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Southern African geomagnetic secular variation from 2005 to 2009

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Abstract

The southern African region is in close proximity to the South Atlantic Anomaly, a region between Africa and South America where the geomagnetic field is significantly weaker than at other comparable latitudes and is decreasing strongly. Between 2005 and 2009 very dense annual magnetic repeat station surveys were conducted in southern Africa within the framework of COMPASS (Comprehensive Magnetic Processes under the African Southern Sub-continent). This project aims at studying the regional geomagnetic field and particularly its evolutionary behaviour as part of the Inkaba yeAfrica cooperative project between Germany and South-Africa. We have modelled the magnetic field and its secular variation by means of two different techniques, one based on surface polynomials, the other on harmonic splines. Both approaches succeed in describing the characteristic time variations of the magnetic field components in this area. The rapid changes observed in the declination and vertical component during the period of investigation and revealed by the modelling results are of particular interest. Secular variation changes observed in the time-series of the Hermanus and the recently established Keetmanshoop magnetic observatories reveal the occurrence of a geomagnetic jerk in 2007.

1. Introduction

The geomagnetic main field originating in the Earth's outer core varies on a broad range of time scales while showing strong regional characteristics. Rapid field fluctuations and so-called geomagnetic jerks or secular variation impulses occur (Mandea and Olsen, 2009) on the short period end of the spectrum of one year or even less. On geological time scales of hundred-thousands to millions of years complete polarity reversals of the geomagnetic field take place at irregular time intervals. In general the secular variation of the core field is assumed chaotic and not predictable.

The southern African and south Atlantic regions have shown a particularly striking geomagnetic field behaviour over the last decades (Bloxham and Gubbins, 1985, Mandea et al., 2007). Between 1980 and 2010 the field intensity in this region decreased by up to 10%, much faster than the global dipole moment decrease which amounts to 2% over the same period. Moreover, lying at the border of a field region known as South Atlantic Anomaly (Dessler, 1959), the magnetic field strength is already significantly weaker (up to 30%) there than at comparable latitudes. The magnetic shielding against solar wind and galactic cosmic rays is significantly weakened in this area, endangering modern technology, particularly satellites in near Earth orbits, during solar storms (Heirtzler, 2002).

Modern global field modelling revealed that a growing patch of reverse magnetic flux at the core-mantle boundary is responsible for the South Atlantic Anomaly and probably also plays a significant role in the global dipole moment decay (Gubbins and Bloxham, 1985, Jackson et al., 2000, Olson and Amit, 2006). Regional field gradients at the Earth's surface are strong in this region, but the density of geomagnetic observatories which continuously monitor the field change is sparse (Mandea et al., 2007). Despite the availability of satellite magnetic field data over the recent decade, global models like GRIMM2 (Lesur et al. 2010) or CHAOS-2 (Olsen et al., 2009) cannot accurately describe all small scale and rapidly varying geomagnetic field structures, particularly in the southern African region (Geese et al., 2010). A suitable regional description is therefore essential to understand the underlying processes creating the observed remarkable magnetic field variations.

COMPASS (COmprehensive Magnetic Processes under the African Southern Sub-continent), a sub-project of the Inkaba yeAfrica project (www.inkaba.org), aims at a better understanding of the regional geomagnetic field behaviour. This task is assessed through continued improved observations at the southern African repeat station network (Korte et al., 2007), the establishment of an additional observatory in Keetmanshoop, Namibia, in 2005 (Linthe et al., 2007, Korte et al., 2009) and improved regional field modelling (Kotzé et al., 2007, Geese et al., 2010).

In this paper we present and compare the results of two different regional modelling approaches, namely by polynomials and harmonic splines. Section 2 provides an overview of the new repeat station data collected from 2005 to 2009 and the available observatory data used in this work. In section 3, the two modelling techniques are outlined, before a comparative evaluation is carried out in section 4, which includes a global field model for reference. Following the discussion of observed magnetic field features and model differences we conclude with an outlook at planned future work.

2.Data and field surveys

The collaboration within the Inkaba yeAfrica project between Hermanus Magnetic Observatory (HMO) and the Helmholtz-Centre Potsdam, GFZ German Research Centre for Geosciences has created the opportunity to carry out geomagnetic repeat station surveys in South Africa, Namibia and Botswana with good spatial and improved temporal distribution since 2005. Measurements of magnetic declination, inclination and intensity have been carried out annually at nearly 40 locations (Fig. 1 and Table 1) during this period.

