

Equivalent monopole source of the geomagnetic South Atlantic Anomaly

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Abstract

The South Atlantic magnetic Anomaly (SAA) is an important feature of the present geomagnetic field. In this paper we model the space-time evolution of this anomaly for the last 400 years in terms of the resultant between a decrease of a global axial dipole and an increase of a virtual local monopole source. Some characteristics of this evolution are investigated and some considerations are made on the light of a possible special state of the global geomagnetic field dynamical regime. Among the possible speculations, one is made regarding the topography of the core-mantle boundary (CMB) and its possible aspect underneath the SAA region in terms of simple sinusoidal undulations met by the monopole source during its centennial motion.

Keywords: South Atlantic Anomaly; equivalent monopole source; Earth core topography

1. Introduction

The South Atlantic Anomaly (SAA) is a large anomaly of the Earth's magnetic field with significant dimension, covering most of South Atlantic, extending from western part of Africa to most of South America and from equator to Antarctica. This anomaly is characterised by the lowest values of the geomagnetic field at Earth's surface, much lower than expected from a simple inclined geocentric dipole (Heirtzler, 2002; Heirtzler et al., 2002), and its centre is usually defined with the lowest value of the geomagnetic field (Heirtzler, 2002; Pinto et al., 1992). Although its temporal shift in longitude is not uniform (Rangarajan and Barreto, 2000), its mean western drift of around $0.3^\circ/\text{year}$ (Pinto and Gonzalez, 1989) agrees well with the secular western drift of the whole geomagnetic field (Merril et al., 1996). SAA centre can be alternatively defined where the particle radiation flux at middle latitudes coming into the atmosphere is higher (Badwhar, 1997): although its position is slightly different from that of the previous definition, the drift has still the same value (Konradi et al., 1994).

From the high atmosphere and close outer space, SAA is seen as a sort of geomagnetic hole where electric and neutral particles can flow from the Van Allen belts and from the magnetosphere into the atmosphere below. For instance, the proton flux increases at SAA (see e.g. image.gsfc.nasa.gov from AP-8 MAX (SPENVIS)). We find also X-ray microbursts in the low L value region of the SAA (Pinto et al., 1996), enhanced continuous and impulsive pulsations (Trivedi et al., 2005) or changes on the muon flux at sea level (Augusto et al., 2008). During periods of high geomagnetic activity, some authors have been detected over SAA significant enhancements of particle nightglow (Wiens et al., 1999) and unusual ionospheric absorptions (Nishino et al., 2002), both phenomena characterizing energetic particle precipitation in this region. Wiens et al. (1999) estimated a total precipitation during strong magnetic activity of a few MW, that, although three orders of magnitude less than typical auroral precipitations, produces a significant local ionization (e.g. Abdu et al., 2005) and even some enhancement of the local

temperature in thermosphere (Wu et al., 1994). Analysing satellite observations, Fiandrini et al. (2002) find particle precipitations with even higher energies. SAA affects also Doppler satellite data producing systematic positioning errors (e.g. Lemoine and Capdeville, 2006).

Although most of the effects of SAA have been studied for its external interactions with upper atmosphere and magnetosphere, the way SAA changes in time, space and magnitude can provide important clues about our planet's interior and dynamics: this is possible because the cause of the presence of SAA at the Earth surface has its origin in the outer core of Earth. In classical terms, SAA is due to the asymmetry of the Earth's magnetic dipole which is ideally displaced of around 400 km from the Earth's centre towards the Northern Pacific, that is opposed to Southern Atlantic (Fraser-Smith, 1987, Pinto et al., 1992). In more modern terms, SAA can be better explained as the surface manifestation of a reverse magnetic flux at the top of the core (e.g. Hulot et al., 2002, Olson and Amit, 2006); this could be tentatively interpreted as a possible precursor of a geomagnetic excursion or reversal (De Santis, 2007, 2008). The fluid motions that produce the SAA in the deep outer core form an anticyclonic (i.e. counterclockwise) system underneath the Southern Hemisphere (Olson and Amit, 2006), analogous to typical persistent features emerging from turbulent, possibly chaotic flows (e.g., McWilliams, 1984). To our knowledge, SAA persistence is as long as the Great Red Spot on Jupiter's atmosphere, an anticyclonic vortex that has been persistent for 300-400 years (e.g. Beebe, 1997).

Here, with the aim to characterise space-time dynamics of this important feature of the geomagnetic field in order to obtain some information regarding its deep source, we represent SAA temporal and spatial evolution with a simple monopolar source moving just in proximity of the core-mantle boundary (CMB), added to the underlying general decrease of the axial dipole. This paper is composed of the following sections: after this introduction about the SAA, we represent its main space and time characteristics with a simple model. Finally we discuss the results proposing a suggestive speculation.

