SHORT COMMUNICATIONS

RELATIONSHIP BETWEEN E_s AND THE EARTH'S MAGNETIC FIELD AT MIDDLE LATITUDES*

By G. L. Goodwin†

Attempts have been made, with some success, to find an association between changes in the intensity of E_s ionization and in the intensity of the Earth's magnetic field (Wilkie and McNicol 1962; Fatkullin 1965; Goodwin 1965; Ovezgel'dyyev 1965). Nevertheless, the overall results of these investigations have not revealed a consistent relationship between E_s and the Earth's field. This is partly due to the fact that daytime and night-time data, or data for the different seasons, were generally not treated separately. In the present paper an analysis of new observations is presented and the results of some previous analyses are also reappraised. A consistent relationship is found between night-time E_s observations and the geomagnetic field.

Ionosonde and magnetometer data employed in the present analysis were recorded simultaneously at Woomera in 1959 and Adelaide in 1966 and 1969. Ionograms were produced routinely once every hour in 1959 and every 15 min in 1966 with a frequency sweep of 1–15 MHz. For limited recording periods in 1966 and 1969 one ionogram was produced each minute. A proton precession magnetometer was employed with Helmholtz coils providing suitable biasing fields for measuring the three components of the Earth's magnetic field once every 3 min.

An analysis was made of data (the E_s blanketing frequency $f_b E_s$ and the horizontal component H of the geomagnetic field) which were recorded at hourly intervals at 0830, 0930, . . ., 1530 hr L.M.T. during 12 days in September, October, and November 1959. Mean values $\langle f_b E_s \rangle$ of $f_b E_s$ were calculated for the eight local times of observation. Since there were gaps in the data, only some 10 observations were available from the 12 data sets for the calculation of each hourly mean. Values $\langle H \rangle$ of the mean horizontal component of the Earth's magnetic field were calculated similarly. (In the present analysis, $f_b E_s$ was taken to be the minimum frequency at which echoes were received from above the E_s region whether E_s echoes were recorded or not; i.e. it was tacitly assumed that $f_b E_s$ was a measure of the intensity of E_s ionization even if this was not strong enough to produce observable E_s echoes.)

Correlation analyses of $f_b E_s - \langle f_b E_s \rangle$ versus $H - \langle H \rangle$ were performed on the 12 sets of data. Correlation coefficients for the daytime observations were found to change from mainly positive values in September to mainly negative in November. Similarly, data recorded over periods of 7–12 hr from 1830 to 0530 hr L.M.T. during 16 nights in September, October, and November 1959 were analysed. (Values of $\langle f_b E_s \rangle$ and $\langle H \rangle$ were each calculated from some 14 observations for each hour.)

* Manuscript received 19 March 1971.

† Space Research Group, Weapons Research Establishment, Department of Supply, Salisbury, S.A.; present address: School of Physics, South Australian Institute of Technology, North Terrace, Adelaide, S.A. 5000.

Correlation coefficients for the night-time observations were mainly positive for all three months, September, October, and November 1959.

Other data were analysed as follows. Running means ($f_b E_s^*$ and H^*) were calculated (1) over one-hour intervals for data recorded in 1966 at 15 min intervals from 1531 hr L.M.T., 14 November to 0531 hr L.M.T., 15 November and (2) over half-hour intervals for data recorded in 1966 at 3 min intervals from 0943 hr L.M.T., 15 November to 0852 hr L.M.T., 16 November and from 2016 hr L.M.T., 16 November to 0337 hr L.M.T., 17 November, and over half-hour intervals for data recorded in 1969 at 3·6 min intervals on 18–21 November and 16–19 December. Correlation coefficients of $f_b E_s - f_b E_s^*$ versus $H - H^*$ were calculated for day and night separately.

Since most of the observations were made at intervals of 3, 3·6, and 15 min, which were generally less than or of the same order of magnitude as the quasi-period of variation of H and of $f_b E_s$, the effective numbers N_r of strictly independent or random observations were generally less than the numbers N of observations actually made of H or $f_b E_s$. For each set of observations, an approximate value of N_r was calculated (see Ezekiel and Fox 1959) from the formula

$$N_r = N(1-r_a r_b)/(1+r_a r_b)\,,$$

r_a being the autocorrelation coefficient of consecutive $H-H^*$ values observed at 3, 3·6, or 15 min intervals and r_b being defined similarly for $f_b E_s - f_b E_s^*$.

