

## A simulation study of the influence of soft precipitating electrons on the polar ionosphere

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**Abstract** Calculation of the influence of soft precipitating electrons on the polar ionosphere was carried out. The primary results are: (1) During summer time when the sunlight is the main source of upper atmosphere ionization, the additional soft electron precipitation can increase the  $N_mF_2$ . The daily variation of  $N_mF_2$  is mainly controlled by solar EUV radiation. (2) At wintertime, when only soft electron precipitation ionization is considered, a peak at the height of  $F_2$  layer also appears. The altitude profile of electron density is different from that when the sunlit ionization is taken into account.

**Key words** ionosphere, simulation, soft precipitating electron.

### 1 Introduction

In polar region, the geomagnetic fields are open to the outer space and almost vertical to the earth's surface. They have connections with different regions in the outer magnetosphere. High-energy electrons from outer space can penetrate deep into the atmosphere along the magnetic fields. They can excite the atoms and molecules to produce auroras that can be seen with naked eyes. On the other hand, atmospheric neutral particles are ionized, causing changes to properties of the polar ionosphere. The precipitating electrons vary quite a lot in respect of their energetic distribution and magnitude of the fluxes due to different origins and disturbed conditions in the outer space. Spiro *et al.* (1982) and Hardy *et al.* (1985) analyzed statistically the distribution in different magnetic local time, geomagnetic latitude and  $Kp$  index. The section dealing with the pattern of precipitation of soft electrons (with average energies less than 600 eV), is associated with the boundary sheet, cusp region and day-side low-latitude boundary layer (Hardy *et al.* 1985). Zhongshan Station locates right at the place where precipitating soft electrons exist during daytime. The mean ionosphere in winter at Zhongshan Station of Antarctica has maximum value of  $f_oF_2$  around 0900 UT (Liu *et al.* 1997), the so-called magnetic local noon effect. Zhu *et al.* (1998) calculated the ionization rate of electrons under certain conditions. But he did not obtain the altitude distribution of electron and ions concerning the detail photochemical reactions and

transportation effect in the ionosphere. As one of the aspects that have great effects on the polar ionosphere, precipitating electrons should be studied in detail. In this paper, we will first introduce the construction of the model and the numerical methods used in simulating the ionosphere. We will then calculate the effects of precipitating electrons on the ionosphere, especially during summer and wintertime respectively. We will try to use the results to give evidence that the magnetic local noon effect is most probably caused by soft precipitating electrons.

## 2 Polar ionospheric model and numerical technique

For each species  $i$ , the continuity equation is:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = p_i - l_i \quad (1)$$

and momentum equation:

$$\nabla P_i - n_i m_i \mathbf{G} - n_i e_i \mathbf{E} = n_i m_i \sum_n \nu_{in} (\mathbf{V}_i - \mathbf{V}_n) \quad (2)$$

In the above equations,  $n_i$  is the number density of species  $i$ ; and  $\mathbf{V}_i$  denotes the drift velocity;  $p_i$ , the production rate of each ion;  $l_i$ , the loss rate;  $P_i$ , the partial pressure of species  $i$ ;  $m_i$ , the mass;  $e$  the charge;  $\nu_{in}$ , the collision frequency with neutral particles;  $\mathbf{V}_n$ , velocity of the neutral atmosphere;  $\mathbf{E}$ , polarization electrostatic field;  $\mathbf{G}$ , gravitational acceleration.

To obtain equation (2), the viscosity, thermal diffusion and non-linear acceleration term are neglected.

