UT variation of internal $S_q$ currents and the oceanic effect during 1980 March 1–18

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Summary. UT variation of the internal part of $S_q$ currents is examined using the geomagnetic data during 1980 March 1–18, and the effect of the ocean is found. The ratio of the internal currents to the external increases when the external current vortex comes above the Atlantic and Pacific Oceans, and the internal current vortex shifts to the oceans when the external vortex approaches the edge of the oceans. The existence of the ocean increases the total induced current by about 30 per cent and this amount is consistent with model calculations for $S_q$ by previous workers.

1 Introduction

Since Chapman & Whitehead (1923) and Lahiri & Price (1939) pointed out the effect on the internal $S_q$ field, it has been accepted as an important problem to study the currents in the oceans induced by the external $S_q$ field in order to examine the distribution of electrical conductivity in the Earth. Price & Wilkins (1963) used the surface integral formulae, and found that the internal part of $S_q$ became strong when its centre was above the oceans. The modelling of the oceans by spherical cap over a conducting sphere representing the mantle was made by Rikitake (1961), and Hewson-Browne & Kendall (1978) and Hewson-Browne (1978) extended this to oceans of arbitrary shapes. Hobbs & Dawes (1979) calculated the effect of the ocean above a conducting sphere on the $S_q$ field. Hobbs (1981) compared observed internal fields of $S_q$ analyses by Malin & Gupta (1977), Winch (1981) and Parkinson (1977) with the induced field calculated from the external field deduced by each analysis. He found that the comparison was poor and attributed the inaccordance to the fact that the magnetic observatories were not located in regions influenced by the main induced oceanic currents.

Using the Legendre coefficients obtained by Malin & Gupta (1977), Beamish et al. (1980a, b) estimated the contribution of the ocean to the total induced currents to be 14–48 per cent including the contribution due to currents induced in the conductosphere by the oceanic currents. Beamish et al. (1983) made a calculation for an oceanic model with realistic bathymetry and stated that the correct calculation of the $S_q$-induced magnetic field over the ocean should probably be made by using the calculated induced electric currents.

In this paper, we first obtain the equivalent $S_q$ currents as a snapshot at a fixed UT by the
method of Suzuki (1978) and Takeda (1984). Then examining the UT variation of the internal currents relative to the external currents, we study the effect of the ocean on the induced part of $S_q$.

2 Method of analysis

The method of analysis used here is essentially spherical harmonic analysis at a fixed UT developed by Suzuki (1978, 1979). We can obtain an instantaneous equivalent current system from the geomagnetic field variations at an instance only using this method. However, some revisions are made as follows:

1. Nocturnal values are used as base values for all components. Trends due to UT-dependent disturbance fields in $H$ and $Z$-components are corrected by using the $D_{st}$ index.

2. Since geomagnetic observatories are distributed more densely in the northern hemisphere, we improve the spatial resolution to the level necessary to analyse the $S_q$ field, using the data during the equinox and assuming north-south symmetry. This assumption is discussed later. The 'ghost station' or 'weight' devised by Suzuki (1978) is not used in our study.

The method is almost the same as in Takeda (1984, referred to hereafter as paper 1) except for the base value of the $D$-component. In paper 1, the daily mean values was used as the base value for the $D$-component. However, as Mazaudier (1982) and Mazaudier & Blanc (1982) found by the Saint-Santin incoherent radar scatter observations that meridional currents in the ionosphere were always northward during the daytime and the daily mean of the currents was not zero, the daily mean is not always adequate as the base value even for the $D$-component. Therefore we use nocturnal values as the base values for all components. The UT-dependent disturbance fields are corrected by using the $D_{st}$ index for $H$ and $Z$-components. Though the $D_{st}$ correction cannot be applied to the $D$-component, the effect of the $D_{st}$ field seems unimportant to the $D$-component. The coefficients of the spherical harmonics are determined by the condition of the minimization of the two following equations:

$$F_R = \sum_i [(\Delta H_i - \bar{H}_{si})^2 + (\Delta D_i - \bar{D}_{si})^2]$$

and

$$F_Z = \sum_i (\Delta Z_i - \bar{Z}_{si})^2$$

where $\Delta H_i$, $\Delta D_i$ and $\Delta Z_i$, and $\bar{H}_{si}$, $\bar{D}_{si}$ and $\bar{Z}_{si}$ are the observed data and the theoretical values expected by the spherical harmonics expansion at the $i$th observatory, respectively.

