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Validation study of the Ionosphere Forecast Model using the TOPEX total electron content measurements

L. Zhu,[1] R. W. Schunk,[1] G. Jee,[1] L. Scherliess,[1] J. J. Sojka,[1] and D. C. Thompson[1]

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[1] As a part of the validation program in the Utah State University Global Assimilation of Ionospheric Measurement (GAIM) project, a newly improved Ionosphere Forecast Model (IFM) was systematically validated by using a large database of TOPEX total electron content (TEC) measurements. The TOPEX data used for the validation are for the period from August 1992 to March 2003, and the total number of 18-s averaged data is close to 11 million. This model validation work covers a wide range of seasonal (winter, summer, and equinox) and solar (low-$F_{10.7}$, median $F_{10.7}$, and high-$F_{10.7}$) conditions as well as all UT variations with the focus on nonstorm time TEC. The validation results indicate that the features of the spatial distribution of the IFM TEC are systematically consistent with those of the TOPEX TEC. The differences between the IFM TEC and the TOPEX TEC are within 20% for almost all locations and conditions. For many conditions, the differences are even below 10%.

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1. Introduction

[2] A physics-based data assimilation model of the ionosphere is under development as the primary element of a Department of Defense–funded program called Global Assimilation of Ionospheric Measurements (GAIM) [*Schunk et al.*, 2004]. The Utah State University (USU) GAIM model uses a physics-based ionosphere-plasmasphere-polar wind model and a Kalman filter as a basis for assimilating a diverse set of real-time (or near-real-time) measurements. The model covers the low and middle latitudes from 90 to 20,000 km and the high latitudes from 90 to 10,000 km. In addition to the physics-based Kalman filter model, we have also developed a Gauss-Markov Kalman filter model, in which observational data are used as perturbations adding to the background ionosphere that is determined by a first-principle physical model, and a global version of a Gauss-Markov model has been running continuously and autonomously since 1 July 2003. Currently, the USU GAIM models can assimilate in situ electron densities from the DMSP satellites, occultation total electron content (TEC) measurements from three low Earth–orbiting satellites (SAC-C, CHAMP, and IOX), bottomside electron density profiles from ionosondes, and GPS-TEC from a global network of up to 1000 ground receivers. The primary USU GAIM output is a three-dimensional (3-D) electron density distribution as a function of time, and auxiliary ionospheric parameters (for example, NmF2) and the self-consistent ionospheric drivers (for example, auroral convection) are also obtained.

[3] In data assimilation, the first-principle physical model plays an essential role in the accuracy of assimilation results and the forecasting capability of assimilation models [e.g., *Daley*, 1991]. A first-principle physical model either provides background information for the data assimilation or propagates the state vectors of the Kalman filter, which contain the information of observations, forward in time. It does not require that the physical model must be perfect, but the model should include all major physical processes in the regions under study. The results of the physical model not only need to be physically reasonable in a qualitative fashion but also should be quantitatively close to observations for all geophysical conditions.

[4] Because of the importance of the physical model in data assimilation, we not only conduct validation work

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[1] Center for Atmospheric and Space Sciences, Utah State University, Logan, Utah, USA.

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on assimilation results with independent observational data but also perform a systematic validation on the physical models to make sure that the results of these models are quantitatively consistent with the statistical and climatological features of observations. In this work, a newly improved Ionosphere Forecast Model (IFM), which is used as a first-principle physical model in the USU Gauss-Markov Kalman filter model, was systematically validated by using a large database of the TOPEX TEC measurements. The validation results indicate that the features of the spatial distribution of the IFM TEC are systematically consistent with those of the TOPEX TEC.

2. Ionosphere Forecast Model (IFM)

[5] The IFM is a three-dimensional, high-resolution, multi-ion model of the global ionosphere [*Schunk et al.*, 1997] that is based on the USU Time-Dependent Ionosphere Model (TDIM) [*Schunk*, 1988; *Sojka*, 1989]. The IFM has been continuously extended and improved over the years. The model covers the altitude range from 90 to 1600 km and all latitudes and longitudes. The spatial and temporal resolutions of the IFM are flexible. The finest spatial resolution for the present version is 2° in latitude and 5° in longitude and is variable in vertical direction (for example, 4 km for the *E* region and 20 km for the *F* region). The finest temporal resolution is 5 min. All these resolutions can be further increased upon the need of the model user. The IFM is based on a numerical solution of the continuity, momentum, and energy equations of multiple ion species. The equations are solved along magnetic field lines for individual convecting flux tubes of plasma, and the 3-D nature of the model is obtained by following a large number of plasma flux tubes. The model takes account of field-aligned diffusion, cross-field electrodynamic drifts, thermospheric wind, neutral composition changes, energy-dependent chemical reactions, ion production due to solar UV/EUV radiation and auroral precipitation, thermal conduction, diffusion-thermal heat flow, and a myriad of local heating and cooling processes. The model also accounts for the displacement between the geomagnetic and geographic poles.

