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Geomagnetic activity at Northern Hemisphere's mid-latitude ground stations: How much can be explained using TS05 model

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ABSTRACT

For the 2007 to 2014 period, we use a statistical approach to evaluate the performance of Tsyganenko and Sitnov [2005] semi-empirical model (TS05) in estimating the magnetospheric transient signal observed at four Northern Hemisphere mid-latitude ground stations: Coimbra, Portugal; Panagyurishte, Bulgary; Novosibirsk, Russia and Boulder, USA. Using hourly mean data, we find that the TS05 performance is clearly better for the X (North-South) than for the Y (East-West) field components and for more geomagnetically active days as determined by local K-indices. In $\sim 50\%$ (X) and $\sim 30\%$ (Y) of the total number of geomagnetically active days, correlation values yield $r \geq 0.7$. During more quiet conditions, only $\sim 30\%$ (X) and $\sim 15\%$ (Y) of the number of analyzed days yield $r \geq 0.7$. We compute separate contributions from different magnetospheric currents to data time variability and to signal magnitude. During more active days, all tail, symmetric ring and partial ring currents contribute to the time variability of X while the partial ring and field aligned currents contribute most to the time variability of Y. The tail and symmetric ring currents are main contributors to the magnitude of X. In the best case estimations when $r \geq 0.7$, remaining differences between observations and TS05 predictions could be explained by global induction in the Earth's upper layers and crustal magnetization. The closing of field aligned currents through the Earth's center in the TS05 model seems to be mainly affecting the Y magnetospheric field predictions.

1. Introduction

The geomagnetic field measured on the ground is the sum of contributions from very different sources: the Earth's core field (main field), the field of magnetized lithosphere (crustal field), the primary fields of magnetospheric and ionospheric current sources and their secondary contributions due to Faraday induction in the electrical conducting crust and upper mantle (e.g., Hulot et al., 2010). Among these, geomagnetic activity reflects the disturbances in ionospheric and magnetospheric fields due to the interaction with charged particles and electromagnetic radiation from the Sun as well as corresponding induced fields in the crust and mantle. To study the observed geomagnetic activity, at least some basic knowledge of the remaining components is required so that they can be removed or modeled together with the activity signal.

The main and crustal magnetization fields remain constant during a 1-day period, contrary to the other components. They determine the baseline at each station. The main field, due to a dynamo powered by convection in the liquid core of the Earth, can be modeled by an eccentric tilted dipole (e.g., Campbell, 2003). Smaller-scale features can however be resolved from ground-based and low-orbit satellite geomagnetic data, and the field is represented by spherical harmonic (SH) models up to degree 10 to 13. The International Geomagnetic Reference Field model IGRF-12 (Thébault et al., 2015) was used in our study. This model provides sets of definitive SH coefficients at 5-years interval from 1900.0 to 2010.0 and a non-definitive model for 2015.0. Corresponding values at mid-latitude observatories amount to $\sim$ 45000–60000 nT in intensity. Since the geometry and amplitude of magnetospheric and ionospheric current systems is strongly constrained by the geometry and amplitude of the main field (e.g., Pedatella et al., 2011), models as IGRF-12 are also included into magnetospheric models (e.g., Tsyganenko and Sitnov, 2005). The large-scale crustal field can be modeled by internal SH coefficients of degree between $\sim$ 16 and a maximum value above 100 that

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depends on the model (Thébault et al., 2010). However, short wavelengths are currently still difficult to assess, due to distortion by data processing and model regularization. In practice, the crustal field at ground-based stations, which may vary from almost zero to $\sim$ 200 nT (e.g. Mandea and Langlais, 2002), can not be obtained from these models. All the three remaining components of the near-Earth field, namely magnetospheric, ionospheric and induction fields, contribute to the geomagnetic activity observed at the ground level.

Geomagnetic indices are computed from observations of geomagnetic field sub-daily variations at the Earth's surface and, like observations, they display integrated information on various external currents. Different indices use data from different subgroups of magnetic observatories, being representative (proxies) of regional geomagnetic activity (e.g., Mayaud, 1980; Menvielle et al., 2011). At mid-latitudes, the indices Kp (planetary K) and Dst (disturbance storm-time) are the most utilized. The 3-h period planetary Kp index characterizes different levels of global geomagnetic activity in broad terms, ranging from 0 to 9 (e.g., Mayaud, 1980). It is related quasi-logarithmically to the geomagnetic amplitude measured in the most disturbed horizontal magnetic field component, at a group of 13 given sub-auroral stations. Kp values of 4 have been used to separate calm from storm time periods (e.g. McCollough et al., 2008). For a description of geomagnetic activity at a given site, local K-indices are computed from the data of the magnetic observatory at that site. Another index, the 1-h time resolution Dst index, is linearly related to the amplitude of perturbations and has a higher time-resolution compared to K-indices. Dst values are derived from hourly values of H (the horizontal field) obtained at four given magnetic observatories distributed evenly in longitude (e.g., Sugiura, 1964; Mayaud, 1980).