The electron is assumed to come down exactly along the geomagnetic field. In the polar region, the geomagnetic field is almost perpendicular to the earth's surface. Here we consider only one-dimensional situation. The ionosphere is horizontally stratified. Setting the positive axis vertically upward, the continuity equation can be further written as:

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial z} (n_i V_i) = p_i - l_i \quad (3)$$

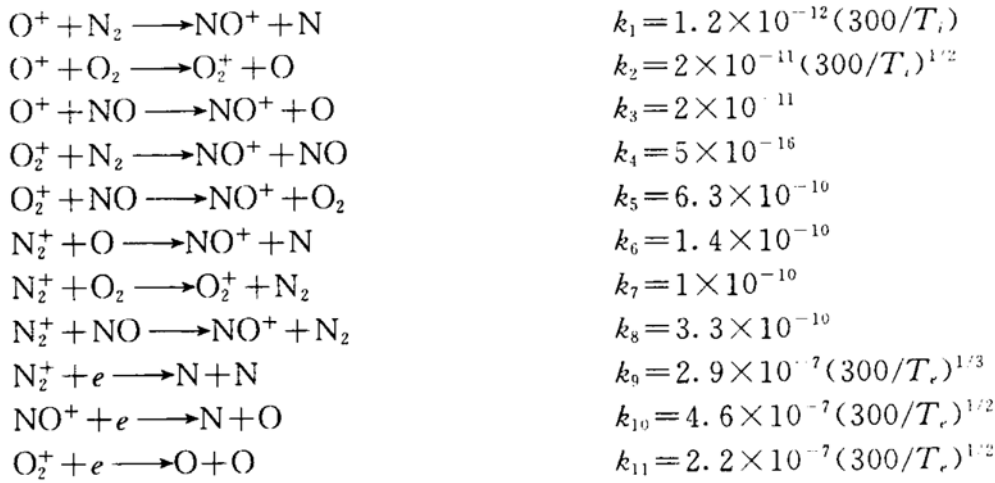
where  $V_i$  is the particle velocity along vertical direction. The expression of  $V_i$  can be obtained as follows by combining the equations of different ions and electron, eliminating polarization electrostatic field and terms of order  $m_e/m_i$ :

$$V_i = V_n - D_i \cdot \left[ \frac{1}{n} \frac{\partial n}{\partial z} + \frac{m_i g}{k T_i} + \frac{1}{T_i} \frac{\partial}{\partial z} (T_i + T_e) + \frac{T_e}{T_i} \frac{1}{n_e} \frac{\partial n_e}{\partial z} \right] \quad (4)$$

Where  $D_i = \frac{k T_i}{m_i \nu_i}$  is the ion's diffusion coefficient in the neutral atmosphere,  $\nu_i = \sum_n \nu_{in}$  is ion's total collision frequency with neutral components.

The fundamental chemical and physical processes are those ionospheric ions including  $O^+$ ,  $O_2^+$ ,  $NO^+$  and  $N_2^+$ . The neutral components considered in the model are  $O$ ,  $O_2$ ,  $NO$  and  $N_2$ . Given by atmospheric model MSIS86 (Hedin 1987). We carry out calculation with the condition of solar minimum, where  $F_{10.7} = 100 \times 10^{-22} \text{ W}/(\text{m}^2 \cdot \text{s})$  and  $A_p = 6.0$ . Photo-ionization, chemical reaction and precipitating electron are considered in the continuity equation (3). The loss of the ions is caused by chemical reactions. The photo-ionization is assumed to be mainly caused by 10 bands of solar EUV radiation (Taieb *et al.* 1978). As for the calculation of photo ionization rate, we use the method of Smith and Smith (1972). Temperatures of ions and electron are taken from IRI90 model (Bilitza 1990). 11 chemical reactions that are important in the region of consideration are included

(Schunk and Walker 1973) as follows:



where  $k_i$  is the reaction rate coefficient in unit of  $\text{cm}^3/\text{s}$ .