Any geomagnetic measurement contains contributions from the core, magnetised rocks in the lithosphere and electrical current systems in the Earth's ionosphere and magnetosphere. However, in this study we are primarily interested in the core field contribution. The lithospheric field contribution is generally assumed to be static as magnetisation induced by the main field in geological structures can vary only slowly and weakly and remanent magnetisation can generally be safely assumed not to change with time on the time scale we consider here. The fast varying external field contributions and their counterparts induced in the ground, however, pose a problem for secular variation studies and have to be eliminated by suitable survey practices and data processing techniques (cf. Newitt et al., 1996). The procedures followed in order to achieve this goal have been described in detail by Korte et al. (2007) and are summarized briefly as follows.

In general, eight sets of absolute measurements are taken at every station, four in the evening and four in the early morning hours. Declination and inclination are determined by means of a non-magnetic Zeiss theodolite equipped with a one-component fluxgate sensor (DI-flux theodolite). Intensity is simultaneously recorded in 5 second time intervals with a GSM19 proton magnetometer by GEM Systems (www.gemsys.co.ca). A three-component fluxgate variometer type LEMI 008 is set up in a distance of a few 100 m to a few km from the absolute station for proper elimination of short term external fields. This instrument is continuously recording vector field variations starting a few hours before the first set of absolute measurements in the evening, through the night and until the end of the last set of observations in the morning.

The data reduction to quiet internal field values according to the standard procedures described e.g. by Newitt et al. (1996) is done in two steps. First the measured values are reduced to the quiet night time level by means of the local variometer recording. For quiet up to moderately disturbed magnetic conditions the average of several night time hours represents the quiet internal field reasonably well (Korte et al., 2007). In order to obtain data for a common time, the quiet night time values then are further reduced to annual means utilizing the recordings of the nearest observatory and taking into account estimates of linear secular variation differences following Newitt et al. (1996).

A detailed discussion of data uncertainties was presented by Korte et al. (2007). A good estimate of uncertainties is obtained from the scatter among the eight individual results at one station and any observed systematic differences between evening and morning observations, giving estimates of about ±3nT in H and Z and up to 1 min in D. The favourable magnetically quiet conditions experienced during the last years due to the unusually long solar minimum should lead to uncertainties of the reduced data only slightly larger than those of observatory annual means.

In addition to the new repeat station data, annual and monthly means of the available observatory recordings have been included respectively in the two modelling approaches discussed below. Three INTERMAGNET observatories (www.intermagnet.org) with longer time-series provide data for the time interval of interest from 2005 to 2009. These are Hermanus (HMO) and Hartebeesthoek (HBK) in South Africa and Tsumeb (TSU) in Nabmibia (see Fig. 1). An additional geomagnetic observatory was installed in the frame of the Inkaba yeAfrica project in Keetmanshoop (KMH), Namibia, in 2005 (Linthe et al., 2007). KMH data have been available from mid-2006 to 2009. The observatory also became an INTERMAGNET observatory in 2008.

3. **Methods**

The aim of any regional modelling approach is to determine magnetic field component values between data positions as well as during the intervals separating different surveys. Differences exist between methods that describe individual components separately and methods modelling the full vector field at once. In the first case, commonly used components of interest are the angle of declination (D), which is the angle between geographic and magnetic north and is of interest also for navigational purposes, and horizontal (H) and vertical (Z) field intensity with respect to the surface of the Earth. In the second case, the input data usually are the cartesian components X (north), Y (east) and Z (vertical), but predictions for any other component can easily be obtained from the vector field model. Beside the two regional modelling techniques that were used in this study, several traditional and newly developed methods exist that are reviewed e.g. by *Haines* (1990) and *Schott and Thébault* (2011). We chose polynomial modeling as an easy to use traditional method for individual components and harmonic splines as one recently implemented method that allows to take the full vector field into account.

3.1 **Polynomial modelling**

Historically, polynomial models are among the most frequently used empirical models for curve fitting and to determine the parameters that have a profound effect on a particular response function. This type of modelling is popular as polynomial models have a simple form, have well known and understood properties, have moderate flexibility of shapes, and they are computationally easy to use. However, polynomial models also have limitations such as weak interpolatory and extrapolatory properties. Polynomials may provide good fits within the range of data, but they will frequently deteriorate rapidly outside the range of the data. In geomagnetism polynomials have been applied with great success to derive regional models of secular variation (*Shu et.al.,* 1996).

