Some Recent Characteristics of Geomagnetic Secular Variations in Antarctica

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Abstract. Some of the most interesting features of the Earth's magnetic field and of its time variations are displayed in polar areas, where the geomagnetic field dipole poles are located. Space time models of the geomagnetic field give a mathematical description that allows generally to undertake a common epoch time reduction of magnetic surveys and to extract magnetic anomaly maps after removing the main part of the geomagnetic field; in addition in polar regions geomagnetic field models allow to follow the location of the geomagnetic dip poles in their time wandering. In this work the development of a dedicated regional magnetic reference model for Antarctica (Antarctic Reference Model, ARM) is presented and compared to the well known IGRF (International Geomagnetic Reference Field) model and it is shown that the first is more appropriate to better study the behaviour of secular variation and its unusual characteristics as observed in Antarctica.

Moreover single and multi-station analyses have been applied to the longest available time series of geomagnetic data for Antarctica in order to investigate the most interesting behaviour of secular variation: the geomagnetic jerks. It was found that geomagnetic jerks are also detectable in Antarctica and that they show a peculiar space time structure.

Introduction

It is known from over 300 years that the geomagnetic field changes with time. Variations in the geomagnetic field observed at the Earth's surface occur on time scales ranging from milliseconds to millions of years. The short-term variations are believed to be primarily of external origin. They arise mostly from electric currents flowing in the ionosphere and magnetosphere and are responsible of the magnetic storms and of the more or less regular daily variation. These rapid variations of the magnetic field are superimposed upon much slower changes occurring over time scales of a few to thousand years. The slower changes, which are related to the dynamo processes acting within the Earth, are generally referred to as geomagnetic secular variation. In detail, the geomagnetic secular variation is the result of inductive effects of fluid motion at the top of the Earth's liquid iron outer core. This means that, at a single epoch, the morphology of the field at the Earth's surface can be used to infer the configuration of flux at the interface between the core and the overlying solid mantle and when the temporal evolution of the field is taken into account in addition to knowledge of the field itself, more can be achieved. Indeed, the secular variation holds information on the flow into the core, and on diffusion of the magnetic field due to the effects of finite electrical conductivity of the core.

One of the most unusual features of the secular variation, for a given field element, is the secular variation impulse commonly named "jerk". A geomagnetic jerk is defined as a rapid change, taking place in a year or two, in the slope of the secular variation or as a step function in the secular acceleration. This means that we can think of the secular variation as a series of straight-line segments separated by geomagnetic jerks. Consequently, the geomagnetic jerks represent a reorganization of the secular variation and are of internal origin, as it has been established through spherical harmonic (Malin and Hodder 1982) and wavelet (Alexandrescu et al. 1996) analysis. Their short time scale implies that they could be due to a change in the fluid flow at the surface of the Earth's core (Waddington et al. 1995) or could result from abrupt magnetic changes generated at the core-mantle boundary. However, little is still understood about their physical origin (Bloxham et al. 2002) and as a consequence they are still largely debated.

Examination of geomagnetic data from worldwide observatories has revealed that this phenomenon is not apparent at all observatories, nor in all components and that it is particularly spectacular in the east (Y) component of European observatories. However, it is usually a worldwide event in extent being present in different components at different points of the Earth's surface and at different times. In particular, it has been noticed that, in the case of the last three jerks of 20th century, for 1969, 1978 and 1991 (the worldwide character of the 2000 jerk is still debated; Mandea et al. 2000), the occurrence of the event in the Southern Hemisphere is a few years after that of the same event in the northern hemisphere (Alexandrescu et al. 1996; De Michelis et al. 2000). These commonly observed time lags for the occurrence epochs are very important because they may imply the existence of higher electrical conductivities in the lower mantle beneath these regions.

We can conclude that the geomagnetic field and its time variation are of geophysical interest, not only for their own sake but also for the knowledge that can be acquired about

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some of the Earth's physical properties, such as electrical conductivity of the mantle and motion of fluid core. The structure of the geomagnetic field on the Earth is such that a dipolar field can approximate it, with poles relatively close to geographical poles. The polar regions of the Earth are then a very peculiar area from a geomagnetic point of view. However only at the end of the fifties, we had the first real opportunity for extensive and continuous geophysical investigation in the polar areas, and especially in Antarctica. Before this period less was known about the Antarctic regions than about any other area of comparable size in the world.