Correlation coefficients for the November 1966 and November and December 1969 data were similar to those for November 1959, being predominantly positive at night and showing a trend towards negative correlation in the daytime.

In order to produce a more significant result from the total available data, a pooled estimate of r based on correlation coefficients for n sets of data may be found (e.g. Moroney 1958) by utilizing Fisher's Z transformation, namely

$$Z_i = \pm 1\cdot 15 \log_{10}\{(1+|r_i|)/(1-|r_i|)\}\,, \tag{1}$$

where r_i is the correlation coefficient for the ith data set consisting of n_i pairs of values; the sign of Z_i is plus or minus according to whether the value of r_i is positive or negative respectively. A mean value of Z for all the data may then be found from the equation

$$Z = \{\Sigma\,(n_i-3)Z_i\}/\{\Sigma\,(n_i-3)\}\,,$$

where the summations are from $i = 1$ to n. The coefficient r may be calculated by means of equation (1) by omitting the subscript i and ignoring the sign of Z; r is then given the same sign as Z and has $\sum\,(n_i-3)$ degrees of freedom. Correlation coefficients were calculated, converted to Student's t-values, and tested for significance.

A significant positive correlation (at the 5% significance level) was found for the total data recorded at night during September, October, and November 1959, November 1966, and November and December 1969. Although the daytime data showed a trend towards a negative correlation in summer, this was not significant.

The simple statistical analysis described above is adequate for the present observations in which the effect of autocorrelation is comparatively small. In particular, there would be very little improvement to the significance of the statistical results if a different, and more accurate, method of analysis were used. This is because the effective numbers of observations are not much less than the actual numbers, being only about 14% less for observations at 3 and 3·6 min intervals and 4% less at 15 min intervals.

As an indication of the magnitude of changes observed in H, Table 1 summarizes the results of observations at 3 min intervals over a total period of about 30 hr in November 1966. It is seen that the magnitudes $|H-H^*|$ have mode values of 1 gamma and medians of approximately 1·2 gammas. Corresponding to the data shown in Table 1, maximum variations in $f_b E_s$ and in $f_b E_s - f_b E_s^*$ were approximately 2 MHz and 0·2–0·3 MHz respectively.

TABLE 1

OBSERVED CHANGES IN H

The values of $|H-H^*|$ shown are from observations at 3 min intervals in 1966 during 0943–0852 hr L.M.T., 15–16 November and 2016–0337 hr L.M.T., 16–17 November

Number of observations	$\|H-H^*\|$ (gammas)	Number of observations	$\|H-H^*\|$ (gammas)
108	0	7	9
171	1	5	10
125	2	5	11
68	3	2	12
44	4	2	13
26	5	2	14–16
20	6	9	>17
12	7	Median	1·2
5	8	Mode	1

Reappraisal of Published Data

Goodwin (1965) found significant positive correlations between changes in H and in the amplitude of E_s echoes recorded near Brisbane:

(i) at night on 3 September 1961, and

(ii) in combined night and daytime observations on 1 October 1961.

These results are in agreement with those discussed above for September and October 1959, taking into account that during October 1959 the daytime correlation appeared to change from a positive value observed in September to a negative value in November. Cole and Norton (1966) remarked that the magnetic field variations $\langle \Delta H \rangle$ dealt with by Goodwin (1965) were apparently far greater than the values of a few tenths of a gamma which would be anticipated if the observations of $\langle \Delta H \rangle$ were associated with the production of E_s, for example, by a wind shear mechanism (Whitehead 1962). Median values of $\langle \Delta H \rangle$ in Goodwin's (1965) data were 1 gamma for data (i) above and 5 gammas for data (ii). These data were purposely selected at times when maximum changes (either increases or decreases) occurred in H, that is, the data were preferentially chosen to include large magnitudes of $\langle \Delta H \rangle$. The medians of

$\langle \Delta H \rangle$ for the selected data should therefore have been appreciably greater than medians appropriate to the whole of the data which would, in fact, be nearer to values of a few tenths of a gamma. Objections to Goodwin's (1965) data on the basis of large values of $\langle \Delta H \rangle$ do not appear to be justified.

Wilkie and McNicol (1962) in Brisbane observed that increased intensity of E_s coincided with decreased values of H. Wilkie's observations as reported by Thomas (1962) indicated that the most pronounced decrease in H occurred during daytime (late afternoon). The seasons when observations were made were not specified.

Fatkullin (1965) in Moscow also observed that decreased values of H coincided with increased intensity of E_s. In particular, he found a negative correlation during daytime in summer (May 1958) which is compatible with the trend observed in summer in the present experiments.