[6] To run IFM, information on neutral composition, neutral wind, $\mathbf{E} \times \mathbf{B}$ drift field, solar UV/EUV radiation, and the precipitation and convection at high latitudes is needed. The outputs of the IFM include 3-D distributions of electrons and various ion species; electron and ion temperatures; TEC; and NmF2, HmF2, and other auxiliary ionospheric plasma parameters.

3. TOPEX Data

[7] In this validation study, we used the TOPEX TEC measurements as an observational basis to validate the IFM model. TOPEX stands for Ocean Topography Experiment, and the mission was started at the Jet Propulsion Laboratory of NASA in 1979. The TOPEX satellite was launched on 10 August 1992. The satellite orbits the Earth at an altitude of 1336 km with an inclination angle of 66° and a period of 112 min. The satellite orbits are close to Sun synchronous, advancing by 2° per day. The satellite covers most of the world's oceans and makes measurements of the height of the oceans using two dual-frequency radar altimeters. Because the ionosphere has a dispersive nature, the measurements at dual frequency provide a direct estimate of TEC along the ray path from the satellite to the surface of the ocean. For the details of the TOPEX mission and its measurements, readers are referred to *Fu et al.* [1994].

[8] The reason we chose the TOPEX data for this study is twofold. First, the database of TOPEX measurements is huge, which can produce solid statistical results. Second, the database has a good geographical coverage that is suitable for comparison to the global TEC distributions produced by the IFM. The TOPEX TEC measurements were taken about every 1 s, and the data used in this validation study were 18-s averaged TEC data. The fluctuation over the 18-s period can be on the order of 4–5 total electron content units (TECU), and the data that we used did not come with error bars. The database used in this study covers the period from August 1992 to March 2003 and has about 11 million 18-s averaged TOPEX TEC data in total.

[9] The 18-s TOPEX TEC data were binned with season, solar activity ($F_{10.7}$), and geomagnetic activity. The seasonal bins are winter (January, February, November, and December), summer (May, June, July, and August), and equinox (March, April, September, and October). The solar activity bins are low (<100), medium, and high $F_{10.7}$ (>150). The bins for geomagnetic activity are low (<1.7), medium, and high *Kp* (>3.3). These binned TOPEX TEC data were then grouped into hourly UT variations and were represented in global distribution patterns. Figure 1 shows one example of the statistical TOPEX TEC patterns. The geophysical conditions for this set of TOPEX TEC distributions are equinox and high $F_{10.7}$ flux. The white spots in the TEC plots correspond to land, and there are no TEC data for the high-latitude regions.

4. Validation Study

[10] It is clear from the data-processing procedure described above that the TOPEX TEC distribution patterns are statistical, and they characterize the climatological variations of global TEC distributions for various geophysical conditions. With an observational database of this nature, the validation study of the IFM needs to focus on climatological variations of the model-produced