The adopted observatories are those of which geomagnetic latitudes are less than $60^\circ$, but not under the equatorial electrojet. However, some observatories are omitted, especially in the European region, in order to avoid the influence of the non-uniform distribution of the observatories. As a result, 49 stations are used for the present study. Their distribution is shown in Fig. 1. Compared with that in paper 1, observatories in China and the Pacific Ocean are added in the present analysis. Particularly the observatories of Midway and Wake Island, which are shown as MDI and WKE in Fig. 1, fill up the greatest gap in the region of the Pacific Ocean pointed out by Price (1969) and improve the accuracy in our analysis of the $S_q$ currents in the Pacific region.

The terms of Schmidt's function $P_n^m (\cos \theta)$ used here are $(n, m) = (1,0), (2,1), (3,0), (3,2), (4,1), (4,3), (5,0), (5,2)$ and $(5,5)$. The total number of the harmonics including cosine and sine terms is 15, and we analyse the $S_q$ field referring to the geomagnetic coordinate.
Figure 1. Distribution of observatories used in the present analysis (dots) and their abbreviation names. Dot-dashed and dashed lines represent $0^\circ$ and $60^\circ$ geomagnetic latitudes, respectively.

The period is during 1980 March 1–18 when geomagnetic activity is exceptionally low. The maximum Kp and AE indices are 3 and 409 nT, respectively. The Kp index is no more than 2+ during 97 per cent of the period, and the AE index is less than 100 nT during 81 per cent of the period. Equivalent current system is calculated at every 2 hr, and we obtain $12 \times 18$ equivalent current systems in all. In this paper, we discuss the UT variation of the current system by averaging the system during 1980 March 1–18 at every UT. Day-to-day variation of the system is discussed in another paper (Takeda & Araki 1984).

3 Results

3.1 EQUIVALENT CURRENT SYSTEM

In Figs 2–4, we show the equivalent current system at every 2 hr (UT) averaged during 1980 March 1–18, in order to represent the standard UT variation. The ordinates and abscissae show the geomagnetic latitude and magnetic local time, respectively, and contours are drawn at every 20 kA. Currents flow counter-clockwise and clockwise around the positive peaks indicated by ‘+’ and negative peaks by ‘−’, respectively. The external current vortex passes above the centre of the Pacific and Atlantic Oceans around 24 UT and 16 UT, respectively. In Fig. 4, it is seen that the internal currents tend to flow in the Pacific Ocean and move duskward from 20 UT to 24 UT. This tendency continues to 02 UT in Fig. 2. The effect of the Atlantic Ocean appears as the tendency of the internal (induced) currents to situate on the Ocean from 12 UT to 20 UT (Figs 3 and 4).

Fig. 5 shows the UT variation of external (left) and internal (right) current vortices. The top, middle and the bottom panels represent the UT variation of local time, latitude and current intensity, respectively. The UT variation of the external currents is mainly attributed to the difference between geographic and geomagnetic coordinates as shown in Takeda (1982). Strictly speaking, the UT variation causes north–south asymmetry. However, our
result is consistent with the result in 1970 March 11–26 described in paper 1 and in 1964 September obtained by Suzuki (1978) who did not assume N–S symmetry. Therefore in spite of the assumption of N–S symmetry, it may be said that our result reproduces the UT variation in the northern hemisphere well.

