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Geomagnetic field evolution. Changes on the way?

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High-quality observations have been obtained from a number of magnetic satellites, complementing the ground available data for the last decade. We present here the issues regarding observatory and satellite data, in order to show how these modern measurements have brought new insights in understanding the Earth's magnetic field. It is only when combined with ground-based data that satellite measurements can provide additional opportunities for studies ranging from core flow, mantle conductivity and lithospheric composition to the dynamics of the ionospheric and magnetospheric currents. Therefore, in this paper a case is presented for the necessity of continuous monitoring of geomagnetic field from ground and space. This contribution is mainly based on some recent work and publications we are co-authoring. *KEYWORDS: Geomagnetic field, secular variation, secular acceleration, satellite measurements.*

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Introduction

The study of planetary magnetism is directed mostly toward understanding the deep interior structure of a planet and the near-planet environment. On Earth, there have been over 150 years of continuous observations of the vector magnetic field, and spacecraft (MAGSAT, Ørsted, SAC-C, CHAMP) have provided a global coverage, thus making it possible to obtain a good, but still incomplete, knowledge of the detailed field morphology and evolution in time. To better understand the magnetic signals of our planet, we also need to go back in time, using historic, archeomagnetic and paleomagnetic information. Understanding planetary magnetism by exploring its diverse manifestations, needs to bring together scientists from different fields, from paleomagnetism to dynamo simulations.

At the Earth's surface, a compass needle swings until it aligns along a magnetic North–South direction. In reality, the Earth's magnetic field has a more complex geometry than a pure North–South axial dipole. Traditionally, and for obvious reasons, magnetic observations have been made at the Earth's surface. The magnetic field is thus commonly described in a local reference frame, either using the Cartesian (X – North, Y – East and Z – Vertical downward) components, or the angles D, I (declination and inclination).

When either a surface observatory or a satellite takes a geomagnetic field measurement, it represents the superposition of many sources. The greatest contribution is generally from the approximately dipolar field generated from the dynamo action within the fluid, iron-rich core of the Earth, known as the core field. Although depending upon the altitude and location of the reading, it may have sizable contributions from the static lithospheric field being generated largely from rock and remnant magnetism within the Earth's crust. Small signals can also be observed from the electrical currents generated by the flow of the oceans. Another significant contribution is that of external field sources, which originate in the ionosphere and magnetosphere. These variable sources include the daily solar quiet variations, the ring current variations, the contributions from the Disturbance Storm Time deviations, and the many other atmospheric current systems (e.g., the field-aligned currents and the auroral and equatorial electro-jets). One must also remember to include the currents induced in the Earth from these external fields. Sporadic magnetic storms and pulses, which have short-term effects, also play a role in the measured magnetic field values. To separate these contributions is not an easy task. However, in 1838 C. F. Gauss already

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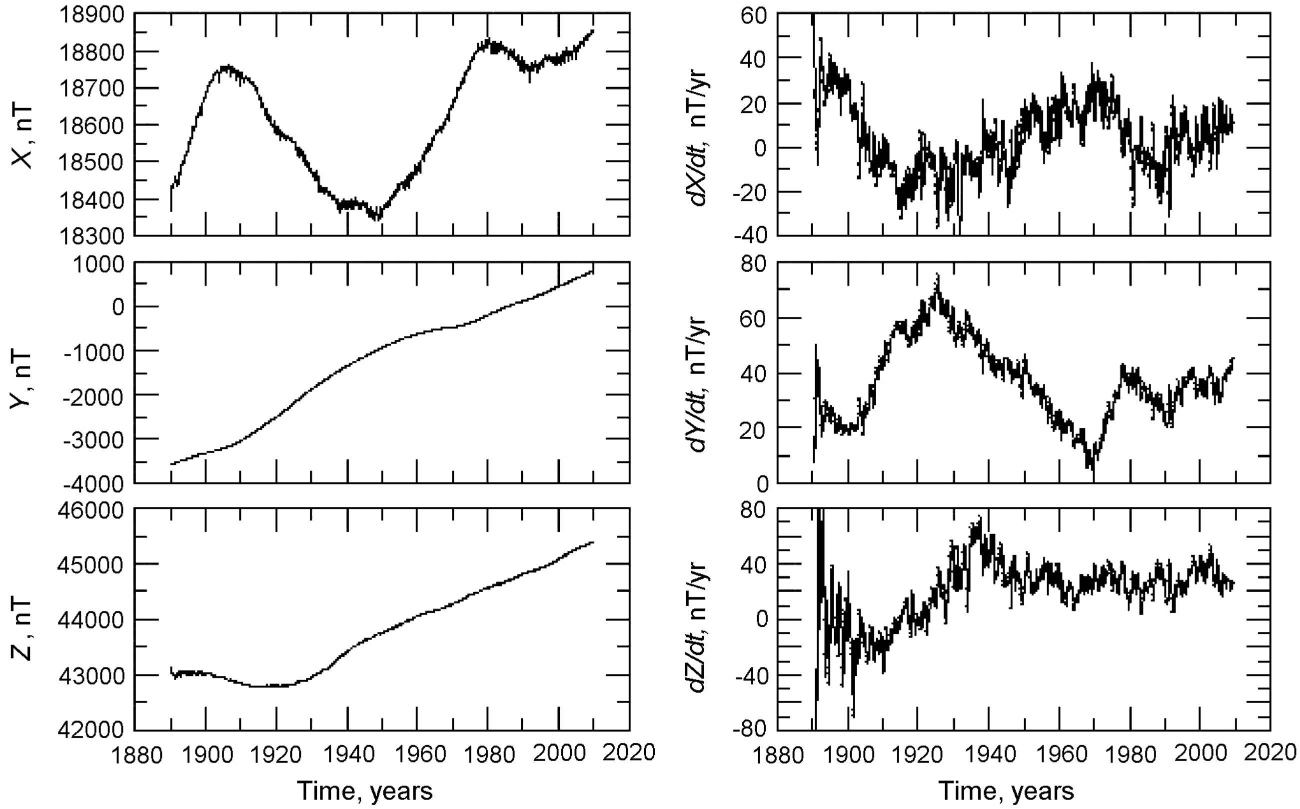