2. Equivalent monopole source analysis of the South Atlantic Anomaly

For our study, we will consider two global geomagnetic models: GUFM1 (Jackson et al., 2000; validity from 1590 to 1990) and IGRF (Macmillan and Maus, 2005; validity from 1900 to 2005). From a global geomagnetic model expressing the magnetic potential in spherical harmonics, i.e. in terms of a series of Gauss coefficients g_n^m (with n =degree and m =order of the spherical harmonic expansion), under given conditions (otherwise the inverse problem is not unique), it is possible to derive a reasonable map of fluid motions at the top of the terrestrial core (i.e., Matsushima, 2005). This way to proceed would allow us to detect important dynamical features in the outer core, but, since we need to make a downward continuation of magnetic data from the Earth surface (and often from satellite altitude), the constraints we apply usually smooth smaller local anomalies, because they could even depend on the field outside the local feature (but see Olsen and Mandea, 2008 for an exception). To overcome this problem we resort to a much simpler solution. We assume that SAA can be simply modelled by the superposition of the global axial geomagnetic dipole (i.e. the field characterised by g_1^0 coefficient and aligned with the rotational axis) and a local equivalent monopolar source placed at the proximity of the CMB. In formula:

$$B_{SAA} = B_{10} + B_m \quad (1)$$

where B_{SAA} is the magnetic field in the SAA region, B_{10} is the field contribution from the axial dipole, and B_m is the local monopole field. The removal of the axial dipole is not casual: this is the dominant part of the whole field which is unchanged by westward drift, typical of recent secular variation, due to its axisymmetric nature and determines the polarity of the geomagnetic field (e.g. Olson and Amit, 2006).

We admit that this local representation is oversimplified in some epochs (see for instance epoch 2000) and at the periphery of the anomaly, however we expect it can grasp most of the important spatial and temporal aspects of this anomaly, at least as regarding its central focus where the model is best. If we remove the axial dipole part from the whole geomagnetic field, the resulting

geomagnetic field is shown in Figure 1 at successive epochs and models: from 1600 to 1950 (GUFM1) and 2000 (IGRF), at steps of 50 years. In all epochs we find a peculiar almost circular anomalous area where the field is maximum at the centre and decreases going towards the periphery: it is this aspect of the field that we will model as an equivalent monopole source placed at a certain depth h from Earth surface. The corresponding formula of the total intensity of the monopolar magnetic field measured at a given altitude H from the surface is given as:

$$B_m = \frac{k}{(h + H)^2} \quad (2)$$

where k is a constant characterising the monopole, also called the strength of the monopole. If r and r_0 are the radial distances, from Earth's centre, of a given measurement and of the monopole, respectively, then $r=r_0+h+H$ (Figure 2). Equation (2) becomes:

$$B_m = \frac{k}{(r - r_0)^2} \quad (3)$$

Monopole models for representing some effects of the geomagnetic field at the Earth's surface are nothing new: for instance, with her "monopoly", Hodder (1982) modelled the main geomagnetic field, while O'Brien and Parker (1994) provided a model with virtual monopoles for the lithospheric magnetic field.

To find the depth of the anomalous monopole there are several methods. For instance, we could estimate it from the vertical derivative of the field. Figure 3 shows an example of this quantity (in nT/km) for the epoch 1600. The thicker circle covers the SAA area of interest: it is relevant to notice that this is the area of the world with greatest vertical gradient ($>13\text{nT/km}$) confirming that the corresponding source is the shallowest one among all sources of the non-axial dipole part of the main geomagnetic field. The very circular shape of the vertical gradient is another confirmation of a possible monopole-like type of the corresponding source. A good estimator of the monopole source depth is the distance between vertical gradient maximum and its half value (e.g. Telford et al., 1990): a rapid calculation provides an estimate of around 2800 km. However, this method is rather

imprecise. Thus, concentrating our attention only on the focus of the resulting anomaly, we prefer to resort to an iterative linear fit over the logarithm of the resulting geomagnetic field at different (logarithmic) values of $r-r_0$ in the centre of the monopolar anomaly. More precisely, for each epoch, we extract from the global model (GUFM1 or IGRF, according to the epoch) a set of 21 points at different altitudes (at steps of 50 km from Earth surface). Then, we draw a log-log plot of the corresponding geomagnetic field intensity B (nT) versus the distance from source (km). By an iterative process we change the distance (in particular $r-r_0$ of formula (3)) until we get a linear slope of -2, which corresponds to the behaviour of a monopole field: this allows us to estimate the depth (i.e. $r-r_0$) of the virtual monopolar source.

Figure 4 shows an example of this analysis for epoch 1950, where we see the great agreement between magnetic field obtained from GUFM1 model after removing the global axial dipole and the equivalent monopole model in the focus of the resulting anomaly. In all analysed years, correlation coefficient between regression line and data has been always greater than 0.999.

Figure 5 shows a comparison between monopole and axial dipole geomagnetic fields at Earth surface from 1600 to 2000 (at steps of 50 years) from GUFM1 and IGRF at the centre of the obtained “monopolar” anomaly. We notice that changes of the axial field are counterbalanced by opposite changes of the monopole field: to the almost general decrease of the axial field corresponds a general increase of the monopolar field over all the period of study.