Variation of the internal currents is fundamentally similar to that of the external currents. However, it is noticeable that some differences exist. Fig. 6 shows the difference of the local time (top) and latitude (middle) of the centre of the current vortices and the ratio of the intensity (bottom) of internal to external currents. Positive values in the top and middle panels represent the internal vortex situated in the afternoon and northward sides of the external vortex, respectively. The ratio increases around 16 UT and 24 UT, which shows that the induced currents are enhanced in the Atlantic and Pacific Oceans. The difference of the local time of the centre of the current vortices becomes positive at 02 UT and 18 UT when the external vortex is situated at the west edges of the Pacific and Atlantic Oceans, respectively, and large negative values at 12 UT and 20 UT when the external vortex is at the east
edges. This shows that the internal current vortex tends to be located in the Oceans. The internal current vortex is situated southward and northward of the external vortex at 14 UT and 18 UT, respectively, though the feature is not so clear. This is also understood by the preference of the internal currents for the ocean, if we remember the configuration of the Atlantic Ocean (see Figs 3 and 4): the African Continent pushes the internal vortex southward at 14 UT, and the South American Continent pushes the internal vortex southward at 14 UT, and the South American Continent pushes it northward at 18 UT.

3.2 ADDITIONAL INTERNAL CURRENTS BY THE OCEANS

In order to extract the induced currents generated by the existence of the oceans, we have made the following procedure. First, we obtain the standard response by averaging the ratio of amplitude and the phase difference of the internal to the external currents about every term of harmonics over the universal time except for that of \( m = 0 \). The obtained standard response is shown in Table 1. The ratio of amplitude is not so far from the results of previous workers (e.g. Malin & Gupta 1977) for the terms of \((n, m) = (2, 1), (3, 2)\) and \((4, 1)\), but smaller than the previous results for those of \((4, 3), (5, 2)\) and \((5, 4)\). This may be explained...
by the currents of higher modes induced by the external (inducing) currents of lower modes; the inhomogeneous conductivity distribution due to the contrast between oceans and lands tends to split the induced current vortex to smaller pieces, and the induced currents of higher modes become strong compared with the external currents of the corresponding modes.

Secondly we multiply the external current intensity by the averaged ratio, add the averaged phase difference to the phase of external currents for each term, calculate the standard internal currents for each term and sum up all terms. We can obtain the standard internal currents at every UT by the above procedure. For the terms of $m = 0$, the original internal currents at each UT are directly used to calculate the total standard internal currents, because the terms mainly consist of the elements independent of UT, and therefore it is difficult to give a physical meaning to the response of these terms. This problem is treated in discussion. The standard internal currents obtained by the above procedure may be regarded as those when the Earth is laterally uniform, and their UT variation is caused by the UT variation of the external currents only. Hence, we can obtain the additional induced currents by subtracting the standard internal currents from the original internal currents at the corresponding UT.
Table 1. Ratio of amplitude and phase difference of the spherical harmonics of the magnetic potential between internal and external parts averaged over the universal times. The first and second columns give the degree and order of the spherical harmonics. The third column shows the ratio of the amplitude of the external part to the internal, and the fourth column gives the phase difference in degrees where the positive value means that the external currents are situated westward of the internal currents.

<table>
<thead>
<tr>
<th>n</th>
<th>m</th>
<th>E/I</th>
<th>(e^-i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>2.8</td>
<td>-15</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2.2</td>
<td>-26</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.4</td>
<td>-19</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1.7</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1.1</td>
<td>-16</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1.1</td>
<td>-1</td>
</tr>
</tbody>
</table>

The additional currents are given in Fig. 7. As the internal current function has a negative sign, the positive values in this figure show that the internal currents are reduced. We see that positive values are generally found above the continents and negative ones above the oceans, though some exceptions exist especially at 12 UT and 14 UT. This confirms that the induced currents flowing in the ocean intensify the total internal currents. The currents are about 30 kA on an average and 58 kA at maximum, and the ratio to the total internal currents (~100 kA) is about 30 per cent. This is consistent with the result of simulation by Beamish et al. (1980a, b) that the contribution of the ocean to the total induced currents is 14–28 per cent for each Legendre coefficient.

