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# The South Atlantic Anomaly throughout the solar cycle

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The Sun–Earth's interaction is characterized by a highly dynamic electromagnetic environment, in which the magnetic field produced in the Earth's core plays an important role. One of the striking characteristics of the present geomagnetic field is denoted the South Atlantic Anomaly (SAA) where the total field intensity is unusually low and the flux of charged particles, trapped in the inner Van Allen radiation belts, is maximum. Here, we use, on one hand, a recent geomagnetic field model, CHAOS-6, and on the other hand, data provided by different platforms (satellites orbiting the Earth – POES NOAA for 1998–2014 and CALIPSO for 2006–2014). Evolution of the SAA particle flux can be seen as the result of two main effects, the secular variation of the Earth's core magnetic field and the modulation of the density of the inner radiation belts during the solar cycle, as a function of the $L$ value that characterises the drift shell, where charged particles are trapped. To study the evolution of the particle flux anomaly, we rely on a Principal Component Analysis (PCA) of either POES particle flux or CALIOP dark noise. Analysed data are distributed on a geographical grid at satellite altitude, based on a L-shell reference frame constructed from the moving eccentric dipole. Changes in the main magnetic field are responsible for the observed westward drift. Three PCA modes account for the time evolution related to solar effects. Both the first and second modes have a good correlation with the thermospheric density, which varies in response to the solar cycle. The first mode represents the total intensity variation of the particle flux in the SAA, and the second the movement of the anomaly between different L-shells. The proposed analysis allows us to well recover the westward drift rate, as well as the latitudinal and longitudinal solar cycle oscillations, although the analysed data do not cover a complete (Hale) magnetic solar cycle (around 22 yr). Moreover, the developments made here would enable us to forecast the impact of the South Atlantic Anomaly on space weather. A model of the evolution of the eccentric dipole field (magnitude, offset and tilt) would suffice, together with a model for the solar cycle evolution.



## 1. Introduction: the particle flux in the South Atlantic Anomaly

Electromagnetic radiation and charged particles from the Sun constantly reach the Earth. The Sun–Earth interplanetary space is populated with magnetic fields and particles carried by the solar wind to form a highly dynamic electromagnetic environment around the Earth. This environment interacts with the Earth's magnetic field, and this interaction is of a high complexity due to the underlying physical processes and the diversity of the temporal and spatial scales that characterize geomagnetic field sources.

One important ingredient in analyzing the Sun–Earth electromagnetic interaction is the morphology and temporal variations of the main geomagnetic field, originating from magnetohydrodynamic processes in the Earth's outer core. This contribution to the measured magnetic field is complemented by the lithospheric field (however, not of interest in our study, as considered as constant over the temporal scales we are interested in), and the external fields, linked to processes in the ionosphere and magnetosphere. The observation and analysis of the main characteristics of the geomagnetic field at the Earth's surface, together with their variations, have enabled the elaboration of data-based models and numerical geodynamo simulations that have been successful in providing explanations for features of the field such as its predominantly dipolar character, secular variation and field reversals (e.g. Christensen et al., 2010; Olson et al., 2014). One of the striking characteristics of the present geomagnetic field is a region denoted the South Atlantic Anomaly (SAA), where the total field intensity is unusually low. There, the field intensity reaches less than 60% of the field strength at comparable latitudes. The loca-

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tion of the minimum has moved from Southern Africa to South America over the last 300 yr (Mandea et al., 2007; Hartmann and Pacca, 2009). The total dipole strength has diminished by 9% from 1840 to 2015, although the field decrease occurs non-uniformly over the globe. Presently, the decrease of the field intensity, which is accurately mapped from low Earth orbiting satellites, is also observed in the Southern African–Southern Atlantic region (Finlay et al., 2016). The weakness of the field intensity in the SAA is caused by a patch of opposite magnetic flux compared to the dipole direction at the core–mantle boundary (Bloxham et al., 1989; Olson and Amit, 2006), stressing that the main contribution to the SAA is internal. This inverse flux patch at the core–mantle boundary (CMB) has been growing continuously from the beginning of the 19th century (Jackson et al., 2000).

We can try to dispense with some of the complexity of the main field to describe the Earth's magnetosphere. The large-scale geomagnetic field is conveniently approximated as a dipole offset from the Earth's centre (e.g. Fraser-Smith, 1987), a simplified model which already takes into account most of the SAA (e.g. Heynderickx, 1996). In this dipole reference frame, the drift shells that trap charged particles are described by the equation $r = L\sin^2\theta$, where $\theta$ is the colatitude, $r$ is distance from the dipole centre and Earth's radius is unit of length. Each value of the $L$ parameter defines a separate shell. The particles population of the shells is depleted through interactions in the atmosphere and the flux of energetic protons (in the range $\sim$ 10 MeV–1 GeV) is particularly high for $L$ values between around 1 and 3 (with maximum at about $L = 1.5$), in the so-called inner radiation belt (Selesnick et al., 2014). Due to the dipole offset towards the western Pacific, the inner Van Allen radiation belt gets closer to the Earth over the SAA region. This means that the mirror points where trapped particles bounce in their spiralling around field lines lie at much lower altitudes there than elsewhere (Vernov et al., 1967; Gledhill, 1976).

