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Seeking a seafloor magnetic signal from the Antarctic circumpolar current

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SUMMARY

Motional electromagnetic induction by ocean currents is a basic phenomenon of geophysics, with application to the monitoring of ocean transport. One of Earth's strongest ocean currents is the Antarctic circumpolar current (ACC). This paper explores the magnetic signals that should be generated by the ACC, and reports an experiment in which a magnetometer recorded natural variations of Earth's magnetic field on the floor of the Southern ocean for some five months in 1996. Magnetometer records from Kingston, Tasmania, and from Macquarie Island give reference information concerning magnetic storms and substorms. The instrument was sited in the region of the major oceanographic subantarctic flux and dynamics experiment (SAFDE), where the ACC passes south of Tasmania, between the major topographic features of the South Tasman rise and the Australia–Antarctica spreading ridge. The SAFDE records give comprehensive control on the actual ocean current flow at the time of the magnetic recording, and allow a magnetic signal to be predicted, in terms of the seafloor conductance. The seafloor conductance for the area is however low, and the amplitude of the predicted signal is low. The seafloor observations confirm that the signal is weak against the effects of ionospheric signals. In future experiments, the choice of sites with thicker seafloor sedimentation would increase the ACC magnetic signal to be observed.

The magnetometer measurements have a result relevant for the SAFDE, in confirming that the correction of electric data for seafloor conductance is small. There is also the result for seafloor magnetic observatories for which motional induction effects are unwanted, that such an observatory can operate even under the ACC, and be substantially protected from motional induction effects by low seafloor conductance.

Key words: Antarctic, geomagnetism, circumpolar current, motional induction, seafloor magnetometers, Southern ocean.

GJI Marine geoscience

1 INTRODUCTION

The global network of magnetic observatories has grown steadily since the first international network was established in the 19th century by Ross (Barraclough *et al.* 1992). The present situation for the Australian region is reviewed by Hopgood (2001).

Only in the last twenty or thirty years have seafloor observatories become a possibility, and much attention is being given at present to the challenge of complementing the network of land observatories with others on the seafloor (Chave *et al.* 1995; Toh & Hamano 1997). This task is especially significant as some two-thirds of the Earth is covered by ocean.

In the present experiment, four seafloor instruments were deployed on the floor of the Southern ocean in 1996 April. Two were recovered a year later in 1997, and two in 1998. The intentions of the experiment were several:

(i) To establish the feasibility of deployment and recovery of the magnetometer package in the hostile environment of the Southern ocean.
(ii) To make initial seafloor measurements in the latitude of the Southern auroral zone.
(iii) to analyse the fluctuation data for ocean-floor conductivity structure in the vicinity of the Antarctic–Australia spreading ridge.
(iv) To examine the data for evidence of a magnetic signal caused by the motional induction of the Antarctic circumpolar current, especially in the context of a major experiment in physical oceanography taking place there at that time.

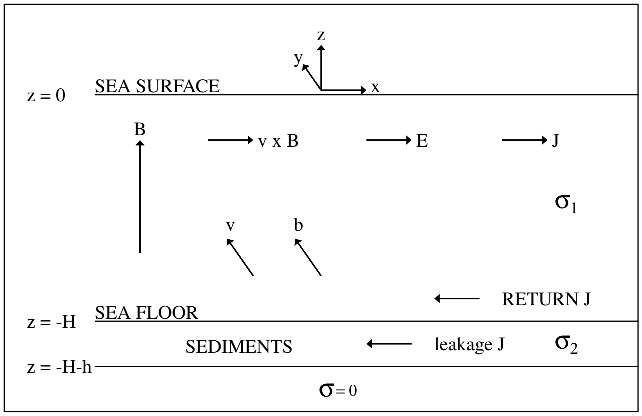

Figure 1. Figure for theory of motional induction.

Of the four instruments deployed, two failed to record any data, and of the two instruments which did record data, just one functioned correctly. The records from this instrument form the basis of this paper, which addresses particularly the fourth of the objectives listed above.

To provide simultaneous magnetic records for reference purposes, a land station was operated at Kingston, Tasmania. This site is to the north of the seafloor sites. Also the magnetic observatory at Macquarie Island, to the southeast of the seafloor sites, provided simultaneous reference data.

The seafloor observations were planned to coincide with a major oceanographic experiment, the subantarctic flux and dynamics experiment (SAFDE) of Luther *et al.* (1997). This experiment, part of the larger world ocean circulation experiment (WOCE), thoroughly instrumented the ACC south of Tasmania for two years, 1995–1996. The results of the SAFDE provide valuable information for assessing the results of the present magnetometer experiment.

Initially in setting a time base for the magnetometer data, elapsed days (or edays) have been defined, as the elapsed time since the start of 1996 January 1 reckoned in units of days. Then, for consistency with the SAFDE data, the SAFDE convention is adopted of defining digital days as those elapsed since the start of 1995 January 1. A 1995 elapsed day value is obtained from a 1996 elapsed day value by the addition of 365. Thus 06.00 h on 1996 January 2 UT would have a 1996 elapsed day value of 1.25, and a 1995 elapsed day value of 366.25.

2 THEORY

The theory for seafloor magnetic fields generated by ocean currents is as developed by Sanford (1971), following Longuet-Higgins *et al.* (1954). There are relevant papers by Chave & Luther (1990) and Larsen (1992). The notation adopted here follows the description in Lilley *et al.* (1993), where examples of seafloor magnetic field generated by the east Australian current (EAC) are reported. The measurement of motional magnetic fields down through the ocean column in the EAC is described by Lilley *et al.* (2001).

The physical circumstances are as in Fig. 1. The sea water has electrical conductivity σ_1, and is underlain by a sedimentary layer of conductivity σ_2, below which the conductivity is taken as zero. The ocean velocity is in the y direction, and varies with z only. Denoting the ocean velocity by $v_y(z)$, the electric current flow by $J_x(z)$, the electric field by E_x, the steady vertical magnetic field by B_z, the perturbation magnetic field due to motional induction by $b_y(z)$, and the local electrical conductivity by $\sigma(z)$, then Ohm's law for a moving medium may be expressed as

$$J_x(z) = \sigma(z)[E_x + v_y(z)B_z]. \qquad (1)$$

For the present paper, an important result is that the seafloor magnetic field, b_s, can be expressed as

