ON THE ELECTRIC PROPERTIES OF ROCKS UNDER THE NETWORK OF EUROPEAN GEOMAGNETIC OBSERVATORIES AS DERIVED FROM SERIES OF ANNUAL MEANS OF GEOMAGNETIC ELEMENTS

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Abstract. The solar-cycle-related (SC) variation, present in the annual means of geomagnetic elements recorded at European geomagnetic observatories between 1952-1980, is discussed in terms of magnetic and electromagnetic induction in the Earth, produced by variations in the external magnetospheric ring current. The vertical component of the SC variation, in which the effect of electromagnetic induction is dominant, has been used to infer information on electrical properties of the underground. The resistance and the inductance of equivalent loops of currents surrounding the observation points have been derived and mapped. The lateral variation of these parameters has been compared with known conductive structures derived from magnetotelluric and deep geomagnetic sounding studies and interpreted in terms of conductors at various depth levels in the crust and mantle.

Key words: solar cycle variation, annual means, geomagnetism, induction, conductive structures

1. INTRODUCTION

The geomagnetic field measured at the Earth's surface results from the superposition of several fields having different sources, namely: the main field, produced by a dynamo process in the external, liquid core, accounting for about 95% of the measured field, the crustal field, due to magnetic properties of rocks above the Curie temperature, with remanent and/or induced magnetization, the external field, with sources in ionosphere and magnetosphere, and the fields induced in the Earth by the variable external field.

It is a well established fact that in the annual means of the geomagnetic elements recorded at observatories [1], [2], [3], [4], [5], [6], [7], [8], [9] as well as in the annual values determined at repeat stations [10], [11], [12], [13] a solar-cycle-related (SC) variation is present.

In a series of papers [7], [8], [9], hereafter collectively called ‘Paper 1’, it was shown, on data sets from the European observatories, how the SC variation present in the annual means of geomagnetic elements can be used to better describe individual observatories as regards the magnetic and electric properties of the interior, characteristic to the site, with possible consequences in improving the secular variation and the main field models. The approach was based on the observation that variable external fields induce variable internal fields both by magnetic and electromagnetic induction and that in case of pure magnetic induction the temporal variations of the SC field at a given observing point is a linear combination of the components of the inductive magnetic force. Fitting data to a pure induction model, the calculated values of the model contain the contribution of the magnetic induction and the residuals contain the contribution of the electromagnetic induction to the observed field.

In the present report we shall apply the principles presented in Paper 1 to infer the lateral variation of the electric properties of the mantle and crust under the

European network of geomagnetic observatories. As it has been shown in Paper 1 that the effects of electromagnetic induction dominate in the vertical component of the SC variation and are absent or masked by noise in the horizontal component, only annual means of the vertical component will be analyzed.

2. DATA AND METHOD

The input data are the annual means of the vertical component of the geomagnetic field at European observatories (http://www.geomag.bgs.ac.uk/gifs/annual_means.html). Two sets of data were analyzed: annual means from 22 observatories in the time interval 1952.5-1980.5 and annual means from 41 observatories in the time interval 1961.5-1980.5. The distribution of the observatories is shown in Fig.1.