Figure 6 shows the horizontal (latitude-longitude) path of the equivalent monopole for both GUFM1 and IGRF models at 25-year steps (exception the addition of 1990 for GUFM1). An apparent anticyclonic rotation of around 800 years of main period (half rotation in around 400 years) is evident. This kind of anticyclonic (anticlockwise) regime is typical of the Southern Hemisphere as confirmed by previous results when analysed the corresponding generating flows at the CMB (e.g. Olson and Amit, 2006). Horizontal and vertical bars represent estimates of the errors of centre determination of the monopolar anomaly, decreasing from older epochs ($\pm 4^\circ$ in latitude and longitude) to most recent ones ($\pm 2^\circ$ in latitude and longitude). It is worth noting as well a

recent acceleration of the motion from 1990 to 2000: we do not know if this is just a mere coincidence or if this acceleration can be associated to recent accelerations of other features of the geomagnetic field, such as the geomagnetic poles (De Santis et al., 2007, 2008) and magnetic dip poles (Newitt et al., 2002), that can be considered as possible phenomenological precursors of an imminent geomagnetic reversal or excursion (De Santis et al., 2004).

The use of the monopole as *equivalent* deep magnetic source of the SAA is advantageous also for two other aspects: i) it can give a unique information about the depth of the source, ii) among all possible virtual multipoles representing the main geomagnetic field decay in altitude at and over the Earth's surface, the monopole is the closest to the CMB. Thus, if we think of this monopole source as floating at the top of the core, its temporal position probably provides information about the “crossed” CMB topography. This is also confirmed by the application by Hodder (1982) who placed her virtual monopoles specifically at the CMB. Figure 7 shows the radial distance r_0 (from Earth centre, given with respect to a mean value of $\langle r_0 \rangle = 3440$ km) of the equivalent monopole position from 1600 to 2000 representing most of the recent SAA dynamics. Vertical bars represent estimates of the errors associated to each depth by applying the Gauss propagation method to the whole analysis. The behaviour in time of this equivalent monopole can be simply modelled by a sine (dashed line in Figure 7), as follows:

$$r_0 - \langle r_0 \rangle = A \sin (2\pi (t - t_c) / T) \quad (4)$$

with $A = 102 (\pm 20)$ km; $t_c = 120 (\pm 90)$ years; $T = 340 (\pm 20)$ years and with $\chi^2 / \text{DoF} = 1414.2$ km², where χ is the residual squares sum and DoF stands for “Degrees of Freedom”. This sinusoidal oscillation could be the result of the space-time sampling of the monopole source during its path with comparable undulations of the CMB topography. Please notice, the parameter A of around 100 km is a measure of the largest variability of the CMB undulations. This value agrees quite well with estimations found by previous geomagnetic analyses (e.g. Yoshida and Hamano, 1995) but it is in contrast with the seismological and geodetic estimations of smaller undulations of peak-to-peak

value of around 24 km (Garcia and Souriau, 2000) or less: 12 km, (e.g. Schweitzer, 2002) or even 3 km (e.g. Bowin, 1986; Sze and van der Hilst, 2003).

3. Discussion

The representation of most of the effect produced by the SAA on the surface in terms of superposition of the axial dipole reduction and a moving equivalent monopole at the CMB provides a simple way to study the space and time evolution of this important feature of the geomagnetic field for the past 400 years. The equivalent monopole has moved as an anticyclonic rotation centred at around (0° longitude, 55° South latitude) with a mean drift of 10-20 km/year, corresponding to a main period of around 800 years, although this motion has accelerated during the most recent years. A simple model of this movement could be that of an equivalent monopole source which is almost following the upper surface of the outer core so as sampling a series of crests and valleys of the CMB topography itself. If this is true, we can think about a CMB topography formed by an elongated crest along the 50S parallel that divides two valleys, one north of this parallel and another south. To the authors' knowledge there are not yet other geophysical evidences of this kind of heterogeneity at the CMB with radial variability of around 100 km, i.e. comparable with A of equation (4). Some papers have appeared indicating an irregular topography together with some heterogeneous patches of 5-50 km thick at the base of the mantle (Garnero and Jeanloz, 2000), detectable from a significant decrease of seismic velocities and possibly correlated with hot spots (Williams et al., 1998). On the other hand, Lister and Buffett (1998) proposes a more regular stratified model with the presence of a layer of 100 km in the upper outer core to accommodate a possible value of the Nusselt number less of unity for the Earth. Thus a presence of such as structure underneath the SAA cannot be excluded. It would be interesting to find other results supporting or rejecting our hypothesis.