$$b_s = -\mu_0\sigma_2\, h\, E_x, \qquad (2)$$

and, using notation $\overline{v^*}$ for $(-E_x/B_z)$,

$$b_s = \mu_0\sigma_2 h B_z \overline{v^*}, \qquad (3)$$

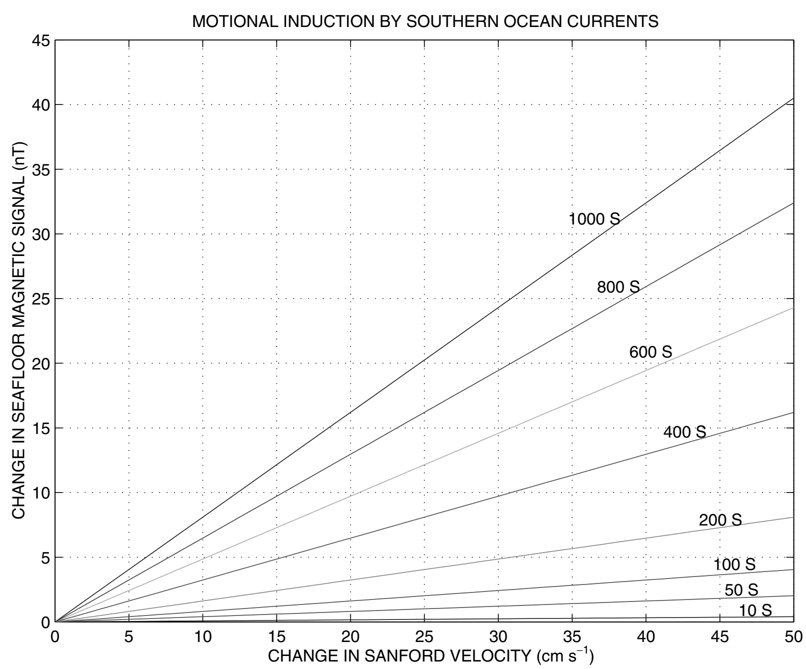

Figure 2. Change in seafloor magnetic signal, in terms of change in the Sanford velocity ($\overline{v^*}$), for different values of seafloor conductance as marked in siemens (S).

where $\overline{v^*}$ is Sanford's vertically-averaged and sea water conductivity-weighted water velocity:

$$\overline{v^*} = \int_{-H}^{0} \sigma(z) v_y(z)\, dz \bigg/ \int_{-H-h}^{0} \sigma(z)\, dz. \quad (4)$$

The seafloor perturbation magnetic field b_s is thus: directly proportional to B_z, the vertical component of the ambient main magnetic field; approximately proportional to the seafloor conductance $\sigma_2 h$ (this quantity also enters weakly into $\overline{v^*}$); and, for constant $\sigma_2 h$, directly proportional to the Sanford velocity as represented by $\overline{v^*}$. For the site Girardin (introduced below) the value of $\mu_0 B_z$ is -8.14×10^{-11} SI units, and, ignoring the negative sign, the relationship of eq. (3) may be expressed as in Fig. 2.

Note that seafloor magnetic data will generally be relative to an unknown zero. This circumstance prevails because the strength of the magnetic field at the seafloor, in the absence of any motional induction contribution, cannot be predicted with sufficient accuracy (and measurements may involve an unknown induction contribution). Seafloor magnetic data may therefore contain information about variation in a motional induction signal, but not its steady value. For this reason, Fig. 2 is plotted in terms of changes in Sanford velocity and seafloor magnetic field. With reference to Fig. 2, for a seafloor conductance of 400 S, a change in the Sanford velocity of the ACC corresponding to 30 cm s^{-1} will give a change in seafloor magnetic signal of order 10 nT. For a lesser seafloor conductance of 40 S, the seafloor magnetic signal is reduced to 1 nT. Seafloor conductance is thus critical in the observation of motional magnetic signals on the seafloor. For the case reported by Lilley *et al.* (1993), the Tasman abyssal plain off the east coast of Australia has a seafloor sediment thickness of order 1 km, giving a seafloor conductance of some 800 S.

Observations in the latitudes of the ACC carry the benefit that the vertical component of Earth's magnetic field, B_z, which enters eq. (3) above, is close to its maximum strength for the Earth. There is the disadvantage, at such latitudes, that magnetic storms and other signals arising in the ionosphere outside the solid Earth are intense, due to the presence of the auroral zone (Campbell 1997). Distinguishing a signal of oceanic origin from one of ionospheric origin may be expected to depend, first, on exploiting differences in frequency content between the two: the oceanic signals sought should be of longer timescale than the ionospheric signals. Secondly, differences in horizontal length-scale may be exploited, as generally an ionospheric disturbance should be coherent over a greater horizontal distance than an oceanic feature such as an eddy.

A further relevant point for the Southern ocean, made by Chave & Luther (1990), is that the vertical variation of electrical conductivity in the ocean column is weak. As a result, in eq. (4), first, the Sanford velocity becomes very nearly the vertically-averaged ocean velocity, with a coefficient dependent on the seafloor conductance. Secondly, if the seafloor conductance is small, the Sanford velocity becomes very nearly, simply the vertically-averaged ocean velocity.

An extra factor in the present case arises with the availability of reference data from the Macquarie Island magnetic observatory. According to the basic theory, such a surface observatory should detect no magnetic signal due to motional induction by sea water. Thus in the analysis below, the Macquarie Island data, after smoothing, will be compared directly with the seafloor data. It is well known that magnetic storm activity at the seafloor will be an attenuated version of what is seen at the surface (due to the attenuating effect of propagation down through the ocean water). However, the sea water attenuating effect is frequency dependent, and will be negligible for periods of several days and longer, which is the period band of the ocean current phenomena of interest.

Table 1. Details of deployment sites (number, name, code, latitude, longitude, ocean depth) of magnetometers in the SOMEx. Details for the land reference sites are also given. The seafloor names record personnel of the D'Entrecasteaux expedition of 1791–1793, which made magnetic measurements in southern Tasmania in 1792, (De Rossel 1808)).

Seafloor1	Bruny	BRN	48°42′S	144°44′E	3860 m
Seafloor2	Huon	HUO	49°49′S	144°14′E	3700 m
Seafloor3	Rossel	ROS	50°38′S	143°49′E	3605 m
Seafloor4	Girardin	GIR	51°45′S	143°17′E	3500 m
Land	Kingston	KIN	43°00′S	147°18′E	Surface
Obsrvtry	Macquarie	MCQ	54°30′S	158°57′E	Surface

3 SEAFLOOR INSTRUMENTATION AND OBSERVATION SITES

The seafloor instruments used were three-component fluxgate magnetometers, as developed at Flinders University of South Australia, Adelaide. The origins of these instruments lie in designs described by White (1979) and Chamalaun & Walker (1982). With various successive improvements, the instruments have been used to record seafloor data in a range of experiments, such as EMSLAB-Group (1988) and White & Heinson (1994). For the Southern ocean