The consideration of precipitating electrons is taken using experimental results of dissipation distribution of precipitating electrons in the neutral atmosphere. The ionization rate is then obtained by combining neutral atmospheric model as follows (Rees 1963):

$$q_p = \int_{\epsilon_{\min}}^{\epsilon_{\max}} \frac{N\epsilon/r_0}{\Delta\epsilon_{\text{ion}}} \cdot \lambda \left[ \frac{Z}{R} \right] \frac{n(M)_z}{n(M)_R} d\epsilon \quad (5)$$

Where  $\epsilon$  is the initial energy of the precipitating electrons, and  $\Delta\epsilon_{\text{ion}}$  the mean energy loss per ion pair formed, which is usually taken the value of 35 eV.  $n(M)_z$  and  $n(M)_R$  denote the neutral number densities for ionizable atoms or molecules at atmospheric depth  $Z$  and  $R$  respectively.  $R$  is the penetration depth for precipitating electrons of some specified energy, and it is related to the initial energy by the power law:  $R = 4.57 \times 10^{-6} \cdot \epsilon^{1.75}$ ,  $r_0 = R/\rho$ .  $\lambda \left[ \frac{Z}{R} \right]$  is the normalized energy dissipation function. The precipitating electrons are assumed to be isotropic for pitch angles between  $0^\circ - 80^\circ$ ,  $N$  is the precipitating electron number flux in unit of  $\text{el.} \cdot \text{cm}^{-2} \text{Str}^{-1} \text{s}^{-1} \text{eV}^{-1}$ .

Using the above description, the production of each ion caused by precipitating electrons are then written as (Rees 1989):

$$P_{N_2^+} = 0.76 \times q(N_2) \quad P_{O_2^+} = 0.66 \times q(O_2) \quad P_{O^+} = 0.33 \times q(O_2) + q(O)$$

Where:

$$q(N_2) = q_p \cdot \frac{0.92 \times [N_2]}{0.92 \times [N_2] + [O_2] + 0.56 \times [O]}$$

$$q(O_2) = q_p \cdot \frac{[O_2]}{0.92 \times [N_2] + [O_2] + 0.56 \times [O]}$$

$$q(O) = q_p \cdot \frac{0.56 \times [O]}{0.92 \times [N_2] + [O_2] + 0.56 \times [O]}$$

From equation (3) and (4), the altitude distribution of each ion and electron can be obtained numerically after properly applying the finite differential scheme to the differential equations.

The numerical domain covers from 110 km to 610 km, with space step of 2 km. As for the boundary conditions, chemical equilibrium is assumed at the bottom, i. e. at 110 km. While at the upper boundary, physical concept is considered (Brekke 1997). For the minor ions such as  $O_2^+$  and  $NO^+$ , bipolar diffusion equilibrium is assumed. For the major  $O^+$ , we take that of IRI90 model. Since the reaction containing  $N_2^+$  is fast compared to transport

process, photochemical equilibrium is assumed throughout the numerical domain (Schunk and Walker 1973).

As for the calculation procedure,  $p_i = l_i$  in equation (3) to obtain the resolution of photochemical equilibrium. The result is then used as the guessed solution of equation (3) and (4). The newly obtained results are again used as the guessed solution and so on, until number density of each species no longer changes significantly at any altitude. Here in this paper, condition  $|n_e^{t+1} - n_e^t|/n_e^t < 10^{-7}$  must be satisfied.

### 3 Numerical results

As a test, we calculated the profile of the ionosphere at Zhongshan Station (69.3°S, 76.3°E) when only photo-ionization is taken into account during summertime. A specific day of October 15 is chosen here in the calculation. Fig. 1a and Fig. 1b show the altitude distribution of the ionospheric components at local noon and midnight respectively. We can see that the distribution of electron density shows apparently the E and F layer at local noon. Also we can see that the major is the molecular ions in the E layer, among which the  $O_2^+$  takes the main part. At local midnight, the ionosphere over Zhongshan Station is still in sunny side but with a larger solar zenith angle. The ionization effect is weaker. Actually the  $N_m F_2$  at noon is larger than that at midnight in Fig. 1. Some more characteristics are that at midnight,  $F_1$  layer disappears, a distinct low valley appears between E and F layer, the density of each ion species decreases as a whole, there are two maximums at about 120 km and 230 km, respectively. The  $N_2^+$  is always the minor.  $O^+$  is the majority at F layer altitude. Transition height between the atom-ion domination and molecular ions is at about 180 km. All of these are similar to the general properties of normal ionosphere.