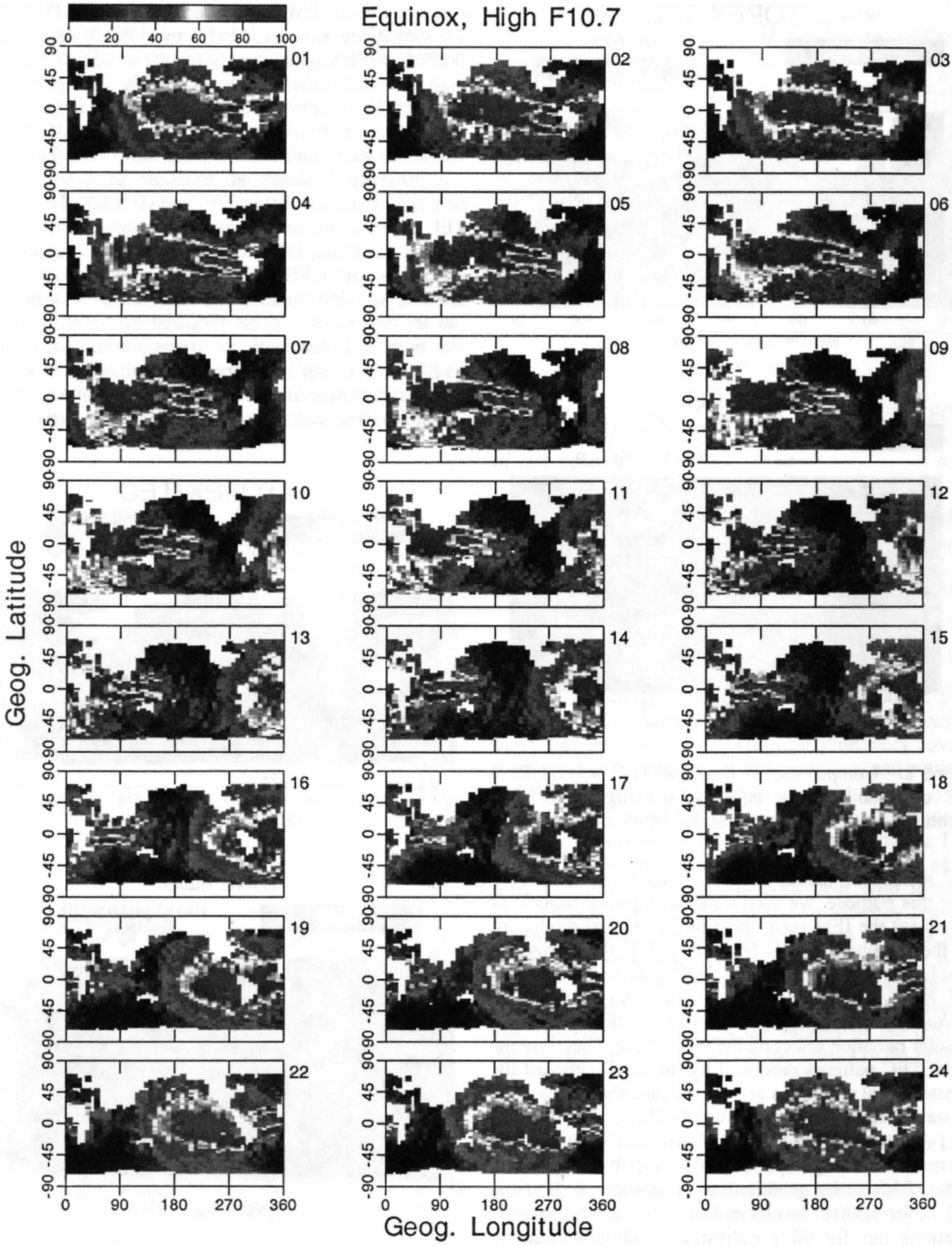

Figure 1. UT variations of the statistical TOPEX TEC distribution for equinox and high solar flux conditions. See color version of this figure in the HTML.

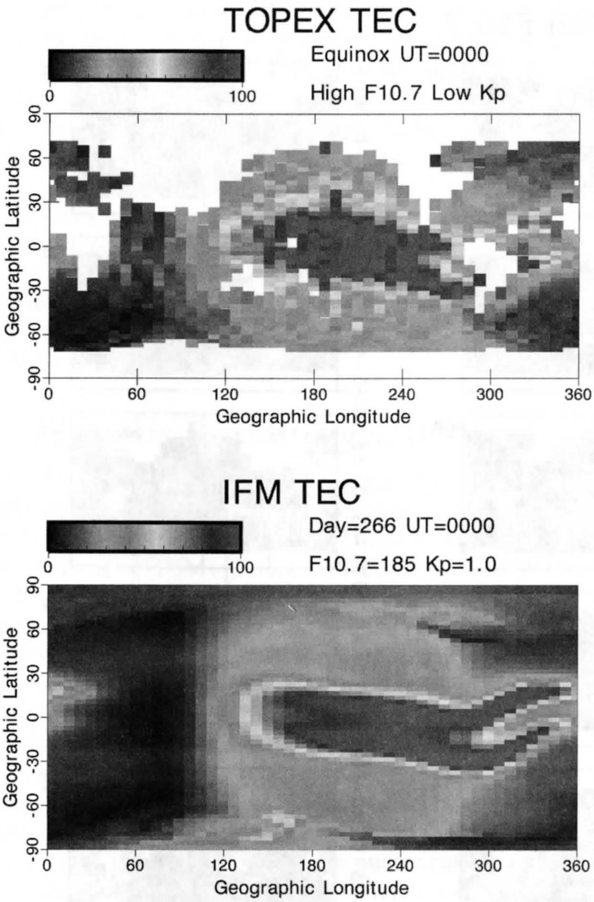

Figure 2. Comparison of the IFM TEC and TOPEX TEC at 0000 UT for equinox and high solar flux conditions. See color version of this figure in the HTML.

