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The changing magnetic field of the Southern African sub-continent: a unique behaviour

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One of the most fascinating geophysical studies in southern Africa is to track the evolutionary behaviour of the geomagnetic field. As part of a cooperative project between Germany and South Africa, called Inkaba ye Africa, the COMPASS (Comprehensive Magnetic Processes under the African Southern Sub-continent) program aims to study the geomagnetic field in this key region. Observations are supported by global monitoring of the magnetic field from satellites like Ørsted, CHAMP and SAC-C in order to better explain and predict the secular variation on a global scale. Comparisons between MAGSAT (1980) and CHAMP (2000 till present) satellite data indicate that the relative decrease of the geomagnetic field is particularly strong in the Southern Atlantic region. This coincides partly with the South Atlantic Anomaly, where the geomagnetic field is significantly weaker (up to 30%) than over the rest of the Earth at equivalent latitudes. It is in this region that the shielding effect of the magnetic field is severely reduced, thus allowing high energy particles of extraterrestrial origin to penetrate deep into the upper atmosphere, reaching altitudes below 100 km. In addition, the orientation of the geomagnetic field in southern Africa is also changing rapidly. In the northwestern part of southern Africa the declination of the magnetic field is propagating eastwards (Tsumeb) and in the southeastern part westwards (Hermanus and Hartebeesthoek). This results in the spatial gradient over the sub-continent to increase with time. This intriguing and complex behaviour of the geomagnetic field over the southern African sub-continent is discussed in the present investigation.

Introduction

In order to better understand the mechanisms underlying the generation of the Earth's magnetic field, it is desirable to have as long a record as possible of the evolution of the field. On the one hand, palaeomagnetism provides valuable low-resolution information about the field over time-scales of thousands of years to hundreds of millennia, whereas direct measurements of the field can reveal much higher spatial resolution, albeit restricted to the last few hundred years. In some places, such as Paris, London and Rome, the evolution of declination (the angle between the geographic and magnetic north directions) and inclination (the angle of the magnetic field with respect of the horizontal direction) of the magnetic field have been measured over many centuries (Alexandrescu *et al*., 1996, Mandea, 2000). During the nineteenth century measurements of the intensity of the field were started, and the first magnetic observatory, recording three field components, was built by Carl Friedrich Gauss in Göttingen (1832). Nowadays some 150 observatories are operated around the world. Gauss also provided us with the necessary mathematical tools to separate the magnetic field sources into internal (from the Earth's core and lithosphere) and external ones (from the ionosphere and magnetosphere).

The magnetic field, produced in the core by a self-consistent dynamo mechanism and also known as the "main field", has a magnitude of approximately 60000nT in the polar regions, and decreases to values less than 20000nT in the South Atlantic Anomaly region. This internal part of the field is varying slowly in time, with a time-constant that can vary between several decades to a century. This variation is known as "secular variation". The shortest periods of internal origin are found in the so-called "secular variation impulses" or "geomagnetic jerks", expressed in the field component as two second degree polynomials of time, with a sudden change in curvature at the time of the event; the corresponding secular variation (the first time derivative of the geomagnetic field) is a V-shaped graph, the second time derivative is step-like, and the third time derivative is a Dirac distribution. The lithospheric field, on the other hand, having its origin in the crust and upper mantle, is considered constant with time. External field contributions, however, can vary on time scales from seconds to decades, with variations ranging from several nT to thousands of nT during large magnetic storms. More details on magnetic field contributions are to be found in Mandea and Purucker (2005).

The temporal evolution of the geomagnetic field, as monitored by geomagnetic observatories, provides several opportunities for practical applications, ranging from upgrading declination maps for navigation purposes, to the evaluation of disturbance periods, which has consequences for satellite operations as well as electric power transmission lines. The global distribution of these observatories is extremely non-uniform, with a good coverage in some continental areas (Europe, Northern America), but only a fair distribution in other regions (Africa, Southern America or Siberia), and the oceanic zones (Figure 1).