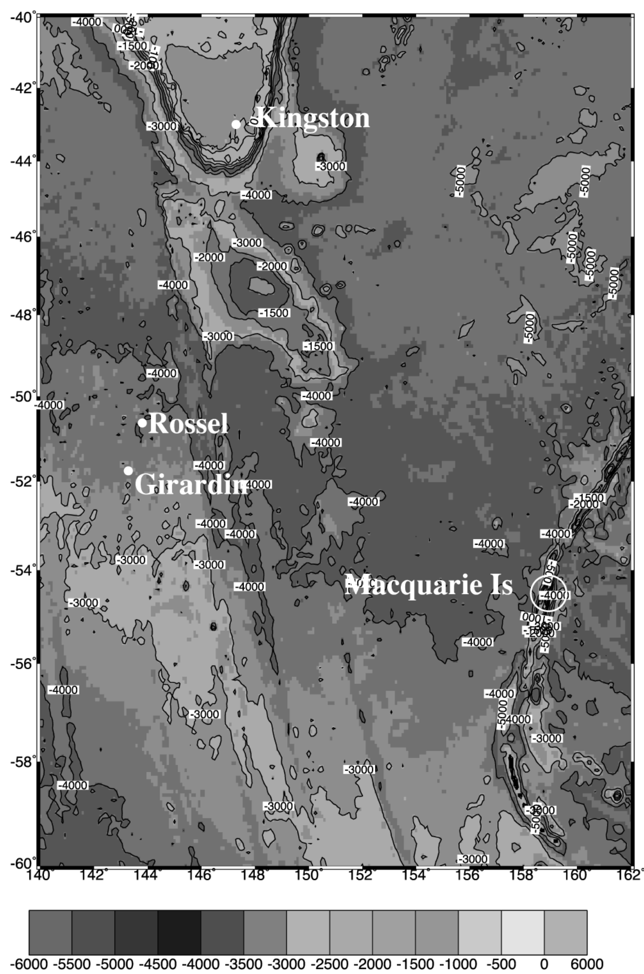

Figure 3. Map showing the magnetometer sites and bathymetry (m).

magnetometer experiment (SOMEx) deployments each magnetometer was packed into the space available inside a standard acoustic-release glass sphere, without compromising the acoustic release facility. The spheres were of diameter 17 in (0.43 m), thus making a compact instrument for deep-ocean marine studies. For the SOMEx deployments, the replacement of the earlier linear fluxgate sensors with newly-developed ring core fluxgate sensors was a recent design improvement.

The magnetometers were set to record at a data interval of 60 s, and so (with the memory capacity of that time) could record for six months. Deployed in 1996 April from the Antarctic vessel Aurora Australis during its Voyage 6 of 1995–96, they were allowed a mechanical and thermal stabilisation period of two months, and then were set to commence recording at 00.00 h on 1996 June 1 UT.

During deployment the instruments are released from the deploying vessel, and free-fall to the ocean floor, at a descent rate of approximately 1 m s^{-1}. On the seafloor the orientation in which a magnetometer settles is recorded and recovered by the three components of magnetic field that are recorded absolutely, and by two tiltmeters which record the tilts, from the horizontal, of the (ideally) horizontal magnetic sensors.

Details of the four deployments are given in Table 1, and the sites of the two seafloor instruments which returned data are shown in Fig. 3. In Table 1, positions are given to the nearest minute, as greater precision is not considered justified in view of the free-fall method of deployment in a region of strong ocean currents.

Retrieval of the instruments took place during 1997 April (Aurora Australis Voyage 6 of the 1996/97 season), and 1998 March (Southern Surveyor Voyage 2 of 1997/98 season). Retrieval is accomplished by a coded acoustic signal transmitted from the retrieving vessel. This signal triggers a release on a targeted instrument, which separates from its mooring weight and, then buoyant, rises to the ocean surface to there transmit a radio signal and (at night) display a flashing light-beacon. Burn-wire releases were used, and these proved reliable after two years on the ocean floor. Instruments rise to the sea surface at typical speeds of 0.8 m s^{-1}.

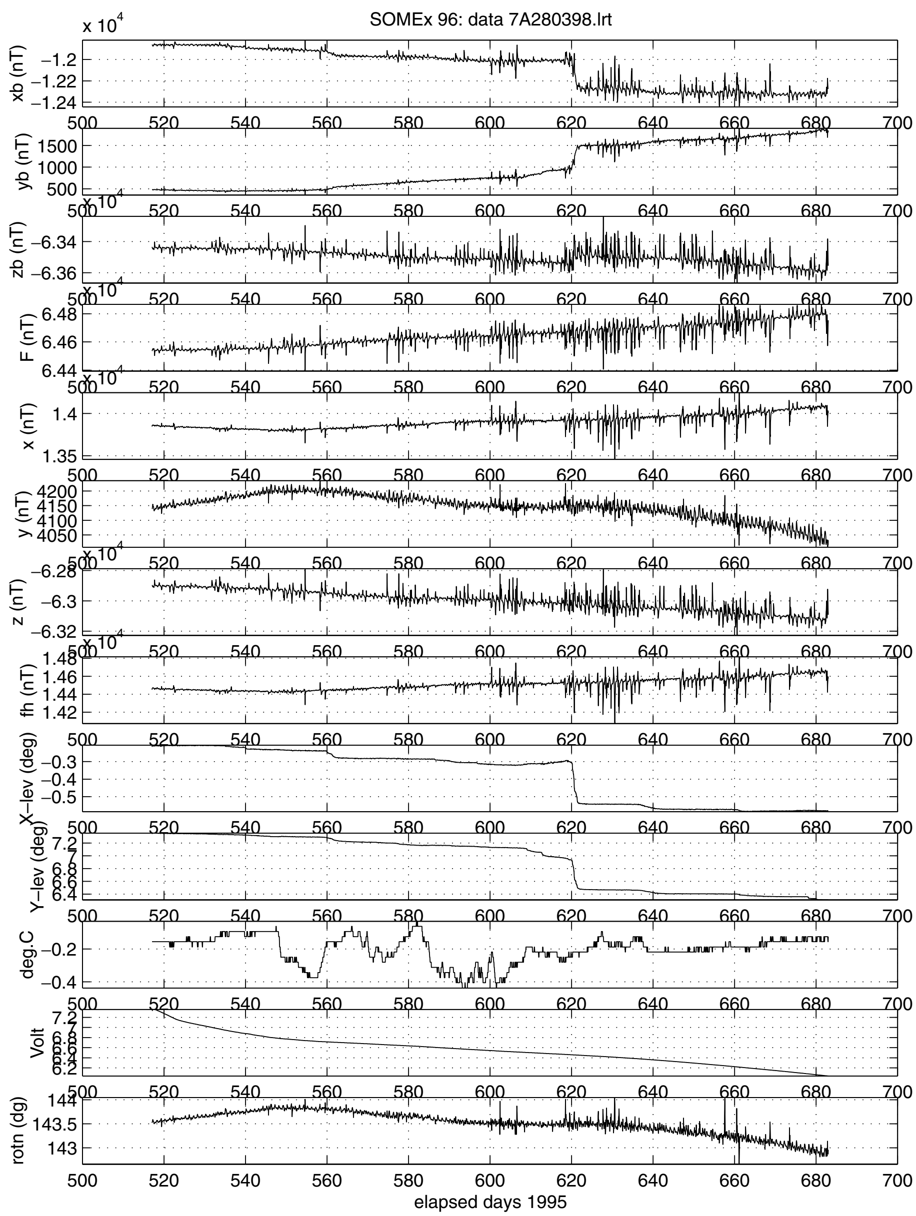

Figure 4. Plots of the time-series recorded by the site Girardin.

