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Spatial and temporal resolution of millennial scale geomagnetic field models

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Abstract

We assess the resolution and reliability of CALS7xK, a recently developed family of global geomagnetic field models. CALS7xK are derived from archaeo- and palaeomagnetic data and provide a convenient temporally varying spherical harmonic description of field behaviour back to 5000 BC. They can be used for a wide range of studies from gaining a better understanding of the geodynamo in the Earth's core to enabling the efficient determination of the influence of the geomagnetic field on cosmogenic nuclide productions rates. The models are similar in form to those derived from modern satellite observations, observatory and historical data, and used for the International Geomagnetic Reference Field, but their spatial and temporal resolution are limited by data quality and distribution. We find that spatial power is fully resolved only up to spherical harmonic degree 4 and temporal resolution is of the order of 100 years. Significant end effects associated with the temporal development in natural B-splines affect some features of the models in both the earliest and most recent century. Uncertainties in model predictions of declination, inclination and field intensity in general are smaller than 2° and 1.5 μT respectively, but can be as large as 8° and 5 μT for certain regions and times. The resolution studies are complemented by a detailed presentation of dipole moment and dipole tilt as predicted by the model CALS7K.2. These largest scale features are resolved more reliably than complex details of the field structure and are useful, for example, in studies of geomagnetic cutoff rigidities of cosmogenic isotopes.

Keywords: Geomagnetic field model; Dipole moment; Archaeomagnetism

1. Introduction

The geomagnetic field surrounds the Earth like a giant shield, influencing the path of the solar wind and the trajectories of solar particles and cosmic rays. At the Earth's surface, a dipole currently tilted by about 11° accounts for 90% of the observed geomagnetic field. The main part of the internal or core field is caused by the geodynamo operating in the fluid outer core of the Earth. The region around the Earth which is influenced by the magnetic field is the magnetosphere, and electric currents flowing in various regions within the magnetosphere cause additional magnetic fields, the so-called external field contributions. The magnetosphere extends to about 10 Earth radii on the sun-ward side and is stretched far out under the influence of the solar wind on the side away from the sun. Whether incoming particles can reach the atmosphere or not is determined by their energy and the geomagnetic field strength, which sets the geomagnetic cutoff rigidity. Only particles with energies above a certain level can penetrate the magnetic field and reach the atmosphere.

Models that describe the magnetosphere and near-Earth geomagnetic field are used to study geomagnetic cutoff and cosmogenic nuclide production rates. A series of such models has been developed by Tsyganenko and co-workers (Tsyganenko, 1995, 2000, 2002a,b; Tsyganenko et al.,

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2003; Tsyganenko and Sitnov, 2005),[1] describing the time-varying magnetosphere as a function of orientation of the magnetic dipole axis relative to the sun, solar activity and interplanetary magnetic field. In these models the geomagnetic main field is sometimes simply approximated by an axial dipole, but this is a crude assumption which might lead to significant errors in geomagnetic cutoff calculations. The dipole tilt and significant deviations from simple dipole symmetry in some regions of the Earth are not in general small enough to be considered negligible. These effects can be taken into account if geomagnetic main field models like the International Geomagnetic Reference Field (IGRF,[2] e.g. Macmillan et al., 2003) are used. Main field models are based on a spherical harmonic representation where the field is described through the sum of the best-fitting tilted dipole (spherical harmonic degree 1) and more complex structure from higher spherical harmonic degrees.

Ice cores or rocks of the Earth's crust can contain isotopes which offer the possibility to study past rates of nuclide production (mainly ^{10}Be, ^{14}C, ^{36}Cl), used to determine past solar irradiation rates and climate changes (e.g. Solanki et al., 2004). These nuclide production rates, however, are also influenced by the temporal variability of the geomagnetic field (e.g. Elsasser et al., 1956; Lal, 1988; Stuiver et al., 1991; Masarik and Beer, 1999; Muscheler et al., 2005). Dipole strength, dipole tilt and the more complex features of the geomagnetic field all change with time, but the first two clearly have the strongest influence on global production rates on the time scale of several thousand years. Changes of the geomagnetic field on the millennial time-scale, however, have not been known in much detail until recently. Virtual (axial) dipole moments (VDMs, VADMs) and virtual geomagnetic pole positions (VGPs) were used to describe the field evolution from the limited amount of archaeo- and palaeomagnetic data available. A problem with these descriptions is that they cannot correctly account for contributions from the non-dipole field (VDMs, VGPs) or even the non-axial dipole field (VADMs). This leads to significant uncertainties in determining the geomagnetic dipole moment, and causes systematic errors of the kind shown by Korte and Constable (2005b) for VADM estimates of the past 7 kyrs (McElhinny and Senanayake, 1982; Yang et al., 2000). A further problem is that in attempts to minimise the influence of the more complex field contributions, VDMs and VADMs are usually averaged over periods of several centuries to a millennium, significantly limiting the temporal resolution of such dipole moment estimates.

With the advent of global palaeofield modelling, more detailed studies of geomagnetic field behaviour have become feasible. First attempts were made by Ohno and Hamano (1993) and Hongre et al. (1998). The limited global distribution of available data led them to truncate the spherical harmonic expansion at low degrees. While the data distribution limits the resolution of smaller spatial scales, a simple truncation of the series leads to spatial aliasing effects, i.e. mapping of power from more complex structure into dipole and quadrupole coefficients, thus affecting the reliability of even these strongest field contributions. Constable et al. (2000) were the first to expand the spherical harmonic series to higher degrees and apply regularisation techniques in the same way as used in models from current data to avoid spatial aliasing effects. The first model only consisted of snapshots every 100 years for the past 3000 years, but in the meantime this family of models has been improved first by using a description that is continuous in time (CALS3K.1 (Korte and Constable, 2003)), then constraining the models by a larger amount of data (CALS3K.2) and extending them further back in time. The latest version is CALS7K.2 covering the time span from 5000 BC to 1950 AD (Korte and Constable, 2005a) and further extensions to 10 kyr seem feasible (Korte and Constable, 2006b).

Here we summarise the general characteristics of the CALSxK family of models and the particular properties of the latest version, CALS7K.2. We present uncertainty estimates for model predictions, discuss limitations of the model for various applications and show the evolution of dipole moment strength and tilt as predicted by the model.

2. The model

2.1. Data and method

The name CALSxK.*n* stands for Continuous models of Archaeomagnetic and Lake Sediment data for the past x kyrs, with the version number of the model indicated by the integer *n*. CALSxK models are constructed entirely from palaeomagnetic data, which overlap temporally with systematic direct observations of geomagnetic field directions for about 400 years (Jonkers et al., 2003) and with absolute field intensity for less than 200 years (Gauss, 1839). Although it might be argued that a superior field model could be constructed by combining both historical and palaeofield data, the exclusion of historical observations allows them to be used in an important check on the validity of CALSxK against relatively high quality data for 1590–1950 AD.

The indirect palaeomagnetic archives are provided by archaeological materials, lavas, and sediments which acquired and preserved a magnetisation related to the geomagnetic field at some time in the past. In hot lava, or clay which is fired to form bricks or vessels, the magnetic moments associated with ferromagnetic minerals in the material preferentially align with the ambient geomagnetic field. This magnetisation is "frozen in" when the material cools below the Curie-temperature of the magnetic minerals, acquiring a thermoremanent magnetisation. During sedimentation, magnetic grains are preferentially aligned with the geomagnetic field during the depositional process,

[1] http://nssdc.gsfc.nasa.gov/space/model/magnetos/data-based/modeling.html.

[2] http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html.