Figure 1. Temporal evolution of three geomagnetic field components X, Y, Z (in nT, left column) and their secular variation (in nT yr^{-1}) right column), as recorded in or adjusted to the Niemegk observatory, between January 1890 and December 2009.

proposed and used the spherical harmonics analysis of magnetic data and developed a model of the geomagnetic field, providing, for the first time, a separation between internal and external contributions to the geomagnetic field. More details on magnetic field contributions can be found in an overview paper by *Mandea and Purucker* [2005] or a book by *Mandea and Thébault* [2007].

The geomagnetic field is also subject to temporal variations over various time scales. The so-called short-term variations are detectable over time scales ranging from hundredth of seconds to decades. The very short period variations (seconds to hours) are usually attributed to the Earth's external sources, while the longer-period variations (annual to decades) are due to solar cycle variations and its harmonics superposed on the core field variation, known as secular variation.

The main part of the geomagnetic field is believed to be generated by convective motion in the Earth's iron-rich, electrically conducting, fluid outer core, by a process known as the geodynamo. This process is not fully understood, because only a few indirect observations exist to constrain it. According to the dynamo theory, the observed magnetic field is a product of this process, and its structure within the core is very complex. So, one can consider that the core field morphology at the Earth's surface is relatively simple, however it allows to estimate the fluid flow at the core-mantle boundary, and so a view on the interior of our Planet. The lithospheric (crustal) magnetic field is not only weaker, but also of much smaller spatial scale, when compared to the large scale core field. Its complexity goes back to geological and tectonic origins, and depends on magnetic minerals, mainly magnetite with varying content in titanium. Therefore, the lithospheric magnetisation is limited to a layer of about $10 - 50$ km in thickness, depending on the local heat flow, and again is a source of information about the Earth's interior.

Moreover, the geomagnetic field can have a significant influence on the dynamics of the various processes occurring in the envelopes surrounding our planet. The key factor is the force that magnetic field exerts on moving charged particles, forming this way our magnetosphere. The solar wind is then more efficiently deflected around the Planet. Recently, more and more evidences are accumulating to suggest that the magnetic field has a significant influence on shaping the air distribution of the Earth's upper atmosphere. There, ionized particles play a mediating role between the field and the atmosphere. For example, the highest air density and temperature above the Earth are not found at the sub-solar point, but at latitudes some 25° off the magnetic dip equator. Furthermore, there is an almost continuous up-welling