1.1. Tsyganenko magnetospheric models

Earth's magnetospheric models like those of Tsyganenko and collaborators (T/TS models) provide a description of geomagnetic activity due to magnetospheric sources (see Tsyganenko, 2013; for a review). In these models, the storm-time magnetospheric contribution for the geomagnetic field has been resolved into different separate terms that reflect different current geometries with specific external drivers, relaxation times and saturation thresholds. T/TS models have been successful in such different applications as tracing trajectories of charged particles in the Earth's magnetosphere (e.g. Smart and Shea, 2005), explaining geomagnetic storms observed at geosynchronous orbit in terms of different current sources (e.g. Huang et al., 2008) or studying the relative contribution from different magnetospheric current systems to mid-latitude geomagnetic indices (e.g. Dubyagin et al., 2014). The TS05 model (Tsyganenko and Sitnov, 2005) used in this study has reached a stage of complexity where each current system is driven by the previous history of solar wind conditions. Each current representing an individual field source is modeled using an empirical equation that explains its time evolution as the combination of a driving term, dependent on solar wind parameters, and a loss term, proportional to the level of the source field amplitude.

Ground-based geomagnetic indices used in previous versions of the model to parameterize the amplitude of different magnetospheric sources (Tsyganenko, 2013) have been almost completely replaced by external parameters as solar wind density, speed and ram pressure, the components of the interplanetary magnetic field (IMF) and the Earth's magnetic dipole tilt angle (the angle between the z-axis of magnetospheric (GSM) and dipole magnetic (SM) frames, e.g., Laundal and Richmond (2016)). This facilitates the separation between sources of geomagnetic activity and their effects. Nevertheless, the SYM-H index (corresponding to the high time resolution version of Dst, see Wanliss and Showalter (2006)) is still present to control the position of the cross-tail current sheet along the tail axis, so that during geomagnetic storms (larger values of $|\mathrm{SYM}-\mathrm{H}|$) the tail current sheet is moved closer to the Earth (Tsyganenko and Sitnov, 2005). Finally, the modular structure of the TS05 model allows to disentangle the contributions of different sources, namely the magnetopause (or Chapman-Ferraro, CF) current, the cross-tail current sheet (TAIL), axisymmetric (SRC) and partial (PRC) ring currents, and Birkeland (or field-aligned, FAC) currents for Regions 1 and 2. One physically unrealistic feature concerning magnetospheric currents and still remaining in the TS05 model, is closure of FAC currents through the Earth's center rather then through the ionosphere via Pederson currents (e.g. Dubyagin et al., 2014). This approach allowed to take advantage, in calculations, of certain symmetry properties found in a conical current sheet (Tsyganenko, 2002a). At the altitude of satellites used to fit the TS05 model parameters, differences between geocentric and ionospheric closing of FAC currents are not important. However, at the Earth's surface, significant differences are expected especially at high latitudes.

1.2. Ionospheric and related induction contributions

To compare ground surface data from observatories with predictions from the TS05 model, all contributions but the magnetospheric signal have to be subtracted from data or, in some way, separately modeled. The regular daily variation observed during magnetospheric quiet conditions (low Kp values) and referred to as quiet daily (QD) variation (e.g., Pedatella et al., 2011; Yamazaki and Kosch, 2014) has a main contribution from the ionospheric dynamo (e.g., Campbell, 2003) that is termed Sq (for solar quiet-day) (e.g., Pedatella et al., 2011; Yamazaki and Kosch, 2014). However, it is also known that the QD variation contains a superposed magnetospheric contribution (e.g., Olsen, 1996) and the separation is not simple (e.g., Langel et al., 1996). The amplitude of the QD daily curve can change from 10 to 30 nT, at mid-latitudes. This is significant compared to magnetospheric field variations on ground, which have values from some few nT in quiet periods to $\sim$200 nT during geomagnetic storms.

Besides ionospheric and magnetospheric primary signals, the QD variation also comprises related secondary (induced) fields. Secondary fields due to induced currents in the crust and upper mantle (e.g Schmucker, 1985), have strength roughly one third that of inducing fields, as determined from data, e.g., by Matsushita and Maeda (1965) and Langel and Estes (1985). That is, the contribution of induced currents affects significantly the ionospheric and magnetospheric variations by reducing the vertical component and increasing the X and Y components (e.g Yamazaki and Maute, 2016). Most often, a 1-D conductivity model is used to explain this effect, consisting of an insulating crust and upper mantle and a superconductor below some depth. In this scenario, the secondary field is simply proportional to the primary inducing field and the thickness of the insulating upper layer is adjusted in order that the proportionality constant is $Q \sim 0.27$, in agreement with observations (e.g Olsen et al., 2005). More realistic models allowing for lateral variations of conductivity show that the Z (vertical) geomagnetic field component is the most affected by the conductivity model simplification (e.g Kuvshinov et al., 1999). However, in this study only X and Y field components will be analyzed, for which a spherically symmetric upper mantle conductivity model is a good approximation to explain how primary and secondary fields relate.

1.3. Crustal and secondary magnetospheric contributions

Even after subtracting the main field contribution and a QD model from data, a bias between ground surface data and TS05 predictions is expected to remain, mainly due to local crust magnetization fields (e.g., Mandea and Langlais, 2002). Crustal biases tend to remain constant over decade time periods (Verbanac et al., 2015).

Also, a scale factor is expected between observations and predictions because of the magnetospheric induced signal in the data which is not present in TS05 estimations. For TS05 estimations, only primary magnetospheric sources contribute. Assuming that secondary fields can be computed as explained in the previous section, it can be anticipated that induction is responsible for an amplification of the magnetospheric primary signal at the ground level, that can amount to several tens of nT