Acknowledgements

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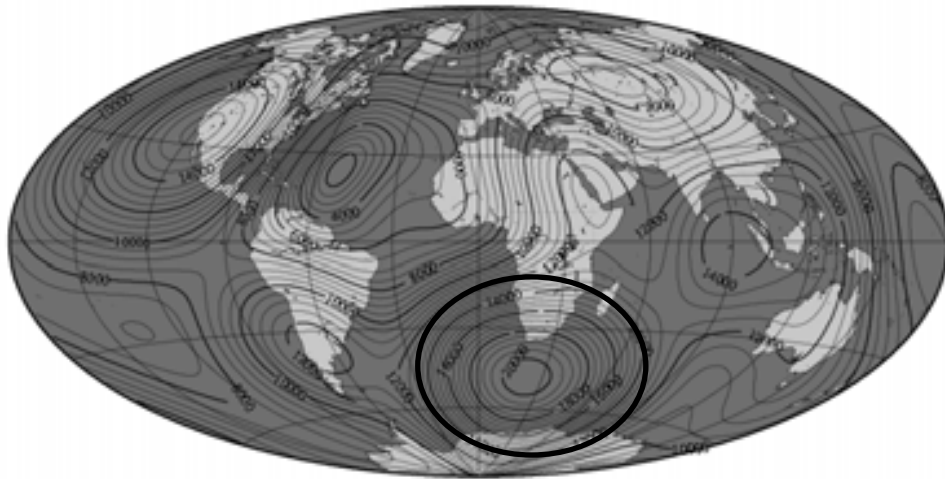
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Figures and Figure Captions

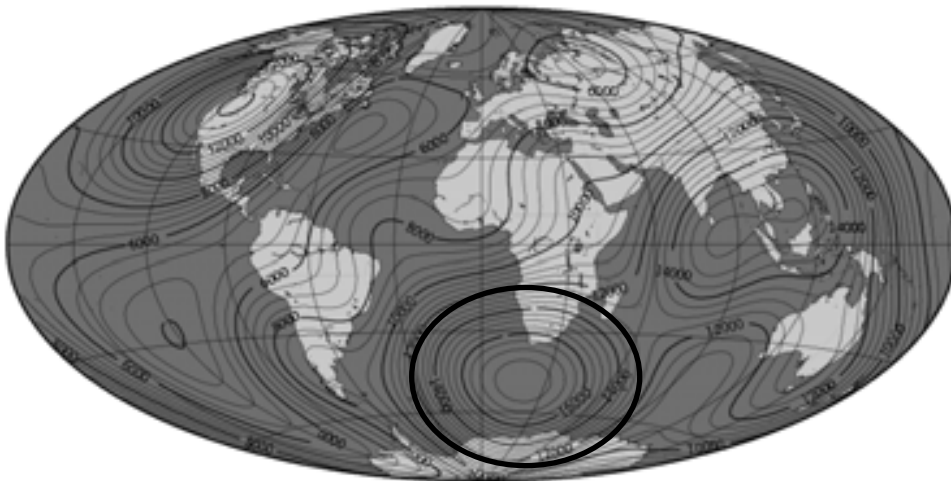
Figure 1. Total intensity of the nonaxial dipole part of the geomagnetic field (i.e., that obtained from the whole field removing the dipole aligned with the rotational axis) from 1600 to 1950 (GUFM1), 2000 (IGRF), at steps of 50 years. The resulting anomaly in the South Africa and South Atlantic (evidenced by the thick circle) can be modelled by an equivalent local magnetic monopole placed closed to the core-mantle boundary, whose fit is performed only along the vertical of the resulting anomaly focus.

