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# Rapid decrease in total magnetic field F at Antarctic stations - its relationship to core–mantle features

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**Abstract:** The Indian Institute of Geomagnetism (IIG) in 1982, 1986, and 1996, operated a Proton Precession Magnetometer (PPM) at its Antarctic stations Dakshin Gangotri/ Maitri (located at ~70°S, ~12°E). Comparison of the average quiet-time value of total intensity *F* for these years with values of *F* obtained at the same geographic location (interpolated from iso-intensity contours of *F* on World Magnetic Charts and IGRF Maps) for earlier years, suggested that over the last 75 years at this location, *F* has dropped from ~49 000 nT in 1922, to ~40 000 nT in 1996 i.e. ~120 nT per year. Further inspection at nearby Antarctic stations reveals a drop of ~108 nT $yr^{-1}$ at Novolazarevskaya, ~100 nT $yr^{-1}$. at Georg Forster and ~95 nT $yr^{-1}$ at Syowa; Mawson situated still further away shows a drop of ~72 nT $yr^{-1}$, while Dumont d'Urville located very near the magnetic pole showed a drop of ~50 nT $yr^{-1}$ until 1994. A study of the observed *F* values over the past five decades at 23 observatories from the Antarctic and sub-Antarctic regions indicates that contours of yearly decrease in *F* follow a definite pattern, with maximum decrease lying in a belt encompassing Maitri. These observations are of importance in the light of modelling works at the Earth's Core–Mantle boundary pointing to two prominent regions of reverse magnetic flux (RMF) occurring beneath South America, South Africa and a large part of Antarctica, and which may merge sometime to cause reversal of the present geomagnetic field polarity. The importance of continuous monitoring of *F* at various locations in Antarctic and sub-Antarctic regions is brought out in this work. It is equally important to understand the cause behind this rapid decrease in *F*.

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**Key words:** core–mantle boundary, reverse flux regions, secular variation, total magnetic field intensity

## Introduction

Secular variations in the geomagnetic field refer to long-period variations exhibited by the various components of the Earth's magnetic field. The time-period for these can range from a few millions of years (reversals of the internal dipole), through a few hundreds of years for changes in intensity of the dipole, to a few years for phenomena like the magnetic "jerk" discussed by Cain (1987, pp 55–70). These secular variations are believed to originate within the Earth in (1) the liquid core where the geodynamo creates the geomagnetic field, and (2) in interactions between the liquid core and the mantle.

The field variations which are external in nature and which originate in space around the Earth generally have shorter time-periods of a few years (the 22 year solar magnetic reversal cycle, and the 11 year solar sunspot cycle), through a few days (magnetic storms) to a few seconds (ULF pulsations) (Lanzerotti 1978, pp 130–156). Since the Earth's magnetic field is not a pure dipole, but has substantial quadrupole and higher order polarity components, it has a complexity which can be unravelled only by examining various aspects of its behaviour. The secular variation of the geomagnetic field is one such aspect.

Gellibrand in 1634 noticed large changes in the value of declination measured at London; Langel (1987, pp 249–512) pointed out the substantial change in declination (*D*) at London from 11°E in 1580 AD to 24°W in 1800 AD. Edmund Halley's successive crossings of the Atlantic Ocean led to the publication of the first declination chart in 1701. The position of the magnetic dip poles also shows a pronounced secular variation as well as smaller diurnal variations (Dawson & Newitt 1982). Barton (1997) in a study of the main field and secular variation using the seventh generation IGRF1995 found the decrease in the dipole moment for the 20th century to be 6.5%. The north and south dip poles exhibited different behaviours. The north dip pole had an accelerated motion in the north-west direction with a velocity of 21 km $yr^{-1}$ while the south dip pole had a decelerating north–west motion with a velocity of 5 km $yr^{-1}$. The nondipole field behaviour in the 20th century has been examined by Kasyanenko *et al.* (2000) based on the seventh generation IGRF. They identify anomalies in the field and, in particular, find westward drift to be exhibited by only one anomaly which is located in the African region.

Other features of the geomagnetic field which show notable secular variation, are (1) the non-dipole part of the field which is currently drifting westward with average angular velocity of ~0.2° $yr^{-1}$ and is growing or decaying at about 10 nT $yr^{-1}$, and (2) the magnetic moment of the dipole which over the past century has been decaying at an average rate of about 0.4% per year (Nagata 1967, pp 627–629).