4 DATA RECORDED

4.1 Girardin

As a demonstration of the circumstances of seafloor recording, and the process of data reduction, the records from station Girardin over five months, and derived time-series, are shown in compressed form in Fig. 4.

The top three traces show the signals recorded by the three magnetometer sensors on the seafloor. The next trace, F, is a total field signal computed from the upper three. The next three traces, X, Y and Z, are the geographic north, east, and downwards components respectively, obtained by levelling the observed traces according to the tilt records (X-lev and Y-lev, ninth and tenth traces), and then rotating the axes of observation horizontally so that X is in the direction of geographic north at the start of the observing period. The tilt calibrations applied have been for an ambient temperature of zero degrees. The eighth trace, fh, is the horizontal component in the direction of magnetic north.

The lower three traces are the temperature recorded in the magnetometer (readings were taken every 156 min), the voltage supply (steadily decreasing, in accordance with correct operation), and (bottom trace) the angle for rotation of the axes to magnetic north (which corresponds to the value of the Y trace, sixth trace down).

It can be seen that Girardin changed orientation slowly, except for a shift at day 620. It experienced some changing temperature conditions from day 550 to 630, of amplitude some half-degree centigrade.

The design of the magnetometers incorporates voltage regulation to counter the effect of weakening batteries, and so reduce the effects of drift that a weakening power supply might cause. The deployments in the SOMEx produced the longest records yet observed by the magnetometers. In Fig. 4 it is therefore difficult to judge what is instrumental drift and what might be true long-period signal.

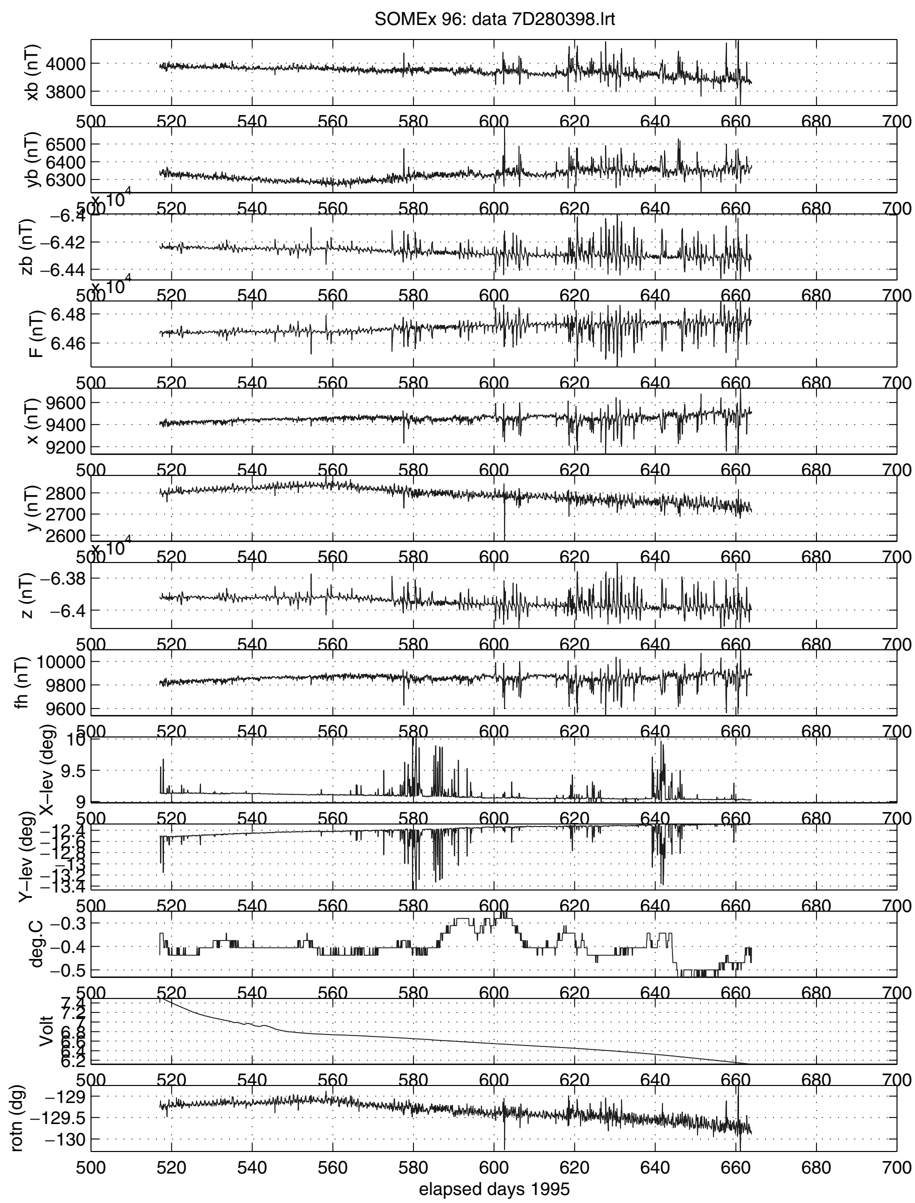

Figure 5. Plots of the time-series (edited) recorded by the site Rossel. Some remaining noise spikes are evident.

Extra information comes from the independent instrument at Rossel, discussed in the next section.

4.2 Rossel

Records from station Rossel over five months, and derived time-series, are shown in compressed form in Fig. 5.

The station Rossel, however, incurred intermittent faults. While editing many obvious spikes in the magnetic time-series has reduced the impact of these faults, the Rossel time-series is generally judged to be unsuitable for seeking small changes of long timescale. There are, however, some periods for which the Rossel time-series is error free. One such day from Rossel is included below in Fig. 6, which shows plots of data from four stations.

The long-term drifts of the Rossel sensors may be compared with those of Girardin, to look for consistency due to real secular change. Generally the drifts are too great, and too inconsistent between the two instruments, to expect them to be real. For example, the international geomagnetic reference field (IGRF) model predicts a secular change of -14 nT yr^{-1} in the total field, F, at Girardin and Rossel, while Figs 4 and 5 indicate changes of hundreds of nT yr^{-1} (positively).

This behaviour of the seafloor instruments emphasizes the stringent stability required for seafloor observation over long periods. The seafloor environment is stable regarding temperature, as shown by the temperature data in Figs 4 and 5. However, from the start to the finish of the recording period the instrument is operating remotely, and no independent orientation checks or calibrations are possible.

4.3 Macquarie Island

The records from Macquarie Island are from the established magnetic observatory there, described by Hopgood (2000). As is evident in Fig. 6, the Macquarie Island data recorded strong magnetic events, as expected for a station in this latitude near the auroral zone.