GUFM1

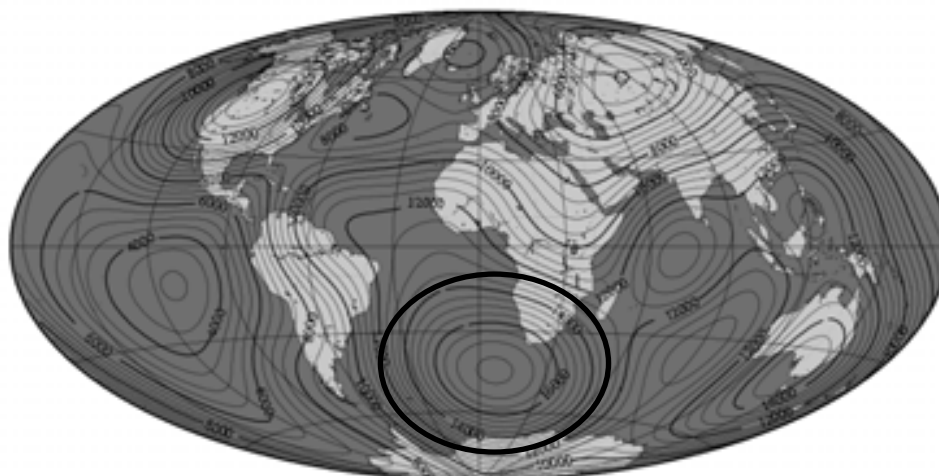
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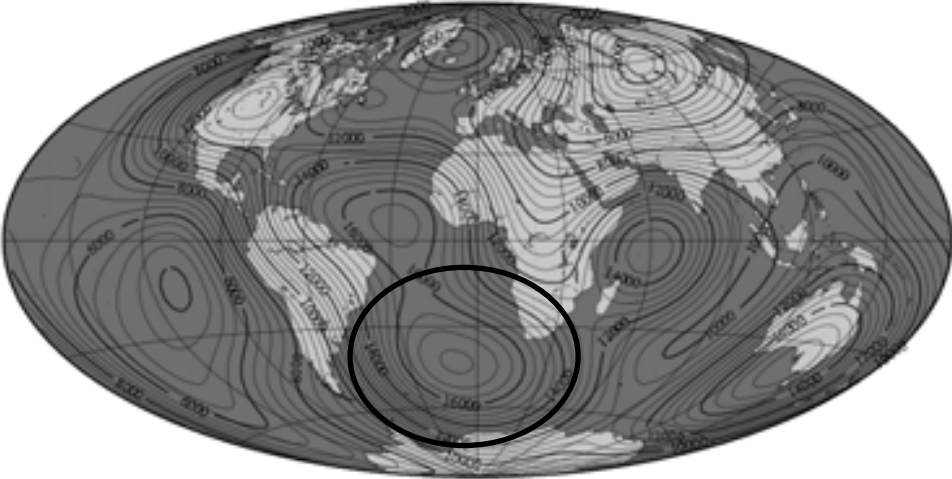
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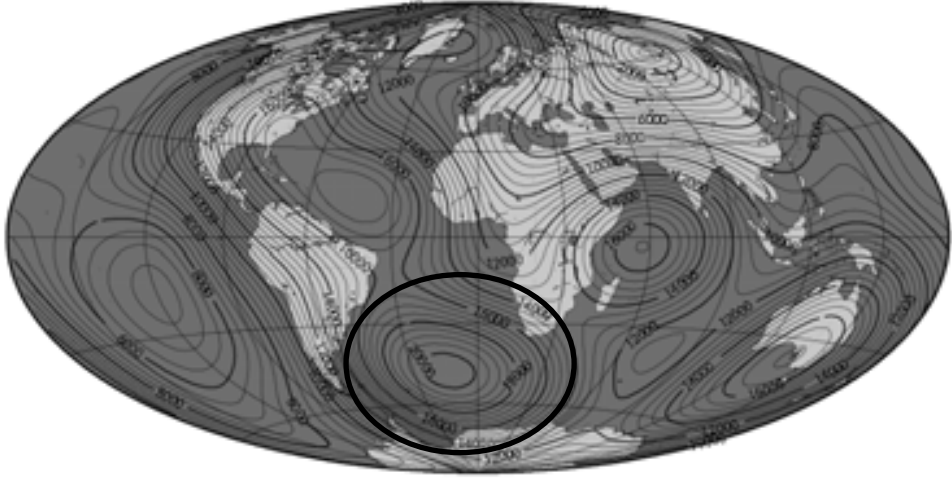
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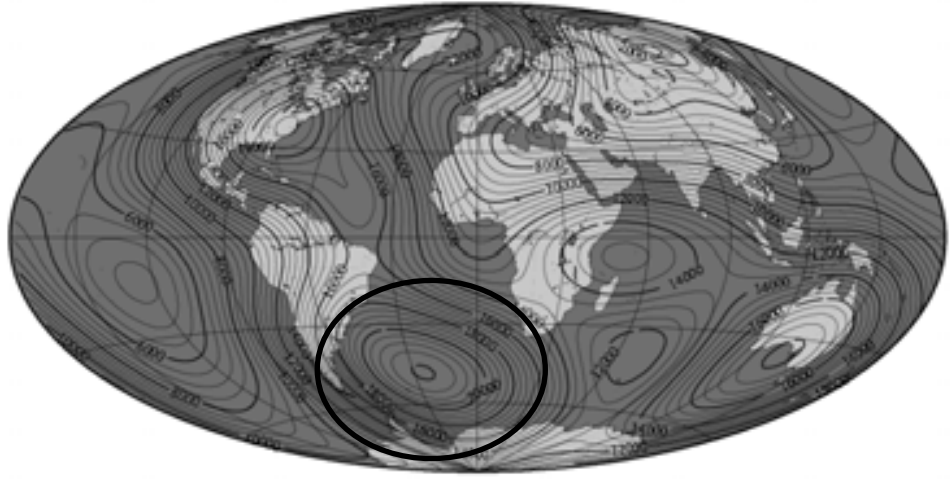
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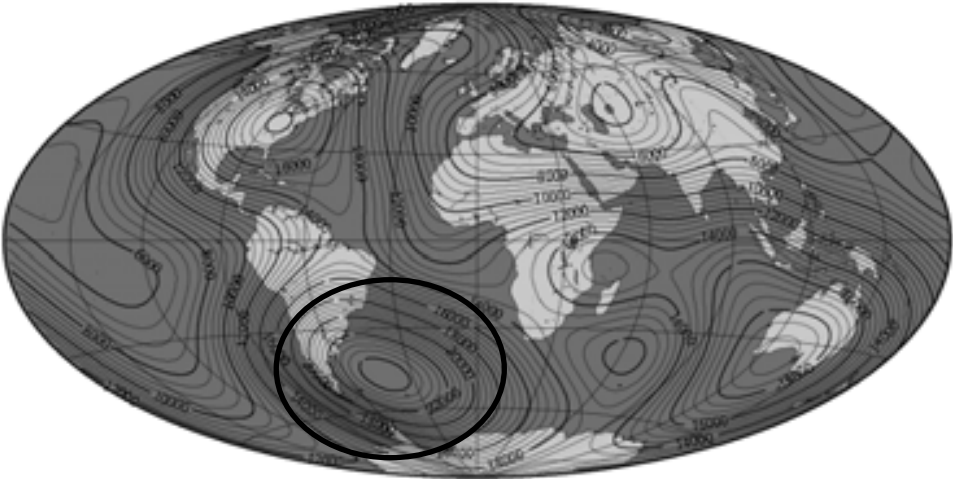
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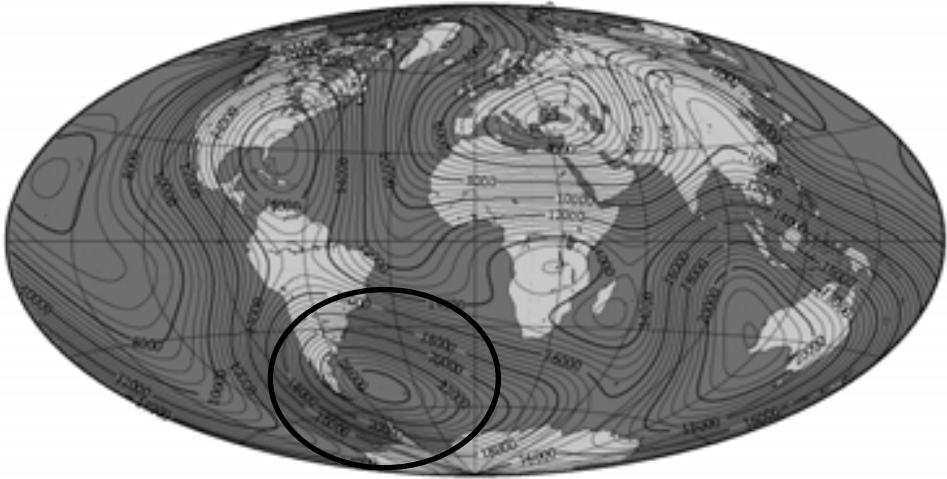
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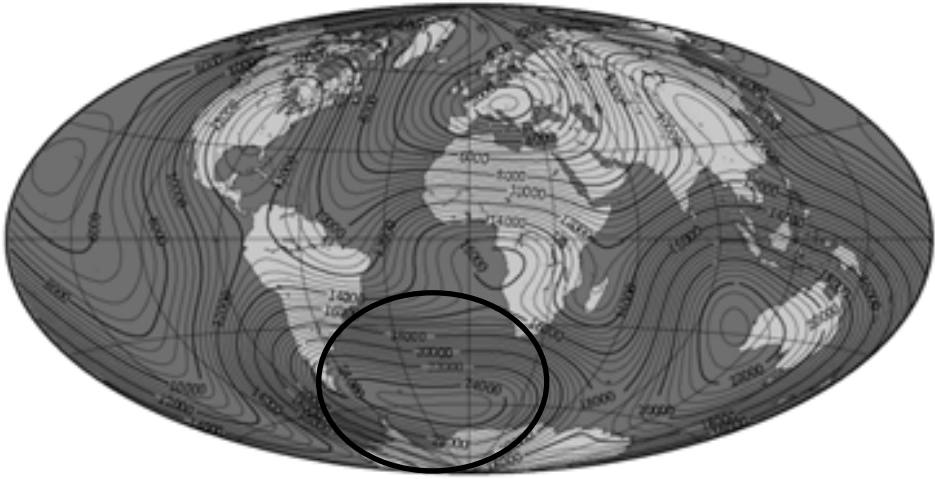