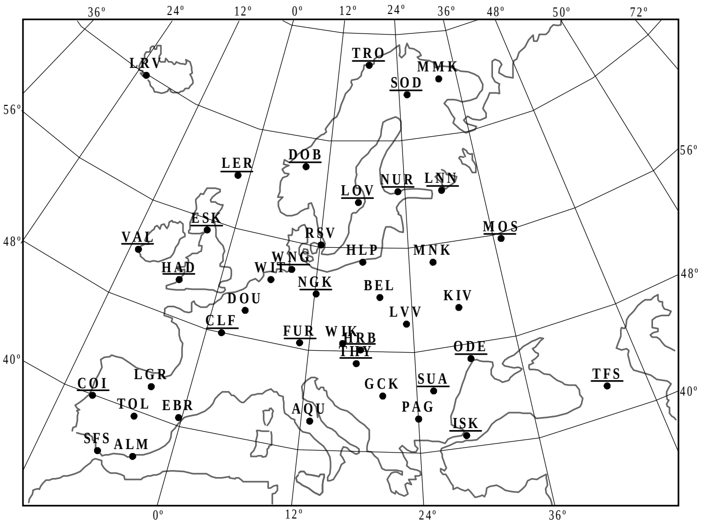

Fig. 1 – Distribution of the observatories used for analysis. Underlined symbols: set of 22 observatories with longer series of data

Data were processed to show the SC variation by modeling the variation of the core field with a sum of sinusoids (see for details Paper 1), to remove the general trends as well as long-period trends known to exist in the time variation of the main field [14], [6], [11], [15], [16]. We adopted this approach rather than synthesizing the SC variation from a Fourier analysis, in order to avoid losing correlated information and/or generating spurious waves, which might contaminate the results [17]. As in Paper 1, we fit the Z_S data to a model of pure magnetic induction, in which the temporal variation of Z_S at a given observing point is a linear combination of the components of the magnetic force. As estimates of the latter, we took the components of the field produced by external sources, as calculated from the external dipole spherical harmonic coefficients of [6] (Table 4b) using the following equations [1]:

$$\begin{aligned} X_d &= -g_1^0 \sin\theta + \cos\theta\left(g_1^1 \cos\varphi + h_1^1 \sin\varphi\right) \\ Y_d &= g_1^1 \sin\varphi - h_1^1 \cos\varphi \\ Z_d &= g_1^0 \cos\theta + \sin\theta\left(g_1^1 \cos\varphi + h_1^1 \sin\varphi\right) \end{aligned} \tag{1}$$

where g_0^1, g_1^1, h_1^1 are the external first degree coefficients, θ the colatitude, and φ the longitude of the given observatory.

For each observatory, we have at time *t*

$$\Delta Z_S(t) = \beta_x \Delta X_d(t) + \beta_y \Delta Y_d(t) + \beta_z \Delta Z_d(t) \tag{2}$$

where Δ denotes variations about temporal averages for the considered time interval. The coefficients β depend on the effective magnetic permeability, which in turn depends on the position of the observing point. They can be calculated by a least squares procedure. Then the calculated ΔZ_S of eq.2 contain the contribution of the magnetic induction, and the residuals, $REZ_Z = \Delta Z_S - \Delta Z_S$(calc.), contain the contribution of the electromagnetic induction to the observed field.

3. RESULTS AND DISCUSSION

The SC variation for the 22 observatories data set, Z_S, is shown in the upper panel of Fig.2. The Z_S curves for individual observatories were superimposed to show, on one hand, the coherency of this variation, suggesting a common source, and, on the other hand, differences in amplitude and phase, reflecting peculiarities of the site.

The analysis of the above series of data by means of the magnetic induction model was extended only to 1973.5, the last epoch with available external first degree coefficients. In the middle and lower panels of Fig.2, ΔZ_S(calc.) and REZ_Z are shown.