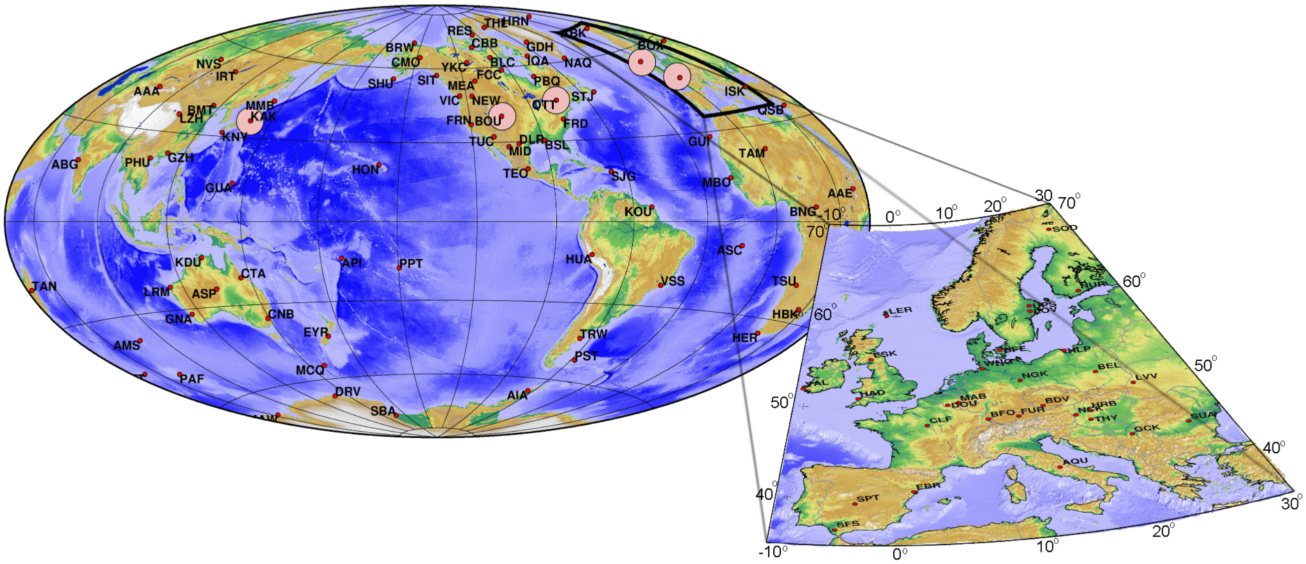

Figure 2. Distribution of the geomagnetic observatories operating in the frame of INTERMAGNET programme. Currently, six Geomagnetic Information Nodes are operating in Edinburgh (Scotland), Golden (Colorado), Kyoto (Japan), Hiraiso (Japan), Ottawa (Canada), Paris (France), and they are also indicated.

of air in the region of the ionospheric cusp. This may well be related to the observed outflow of atomic oxygen. Without the support of a geomagnetic field this element would be too heavy to leave the Earth's gravity field. On the other hand, the geomagnetic field prevents an excessive erosion of the atmosphere by the solar wind.

Observations of the geomagnetic field have been collected for over one hundred years, providing information about its morphology and time-evolution. One example is Niemegk observatory (Germany). Time variations, as shown in Figure 1, are revealed by continuous magnetic records where permanent installations of instruments at magnetic observatories ensure reliable measurements of the geomagnetic field over more than a century. Magnetic repeat-station measurements are also regularly made to determine the geomagnetic field at a particular location and to resolve the secular variation in that area. In addition, new satellite measurements, continuously available since 1999, have greatly improved our knowledge of the geomagnetic field all over the globe.

Measurements: From Ground-Based and Space Platforms

Two types of measurements are needed to characterise the geomagnetic field: scalar and vector. The Overhauser magnetometer, a type of proton precession or resonance magnetometer, is typically installed at magnetic observatories, but is also used for some other ground observations or on the Ørsted and CHAMP magnetic satellites. In contrast, vector measurements made with fluxgate magnetometers are subject to instrument drift. To minimise this drift contribution in the final data different approaches are used for ground or satellite measurements.

All modern land-based magnetic observatories use similar instrumentation to produce similar data products (for a full description see the INTERMAGNET web site http://www.intermagnet.org). Generally, the fundamental measurements recorded are averaged one-minute values of the vector components and of scalar intensity. The one-minute data are important for studying variations in the geomagnetic field external to the Earth, in particular the daily variation and magnetic storms. Data from a sub- network of observatories are used to produce the Kp and magnetic activity indices. From the one-minute data, hourly, daily, monthly and annual mean values are produced. The monthly and annual mean values are used to determine the secular variation generated from the Earth's core. Figure 1 shows the magnetic field evolution for the three components (North – X, East – Y, vertical – Z), and the corresponding secular variation, as measured at Niemegk observatory. It is very clear that the quality of secular-variation estimates (sometimes of the order of a few nT yr^{-1}) depends critically upon the quality of the measurements at each observatory. The secular variation plots indicate, mainly for the Y component, that there have been several abrupt changes having typical time scales of a few months. The most representative changes occur around 1925, 1969, 1978, 1992, 2000. These sudden changes known as geomagnetic jerks (or impulses) are not yet well understood; certainly they are not predictable.

