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14. ABSTRACT
We developed two physics-based data assimilation models of the ionosphere under a program called Global Assimilation of Ionospheric Measurements (GAIM). One of the data assimilation models is now in operational use at the Air Force Weather Agency (AFWA) in Omaha, NE. The GAIM models assimilate bottom-side Ne profiles from ionosondes, slant TEC from ground GPS/TEC stations, in situ Ne from four DMSP satellites, occultation data, and line-of-sight UV emissions measured by satellites. The project involved: (1) Test assimilation strategies for the SSULI UV data in an effort to mitigate the noise problem; (2) Assimilate GUVI UV data, which is a new data source that will be available at AFWA; (3) Assimilate UV data from the Tiny Ionospheric Photometer (TIP) on the 6 COSMIC satellites; (4) Continue validation of the Gauss-Markov model in collaboration with the Air Force Research Laboratory; and (5) Continue testing and perfecting the driver determining algorithms in the Full Physics GAIM model. We also were to deliver new versions of the operational models to AFWA as the models are upgraded and new data are assimilated.

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ionosphere, assimilation, specification, forecast

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FINAL REPORT

Continued Development and Validation of the USU GAIM Models

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LONG-TERM GOALS

The primary goal of the project is to continue the development and validation of the USU GAIM models. A secondary goal is to provide support for the Air Force Weather Agency (AFWA) and other DoD organizations in connection with the operational GAIM model.

OBJECTIVES

We developed two physics-based data assimilation models of the ionosphere under a program called Global Assimilation of Ionospheric Measurements (GAIM). One of the data assimilation models is now in operational use at the Air Force Weather Agency (AFWA) in Omaha, Nebraska. This Gauss-Markov data assimilation model (GAIM-GM) uses a physics-based model of the ionosphere (IFM) and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. The second data assimilation model uses a physics-based ionosphere-plasmasphere model (IPM) and an ensemble Kalman filter as a basis for assimilating the measurements. This full physics model (GAIM-FP), which covers the altitude range of from 90 to 30,000 km, is more sophisticated than the GAIM-GM model, and hence, should provide more reliable specifications in data poor regions and during severe weather disturbances. The GAIM-FP model is scheduled for delivery to the DoD in 2012. Currently, the GAIM models are capable of assimilating bottom-side N_e profiles from a variable number of ionosondes, slant TEC from a variable number of ground GPS/TEC stations, in situ N_e from four DMSP satellites, occultation data, and line-of-sight UV emissions measured by satellites. The goal of this project is to continue the development and validation of the USU GAIM models, and the objectives are (1) Test assimilation strategies for the SSULI UV data in an effort to mitigate the noise problem; (2) Assimilate GUVI and/or SSUSI UV data, which might be new data sources available at the Air Force Weather Agency (AFWA); (3) Assimilate data from the 6 COSMIC satellites; (4) Continue the validation of the GAIM-GM model in collaboration with the Air Force Research Laboratory; and (5) Continue testing and perfecting the driver determining algorithms in the GAIM-FP model. Also, new versions of the GAIM models are to be delivered to AFWA as the models are upgraded and new data are assimilated. AFWA has scheduled GAIM deliveries up through 2012.

APPROACH

The Gauss-Markov data assimilation model (GAIM-GM) was developed as part of the MURI effort (*Schunk et al., 2004a, 2005a; Scherliess et al., 2004, 2005, 2006*). It is a data assimilation model of the ionosphere that is based on the Ionosphere Forecast Model (IFM) (*Schunk*, 1988; *Sojka*, 1989; *Schunk et al.*, 1997), which covers the E-region, F-region, and topside ionosphere up to 1400 km, and takes account of six ions (NO^+, N_2^+, O_2^+, O^+, He^+, H^+). In the Gauss-Markov Kalman filter, the ionosphere densities obtained from the IFM constitute the background ionosphere density field on which perturbations are superimposed based on the available data and their errors. To reduce the computational requirements, these perturbations and the associated errors evolve over time with a statistical model (Gauss-Markov process). As a result, the Gauss-Markov Kalman filter can be executed on a dual CPU workstation. Like all assimilation techniques, the GM model uses the errors on the observations and model in the analysis, and computes the errors in the match. This model also has both regional and global modes, and has latitude, longitude, and temporal resolutions that are adjustable. To date, we have conducted numerous simulations with several different data types. We have assimilated GPS/TEC from up to 1000 ground receivers, in situ N_e from 4 DMSP satellites, bottomside N_e profiles from 70 digisondes, occultation data from 3 satellites (IOX, CHAMP, SAC-C), and UV emission data (*Scherliess et al., 2005a; Sojka et al., 2007; Thompson et al., 2006*).