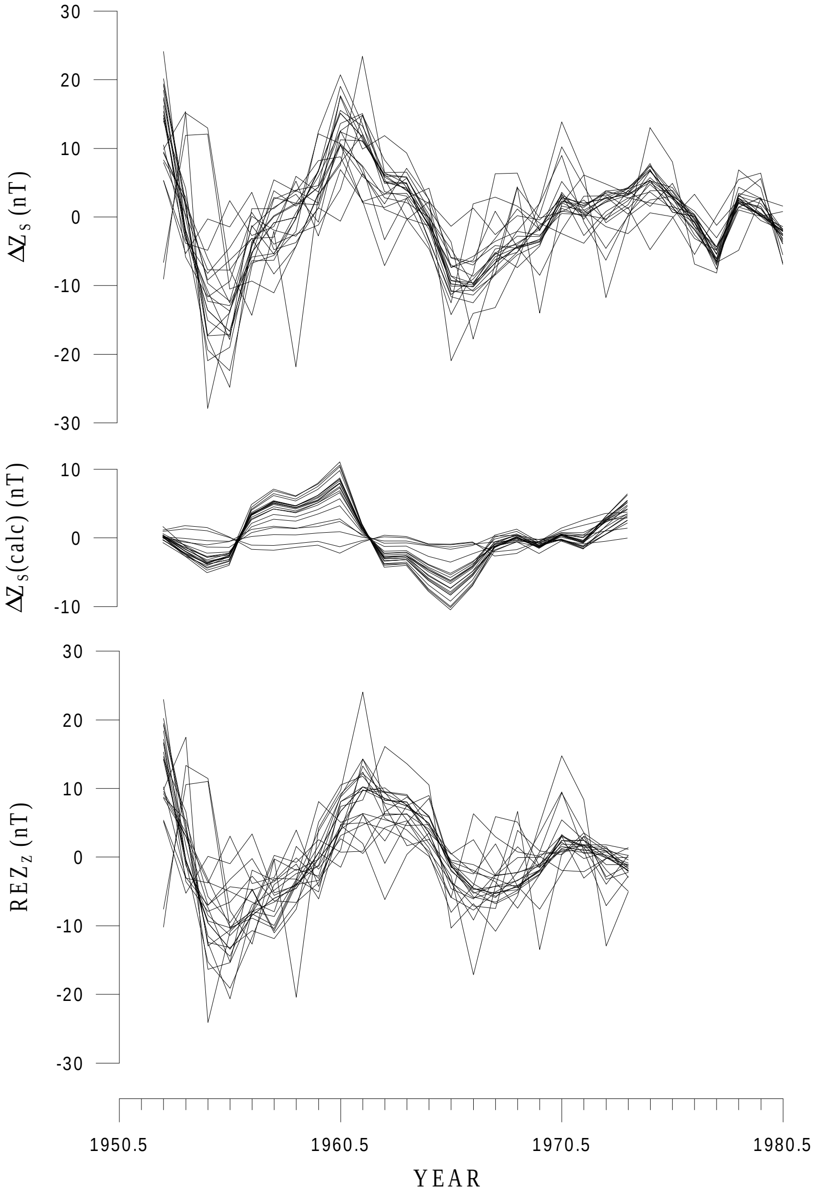

Fig. 2 – Solar-cycle-related variation of the vertical component (upper plot)and the output of the magnetic induction model: calculated ΔZ_S (mid plot) and residuals (lower plot). Set of 22 observatories with longer series of data

That the residuals describe the electromagnetic induction component was shown by [9]. The noise in the initial data propagate in Z_S, in ΔZ_S(calc.), and residuals, being more important in the latter. However, in spite of the rather large noise, the residuals show a systematic behavior, with lows at around 1955.5 and 1966.5 and highs at around 1961.5 and 1970.5. The residuals correlate well with

$-\dot{Z}_d$, which should be the case if residuals were the effect of the electromagnetic induction produced by the varying external field Z_d, since the induction electromotive force is given by the negative time derivative of the magnetic flux of the inducing field.

In terms of loops of current flowing in the more conductive layers, having in view that the magnetic field produced in the center of a circular loop of radius *a* by a current of intensity *I* is given by

$$B = 2\pi k \frac{I}{a} \tag{3}$$

where $k = 10^{-7}\ \mathrm{WbA^{-1}m^{-1}}$, the residuals could be viewed as a measure of the intensity of the current in an equivalent circular loop of radius unity surrounding the point of observation. This allows us to estimate the inductance, L, and the resistance, R, of the equivalent circuit, based on the relation between the instantaneous values of tension, *u*, and intensity, *i*, in a R-L circuit:

$$u = \mathrm{L}\frac{\mathrm{d}i}{\mathrm{dt}} + \mathrm{R}i \tag{4}$$

which, with the above established equivalents reads

$$-\dot{Z}_d(t) = \mathrm{L.R\dot{E}Z}(t) + \mathrm{R.REZ}(t) \tag{5}$$

L and R can be evaluated for each observatory for the given time interval by a least squares procedure. The lateral distribution of L and R can be mapped, resulting in images of the lateral variation of the electric properties of rocks beneath the observing point.

