EARTH-CURRENT RESULTS, HUANCAYO MAGNETIC OBSERVATORY, 1932-1942

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EARTH-CURRENT RESULTS FROM HUANCAYO OBSERVATORY, PERU, 1932-1942

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PREFACE

Earth-current investigations of the Department of Terrestrial Magnetism were begun in 1918. After considerable experimentation in electrode performance, measuring systems for continuous registration were designed, and the first installation was made at Watheroo Magnetic Observatory in Western Australia in 1923. The second installation was made at Huancayo Magnetic Observatory in Peru in 1926, and the third was made at Tucson Magnetic Observatory of the United States Coast and Geodetic Survey near Tucson, Arizona, in 1931.

Earth-current data are comparatively scarce in the literature, particularly where detailed results are concerned. Most of the results reported for these and other stations have consisted chiefly of summaries, average values, and the like. Practically the only exception has been the investigation at Ebro, Spain, for which station the individual hourly values of potential were published in the monthly bulletins of the Ebro Observatory from 1910 to 1938.

To augment the amount of basic data available for study and analysis of earth currents, individual hourly values for the two stations of the Department of Terrestrial Magnetism and the co-operative station at Tucson are being published for the period during which they were operating simultaneously. Since the Tucson earth-current project was in operation only from May, 1931, to February, 1943, the records cover a period just about equal in length to the normal 11-year sunspot-cycle. With the completion of the present program, there will be made available simultaneous records from three first class stations, including for the first time an equatorial station.

A full 20-year record from Huancayo Magnetic Observatory, which is located near the geomagnetic equator, has been completed, reduced, and compiled. In addition, a resistivity survey of the region about the earth-current lines was made in 1929 to supplement the usual potential records. The present volume gives mean hourly values of earth-current potential for the years 1932-1942, together with summaries of the more periodic variations and a brief discussion of their significance.

The author wishes to acknowledge his indebtedness to Dr. John A. Fleming, former Director of the Department of Terrestrial Magnetism, for support and encouragement in initiating and carrying out the program; and to O. H. Gish, Assistant Director, chief of the section of terrestrial magnetism, who was mainly responsible for the plans, equipment, and layout of the measuring system. Acknowledgment is also due to the observers-in-charge of the Huancayo Magnetic Observatory over the 20-year period of operation, W. C. Parkinson, R. T. Booth, R. H. Goddard, O. W. Torreson, P. G. Ledig, S. E. Forbush, and J. E. I. Cairns, for the skill and solicitude with which the installation, maintenance, and operation of the equipment were carried out.

Earth-current recording at the Huancayo Observatory stopped at the end of 1946. On July 1, 1947, the observatory was transferred by gift of the Department of Terrestrial Magnetism to the Peruvian Government and has operated since under the title of "Geophysical Institute of Huancayo." Its control is vested in a Directive Committee of which Dr. J. A. Broggi, Director of the Geological Institute of Peru, is Chairman.

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INTRODUCTION

Registration of earth-current potentials at the Huancayo Magnetic Observatory of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, was begun in November, 1926. This observatory is located in the high Andes of Peru, about 160 km east of Lima, in latitude 12° 02′.7 south and longitude 75° 20′.4 west. The elevation above sea level is approximately 3350 meters. Although the surrounding country is generally mountainous, the observatory is situated on a broad and comparatively flat plateau. The views shown in Figures 1, 2, and 3 indicate the topography in the region about the observatory site.

DESCRIPTION OF APPARATUS AND OPERATION

Lines

The design and equipment of the earth-current measuring system are similar for both Huancayo and Watheroo Magnetic Observatories [1]. The chief features of both installations are: (a) provision for obtaining two or more independent records of each component of the potential gradient, and (b) the use of a compensation or null method of measuring the potentials.

The layout of the earth-current lines at Huancayo and the principal topographical features of the immediate vicinity are shown in Figure 4. To provide independent records, the system is a dual one with two sets of electrodes, each arranged in the form of a cross. The set near the observatory site on Pampa Paccha is referred to as system 3; the other set, located at a slightly lower level on the relatively flat Pampa Sicaya, is designated system 1. This arrangement was found best suited to the topography at Huancayo and has an advantage over the "right-angle common point" layout used at the observatory at Watheroo because it gives no undue weight to effects associated with a single common electrode.