In this paper we have focalized our attention on the study of the secular variation and on its impulse (i.e. jerk) in the Antarctic region. In detail, we have reported the development of a regional magnetic reference model to study the behaviour of the secular variation and we have reconstructed the intensity distribution of the last jerks of 20th century.

Models of the Geomagnetic Field

The most important and commonly used method to describe quantitatively the Earth's magnetic field is through spherical harmonic analysis. Various combinations of global observatory, satellite, and magnetic field survey data sets are used to obtain the coefficients of the truncated spherical harmonic series, in order to quantitatively describe the Earth's magnetic field and its secular variation. Models of the field itself are determined essentially from land, sea, airborne, and satellite data while the secular variation models are based mainly on data from continuously recording observatories and to some extent on repeat-station data. The International Geomagnetic Reference Field (IGRF) is the standard mathematical description of the Earth's magnetic field, undertaken by a spherical harmonic analysis implemented by means of Legendre polynomials and Fourier series (e.g., Mandea and Macmillan 2000). Torta et al. (2002) and De Santis et al. (2002) used the Spherical Cap Harmonic Analysis (SCHA; Haines 1985) to represent in a more accurate way the field in the cap delimited by latitude 60° South, that encircles all the Antarctic continent and large part of the Southern Ocean. SCHA is a regionalization of the global model for a spherical cap by means of non integer Legendre polynomials and Fourier series. The Antarctic reference model based on the use of this technique was called Antarctic Reference Model (ARM).

In the most recent ARM version (Gaya-Piqué et al. 2004), annual means of X, Y and Z components registered at Antarctic observatories, as well as a selected subset of satellite total field values data, have been used to develop a model, which is formed by 123 coefficients, that permits the computation of the main field and its secular varia-

