Scientific Studies of the High-Latitude Ionosphere with the Ionosphere Dynamics and ElectroDynamics - Data Assimilation (IDED-DA) Model

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LONG-TERM GOALS

The goal of the project is to conduct scientific studies to elucidate the momentum and energy processes that play a significant role in magnetosphere-ionosphere coupling at high latitudes, with the emphasis on mesoscale (~ 100 km) plasma phenomena.

OBJECTIVES

We will conduct simulations with a high-latitude data assimilation model. The specific objectives are to study magnetosphere-ionosphere (M-I) coupling processes for: (1) super storms, pulsating storms, and substorm, (2) different seasons and solar activity levels, (3) relatively smooth and highly structured convection and precipitation scenarios, and (4) both northward and southward Interplanetary Magnetic Field (IMF) configurations.

APPROACH

Our approach is to use our Ionosphere Dynamics and ElectroDynamics - Data Assimilation (IDED-DA) model to accomplish the goal and objectives outlined above. Our IDED-DA model is a physics-based, ensemble Kalman filter model of the high-latitude ionosphere and electrodynamics that can account for rapid time variations of the order of minutes and spatial scales less than 100 km (Schunk et al., 2006; Zhu et al., 2012). The IDED-Data Assimilation model is based on three physics-based models, including a magnetosphere-ionosphere (M-I) electrodynamics model, an ionosphere model, and a magnetic inversion code. The ionosphere model is a high-resolution version of the Ionosphere Forecast Model (IFM), which is a 3-D, multi-ion model of the ionosphere that covers the altitude range from 90-1500 km (Schunk, 1988; Sojka, 1989; Schunk et al., 1997). The main electrodynamics inputs to the IFM are the plasma convection and precipitation patterns, which are obtained from the M-I electrodynamics model. The IFM calculates global distributions for plasma densities (N_e, NO⁺, O₂⁺, N₂⁺, O⁺, H⁺), temperatures, and velocities. The M-I electrodynamics model is a high-resolution (10 km), time-dependent (5 sec) model of M-I coupling at high latitudes (Zhu et al., 1993, 2000, 2005). The model is based on a numerical solution of the MHD transport equations and Ohm’s Law, with
height-integrated Hall and Pedersen conductivities obtained from the IFM. The model calculates currents and electric fields. The magnetic inversion code takes a 3-D current system as an input and calculates the associated $\Delta B$ in space and on the ground. The three physics-based models are used with an ensemble Kalman Filter to assimilate SuperDARN radar velocities, in situ velocities from the DMSP satellites, and $\Delta B$ from both ground and satellite magnetometers. The output of the IDED-DA model is a full set of self-consistent, time-dependent plasma and electrodynamics parameters for the high-latitude regions, including Electric Potential, Convection Electric Field, Energy Flux and Average Energy of Precipitation, Field-Aligned and Horizontal Currents, Hall and Pedersen Conductances, Joule Heating Rates, 3-D Electron and Ion Densities, 3-D Plasma Drifts, 3-D Electron and Ion Temperatures, Total Electron Content (TEC), and Ground and Space Magnetic Disturbances ($\Delta B$).

WORK COMPLETED

(1) Previously, we conducted IDED-DA simulations with measurements from 40 – 60 ground magnetometers and ACE satellite data. In the course of these studies, we discovered three ‘new’ physical features: (1) A field-aligned current along the solar terminator due to the conductivity gradient, (2) The break-up of a stable tongue-of-ionization into plasma patches in the polar cap during a northward IMF excursion, and (3) A plasma tongue-of-ionization the originates from the 1800 local time sector. Also previously, two scientific papers have been submitted for publication describing our initial findings. During the last year, additional data have been collected, additional runs of the IDED-DA model have been conducted, and some of the model results have been validated.

