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Terminator field-aligned current system: Its dependencies on solar, seasonal, and geomagnetic conditions

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ABSTRACT

A new field-aligned current system in the high-latitude ionosphere, the terminator field-aligned currents, was recently discovered by Zhu et al. (2014). A series of modeling, observational, and theoretical studies need to be performed in order to get a full picture of the behavior and properties of this newly discovered current system, understand the underlying physics, and explore its effects on the electrodynamics and plasma dynamics of the high-latitude ionosphere. As a first step in this direction, we performed a systematic study on the seasonal, solar, and geomagnetic dependencies of the general properties of the terminator field-aligned currents. The study was conducted by using a physics-based data assimilation model, Ionospheric Dynamics and Electrodynamics Data Assimilation (IDED-DA) Model, with the ingestion of observational data.

1. Introduction

In the high-latitudes, the field-aligned currents is one of the major means that transfer the energy derived from the interactions between the solar wind and the magnetosphere to the ionosphere, in addition to the convection electric fields and particle precipitations. Several field-aligned current systems have been documented and well-studied in the past, which include the region 1 and 2 currents around the auroral oval, the Northward Bz currents in the dayside polar cap during northward IMF, as well as the cusp field-aligned currents that are directly connected to the solar wind via the open magnetic fields (Iijima and Potemra, 1976; Iijima et al., 1984; Strangeway et al., 2000; Kamide and Rostoker, 1977; Zhu et al., 1991; Gjerloev et al., 2011). Most recently, a new field-aligned current system in the high-latitude ionosphere was reported by Zhu et al. (2014) and the discovered current system was termed as the terminator field-aligned current system since it develops and evolves along the ionospheric terminator. The discovery was based on the reconstructions from a physics-based data assimilation model, Ionospheric Dynamics and Electrodynamics Data Assimilation (IDED-DA) Model (Schunk et al., 2006; Zhu et al., 2012), with the ingestion of observational data.

The discovery of the terminator field-aligned currents has its important significance. First, it is a new element to the complicated current system of the high-latitude ionosphere with its unique features, which was never reported before. Second, the discovery is a good example showing the unique strengths of physics-based data assimilation models in discovering important physical processes that are missed due to sparse measurements or observational limitations. Third, more importantly, it is a field-aligned current system that has an ionospheric origin and reflects the active role of the ionosphere in Magnetosphere-Ionosphere (M-I) coupling, which is different from all the other field-aligned current systems documented to date.

Since the terminator field-aligned currents is a newly discovered current system in the high-latitude ionosphere and is connected to the active role of the ionosphere in the M-I coupling, which is important for the self-consistent study of global-scale electrodynamics of the M-I system and is responsible for the development of many small-scale electrodynamic and plasma structures in the high-latitude ionosphere, a series of modeling, observational, and theoretical studies need to be performed in order to get a full picture of its behavior and properties, understand the underlying physics, and explore its effects on the electrodynamics and plasma dynamics of the high-latitude ionosphere as well as the active role in the M-I coupling. As a first step in this direction, we performed a systematic study on the seasonal, solar, and geomagnetic dependencies of the general properties of the terminator field-aligned currents. The study was conducted by using the IDED-DA model with the ingestion of observational data and this brief paper is to report the major findings from the study.

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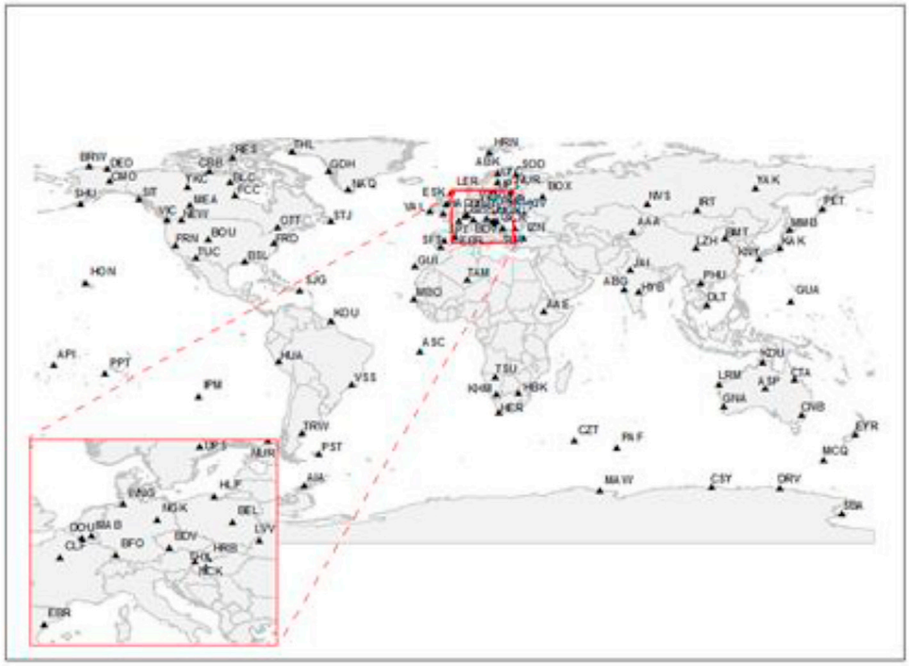

Fig. 1. Distribution map of the INTERMAGNET stations (courtesy of the INTERMAGNET) and only the magnetometer data from the stations that are at the colatitudes from 0 to 40° are used in this study.