4.4 Kingston, Tasmania

A series of land magnetometers was run at a suitable site in the grounds of the Antarctic Division, Kingston, Tasmania, to monitor magnetic activity and provide a reference station on the closest land to the north of the seafloor sites. An example of data as recorded at Kingston is included in Fig. 6.

5 DATA REDUCTION

Median smoothing, as discussed by Press *et al.* (1992), has been applied to the Girardin X and Y time-series shown in Fig. 4. Windows of 2, 4, 7, 20 and 35 days have been taken, in the first instance to smooth out the magnetic storm activity, which typically has periods

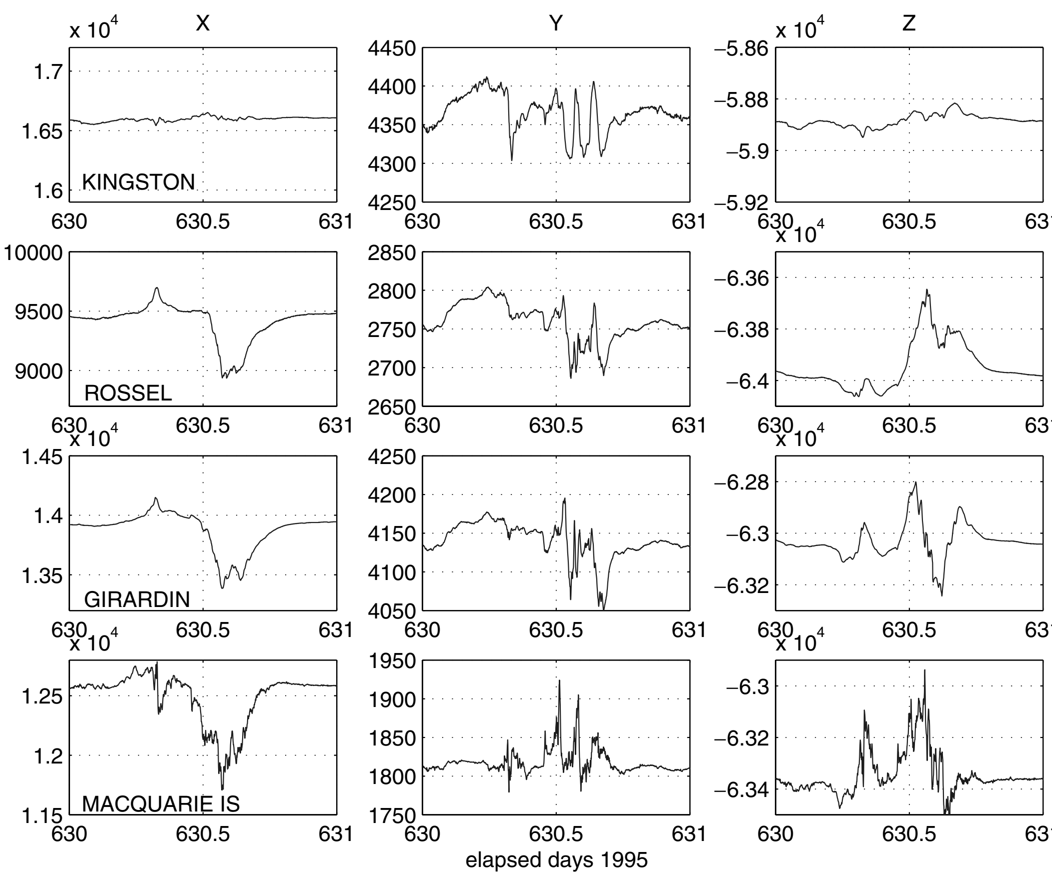

Figure 6. Examples of simultaneous data from the two seafloor sites, Rossel and Girardin, and the two land reference stations, Kingston and Macquarie Island, for one day (1996 September 22 UT), in the three geographic components of variation. Note the different scales used for the X, Y and Z plots, the ranges of which are 1300 nT, 200 nT and 600 nT, respectively.

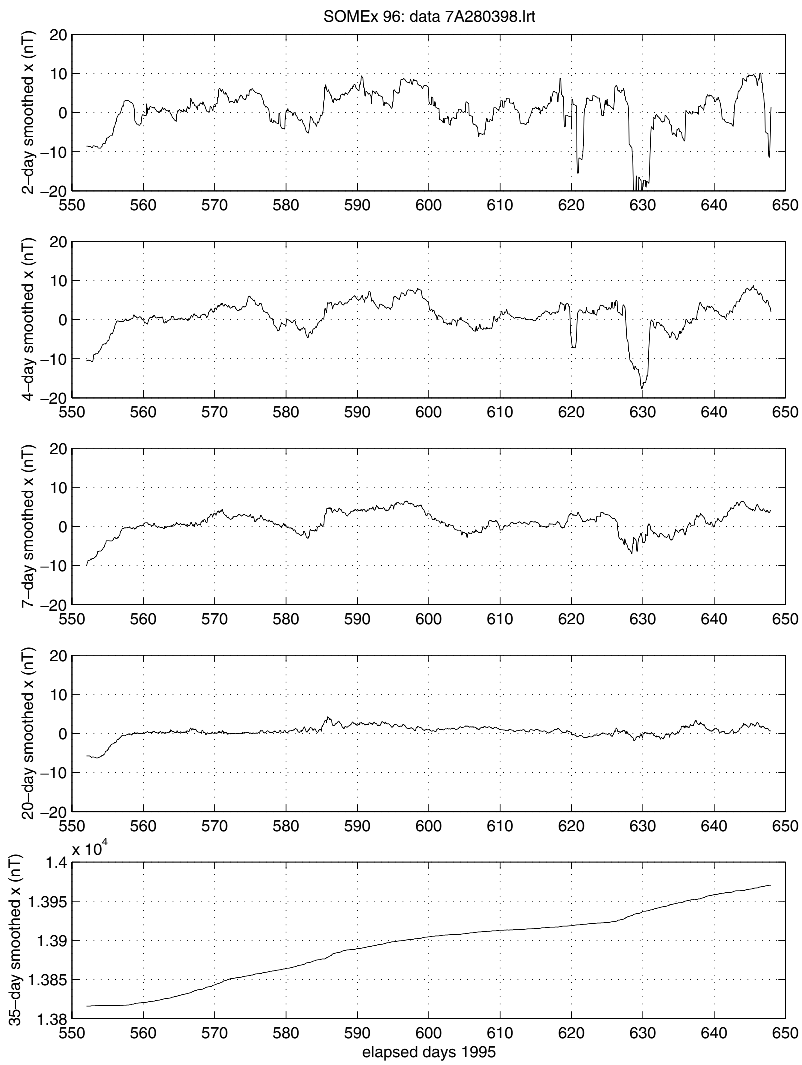

Figure 7. The geographic north (X) component of data from site Girardin median smoothed, over windows of 2, 4, 7, 20 and 35 days. The upper four traces have been plotted with the bottom 35 day trace already subtracted as an estimate of baseline drift.

less than one day, and the magnetic daily variation. These reduced data, for the X component, are shown in Fig. 7.

