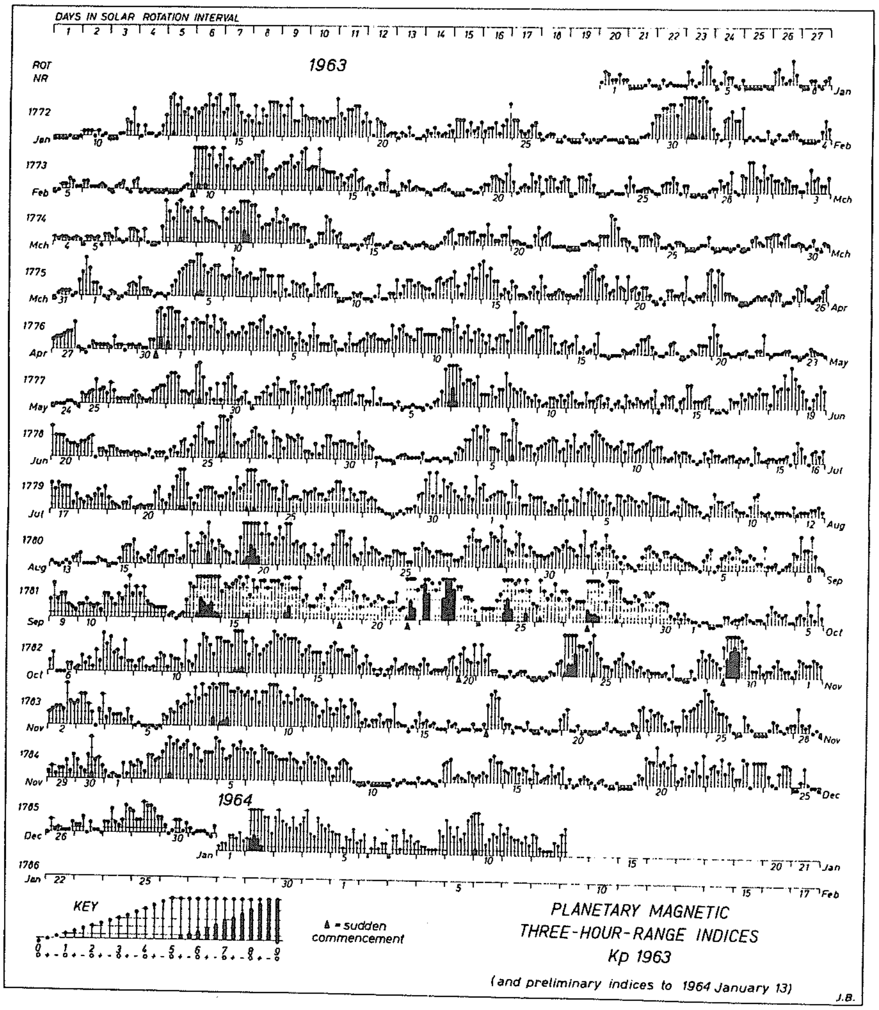


Fig. 6. 27-day recurrence by musical note diagram of Kp prepared by Bartels.

knowledge of these streams. Some of the relationships that are currently used in forecasting are outlined in this section.

In the two years after sunspot maximum through minimum epoch, the 27-day recurrence tendency in geomagnetic activity is perhaps the best criterion for predicting disturbances. These disturbances are associated with the so-called *M* regions on the sun, since as yet no optical or radio emission phenomena have been observed which satisfactorily explain these 27-day repetitive sequences. The musical note diagram after Bartels for 1963 in which *Kp* are ordered in 27-day sequences demonstrates this principle (see Fig. 6). Disturbance tended to repeat on the fifth through tenth days of the cycle throughout the year. The cycle days in the musical note diagram are those of the solar rotation period according to Carrington. Cycle 1717 began 16 December 1958.