(2) For several quiet, storm, and substorm periods, addition data sets have been collected both for assimilation and validation. The data collected for assimilation include line-of-sight plasma velocities from the SuperDARN radars, cross-track velocities from the DMSP satellites, and magnetic perturbations from ground-based magnetometers. Secular variations and Dst ring current signatures were removed from the magnetometer data in order to identify the currents in the ionosphere. The validation data collected were the electron densities ($N_e$), electron temperatures ($T_e$), and ion temperatures ($T_i$) measured by the DMSP satellites.

(3) IDED-DA simulations were conducted for two storm periods and the simulation results were compared to $N_e$, $T_e$ and $T_i$ measured in situ at about 800 km by the DMSP satellites.

(4) Since the terminator current was a newly discovered feature of the high-latitude ionosphere that was caused by the ionospheric density gradient across the terminator and not by the magnetosphere, we conducted a comprehensive study to determine its characteristics for different solar, seasonal, and magnetic activity levels.

RESULTS

As noted above, the IDED-DA model was used to systematically study the field-aligned terminator current. More than 20 runs of the model were conducted and in each run magnetometer data from more than 40 ground stations were assimilated. These stations had good geographic latitudinal (less than one degree) and longitudinal coverage. The sampling rate of the magnetometer data was 1 sec and we used the 1-minute average values. The 20 runs covered winter, summer, and equinox; the solar
variations of low, medium, and high F10.7; and the geomagnetic variations of low and high Kp. All major electromagnetic and plasma parameters from the results of each simulation were plotted and analyzed, which allowed us to determine the statistical features of the terminator field-aligned current in terms of seasonal, solar, and geomagnetic conditions. Figure 1 shows a snapshot of the ionospheric environment for winter, low solar activity, and low magnetic activity.

A summary of the statistical features of the terminator field-aligned current is as follows:

- Develops and evolves along the night-side edge of the ionospheric terminator.
- Single field-aligned current sheet, which indicates that the current source for the terminator field-aligned current is the ionospheric horizontal current.
- Last for 3-7 hours.
- During summer, the current is mainly downward and appears at an early UT time. During winter, the current is mainly upward and appears at a late UT time. During equinox, the current can be either upward or downward.
- The currents can appear on both the dayside and night-side of the polar cap.
- Current density varies from $10^{-7}$ to $10^{-6}$ A/m$^2$, depending on solar conditions.
- The current is not sensitive to geomagnetic conditions. But during strong storm periods, when the terminator conductance mixes with the oval conductance, the morphology of the terminator field-aligned current can be complex.

In another IDED-DA study, we simulated the northern high-latitude region for the quiet period and storm period of April 5 through 10, 2000. The data assimilated for the electrodynamics drivers of the high-latitude ionosphere were magnetic deflections from 105 ground magnetometers obtained from SuperMAG at APL, line-of-sight velocities from SuperDARN, and DMSP cross-track ion drift velocities. The resulting ionosphere dynamics was compared with the DMSP ion density, ion temperature, and electron temperature measured by the DMSP F12, F13, F14, and F15 satellites. The comparison between model and data shown on Figure 2 is reasonable, but the fine structure seen in the ionospheric densities and temperatures in the polar cap displays significantly more variability than what was modeled.

**IMPACT/APPLICATIONS**

Numerous countries have become interested in the Arctic because of the melting of the ice and the gas and oil reserves that have become accessible. Hence, this region is now a focus of the DoD. In the future, the IDED-DA model will be able to provide ionosphere specifications and forecasts for the polar region. These specifications and forecasts will be useful for DoD command and control operations, including scintillation identification, HF communication links, over-the-horizon (OTH) radars, surveillance, and navigation systems that use GPS signals.

**RELATED PROJECTS**

None
REFERENCES


PUBLICATIONS

Figure 1. Distributions of Pedersen conductance (top left), field-aligned currents (top right), convection potential (bottom left), and Joule heating rate (bottom right) for winter, low solar and low magnetic conditions. The day is 347 of year 2000 and the time is 1800 UT.
Figure 2. Comparison of the IDED-DA model results (blue) with those measured by the DMSP F13 satellite (red).