TEC instead of the day-to-day weather variations. To serve this purpose, we used various empirical models as drivers for the IFM runs, including empirical models of the thermosphere MSIS [*Hedin*, 1991], the horizontal wind [*Hedin et al.*, 1991], and the **E** × **B** drift [*Scherliess and Fejer*, 1999]. In addition, a solar flux model [*Richards et al.*, 1994] was used in the IFM to include the solar radiation effect on the ionosphere. Therefore the global TEC patterns produced by the IFM represent the climatological variations and can be directly compared to the statistical TEC patterns from TOPEX.

[11] To assure the accuracy of assimilation results and a better forecasting capability, the output of a physical model needs to be quantitatively consistent with statistical observational results not just for a few specific situations but for all geophysical conditions. Bearing this in mind, we designed a large number of IFM runs that systematically cover a wide range of seasonal, solar activity conditions as well as all UT variations and then compared these IFM TEC patterns to those of TOPEX in a systematic way. It needs to be noted that because of the limited TOPEX observations for the conditions of very high *Kp* (>5.7), the statistical TOPEX TEC patterns in our high-*Kp* category (>3.3) may not well represent the features of storm time TEC. Therefore the following validation study will focus on nonstorm time TEC.

[12] Figure 2 shows an example of a one-on-one comparison of the IFM TEC and TOPEX TEC. Both TEC distributions are represented in geographical coordinates, and the UT time is 0000. The geophysical conditions for TOPEX TEC are equinox, high solar flux, and low *Kp*. Correspondingly, the conditions for the IFM run are day = 266, $F_{10.7}$ = 185, and *Kp* = 1.0. It is clear that both TEC distribution patterns are not just qualitatively similar but also are quantitatively close. The difference of maximum TECs in the equatorial region is within 10%, and overall, the differences between the

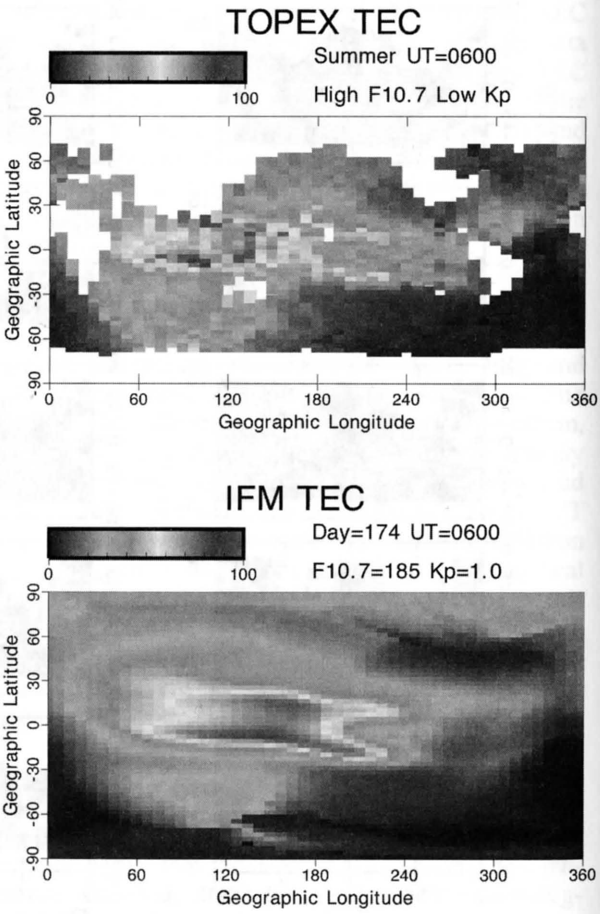

Figure 3. Comparison of the IFM TEC and TOPEX TEC at 0600 UT for summer and high solar flux conditions. See color version of this figure in the HTML.

IFM TEC and TOPEX TEC are within 20%. Figure 3 shows the TEC comparison for summer and high solar flux conditions, and again the features of both TEC patterns are qualitatively similar and quantitatively close. An example of the IFM TEC and TOPEX TEC comparison for low solar flux is shown in Figure 4. These quantitative similarities between the IFM TEC and TOPEX TEC also hold for the medium-Kp conditions in our validation work, and the results are not shown here.