Installed mainly on continents, the magnetic observatories are very unevenly and sparsely distributed (Figure 2). This is the reason why in some regions, as for example the Pacific Ocean, the ground-data based models uncertainty is very large. One possibility for improving the geomagnetic models

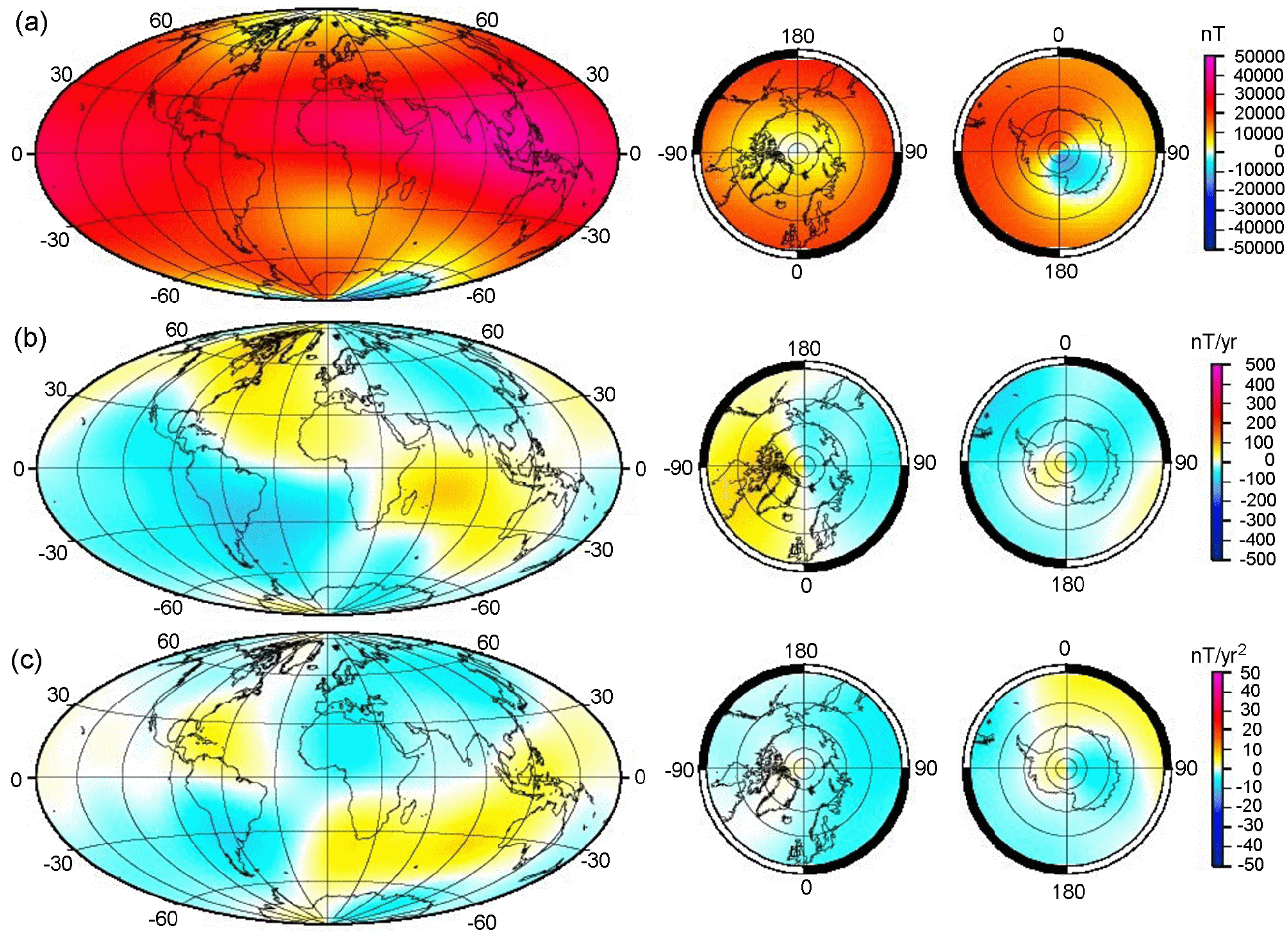

Figure 3. Contour maps of: (*a*) *X* component (in nT), (*b*) its secular variation (in nT year^{-1}) at 2010.0, (*c*) its secular acceleration at 2008.0 (in nT yr^{-2}). Geomagnetic field is represented at the Earth's surface.

in such areas is to consider some other sources of data, as those provided during the last decade by satellites.

