Application of dynamical equilibrium model to topside ionosphere specification

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A semi-theoretical plasma distribution in the topside ionosphere was derived using ionosonde and GPS observations under the assumption of a dynamical equilibrium condition. Plasma density profiles around the F layer peak and in the bottomside ionosphere were adopted by the IRI model using the observed NmF_2, h_pF_2 and the solar flux $F_{10.7}$. The shape of topside F layer was determined to fit the integrated plasma density distribution to the total electron content (TEC) obtained by GPS satellite measurements. The model profiles in nighttime and morning time showed a good agreement with the electron density profiles obtained by the incoherent scatter observation of the MU radar at Shigaraki, Japan.

INTRODUCTION

It is important to understand the behavior of the steady state ionosphere for predicting and forecasting disturbances in the ionosphere. The International Reference Ionosphere (IRI) 2000 model [1] is a widely used empirical model of the ionosphere. While the IRI model has been updated annually, there are still some shortcomings in the topside part of the model, such as overestimation of the electron density and an unrealistic form of the plasma profile. To refine this empirical model, it would be practical to establish a semi-theoretical model based on a database of observations.

Total Electron Content (TEC) is an essential parameter of the ionosphere in various space weather applications. Recently, the Global Positioning System (GPS) is used to obtain TEC from the differential delay between the two frequencies emitted from the GPS satellites.

In this study, a theoretical plasma distribution under the assumption of a dynamical equilibrium condition was applied to represent the topside ionospheric plasma density profile, modifying the empirical model using ionosonde and GPS observation data.

TOPSIDE IONOSPHERE

The ionosphere can be divided into three parts. In the bottomside ionosphere, below the F layer peak, chemical reactions, such as the photoioniztaion, ion-molecular reactions, and electron-ion recombination, dominate plasma distributions. This region is well described in the IRI2000 empirical model [1]. Above the F layer peak, plasma distributions are controlled by the plasma transport process, and field-aligned plasma flows play an important role in determining the plasma density profiles. The region which extends from the altitude of the F layer peak to the upper transition height (UTH) is called “topside ionosphere”, and the region which is located above the UTH is called “protonosphere” or “plasmasphere”. In the protonosphere, H^+ is a major ion species and distributes under the condition of a diffusive equilibrium, i.e., H^+ decreases exponentially with altitude. In the topside ionosphere, O^+ is the dominant ion and distributes following the dynamic equilibrium. O^+ density and H^+ density are equal at UTH. To maintain the charge neutrality, the ions and electrons move together in the ambient neutral atmosphere (ambipolar diffusion). Assuming that the plasma contains major ions (O^+ for the topside ionosphere), electrons, and one neutral species (atomic O) for convenience, a classical diffusive equilibrium equation is solved easily for an isothermal atmosphere, which yields the solution of electron density N_e at the altitude of z,

$$\mathrm{N}_e = (1-\alpha)\, N_0 \exp(-(z-z_0)/H_p) + \alpha N_0 \exp(-(z-z_0)/H_n)\,, \qquad (1)$$

where N_0 and z_0 are the reference plasma density and altitude, H_p and H_n are the scale heights of the plasma and neutral atmosphere, and α is a coefficient whose maximum value is limited to 1. $\alpha = 0$ represents that the profile is completely in the diffusive equilibrium condition, while $\alpha > 0$ ($\alpha < 0$) means that there is an upward (downward) flux along the magnetic field lines.

PROCEDURE FOR THE CALCULATION OF ELECTRON DENSITY PROFILE

Electron density profiles for the three separated regions were calculated. The topside ionosphere was reproduced using (1). This calculation requires several input parameters, including the electron temperature T_e, ion temperature T_i, neutral temperature T_n to calculate H_p and H_n. Empirical models were used for these parameters: T_e and T_i were derived from the IRI model [1], and T_n is from the NRLMSISE-00 model [2]. The NmF_2 and h_pF_2 obtained by ionosonde observations at Kokubunji (35.7°N, 139.5°E) were used as fixed N_0 and z_0. The h_pF_2 was derived from the ionospheric transmission factor $M3000F_2$ [3]. For the bottomside ionosphere, IRI model was used. And for the protonosphere, an exponential function following the T_e obtained from the IRI model was adopted. For UTH, an empirical model provided by Triskova et al. [4] was used. The parameter α was determined so as to fit the integrated value of N_e to the TEC obtained by GPS measurements [5].