[13] In this validation study, we also produced the ratio of the IFM TEC and TOPEX TEC for every IFM run to quantitatively check the differences between the two. Figure 5 shows one example of this comparison. It can be seen that for most of the locations, the ratios are around 1 except in a few individual spots. It should be pointed out that in this IFM validation study, the qualitative similarity and quantitative closeness between the IFM TEC and TOPEX TEC patterns shown in preceding examples systematically and consistently exist for all solar and seasonal conditions, which validates the appropriateness of the IFM for ionospheric assimilation.

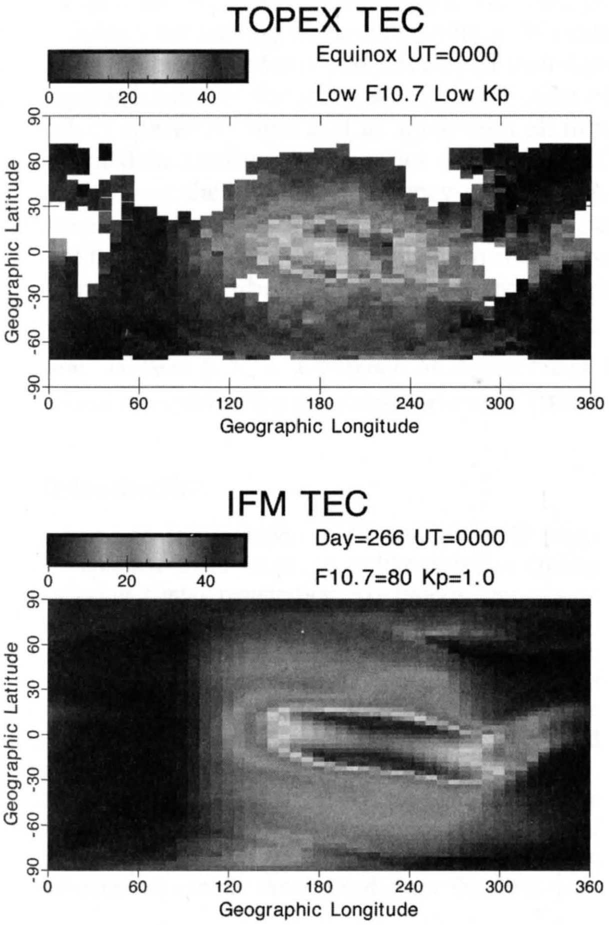

Figure 4. Comparison of the IFM TEC and TOPEX TEC at 0000 UT for equinox and low solar flux conditions. See color version of this figure in the HTML.

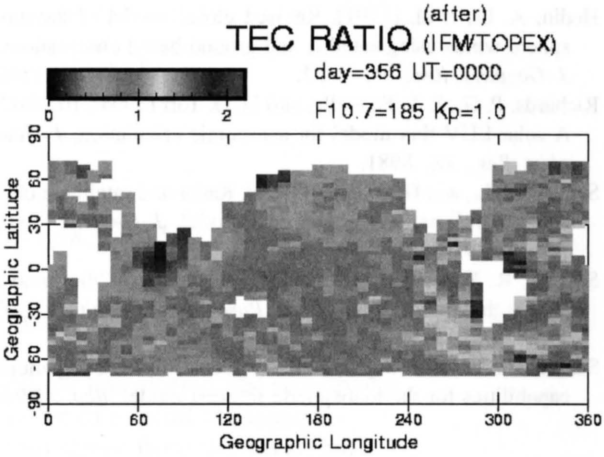

Figure 5. Ratio of the IFM TEC and TOPEX TEC for winter and high solar flux conditions. See color version of this figure in the HTML.

5. Summary

[14] A systematic validation of the Ionospheric Forecasting Model (IFM) using the TOPEX TEC measurements has been conducted. The validation work covered a wide range of seasonal (winter, summer, and equinox) and solar (low-$F_{10.7}$, medium-$F_{10.7}$, and high-$F_{10.7}$) conditions as well as all UT variations with the focus on the quantitative features of nonstorm time ionospheric TEC. The validation results indicate that the features of the IFM TEC are systematically consistent with those of the TOPEX TEC. Relatively, the consistency between the two TECs at the nightside ionosphere is not as good as that on the dayside. A possible reason for this is the difficulty of defining the topside flux for the nightside ionosphere because of the lack of observations. Overall, this validation work proves the validity of the IFM for the ionospheric assimilation in the USU GAIM project.

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G. Jee, L. Scherliess, R. W. Schunk, J. J. Sojka, D. C. Thompson, and L. Zhu, Center for Atmospheric and Space Sciences, Utah State University, 4405 Old Main Hill, Logan, UT 84322-4405, USA. (zhu@cc.usu.edu)