Figure 2. Schematic drawing of Earth's interior with indication of depths or distances used in the text. P is the point of observation at height H above the Earth's surface, the latter is defined by the radial distance r_0+h . CMB is defined at radial distance r_0 from Earth's centre.

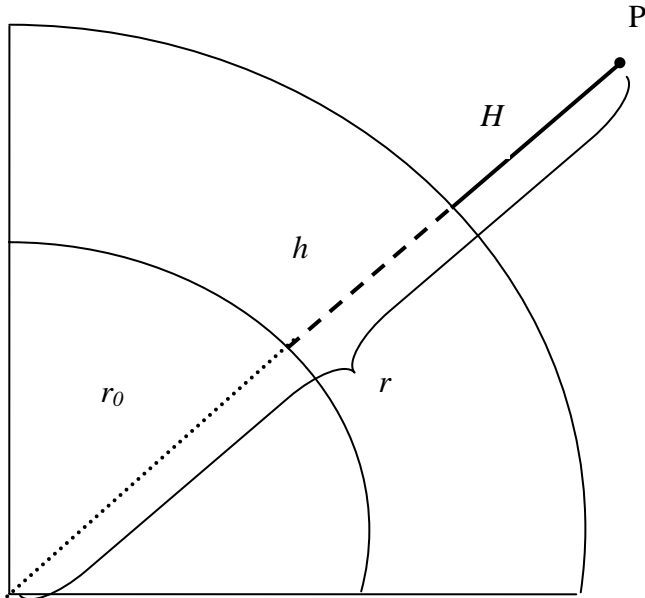


Figure 3. Vertical gradient of the nonaxial dipole part of the geomagnetic field at 1600 (i.e. that obtained from the whole field removing the axial dipole). The thick circle covers the SAA area of interest. Contour values are in nT/km.