A global coverage of magnetic field measurements was for the first time made possible with the launch of the MAGSAT satellite in 1979 (Langel *et al*., 1998), revealing the hitherto unexplored potential of space magnetometry in understanding the origin and dynamics of the geomagnetic field. MAGSAT mapped this field from its largest (dipolar) scale down to a 1000 km scale, and in the process revealed that the geomagnetic field is composed of predominantly two components with different characteristics. Unfortunately, no other MAGSAT-type mission was possible during the following 20 years. However, in February 1999, the Danish Ørsted satellite was launched, soon followed by the German

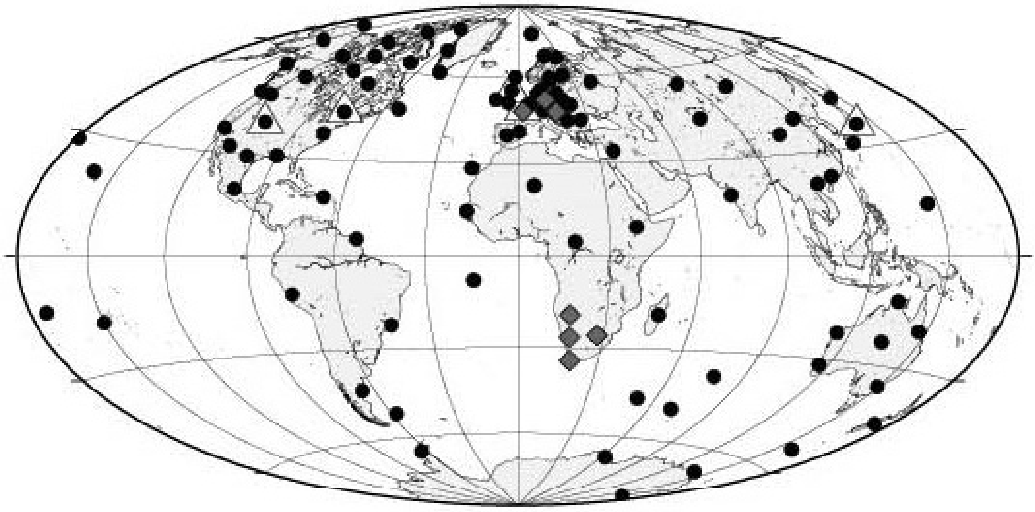


Figure 1: Map of location of the INTERMAGNET observatories (full black circles), with those situated on the Southern African continent and Europe, which are used in the present study shown as dark grey diamonds. The GINs are also represented (white triangles).

CHAMP mission (July 2000), and the Argentinean SAC-C mission (November 2000), which was only capable to produce scalar data (details on magnetic satellite missions are to be found in Mandea and Purucker, 2005).This series of low-Earth orbit satellite missions initiated an area of continuous monitoring of the planetary field from space which, it is hoped, could continue until the end of the decade, as recommended by IUGG (International Decade of Geopotential Research), with the multi-satellite ESA Swarm mission (Friis-Christensen *et al*., 2006), scheduled for 2010.

This paper aims to demonstrate the importance of measuring the Earth's magnetic field, both from ground and satellite platforms, focussing on the Southern African Continent. Some recent results in modelling and interpreting the magnetic field in this specific area are also presented.

Magnetic field observations over southern Africa

Ground-based measurements

The magnetic field information over the southern African sub-continent is obtained on a continuous basis at four geomagnetic observatories (Figure 1 and Table 1). In addition to these permanent observatories operating on a continuous basis, several repeat stations (a maximum of 70 are available) are used at regular intervals, ranging from 1 to 5 years (Figure 2), to obtain information on the time variation of the geomagnetic field in this region.

Magnetic observatories

In magnetic observatories the vector representing the Earth's field is described in two ways: (1) three orthogonal component field directions with positive values for geographic northward (X), eastward (Y) and vertical into the Earth (Z) (typically called XYZ-components) or (2) the horizontal magnitude (H), the eastward (minus sign for westward) angular direction (D) and the downward vertical component (typically called HDZ-components).

INTERMAGNET standards (www.intermagnet.org) are practised at all magnetic observatories, with Hermanus, Hartebeesthoek and Tsumeb classified as INTERMAGNET observatories. One-minute values for HDZ components are recorded together with total field strength (F). Moreover, once a week absolute measurements ensure a continuous baseline control. Hermanus started to operate on 1 January 1941, followed by Tsumeb in 1964 on the premises of a research station of the Max-Planck Institute for Aeronomy in Namibia, while Hartebeesthoek was established in 1973 on the premises of a satellite tracking station.

