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The 1977–1979 Geomagnetic Impulse: Its Induction Effect and Dependence on Magnetic Activity

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Abstract. All-day and quiet-day annual means from 39 globally distributed observations were used to study further the 1977–1979 secular variation impulse. For the rising part (1977–1978) of the impulse the first order external and internal spherical harmonic coefficients for all-day secular variation were found to be 18 nT/a and 1.3 nT/a, respectively. For the decaying part (1979–1980) these values were 50% lower. A clear difference, up to 50%, was found between all-day and quiet-day amplitude. The difference was largest in *H* near the equator and in *Z* at high latitudes where observed amplitudes did not fit well with a distant ring-current field. These differences were probably due to more localized current systems such as equatorial and auroral electrojets. Using a spherical conductivity model of the Earth with a homogeneous inducing external field which grows and decays exponentially, a range from 5 S/m to 20 S/m was found for the electrical conductivity of the upper mantle down to 1,500 km.

Key words: Geomagnetic impulse – Secular variation – Magnetic activity – Induction

Introduction

Nevanlinna and Sucksdorff (1981) showed that in the late '70s there was a sudden enhancement (impulse) in the global "secular variation". The impulse started at the end of 1977 and ended at the beginning of 1980. Using the first order spherical harmonic (*SH*) coefficients they showed that the impulse was of external origin, probably due to a magnetospheric ring-current.

The observed annual means used by Nevanlinna and Sucksdorff (1981) mainly concerned the rising part (1977–1978) of the impulse. The decaying part (1979–1980) is analyzed in this paper. The effect of magnetic activity on the impulse amplitude is studied by means of all-day and quiet-day means from 39 observatories all around the globe.

Estimates of the electrical conductivity of the upper mantle are obtained by calculating the induction of an exponentially rising and decaying external impulse field on a homogeneous and spherical Earth with a constant electrical conductivity.

The Data

The data used were annual means of *Z* and *H* components for all-days and quiet days from 1973 to 1981 from 39 geomagnetic observatories listed in Table 1. To separate the impulse from long-term internal secular variation, a quadratic polynomial in time was fitted to the annual secular variation values for each observatory. The rising (1978–1977) and decaying (1980–1979) years were excluded from the fit (see Fig. 1). The amplitude of the impulse was then obtained by subtracting the polynomial value from the corresponding value for the differences 1978–1977 (rising part) and 1980–1979 (decaying part). As an example, Fig. 1 shows annual differences and the polynomial values of the *Z* component for the Nurmijärvi observatory ($\phi = 60^\circ 30' \mathrm{N}$, $\lambda = 29^\circ 39' \mathrm{E}$).

To calculate the first-order internal and external *SH* coefficients $\dot{g}_{1i}$ and $\dot{g}_{1e}$, respectively, the amplitudes ($\Delta\dot{Z}$ and $\Delta\dot{H}$) of the impulse at different geomagnetic colatitudes were fitted to the following equations:

$$\begin{aligned} \Delta\dot{Z} &= C\cos\theta, \\ \Delta\dot{H} &= S\sin\theta \end{aligned} \tag{1}$$

where

$$\begin{aligned} C &= \dot{g}_{1e} - 2\dot{g}_{1i}, \\ S &= -(\dot{g}_{1e} + \dot{g}_{1i}) \end{aligned} \tag{1'}$$

where θ is the geomagnetic colatitude. Using these equations, $\dot{g}_{1i}$ and $\dot{g}_{1e}$ can be calculated as follows:

$$\begin{aligned} \dot{g}_{1i} &= -(C+S)/3, \\ \dot{g}_{1e} &= (C-2S)/3. \end{aligned} \tag{1''}$$

Table 2 shows the values of *C* and *S* obtained by the least-squares fit. Also shown are the calculated values of $\dot{g}_{1i}$ and $\dot{g}_{1e}$.