Polynomials have been used extensively to model ground magnetic field measurements to derive secular variation models for southern Africa (*Kotzé*, 2003). The field surveys conducted since 2005 enabled polynomial-based secular variation models to be derived. We selected a two-dimensional polynomial presentation (*Xu et al.*, 1992):

$$\frac{dB}{dt}(\lambda,\varphi)=\sum_{n=0}^{N}\sum_{m=0}^{M} a_{n,m}(\lambda-\bar{\lambda})^{n}(\varphi-\bar{\varphi})^{m}$$

Where dB/dt is the magnitude of secular variation for each component of the geomagnetic field at the point with geographic latitude λ and longitude φ, $a_{n,m}$ is a numerical coefficient, and $\bar{\lambda}$ and $\bar{\varphi}$ are the coordinates of the centre of the modelled area: $\bar{\lambda}$ = 26°S and $\bar{\varphi}$ = 24°E.

Since secular variation is not measured directly, but is derived as a time derivative of the geomagnetic field, one can model the main field and then differentiate the corresponding field model to get a secular variation model, or 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 which is a significant source of uncertainty in determining a main field model (*Cain et al.,* 1965, *Dawson and Newitt,* 1978) and has been applied here. First central differences from annual mean observatory as well as repeat stations data, divided by their respective time intervals in years, are used as input data to our secular variation model. As observatory data, in general, are more accurate than repeat survey data (because of better baseline control and because seasonal and other short-term variations are more effectively removed by using annual means) we weighted 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. The maximum number of vector differences for each epoch was 120 from 40 repeat stations, varying due to missing data from some stations, and additionally 9 vector differences from the 3 observatories. Secular variation models for the periods 2005.5-2006.5, 2006.5-2007.5, 2007.5-2008.5, and 2008.5-2009.5 were subsequently derived by quadratic polynomial fits (N=M=2), which corresponds to a minimum resolvable wavelength of 5000 km for our area of 2500 by 2500 km. The least-squares routine used to fit the data is the stepwise regression procedure described by *Efroymson (*1960) that has the ability of both entering and removing variables at given levels of statistical significance. The scatter about the fit for declination secular variation is less than 1 min/y and in the order of 3 to 4 nT/yr for the X,Y and Z components.

Main field models based on polynomials were also derived for epochs 2005.5, 2006.5, 2007.5, 2008.5 and 2009.5. The crustal biases of all stations found as residuals between data and polynomial main field models show excellent agreement within 5% of those co-estimated and reported in the next section.

3.2 **Harmonic spline modelling**

In parallel to the polynomial approach, we take advantage of harmonic spline functions to derive a continuous regional field model for southern Africa. That kind of functions was first introduced by *Shure et al.* (1982) for global magnetic field modeling, but it is as well suitable for regional field modelling. Regional models benefit from their interpolation characteristics, that allow an exact fit of the data. Regularizations can be applied to trade off the closeness of fit against smoothness of the model. The functions satisfy Laplace's equation, therefore allowing a potential field approach combining the individual components in a physically meaningful way. Despite these favorable features, spline functions have scarcely been used in the past. They have recently been revisited by *Geese et al*. (2010) to model the magnetic field of southern Africa between 1961 and 2001. A detailed description of the method can be found there.

Whereas polynomials are computationally very easy to use, harmonic splines are based on Legendre polynomials and require a somewhat more complicated implementation. For each data location (in this case: for each repeat station or observatory) defined by its coordinates (r_i , θ_i , φ_i), we calculate a radial kernel F_i^L according to

$$F_i^L(\theta,\varphi,r)=\sum f_l(l+1)\left[\left(\frac{a}{r_i}\right)^{l+2} Y_l^m(\theta_i,\varphi_i)\right]\left(\frac{a}{r}\right)^{l+1} Y_l^m(\theta,\varphi)$$

where a is a reference radius and L the maximum spherical harmonic degree. Y_l^m are the Legendre functions of degree l and order m and the parameter f_l stands for $f_l=\frac{2l+1}{4\pi(l+1)^4 l^2}$. The gradient of the functions F_j^L has a localized shape peaking at the location of the data point at geocentric radius r_i , co-latitude θ_i , and longitude φ_i . The parameter f_l imposes smooth characteristics on the derived field model. The magnetic field can then be expressed as the superposition

$$B(\theta,\varphi,r)=-\sum \alpha_i \nabla F_i^L(\theta,\varphi,r)$$

with the model coefficients α_i and the harmonic spline functions $\nabla F_i^L(\theta,\varphi,r)$. We used a maximum degree of L=20, corresponding to a minimum resolvable wavelength of 2000km and high enough to describe small scale features but small enough to map contributions originating mainly in the core. Similar base functions are derived with kernels along the North and East direction.