The full physics-based data assimilation model (GAIM-FP) rigorously evolves the ionosphere and plasmasphere electron density field and its associated errors using the full physical model (*Schunk et al.*, 2004b, 2005b; *Scherliess et al*., 2004, 2005). Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of "severe weather." The data assimilation model is based on a new physics-based model of the ionosphere-plasmasphere system (IPM) that covers low and mid-latitudes. The new physics-based model is state-of-the-art and include six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. The model uses the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The physics-based model covers the altitude range from 90 to 30,000 km, which includes the E-region, F-region, topside ionosphere, and plasmasphere. The different data sources are assimilated via an ensemble Kalman filter technique and quality control algorithms are provided as an integral part of the Kalman filter model. The GAIM-FP model provides 3-dimensional ion and electron density distributions as a function of time. In addition, the GAIM-FP model provides *self-consistent* distributions for the *global drivers* (neutral winds and equatorial electric fields), and in its specification mode it provides *quantitative estimates of the accuracy of the reconstructed plasma densities.*

These GAIM data assimilation models were used to accomplish the goals and objectives outlined above.

WORK COMPLETED

During the three-year project, we accomplished the following tasks:

(1) Several versions of the GAIM-GM model, which included upgrades and improvements, have been delivered to NRL, AFRL and AFWA. One version included a bug fix in the background NmF2 output file and an improved background ionosphere construction to eliminate difficulties when the IFM density is very low (typically at night at low latitudes). These improvements yield much

better hmF2 values in the affected areas. Also, a computationally efficient hot-start capability (requested by AFWA); construction of an independent latent data acceptance window for SSIES data; and matrix optimizations suggested by Northrop Grumman were included.

(2) Another significant upgrade of the GAIM-GM model was delivered to NRL, AFRL and AFWA during the third year of the project. The main improvement was that the global model was turned into a multi-region model in an effort to speed up the run time. Three longitude sectors are now running in parallel and the GAIM-GM model is now five times faster than the original global model. The speedup was requested by AFWA.

(3) We worked extensively with the SSUSI -UV limb and disk data. We delivered the GAIM-GM model, and the data reduction and quality checking algorithms capable of using SSUSI disk and limb data from F16 and F17. We also developed utilities to reduce and assimilate the GUVI data.

(4) SSULI data from F16 and F17 appear to be contaminated by noise owing to the instrument design and placement. This has precluded using the data for any research and development at USU.

(5) TIP data were used extensively to compare against the GAIM-GM model results. However, the data were contaminated by a red light leak, and was therefore biased too high in certain regions. In particular, city lights and reflected moonlight caused difficulties. While there has been some work at NRL to mitigate these effects, the data have not been corrected to a level that makes assimilating the data by GAIM-GM warranted.

(6) We continued the testing and validation of the GAIM-FP model. The advantage of the Full Physics model is that the self-consistent drivers of the ionosphere are calculated along with the ionospheric reconstruction. In recent simulations, we obtained both neutral winds and electric fields throughout the low-mid latitude region for several geophysical conditions. Validation with data that was not assimilated indicated the GAIM-FP model is working correctly.

(7) The GAIM-FP data assimilation model now routinely incorporates ground GPS TEC data, bottom-side electron density profiles from ionosondes and radio occultation data from the COSMIC satellites.

(8) As part of the validation effort, we conducted simulations to determine the effect that upward propagating waves from the lower atmosphere have on the ionosphere-thermosphere system. Tides, gravity waves and sound waves can have a significant effect on the lower thermosphere, but they are difficult to incorporate in the GAIM models because of their small spatial and temporal scales.