The *SH* coefficients in Table 2 show the dominant external character of the impulse: the ratio external/internal is roughly 10. It can also be seen from Table 2 that the amplitudes *C*, *S* and $\dot{g}_{1i}, \dot{g}_{1e}$ for the rising part

Table 1. List of geomagnetic observatories used in the determination of the impulse amplitudes. ϕ is geographic latitude and λ east longitude, θ is geomagnetic colatitude

Observatory	Coordinates		
	ϕ	λ	θ
New Aalesund	78.9°N	11.9°E	14.8°
Bear Island	74.5	19.0	19.1
Leirvogur	64.2	338.3	20.0
Barrow	71.3	203.4	21.2
Tromsö	69.7	18.9	23.2
Cape Chelyuskin	77.7	104.3	23.8
College	64.9	212.2	25.1
Loparskaya	68.6	33.3	26.5
Dixon	73.6	80.6	27.1
Lerwick	60.1	358.8	27.8
Dombås	62.1	9.1	28.0
Tixie	71.6	129.0	29.6
Sitka	57.1	224.7	29.7
Eskdalemuir	55.3	356.8	31.8
Nurmijärvi	60.5	24.6	32.4
Rude Skov	55.8	12.5	34.4
Newport	48.3	242.9	34.7
Wingst	53.8	9.1	35.7
Niemegk	52.1	12.7	38.0
Moscow	55.5	37.3	39.4
Fredericksburg	38.2	282.6	40.4
Boulder	40.1	254.8	40.8
Odessa	46.8	30.9	46.6
Tucson	32.2	249.2	49.3
Memambetsu	43.9	144.2	55.9
Kakioka	36.2	140.2	63.9
Honolulu	21.3	202.0	68.6
Hyderabad	17.4	78.6	82.6
Guam	13.6	144.9	85.9
Huancayo	12.0S	284.7	90.5
Tsumeb	49.2	17.6	108.4
Hermanus	34.4	19.2	123.6
South Georgia	54.3	323.5	134.3
Port Alfred	46.4	51.9	141.6
Argentine Islands	65.3	295.7	143.7
Port-Aux-Francaise	49.4	70.2	147.6
Dumont Durville	66.7	140.0	165.6
Mirny	66.6	91.0	167.0
Vostok	78.5	106.9	179.5

of the impulse are roughly twice as large as for the decaying part. There is also a clear difference in amplitude between all-days and quiet-days, especially in the H component, where the difference is about 50% near the equator. In Z, the difference is largest at high northern and southern latitudes. Note that $\dot{g}_{1i}$ has the wrong sign for quiet-day means. This is partly due to inaccuracies in amplitude determinations, partly due to a rather high disturbance level of Z at high latitudes even during quiet days. This produces higher $\dot{Z}$ amplitudes (C) at high latitudes than $\dot{H}$ amplitudes (S) near the equator, thus $C+S$ in Eq. (1'') will be positive.

There is also a slight correlation between yearly secular variation and differences in magnetic activity index A_k as shown in Fig. 1 for the Nurmijärvi observatory. ΔA_k fluctuates in the same manner as the yearly secular variation during 1977–1979. However, changes in ΔA_k are not exceptionally larger than in earlier years. Note that Voppel (1982) has recently reported a correlation between yearly secular variation and changes in the A_p index.

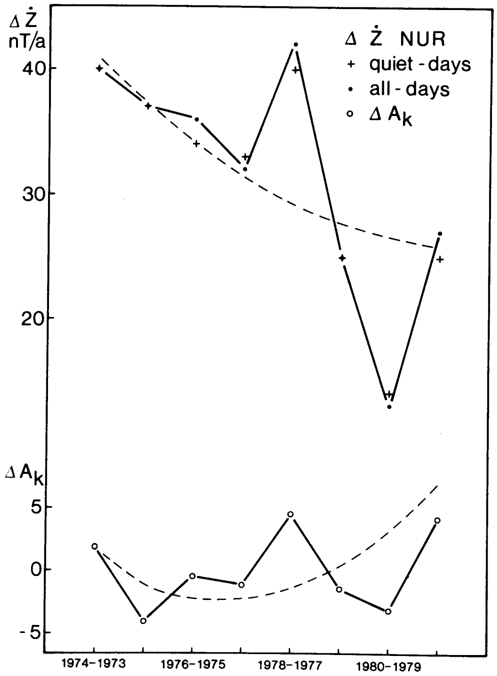

Fig. 1. *Top:* Yearly secular variation (all-days and quiet-days) of the Z component as observed at the Nurmijärvi Observatory. The broken line depicts all-day secular variation smoothed by a 2nd degree polynomial. *Below:* Differences in yearly means of the A_k-index and their smoothed values (broken line)