A time dependency is introduced by expanding each of the coefficients $\alpha_i = \alpha_i(t)$ on a basis of B-splines in order to obtain a continuous field model. The knot points of the splines are set to the years 2005.0, 2007.5 and 2010.0. A benefit of the continuous approach is that the quiet night time field data can be used directly without any reduction to a specific epoch. Like this, we avoid to introduce additional errors arising from the non-uniform field behaviour between the observatories and the distant field stations during the reduction process. Furthermore, the secular variation as first temporal derivative can easily be obtained from the continuous model by simply differentiating the B-spline functions in time. To avoid overfitting of the data, regularization in space and time is applied to damp smaller scale oscillations.

The spline method was used to model the North (X), East (Y) and vertical (Z) component of 142 data vectors measured at 31 stations that were at least visited four times between 2005 and 2010. To fill the temporal gaps between the subsequent field surveys and hence to obtain a robust continuous model in time, monthly mean values from the four observatories located in that area complete the data set with additional 176 vector data.

Crustal offsets have to be taken into account due to the fact that the field instead of secular variation data are used. As explained in *Geese et al.* 2010, these biases can be co-estimated in the modelling, which leads to three additional free parameters per station. The crustal contributions that we obtained are listed in Table 1 for each of the stations.

4. **Modelling results**

Regional and global main field descriptions appear rather similar even over the southern African region due to the relatively large values and the strong dipole contribution. We are interested in secular variation descriptions here. In the polynomial model, the lithospheric field in that case is eliminated by directly using first difference data. In the spline approach, the co-estimation of crustal biases ensures that the static lithospheric field does not influence the secular variation prediction of the model.

Both modelling methods in general give similar results for the areas covered by data, as shown in some examples for the declination and vertical component in Fig. 2 and 3. Differences in details over South Africa, Namibia and Zimbabwe originate from the different modelling methods, while larger differences over the oceans and Zimbabwe are meaningless as no regional modelling method performs well in extrapolation outside the region of data.

Comparing the fit of the two regional models and the recent global GRIMM-2 model (Lesur et al., 2010) to the secular variation data obtained as first differences between annual means of the observations, it is obvious that the regional models provide a closer fit. Table 2 shows the root-mean-square deviations between the three models and the secular variation data calculated as difference between the annual mean results of the 2008.5 and 2007.5 survey. Although the spline model shows most structure, the polynomial model fits the data best. The main reason is that the polynomials fit each component and epoch independently without any potential field or temporal smoothness constraints. Moreover, this is the only model that directly used these secular variation data. In the GRIMM-2 model no repeat station data have been considered, and in the spline-based approach secular variation is derived from fitting continuous functions to the main field data.

	dD/dt [min/yr]	dH/dt [nT/yr]	dZ/dt [nT/yr]
Splines	1.94	9.86	5.1
Polynomial	1.27	5.16	4.93
GRIMM	2.43	12.88	7.71

Table 2: Root-mean-square deviations between secular variation data and model prediction for epoch 2008.0.

The differences between the continous models can have two main reasons: an inadequate fit of global models to rapid and somewhat small-scale secular variation in this area, or different influences of external field leakage into the different models. No data processing or modelling technique can achieve a complete separation of internal, external and induced field contributions. Global modelling techniques offer better possibilities than regional methods to co-estimate or reject external field contributions when modelling the internal magnetic field. The regional models, particularly the individual polynomials might be somewhat more influenced by external field leakage despite careful data processing and the fact that magnetic field conditions were favourably quiet during the studied time interval.

5. **Discussion of field characteristics**

Results obtained in this investigation by modelling secular variation over southern Africa for the period 2005 – 2009 by means of both a spline-based model as well as a polynomial approach reveals a very dynamic geomagnetic field pattern for this region. In particular the declination secular variation is dominated by an eastward changing pattern in the north-western part of the region, while the south-eastern region of southern Africa is under the influence of a westward variation (Figure 2). Both modelling approaches, using annual field survey results reveal a rapid change from year to year. This is quite evident when observing the annual movement of particularly the zero secular variation contour line as displayed in figure 2. Of particular interest is to note that the westward change in declination secular variation in the southern part of the region, centred around Cape Agulhas, has slowed down from 8min/year in 2007.0 to approximately 4 min/year in 2009.0. In contrast to this, the eastward change in the declination secular variation as displayed in the northern part of Namibia, stayed constant around 8 min/year. This indicates a decreasing gradient in the orientation of the geomagnetic field of southern Africa in a north-west, south-eastern direction as revealed during the period 2005 – 2009.