Recorder

The recorder used is a Leeds and Northrup multipoint, multirange recording potentiometer. Photographs of the recorder and of its panel board are shown in Figures 5 and 6, and wiring diagrams indicating the provisions made to obtain a variety of ranges are given in Figures 7 and 8.

At its highest sensitivity, which has been used throughout the recording, the value of one division on the record paper is one millivolt. Since the paper has 80 divisions, the range of voltage which can be covered in registration is 80 millivolts. The somewhat unusual arrangement of the slide-wire connections, as shown in Figure 7, makes it possible to shift the base line or zero line by appropriate connections to the two right-hand columns of binding posts shown in Figures 5 and 6.

Usually potentials were recorded between four pairs of electrodes to obtain two independent records for each of the components, northward and eastward. In this case, each pair was connected to three of the 12 pairs of recorder points. Approximately one minute is required for the recorder to balance and print, so that the cycle of the recorder--consisting of a potential record for each of the 12 points and a record of the balance of the potentiometer circuit against a standard cell--is completed in about 13 minutes. Hence the records for individual lines consisted of approximately 14 points per hour.

Sample connections showing the flexibility of the recording system are given in Figure 8. Here eight ground points are shown connected to give readings of potential between five instead of four different pairs of points. As connected, the potentials between points IIIa-IIIb are recorded on points 1, 5, and 9 and could vary from +40 to +120 millivolts and still be recorded. Potentials between points IIIc and IIId are recorded twice each cycle on points 2 and 10, between 1a and 1b three times on points 3, 7, and 11; between 1c and 1d, three times on points 4, 8, and 12, and between IIIc and 1d once each cycle on point 6. The measurable ranges for the last five combinations cited are +60 to +140, +80 to +160, +100 to +180, and +180 to +220 millivolts, respectively. Although all five combinations are shown on different ranges in Figure 8, two or all of the combinations may be used on the same range if desirable. Furthermore, the connections to a given pair of electrodes may be reversed at the left-hand pair of binding post columns, in which case the signs of the limiting values would be reversed. In this way 23 different scale ranges are available, each 80 millivolts in width, covering all values between -260 and +260 millivolts.

Electrodes

The electrodes are web-shaped grids of lead wire, built up of five concentric circular loops of wire with eight approximately radial arms connecting the loops and meeting at the center of the grid to form a core to which connection to the lines is made. The outside diameter of the grid is about six meters. Electrodes of this type can be installed with less excavation for a given electrode than can the spiral-coil type which was used at Watheroo Observatory. Necessary excavation was a matter of some concern because of the extremely hard subsoil found at Huancayo. All the electrodes are placed at depths of 1.5 meters or more in order to be below the region of diurnal temperature variation. At most of the electrode points two electrodes, separated about 12 meters as at Watheroo, were installed to permit the investigation of electrode effects. The electrode performance in this case has been so satisfactory, that at points M and C of system 3, where new electrodes were added in September, 1929, and July, 1930, respectively, only a single electrode was installed.

Since the cost of installing underground conduit was prohibitive at this site because of the nature of the soil and the diversity of ownership of the fields traversed by the lines, all connections from the electrodes to the recording instrument were made by overhead conductors of No. 14 (Brown and Sharpe gage) bare copper. Eucalyptus poles were used at first, but these would not withstand the violent and frequent mountain storms. Replacement of the wooden poles by poles of reinforced concrete was begun in 1928 and completed in 1930. This has reduced the cost of line maintenance and the loss of record caused by broken lines. The lengths of the several lines and the factors to reduce the recorded values to millivolts per kilometer appear in the following table.

