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A SELF-CONSISTENT NUMERICAL MODEL FOR THE IONOSPHERIC DYNAMO

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We present a calculation of the ionospheric electric fields due to the equatorial E- and F-region dynamos, where the electron continuity equation and the F-region wind equation are solved explicit and simultaneously. Several results are given for the electron density and plasma drifts in the F-region, showing that the model is a powerful tool for the understanding of the dynamo process, especially when effects of different parameters are to be isolated.

Key words: Ionospheric dynamo; Numerical model; E- and F- region of the ionosphere.

UM MODELO NUMÉRICO CONSISTENTE PARA O DÍNAMO DA IONOSFERA – *Apresentamos uma simulação dos campos elétricos na ionosfera, devidos aos dínamos nas regiões E e F, onde a equação da continuidade para os elétrons e a equação do vento na região F são resolvidas simultaneamente e em forma explícita. Vários resultados são fornecidos para a densidade eletrônica e para as derivas do plasma, mostrando que o modelo é uma ferramenta poderosa para se entender o processo do dínamo, especialmente quando se quer isolar os efeitos de diferentes parâmetros.*

Palavras-chave: *Dínamo da ionosfera; Modelo numérico; Regiões E e F da ionosfera.*

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INTRODUCTION

In the ionosphere we have production of ionization and temperature gradients in the neutral and ionized atmosphere, due to the Sun's radiation. The temperature gradients correspond to pressure gradients that set the neutral air in motion, causing the winds. In the region of our interest, between 170 km and 1000 km, atomic oxygen is the dominant neutral and ionized species. The ionized oxygen will be simply referred as "ions" from now on. As the wind blows, collisions between neutral particles and ions force the latter to move in a direction perpendicular to both the wind and the earth's magnetic field. As the collision frequency between neutrals and electrons is much less than the ion-neutral collision frequency, the electrons do not follow the ions. As a consequence of this process, electric currents perpendicular to both the wind and magnetic field are developed. These currents are proportional to the ion density whose gradients cause the set up of and electrostatic field. While it is difficult for electric charges to move perpendicularly to the magnetic field, it is very easy for them to move along it. For this reason the earth's magnetic field lines are excellent electric conductors [Farley, 1960]. Then, the build up of electrostatic fields in the above process will depend on how conducting is the ionosphere at all points of the field lines, in the direction perpendicular to these field lines. This is measured by the value of the Pedersen conductivity. This conductivity is high during the day, at about 100 km, i.e., in the E-region. Therefore, we expect to have strong electrostatic fields caused by the described process only at night. This process of generation of electrostatic fields by the wind is called the 'atmospheric dynamo' and, more specifically, the F-region dynamo, since there is another dynamo in the E-region of the ionosphere.

In the E-region, situated around the height of 100 km, there is another dynamo process that is different from the F-region especially due to the fact that the E-region is 'narrow' as compared to the F-region, so that currents flow mostly on the surface of a spherical shell. In addition, the collision frequency between ions and neutrals is greater than that in the F-region which increases the effect of the wind on the ions.

Now we come to the connection between both E- and F-dynamos and the ion(electron) density. Due to the well conducting magnetic field lines, the electrostatic field due to the E-region dynamo maps itself to higher heights [Rishbeth, 1971a,b]. At these heights, the plasma will suffer electrodynamic drift, or $\mathbf{E} \times \mathbf{B}$ drift, so that the interaction with the wind changes, affecting the F-region dynamo. Another effect on the F-region dynamo comes through the distribution of ionization that will diffuse due to the drifts and gravity. The effect on the E-region comes through the flow of currents due to the F-dynamo along the magnetic field lines, which will affect the electric field due to that dynamo, and so on. This is, of course, an idealized picture, since all the effects above take place at the same time - it is a self-consistent process.

The wind in the upper atmosphere is mostly due to both the heating of the atmosphere by the sun and the gravitational influence due to the moon. So the wind field can be thought as of composed of several "tides" or tidal modes of solar or lunar origin. Most of the early works on dynamo theory consisted in determining which of the tidal modes were of greater importance for the generation of electric currents in the ionosphere. The model of Tarpley [1970] is the originator of the modern models and was written for this purpose.

Tarpley's model considers a dynamo in a finite thickness E region, where the vertical currents are neglected. All currents flow only inside the E region - a closed E region. This makes $div_h \mathbf{J} = \mathbf{O}$ everywhere, inside the region, where $\mathbf{J}$ is the height integrated current density, and h denotes that the divergence is in the horizontal plane. Then $\mathbf{J}$ can be expressed in terms of a current function. The total electric field is made up of two contributions: a dynamo electric field $-\mathbf{U} \times \mathbf{B}$ and a polarization electric field due to large scale charge separation. Here $\mathbf{U}$ is the wind velocity and $\mathbf{B}$ is the geomagnetic field. The above currents can be expressed as functions of this total electric field and of the conductivity tensor of the medium, which is obtained by height integration of the Pedersen, Hall and direct conductivities. The electrostatic potential is eliminated between the two equations and a solution for the current function is obtained. From there, the electrostatic potential and the currents can be obtained. In a latter work [Richmond et al., 1976], the electric field due to this potential is mapped into the F region, and the corresponding plasma drifts are calculated.