The pattern displayed by the Z-component secular variation (Figure 3), clearly indicates that southern Africas secular variation is dominated by a central area where the vertical component of the magnetic field is declining at a rapid rate between 20 and 40 nT/year. Over the south-western part of the subcontinent the decay of Z is the most prominent, characterised by a rapid change between 2007 and 2008, reminiscent of a geomagnetic jerk that occurred in this time interval as reported by Chulliat et al. (2010). A plot of dY/dt versus time (Figure 4) for the Hermanus (HER) and Keetmanshoop (KMH) observatories confirms that indeed an extremely strong secular variation impulse with a power of more than 20 nT/year^2 occurred in the southern African area around 2007.5 following a linear fit to the data. This is more than 4 times stronger than the global geomagnetic jerk of 1982/3. Even though the continuous model cannot reproduce that high power, the jerk is still clearly evident whereas the GRIMM2 prediction shows a smoother change. Note that the KMH data were not part of the data basis for GRIMM2, but were included in the spline model. Nevertheless each model fits both data series equally well. However, further work and longer time series are required to fully understand the origin of the differences between the two models and whether fast and small-scale core secular variation is not described accurately enough by the global model, whether mantle filtering or induction effects in the lithosphere lead to apparent secular variation structures here, or whether external field leakage in the regional model is responsible for the faster and smaller-scale features.

Since the first magnetic field measurements 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. In particular, the most rapid decrease of the core field is observed across the Southern Atlantic region and the global field decay is likely linked to a growing region of reversed magnetic flux identified under this region in global geomagnetic models. Our regional models for the time interval 2005 to 2009 confirm the ongoing, but quite variable decrease of field strength. In this regard, southern Africa provides an ideal opportunity to study these geomagnetic field changes. Since the establishment of the Hermanus Magnetic Observatory in South Africa in 1941, the total field intensity across southern Africa has decreased by 20%.

The growth and position changing of patches of reverse flux under the southern African region, from 1840 onwards, may be responsible for changes in dipole moment. Most interestingly in this regard, it has been shown recently (*Dormy and Mandea*, 2005) that patches of intense secular variation appear in the South Atlantic hemisphere that are very rapidly displaced in a south-east – north-west direction. This appears consistent with observations of the present study, particularly the movement of the zero SV line in Figure 2. These measurements will have to be continued in future in order to track this patch and monitor its evolution with time. The last full southern African field survey involving all 75 repeat station beacons was conducted in 2000. Since 2005 close to 40 of these stations were visited on an annual basis. Results obtained during these field survey campaigns as well as the modelling of this data set show that information about secular variation, especially in southern Africa, must be obtained at regular short intervals, and that averaging over 5 years does not represent the true pattern for the time-varying geomagnetic field. Real-time monitoring of the geomagnetic field is also of the utmost importance as secular variation impulses can take place over a period of a few months in a rather restricted region (Olsen *et al.*, 2009) due to the morphology of the main geomagnetic field.

6.Conclusions and Outlook

The intensified magnetic field measurements in the frame of Inkaba ye Africa covering South Africa, Botswana and Namibia, enabled us to map the field with high accuracy. The two modelling techniques presented in our study both benefit from this dense data set leading to accurate models for the main field and the secular variation. Both approaches feature their own advantages and drawbacks in respect to their usability, physical meaning, and inter- and extrapolation characteristics. Nonetheless, both methods provide similar results within the area of observation, revealing non-linear time-varying characteristics of the geomagnetic field in southern Africa. Nevertheless, the detailed time series from the repeat stations still are rather short for a comprehensive understanding of the geomagnetic secular variation around rapid jerks and a better comprehension of possible unaccounted external or induced field signal in the repeat station data. A continuation of the repeat station surveys is highly desirable to reach these goals. If at least one full solar cycle of ~11 years could be covered, remaining external influences, which e.g. are also present in observatory annual means, can be much better determined. At the time of writing, the survey for 2010 was in progress and will provide new data for extended detailed field models.