Figures 2 and 3 show the observed amplitudes $\Delta\dot{H}$ and $\Delta\dot{Z}$ for each observatory. It can be seen that $\Delta\dot{Z}$ and $\Delta\dot{H}$ have opposite signs during the rising and decaying parts.

Induction by an External Magnetic Impulse

In this section the electrical conductivity of the upper mantle is estimated using the SH coefficients of the 1977–1979 impulse shown in Table 2. The assumption is that the Earth is a homogeneous sphere with a radius R_e. Inside the Earth there is a concentric conducting sphere (radius qR_e; $0 \leqq q \leqq 1$) with constant conductivity σ. The inducing external magnetic field is assumed to be a uniform field in the direction of the dipole axis of the Earth corresponding thus to the field of a distant equatorial ring-current. During the rising part of the magnetic impulse the external field $B=g_{1e}(t)$ increases exponentially with a time constant a^{-1} (see Fig. 5) as follows:

$$g_{1e}(t)=E_0[1-\exp(-a\,t)] \tag{2}$$

where E_0 is the value of g_{1e} when $t=\infty$. At moment $t=t'$, the external field starts to decay with the same time constant as in Eq. (2); thus

$$g_{1e}(t)=E'_0\exp[-a(t-t')]; \qquad t \geqq t' \tag{2'}$$

where

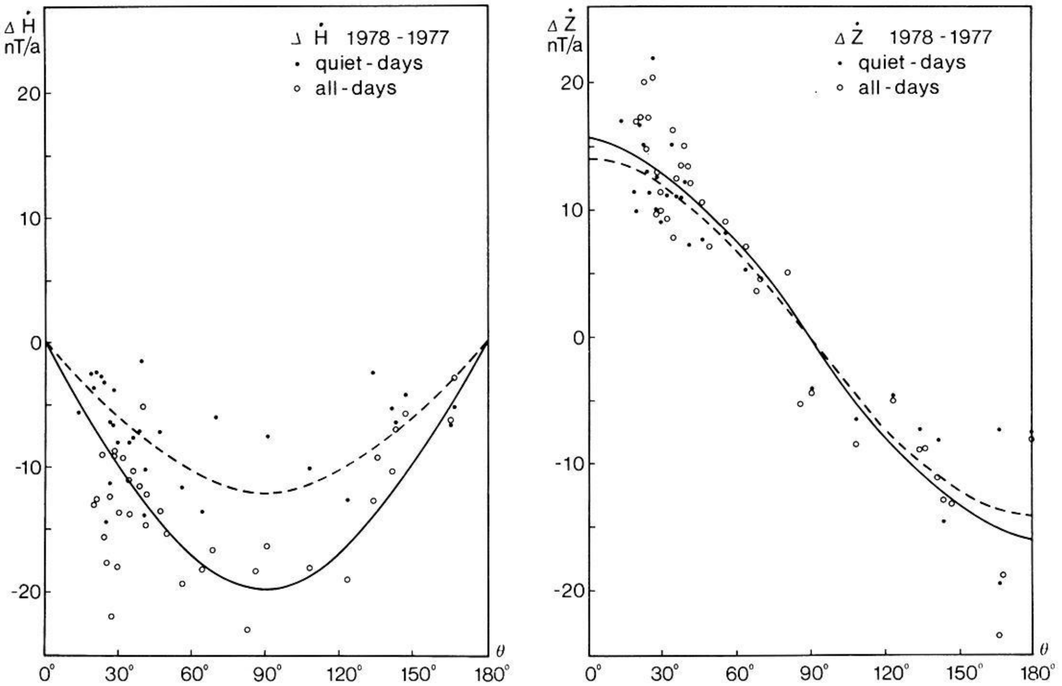

Fig. 2. All-day and quiet-day amplitudes ($\Delta\dot{Z}, \Delta\dot{H}$) of the rising part of the impulse as a function of dipole colatitude θ. Solid (broken) lines are the least-squares fits (see Eq. 1) of all-days (quiet-days)

