SECULAR CHANGE IN THE MAGNETIC SOLAR-DIURNAL VARIATIONS AT THE HUANCAYo MAGNETIC OBSERVATORY

By A. G. McNish

Abstract—A complete change of the character of the solar-diurnal variations of vertical magnetic intensity observed at the Huancayo Magnetic Observatory during the past sunspot-cycle is described. Characteristics of the southern type of variation, present during the northern summer solstice during 1922, give place to a form of variation characteristic of the Northern Hemisphere in 1932. This change is associated with the secular change of the Earth's general magnetic field which consists partly of a southern shift of the magnetic equator in the region around Huancayo.

Detailed features of this change are discussed and found to be qualitatively in agreement with expected changes. The large magnitude of the changes indicates that the solar-diurnal variation is a complex function of the Earth's general field such as is called for by the atmospheric-dynamo theory of Balfour Stewart. Statistical considerations lead to the conclusion that the reality of the change is established to an extraordinarily high degree of probability.

It is quite generally accepted that the magnetic solar-diurnal variations are due to an effect of the Sun acting in conjunction with the Earth's general magnetic field. A few theories, proposed many years ago, which assumed that the variation-field was superposed upon but independent of the Earth's general field met with insuperable difficulties. Distinctly different variations recorded at stations in approximately the same geographic latitude have been explained as due to irregularities in the Earth's general field.

If the Earth's general field does play an essential part in causing the variation-field then there should be a secular change in the form of the variations at every station following the secular change in the Earth's general field. Owing to fluctuations in the variation-field caused by seasonal effects and by sunspot-effects the observation of such secular changes is extremely unlikely. Even the lengthy series of data from Bombay and Greenwich show no distinct change in the form of the diurnal variations from 1879 to 1923 and from 1889 to 1923, respectively. Such changes, however, should not be expected at those stations during a few decades for the grosser features of secular variation are consummated but gradually. On the other hand, a magnetic observatory located in one of the transition-regions where the form of the diurnal variation changes rapidly with location might be expected to show a definite trend in the form of the variations within an even shorter time.

The observatory of the Carnegie Institution of Washington at Huancayo, Peru, is advantageously located for the discovery of such an effect. Shortly before the Observatory was established in 1922 the magnetic equator was slightly north of the site of the Observatory. When magnetograph-observations were begun the magnetic equator had shifted to a position south of the Observatory, which trend has continued up to the present time at a fairly constant rate. The value of the vertical intensity and inclination in 1932 were 1021 γ and 1° 58'.5, respectively, both characteristic of the Northern Hemisphere. This shift in the magnetic equator is illustrated in Figure 1.

The effect of this shift of the magnetic equator on the magnetic diurnal-variations is illustrated in Figure 2, in which are plotted the variations in magnetic vertical intensity for the five international quiet days of May, June, July, and August from 1922 to 1932. The international quiet days were selected for this study to minimize any effect due to increased magnetic activity during years of high sunspot-numbers.
A distinct change in the character of the variations is evident. During the earlier years when the magnetic equator was quite close to Huancayo the variations exhibited two maxima, the second of which, occurring about noon, was characteristic of variations in vertical intensity in the Southern Hemisphere. By gradual changes this second maximum disappears, giving place to a midday minimum, characteristic of the vertical-intensity variations in the Northern Hemisphere.

Similar but less marked changes are exhibited by the curves in Figure 2 for the months of January, February, November, and December. The variations during the earlier years are of a distinct southern type in which a midday maximum of vertical intensity is manifest. During the later years the amplitude of the variation is less and its symmetry is greatly impaired. In this series of curves the effect of increased magnetic activity on the variations is revealed by the large amplitudes from 1926 to 1929.

Less striking but perhaps more convincing evidence that a change has occurred in the form of the daily variations in vertical intensity at Huancayo is supplied by the curves in Figure 2, based upon the yearly means of the quiet days. While the variations during the earlier years are distinctly characteristic of the Southern Hemisphere, the variations during the later years are not characteristic of either hemisphere. A continual shift in phase of the variations is evident from the gradual movement of the maximum from noon to about 8 hours.