In order to verify the results, the electron density and neutral wind obtained by the Middle and Upper atmosphere (MU) radar at Shigaraki, Japan (34.8°N, 136.1°E), was used [6], [7]. The electron density profiles are obtained from about 100 km to 1000 km, and the neutral winds around F region altitudes (220 to 450 km) are also observed by the MU radar.

RESULTS

Fig. 1 shows profiles of electron density on 20 September, 2001. They are at the times of midnight (0100 LT), morning (0700 LT), and noon (1300 LT) from the left. The solid line, dotted line, and open circles represent the current model, IRI prediction, and MU radar observation. The horizontal dashed line illustrates UTH. It can be seen that the model well agrees with the MU radar observations in morning and nighttime, while there are some disagreement in daytime; the model has smaller scale height just above the peak than the MU radar observation.

Fig. 2 represents daily variations of GPS-observed (dots) and modeled (solid) TEC (left), UTH model (center), and coefficient α (right) on the same day. The positive value of α during daytime means that there exists field-aligned upward plasma flux, and the negative value of α during nighttime means the existence of field-aligned downward plasma flux. This is consistent with ionospheric breezing; during daytime, plasma produced by photoionization in the lower F region diffuses upward along the magnetic field lines. During nighttime, downward flux supplies plasma into the lower F region where the recombination proceeds. The model also shows a large upward flux at sunrise, when the vertical gradient of plasma density is steep.

DISCUSSION

Here we discuss the disagreement between the calculated and MU radar-observed electron density profiles in daytime. One of the possible reasons of the difference is that the transition height model is not appropriate. We modified the procedure on the model calculation; first, α is fixed to make the calculated N_e profile aligned to the MU radar observation above the F layer peak, then UTH is determined to fit the integrated N_e to GPS-TEC. Fig. 3 is a calculated profile at 1300 LT using this modified procedure. Fig. 4 is the daily variation of the calculated TEC (dots in the upper panel), and selected UTH (dots in the lower panel). Asterisks in the upper panel represent the GPS-TEC, and in the lower panel are the UTH model used in the original modeling. Solar flux $F_{10.7}$ is from 150 to 250 (moderate to high solar activity on September) in the left panel, and from 80 to 150 (low to moderate solar activity in April) in the right panel. TEC values are proper both in the left and the right panels, otherwise the UTHs show large dispersion especially in the lower solar activity case. The UTH model is an empirical model based on the satellite data mostly obtained during a high solar activity period [4]. It may not be appropriate for the plasma density distribution in a low solar activity period.

Some other reasons for this disagreement are mentioned briefly. From Fig. 1, the scale height of the mode; profile is smaller than that of the MU radar observation just above the F layer peak. The temperatures of plasma and/or neutral atmosphere should be higher than those of the model to create a broad peak.

We have ignored the effect of neutral winds, but according to the HWM empirical neutral wind model [8], there exists a poleward wind during daytime in the period of equinox. The poleward wind lowers the F layer height. The wind effect was simulated by the SAMI2 model [9], which showed the increase in the scale height above the peak during daytime the HWM wind was included (Jin, private communication). The MU radar observations, however, show that the amplitude of the wind is smaller than that of HWM model during a high solar activity period[10]. It may not yield significant errors to neglect the wind effect when $F_{10.7}$ is large.