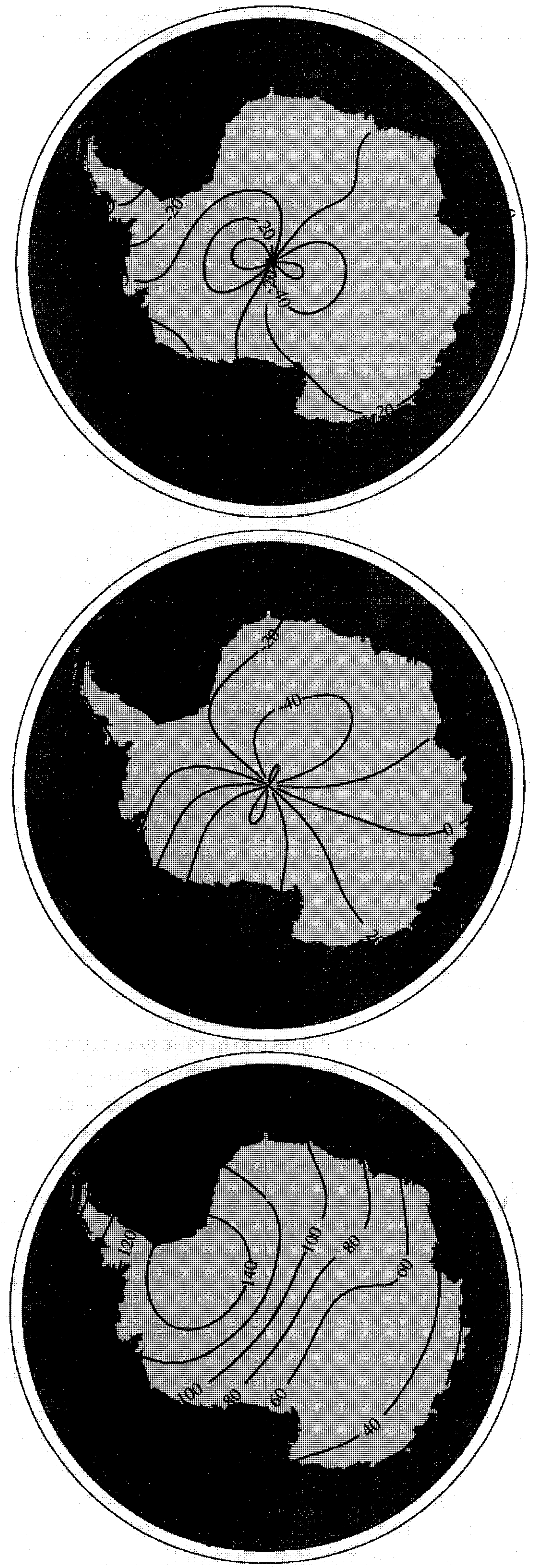

Fig. 7.5-1. Secular variation for X (*top*), Y (*centre*) and Z (*bottom*) components of the magnetic field at sea level for the epoch 1995.0 computed from ARM. Contour lines every 20 nT

tion over the Antarctic regions from 1960 to 2005. The method of the Main Field Differences, proposed by Haines (1993), was applied for the time variation.

The comparison of rms fits to real data (main field values and observatory differences) with those of IGRF allows us to confirm that ARM represents a clear improvement with respect to the global model when representing the field and, especially, its secular variation. Indeed, the comparison of ARM versus IGRF clearly shows that the former fits better than IGRF the observatory differences with regard to the respective mean values for each magnetic element: the rms for X, Y, and Z magnetic elements are respectively 42.6 nT, 55.3 nT, and 121.8 nT for the IGRF, and 23.9 nT, 28.5 nT, and 35.2 nT for the ARM. The clear improvement of ARM with respect to IGRF, almost greater than 50% for all three elements, is probably due to the fact that the latter model presents a constant secular variation pattern at 5-year intervals.

Once the validity of ARM has been checked in terms of rms fits to real input data sets, geomagnetic charts can be depicted for each of the magnetic elements, for a given epoch and elevation (a.s.l.). As an example, we present sea-level maps of the secular variation for X, Y, and Z components at epoch 1995.0 in Fig. 7.5-1.

Study of Geomagnetic Jerks

The internal Earth origin of the geomagnetic jerks has made this event a key factor in understanding the Earth's internal dynamics. The comprehension of this phenomenon and of its space-time distributions is, moreover, directly associated with the solution of the main problem of geomagnetism, i.e. the origin of the magnetic field and its variations, with the evaluation of the electrical conductivity of the lower mantle and with the verification of some hypothesis regarding the internal structure of the Earth. For this reason the knowledge of the spatial and temporal distribution of a given jerk in any part of the world, included the Antarctic region, is particular important. It is known that the secular change is a global phenomenon but with local characteristics. Indeed, the secular change does not proceed in a regular way all over the Earth, giving rise to regions where the field changes more rapidly than elsewhere. As a consequence of this behaviour, the sudden change in the trend of the secular variation that can be found in localized regions does not always reveals a worldwide character. For this reason the investigation of the characteristics of the secular variation trend in the Antarctic region is very important.

Figure 7.5-2 shows the trend of the secular variation relative to different magnetic field components in the case of five selected Antarctic geomagnetic observatories (Argentine Island (AIA), Mawson (MAW), Dumont D'Urville (DRV), Casey (CSY) and Syowa Station (SYO)). The an-