Archaeomagnetic data indicate that the total field intensity (*F*) has over the past 2000 years dropped from a value of 0.42 G to about 0.32 G, but that over the preceding 3000 years

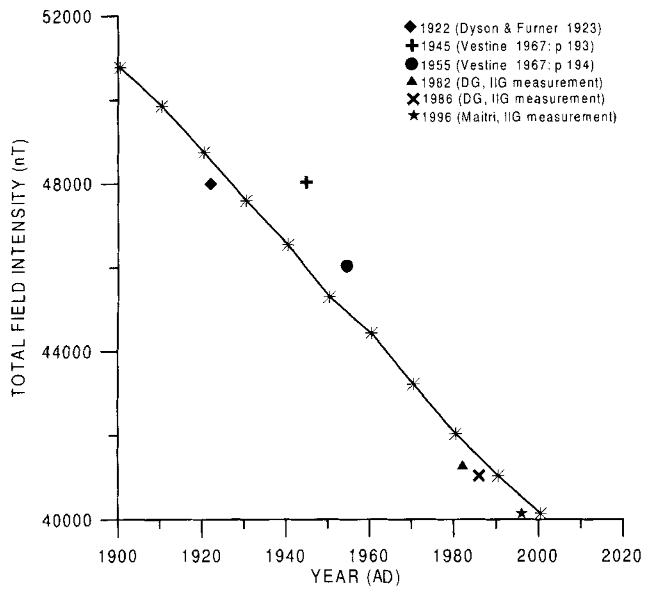


**Fig. 1.** Values of $F$ for the location of 70°S, 12°E (Dakshin Gangotri) at 10 year intervals over the period 1900–2000, estimated from IGRF models. Also shown are values for different epochs obtained from sources as indicated in the legend. Note that values for 1982, 1986 and 1996 are measured ones.

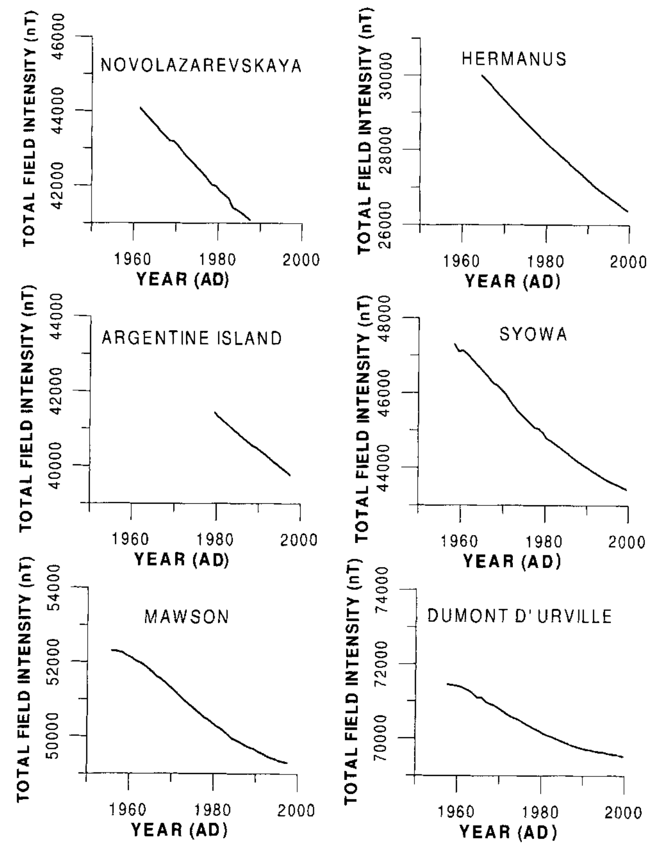


**Fig. 2.** Rapid decrease in $F$ shown by other southern hemisphere high-latitude stations, Novolazarevskaya, Hermanus, Argentine Island, Syowa, Mawson and Dumont d'Urville. The annual rate of decrease for these stations is shown in Table I. Interestingly, Dumont d'Urville showed a drop of ~50 nT up to 1994 after which the drop was only ~16 nT $yr^{-1}$, possibly due to a new absolute pier adopted in 1995.

it had increased by practically the same value (McElhinny & Senanayake 1982).

The purpose of this work is to point out the drop of about 9000 nT which has occurred in the total magnetic field intensity ($F$) over the last 75 years at the location of the Indian Antarctic station Maitri (70.77°S, 11.75°E) and to compare it with the decrease observed at other Antarctic locations. Bormann *et al.* (1995, pp 39–57) pointed out that the German station Georg Forster and the Russian station Novolazarevskaya (some 6 km from Maitri) experienced drops of ~100 nT $yr^{-1}$ and ~116 nT $yr^{-1}$, respectively, over the past few decades. In this work, the importance of continuous monitoring of $F$ in regions which experience a rapid decrease is discussed in the light of the work of Gubbins (1987), which relates possible reversals of geomagnetic field polarity to increasing areas of "reverse magnetic flux" in the Southern Hemisphere.

The first mention of decrease in total field intensity affecting a large area of the southern hemisphere is possibly by Fisk (1931), and this was followed by Chapman (1951, fig. 8). It may be mentioned that Nagata (1961) had found the secular variation in vertical component ($Z$) at Antarctica to be very large and further (Nagata 1982) suggested that the non-dipole field does not drift westward in the Antarctic region. His observations have relevance to the present work because at high latitudes, the major contribution to $F$ is from $Z$. That the Southern Hemisphere is experiencing a rather rapid decrease in $F$ has been brought out in contour plots shown by Langel (1987, p413). Arun *et al.* (2000) have discussed the rapid fall in total field at Maitri and suggest it may be due to the toroidal field. What is surprising is that while this striking feature of the large decrease in $F$ over Antarctica is textbook material, it does not seem to be receiving the active research interest which it warrants.