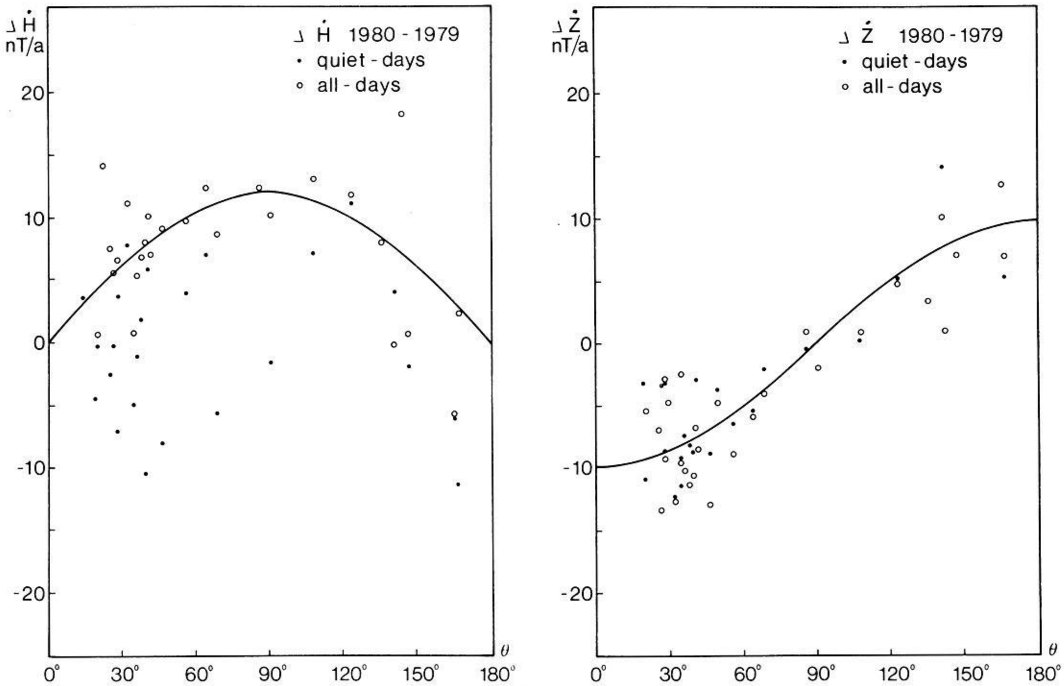

Fig. 3. All-day and quiet-day amplitudes ($\Delta\dot{Z}, \Delta\dot{H}$) of the decaying part of the impulse as a function of dipole colatitude θ. The solid line is the least-squares fit of all-day amplitudes (see Eq. 1)

$$E'_0 = E_0[1-\exp(-a\,t')]. \qquad (2'')$$

According to Chapman and Bartels (1940; Vol. II, p. 748), the induced magnetic field (g_{1i}) at the Earth's surface induced by any field $g_{1e}(t)$ can be written as follows:

$$g_{1i}(t)=\Phi(0)\,g_{1e}(t)+\int_0^t g_{1e}(t-u)\,(d\Phi(u)/du)\,du \qquad (3)$$

where the function Φ is defined by

$$\Phi(u)=3q^3\sum_{s=1}^{\infty}\alpha_s\exp(-u/\alpha_s A) \qquad (3')$$

where

$$\alpha_s=(s\pi)^{-2}; \qquad A=\sigma\,\mu_0\,q^2\,R_e^2. \qquad (3'')$$

Table 2. Amplitudes (C, S) and spherical harmonic coefficients ($\dot{g}_{1i}, \dot{g}_{1e}$) with standard deviations. Q denotes quiet-day and A all-day values, N is the number of observations used. The unit is nT/year