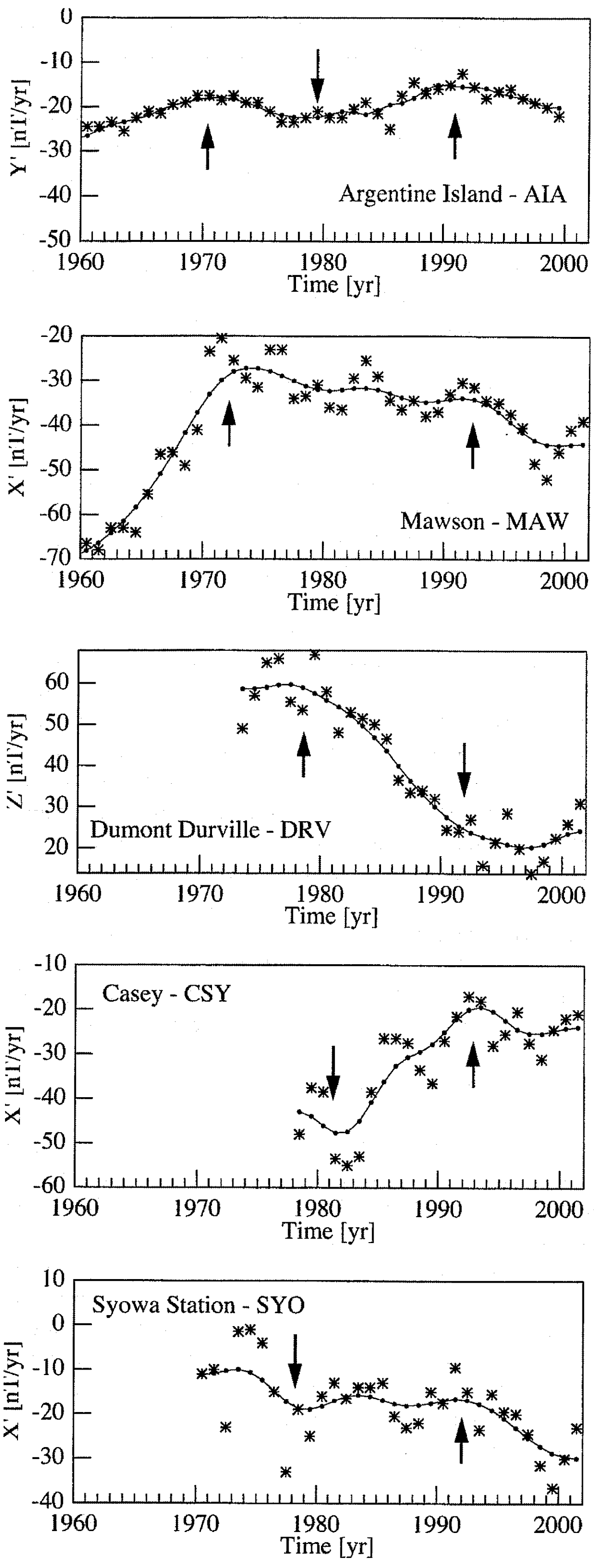

Fig. 7.5-2. Secular variation trend in the case of five different geomagnetic observatories localized in Antarctic region. The *circles* represent the trend of the secular variation after a smoothing operation, the *stars* are the original data and the *arrows* identify jerk events

nual mean values of the geomagnetic field used to evaluate the secular variation come from the British Geological Survey website. The stars represent the secular variation obtained from the original data while the circles represent the trend of the secular variation after a smoothing operation (moving window on three points iterated twice). The arrows show the existence of jerks around: 1969, 1978 and 1991. Actually, these events are temporally shifted with regards to these typical years. As well known, the observatories localized in the Southern Hemisphere are indeed characterized by a time delay in the record of the jerk events. The figure shows immediately the intrinsic difficulties of the jerk study in Antarctica: a limited temporal duration of available data, perturbed data from external magnetic disturbances and, also for this reason, an objective higher difficulty in obtaining high quality data.

Taking into account these problems it is clear that the classical methods of analysis of the geomagnetic jerks (i.e. traditional straight-line fit or wavelet analysis) may be problematic especially if the analysis is limited to Antarctic region without the help of other observatories localized in the Southern Hemisphere. In this paper we reconstructed the intensity maps relative to the last three jerks in Antarctic region by merging the analysis of the trend of the secular variation recorded in Antarctic observatories with that coming from other Southern Hemisphere observatories. In order to evaluate the intensity distribution of a jerk, the secular variation time series must be fitted using a bilinear functional form. The point where the two straight lines intersect defines the time of the jerk event while the difference between the angular coefficients of the two straight lines before and after the jerk event defines the intensity of the phenomenon. Figure 7.5-3 shows intensity maps expressed in [nT yr^{-2}] for the last three jerks of 20th century. The three events appear similar in the intensity distribution structure and all three show a focus with a maximum intensity. A peculiar feature seems to appear in these maps, indeed it looks like the focus of the maximum of the jerk intensity rotates longitudinally during the years, from 120° E to 20° W and finally to 20° E. However, we cannot exclude that this result can be influenced by data non-uniformly distributed or by the data noise, where the noise is defined as error due to instrument drift and malfunction, calibration errors, man-made magnetic signals, and possible errors in the data processing that produces annual means.