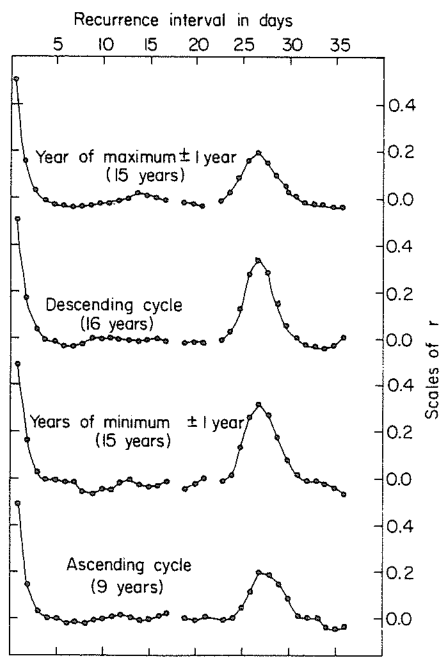


FIG. 7. 27-day recurrence tendency by average yearly correlation coefficients at different stages of sunspot cycle (after Shapley [1947]).

The recurrence tendency is operable throughout the solar cycle. Shapley [1947] demonstrated this fact by autocorrelation coefficients of the *Ci* indices, as shown in Fig. 7. Prediction formulas for the daily *Ci* indices based on the method of least squares for the mean autocorrelation coefficients formed from the data from 1890–1944 are

$$x_0' = 0.23\bar{x} + 0.44x_1 + 0.11x_{26} + 0.12x_{27} + 0.02x_{28} + 0.08x_{54} \quad \text{(strong years)}$$

$$x_0' = 0.33\bar{x} + 0.47x_1 + 0.06x_{26} + 0.07x_{27} + 0.03x_{28} + 0.04x_{54} \quad \text{(weak years)}$$

where the subscripts represent days; 0 for day of prediction, 1 for day before, 26 for 26 days before, etc., and the strong years are those of the descending cycle and minimum and the weak years those of the ascending cycle and maximum. Thus one can make reasonable forecasts, especially for the years approaching minimum, by recurrence forecasts anticipating that disturbed or quiet intervals will repeat in 27-day intervals. These are typically the gradual beginning type of storm.

The "cone of avoidance" theory for the production of *M*-region disturbances was set forth by Pecker and Roberts [1955] and reconfirmed by Saemundsson [1962]. Using 1952–1953 data, Pecker and Roberts showed a maximum in the number of quiet days about three days after the central meridian passage of active solar centers. This "cone of avoidance" is formed by deflection of the corpuscles over an active region by the action of the magnetic field of the region. Thus, disturbances occur when no active centers are at central meridian or, in other words, at the edges of the cone. Saemundsson analyzed data from 1919–1954. He found geomagnetic storms have a definite relationship to the central meridian passage of active regions, but there are two types of solar corpuscular emission. One type is the prolonged *M*-region emission that occurs 30°–90° from the active regions, particularly on the following side or "cone of avoidance." The other type is the transient emission from active areas. Obayashi et al. [1964] published a series of papers dealing with solar *M* regions which also favor the "cone of avoidance" hypothesis. These papers present a thorough survey with extensive bibliographies.

Glushkova [1962] claims that geomagnetic storms during 1947–1958 at Voyeykovo, U.S.S.R. had a tendency to recur from year to year on the same days. Data from Slutskaya from 1891 to 1940 confirmed this recurrence. The majority of forecasts for storms in 1959 based upon this technique were correct. Other studies have not been able to uncover such a relationship. Pohrte et al. [1960] using *Ci* indices from 1890–1957 by many subdivisions for both *SC* and recurrent storms at high and low solar activity and for dates of both high and low indices, were unable to find any singular days for geomagnetic disturbance.

At times of intense solar activity, rather than recurrence being the most useful tool, knowledge of outstanding solar events is more valuable. Since these solar events take place at any time during the 24 h of the day, international data exchange programs are necessary for the different forecasting centers throughout the world to have the necessary data at hand in time to make suitable forecasts. This program of international data interchange is one of the objectives of the International Ursigram and World Days Service (IUWDS). The IUWDS is a Permanent Service of the Federation of Astronomical and Geophysical Services of the International Council of Scientific Union, c/o Secretary-General of URSI, Place Emile Danco 7, Brussels 18, Belgium.