The Danish ⊘rsted satellite (http://www.spacecenter.dk/research/solarphysics/orsted), launched in 1999, opens the decade dedicated to measuring the magnetic field from space, being followed by CHAMP and the less successful SAC-C. The primary goals of this mission have been to study the variations of the magnetic field of the Earth and its interaction with the sun particles stream. As a result, the satellite altitude is too high to provide us with a high resolution view of the core and lithospheric field sources. The CHAllenging Minisatellite Payload (CHAMP) is a German satellite, in a low orbit. Since its launch on July 15, 2000, this satellite has supplied high precision, invaluable magnetic, gravity, and ion drift measurements. The geomagnetic field measurements, coupled with the other orbiting missions have allowed for the development of global field models of the core and its secular variation with unprecedented resolutions. Recent examples would include core field models like the CHAOS [*Olsen et al.*, 2009] or GRIMM series [*Lesur et al.*, 2008] and static lithospheric field models such as MF series [*Maus et al.*, 2008].

Geomagnetic Models – Windows to the Deep Earth's Interior

Near the Earth's surface, in a source-free region, the magnetic field is expressed as the negative gradient of a scalar potential that satisfies Laplace's equation. A solution to Laplace's equation in spherical coordinates is expressed by a combination of spherical harmonics weighted by Gauss coefficients. Internal or external sets of coefficients are used for modeling the field generated inside or outside the Earth, respectively. For its internal part, the separation of the core and lithospheric fields is considered to be around spherical harmonic degrees 13–15.

Some very accurate geomagnetic models describe the Earth's magnetic field over the last decade. The CHAOS or GRIMM series model the geomagnetic field up to spherical harmonics degree larger than 50 for the static field, for degrees as large as 13 for the first time derivative (secular variation), and 8 for the quadratic and cubic time derivatives. Both model series have been developed using geomagnetic measurements from ⊘rsted, CHAMP and SAC-C,