Table 1: Coordinates of geomagnetic observatories operated on the Southern African sub-continent

Observatory	Year	Code	Geographic Coordinates		Geomagnetic Coordinates	
			Latitude	Longitude	Latitude	Longitude
Hermanus	1941	HER	34.42 S	19.23 E	-42.60	82.91
Hartebeesthoek	1973	HBK	25.88 S	27.70 E	-36.29	95.36
Keetmanshoop	2005	KMH	26.53 S	18.10 E	-35.68	85.53
Tsumeb	1964	TSU	19.20 S	17.58 E	-31.07	86.86

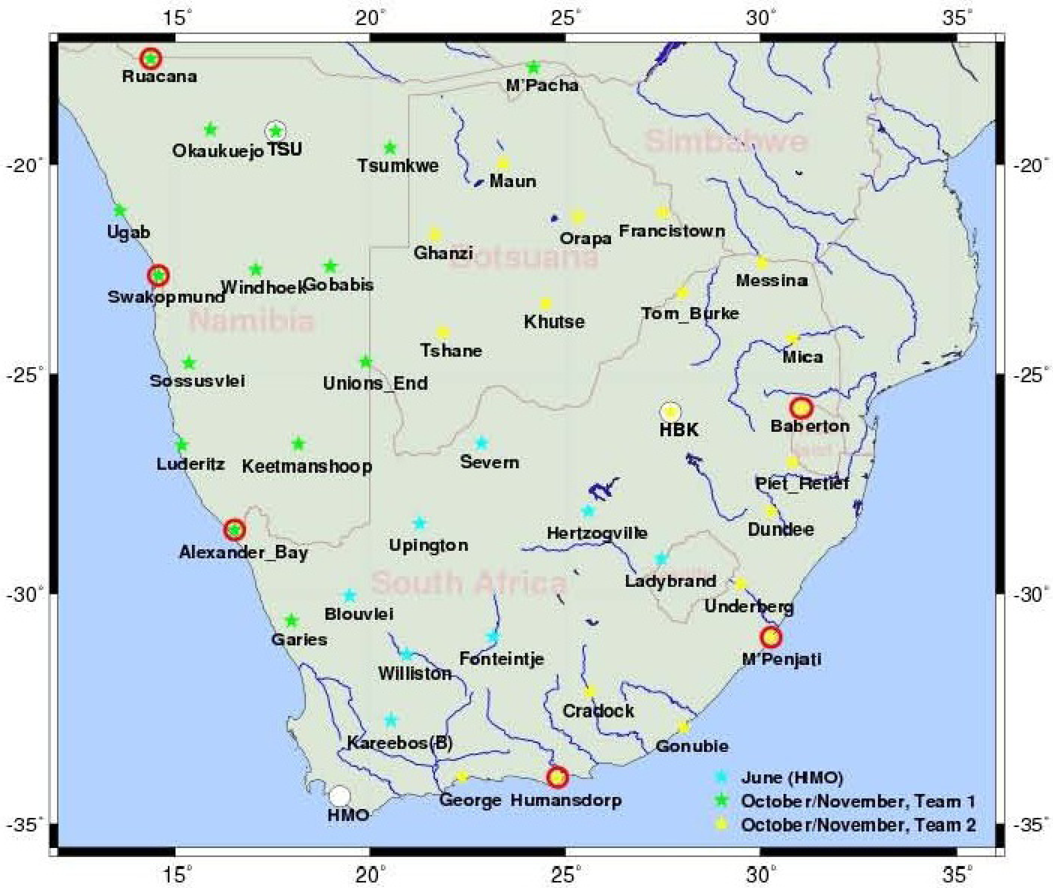


Figure 2. Map of distribution of repeat stations over the Southern African region.

The Keetmanshoop observatory was installed in 2005 on the premises of the Keetmanshoop Airport (Linthe *et al*., 2007) as part of a collaboration project between Hermanus Magnetic Observatory (HMO) and GeoForschungsZentrum Potsdam, Germany (GFZ). This location was specifically chosen about halfway between Hermanus in the south and Tsumeb in the north in order to correct for disturbance effects from external sources and to refer the repeat station data to a common epoch during field surveys. This newly established INTERMAGNET-grade observatory will play a key role in the region, as a reference magnetic observatory for field stations within a radius of 600 km. It is located in the large area between the Northern Cape and southern Namibia, a region which has not been adequately covered in the past, and will provide an accurate monitor of spatial changes in secular variation across southern Africa. At present the declination secular variations at the southeastern and northwestern borders of southern Africa are 11 arc min/yr westwards and 6 arc min/yr eastwards, respectively (see below). The Keetmanshoop observatory, located between HER and TSU in a north-south direction, as well as in an east-west direction on approximately the same magnetic latitude as Hartebeesthoek, will help to accurately monitor the spatial change of secular variation across southern Africa.