To get images of L and R at the European scale, the shorter series of observatory data (1961.5-1980.5, from 41 observatories) have been processed in the way described above. The resulting R and L are mapped in Fig.3 and Fig.4, respectively.

The effect the shorter time series has on the calculated parameters is illustrated in Fig.5, in which R and L derived from longer and shorter series of data are compared. One can see that the range of values is larger in case of the shorter series parameters than for the longer series ones. The two sets of parameters are, up to an additive constant, proportional, so the maps based on shorter series would be similar to maps constructed with longer series parameters. Shorter series R and L are less accurate than longer series ones, which is most probably the reason for the dispersion about the regression lines in Fig.5. The consistency of values over large areas in Fig. 3 and 4 indicates, however, that the maps can be considered as coherent images of the lateral variation of electric properties of the rocks under the network of European geomagnetic observatories.

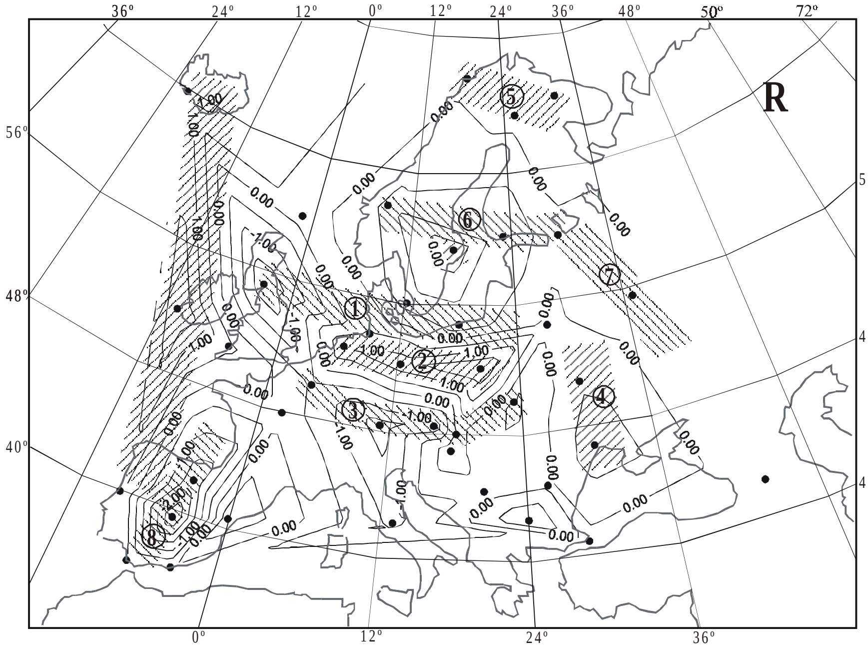

Fig. 3 – Lateral distribution of the parameter R (contours). Stippled areas: strips of high and low R