At magnetic local noon (at about 1500 LT), Zhongshan Station locates at cusp region.

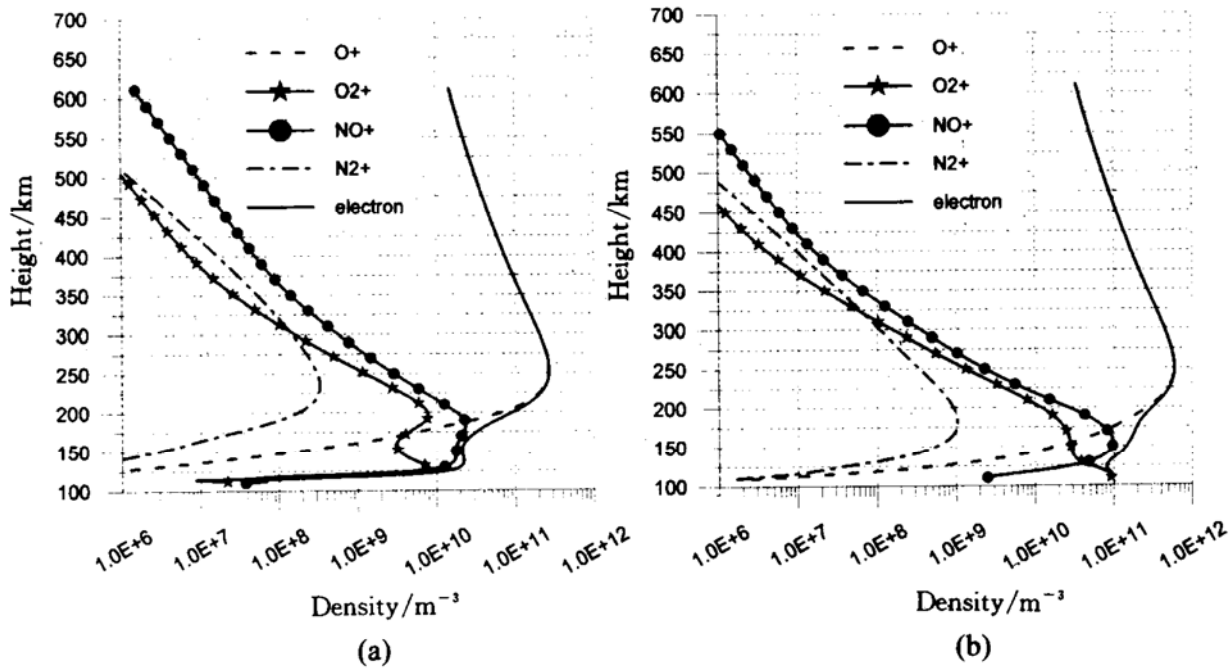


Fig. 1. The calculated ions and electron's height distribution (a) at  $t=0000$  LT; (b) at  $t=1200$  LT.

The precipitating electrons at this region of the magnetosphere show the characteristic of soft electrons. And the energy distribution is power law. The expression is:

$$N = N_0 e^{-\alpha} \quad (6)$$

where the factor  $N_0$  and  $\alpha$  determines the total precipitating energy fluxes and the mean energy of the electrons.

We consider two beams of electrons. They have the same total energy flux of  $1.16 \times 10^8 \text{ keV}/(\text{cm}^2 \cdot \text{s})$ , but the energy distributions are different. The total energy is chosen according to real observations. The characteristics of the two beams are shown in Table 1. Where  $E_{\text{Ave}}$  and  $N_{\text{Total}}$  are mean energy and the total number flux of the electron beam respectively. The energy range varies from 0.1 keV to 4.0 keV.