Line	Length in meters	Reduction factor	Period of use
1 S - 1 N	2854	0.3504	. . . .
1 W - 1 E	2415	0.4141	. . . .
3 S - 3 N	3398	0.2942	Prior to July 31, 1930
3 S - 3 C	1757	0.5691	Since Aug. 1, 1930
3 W - 3 E	3212	0.3113	Prior to Sep. 15, 1929
3 M - 3 E	1951	0.5126	Since Sep. 16, 1929
3 W - 1 E	6750	0.1480	Discontinued Aug. 1, 1929

Potential Measurement

The recorder has been in operation almost continuously since November, 1926, but the percentage of complete and satisfactory daily records obtained during the first three years was not nearly so high as that obtained at Watheroo. The reasons for this were threefold. First, the frequent failure of the eucalyptus poles of the original installation caused considerable loss of record. Second, the range of variation of the potentials was greater than had been anticipated and there was loss of record due to the passing of the potentials beyond the particular range in use on the recorder at the time. The loss from this source was more frequent on the lines of system 3 because of the greater length of the lines and also because the average resistivity of the ground is somewhat higher in the vicinity of that system than about system 1. Third, the frequency of thunderstorms in the region was a source of trouble both in maintaining the system in operation and in obtaining complete and undistorted records. The fact that thunderstorms are mostly confined to one portion of the day, usually between 14h and 20h, makes the resulting distortion in the mean records much more pronounced than if their distribution was more random.

The first difficulty was eliminated by the change to concrete poles. Marked improvement in the second respect was effected by reducing the length of the lines of system 3 by the addition of the electrodes at 3 M and 3 C and the use of these in place of 3 W and 3 N as the western and northern termini, respectively, of the lines. To eliminate the extraneous effects due to thunderstorms, however, would have required that all the lines be placed underground. This action, as mentioned before, was not considered practicable.

Despite these interruptions, satisfactory daily records were obtained on well over half of all days, even in the first three years, and sufficient data to be representative have been obtained for every month. However, the loss of record has made it necessary to take all the available data into consideration in studying the early records. Such investigations as have to do with the differences between calm and disturbed days were necessarily postponed until after completion of the changes referred to, and the loss of record was reduced to normal proportions.

During the first 20 months of operation, simultaneous records were obtained from the electrode combinations 1 S - 1 N, 3 S - 3 N, 1 W - 1 E, 3 W - 3 E, and 3 W - 1 E. The numerals here refer to the electrode system, the letters to the respective electrodes. The diurnal-variation curves for each component of the potential gradient were found to be in very close agreement as to phase and general appearance but differed somewhat in amplitude. The difference was most marked in the case of the eastward component, the mean amplitude of the diurnal variation in the gradient obtained from the line 3 W - 3 E being always about 75 per cent greater than that obtained from 1 W - 1 E. The amplitude of the variation in gradient recorded with the combination 3 W - 1 E was in every case almost the exact mean of those recorded on 3 W - 3 E and 1 W - 1 E, indicating that the difference between the latter was not due to electrode-effects or other factors associated with the method of measurement.

Earth-Resistivity Survey

During the last half of 1929, an earth-resistivity survey was made of the region surrounding the earth-current lines to supplement the records of potential. While the resistivity of the soil near the surface varied from over 100,000 to less than 2,000 ohm cm, depending on the character of the overburden, the mean values tended to converge to a value around 10,000 ohm cm as earth to depths of 200 to 300 meters was included in the measurements. These results are typical for an underlying structure of new (geologically) sedimentary rocks. The seasonal variation, as determined by measurements made at the height of the dry season and repeated at intervals until the wet season was well under way, was found to be negligible except for the resistivity of a superficial surface layer.

The most interesting feature of the resistivity survey from the standpoint of earth currents was the indication of the existence of a local area of high resistivity in the southwestern part of Pampa Paccha. Here the average values were about three times as great as those found generally in the rest of the area surveyed.

A detailed report of the resistivity survey, describing method, apparatus, extent of the survey area, and results obtained will be found in Appendix I of this volume.

At the end of July, 1929, recording on line 3 W - 1 E was discontinued, the records from this line having served their purpose of establishing the validity of the results from the other west-east line. In September, 1929, a new electrode 3 M was installed and was used thereafter in place of 3 W for recording the eastward component. Since this new electrode was installed before the resistivity survey was well under way, the change was made primarily to reduce the amplitude of the variations in the recorded potentials and thus reduce loss of record due to off-scale deflections. As soon as recording with the combination 3 M - 3 E was begun, however, it was found that the change had also eliminated the discrepancy in the amplitudes of variations for the eastward component as recorded on the two systems. This circumstance, considered in connection with the results of the earth-resistivity survey of the region, showed that the discrepancy in the earlier records was due to the existence of the local area of high resistivity into which the original lines of system 3 extended. The western half of the original west-east line of system 3 reached far enough into this high-resistivity area for this to offer an adequate explanation for the larger amplitudes in diurnal variation of the gradient components obtained in the early years of recording on system 3.