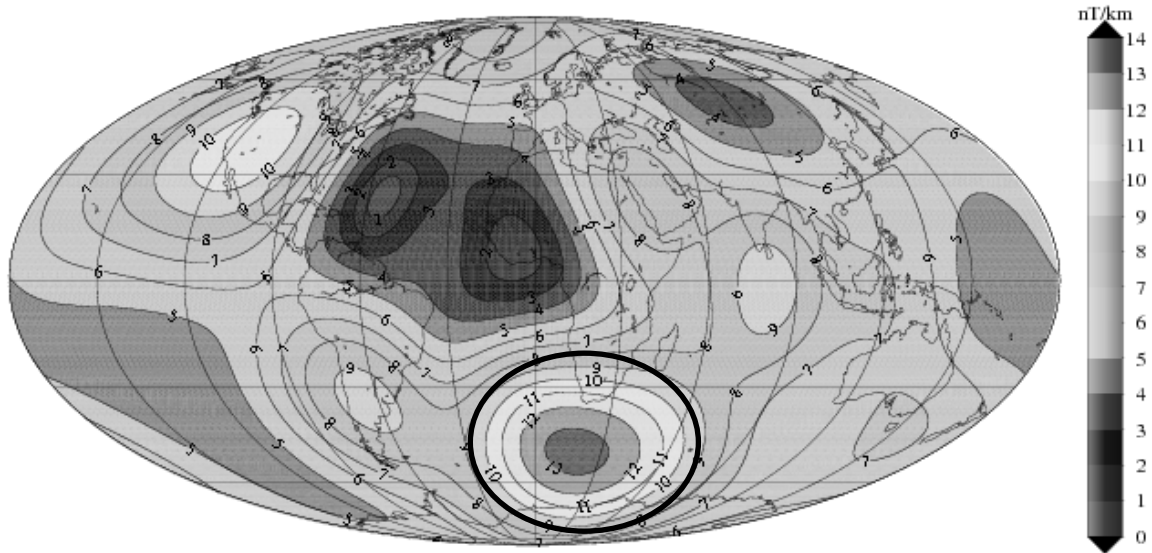


Figure 4. For each epoch, given a set of geomagnetic field intensities at points with different altitudes (21 points at steps of 50 km from Earth surface) extracted from the global model (GUFM1 or IGRF, according to the epoch), we can draw a log-log plot of the corresponding geomagnetic field intensity B (nT) vs. the distance from source (km). By an iterative process we change the distance in order to get a linear slope of -2, which corresponds to the behaviour of a monopole field. Here we provide an example for the epoch 1950. Ln stands for “natural logarithm”.

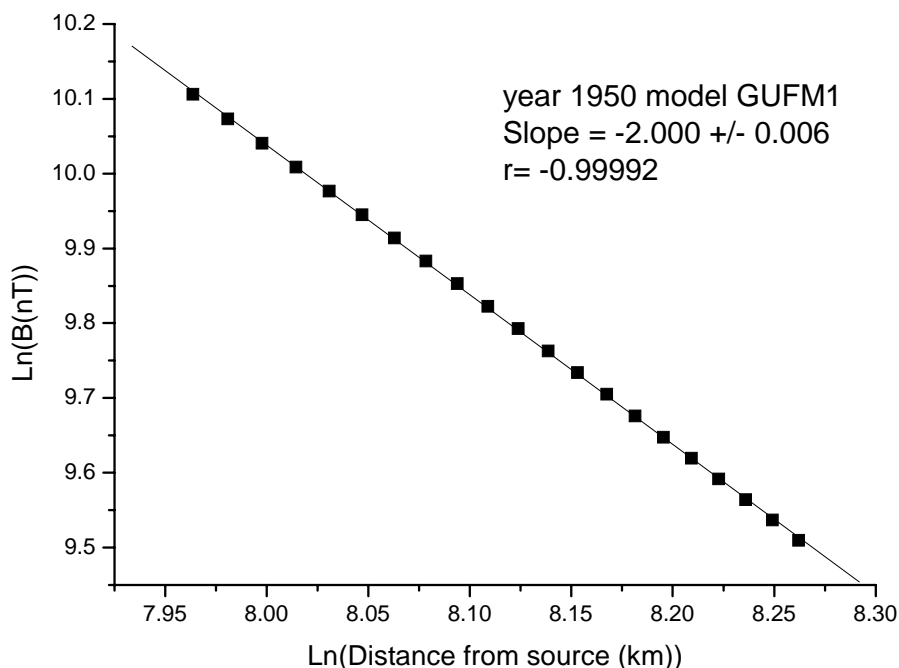


Figure 5. Monopolar and axial (g_1^0) dipole geomagnetic fields from 1600 to 2000 from GUFM1 and IGRF global magnetic models at the centre of the obtained “monopolar” anomaly. The first kind of magnetic field is obtained modelling with a monopole source the nonaxial dipole part of the total field, i.e. after the removal of the axial (rotational) dipole from the total field given by the two global models and looking at the position of the largest value in the region.