Magnetic repeat stations

An extensive network of repeat stations has been established over southern Africa within countries such as Namibia, Botswana, Zimbabwe and South Africa, since 1947. Until 2000, these field stations were visited at regular 5 year intervals, but as the magnetic field over southern Africa started to display a pattern of rapid changes, it became important to conduct field surveys at shorter intervals. It was therefore decided to visit 10 selected repeat stations at annual intervals for 2003 and 2004. The experience gained from these surveys has shown that the limited number of stations over the Southern African region is insufficient to accurately model the secular variation, due to the increasing temporal and spatial gradients. A better spatial resolution, however, demanded an increase in the density of the repeat stations. In 2005 a total of 40 stations were selected for a survey campaign. At 34 stations it was possible to obtain good quality results.

The repeat station measurements during this field survey included the on-site recording of the magnetic field intensity, conforming to international quality standards (Korte *et al*., 2007). The 2005 campaign has revealed that at some stations measurements were very difficult to obtain, either because the environment is no longer magnetically quiet, or because the station had been destroyed for urban expansion projects. The stations where problems were encountered are indicated by red circles in Figure 1. In spite of these challenging conditions, some interesting results have been obtained (see below).

Space-based observations

At present the geomagnetic field is monitored from space by a fleet of dedicated satellites, like Ørsted (launched in 1999), CHAMP (Reigber *et al*., 2005) and SAC-C (both launched in 2000). Global models of the magnetic field based on these measurements have been derived with an unprecedented accuracy (Maus *et al*., 2006). The secular variation over the last few years, when satellite data have been available, has recently been computed at higher degrees than was previously possible, when modelling the main field as shown by the CHAOS model (Olsen *et al*., 2006). The short lifetime of these magnetic satellite missions makes it difficult to obtain secular variation results at decadal or even longer scales; however, Olsen, *et al*. (2007) proved that secular variation impulses can be detected using satellite data.

Modelling the Earth's magnetic field over the Southern African region

Over the past few years since 2000, satellite data have been used extensively to model the main field over southern Africa, especially to obtain information over areas not accessible by ground survey teams, such as the surrounding ocean areas. Models derived in this way proved to be superior in resolution as well as accuracy to global field models when compared with ground observations (Kotzé, 2001). On the other hand, however, ground magnetic field measurements have been exclusively used to derive secular variation models for southern Africa. The field survey conducted in 2005 enabled polynomial-based secular variation models to be developed, which are superior to the global IGRF 10 model (Kotzé *et al*., 2007). The models derived were based on 3rd degree polynomials as a function of latitude and longitude, with 10 statistically significant coefficients for each magnetic field component modelled:

$$SV = A + BX^3 + CYX^2 + DXY^2 + EY^3 + FX^2 + GXY + HY^2 + IX + JY$$

Where:
X=26˚ - latitude
Y=24˚ - longitude
SV=secular variation component (F, H, D, Z)
A-J=coefficients derived from field survey data using least squares fit

In some cases the improvement obtained is more than 50% for certain components. This underlined the fact that ground magnetic field observations over a vast region such as southern Africa are the preferred way if accuracy is of paramount importance.

Since secular variation is not measured directly, but is derived as a time derivative of the geomagnetic field, one can either model the main field and then differentiate the corresponding field model to get a secular variation model; or alternatively one can numerically differentiate the main field data and then fit a secular variation model directly. The latter derivative-fit approach is able to remove crustal contamination and has been applied in this study of observatory and repeat station data. First central differences from annual mean observatory data as well as repeat stations, divided by their respective time intervals in years, were used as input data to our secular variation model. As observatory data are in general more accurate than repeat survey data due to better baseline control and because seasonal and other short-term variations are more effectively removed by using annual means, we introduced weighing factors for both observatory and repeat station secular variation data in a ratio 1:0.7 in the least-squares solution. This ratio was determined by minimizing the RMS difference between model fits and survey data. There were 96 vector differences from 32 repeat stations and 9 vector differences from the 3 observatories, providing a total of 105 data values for the present time interval. A secular variation model for the period 2005.5 till 2007 was subsequently derived. The least-squares routine used to fit the data was the stepwise regression procedure described by Efroymson (1960), which has the ability of both entering and removing variables at given levels of statistical significance. The scatter about the fit for declination secular variation was less than 1 min/y.

Results obtained by modelling the declination observations, as obtained during the 2005 field survey of southern Africa, can be seen in Fig. 3. A second degree polynomial was used to model both the declination as well as the secular variation data. This revealed a steep gradient in declination over southern Africa, ranging from almost 26 degrees west of true north in the southern parts to almost 8 degrees west of true north in the northern region of the sub-continent. On the other hand the secular variation pattern for declination is dominated by a westward variation in the southeast, in contrast to an eastward variation in the northwest of the southern African sub-continent. As a result the gradient in declination over this part of Africa is continuously growing with time.