In July, 1930, another electrode 3 C was added to the system and thereafter used in place of electrode 3 N. This shortening of the south-north line effectively reduced the loss of record for the northward component and brought the amplitude of the variations as recorded on the two systems into still closer agreement, although the records from the original 3 S - 3 N line were never affected so seriously by the resistivity factor as were those from 3 W - 3 E. No further alterations or rearrangement of the lines of either system were found necessary, and the recording has been continuous and satisfactory since 1930.

REDUCTION OF RECORDS

Until September, 1934, the records from both lines of both systems were reduced for all days and carefully compared. A remarkable degree of agreement was found by the comparison both for diurnal and for other variations of shorter or longer periods. So nearly identical were the records from the two systems for the period of four years after the rearrangement of system 3 that complete reduction of the records from that system was discontinued beginning October, 1934. Thereafter only the records from system 1 were reduced completely while those from system 3 were reduced only for ten days each month or when some unusual feature appeared in the traces. System 1 was chosen for complete reduction because it has operated unchanged over the whole period of recording and because the topography and resistivity of the Earth in this vicinity are more uniform than around system 3. It should be stressed, however, that all the results and conclusions presented hereafter would be almost exactly the same whichever set of data had been used.

The records for the entire 20-year period 1926 to 1945 have been reduced, tabulated, and analyzed. However, detailed data are presented here only for the 11-year period 1932 to 1942. This interval was chosen because it is about equal to the length of a normal sunspot-cycle and because it covers the period during which all three of the major earth-current projects of the Department of Terrestrial Magnetism--Watheroo, Huancayo, and Tucson--were operating simultaneously. The data are consequently adapted to studies of the chief systematic variations, such as those with time of day, season of the year, and solar activity, and also to correlation with results from the other two stations. Hence, for the first time, the record of a full sunspot-cycle from three major stations, one of which is an equatorial station, will be available when reports for the three observatories have been completed.

The mean hourly values of potential as recorded on the northward and eastward lines of system 1 are shown in Tables 29 to 292. The number of complete daily records included is 3667 for the northward component and 3729 for the eastward component, over 90 per cent of which are the same for both lines. During the first three years of recording, 1927 to 1929, only about 18 complete days' records per month were obtained for reasons already described. The average of about 28 days per month shown in the tabulations indicates the effectiveness of the changes made in 1929 and 1930 and is about as good as is normally obtained in earth current observatories. The difference between the two components in this respect is chiefly due to the fact that because of their local position and the topography of the site electrodes 1 S and 1 N were more exposed to the strong electrostatic fields of the frequent wet-season thunderstorms than were electrodes 1 W and 1 E. Both electrodes 1 S and 1 N were struck by lightning a number of times, and the surges due to passing thunderstorms were generally larger on the south-north line than on the west-east line with, consequently, greater loss of record.

DISCUSSION OF RESULTS

General Considerations

In examining or analyzing the data in the 264 tables of hourly means, it must be borne in mind that the absolute values of potential are practically meaningless so far as earth-current flow is concerned. This is so because the greater part of the recorded value, particularly on lines of only a kilometer or two in length, depends chiefly on "contact potentials" due to electrochemical action in the soil at and near the electrodes rather than on current flow in the ground between them. In studying the tables, it is then immaterial whether the potential read between electrodes 1 S and 1 N, or between 1 W and 1 E, at a given instant is +30 millivolts or -20 millivolts, to take some values at random as an example. The important fact is how the readings change with time. At Huancayo, as elsewhere, the absolute values have been found, by comparison of the simultaneous records, to be independent of the length or orientation of the line and to exhibit no characteristics which would indicate current flow. So far as they are concerned then, it suffices to say that at Huancayo the magnitude of the contact potentials is relatively small and that the moderate changes they undergo are definitely attributable to changes in the moisture conditions in the soil about them and, for this reason, are most pronounced at the times of change from dry to west season and back again.