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Number	Latitude	Longitude	2005	2006	2007	2008	2009	dX [nT]	dY [nT]	dZ [nT]
1	-33.86	24.78		x	x	x	x	-11.2	44.6	-25.4
2	-33.83	22.38	x	x	x	x		20.9	21.6	-39.4
3	-32.76	28.03	x	x	x	x		-82.1	-18.0	72.1
4	-31.99	25.63	x	x	x	x	x	53.9	-23.7	-74.4
5	-30.80	30.28			x			-5.8	-92.4	-59.7
6	-32.62	20.54		x	x	x	x	-9.4	-39.1	34.7
7	-29.62	29.49					x	-169.4	-97.2	-20.5
8	-30.78	23.15	x	x	x		x	-146.9	-112.7	61.6
9	-31.18	20.94	x	x	x	x	x	-41.0	8.4	-97.4
10	-28.19	32.42			x	x	x	9.5	-8.7	-57.8
11	-29.05	27.46	x	x	x			-26.3	-62.9	120.9
12	-30.43	17.99	x	x	x	x	x	83.2	-19.1	18.7
13	-27.96	30.30	x	x	x			45.0	46.4	-11.5
14	-29.88	19.47	x	x	x	x	x	85.1	-31.0	211.9
15	-28.94	23.74		x	x	x	x	-54.3	29.1	23.0
16	-27.99	25.59	x					148.2	22.9	-103.8
17	-26.92	30.89	x	x	x	x	x	-75.2	34.5	75.9
18	-28.26	21.30	x	x	x		x	-50.8	5.5	70.6
19	-28.41	16.52		x	x	x	x	-267.5	-35.0	2.9
20	-26.44	22.86	x	x	x	x	x	197.7	165.1	-26.6
21	-24.02	30.84	x	x	x		x	19.5	226.1	141.3
22	-26.46	15.18	x	x	x	x		-68.6	0.7	-58.7
23	-24.57	19.89	x	x	x	x	x	-61.0	17.7	-49.8
24	-22.93	28.00	x	x	x	x	x	83.4	125.2	1.0
25	-23.88	21.87	x	x	x	x	x	-232.5	-31.6	149.2
26	-22.23	30.05	x	x	x		x	30.3	-49.7	72.9
27	-23.19	24.50	x	x	x	x	x	-23.5	-27.7	-248.7
28	-24.59	15.35	x	x	x	x	x	-43.9	35.8	165.5
29	-21.04	27.50	x	x	x	x		88.1	-40.5	467.7
30	-22.32	18.99	x	x	x	x	x	-28.0	120.4	-45.0
31	-21.14	25.31	x	x	x	x	x	-50.2	16.7	59.2
32	-22.43	17.10	x	x	x	x	x	31.3	-12.5	-44.0
33	-21.56	21.66	x	x	x	x	x	-20.2	32.0	49.0
34	-22.53	14.57				x	x	273.1	137.2	-53.0
35	-19.85	23.43	x	x	x	x	x	67.1	-34.6	2.7
36	-20.99	13.58	x	x	x	x	x	107.6	90.6	-269.8
37	-19.48	20.52			x	x	x	-266.3	30.1	-89.4
38	-17.52	24.18	x	x	x		x	-7.6	92.3	-14.1
39	-19.03	15.91	x	x	x	x	x	-34.4	32.1	65.5
40	-17.31	14.38		x	x	x	x	-23.85	-5.82	143.91

Table 1: Location of the field survey stations and years of visit. The station numbers correspond to those given in Figure 1. The three right columns indicate the crustal biases derived from the continuous model.