The complexity of the magnetic field over the southern African area

At the Earth's surface

Since the first magnetic field measurements started

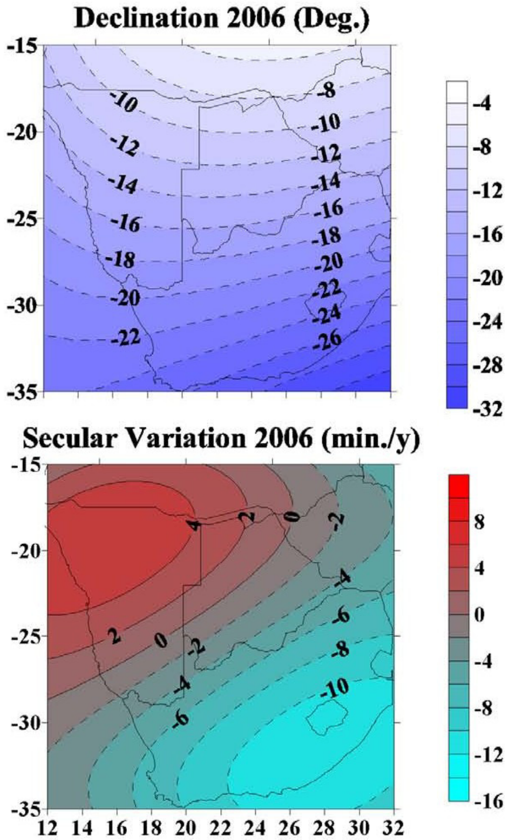


Figure 3. Contour plots showing the declination pattern for southern Africa, as well as the corresponding secular variation as determined from a field survey in 2005.

in the nineteenth century, a continuous decrease of the Earth's magnetic dipole moment has been observed. The change in the field strength is, however, not evenly distributed over the globe. At the Earth's surface the most rapid decrease of the core field is observed in the Southern Atlantic region. Southern Africa is in this regard the continental area where these geomagnetic field changes can be best studied. Since the establishment of the Hermanus Magnetic Observatory in South Africa in 1941, the total field intensity has decreased by more than 20%, which is greater than decreases observed at any other magnetic observatory.

In order to show how much the magnetic field changes over spatial scales comparable to the southern African continent, a comparison with three European observatories have been made. This comparison is based on three field components in order to reveal variations of the complete field vector. The secular variation for the X, Y, Z components by the three southern African observatories (Hermanus - HER, Hartebeesthoek - HBK, Tsumeb - TSU) and three European observatories (Chambon la Foret - CLF, Niemegk - NGK, Surlari - SUA), located at comparable distances of separation are shown in Figure 4. At the southern African observatories, though all the curves show a declining trend, neither the rate of change nor its temporal variation is identical at the three sites. It can therefore be concluded that significant gradients exist across the sub-continent, which are smaller in scale than the separation of the recording sites. In contrast, the European observatories exhibit trends, as well as rates of change in comparable proportion to each other.

In addition, the orientation of the geomagnetic field in southern Africa is also changing at a rapid rate. In the northwestern part of southern Africa the declination of the magnetic field is propagating eastwards (Tsumeb) and in the southeastern part westwards (Hermanus and Hartebeesthoek), as shown in Figure 5. This indicates a spatial gradient over the sub-continent that is presently increasing with time. In sharp contrast, the declination of the magnetic field is comparable for all European observatories. This underlines the complexity of field behaviour in southern Africa and stresses the importance to further investigate the temporal and spatial structure of the rapid field decrease below southern Africa. A greater density of observation positions is required in order to resolve the structure of the field orientation and its evolution over the southern African area. This can be achieved using low Earth orbit satellite measurements, which most definitively need to be supported by ground-based measurements.

At the Core Mantle Boundary (CMB)

Observations of the long-term geomagnetic field changes are one of the few means to estimate the material flows at the top of the core (Hulot *et al*., 2002). In particular, the radial field component and its temporal variation are of interest for this purpose. Recent studies have identified distinct patches of reversed magnetic flux at the poles and below Africa, which can account for about 90% of the present day field decrease (Gubbins *et al*., 2006). The most prominent feature in this respect is the growing patch of reverse magnetic polarity beneath South Africa. To give an indication of recent changes, Figure 6 shows the distribution and evolution of the radial magnetic field component at the core/mantle boundary during the past century. The model used here (Jackson *et al*., 2000) shows a region of reversed field direction (red area), which propagates northwestwards. At present this patch is just below South Africa. Moreover, it has been shown recently (Dormy and Mandea, 2005) that patches of intense secular variation appear in the South Atlantic area, with a very rapid displacement in a southeast – northwest direction. A close monitoring of the magnetic field changes in the southern part of Africa will provide us with an opportunity to track this patch and record its evolution. An objective in this regard is to use dedicated measurements for constructing detailed models of the core flow in this region, which seems to play a key role in the presently observed magnetic field decline.