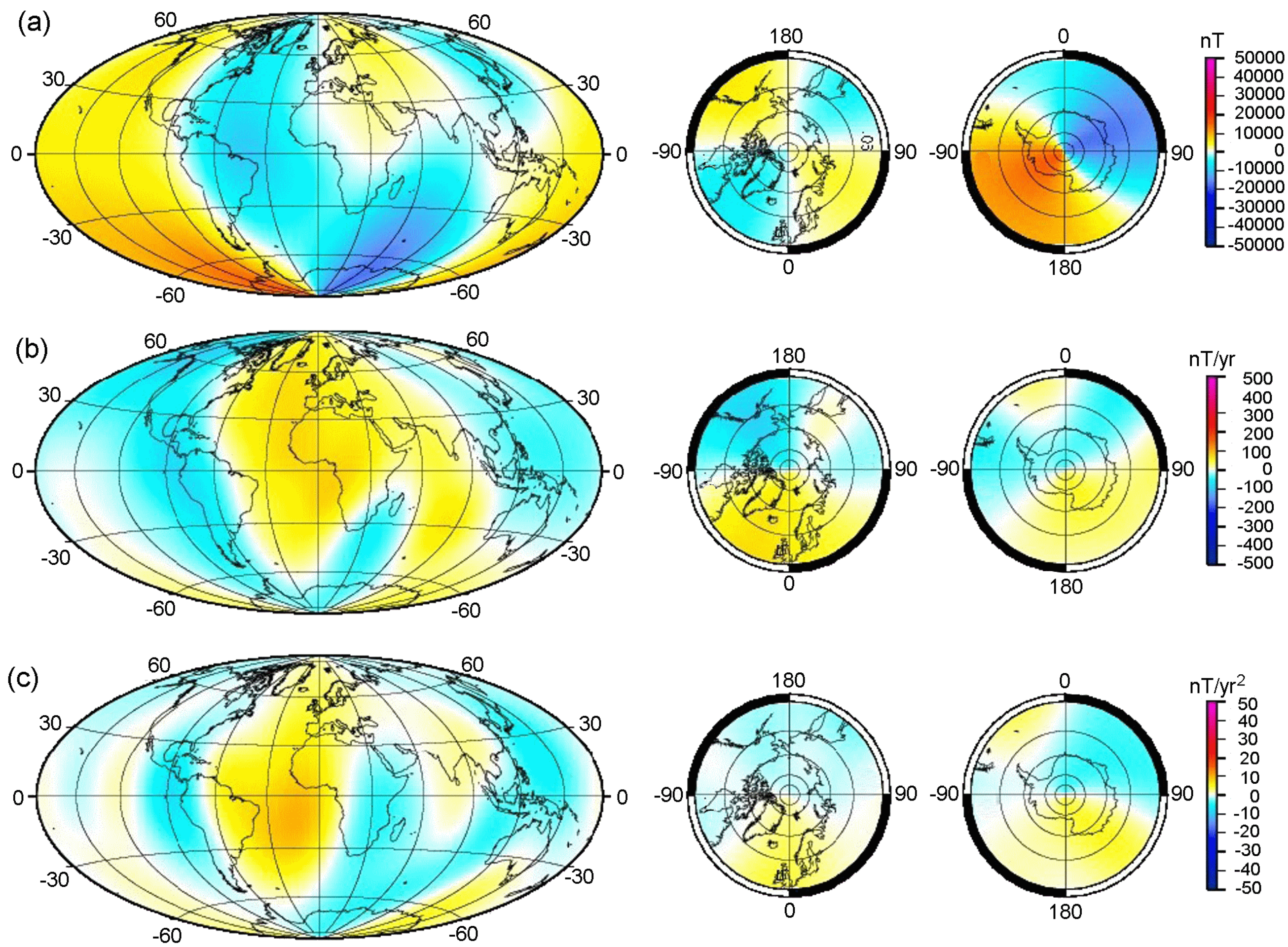

Figure 4. Contour maps of: (*a*) Y component (in nT), (*b*) its secular variation (in nT year^{-1}) at 2010.0, (*c*) its secular acceleration at 2008.0 (in nT yr^{-2}). Geomagnetic field is represented at the Earth's surface.

spanning a decade of high-precision geomagnetic satellite data. They also incorporate into their datasets hourly means provided by geomagnetic observatories. Temporal variation of the core field is described by splines. They are able to co-estimates the Euler angles that describe the transformation from the magnetometer frame to the star imager frame, thus avoiding the inconsistency of using vector data that have been aligned using a different (pre-existing) field model. They also co-estimates the large scale contribution of external origin.

This kind of field representation makes it possible to build maps for the core field, its secular variation and acceleration at the Earth's surface. Figure 3, Figure 4, and Figure 5 show maps of values at the Earth's surface of the X, Y, Z components at epoch 2010.0, i.e. on 1 January 2010, and also their predicted secular variations. Moreover, the secular acceleration is plotted, for epoch 2008.

A crucial interest comes for describing the vertical component and its secular variation at the core-mantle boundary (Figure 6), using these two quantities makes it possible to estimate flow motions at the top of the core. The structure of the vertical field at the core surface is considerably more complicated than at the surface, because higher degree spherical harmonics are amplified during the downward continuation procedure. This is one reason why it is preferable to downward continue regularized field models rather than those that have been simply truncated, and may contain noise contributions in the higher degree spherical harmonics.

One of the most prominent features in the maps of the vertical field at the core surface is the high-intensity flux patches (the areas of flux maxima, of either sign) under Arctic Canada and Siberia in the Northern hemisphere, and under the eastern and western edges of Antarctica. These lobes are responsible for the predominantly axial dipole field structure observed at the Earth's surface.

We cannot predict the long term changes in Earth's core, but it is inevitable that the field will continue to exhibit secular variation on all time scales [*Olsen and Mandea,* 2008] and the current dipole moment will continue to change. If the dipole moment drops to 50% of its current value one can expect a corresponding decrease in the radius of the magne-