(9) We continued to support Northrop Grumman, AFWA, NRL, and AFRL in their validation and implementation efforts.

(10) Several GAIM papers and talks were presented at scientific meetings, including the Community Coordinated Modeling Center (CCMC) workshop in November 2007; the Fall AGU Meetings in December 2007, 2008; the American Meteorological Society (AMS) Meeting in January 2008, 2009; the Space Weather Workshop in April 2008, 2009; the Ionospheric Effects Symposium

(IES) in May 2008, the NSF CEDAR meeting in June 2008, 2009; and the international COSPAR symposium in Montreal, Canada in July 2008.

(11) We attended GAIM Summit Meetings at AFWA in March and August 2008 and in April 2009.

RESULTS

The GAIM-FP model was used to determine the ionospheric electron density and drivers in the middle-low latitude domain. The goal was to obtain a 3-dimensional electron density reconstruction and the neutral wind and electric field that were responsible for the electron density configuration. The simulation covered a several day period in March/April 2004, during which the magnetic activity was low. Slant TEC measurements from a worldwide distribution of 162 GPS ground receivers were assimilated into the GAIM-FP model. Digisonde electron density profiles were also available for this period, but they were not assimilated. Instead, they were used for validation purposes. Figure 1 shows a snapshot of the vertical TEC distribution on day 80 at 11:00 UT, 2004. In the top panel the slant TEC was converted to vertical TEC with an angle factor and plotted at 350 km in order to show the measurements. The bottom panel shows the corresponding global TEC distribution obtained from the GAIM-FP data assimilation model. A comparison of the reconstructed electron density profiles with the digisonde profiles indicated that the GAIM-FP model successfully reproduced the ionospheric conditions at that time. The deduced meridional neutral wind was also shown to be consistent with the TEC distribution calculated by the GAIM-FP model.

In another study, the GAIM-FP model was used to investigate the morphology of the low-latitude ionosphere, with the emphasis on the 4-cell longitude pattern frequently observed in the equatorial ionization anomaly. The 4-cell pattern is a result of the interaction of the upward propagating, wavenumber-3, non-migrating, tidal mode with the zonal wind in the lower thermosphere, which yields a wavenumber-4 tidal mode. The net wind generated from this interaction creates a dynamo electric field that ultimately produces the 4-cell pattern in the equatorial anomaly. In the following example, we assimilated COSMIC radio occultation data in the GAIM-FP model in order to investigate if this low-latitude pattern can be observed in our data assimilation results. For this study, the radio occultation data from the six COSMIC satellites were continuously assimilated over a 4-day period in April 2007 (days 90-93) and the model, in return, provided the 3-D electron density distribution from 90 km to geosynchronous altitude (30,000 km). Figure 2 shows, as an example, a TEC map obtained from our model results for April 1, 2007. The results pertain to a fixed solar local time (SLT= 1730) and are shown as a function of geographic longitude and latitude. The vertical TEC data were obtained by integrating through the 3-D ionosphere-plasmasphere from 90 km to the upper boundary. The four TEC peaks seen in this figure are associated with the wavenumber-4 tidal forcing. An inspection of the 3-dimensional model densities (not shown here) indicates that the observed wavenumber-4 signatures are also evident in the equatorial and low-latitude F-region peak heights (hmF2) and peak densities (NmF2). Figure 2 clearly shows that our physics-based data assimilation model reliably specifies the formation of these plasma density structures at low-latitudes.

IMPACT/APPLICATIONS

The USU GAIM-GM and GAIM-FP data assimilation models provide ionosphere specifications and forecasts on both global and regional grids. These specifications and forecasts are useful for DoD and civilian command and control operations, including HF communication links, geo-locations, over-the-horizon (OTH) radars, surveillance, and navigation systems that use GPS signals.

TRANSITIONS

Several versions of the operational GAIM-GM model, which included upgrades and improvements, were delivered to NRL, AFRL and AFWA during the course of this project.

RELATED PROJECTS

This project resulted from a basic research DoD MURI program called Global Assimilation of Ionospheric Measurements (GAIM). A research grade version of our GAIM-GM data assimilation model was developed under the MURI program.