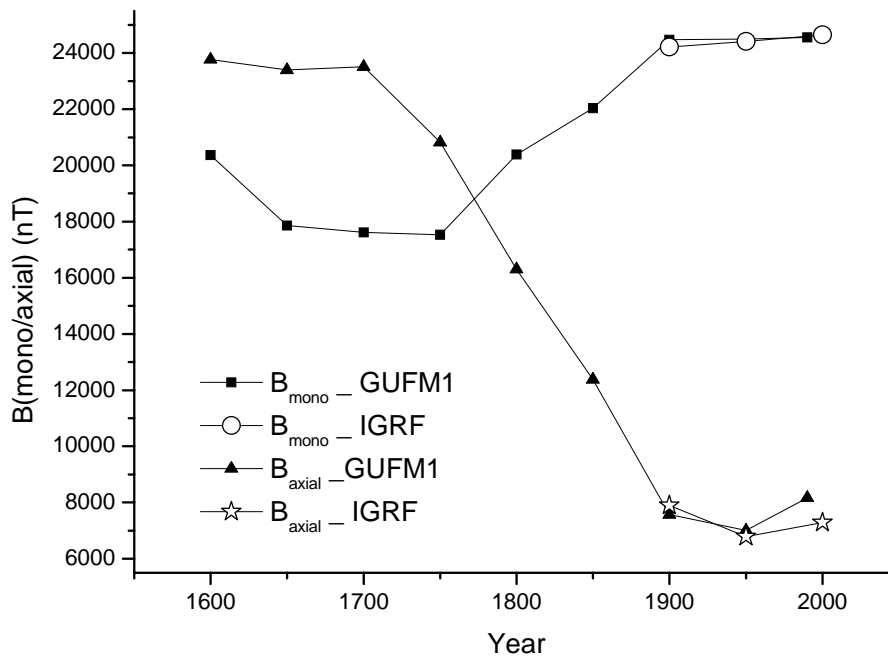


Figure 6. Horizontal path of the equivalent monopole for the SAA when the axial (rotational) dipole is removed from the total field. Data are presented at 25-year steps (exception the addition of 1990 for GUFM1). An apparent anticyclonic rotation of around 800 years of main period (half rotation in around 400 years) is evident. Also a recent acceleration of the motion is visible.

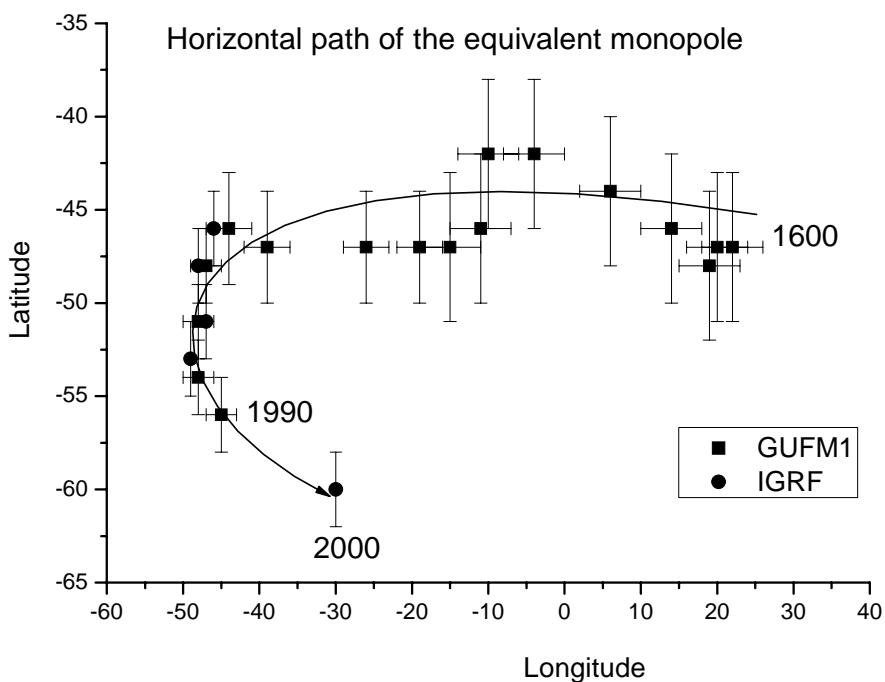


Figure 7. The suggested sinusoidal oscillation in time (dashed curve) of the monopole depth, compared with estimated results. This oscillation could be the result of the sampling of the virtual monopole source during its path with comparable undulations of the CMB topography. $\langle r_0 \rangle$ is 3440 km.