## Instrumentation

A Proton Precession Magnetometer (PPM) designed and fabricated at the Indian Institute of Geomagnetism (IIG) is used to measure the total intensity of the Earth's magnetic field ($F$) at Maitri. The instrument is based on the nuclear magnetic resonance related property of protons and the fluid used in the sensor is Hexane.

The working mode of the PPM is as follows: A current of 1 Amp is passed through a noise cancelling dual solenoid coil with an inductance of 39 milliHenry. These solenoids are immersed in the proton rich liquid (Hexane). The field produced by passing of current through this sensor is high (~100 G). This forces the protons to align their spin momenta along the direction of the field. When the current is withdrawn, the protons experience a torque and start precessing about the direction of Earth's magnetic field. As they precess, an induced EMF of the order of a few μV is generated in the coil.

This EMF is amplified to give an output signal of a few Volts. The signal decays in 1–2 sec due to the thermal motion and gradient in the field.

The output of the PPM is in the form of pulses. The frequency of the pulse train is measured and is related to the gyromagnetic ratio of protons. This being an atomic constant, the accuracy exclusively depends upon the measurement of the frequency of proton precession. The measurement of frequency entails passing the pulse train through a gate for a known period. The accuracy of this period $T$ would determine the accuracy of the instrument. The accuracy of the gating time $T$ can be verified to 1 in $10^7$ using a stable crystal oscillator with which every precision counter is equipped. Thus by checking the frequency of the time base in the PPM that generates the gating period $T$, against standard high precision counter, one can put a figure on the accuracy thereof. As the gyromagnetic ratio is known to about 2 parts in $10^6$, a favourable comparison of gating time with a time base of a stability of 1 in $10^7$ or higher is good enough. The accuracy of the gating time for the instrument at Maitri was found to be 1 part in $10^5$.

The signal amplitude depends on the orientation and height of the sensor from the ground level. In order to get optimum signal, the sensor coils are placed perpendicular to the geomagnetic meridian and at a height of ~1.5 m from the ground, on a totally non-magnetic stand or platform. The unit has an operating range of 25 000 to 60 000 nT and sensitivity of ± 1 nT for the entire range. The sampling rate can be adjusted from 10 sec to 150 sec. The instrument works on a DC supply of 12 V/1.5 Amp.

## Observations

The Total Field $F$ observations were started during the very first Indian Antarctic Expedition in 1981. This being a summer expedition, the observations were taken during the three weeks stay of the team at Dakshin Gangotri. The observations were repeated during the next expedition. With the commissioning of the first Indian permanent station at Dakshin Gangotri in 1983, the observations were continued during 1986 and 1987. The total field $F$ observations were restarted at Maitri during the year 1995–96. Since observations for 1996 were taken only for a period of about a week during summer, the representative annual mean value for this year has been obtained by considering the observations taken when 3-hourly Kp values were least, typically about 1- and 1o.

Figure 1 shows the decrease in the total field intensity $F$ at the location of 70°S, 12°E i.e. at the location of Indian Antarctic station Dakshin Gangotri (DG) according to IGRF and DGRF predictions (making use of the website of WDC-A, USA). Also shown are points (marked by special symbols) whose values have been obtained for the location 70°S, 12°E, from different sources as indicated in the figure legend (Dyson & Furner 1923, Vestine 1967). We consider both the stations, Maitri and DG (MAI/DG), together because India's first Antarctic station Dakshin Gangotri (70.08°S, 12.00°E) gradually got buried under drifting snow over 1983–1988, and had to be relocated at Maitri (70.77°S, 11.75°E). The triangle, cross and star (symbols on the curve in Fig. 1) denote actual measurements of $F$ made at MAI/DG with a proton precession magnetometer. A declining trend is seen even in these three values. Similarly values of $F$ were read at this location 70°S,

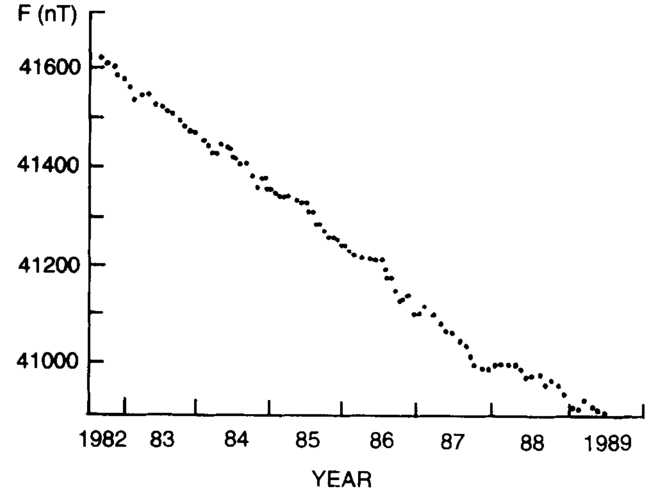


**Fig. 3.** Fall in total field $F$ shown by the German station Georg Forster (70°46'S, 11°52'E). Values plotted are monthly means (From Bormann *et al.* 1995). This station is close to the Indian Antarctic station Maitri.