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HONORS/AWARDS/PRIZES

R. W. Schunk was inducted into the International Academy of Astronautics,

J. J. Sojka was elected to be the next president of the Space Physics and Aeronomy (SPA) section of the American Geophysical Union.

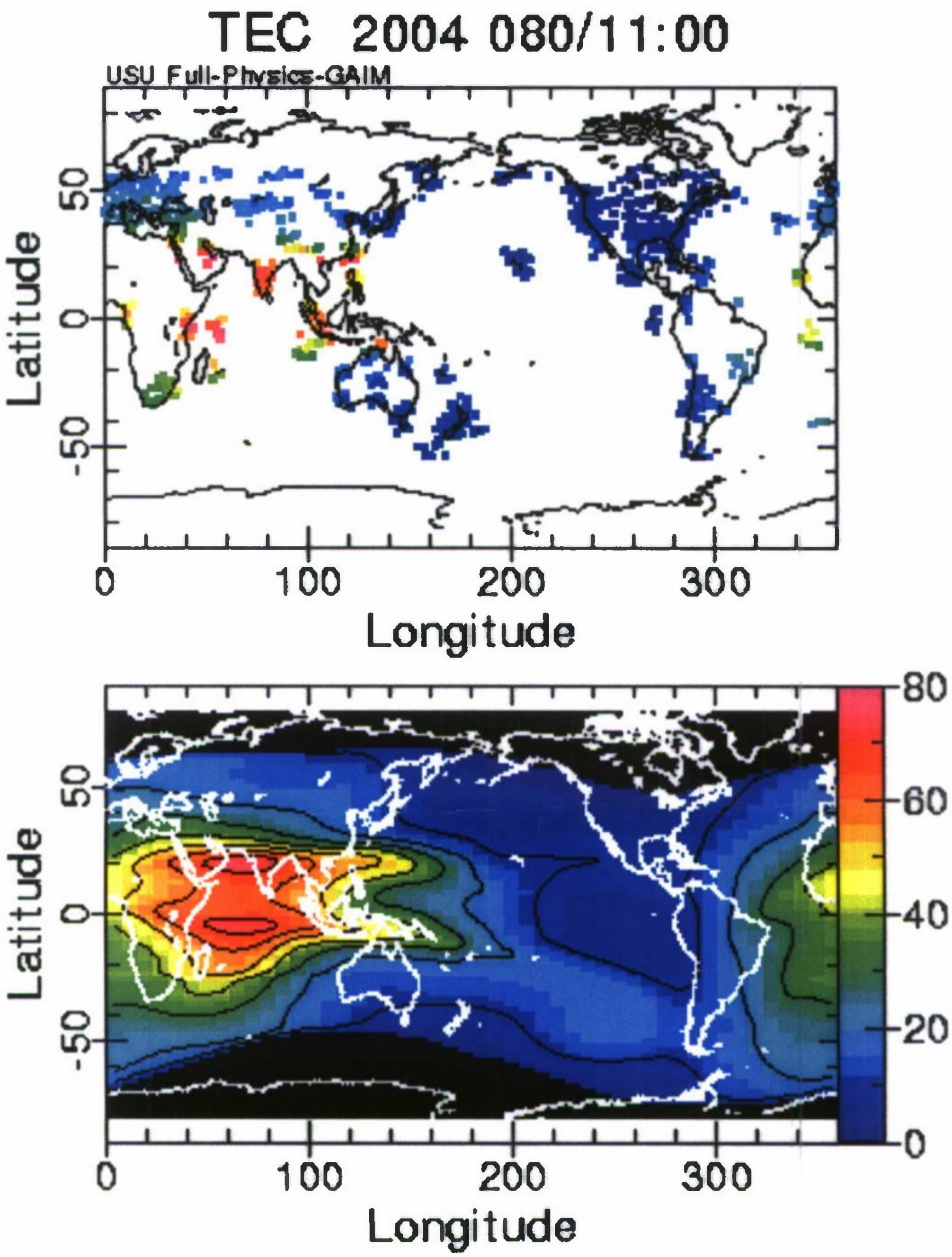

Figure 1. Distributions of vertical TEC obtained from GPS measurements (top) and the GAIM-FP model (bottom). The units are 10^{16} el/m^2.