Table 1. Characteristic parameters of the two precipitating electron beams

	$N_0$	$\alpha$	$E_{\text{Ave}}/\text{eV}$	$N_{\text{Total}}/(\text{el.} \cdot \text{cm}^{-2} \cdot \text{s}^{-1})$
Case 1	$2.34 \times 10^6$	4.0	150	$7.79 \times 10^5$
Case 2	$3.44 \times 10^7$	1.73	495	$2.36 \times 10^5$

The height distribution of ionization rate of the two beams on the ionosphere is shown in Fig. 2. It can be seen that the average energy of the precipitating electrons determines the shape of the altitude distribution of each ion's ionization rate. The situation of the average energy of 150 eV makes the maximum ionization rate appear at about 270 km, while the 495 eV case has its maximum at about 120 km. Despite of the difference of ionization rate, both cases have the similar results of ionospheric profile. There exists maximum electron number density at the altitude of  $F_2$  layer. This can be seen clearly in Fig. 3a and Fig. 3b. The main difference is that a broad area of the same number density appears between altitude range of 120 – 170 km for the higher average

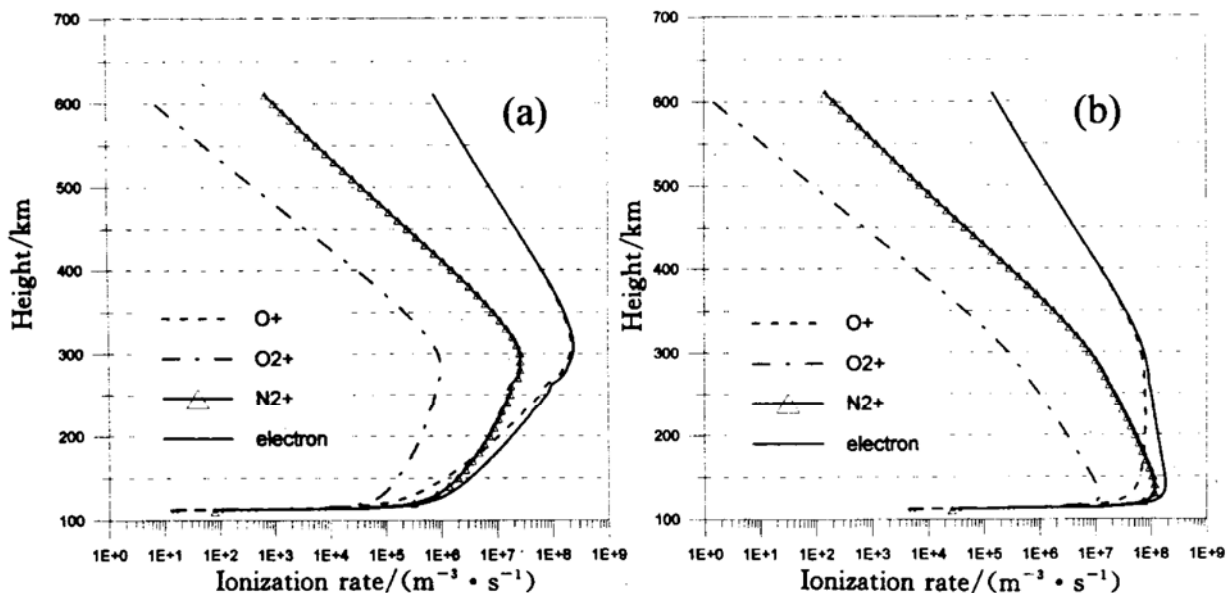


Fig. 2. Height distribution of ionization rate. Two cases are illustrated with the same energy flux while the average energy is different. (a) average energy 150 eV; (b) average energy 495 eV.

energy situation. Since the two cases have the same total energy fluxes, and the lower average energy case has more electrons at the lower energy end. The resulting  $N_m F_2$  is obviously larger at a higher altitude.