Regional Warning Centers have been established at the Telecommunications and Space Disturbances Services Center of the Institute for Telecommunication Sciences and Aeronomy, Environmental Science Services Administration, Ft. Belvoir, Virginia 22060, U.S.A.; Service des Ursigrammes et Jours Mondiaux, Observatoire, 92 Meudon, France; FTZ Arbeitsgemeinschaft Ionosphäre, Rheinstrasse 110, 61 Darmstadt, Federal Republic of Germany; Institute of Terrestrial Magnetism, Ionosphere and Radio Propagation, p/o Akademgorodok, Moscow region, U.S.S.R.; Radio Research Laboratories, Kokubunji, P.O. Koganei-shi, Tokyo, Japan; and Ionosphere Prediction Service, Commonwealth Centre, Chifley Square, Sydney, NSW, Australia; Associate centers are at Royal Board of Swedish Telecommunications, Fack, Farsta 1, Sweden; National Physical Laboratory, New Delhi-12, India; Czechoslovak Academy of Sciences Geophysical Institute, Ionosphere Department, Bocni II, Praha 4, Sporilov, Czechoslovakia; and SibIZMIR, Irkutsk 3, Box 65, U.S.S.R.

These centers collect data daily from observatories in their region and disseminate these data at least once a day to each of the other centers. Using these data, forecasts are prepared at almost all of the forementioned centers. The forecasts are distributed for regional use.

Bell [1963] summarizes many of the types of solar-terrestrial relationships which are fruitful for the formulation of geomagnetic storm forecasts. Several tables give statistical associations for data from 1957–1960 upon which predictions can be made. For example, great storms follow 33% of the Type IV solar radio noise bursts[3] that are strong at both centimeter

[3] Type IV solar radio noise bursts are intense continuum radiation first identified by Boischot [1957]. This emission may last from a few minutes to several hours over a broad range of frequencies. Type IV bursts vary more or less smoothly in intensity and can be explained by synchrotron emission of electrons spiralling in magnetic fields. These bursts are closely associated with the occurrence of solar flares, usually of importance 2+ or greater. As is well known, these major flares have a periodicity similar

and meter wavelengths and are of duration greater than 15 min. If moderate and small storms are included, 88% of such Type IV bursts are followed by storms within three days of their occurrence. These are usually the *SC* or sudden commencement type of storms. These Type IV bursts are strongly associated with the major 3 or 3+ flares and complex sunspot groups. When the solar region is within 30° of central meridian at the time of these bursts, more intense storms may be expected.

When the storms were studied to see what solar activity preceded them, the following conclusions were reached. The eight most severe *SC* storms were all preceded by major flares, Type IV bursts, and polar cap absorption (PCA) events. PCA will be discussed in Chap. IV-1. For the next 16 most intense storms, 88% were preceded by major flares, 75% by Type IV bursts and 56% by PCA. Associated with 30 moderate storms were 80% flares, 77% Type IV, and 20% PCA. Before 18 small storms were 72% major flares, 72% Type IV, and 6% PCA. The seven smallest storms had percentages of 43 for major flares, 43 for Type IV, and 4 for PCA and were therefore not significantly different from random sample percent of 41, 32, and 9. If the storms had gradual beginnings, the only somewhat better than chance association was that 53% of the moderate storms were preceded by major flares.

Thus, a Type IV burst recorded over a wide range of frequencies has a high probability of being followed by a great or at least moderate-intensity magnetic storm. The optical importance of the associated flare is important in that unless the flare importance is great the storm intensity is likely to be small. The magnetic class of the sunspot has value in that it is indicative of whether the region is apt to produce mjaor flares or Type IV bursts. $\beta\gamma$ or γ sunspots are about five times more likely than α or β spots to do so. The great storms can be expected if the activity occurs when the region is within 20° of the central meridian. If the region is more than 40° from central meridian, the intensity of the storm is apt to be less or even small.