The discussion then must deal with variations. The first variations notable in any earth-current records are the short-period fluctuations which usually accompany magnetic disturbances or storms. Studies of variations of this type call for detailed examination of the original records since they are quite complex and cannot be readily summarized or described. Moreover, the intermittent character of the recording at this station is not well suited for registration of short-period disturbances. Hence no extended discussion of disturbances is attempted here except to say that they parallel the magnetic disturbances and show a high degree of correlation with sunspot number and solar activity in general. For more detailed discussion of the results we pass on to the more regular periodic variations which are much more susceptible of analysis and description.

Solar Diurnal Variation

First among the regular variations is the solar diurnal variation. From a study of this and its modifications, the nature and characteristics of earth-current flow can be determined most readily.

The data on solar diurnal variation have been summarized in Tables 3 to 6 and are given for each month of the 11-year period in Tables 7 to 28.

Character of Diurnal Variation

Over-all curves of the diurnal variation for the 11-year period are shown in Figure 9. Positive values indicate a component of the current directed northward or eastward. The number of days included in these means is 3667 for the northward and 3729 for the eastward component, about 90 per cent of which are the same for the two. All available complete days of record were used, no attempt being made to classify them. Since, however, the more disturbed the day the less likelihood there is of obtaining a complete record, quiet days undoubtedly predominate.

The range of the northward component is 2.45 mv per km. A pronounced maximum occurs shortly after 09h (75th west meridian time), with a scarcely less prominent minimum at about 15h. The range of the eastward component is 3.17 mv per km. The minimum in this component corresponds very closely in time with the morning maximum of the northward component, and the eastward maximum corresponds similarly with the afternoon minimum of the northward component. Throughout the entire day the curves for the two components are remarkably alike except for the reversed sign and the slightly greater magnitude of the eastward component. This close similarity in character is brought out even more emphatically by a comparison of the phase angles resulting from a Fourier analysis. It will be seen from an examination of Table 1 that the difference in phase between a given harmonic of the northward gradient and the corresponding harmonic of the eastward gradient is throughout very close to 180°. The mean departure from this difference is less than 1° for the phase angles derived from the 11-year means of the diurnal-variation data and less than 4° for any of the mean monthly curves. Hence it appears that the flow of earth currents as indicated by the diurnal variations at Huancayo is closely analogous to a shuttle-like motion back and forth along a line which runs approximately 52° west of north. Thus the resultant gradient undergoes changes in magnitude between positive and negative limits without appreciable change in direction, the sign reversing around noon and midnight and the magnitude becoming feeble during the hours of darkness.

The diurnal variation differs radically at this station from that found at Watheroo [2] and other stations in higher latitudes, such as Ebro [3] and Berlin [4]. The most conspicuous difference is perhaps the appearance of only one pronounced maximum instead of the two or three observed at the middle-latitude stations. The principal maximum and minimum at Huancayo occur roughly at times when the variation is zero at Watheroo. Also in keeping with this, the phase angles of the first three terms of the Fourier analysis for the Huancayo data exceed those for Watheroo data by about 90°. Thus the curve for the Watheroo variation in the northward component is roughly the derivative of the curve for the corresponding component at Huancayo. The first-term amplitudes in the Fourier series for the Huancayo data are, however, about five times the corresponding coefficients for the Watheroo data. This relationship seems too definite to be regarded as a mere coincidence. It is in fact consistent with relations between the variations in the magnetic X- and Y-components at the two places if we assume that the principal part of the northward earth-current component (N) at Huancayo is due to interference by some gross topographical or geological features with the earth-current flow in this region. In this connection, it is suspected that the Mantaro River valley, which has a general southeasterly direction here between high mountain ranges, is an important factor, since the river valley without doubt offers the path of least resistance. In the relationship between the magnetic components, mentioned above, one sees by an inspection of the coefficients resulting from Chapman's analysis [5] of the Earth's diurnal-variation field that for latitude 10° south the variation in the Y-component has the form of a time-derivative of the variation in the X-component. Then from the relation between earth-current components and magnetic components observed at Berlin, Ebro, and Watheroo, namely, that the diurnal variation in N has approximately the form of a time-derivative of Y, we may expect the variation in the eastward component (E) here to have the same characteristics as found in Y there. From the general analysis, however, it is found that the characteristics of the diurnal variation in Y do not change much with latitude; hence we may expect the diurnal variation in E at Huancayo and that in Y at Watheroo to be in phase. Furthermore, since N at Watheroo has the form of a time-derivative of Y, it is seen that the Fourier terms of the diurnal variation in E at Huancayo and those of the diurnal variation in N at Watheroo, may be expected to differ in phase by 90°. From the expressions derived by Chapman and Whitehead [6] for the earth-current potential gradients, one sees that the eastward component should predominate in low latitudes. In order to reconcile this theoretical prediction with the observed facts, it is necessary to take the view that the direction of earth-current flow at Huancayo is considerably influenced by geographical conditions. At Berlin, Ebro, and Watheroo the northward component was found to be considerably greater than the eastward, while at Huancayo the eastward is markedly larger, so that a tendency in the direction of the theoretical prediction can be seen without invoking distorting influences, particularly since the prevailing declination at Huancayo, about 7°, can account for a considerable part of the departure from a due west-east direction.