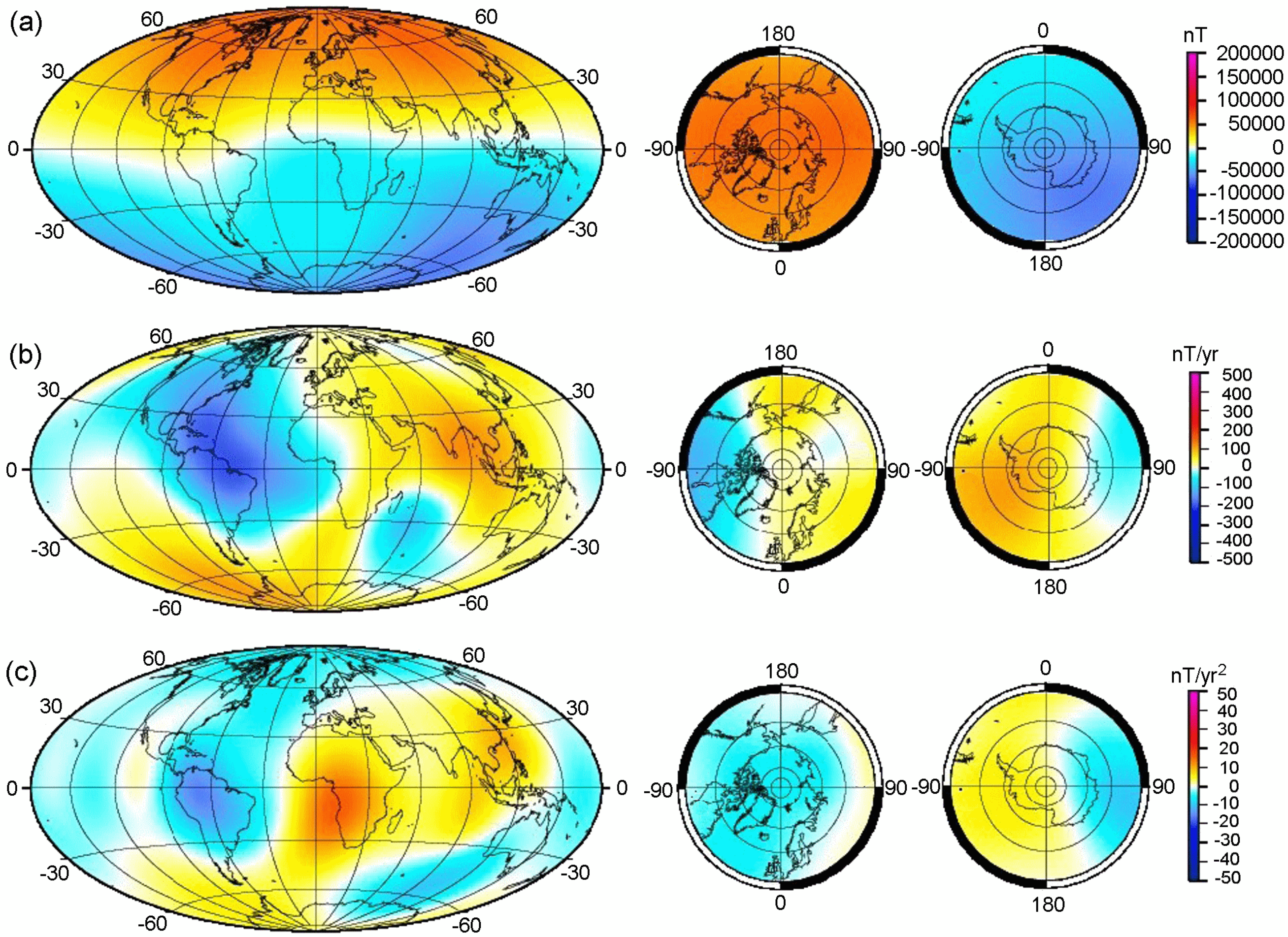

Figure 5. Contour maps of: (*a*) Z component (in nT), (*b*) its secular variation (in nT year^{-1}) at 2010.0, (*c*) its secular acceleration at 2008.0 (in nT yr^{-2}). Geomagnetic field is represented at the Earth's surface.

tosphere, whose size is controlled to first order by a balance between static pressure generated by the geomagnetic field and the dynamic pressure of the solar wind. One should expect such changes to influence cosmic ray activity in the upper atmosphere as well as the nature and impact of geomagnetic storms. The effect of increased radiation dosage due to enhanced cosmic ray activity on the evolutionary development of individual species is generally considered to be negligible, but the influence of space weather is less clear...

Conclusions

To even better understand the planetary magnetic fields, with contributions internal and/or external in origin, we must take advantage of the unique situation in the geomagnetism observation which will come in the imminent future. The ESA mission Swarm is planned for 2011. The objective of the Swarm mission is to provide the best-ever survey of the geomagnetic field and its temporal evolution, as well as gain new insights into improving our knowledge of the Earth's interior and climate [*Friis-Christensen et al.*, 2004]. This multi-satellite mission will be able to take full advantage of a new generation of magnetometers, and enables measurements to be taken simultaneously over different regions of the Earth. This mission is accompanied by a dramatically improvement of the ground observation distribution, particularly in key areas such as the South Atlantic Anomaly, and of the quality of data they produce.