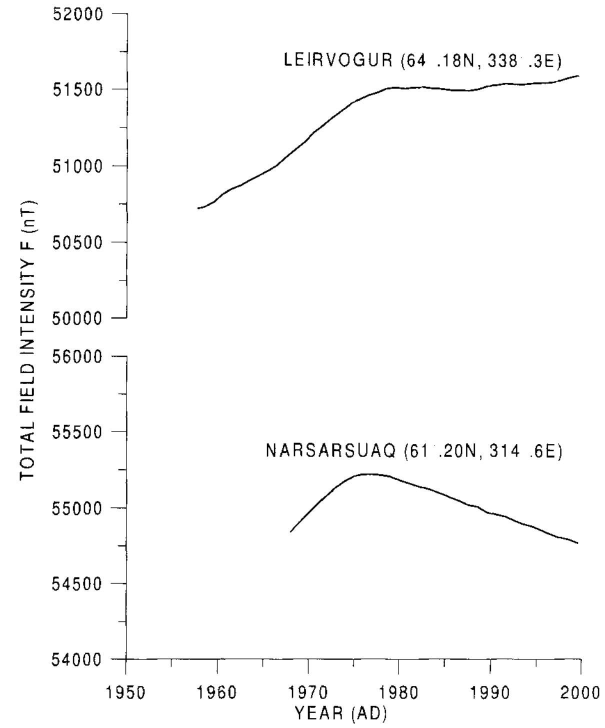


**Fig. 4.** Pattern of total field variation shown by stations Leirvogur (64°18'N, 338°3'E) and Narsarsuaq (61°20'N, 314°6'E) in the Northern Hemisphere and near-conjugate to Maitri. These stations do not show any steep fall. This may imply that the fall in the Southern Hemisphere is due to the toroidal and not the poloidal field (from Arun *et al.* 2000).

**Table I.** List of Southern Hemisphere stations used in this study.

| Geographic | | Geomagnetic | | ΔF | Station | Data interval |
|---|---|---|---|---|---|---|
| Lat. | Long. | Lat. | Long. | nT yr$^{-1}$ | | |
| -70.77 | 11.82 | -66.87 | 56.31 | -108 | Novolazarevskaya | 1961.5–1987.5 |
| -70.32 | -2.58 | -64.36 | 46.57 | -108 | Sanae Iii | 1980.5–1989.5 |
| -34.42 | 19.23 | -33.78 | 82.97 | -105 | Hermanus | 1950.5–1999.5 |
| -65.25 | -64.27 | -54.38 | 4.90 | -103 | Argentine Islands | 1957.6–1997.5 |
| -69.00 | 39.58 | -70.17 | 81.23 | -94 | Syowa | 1958.5–1999.5 |
| -75.52 | -26.60 | -66.50 | 26.12 | -91 | Halley Bay | 1957.7–1980.5 |
| -62.17 | -58.48 | -51.48 | 9.44 | -90 | Arctowski | 1978.8–1995.5 |
| -78.45 | 106.87 | -89.22 | 148.98 | -89 | Vostok | 1958.5–1998.5 |
| -67.67 | 45.85 | -70.20 | 89.11 | -81 | Molodezhnaya | 1967.5–1998.5 |
| -67.60 | 62.87 | -73.31 | 107.33 | -72 | Mawson | 1955.8–1997.5 |
| -68.57 | 77.97 | -76.76 | 125.15 | -73 | Davis | 1979.4–1995.5 |
| -43.25 | -65.32 | -32.43 | 5.00 | -69 | Trelew | 1957.8–1998.5 |
| -77.85 | 166.78 | -78.86 | -67.31 | -58 | Scott Base | 1957.7–1999.5 |
| -66.55 | 93.02 | -76.69 | 151.80 | -60 | Mirny | 1958.5–1998.5 |
| -66.67 | 140.02 | -74.94 | -127.98 | -33 | Dumont d'Urville | 1957.5–1998.5 |
| -31.67 | -63.88 | -20.88 | 6.59 | -55 | Pilar | 1950.5–1996.5 |
| -43.42 | 172.35 | -47.40 | -106.22 | -35 | Eyrewell | 1978.5–1999.5 |
| -74.68 | 164.12 | -77.32 | -81.07 | -44 | Terra Nova Bay | 1987.1–1997.0 |
| -35.01 | -57.69 | -24.39 | 12.06 | -47 | Las Acacias | 1961.8–1996.5 |
| -54.50 | 158.95 | -60.44 | -115.51 | -31 | Macquarie Island | 1954.5–1997.5 |
| -35.31 | 149.36 | -43.25 | -133.78 | -19 | Canberra | 1979.5–1998.5 |
| -37.53 | 145.47 | -45.92 | -137.20 | -15 | Toolangi | 1953.5–1979.2 |
| -37.83 | 77.57 | -46.85 | 143.11 | +38 | Martin de Viviès | 1981.6–1998.5 |

Geomagnetic coordinates are for the year 1993.