Conclusions

The rather dynamic variation of the magnetic field in the southern African region requires investigation by a denser array of suitable ground-based observations. This region with its rapidly changing internal magnetic field is ideally suited to test the idea that rapid secular variations can induce currents in highly conductive lateral structures in the lithosphere or upper mantle. The magnetic signature caused by these confined currents is expected to change at the rate of the secular variation and not of the field itself. From the results obtained in such an investigation, it will be possible to determine whether similar studies in other parts of the world can produce convincing results.

More interestingly, the growth and spatial changes of patches of the reverse flux under the South African region, from 1840 onwards, can be responsible for changes in dipole moment, represented by changes in Z cos θ (where θ is the co-latitude). Recently, Gubbins *et al*. (2006) showed that by separating contributions of the two hemispheres in the change of axial dipole (g_1^0), most of the dipole decay has come from the southern hemisphere. Recent satellite-based models (such as CHAOS) also show that the reverse flux patches under the African region continue with a similar displacement. These reverse flux patches are likely to be linked to the expulsion of toroidal flux, which during the last decades seems to be in an active period of expulsion through the core surface.

The challenge now is to continue gathering data from both ground stations and satellites, and to perform joint analyses of these ground-based and space-borne data. This is an important step, as both platforms provide

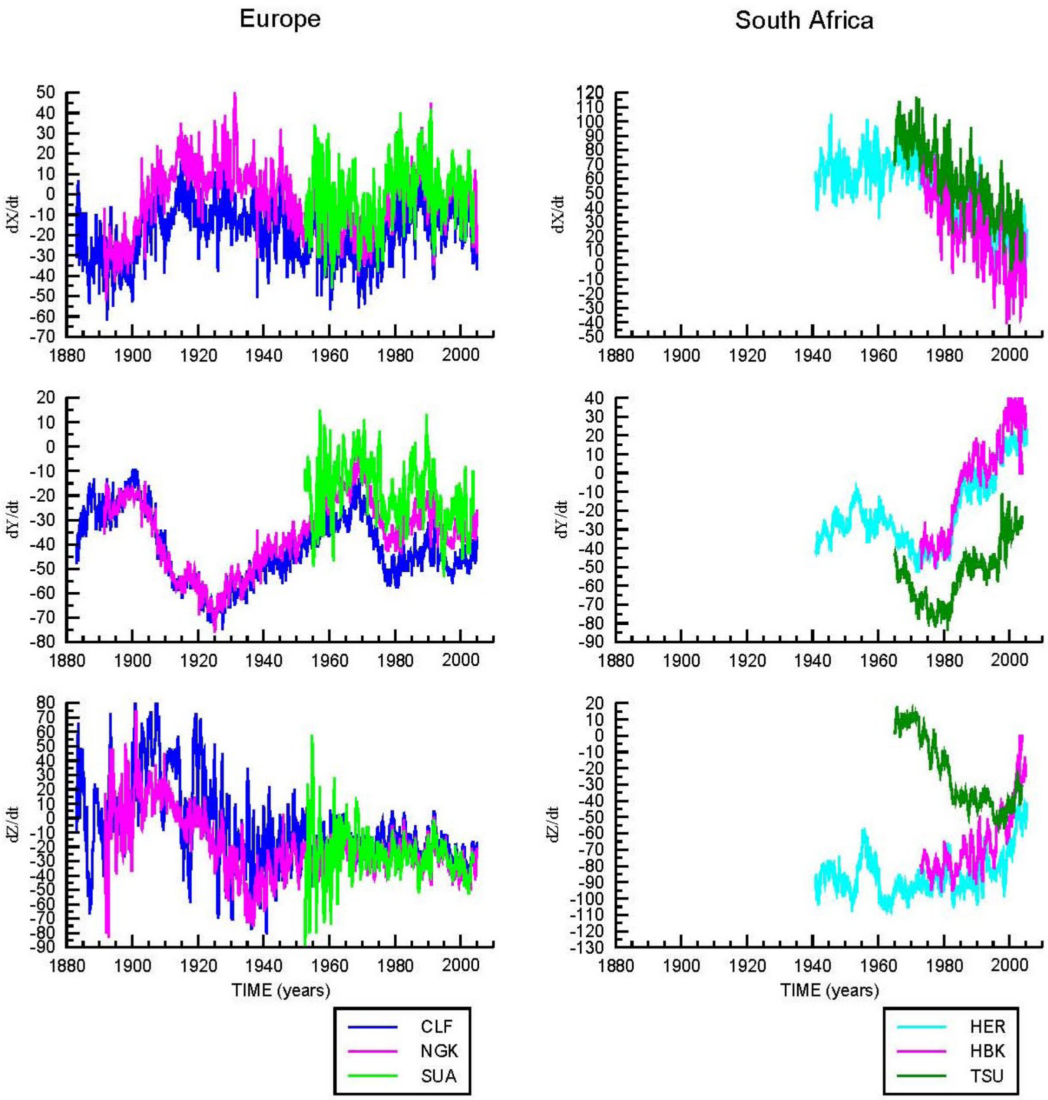
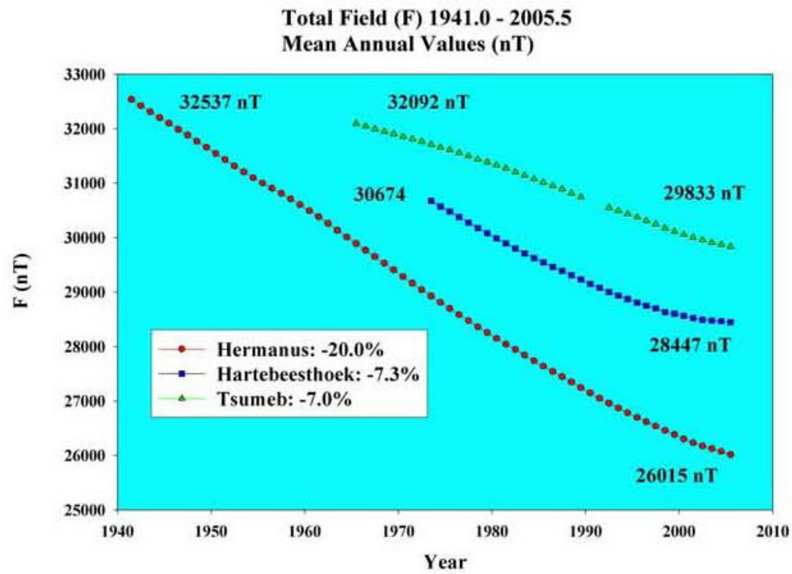