The diurnal variation of the resultant gradient at Huancayo could be readily constructed by combining the two curves in Figure 9. It would, because of the restricted direction of current-flow, be very similar to one or the other of the component curves, depending on the direction chosen as positive, and would have a range of about 4.0 mv per km. The mean diurnal range here is nearly four times as great as that at Watheroo, where the mean range of the northward component, 1.10 mv per km, may be taken as equivalent to that of the resultant in view of the minuteness of the eastward component there [2]. This does not, as might at first appear, indicate a greater flow of current at Huancayo since, as shown by the results of surveys made at both places, the average resistivity of the ground here is at least ten times as great as that at Watheroo. Hence the magnitude of the Huancayo variations, if expressed in terms of current-density, appears to be not more than 40 per cent of that at Watheroo.

These general features of the diurnal variation at Huancayo are of unusual interest when considered in conjunction with the records from stations at higher latitudes. Since Huancayo is practically the only equatorial station at which extensive earth-current measurements have been made, the data have proved extremely useful in synthesising the results and arriving at a clearer idea of the general circulation of induced currents in the Earth as a whole. Gish, in 1937, using many of the data presented here in combination with the records from Watheroo, Tucson, and the polar year (1932-33) stations at Fairbanks and Chesterfield Inlet, was able to construct maps showing the circulation responsible for the diurnal variation at all these stations and to infer the general circulation over the entire earth. These maps and their significance can be appreciated best by reference to the chapter "Earth-Currents" in Physics of the Earth, vol. VIII, Terrestrial Magnetism and Electricity, pp. 270-307.

Seasonal Variation

Tables 5 and 6 give the mean hourly departures from the mean of day by months. Average values for the 11-year period are shown and indicate that the amplitude- and phase-relation between the two components remains practically unchanged in the diurnal-variation curves for the individual months of the year. The mean range is 1.74 mv per km for the northward and 2.38 mv per km for the eastward component. The ranges are smallest in June and usually greatest in the equinoctial months, at which times the northward component attains a range of over 3.00 mv per km and that of the eastward component reaches 3.75 mv per km. This change with season in the diurnal range is shown graphically in Figure 10. The records from Watheroo [2] and from three stations in the Northern Hemisphere, Ebro, Berlin, and Greenwich, have also been found to exhibit a similar relationship between the position of the Sun and the normal activity of earth currents as indicated by the diurnal range [3]. Minimum activity at the northern stations, of course, occurs not in the same month, but at the same season, namely, midwinter.

The constants for the harmonic series $\Sigma c_n \sin(n\theta + \phi_n)$ as determined for the diurnal-variation data shown in Figures 9 and 10 and in Tables 5 and 6 are given in Table 1; $\theta = 0$, here corresponds to local midnight. Here again the close parallelism between the records for the two components is the outstanding feature of the results. The first harmonic or 24-hour wave predominates throughout the year. At Watheroo and other stations at higher latitudes, on the other hand, the amplitude of the first harmonic has been found to be consistently smaller than that of the second. This difference in the results has already been pointed out in the discussion of the general shape of the curves in Figure 9. At Huancayo the second harmonic, 12-hour wave, has an amplitude from 80 to 90 per cent that of the first, and the third harmonic with amplitude slightly less than half that of the first, comes next in order of importance. The changes in amplitude of the several harmonics with season are all very similar and consequently quite like those in the range of diurnal variation shown in Figure 10. There is comparatively little shift from month to month in the phase angles of the three principal harmonics. This is another point in which the results differ from those obtained at Watheroo, Ebro, and Berlin, where the seasonal change in amplitude is accompanied by a definite shift in phase and consequently in the times of occurrence of the principal maxima and minima of the diurnal-variation curves.