For describing specific contributions to the geomagnetic field, an "experimental design" approach, as it is sometimes applied for seismic surveys, is useful for studying the planetary magnetic field, because it has a strong impact on the quality of the final results. Closely related to this is the estimation of best accuracy than can be expected for a model and what is its true "error" in a model. Some mathematical and statistical tools exist to estimate these errors or error bounds, but they need to be applied or adapted to magnetic models. To improve the quality of models, new regulariza-

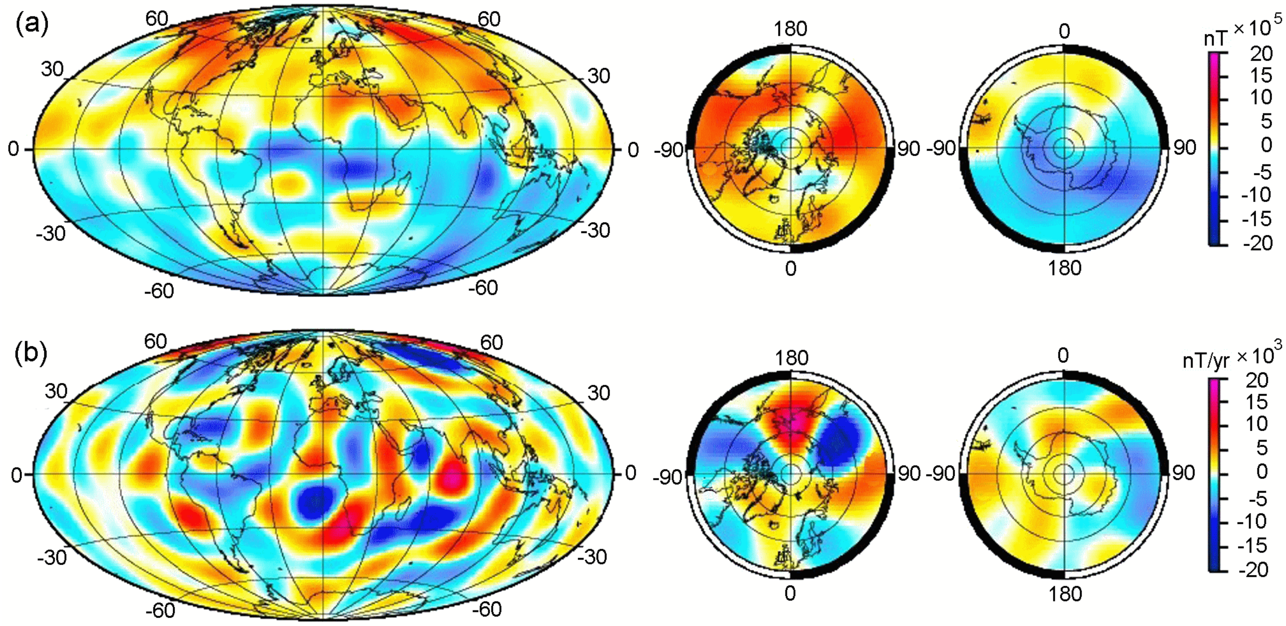

Figure 6. Contour maps of: (*a*) Z component (in nT), (*b*) its secular variation (in nT year^{-1}) at 2010.0, at the core-mantle boundary.

tion techniques are necessary, and this is especially true for modeling the geomagnetic field in area where relatively few data are available. As magnetic data are often inhomogeneous in terms of quality and/or density, localized modeling approaches are needed. These local modeling techniques are still in development and it is not yet known how to estimate the accuracy of the resulting models. Significant improvements in our understanding of the sources and behavior of geomagnetic field can be expected through the development of such mathematical tools and techniques.

But observation and data analysis are not the only key factors for the near future. Numerical simulations are the prime tools to explore magnetohydrodynamical processes linked to the Earth's dynamo. They have been very successful in explaining many features of the geomagnetic field and can be expected to improve our understanding of the geomagnetic field. Laboratory dynamo experiments are a necessary complement of numerical simulations because numerical models cannot employ the parameters appropriate for the Earth's core. In particular, fluid viscosities are generally many orders of magnitude too large in order to damp the small scale turbulence that can not be resolved with today computers. Laboratory experiments, on the other hand, work with realistic fluids but have to adopt unrealistic geometries and driving mechanisms. A close collaboration of both research areas can help to bridge the gap between models and reality. Experimental and numerical dynamos also play a key role for understanding the fundamental processes of magnetic field generation. The flexibility of the setups allows one to conduct systematic studies that can help elucidate the rather complex interaction of magnetic and convective processes in the dynamo regions.

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