12°E from World Magnetic Charts of *F* for 1922, 1945 and 1955; these are shown as a diamond, plus sign and a circle respectively. A fairly steep decrease amounting to ~107 nT yr$^{-1}$ is shown by the curve. Figure 2 shows the annual mean values of *F* for the past few decades at the Antarctic locations Novolazarevskaya, Hermanus, Argentine Island, Syowa, Mawson and Dumont d'Urville. The first four stations show a declining rate in *F* greater than 100 nT yr$^{-1}$. The geographic latitudes and longitudes of these stations are given in Table I. Figure 3 shows the *F*-variation pattern at Georg Forster station making use of monthly means (from Bormann *et al.* 1995). As seen from the geographic coordinates, this station is very close to the Indian station Maitri. Figure 4 shows the total field intensity observed at Leirvogur and Narsarsuaq which are located in the Northern Hemisphere in an area with geomagnetic conjugacy to Maitri. These do not show a rapid drop in *F* value as shown by Maitri over the past few decades, suggesting thereby that this feature seems to be confined to the Southern Hemisphere. With several Antarctic stations showing such large decrease, we decided to examine *F* over the past five decades (1950–to date) for as many stations between 30°S and 90°S as we could procure. Only those stations have been considered that show a continuous decrease throughout the second half of the 20th century. However, stations that show an increase for a year or two in-between before continuing the decreasing trend have also been included to have a better coverage. The *F* data for these 23 stations are from the website (www.nmh.ac.uk/gifs/annual_means) of the British Geological Survey, and their geographic and geomagnetic coordinates, along with other relevant data are listed in Table I. Figure 5 shows star symbols at the location of each station. Contours of total field average variation are drawn for these Antarctic and sub-Antarctic locations, in both geographic and geomagnetic coordinates of reference (Fig. 5). The following points stand out:

1) The contours leave no doubt at all, that a large region of the southern hemisphere has suffered a large decrease in *F* over the past five decades.

2) The contours are better distributed and cover a wider area in the geomagnetic frame of reference (Fig. 5b) than in the geographic one (Fig. 5a). There is every chance that with the presence of more observatories most of the contours presently with loose, open ends could be closed up.

3) The maximum decrease in *F* occurs in a belt covering Argentine Island, Sanae, Maitri, Novolazarevskaya, Syowa and Hermanus. On either side the contours show falling rates of decrease.

Figures 1 & 2 had shown the rate of decrease in *F* at some of the stations lying in this belt of maximum decrease. Clearly major changes are at work within the Earth's geodynamo underneath this belt of maximum decrease in Antarctica and its surroundings.

## Discussion

It is an observed fact that over the past few centuries, the dipole moment has been dropping rapidly (Barton 1997). Gubbins