Discussion and Conclusions

In the present experiments, correlation analyses of daytime values of $f_b E_s - \langle f_b E_s \rangle$ versus $H - \langle H \rangle$ and $f_b E_s - f_b E_s^*$ versus $H - H^*$ yield non-significant correlation coefficients for each set of data, and the values are still not significant when the data are pooled by month. For night-time observations, again each set of data yields a non-significant correlation coefficient, with still no significance for the data by month. However, on pooling the data for all months a value of $0 \cdot 057$ (with 1254 degrees of freedom) is obtained which is significant at the 5% level. From the present results together with the interpretation of published data given above, it is seen that at middle latitudes changes in the intensity of E_s echoes and in H (1) have a significant positive correlation at night in spring and summer months and (2) during daytime tend to be negatively correlated in summer.

The results suggest that two mechanisms may operate simultaneously, one being predominant at times when positive correlations are observed and the other at times of negative correlation.

A positive correlation may be explained (Goodwin 1965) in terms of wind shear theory (Whitehead 1962) from which it follows that the resultant geomagnetic field is the vector sum of the Earth's field and that due to a current loop in the E_s region (Goodwin 1965). At the Earth's surface the resultant horizontal component H exceeds that due to the Earth's field alone. It follows that H should increase at the Earth's surface at the same time that an E_s layer is formed. (Whitehead (1962) stated erroneously that H would decrease at such times (Hines 1964).) According to wind shear theory, H should change by a few tenths of a gamma when an E_s layer appears, which is similar to values of the order of 1 gamma commonly observed, as discussed above. It is concluded that wind shear theory is compatible with the night-time data considered here. This result corroborates the previous predominantly night-time observations of Goodwin (1965).

A negative correlation may be explained in terms of a restricted interpretation of Cole's (1963) mechanism, as given by Goodwin (1965), in which an E_s layer could be formed by the action of the Lorentz force on an ionized medium carrying an electric current. On this basis it can be shown that the horizontal component H of the resultant geomagnetic field decreases at ground level when an E_s layer forms.

Predictions of Cole's theory are compatible with the observations of Wilkie and McNicol (1962) and Fatkullin (1965), and with the trend of the present summer daytime (November–December) observations.

It appears that positive correlations which are predicted from Whitehead's (1962) wind shear theory may be associated with a predominance of constant height E_s (E_{sc}), whereas negative correlations which are compatible with the present restricted interpretation of Cole's (1963) theory may be associated with predominantly sequential E_s (E_{ss}).

It is noted that all the observations reported here were made at times of weak to moderate magnetic activity, as indicated by K-indices. Explanations of the observations involving large variations in the geomagnetic field would therefore seem to be inappropriate.

Acknowledgments

The magnetometer was provided by the U.S. Naval Research Laboratories and the U.S. National Aeronautics and Space Administration. Magnetograms and ionograms were produced by staff members of the Weapons Research Establishment.

References

Cole, K. D. (1963).—*Planet. Space Sci.* **11**, 759.

Cole, K. D., and Norton, R. B. (1966).—*Radio Sci.* **1**, 2,235.

Ezekiel, M., and Fox, K. (1959).—"Methods of Correlation and Regression Analysis." (Wiley: New York.)

Fatkullin, M. N. (1965).—*Geomagn. Aeronomiya* **5**, 3, 435 (English translation: *Geomagn. Aeronomy* **5**, 3, 335).

Goodwin, G. L. (1965).—*J. atmos. terr. Phys.* **27**, 535.

Hines, C. O. (1964).—*J. geophys. Res.* **69**, 1018.

Moroney, M. J. (1958).—"Facts from Figures." (3rd Ed.) (Pelican: Middlesex.)

Ovezgel'dyyev, O. (1965).—*Geomagn. Aeronomiya* **5**, 5, 944 (English translation: *Geomagn. Aeronomy* **5**, 5, 742).

Thomas, J. A. (1962).—*In* "Ionospheric Sporadic-*E*". (Eds. E. K. Smith and S. Matsushita.) p. 123. (Pergamon Press: New York.)

Whitehead, J. D. (1962).—*In* "Ionospheric Sporadic-*E*". (Eds. E. K. Smith and S. Matsushita.) p. 276. (Pergamon Press: New York.)

Wilkie, J. R., and McNicol, R. W. E. (1962).—*Aust. J. Phys.* **5**, 236.