Figure 5. UT variation of external (left) and internal (right) equivalent \(S_q\) current vortices. Top and middle panels show the location of the focus (local time and latitude), and bottom panels represent current intensity.
Figure 6. Top and middle panels show the UT variation of the difference in the location of external and internal current vortices (internal minus external). Bottom panel gives the UT variation of the ratio of internal current intensity to external.

4 Discussion

We have assumed N–S symmetry of equivalent currents to obtain the equivalent current system in the northern hemisphere during equinox. As discussed in paper 1, this method is suitable to depict the equivalent current system in the northern hemisphere, including the UT variation of $S_q$ which causes N–S asymmetry. As the morphology of the oceans is not so far from N–S symmetry, except for the Indian Ocean, it seems that we can discuss the effect of the ocean in the northern hemisphere by using our result of the analysis.

Induced oceanic currents produce the coastal effect at the observatories within 500 km from the coastline (Hobbs & Dawes 1980). Schmucker (1970) found this effect on the vertical component of $S_q$ near the coast of California, and Hobbs & Dawes (1980) succeeded in the reproduction of this effect by simulation. In fact, the induced oceanic currents may be detected mainly through the coastal effect, because the magnetic observatories are generally distributed in the coastal region. However, the scale size of the coastal effect is relatively small compared with that of the external $S_q$ field, and the effect is influenced by local bathymetry and coastline configuration. Therefore, the locations of observatories may affect the estimation of the induced oceanic currents. The currents of opposite sense in the Atlantic Ocean at 12 UT and 14 UT obtained by the present analysis may be explained by this effect. However, since our analysis uses several observatories near the Atlantic Ocean and over 10 observatories near the Pacific Ocean including some island observatories, we may expect to
Figure 7. Additional internal currents at 02–24 UT. For more details, see the text.
obtain the smoothed internal current system, though this problem needs to be examined more precisely.

We have found that induced $S_q$ currents are enhanced when the external current vortex is above the ocean. However, it is not clear whether the enhancement is caused only by the induced currents in the oceans and currents in the conductosphere induced by the oceanic currents or not, though our result is consistent with simulation of the induced oceanic currents by Beamish et al. (1980a, b). It may become possible to discuss the difference of the conductosphere under the continents and the oceans when enough ocean bottom magnetometers are installed and comparison between the results from the land stations and from the ocean bottom magnetometers is possible.

We have used values at local night as the base values of $S_q$. Since the ionospheric conductivity is much lower at night than in the daytime, nocturnal values are suitable as the base values for $S_q$ when we consider the currents in the ionosphere. However, as Ashour & Price (1965) pointed out, the time-independent terms of external field cannot induce any internal currents, and therefore the induced currents do not become zero at night, because internal zonal currents flow at night to balance those in the daytime. If we take this into consideration, nocturnal values are not necessarily suitable as base values. However, it is difficult to determine the reasonable base value other than the nocturnal value, and we are obliged to adopt it as a base value. Therefore we cannot give a positive meaning to the internal terms of $m = 0$, though they may reflect the currents induced by the variation of the amplitude of $S_q$, for example with a period of 27 day or 11 yr. On the other hand, there is no obvious time variation in the $H$-component in low latitudes at night at least during sunspot minimum (Rastogi & Iyer 1976). Hence, it is not probable that the strong vortex of internal currents exists at night without the external field during the daytime, and if internal currents exist at night, they may flow along circles of latitude, and it does not seem that the internal currents at night affect the geomagnetic field other than the base value. In any case, the problem of internal currents of $S_q$ at night needs to be examined in more detail.

5 Conclusions

We analysed the $S_q$ field during 1980 March 11–18 and found the effect of the ocean on the UT variation of internal currents. The principal features of the internal currents were as follows:

(1) Internal currents are enhanced when the external current vortex comes above the ocean.

(2) Internal current vortex tends to be located in the ocean when the external current vortex comes near the edge of the ocean.

(3) The amount of the oceanic effect on the internal currents is about 30 per cent of the total internal currents, including the effect of the conductosphere.

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References