The longer windows have been taken as a way of estimating the drift of the magnetometers, and the 35 day median-smoothed time-series has been subtracted from the others as an effective way of removing a baseline drift.

For use with the Girardin records, a set of equivalent data was compiled from the Macquarie Island observatory records. These data, smoothed in the same way, are shown in Fig. 8.

The Macquarie Island records are expected to be free of ocean current signal. In seeking to isolate any motional induction signal at Girardin from ionospheric effects, the first step is therefore simply to difference the smoothed Girardin and Macquarie Island records. The results of this exercise, for the north (X) component data, are shown in Fig. 9.

Similarly the east (Y) component data are shown differenced in Fig. 10. Such differenced signals may be expected to show a combination of motional induction, remaining ionospheric signals, and noise. In addressing whether the motional induction part can be distinguished, a prediction of its strength will be made.

6 DISCUSSION

6.1 Seafloor geology at the magnetometer observing sites

As noted by Hill *et al.* (2001) and Hill & Moore (2001), the ACC flows south of the South Tasman rise through the gateway opened up some 33 Ma as part of the process of the separation of Australia from Antarctica (Exon *et al.* 2001). The dramatic topography on the western side of the South Tasman rise (see Fig. 3) is caused by the Tasman fracture zone. The SOMEx magnetometer sites are generally to the west of the Tasman fracture zone, in a region described as the southeast Indian basin. The seafloor topography is rough.

A number of seafloor samples such as recovered by piston cores indicate that the seafloor sedimentation consists of foraminiferous and radiolaria oozes. Typically, from the sparse information available for the area, seismic two-way traveltimes are of order 100 ms, indicating sediment thicknesses of order 100 m, for typical seismic speeds in the ocean-floor sediment of 1800 m s^{-1}. These speeds are measured, for example, at the deep-sea drilling project site DSDP 280, some 200 km east of the SAFDE and magnetometer line. Here, where the two-way traveltime is 535 ms, the core results show a

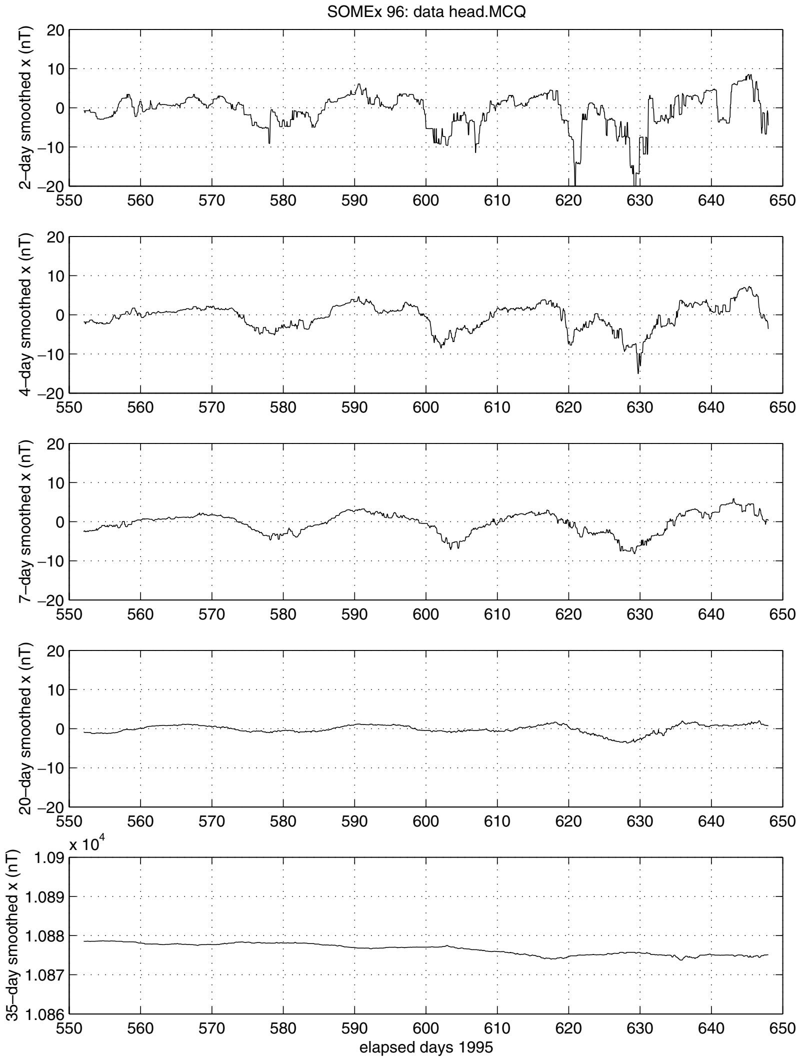

Figure 8. The geographic north (X) component of data from site Macquarie Island median smoothed, over windows of 2, 4, 7, 20 and 35 days. The upper four traces have been plotted with the bottom 35 day trace already subtracted as an estimate of baseline drift.

sediment thickness of 519 m, consisting of oozes, clays and silts. Note that this greater thickness of sediment at DSDP 280 results from a seafloor position more sheltered from the ACC.

Regarding sediment electrical conductivity, for Ocean Drilling Project (ODP) site 1171 on the South Tasman rise some 150 km further east again, an induction log gives a value of 1.4 ohm.m for the upper part of the sediment column, which comprises fossil oozes. Combining this conductivity value with the sediment information described above predicts a seafloor conductance value at the magnetometer sites of order 70 S, with an error of order 30 S.

6.2 SAFDE evidence of ocean currents during the observing period

The SAFDE experiment in the Southern ocean monitored the ACC and its variability for two years, 1995–1996. The line of the observing stations covered a latitude range from 48°S to 53°S, and its general position is shown in Fig. 3 by the Rossel–Girardin axis. The SAFDE experiment included, as a novel feature, lines of both inverted echo sounder (IES) instruments and horizontal electric field (HEF) recorders (Luther *et al.* 1998). Combined with other observations, these IES and HEF data provided absolute velocity profiles down through the ocean column (Meinen *et al.* 2002). For comparison with the magnetometer data, only the vertically-averaged currents are needed. These are presented in two forms. First, the IES-derived shears are vertically-averaged under the assumption of zero current velocities at the sea floor (that is, no HEF data are employed to produce an absolute reference for the IES shears). Secondly, the vertically-averaged absolute currents are derived solely from the HEFs, with the IES shears being employed only to correct for the small bias caused by the vertical variation of conductivity in the ocean. Therefore, the differences between these two measures of vertically-averaged currents represent the magnitude of the so-called barotropic, or depth-independent, component of the flow field.

For the time of the seafloor magnetometer recording at Girardin, SAFDE station 13 has both good HEF and IES data, which are reproduced in Fig. 11. A number of energetic excursions of the ocean current are shown, with vertically-averaged velocity changes of up to 30 cm s^{-1}. Also added to Fig. 11, are the differenced Girardin and Macquarie Island traces (7-day smoothing) from Figs 9 and 10.