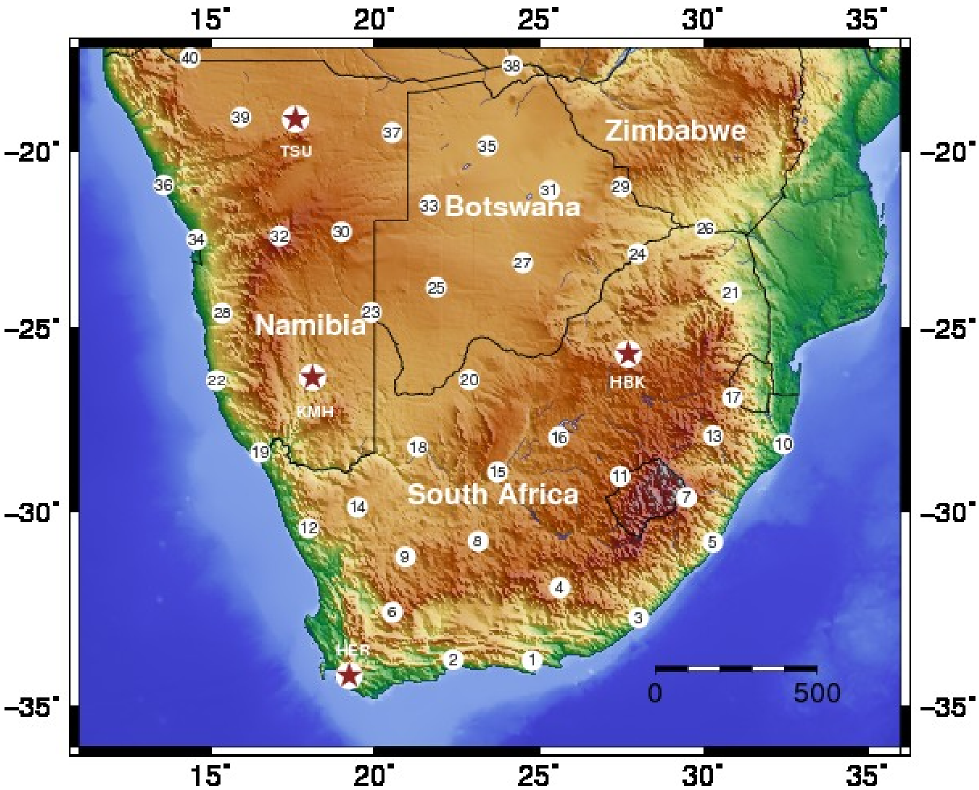

Figure 1: Map of distribution of observatories (red asterisks) and repeat stations (numbered white dots) in the southern African region. Observatories are situated in Hermanus (HER), Tsumeb (TSU); Keetmanshoop (KMH) and Hartebeesthoek (HBK). The exact locations of the repeat stations are given in Table 1.

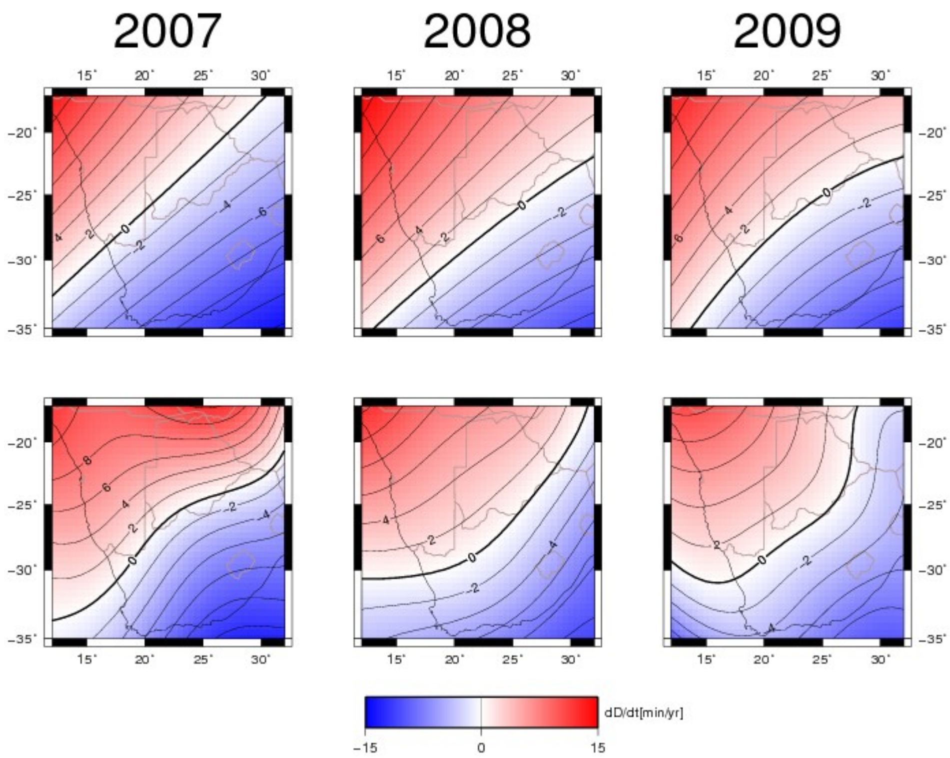

Figure 2: Secular variation of the Declination for the three epochs 2007.0, 2008.0 and 2009.0 from left to right. The top panel shows the field model derived from the polynomial approach, the bottom panel refers to the spline-based model.