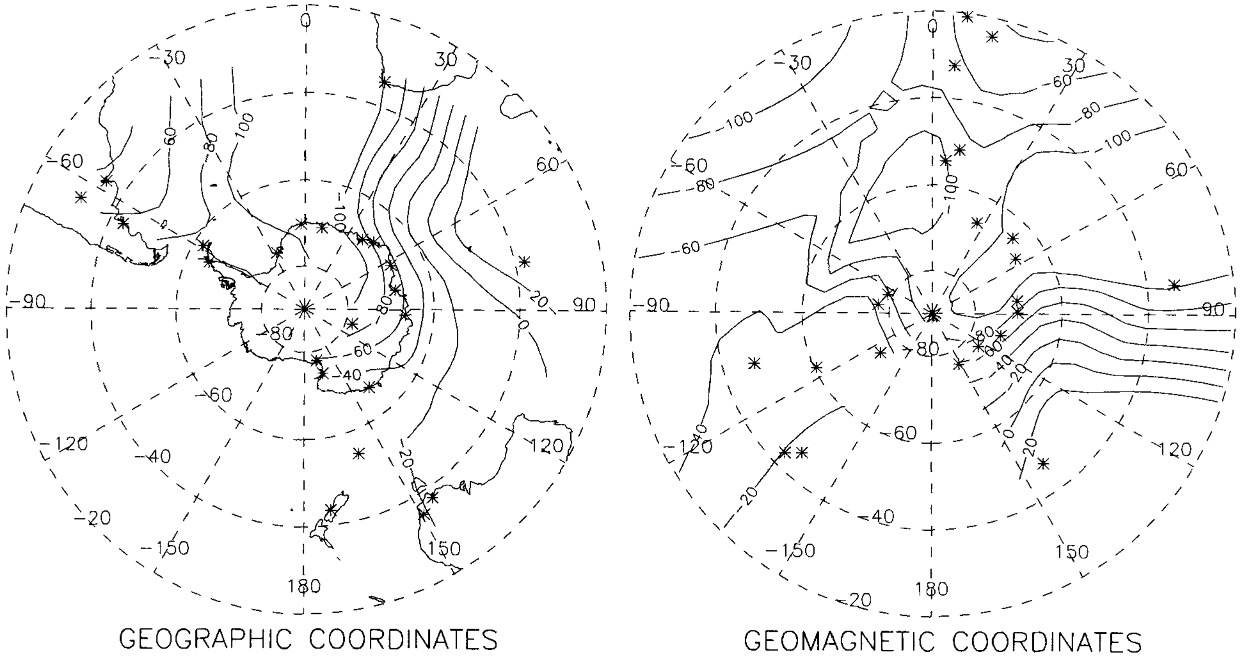


**Fig. 5.** Contours of rate of average decrease in $F$ in nT yr$^{-1}$, over the past five decades (1950–99) for Antarctic and sub-Antarctic stations between 30–90°S in geographic and geomagnetic coordinates. The locations of the stations considered are shown using star symbols. The stations and their details are listed in Table I. The contours are better distributed in geomagnetic coordinates, covering a wider area compared to their depiction in geographic coordinates.

(1987) showed the rapid drop in the Gauss coefficient $g_1^0$ observed over the past century; $g_1^0$ is proportional to the axial dipole moment $M$ by virtue of the relationship

$$M = (4\pi a^3 g_1^0)/\mu_0 \qquad (1)$$

where $a$ – radius of Earth

$\mu_0$ – permeability of free space

This drop in axial dipole moment has continued since the 16th century as shown by Barton (1989, pp 560–577). The same study also showed that the Northern Hemisphere geomagnetic pole had moved westward and southward over the past four centuries. Barton (1997) observed that the north geomagnetic pole had a clockwise precession for the first half of the 20th century which then changed to a more poleward motion. McElhinny & Senanayake (1982) analysed archaeomagnetic data going back still further in time to 10 000 BC and showed that there have been fluctuations of a sinusoidal nature in the dipole moment over the millennia. The last 2000 years have seen a drop of 3 x $10^6$T km$^3$ in dipole moment; for readers who work in problems at low latitudes this translates to a drop of ~0.12 G in the horizontal field intensity $H$ (given that $M = Ha^3$ where $a$ is the radius of the Earth). Estimated in the same manner, the 3000 years preceding this interval had seen a rise of 0.15 G in $H$.

While all these observations talk of slow secular changes in the geomagnetic state of the Earth, the changes observed over the Antarctic and sub-Antarctic regions point to a "rapid" secular change. Such regions have been referred to as "foci", and as early as 1939, Fleming (1939) pointed out the existence of a large number of such "foci" in isopores (rate of change of component with time) of the $H$, $D$ and $Z$ components mainly over continental areas with hardly any foci seen over ocean surfaces. Coe & Prévot (1989) conducted palaeomagnetic studies on Miocene volcanic sequence at Steens Mountain, Oregon, and observed large field variations of nearly 300 gammas per day. They suggested that this could imply a very rapid field variation during geomagnetic reversals. In this context, we feel that our observation of the rapid decrease in the Antarctic region assumes considerable importance.

### *Causes of secular variation*

The secular variations of the Earth's magnetic field are believed to have several causes, amongst them being

1) varying pattern of electrical diffusion within the core,

2) slippage between liquid core and mantle (which could explain westward drift),

3) temperature anomalies in the mantle, which can drive fluid flow in the core e.g. a cold spot in the mantle can cause down-welling of fluid (as in the Central Pacific); on the other hand a hot spot can cause upwelling with fluid flowing out in all directions and hence can show zero magnetic flux (e.g. near the poles of Earth),

4) expulsion of toroidal field from the Earth's liquid core into the mantle which will result in patches of intense flux