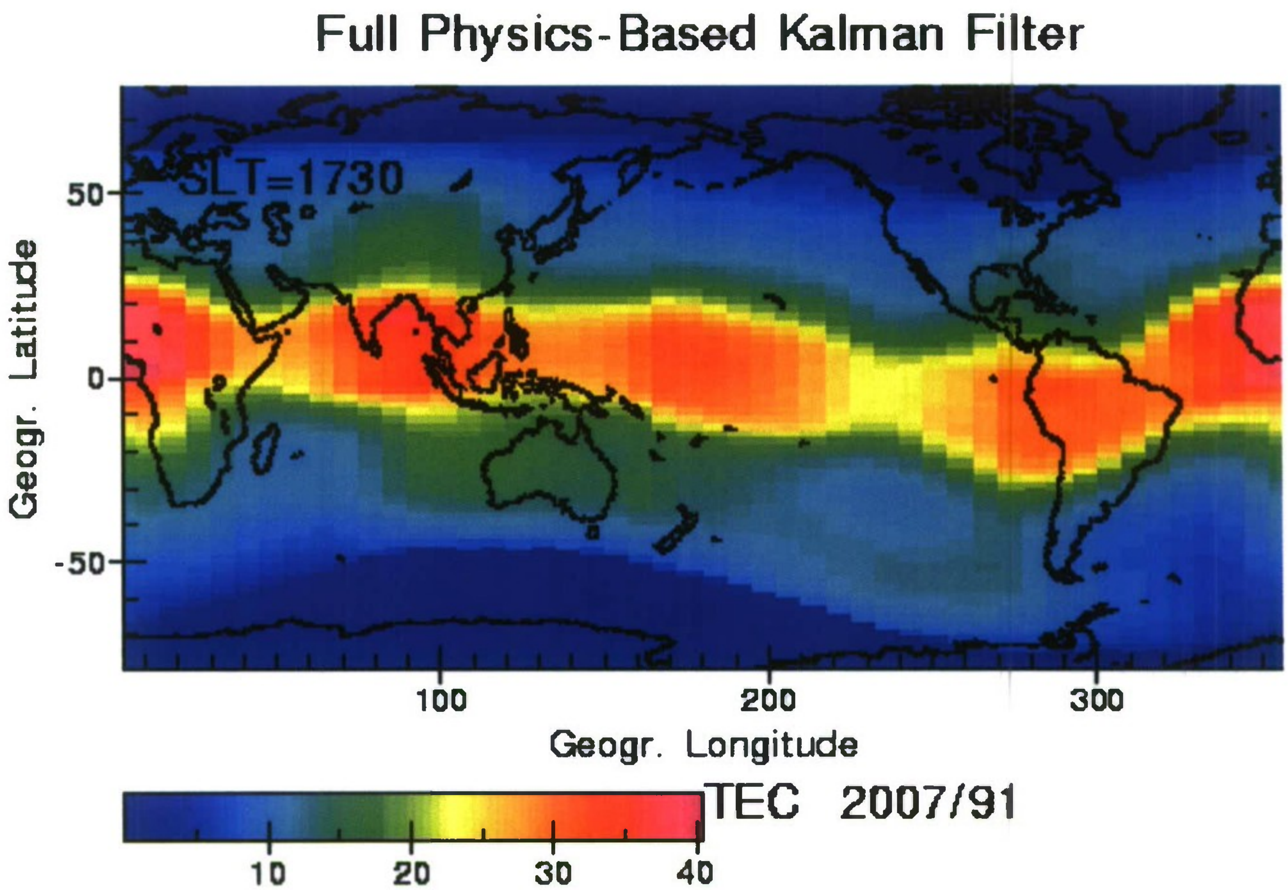

Figure 2. Example of a TEC map obtained from our Full Physics-Based Kalman filter model for April 1, 2007. The TEC values are shown for a fixed solar local time (SLT=1730). Clearly seen is the wave number-four structure in the low-latitude TEC distribution. From Scherliess et al., 2009.