Figure 4: Secular variation for the X, Y, Z components at Hermanus, Hartebeesthoek, and Tsumeb (left side), and Chambon-la-Foret, Niemegk and Surlari (right side).



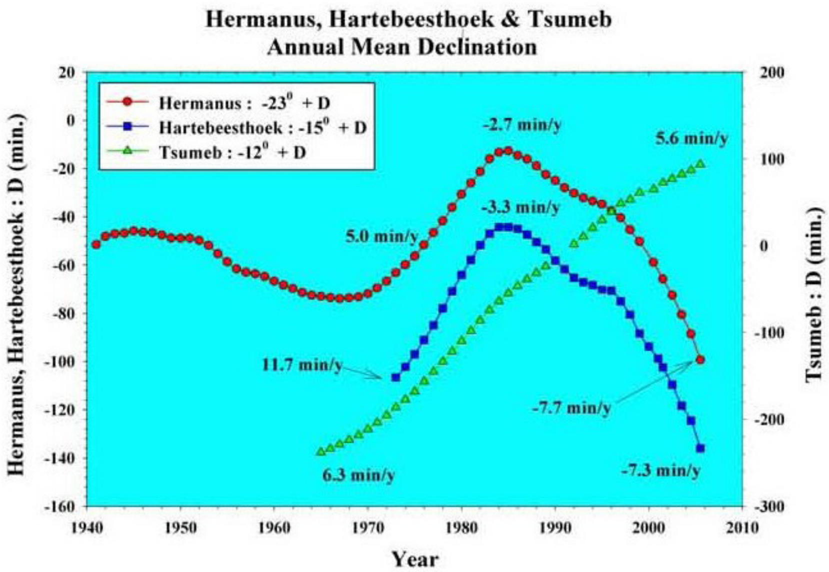


Figure 5: Total field intensity and declination variations at Hermanus, Hartebeesthoek, and Tsumeb observatories. No clear change in direction for Tsumeb data appears after the geomagnetic jerk in 1983.

data with different distributions in space and in time. These measurements will not only provide valuable information on the geomagnetic field in southern Africa, but will also have practical applications in many different areas, such as resource exploration, space weather, radiation hazards, and navigation, all of which are important to the southern African sub-continent.