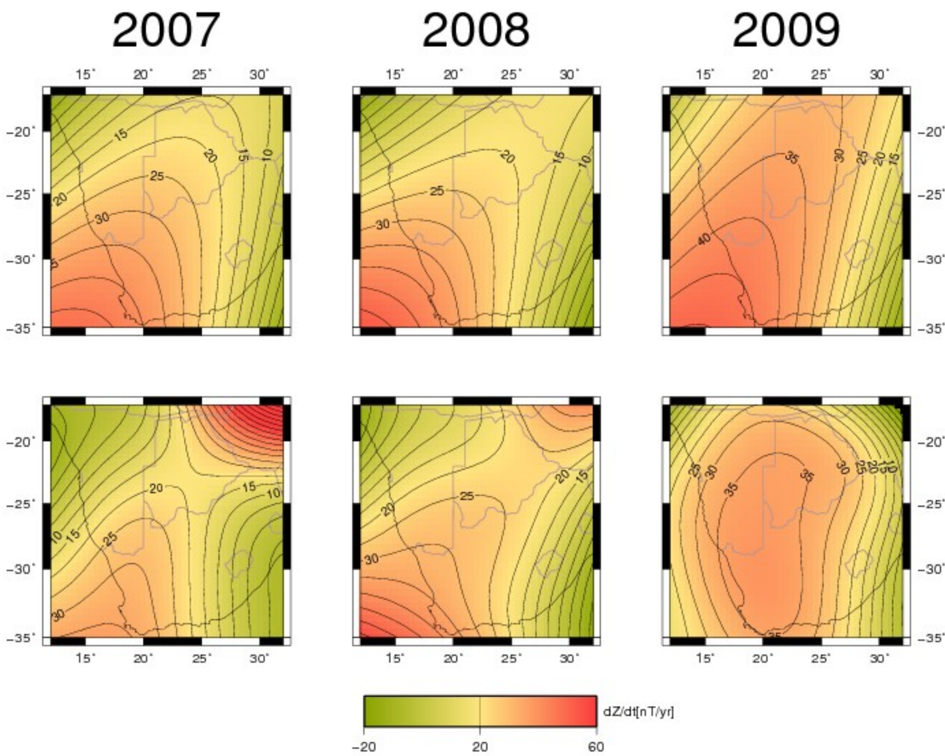

Figure 3: Same as figure 2 for the secular variation of the vertical component. Note that positive values mean a decrease of vertical intensity absolute value due to the negative sign of this component in the southern hemisphere.

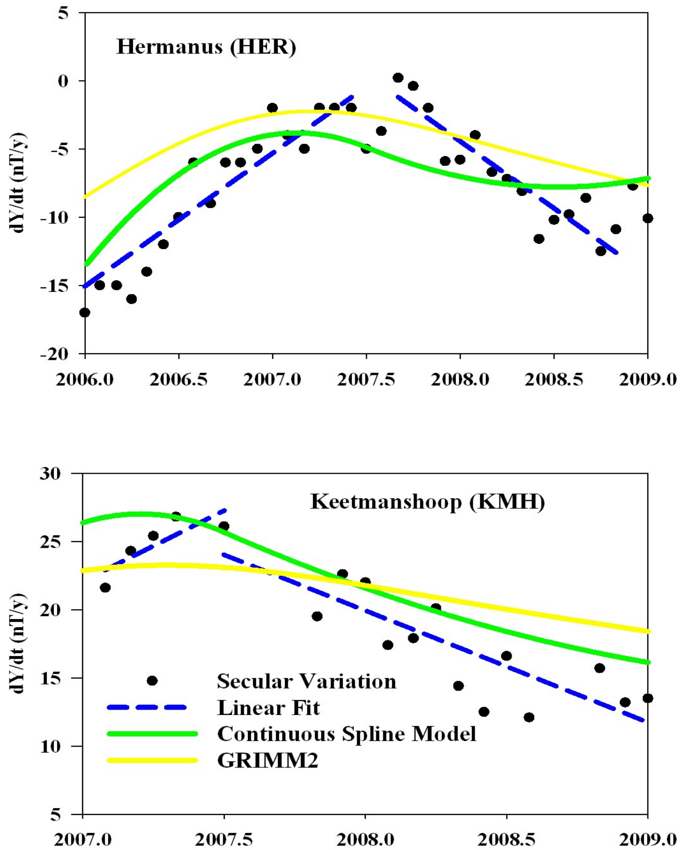

Figure 4: Secular variation of the East component at Hermanus (HER, top) and Keetmanshoop (KMH, bottom) observatories. The black dots show monthly mean secular variation estimates derived as running annual differences. The green curves represent the continuous spline model, while the dashed blue lines show piecewise linear fits. The GRIMM2 model prediction is plotted in yellow for reference. Note the different time scales.