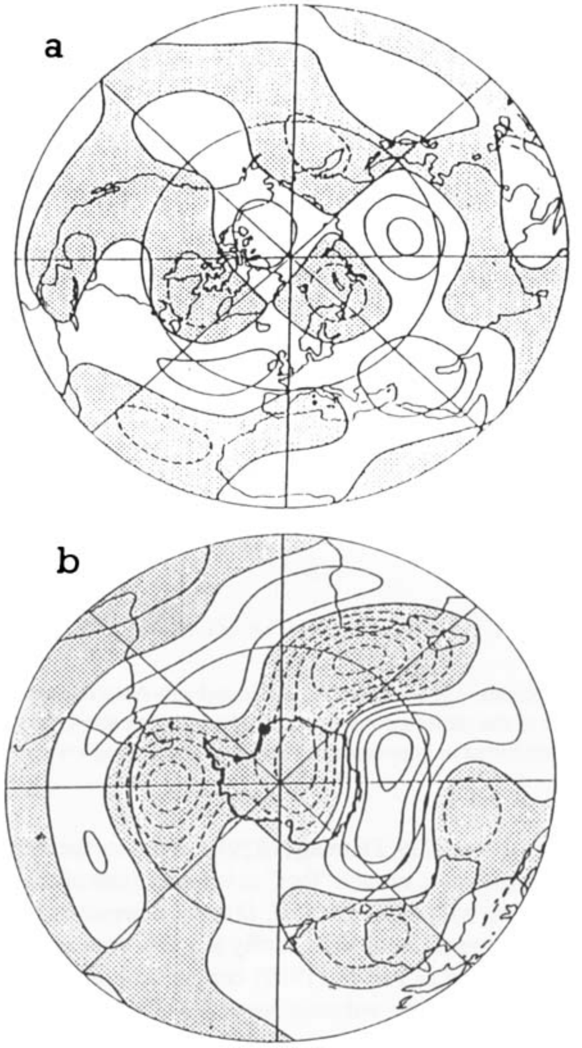


**Fig. 6.** Figures showing time rate of change of field $Z\cos\theta$ at the core–mantle boundary in the **a.** Northern Hemisphere, and **b.** Southern Hemisphere for epoch 1945 (Gubbins 1987). There is hardly any negative time variation (dotted contours) in the Northern Hemisphere while, in sharp contrast, the Southern hemisphere shows several such features.

of opposite sign (just as within a sunspot). Since the flux returns into the core, what is observed is reverse magnetic flux which reduces the Earth's dipole moment (as seen below South Africa and Antarctica),

5) electromagnetic coupling between core and mantle which can arise from variations in electrical conductivity of the mantle; this can influence the geomagnetic field as well as flow in the liquid core through the Lorentz force,

6) finally topographic irregularities (bumps) on the CMB could also influence core flow and manifest themselves as magnetic field oscillations e.g. beneath Indonesia. These bumps could arise from cooler, denser mantle material settling down in irregular patterns at the surface of the core. The same process could also give rise to topographic irregularities at the boundary between the liquid outer core, and the solid inner core.

Yet another explanation is by Yoshida & Hamano (1993) who investigated the westward drift and showed that this could be caused by forced magnetohydrodynamic waves.

*Relationship of Antarctic field decrease to the reverse flux theory of Bloxham & Gubbins*

The Gauss coefficient $g_1^0$ is related to the radial field $Z$ at the Core Mantle Boundary by an integral over the core surface thus

$$g_1^0 = [3c^3/(8\pi a^3)] \int Z \cos\theta \, ds \qquad (2)$$

where c - core radius

$a$ - Earth radius

$\theta$ - colatitude

$Z$ - vertical component of geomagnetic field

The contours shown in Fig. 6a for the Northern Hemisphere and in Fig. 6b for the Southern Hemisphere are the time rate of change of the quantity $Z\cos\theta$ at the core–mantle boundary for epoch 1945 (Gubbins 1987). Full curves show contours where the time rate of change of magnetic flux is positive while dotted contours refer to regions where the rate of change is negative. These latter contours are found to partly overlap with regions of Reverse Magnetic Flux (RMF): regions where the radial field points in a direction opposite to that expected for a dipole field. The contours of negative time variation are seen to straddle almost the whole of the Antarctic continent and large expanses of the adjoining ocean areas below South America and South Africa. The Indian Antarctic station Maitri for one, clearly lies right above such a region, where the time rate of change of flux is negative.

The contour plots of Bloxham & Gubbins (1985), of the radial field ($Z\cos\theta$) at the CMB for various epochs 1715 AD, 1777 AD, 1842 AD, 1905 AD, 1969 AD, and 1980 AD, show amongst other features of global secular variation:

a) Rapidly drifting flux spots of pronounced negative variation, which commenced at about 90°E (Indonesian region) and have drifted westwards and southwards towards 75°W over this epoch. These are the reverse flux regions described above.

b) Four static flux bundles of intense flux, the two northern ones being located below Arctic Canada and Siberia, and the two southern ones located below Antarctica. This feature differs from a dipole field which would show only two regions of intense flux, one near each pole. These four flux bundles have remained almost stationary for over 250 years (1715–1980 AD).

c) Static patches of zero flux very near the north and south magnetic poles (and in the northern Pacific region). This observation is very surprising because the patches are located just where a dipole field should normally show maximum flux.

The regions of reverse magnetic flux described above are interpreted by Bloxham & Gubbins (1985) as the expulsion of toroidal magnetic field from the core into the mantle (in a manner similar to the process generating sunspots). Instead of emerging into the crust and outer space from the mantle however, the field lines return into the core, and thereby exhibit polarity different from those which emerge. This gives rise to patches of intense flux of different polarity which can intensify and drift e.g. the reverse flux patches in the south Atlantic region and over Antarctica. Over the period 1842 AD to 1980 AD when the dipole decayed by 7%, these reverse flux patches have increased in size and in intensity. The observation suggests a direct connection between the reverse flux patches and decrease in the Earth's axial dipole moment. The work of Bloxham & Gubbins (1985) brought out the possibility that flow in the liquid core is coupled to the mantle.

Bloxham & Jackson (1992) made use of observatory, satellite and survey data to create maps of the radial magnetic field at the core–mantle boundary for different epochs from 1690–1990. Their study corroborated Gubbins's (1987) observation of the association of reverse magnetic flux features in the southern hemisphere high latitudes to the decreasing dipole moment of the Earth. Further, they showed that there is significant magnetic diffusion in the lower mantle.