When Zhongshan Station locates at cusp region in summer time, the source of ionization mainly comes from the solar EUV radiation and precipitating electrons. The simulation results are shown in Fig. 4 when the two ionization sources are taken into account. The influence of precipitating electrons is mainly for the increase of the number density of F layer maximum, while there is little change of the shape of electron's altitude distribution. For the situation considered in this paper,  $N_m F_2$  increases from  $5.97 \times 10^{11}/\text{m}^3$  to  $7.83 \times 10^{11}/\text{m}^3$ . There is small change of  $h_m F_2$ , from 250 km to 256 km. The area below  $h_m F_2$  has almost the same shape of the pure photo-ionization situation. Fig. 5 illustrates the mean properties of the variation of  $f_o F_2$  versus universal time in 1995 summer time (solid line). Also shown in Fig. 5 is the simulated variation when only photo-ionization is considered (dashed line). We can see that the variation trend of the two lines is very similar. The maximum appears between 0600 – 0900 UT o'clock,  $f_o F_2$  decreases between 1100 UT and 1900 UT o'clock. This means that the ionosphere over Zhongshan Station at summer time is mainly controlled by the solar EUV radiation.

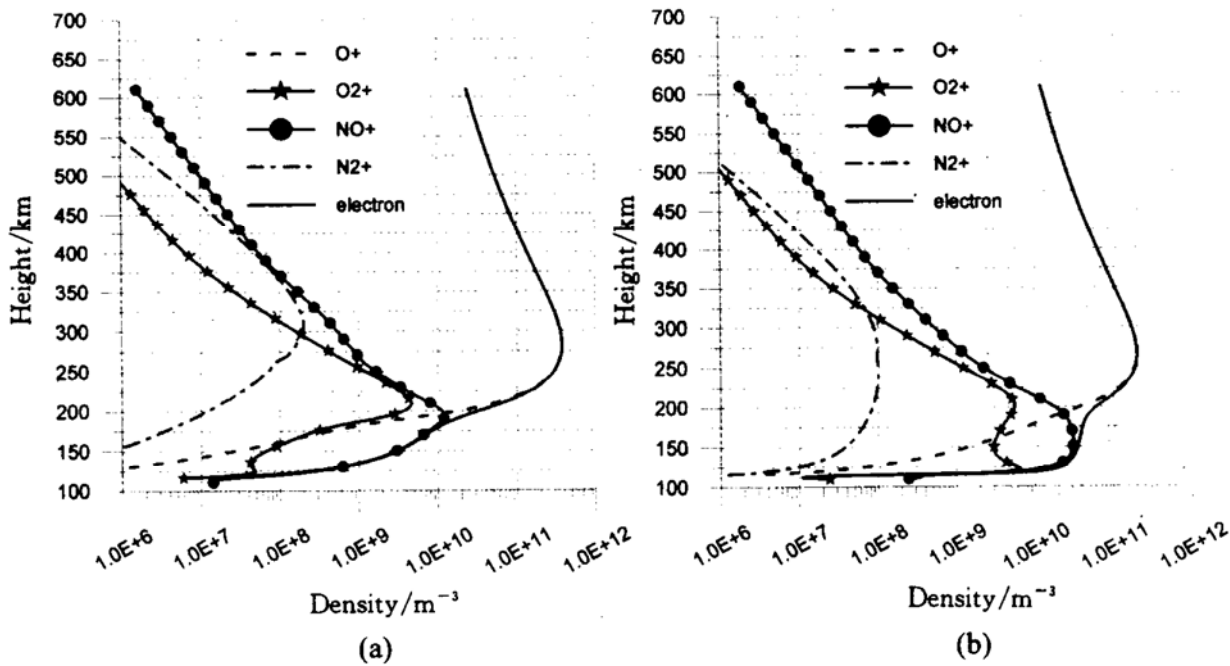


Fig. 3. Height distribution of ionosphere due to different energetic precipitating electrons. (a) average energy 150 eV; (b) average energy 495 eV.