	Rising part 1977–1978				Decaying part 1979–1980			
	C	N	S	N	C	N	S	N
Q	14.0±3.4	29	−12.2±2.9	30	–	–	–	–
A	15.7±3.5	39	−19.7±3.9	34	−9.9±3.1	28	11.9±6.1	28
	$\dot{g}_{1e}$		$\dot{g}_{1i}$		$\dot{g}_{1e}$		$\dot{g}_{1i}$	
Q	12.8±1.5		−0.6±2.2		–		–	
A	18.4±1.7		1.3±2.8		−11.2±2.3		−0.7±4.2	

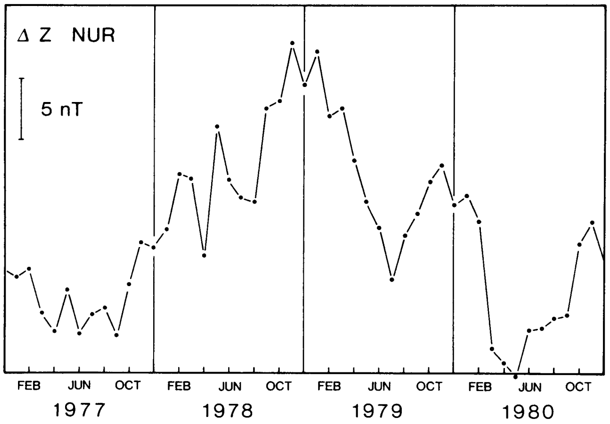

Fig. 4. All-day monthly values of the Z component at the Nurmijärvi Observatory after removing long-term secular variation

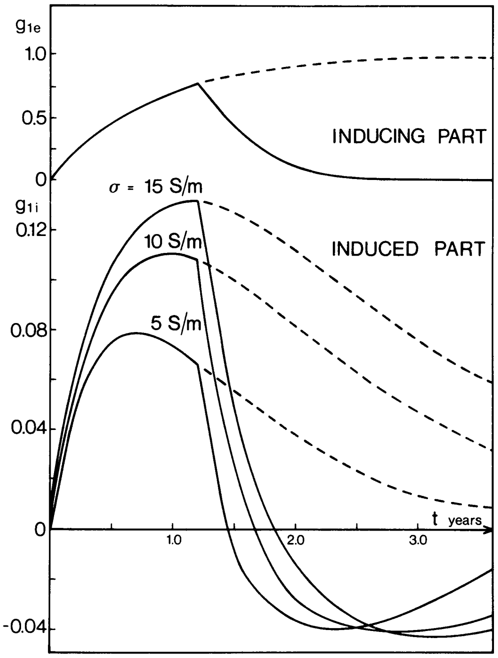

Fig. 5. *Top:* The exponential growth and decay of the inducing external magnetic field g_{1e}. The broken line shows the external field without decay. The values of $g_{1e}(t)$ are normalized so that 1.0 corresponds to $g_{1e}(\infty)=E_0$, see Eq. (2). *Below:* The induced part (g_{1i}) of the magnetic field as a function of time (t) when the conductivity (σ) is 5 S/m, 10 S/m and 15 S/m. Broken lines show the induced field when the external field alone grows

Using the exponential growth Eq. (2) of the impulse when $t \leq t'$, Eq. (3) leads to:

$$g_{1i}(t)=3q^3 E_0 \sum_{s=1}^{\infty} \alpha_s^2[\exp(-t/\alpha_s A) - \exp(-a t)]/(\alpha_s-(A a)^{-1}). \tag{4}$$