2. IDED-DA model and specific runs

The physics-based data assimilation models have their unique strengths over the first-principle physical models as well as the empirical models and have been successfully used for the past decades as a dominant tool for specifications and forecasts in meteorology and oceanography (e.g., Daley, 1991). For the ionosphere, a numbers of data assimilation models have been developed in the past and these models have demonstrated their unique strengths and promising capabilities in the space weather specifications as well as the forecasts, especially the short-term forecasts (e.g., Pi et al., 2003; Schunk et al., 2004; Bust et al., 2004). This is because that the reconstructions produced by the data assimilation models constitute an internally consistent time series of global three-dimensional fields which are based on the combination of the first-principle physics and observations. Because of its internal consistency of physics and the completeness of descriptions on the status of global systems, the physics-based data assimilation models have also been a powerful tool to identify the systematic errors in measurements of observing systems, reveal the missing physics in physical models, and discover the important physical processes that are inadequately observed or missed by measurements due to observational limitations. The discovery of the terminator field-aligned currents is an example of the last unique strength of physics-based data assimilation models mentioned above. In our further study of the terminator field-aligned currents using the IDED-DA model, the internal consistency of physics and the completeness of descriptions on the status of global system of the data assimilation model would provide us unique strengths in characterizing its dynamic features, discovering the underlying physics, and investigating its interconnections with and impacts on other electrodynamic and plasma processes in the high-latitude ionosphere.

The IDED-DA is a 3-dimensional time-dependent physics-based data assimilation model for the high-latitude ionosphere (Schunk et al., 2006; Zhu et al., 2012). It consists of a 3-D first-principle model for the ionosphere dynamics and electrodynamics which can account for rapid time variations (~min) and small spatial scales (horizontal, ~10 s km, vertical, 4–10 s km) (Schunk, 1988; Schunk et al., 1997; Sojka, 1989; Zhu et al., 1999, 2000), an ensemble Kalman filter which is a recursive algorithm to minimize the error and find the best estimate of the state at a time t based on all information prior to this time (Daley, 1991), and the measurements and data ingestion which is able to assimilate ground-based magnetometer data, DMSP cross-track ion drift measurements, SuperDARN line-of-sight velocities, and IRIDIUM in-situ magnetometer measurements presently. A number of validation and comparison model runs have been conducted to check the validity of the model for space weather specifications (e.g., Zhu et al., 2012). By assimilating the ionospheric data from multiple observational resources, the IDED-DA model can produce a self-consistent time-series of the complete descriptions of the global high-latitude ionosphere, which includes the convection electric field, horizontal and field-aligned currents, conductivity, as well as 3-D plasma densities and temperatures.

The data ingested into the IDED-DA model in this study are similar to our initial study of the terminator field-aligned currents (Zhu et al., 2014), but they cover a much wider range of solar, seasonal, and geomagnetic conditions. They are the ground-based magnetometer data from about 45 INTERMAGNET stations in northern high-latitude regions. Fig. 1 is a distribution map of the INTERMAGNT stations and we only used the data from the stations that fall into the colatitudes from 0 to 40°. These stations have a geographic latitudinal coverage of less than one degree and a geographic longitudinal coverage with a few gaps due to the oceans. The coarse longitudinal coverage is largely compensated by a continuous rotation of the stations in the geomagnetic coordinate and a high data ingestion rate (1 min). The sampling rate of the magnetometer data is 1 s and we used the 1 min average values. The baselines of the magnetometer data vary from station to station and they were determined by a best-fit polynomial analysis with the multi-year data on the quiet days. The error of the processed 1 min average values of the magnetic perturbations ingested into the model is estimated to be about 10%, which is based on the instrumental resolution (0.1 nT) and the error introduced when a numerical scheme was used to remove the secular components (1–2 nT). In the IDED-DA model, the zero-order magnetospheric drivers were determined by solar wind and IMF data from the ACE satellite. These magnetospheric drivers were continuously modified by a Kalman filter data assimilation process that is based on 25 ensemble runs of the coupled physical model (e.g., Zhu et al., 2012) with the ingestion of magnetometer measurements. The time steps and spatial resolutions of the IDED-DA are flexible. For all the runs in this study, the