One additional fact in connection with the seasonal variation is worthy of brief comment. As stated previously, the maximum range of the diurnal variation here as elsewhere tends to occur at the equinoxes. Reference to Figure 10, however, will show that if a smooth curve were drawn with its minimum at the winter solstice and maxima at the equinoxes, the point representing the month of January would fall well above the smoothed curve. On the basis of such a curve and of the ranges recorded in adjacent months we should expect the January ranges to be about 2.90 mv per km for the northward component and 3.35 mv per km for the eastward component instead of 3.10 and 3.65 mv per km as recorded. This increase in range, amounting to about 10 per cent, would appear unimportant if considered by itself. However, in the earth-current records from Tucson [7], a distinct January anomaly consisting of an increase in amplitude sometimes as great as 150 per cent is found, and a similar anomaly is found in the variations of the geomagnetic field at that station. The smaller anomaly here noted may therefore be of considerable significance as indicating a much more extensive asymmetry in the upper atmosphere current systems than would be required to explain a purely local effect at Tucson.

Variation With Solar Activity

Table 2 gives the range of diurnal variation in comparison with sunspot number, and Tables 3 and 4 show the diurnal variation for individual years. Variations in the frequency and intensity of earth-current disturbances with solar activity, as indicated by sunspot number, are a well-established feature of all earth-current records. In addition to this effect, the normal activity in earth-current flow as evidenced by the amplitude of the regular periodic variations, is also found to vary markedly over the sunspot-cycle. In Figure 11 will be found hodograms showing in a general way how the normal activity in earth-current flow follows the sunspot number. The central hodogram is that for the entire 11-year period and the grams on either side are for years which came near the time of sunspot minimum and maximum, respectively. Similar hodograms for the remaining years of the cycle can be constructed from the data in Tables 3 and 4. More detailed and quantitative determination of the dependence of normal earth-current activity on solar activity may be obtained through comparing the individual monthly data in Tables 7 to 28 with sunspot number. The variation from month to month is of course a combination of a large seasonal variation with a somewhat smaller change which follows the sunspot-cycle. Since the seasonal changes at Huancayo are very regular and consist almost entirely of changes in amplitude, allowance can be made for them without too much difficulty. The results of an investigation of this kind covering the 11-year period from 1927 to 1937 and dealing with the earth-current records from Huancayo, Watheroo, and Tucson are given in Appendix II and indicate that more than half of the month to month change in earth-current activity is closely related to the condition of the Sun.

Lunar Diurnal Variation

A definite lunar diurnal variation in the geomagnetic field has been shown by a number of investigators; a similar variation in earth-current flow is inevitable. Preliminary evaluation of this lunar diurnal variation has been made using the data from a single year, 1932. Details of this part of the investigation are given in Appendix III, which brings out the general features of the variation at Huancayo and also Tucson. The results may be briefly summed up as follows. A definite lunar diurnal variation of markedly double period is found in both components of the potential gradient. Harmonic analyses of the mean curves show that the amplitude of the second harmonic is about one-sixth that of the solar diurnal variation for the same year, while the amplitudes of the first, third, and fourth harmonics are negligibly small.

The manner in which the lunar diurnal variation changes with the phase of the Moon was also examined. For both components, the curves constructed for the four main phases of the Moon show a marked increase in activity during daylight hours and a corresponding diminution during the night so that the individual curves are no longer semidiurnal.

These results are in close agreement with the results of study of the magnetic lunar diurnal variation at Huancayo, which also indicate a large difference between day and night activity in lunar diurnal variation at that station. On the basis of earth-current work at Tucson and Ebro (see Appendix III) and magnetic investigations at a number of stations, there is apparently less difference between the conditions during day and night affecting lunar diurnal variation in middle latitudes than near the equator.

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