Events such as those just described are the type interchanged between the Regional Warning Centers. One of the Regional Warning Centers is designated as the World Warning Agency. As of 1964, the I.T.S.A. Telecommunications and Space Disturbances Services Center (cable address AGIWARN WASHINGTON DC) serves in that capacity. It has the re-

to that of the solar cycle. Thus, the probability of occurrence of such flares and Type IV events is greatest at sunspot maximum, and few, if any, will occur in the years surrounding sunspot minimum.

sponsibility of making daily decisions with advice from the other centers for the announcement of geophysical alerts that are disseminated world wide for the use of scientists in the various geophysical disciplines. The alerts are used for coordination of experiments or at times when more rapid data reduction for submission to the World Data Centers is desirable.

Highlights of the World Days program for the International Years of the Quiet Sun 1964–1965 are given below. Similar programs are expected to continue indefinitely under the auspices of the IUWDS. A yearly calendar marks world days and intervals that can be fixed in advance. Alerts give notice of geomagnetic storms, geomagnetic calm, cosmic-ray flux changes, stratospheric warmings, solar quiet, and solar activity. The alerts give notice that these conditions exist, or in some cases are expected to occur in a few hours. Retrospective intervals are selected for outstanding cases of ionospheric and geomagnetic storms, for outstanding cosmic-ray flux changes, for periods of interesting geomagnetic pulsations, for periods of extremely quiet solar-geophysical activity, and for periods of unusual ionospheric absorption. Calendar records of indices and highlights for each day are published. Such records have been published for the IGY and IGC periods (July 1957–December 1959) in the Annals of the International Geophysical Year, Volume XVI, Parts I and III. For following years, such records will be published in suitable publications. Abbreviated forms are published in IQSY Notes for the IQSY period.

Each geophysical discipline has made recommendations for IQSY for scientific programs for world days and intervals. Those for geomagnetism are quoted below:

"It has always been a leading principle for geomagnetic observatories that operation should be as continuous as possible. Thus the great majority of stations taking part in the geomagnetic program of the IQSY will undertake the same program without regard to the IQSY International Geophysical Calendar. The days marked on the Calendar will be of interest mainly to the following two types of geomagnetic stations:

(a) Stations recording quick-run micropulsations (with fast chart speeds) are requested to make such records on every Regular Geophysical Day (RGD)—each Wednesday UT. The following schedule is to be used: 1 January 1964 from 0000–0400 UT; 8 January 1964 from 0100–0500 UT; 15 January 1964 from 0200–0600 UT, etc.

The observatories are not obliged to send their recordings to the World Data Center or IAGA Commission 4 working group (see Retrospective World Intervals on MICROPULSATIONS, below).

(b) Stations which, in addition to other IQSY activities, are equipped for making magnetic observations, but which cannot carry such observations and reductions on a continuous schedule are encouraged to undertake such work at least on RWD and during times of MAGSTORM Alert.

"Attention is called to the opportunity which the expected quiet conditions of the IQSY period may provide for a profitable study of the geomagnetic effect of solar eclipses, marked on the Calendar.

"Since some of the types of geophysical and solar activity events to which Alerts call attention will very often be characterized by the geomagnetic activity displayed in them, investigations based on the intensified observations of such events will be of particular interest to geomagneticians.

"MAGCALME Alerts call attention to periods likely to be relatively free from magnetic disturbance, and hence identify some of the appropriate times for magnetic absolute and survey measurements.

"MAGSTORM, MAGCALME, and SOLACTIVITY Alerts can be helpful in connection with magnetic measurements from aircraft, rockets, and space probes.

"For selection of the retrospective MICROPULSATIONS intervals, observatories should send every month their proposed selected intervals together with the usual data to the Tortosa Center. Upon selection of the retrospective intervals by the IAGA Commission 4 and announcement of the selections, observatories are requested to send copies of all materials obtained during those intervals to the World Data Centers."

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