The solution of Eq. (3) when $t \geq t'$ can be obtained if the integration in Eq. (3) is carried out first from $u=0$ to $u=t-t'$ with g_{1e} from Eq. (2′) and then from $u=t-t'$ to $u=t$ with g_{1e} from Eq. (2). If the value of g_{1i} when $t \geq t'$ is denoted by $g_{1i}(t)_{t \geq t'}$, the solution of Eq. (3) is

$$g_{1i}(t)_{t \geq t'}=g_{1i}(t)-g_{1i}(t-t'). \tag{5}$$

Note, that $g_{1i}(t)$ increases if the rising time of the impulse shortens (i.e., $a^{-1} \to 0$). Then we obtain from Eqs. (3) and (4)

$$\lim_{a \to \infty} g_{1i}(t)=E_0 \Phi(t); \quad t \leq t' \tag{6}$$

Thus, at the moment $t=0$, g_{1i} approaches its maximum value $(1/2)\, g_{1e}(0)\, q^3$ (because $q^{-3}\Phi(0)=3\sum_s(\pi s)^{-2}=1/2$) which is independent of the conductivity.

Figure 4 shows details of the impulse based on monthly means of the Z component as observed at the Nurmijärvi observatory. It can be seen that the impulse started roughly in October 1977 and was at a maximum in December 1978 to January 1979, some 1.2 years later. The inducing external field (Eqs. (2) and (2′)) approximates to the observed global magnetic impulse in 1977–1979 when its time constant is fixed 10 months ($=a^{-1}$ in Eq. (2)). The model external field in Fig. 5 grows when $0 \leq t \leq t'=1.2$ years and decays exponentially when $t \geq t'$. Figure 5 also shows the induced part (g_{1i}) when $\sigma=5$, 10 or 15 S/m. The radius of the conducting sphere is chosen to be $0.9\,R_e$, which is the same as in other studies with the same conducting model (e.g. Yukutake, 1965). The induced field in Fig. 5 grows rapidly after the onset of the external field. The maximum is attained in 0.5 to 1.2 years and the corresponding maximum amplitude is $0.08\,E_0$ to $0.13\,E_0$ (depending on the conductivity chosen), which is less than 30% of an infinitely rapid ($a^{-1}=0$) impulse (see Eq. (6)).

Table 3. Values of $\dot{g}_{1i}$ caused by changes in an exponential inducing field g_{1e}, as calculated for different values of the conductivity (σ) using a spherical conductivity model (radius $0.9\,R_e$). The unit is nT/year

	$\sigma = 5$ S/m	$\sigma = 10$ S/m	$\sigma = 15$ S/m	obs.	
$\dot{g}_{1i}$	2.0	3.1	3.8	1.3	Rising part (1977-1978)
	−0.7	−1.8	−2.4	−0.7	Decaying part (1979-1980)
$\dot{g}_{1e}$	18.4	18.4	18.4	18.4	Rising part (1977-1978)
	11.2	11.2	11.2	11.2	Decaying part (1979-1980)

When the decay of the external field starts at $t = t'$, the induced field decreases to negative values within about 0.5 years. The decay is much slower than the growth because 3 years after the onset of the inducing field, the induced field is still more than 30% of its maximum value.

Table 3 shows values of $\dot{g}_{1i}$ and $\dot{g}_{1e}$ as calculated from Eqs. (2), (2′) and (5). These values are differences between successive one-year mean values of g_{1i} and g_{1e}, respectively. In Fig. 5, g_{1e} varies between 0 and 1, but for Table 3, $\dot{g}_{1e}$ was normalized to correspond to the observed 1978-1977 difference 18.4 nT/a. Using this normalization we get the value 11.2 nT/a for the difference 1980-1979, which is the same as observed (see Table 2).

As can be seen in Table 3, induction with the conductivity value 5 S/m seems to produce $\dot{g}_{1i}$ values which fit rather well with the observed ones. However, if we include the error limits of observed $\dot{g}_{1i}$ shown in Table 2, conductivity values up to 20 S/m are inside the error range.