SUMMARY

A semi-theoretical model of topside ionosphere electron density was constructed using N_mF_2 and h_pF_2 observed by the ionosonde, and TEC derived by the GPS measurements. The model results were compared with the MU radar observations, and showed a good agreement with each other during nighttime and around sunrise. The discrepancy of the model and the observed profiles during daytime should be caused by several factors; such as an inappropriate UTH and/or T_e, T_i, and T_n models, and the effect of neutral winds. Further study is needed to establish the more reliable topside ionospheric model.

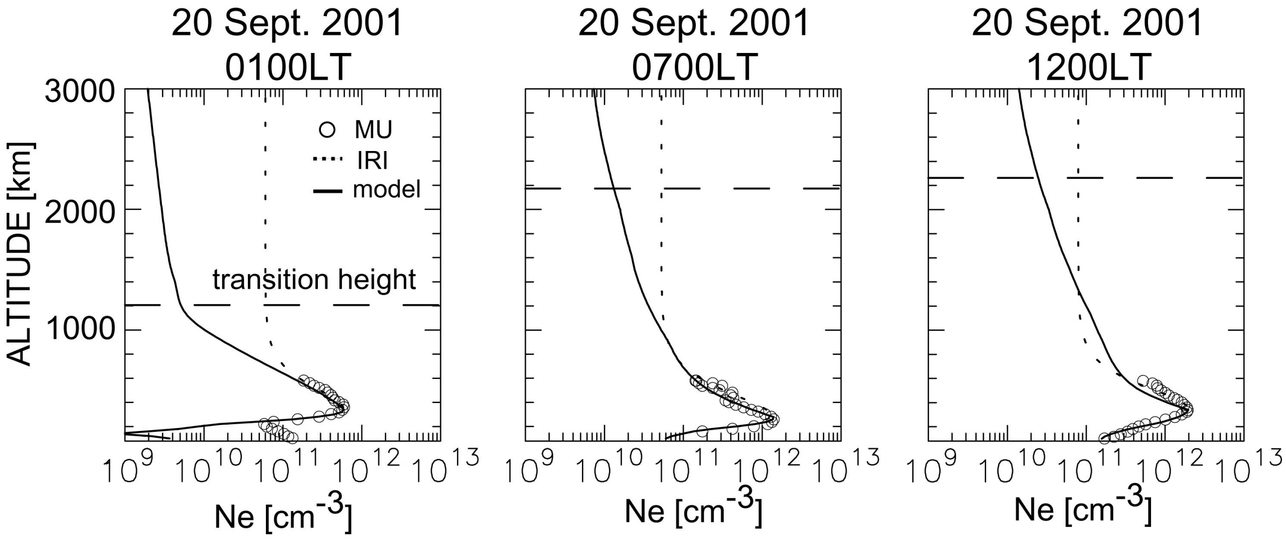

Figure 1: The electron density profiles of the current model (solid line), IRI (short-dashed line), and the MU radar observations (open circle) on 20 September, 2001 for three local times; nighttime (0100 LT), morning (0700 LT), and daytime (1300 LT) from the left. The horizontal long-dashed lines represent the empirical UTH model.