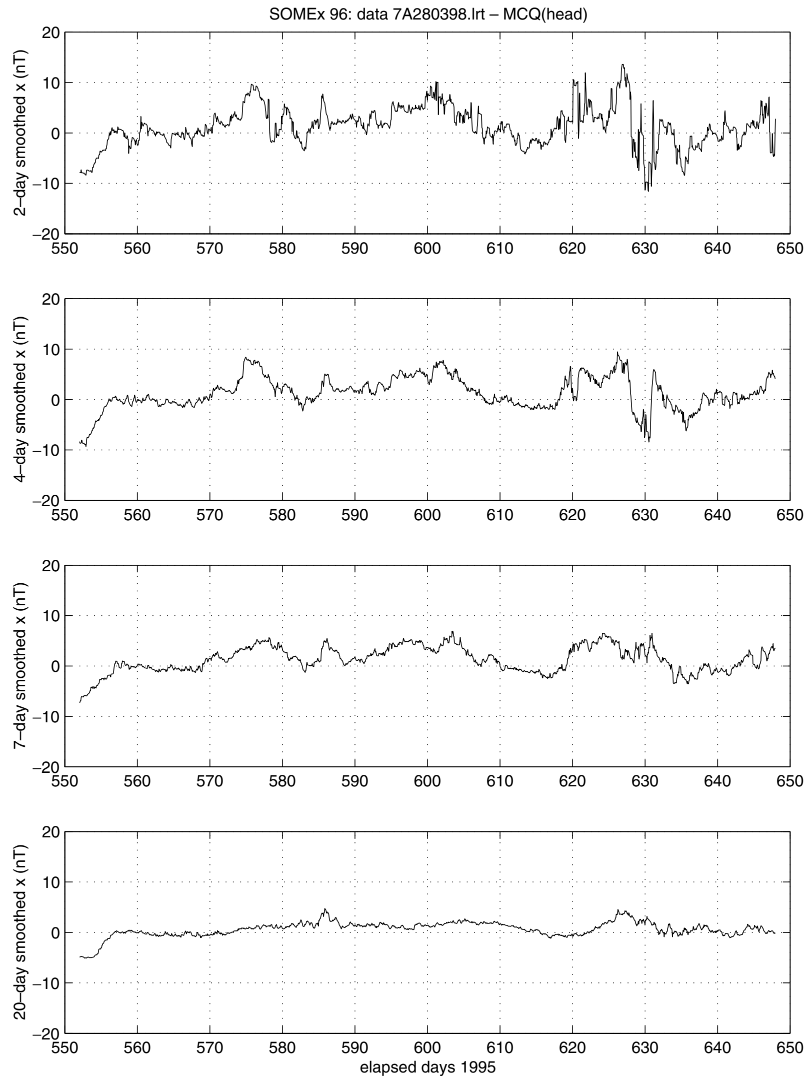

Figure 9. The geographic north (X) component of data from sites Girardin and Macquarie Island median smoothed over windows of 2, 4, 7 and 20 days, as in Figs 7 and 8, then differenced. Baseline drifts have first been removed.

Combining results from Section 2 and Section 6.1 above, for a seafloor conductance of 70 S the velocity changes shown in Fig. 11 would be expected to generate seafloor changes in magnetic field of value 2 nT. Such weak signals may be resolvable in the records of Girardin in Fig. 11, but inspection of the figure suggests that the seafloor magnetic records are in fact dominated by ionospheric signals still remaining after the median smoothing.

The possibility of establishing a linear relation between the various time-series in Fig. 11 was tested using procedures established for the robust remote reference processing of magnetotelluric data (Chave *et al.* 1987; Chave & Thomson 1989). The basic output channels were taken as the Girardin magnetic X and Y series, with inputs the Macquarie Island X and Y series, and the SAFDE Site 13 north (v) and east (u) IES series. While transfer functions were determined between the seafloor magnetic data and the Macquarie Island observatory, no linear relation was observed, above error level, between the seafloor magnetic components and the IES time-series.

The result to draw, is that the motional induction magnetic signals, indeed expected to be present, are of too low amplitude to be detected in the presence of the ionospheric signals. That the motional induction signals are so subdued, confirms the low seafloor conductance estimate made from the sedimentation data and indicates that there is no unexpected high conductance in the seafloor basalt layer, under the thin sediments.

7 CONCLUSIONS

Seafloor magnetometers, with the distinctive information that they can return on the integrated water flow through the ocean column, are a feasible component for a fully-instrumented experiment in physical oceanography. In addition, as well-demonstrated in the present case, a comprehensive experiment in physical oceanography can be an excellent control on the measurement of magnetic fields generated by ocean dynamo action. This paper has highlighted the challenges of observing in the Southern ocean, especially the circumstance of weak signals due to low seafloor conductance in the present of strong ionospheric signals from the auroral zone.

On the basis of the experience reported, further exploration of the magnetic signal of the ACC may be rewarding. Magnetometer design has advanced since instrumentation was first planned for the