The eccentric dipole is currently offset from the Earth's centre by about 550 km in a direction approximately 22°N, 140°E. This distance is steadily increasing and the location of the eccentric dipole centre is drifting in the westward direction and slightly northward. In the antipodal direction, which corresponds to the location of the SAA, the drift shells get closer to the Earth's surface and move mainly westward and slightly southward. We thus have three ways to describe the SAA position, either as the location of a local minimum of the magnetic field intensity (for a given altitude), as the place where the flux of charged particles is maximum, or as the location of the antipodal point of the geographic location of the eccentric dipole (Heynderickx, 1996). These three descriptions are obviously connected, as the high particle counts observed in the SAA region are correlated with the local weakness of the Earth's magnetic field which can be explained in terms of the departure of the eccentric dipole. Despite this fact, the three approaches to define the SAA provide images which are not completely identical, the shape and even evolution of the anomaly being different. This provides the motivation for a dedicated study of the SAA morphology and evolution.

So far we have outlined the contribution of the main geomagnetic field morphology for the intense radiation fluxes met by satellites over the South-Atlantic Brazilian coast region. An accumulation of satellite data since the 60s has brought to light decadal and sub-decadal variability of the SAA, seemingly due to particle feeding and depletion mechanisms in the inner radiation belt (e.g. Gledhill, 1976; Selesnick et al., 2014). The neutral atmosphere expands during the ascending phase of the solar cycle and, at altitudes above 100 km, its density increases (Solomon et al., 2013). As a result, in regions where mirror points are low enough, protons are removed from the inner belt through nuclear collisions with atmospheric neutral particles (Gledhill, 1976), explaining why the particle flux in the SAA region is anti-correlated with the solar activity as measured by the 10.7 cm radio flux of the Sun (Fürst et al., 2009; Casadio and Arino, 2011; Qin et al., 2014). This effect is maximized for the low values of $L$ that correspond to the highest energy proton shells (Vacaresse et al., 1999). Different source mechanisms are thought to be responsible for feeding the inner-belt with lower ($\lesssim$ 40 MeV) and higher energy protons, the trapping of solar protons for the former and the beta decay of neutrons created as a result of the interaction of galactic cosmic rays with the upper atmosphere (CRAND mechanism) for the latter (Selesnick et al., 2014). Finally, an annual variation of the SAA has recently been described (Schaefer et al., 2016).

Also important to stress is the hazard due to the unusually high flux of high energy particles in the SAA region, resulting in significant space weather effects in space, such as satellite outages (Heirtzler, 2002) or even on ground, as in communications, induced currents in pipelines and transmission lines (Pulkkinen et al., 2012; Boteler and Pirjola, 2014). High energy protons affect the oscillator of space clocks in the SAA region (Belli et al., 2015; Capdeville et al., 2016). They also hit the detectors of stellar cameras on board Low Earth Orbiting (LEO) satellites, such as CoRoT (Auvergne et al., 2009). All these practical concerns together with a large amount of available data, make studies contributing to a more accurate description of the SAA both relevant and timely.

Here, we are interested in using data sets provided by different platforms. We take advantage of information provided by different satellites orbiting the Earth and carrying diverse instruments. For the particle flux studies we have used two different data sets, the proton omni-directional detections from the POES NOAA 15 satellite (Evans et al., 2008) and the dark noise data from the CALIPSO satellite (Noel et al., 2014). In order to describe the main magnetic field and the evolution of the eccentric dipole, the most recent CHAOS model, CHAOS-6, was used (Finlay et al., 2016). Unlike most previous authors who chose either Gaussian (e.g. Konradi et al., 1994) or Weibull (Fürst et al., 2009) functions to describe the shape of the SAA, we do not assume a priori geometry of the anomaly. Spatial patterns emerge instead from the Principal Component Analysis (PCA) of either POES particle flux or CALIOP dark noise data, which are distributed on a geographical grid.

The paper is organized as follows. The data and models are described in the next section. Thereafter, in section 3, we present our methods to investigate the data sets. Results are presented in section 4. Finally, we discuss these results and conclude.

## 2. Data and models available

### 2.1. CHAOS-6 model

The CHAOS-6 model (Finlay et al., 2016) is the latest in the CHAOS series of Earth magnetic field models (Olsen et al., 2006). It combines data from some 160 ground observatories (annual differences of revised monthly means) together with satellite data, including the most recent Swarm data, collected from a 3-satellite constellation in orbit since end of 2013 (Olsen et al., 2015). The time variation of the field is described by cubic B-splines with 6 months knot spacing, from 1996 to 2016.5. The actual temporal resolution is not so high because of regularisation. The model is precise enough to resolve peaks of secular acceleration (second time derivative of the field) separated by about 3 yr, up to harmonic degree $n = 15$. We have used it to identify trends of the SAA that depend on the morphology of the main field, such as the latitude and longitude of the location of minimum field intensity and the time evolution of this minimum. The evolution of the minimum depends on the spherical surface on which it is calculated. At the surface of the Earth, a westward drift of 0.30°/yr