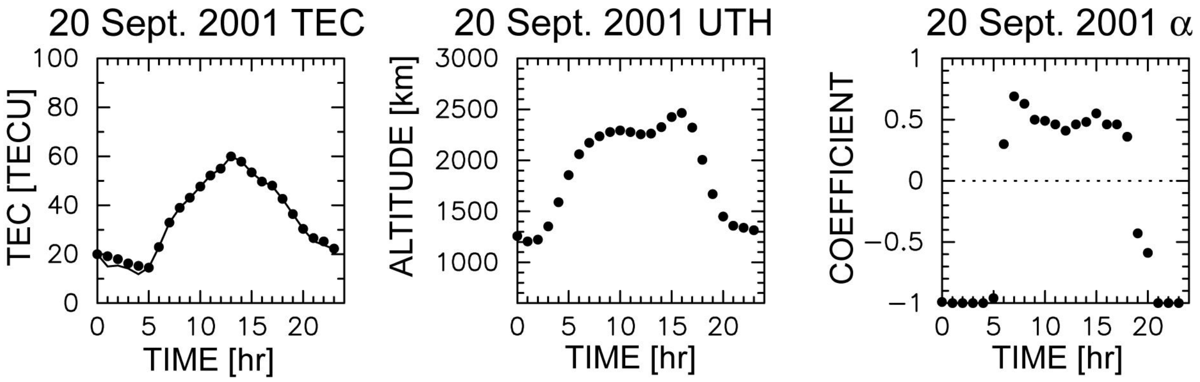

Figure 2: Daily variations of observed (dots) and calculated (solid line) TEC (left), UTH model (center) and α (right) on 20 September, 2001.

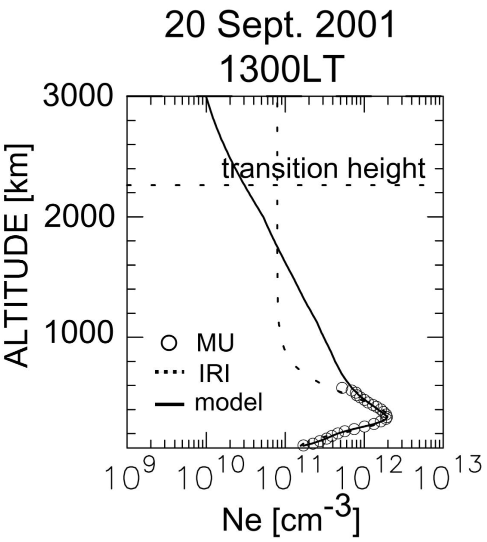

Figure 3: The calculated profiles of ionosphere (solid line), IRI model profiles (dashed line), and the results of MU radar observations (open circle) during daytime (1300LT) on 20 September, 2001. The calculated profile was fit to the MU radar observation above the F layer peak. The transition height was adjusted to fit the integrated N_e with GPS-TEC.

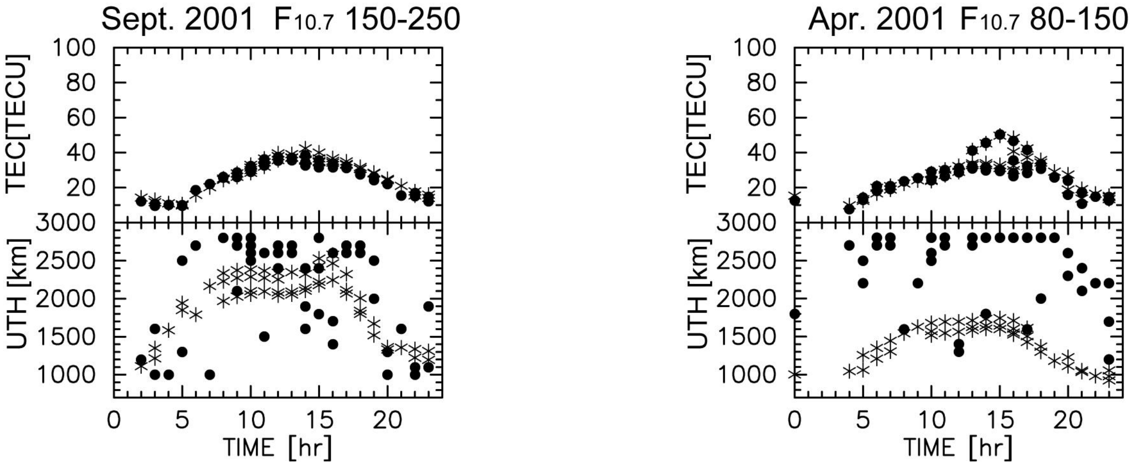

Figure 4: Daily variations of TEC (upper) and UTH (lower). The dots are obtained from the calculation. Asterisks are the observation (TEC) and the empirical model (UTH). The left panels are for a period of maximum solar activity ($F_{10.7}$ = 150 - 250), and the right for a period of moderate solar activity ($F_{10.7}$ = 80 - 150).

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