A simple explanation of these changes may be offered. Seasonal changes in magnetic diurnal-variations are due to the expansion and intensification of the area covered by the northern or southern variation-system around the June or December solstices, respectively. During the June solstice the northern variation-system had less effect on Huancayo
in the earlier years, but, with the southern shift of the magnetic equator, the northern variation-system increased its domains and became dominant in determining the variations at Huancayo. Throughout the entire period the southern variation-system has dominated the variations during the December solstice, although its effect has decreased in later years.

It is supposed, and a preliminary examination of current records sustains this supposition, that during the next few years the variations at Huancayo will more strongly take on the characteristics of the Northern Hemisphere, a shift back toward the southern type occurring only after a very long time, perhaps a century. Similar changes in the character of the variations in magnetic declination have also been noted but since they are less pronounced they are not presented.

A more comprehensive insight into the nature of these changes is derived from a study of the Fourier components of the variations during the season of northern summer for the eleven years considered. The amplitudes in gammas and the phase-angles in hours, reckoned from midnight 75° west meridian mean time as origin or \(0^h\), are represented in Table 1. The definitions of the terms are given by the expression

\[
\Delta Z_h = \Sigma c_n \sin \left(\frac{2\pi n}{24}\right) (h + \phi_n)
\]
in which $\Delta Z_h$ is the departure of $Z$ from the mean of the day $h$ hours after local midnight. Increase of vertical intensity, considered positive in the Northern Hemisphere, is reckoned positive.

Table 1—Fourier analyses of mean diurnal variations in magnetic vertical intensity, Huancayo Magnetic Observatory, for five international quiet days in May, June, July, August, 1922-1932

<table>
<thead>
<tr>
<th>Year</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
<th>$\phi_3$</th>
<th>$\phi_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1922</td>
<td>2.37</td>
<td>0.83</td>
<td>1.34</td>
<td>0.95</td>
<td>23.8</td>
<td>3.6</td>
<td>4.5</td>
<td>0.3</td>
</tr>
<tr>
<td>1923</td>
<td>1.56</td>
<td>1.11</td>
<td>1.82</td>
<td>1.35</td>
<td>22.5</td>
<td>1.9</td>
<td>4.6</td>
<td>0.2</td>
</tr>
<tr>
<td>1924</td>
<td>1.49</td>
<td>0.76</td>
<td>1.52</td>
<td>0.97</td>
<td>21.5</td>
<td>1.2</td>
<td>4.1</td>
<td>0.0</td>
</tr>
<tr>
<td>1925</td>
<td>1.50</td>
<td>0.38</td>
<td>1.22</td>
<td>0.79</td>
<td>1.2</td>
<td>2.9</td>
<td>4.4</td>
<td>0.1</td>
</tr>
<tr>
<td>1926</td>
<td>2.78</td>
<td>0.69</td>
<td>0.87</td>
<td>0.68</td>
<td>22.1</td>
<td>3.3</td>
<td>4.7</td>
<td>0.9</td>
</tr>
<tr>
<td>1927</td>
<td>3.16</td>
<td>0.87</td>
<td>1.17</td>
<td>0.88</td>
<td>0.1</td>
<td>4.7</td>
<td>4.6</td>
<td>0.5</td>
</tr>
<tr>
<td>1928</td>
<td>3.24</td>
<td>0.45</td>
<td>1.43</td>
<td>0.76</td>
<td>1.8</td>
<td>0.4</td>
<td>4.7</td>
<td>0.9</td>
</tr>
<tr>
<td>1929</td>
<td>4.27</td>
<td>2.10</td>
<td>0.88</td>
<td>0.93</td>
<td>0.1</td>
<td>5.0</td>
<td>5.7</td>
<td>0.3</td>
</tr>
<tr>
<td>1930</td>
<td>3.56</td>
<td>1.44</td>
<td>0.38</td>
<td>0.73</td>
<td>1.9</td>
<td>7.1</td>
<td>3.6</td>
<td>0.5</td>
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<tr>
<td>1931</td>
<td>4.66</td>
<td>2.06</td>
<td>0.59</td>
<td>0.72</td>
<td>2.8</td>
<td>7.5</td>
<td>3.1</td>
<td>0.8</td>
</tr>
<tr>
<td>1932</td>
<td>5.28</td>
<td>2.03</td>
<td>0.76</td>
<td>0.89</td>
<td>4.0</td>
<td>8.1</td>
<td>4.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