### *Importance of rapid geomagnetic field changes in understanding internal Earth processes*

Modern studies reflect the thinking that rapid changes in surface magnetic field are pointers to flow motions in the deep interior of Earth. Bloxham & Jackson (1992) suggest that the westward drift is better exhibited by the declination on the Earth's surface rather than the radial field at the CMB. Dziewonski (1984) associates hotspots in the mantle with regions of low seismic velocity, and the regions of RMF discussed earlier could be associated with these. The work of Bloxham & Gubbins (1985) suggests convective cells of flow in the liquid core are coupled to the mantle, with considerable magnetic diffusion in the lower mantle.

A question arises at this point. Is it the poloidal field or the toroidal field which is contributing to this large decrease in $F$? If it is the former, similar changes should be seen at conjugate regions of Earth, and this is not the case (cf. Fig. 4 showing northern near-conjugate regions for Maitri). This point has also been made by Arun *et al.* (2000) in their analysis of the rapid fall of $F$ at Maitri. Thus it must be the toroidal field, and this supports Gubbins' (1987) argument that it is return of toroidal field lines from the mantle into the Earth's interior which reduces $F$ in the southern hemisphere.

Bloxham & Gubbins (1989) discuss an experiment in which the Earth's interior is simulated by placing a solid sphere within another sphere filled with fluid, and placing the whole into a state of rotation. It was observed that the fluid flows near the poles are weak. Combining this observation with the field patterns derived for the core surface, they infer the presence of three cylindrical vortices of rotation in the outer fluid, located 120° apart. The ends of two of these cylinders they believe, coincide with the four stable regions of maximum flux whose centres lie at the intersection of the lines 60°N, 60°S, 120°E and 120°W in their models of the field at the Earth's core–mantle boundary. The third cylindrical vortex observed in the experiment is missing in the case of the Earth. Gubbins & Bloxham (1987) believe that fluid motions in Earth's liquid core in the Atlantic region, distorted this third cylindrical vortex. Thus, the secular variations of the geomagnetic field may be used to interpret the possible configuration of fluid flow within the Earth's interior, and can even shed light on the geodynamo and its associated magnetic polarity reversals. Herein lies the importance of continuous geomagnetic observations over Antarctica.

Alternatively, conditions of reverse flux could also be created by hydrodynamic waves originating in irregular topographic features at the CMB. In fact the contours of radial field at the CMB show alternating 'highs' and 'lows' of intensity, and suggest the propagation of a wave within the liquid core. These waves would be superimposed on the main steady dynamo in the liquid core, and when they attain large amplitude, they could cause a polarity reversal as discussed by Cox (1975) in the case of a dynamo.

## Conclusions

Our contour plot of average total field variation over the past *c.* 50 years (Fig. 5) based on observations compares well with the $F$ contours of Macmillan & Barton (1997) using IGRF1995. However some points of differences exist as may be expected, between the observations and IGRF model. In our plot, the focus of 100 nT $yr^{-1}$ variation extends well into the Antarctic continent whereas the IGRF-based contour of 100 nT $yr^{-1}$ variation is wholly situated in the oceanic area. Considering the otherwise good match between the two plots and the fact that what we have considered is the average $F$ variation over the past *c.* 50 years, we may conclude that the average $F$ behaviour on timescales of 50 years are very similar to its behaviour on much shorter timescales.

In view of the large decrease in $F$ over most part of the 30–90°S region of Earth, a grid of closely spaced magnetic observatories over the regions of reverse flux is greatly desirable. Unfortunately the southern Atlantic and Indian Oceans, occupy vast areas of planet Earth where it is just not possible to set up permanent observatories, while a sizeable area lies over the Antarctic continent which is difficult for experiments because of its hostile weather and terrain. It is for this very reason that World Magnetic Charts of isointensity contours in the southern hemisphere are far from satisfactory (Cain 1987, pp 55–70). We emphasize that it is greatly desirable for observatories which are operating in Antarctica or on islands adjoining Antarctica to monitor at least *F* continuously, as a sudden change in the field intensity could signify (1) changes in fluid motion within the core, or (2) the onset of an MHD wave at the CMB. Field observations at the Indian Antarctic station Maitri thus have a special importance in view of (1) its location over the reverse flux regions and (2) the markedly large decrease in *F* observed at the station; keeping this in mind, the Indian Institute of Geomagnetism, Bombay, India, monitors *F* continuously at this location.

Since ideas on the origin of the geomagnetic field and the reasons for its secular variation are still obscure, it is not at present possible to predict accurately what the field will be after say 50–100 years. It is for this very reason that monitoring of the surface field is so important, markedly in regions which show large secular variation. There is nothing so valuable as a closely-spaced (at least 1500 km distance apart if not less) (Cain 1987, pp 55–70) grid of regularly measured values of magnetic field on the surface of the Earth to aid understanding of the internal geodynamo and its changes with time.

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