#### 4 Conclusion and discussion

The simulation results show that in winter when soft precipitating electrons are assumed the only ionization source at cusp region, there still exists the  $F_2$  layer

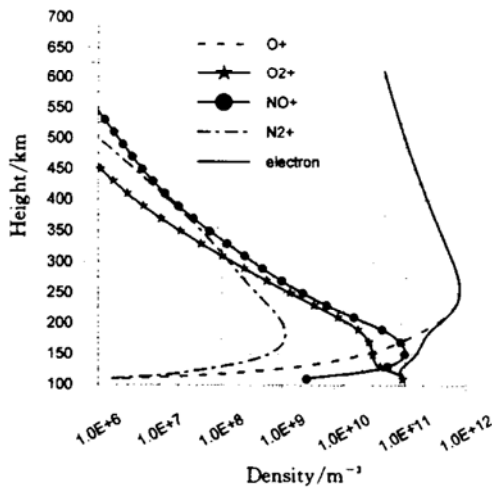


Fig. 4. The height distribution of ions and electron when photo-ionization and precipitating electrons' ionization effect are considered simultaneously. The situation corresponds to summer magnetic local noon at Zhongshan Station.

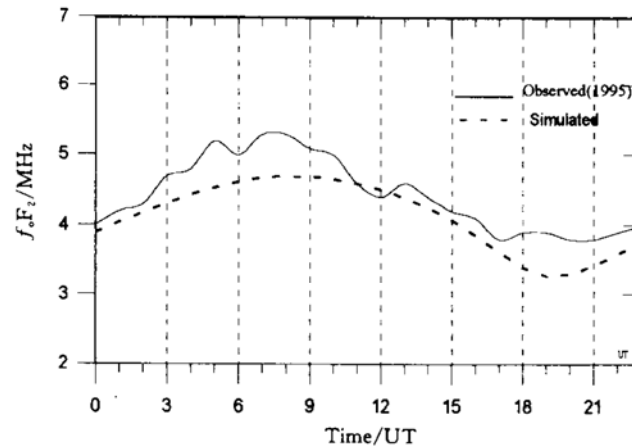


Fig. 5. Comparison between the observed monthly media value variation of  $f_oF_2$  versus universal time (solid line) and the simulated results (dashed line) in the summer time. The ionization effect of precipitating electrons was not included in the simulation.

maximum. The shape of the ionospheric altitude distribution is clearly influenced by the average energy of the soft electrons. The more remarkable influence is at the altitude range below F layer. We have also calculated the influence of another precipitating electron beam. The corresponding energy range is from 1 keV to 4 keV. The average energy is 2.57 keV and not in the soft energy range. The total energy flux is  $2.19 \times 10^8$  keV/(cm<sup>2</sup> · s). The results show that there exist two maximums at E and F region respectively. But the electron number density is greater at E region than that at F layer. These results illustrate that the average characteristic of abnormal increase of  $f_oF_2$  at Zhongshan Station when it passes cusp region at magnetic local noon is most probably caused by soft precipitating electrons. Since  $h_mF_2$  is determined from the primary equilibrium between plasma diffusion and photochemical processes without other dynamic effects, the simulated  $h_mF_2$  has little difference due to different type of soft precipitating electrons.

The precipitating electrons have far less influence on the ionosphere in summer than in winter. This lies in the reason that a larger background electron density is constructed because of solar EUV radiation. The average feature of  $f_oF_2$  shows a clear stable daily variation. In this situation, the influence of precipitating electrons increases mainly the number density at F layer.

Although we have simulated quantitatively the altitude distribution of ions and electron, we have only qualitatively compared the results with average ionospheric features at Zhongshan Station to show that the magnetic local noon effect is most probably caused by soft precipitating electrons. The selection of electron's energetic distribution at cusp region is only under the consideration of its mean characteristic. The more meaningful work should be done when the simulation results are compared with

DPS-4's ionospheric measurement using observed results of precipitating electron distribution from satellite at the top ionosphere. Moreover, thermal effects of precipitating electrons may also influence the relative component of ionosphere through the change of reaction rate coefficient and the transportation effects. Hence the energy equation considering heating effects of precipitation electrons should be included with self-consistency instead of the adoption of empirical temperatures of electron and ions to carry out the simulation of auroral ionosphere.

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