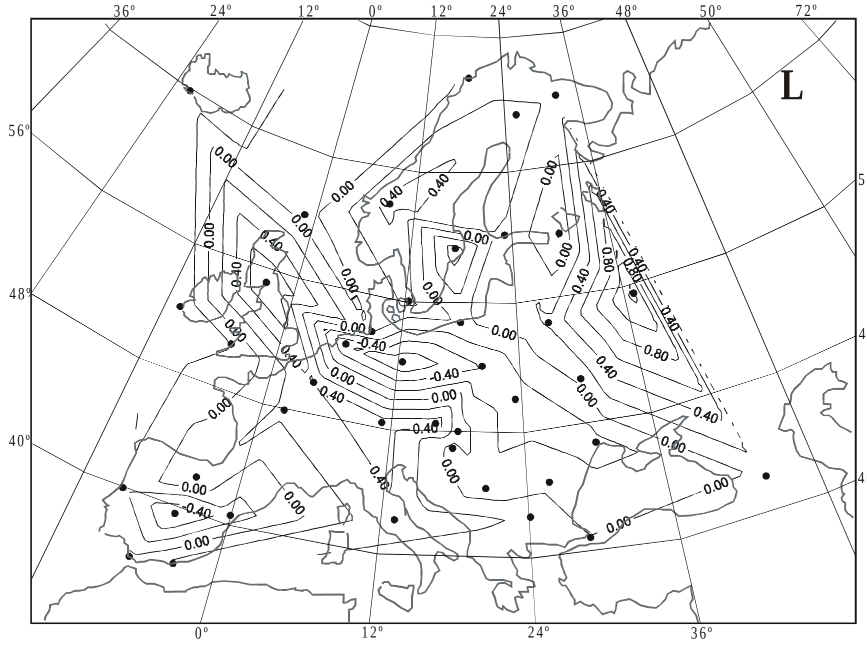

Fig. 4 – Lateral distribution of the parameter L (contours)

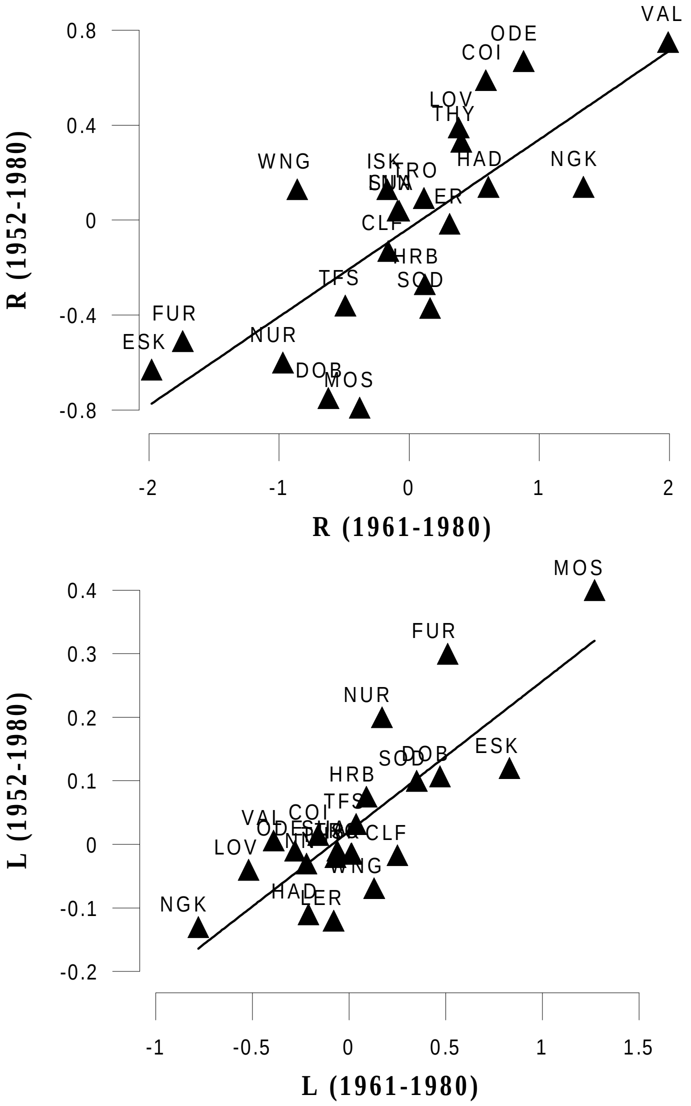

Fig. 5 – Comparison of electrical parameters R and L derived from two series of data