Acknowledgements

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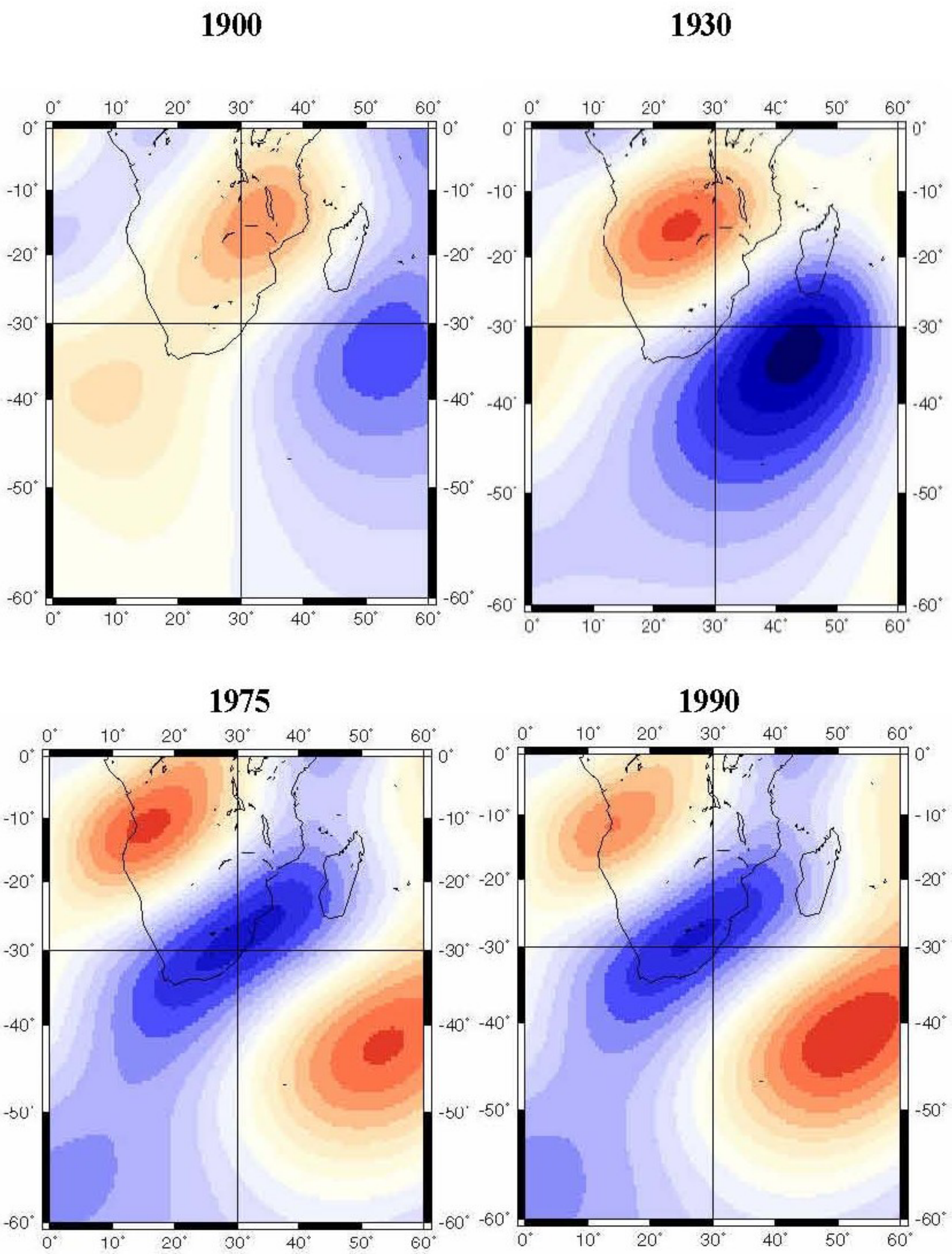

Figure 6: Secular variation of the radial magnetic field component at the core/mantle boundary for the periods 1900, 1930 (top) and 1975 and 1990 (bottom) using the model of Jackson et al. (2000). Blue colour marks areas with diminishing field intensity. Extreme values are ±13 μT/a.

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