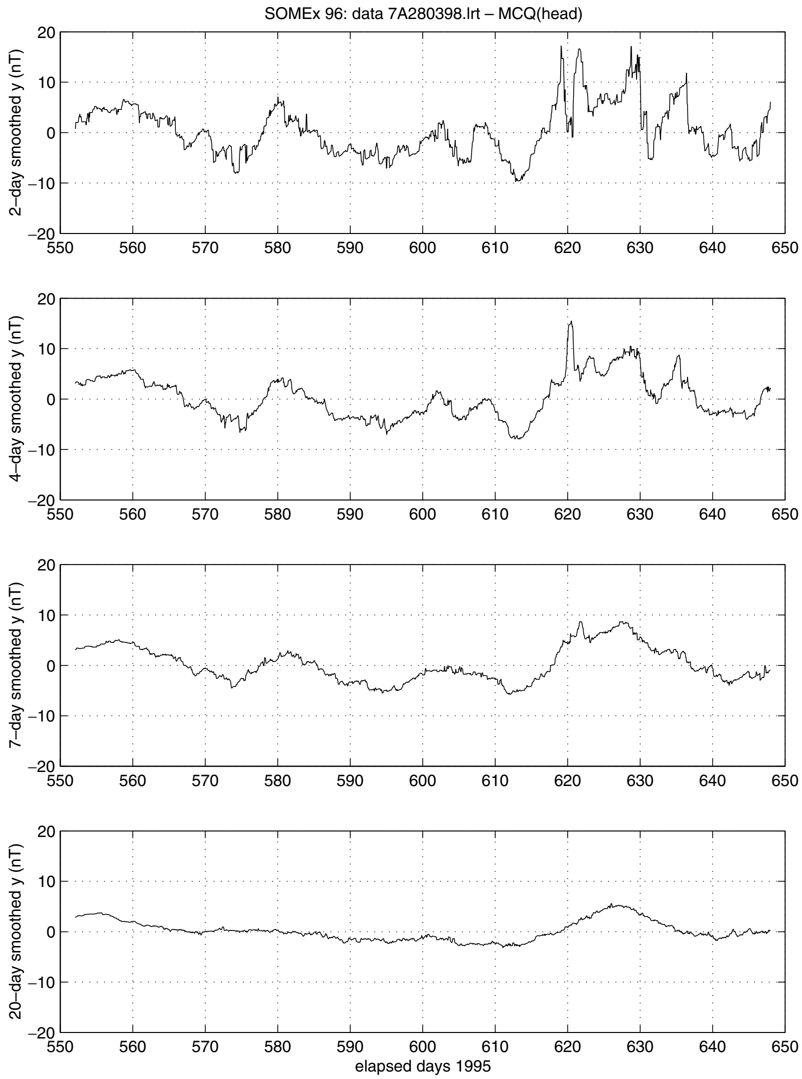

Figure 10. The geographic east (Y) component of data from sites Girardin and Macquarie Island median smoothed over windows of 2, 4, 7 and 20 days, then differenced. Baseline drifts have first been removed.

1996 SOMEx, and improved performance by seafloor recording instruments has been demonstrated on several occasions. A further exercise like the present one could expect an improved data return, and choosing observing sites in areas of higher seafloor conductance would favour the observation of motional-induction magnetic signals. Remote-reference procedures, applied to an array of seafloor recording magnetometers, should be a powerful technique for the removal of auroral-zone effects.

A further magnetometer experiment would be fortunate if supported by oceanographic measurements as comprehensive as the SAFDE of 1995–1996. However, much of the knowledge now held for the characteristics of the ACC south of Tasmania (Phillips & Rintoul 2000; Watts *et al.* 2001) will apply generally for subsequent years.

The exercise reported in this paper may have a useful contribution to make in turn to the SAFDE. Independent observational evidence is presented that the seafloor conductance is low, so that the conductivity correction to the SAFDE HEF data is correspondingly minor.

There may also be a useful contribution to the general topic of seafloor magnetic observatories, not intended for oceanographic purposes, for which marine motional induction effects would be a noise. This paper has shown how even in one of the strongest current regimes on Earth, the ACC, low seafloor conductance substantially protects a seafloor magnetic observatory from induction effects.

ACKNOWLEDGMENTS

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The Macquarie Island observatory data were made available by Geoscience Australia, and G. Burns facilitated the operation of the magnetometers at the Antarctic Division premises at Kingston, Tasmania. D. Luther, A. Chave, R. Watts and colleagues have contributed advice and data from the SAFDE. P. Hill, of Geoscience Australia, gave advice on the sediments on the Southern ocean floor.

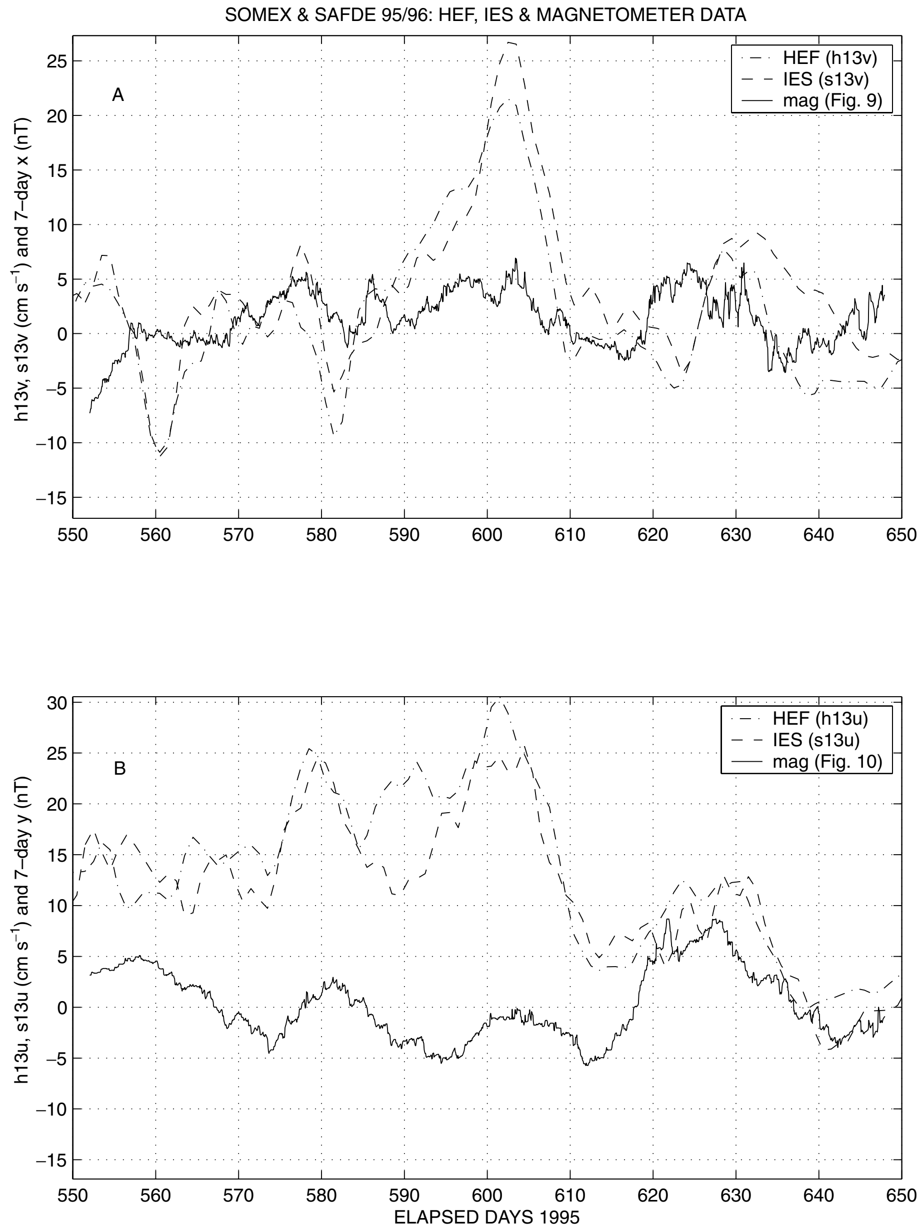

Figure 11. (a) The north magnetometer data from Fig. 9 (Girardin and Macquarie Island differenced), plotted with the SAFDE site 13 north HEF and IES vertically-averaged currents. (b) The east magnetometer data from Fig. 10 (Girardin and Macquarie Island differenced), plotted with the SAFDE site 13 east HEF and IES vertically-averaged currents.

The software of Wessel & Smith (1991) was used to produce Fig. 3. The Southern ocean magnetometer experiment is ASAC project number 852. Two reviewers are thanked for beneficial comments.

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