These data are represented graphically in Figure 3, the components of the single years being grouped to form triennial means for smoothing. During the earlier years the 24-hour wave culminated around 7 h and had an amplitude of less than $2\gamma$. By progressive changes the amplitude increased to $4.4\gamma$ for the last triennial mean while the time of culmination shifted to about 3 h. The total change, vectorially, amounted to about $4\gamma$. The 12-hour wave experienced a change in amplitude from 0.8$\gamma$ to 1.8$\gamma$ with a nearly complete reversal of phase, the time of culmination being changed from 1 h and 13 h to 7 h and 19 h. The vectorial change for this wave amounted to 2.6$\gamma$. The 8-hour wave suffered a reduction in amplitude from 1.5$\gamma$ to 0.5$\gamma$ with a small phase-change, while the
6-hour wave remained fairly constant throughout the period. It must be borne in mind that the actual changes from 1922 to 1932 were in general greater than this, the changes being somewhat diminished by taking triennial means.

The revelation of these changes in the Fourier components of the magnetic variation is astounding, but in view of the changes in the 24-, 12-, and 8-hour waves, the relative constancy of the 6-hour wave, which at many stations is most variable, stands out as a paradox. Such an effect would be observed if the 24-, 12-, and 8-hour waves have different phases north and south of the equator while the 6-hour wave is symmetrical with respect to the equator, or in other words, if spherical harmonics of degree $m = n + 1, 3, 5, \ldots$ contribute most to the 24-, 12-, and 8-hour components while spherical harmonics of degree $m = n + 0, 2, 4, \ldots$ contribute most to the 6-hour component.

To test this possibility, the first four components of the diurnal variation in vertical force at 10° north, 0°, and 10° south were computed from the coefficients obtained by Chapman from an analysis of the vertical-intensity variations at 19 widely-distributed observatories during the months of January 1903, and February, May, June, July, and December, 1902. The coefficients given by Chapman apply for the solstices on the assumption that the variations are symmetrical with respect to the equator, an assumption which, as he himself pointed out, is not in accord with the actual conditions.

The results of this calculation are shown in Figure 4. The trends of the various components as observed at Huancayo are roughly in agreement with the trends shown in the Figure, considering that Huancayo has apparently "shifted" from a southern latitude to a northern one. The comparative constancy of the 6-hour wave is conspicuous. Strict agreement of the magnitude and direction of the observed and predicted changes is not to be expected because the variations at Huancayo are very anomalous, being only roughly predictable from Chapman's

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coefficients. From the calculated values it would appear that Huancayo had shifted about 20° in magnetic latitude while the actual shift is less than 1° as deduced from the change in inclination by the relationship \( \tan I = 2 \tan \Phi \), \( \Phi \) being the geomagnetic latitude. In fact, from so small a change in geomagnetic latitude a change in the character of the diurnal variations was not to be expected and its appearance can be explained only by the hypothesis that the transition from northern to southern variations occurs over a very narrow region in the Western Hemisphere. Further evidence upon this hypothesis will be presented subsequently.

The reality of the phenomena which have been described is not questionable. The continual and gradual trend of the variations from one year to another consummating a total change which considerably exceeds the variations themselves in magnitude is most convincing. However, as a matter of interest, a meager attempt has been made to determine the statistical certainty of the change. For this purpose analyses of the first two components of the variations for the individual days of May, June, July, and August, 1922, were computed. The results of these analyses are shown in Figure 5. The days are numbered in their sequence, there being twenty days in all.