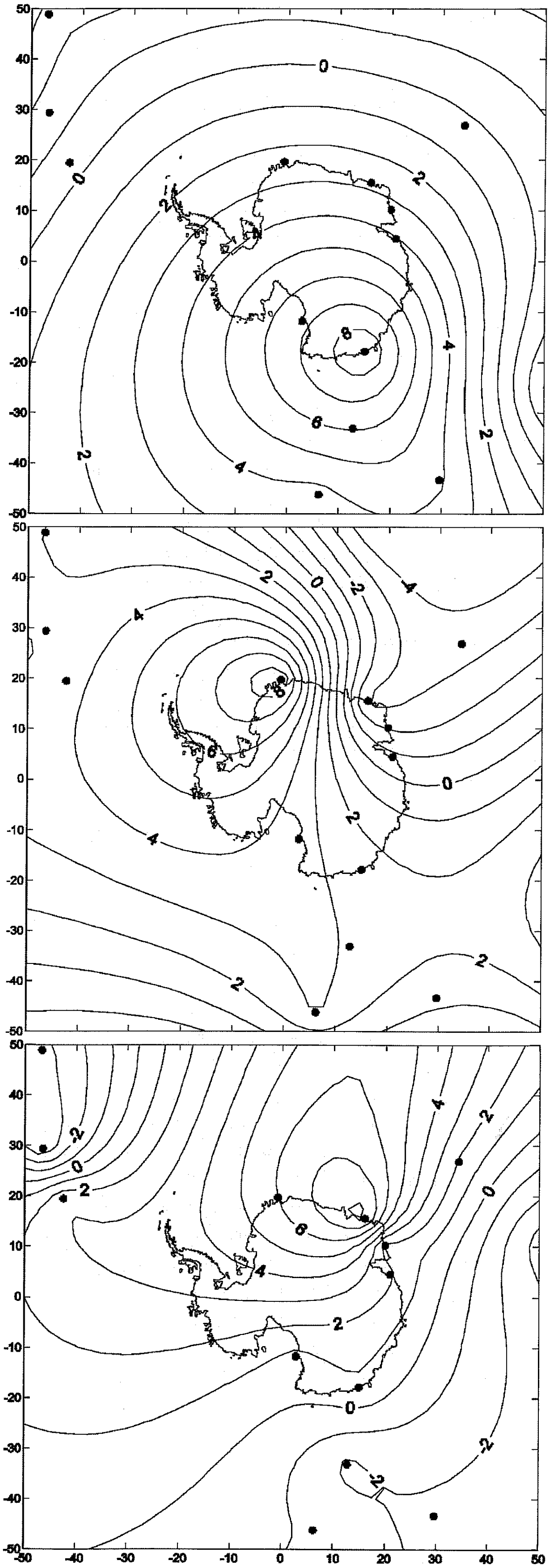

Fig. 7.5-3. Azimuthal equidistant projection of the spatial distribution of the jerk intensity relative to the last three jerks of 20th century: 1969 (*top*), 1978 (*centre*), and 1991 (*bottom*). These distributions, relative to the *Y*-component, have been obtained using observatories located both in Antarctic and in Southern Hemisphere (*full circles*)

Conclusions

Spherical Cap Harmonic Analysis has been applied to obtain a reference model of geomagnetic secular change for Antarctica (ARM) valid for the last forty years. This model improves the fit to the secular variation deduced from observatory data by about 60% relative to IGRF and allows merging data sets taken at different altitudes and epochs in Antarctica. Using this method we have had the opportunity to depict geomagnetic charts for each of the magnetic elements for a given epoch and elevation (a.s.l.).

We have also investigated the secular variation trend in Antarctic region focusing on its particular behaviour: geomagnetic jerks. In detail, using the annual mean values of the geomagnetic field components available for this region we evaluated the intensity distribution of the last three jerks of 20th century (1969, 1978, 1991). A rotation of the jerk focus has been found from a multi-station analysis even if we cannot exclude that this feature can also be influenced by the low quality of the used Antarctic observatory data and/or to the bad distribution coverage of the data. Naturally, we expect that more studies are still needed to better uncover the above found aspects. A better spatial and temporal distribution of the Antarctic observations will be of great importance to improve future investigations on SV characteristics.

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