The interpretation of the maps in Figs. 3 and 4 is not straightforward. Firstly, because of the very low frequency of the input geomagnetic variation, the information they contain refer to a rock volume comprising both the crust and the mantle and, consequently, the mapped values are the cumulated contribution of all conductive and resistive layers beneath the observing point down to mantle depths. Secondly, it is well known that, as a result of screening, no or very little information can be obtained about structures beneath highly conducting formations [18]; however, the resistive blocks between the conducting belts serve as transparent windows for the electrical structure of the deeper levels (lower crust and mantle). Thirdly, the resolution of the maps is about 450 km over most of

Europe; however, a large area, including southern France, northern Italy, northern Romania, western Balkan peninsula, and Greece, is not so well characterized by R and L values, the resolution being about 750 km for this area. We also point out that the maps of Figs. 3 and 4 display electrical properties contrasts rather than actual electrical properties.

As the shape of contour lines and the anomaly width are conditioned by the network density, we prefer to distinguish, in the R map, strips (or belts) of conductive and less conductive (resistive) areas, marked by stipples and numbered 1-8. They are: (1) ESK, WNG, RSV, HLP; (2) WIT, NGK, BEL; (3) DOU, FUR, WIK, LVV; (4) ODE, KIV; (5) TRO, SOD, MMK; (6) DOB, NUR, LNN; (7) LNN, MOS; (8) SFS, TOL, LGR (see Fig.3). A comparison with magnetotelluric (MT) and magnetometer (GDS) data from a comprehensive review by [18] shows striking similarities, in spite of the very different range of frequencies used in the reviewed investigations (periods of $1\text{-}10^4$ sec as compared to 11 years). Positive values in Fig.3 (nos. 2, 4, and 5) correlate with well known elongated conductors or belts at upper and mid crustal depths, which coincide with major terrain boundaries or occur in places with plate boundaries, such as the North German – Polish (with an additional uppermost conductor in the sedimentary cover), the Fennoscandian Shield, and the Kirovograd conductivity anomalies, respectively. Other conductors, as the Southern Finland and Lake Ladoga – Moscow ones, correlate with lower R values in our map (nos. 6 and 7). The lowest R values concentrate in the strips numbered 1, 3, and 8. The first two might be caused by deeper conductors (lower crust, mantle), as there are no surface conductors evidenced in the study of [18] which might screen the information from depth. Area no. 8 in our map is rather well constrained by observatory data. However, we cannot, at the moment, make a specific comment regarding the source of the anomaly, as the Spanish territory has no data in the review by [18].

As regards the inductance, L, the map in Fig. 4 shows alternating low and high values coherent on regional scale, namely: low in southern-central Spain, high in England, France, southern Germany, Switzerland, northern Italy, Austria, Hungary, low in southern Scandinavia, northern Russia, northern Germany, Poland and Carpathian area, high in northern Scandinavia and East European Platform.

4. CONCLUSION

Annual means of the vertical component of the geomagnetic field at European observatories were analyzed to obtain information on the magnetically and electromagnetically induced response of the Earth from solar-cycle-related external variations.

A set of data from 22 observatories in the time interval 1952.5 to 1980.5 was used to estimate the contribution of the magnetic induction which was found to be comparatively weak, and the contribution of the electromagnetic induction, which accounts for a large part of the observed SC variation. The latter has been used to derive information on the resistance and the inductance characterizing a given observing point, in terms of loops of currents surrounding it.

A second set of data from 41 observatories in the time interval 1961.5-1977.5 was used to derive the lateral variation of the electrical properties of the European mantle and crust. A good correlation with independent information from magnetotelluric and magnetovariational data has been found in case of conducting structures at upper and mid-crustal depths, and information from deeper levels (lower crust and mantle) has been inferred for areas not screened by surface conductors.

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