Figure 6 was drawn to estimate the depth range in which induction occurs. It shows the attenuation of the induced currents in the conducting sphere as a function of the penetration depth. The current density (j) at different depths can be calculated from the following equation which is a modified formulation of Eq. (88) by Chapman and Bartels (1940; Vol. II, p. 746)

$$\begin{aligned} j = {} & 3E_0(\sigma/8\pi)\, q^2 R_e^2 r^{-3} \sin\theta \Big[F(k^2 r^2)\, k^{-2} \\ & \cdot \exp(-a t)/\sinh(k^2 q^2 R_e^2) \\ & + 2 \sum_{s=1}^{\infty} F(k_s^2 r^2) \exp(-t/\alpha_s A)/ \\ & [(k^2 - k_s^2)\, F(k_s^2 q^2 R_e^2)] \Big] \end{aligned} \tag{7}$$

where

$$\begin{aligned} & k^2 = \mu_0\, \sigma\, a, \\ & k_s^2 = (\pi s)^2 q^{-2} R_e^{-2}, \\ & F(x) = \cosh(x) - x^{-1} \sinh(x). \end{aligned} \tag{7'}$$

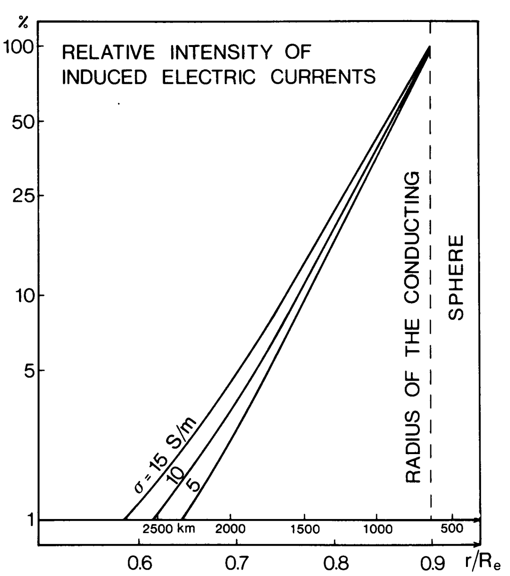

Fig. 6. Attenuation of electric currents as a function of depth 0.5 years after the onset of the impulse. At the surface of the conducting sphere at $0.9\,R_e$ the intensity of the current is normalized to 100%

Figure 6 shows the current density j 0.5 years after the onset of the magnetic impulse. It can be seen that at a depth of 1,000 km 400 km inside the conducting sphere, the current density is roughly 50% of its surface value, and the attenuation is almost the same for all conductivity values studied here. At a depth of 1500 km only 10% of the current is left. Thus, we can conclude that the mean conductivity of the upper mantle down to 1,500 km is 5…20 S/m. This estimate of mantle conductivity is of the same order as found by several other methods by various authors and summarized by Price (1967).

Discussion

The present study on the 1977-1979 geomagnetic impulse shows that the impulse had up to 50% larger amplitudes for all-day means than for quiet-days. The difference is largest in the H component near the equator and in the Z component at high latitudes. All-day annual means differ at the maximum 10 nT/a from the corresponding quiet-day values. Thus, in studies on internal secular variation, quiet-day means are preferable as they are not as contaminated by external sources. But quiet-day values also seem to contain enough external contamination to make them unreliable, at least during some years, for the study of the internal secular variation.

Consideration of the reason for the 1977-1979 impulse is beyond the scope of this paper. The impulse, as observed on Earth's surface, behaves like an enhancement in the magnetospheric ring-current. However, at high latitudes and near the equator, the observed amplitudes of the impulse do not fit the idealized distant ring-current field. These discrepancies are probably due to more localized sources such as polar and equatorial electrojets.

External magnetic impulses like the one studied here, are useful in studies on electrical conductivity of the mantle. Unfortunately, the large scatter in impulse amplitudes at different observatories and the uneven distribution of observatories between the hemispheres make conductivity estimates uncertain. The conductivity range obtained in this study, 5 ... 20 S/m, for the upper 1,500 km of the mantle supports earlier results presented in the literature.

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