The root-mean-square or standard deviation of the 24-hour component of a single day for this interval was found to be 2.6\( \gamma \). Strong interdependence of days which are closely associated in time warns against too free a use of conventional statistical methods in calculating the probable error of a mean. Sixteen of these 20 days were found to be successive, that is, May 2, 3, May 30, 31, June 2, 3, etc. The means of each of these pairs were formed and treated as single days together with the unpaired days, thus making 12 "individual" days. The standard deviation of these 12 "days" was found to be 2.4\( \gamma \). Had the original days been strictly independent the new standard deviation should have been

\[
\sigma \sqrt{\frac{(N-n+n/4)}{(N-n+n/2-1)}} = 0.85 \sigma
\]

in which \( \sigma \) is the standard deviation of a single day, and \( N \) and \( n \) are the total number of days and the number of paired days, respectively. The computed standard deviation is nearly 1.15 times as large as was to be

\[\text{FIG. 5—HARMONIC DIALS, DIURNAL VARIATION}
\text{MAGNETIC VERTICAL INTENSITY, INDIVIDUAL DAYS,}
\text{HUANCAYO, FIVE INTERNATIONAL, JULY, AUGUST, 1922, FOR 18° W. MERIDIAN}
\text{MEAN TIME}
\]
expected, indicating that the accuracy of the mean is not much improved by the paired days. When monthly means are formed their standard deviation is found to be 1.77%. The expected value of the standard deviation of monthly means is $\sigma \sqrt{\frac{4}{(5 \times 3)}}$ or 1.33%. The ratio of the expected to the observed standard deviation is 0.75, indicating a lesser interdependence. Though the number of data used is insufficient to give an accurate measure of precision these considerations clearly invalidate the variability of a mean given as the quotient of the variability of a single day divided by the square root of the number of days included in that mean.\(^3\)

Considering the theory of Lexis, the days within any one season exhibit the tendency of a Lexis-series, that is, days within any one month are more alike than those in different months. For this reason the variability of the mean of many days in one season will be greater than the quotient of the variability of single days included in that mean divided by the square root of the total number of days. On the other hand, when days for the same season are taken from several different years, as was done in the formation of triennial means plotted in Figure 5, the condition of the Poisson-series arises. For illustration, a day in May 1922 will probably resemble a day in May 1923 more than it will a day in August 1922. In a Poisson-series the variability of the mean is less than the variability of the single individuals included in that mean divided by the square root of the number of such individuals. Thus the effects of the Lexis-series and the Poisson-series tend to compensate so that one might be justified in giving the variability of one of the triennial means, which include 60 days each, as the variability of a single day divided by $\sqrt{60}$. However, since the pairing of days indicates that this figure should be reduced by a factor of about 0.75, the conservative quantity $0.7 \sqrt{60}$ will be used in calculating the precision of the triennial means.

Assuming that the standard deviation obtained for 1922 applies to all the years, the standard deviation of the difference of the triennial means 1922-24 and 1930-32 is $1.4 \times 2.61/0.7 \sqrt{60} = 0.7$. The actual difference is 4.0, over 5 times this standard deviation. The chance that this difference is due to statistical fluctuations is only $e^{-25}$, or roughly 1 in $8 \times 10^{10}$. Allowing that the limits of precision are only roughly calculated one may wipe off several orders of magnitude in this probability and still feel that the reality of the change in the 24-hour component is established beyond all reasonable doubt. Comparable reliability is found for the 12-hour wave, the standard deviation of which is 2.4 for single days in 1922. No attempt was made to determine the reliability of the 8- and 6-hour waves.

An interesting feature brought out by the Fourier-representation of the individual days is the association of large departures from the means for the first two harmonics. Thus of the nine days with departures of the 24-hour wave from the mean greater than the probable error, seven exhibit departures greater than the probable error in the 12-hour wave also. It may be seen that, even in 1922, days occurred in which the 24-hour component closely approached the mean 24-hour component for the last triennial group. On no day, however, does the 12-hour component

\(^3\)J. Bartels in Terr. Mag., 40, 1-60 (1935), has given an adequate discussion of the effect of interdependence of data and methods of arriving at correct conclusions when such effects are present.
closely approach the mean of the 12-hour component for the last triennial group.

Thus observations during the last decade at the Huancayo Magnetic Observatory clearly demonstrate the effect of secular change of the Earth’s general magnetic field on the magnetic solar-diurnal variations. Consideration of the individual Fourier-components of the variation indicates that the changes are qualitatively in accord with what was to be expected although the greater magnitude of the observed changes demonstrates that the change from northern- to southern-type variations occurs over a very limited region. The phenomenon is practically conclusive proof that the daily variations depend upon the Earth’s general field and that the relationship must be a complicated one, mathematically, such as is involved by the atmospheric-dynamo theory of Balfour Stewart.

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