The pioneer work on F region dynamo was that if Rishbeth [1971a,b], where the thermospheric wind creates a polarization electric field in the F region. The strength of this field depends on the conductivity of the E region, at the foot of the corresponding magnetic field lines. During the day the F-dynamo would be small, since field aligned currents would flow and short out the electric field. Rishbeth dedicated the paper more to the physical insight of the new idea than to the complications of the real ionosphere. The idea was expanded in the work of Heelis et al. [1974] where both E- and F-dynamos are treated in detail. In this model, of which ours is an extension, the E region is considered as a thin conducting layer, and currents may flow through the boundary between the E and F regions. Symmetry between hemispheres is assumed, so that no currents flow through the equatorial plane. During the day, the conductivity is large in the E region and the F-dynamo is shorted-out so that the F region electric fields are due mostly to the E region dynamo. During the night both E- and F-dynamos contribute to the plasma drift.

As shown by Farley et al. [1986], the shape of the profile of $N\upsilon$, i.e., electron density times ion-neutral collision frequency, is very important to determine the field aligned currents that flow between the E- and F regions. The collision frequency, υ, can be assumed simply to be proportional to the neutrals density but N behaves in a more subtle way. Heelis et al. [1974] consider a simple Chapman layer whose peak density varies according to experimental values. This peak moves vertically in a preset way, based also on experiment, but independently of the calculated plasma drifts. Later, Bonelli [1985] made this motion proportional to the vertical plasma drift. Anderson & Mendillo [1983] consider a simplified version of the F-dynamo, with emphasis on the electron density profile. This profile was calculated using a very complete solution of the plasma continuity equation, where the vertical plasma drift was included. They considered an approximation of a non-conducting E region, valid for nighttime. With this they calculated the zonal plasma drift as a function of height, given a zonal and a meridional winds. The vertical drifts used in their model are experimental values from Jicamarca, Peru. In the work of Batista et al. [1986], the effect of the asymmetry of the two hemispheres is considered, especially with respect to the vertical plasma drift.

In more recent works Crain et al. [1993a, 1993b] use a very sophisticated F-region model, especially with respect to the solution of the plasma continuity equation, and a joint treatment of E- and F-regions, without separating their effects as in the models above. Their conclusion is that the F-dynamo is important for the plasma drifts not only at night, but at all times. In this model, however, the wind field is pre-set, not being able to vary due to interaction with the plasma, through collisions.

We propose a numerical model where the F-region zonal wind, the plasma drifts, and the continuity equation for the electron density (equal to the ions density, since we assume a neutral plasma) are solved self-consistently, neither insisting in specific details about the parameters involved nor on excessive grid resolution of the numerical grid. The model is detailed in the next section.

DESCRIPTION OF THE MODEL

This is an extension of the model by Heelis et al., [1974]. In that model the F-region zonal wind is calculated in the presence of an electron density given by a Chapman profile, where the peak density and the height where it occurs is given by experimental data, regardless of the calculated plasma drift. We moved further towards self-consistency by solving the continuity equation for the F-region electron density simultaneously with both the F-region zonal wind and plasma drifts [Bonelli & Farley, 1990; Bonelli & Carvalho, 1993]. To attain this self-consistency, we solve the parabolic equation for the zonal thermospheric wind (equation 1 of Heelis et al.) in a finite difference explicit form. In this method, given by Potter [1980], the solution is updated for all heights at each point in the latitude-longitude mesh. For each of these points in the horizontal mesh, the electron number density is also updated for all heights, through the continuity equation. The new electron number density enters immediately in the wind equation as the ion number density (since the plasma is assumed to be neutral). The details of the calculations are given next.

The continuity equation is given by

$$\frac{\partial N}{\partial t} = q - l(N) - div(N\mathbf{V}) \qquad (1)$$

where N is the electron number density, q is the production rate and $l(N)$ is the loss term, given by

$$l(N) = \beta N, \qquad (2)$$

with ß as the linear loss rate [e.g., Rishbeth & Garriott, 1969]. The last term in Eq.(1) is the divergence of the flux of electrons, with $\mathbf{V}$ as the plasma drift velocity.

We assume that the plasma drift velocity is due only to electrodynamic drift, so that $\nabla.\mathbf{V} = \mathbf{0}$. Then Eq.(1) becomes

$$\frac{\partial N}{\partial t} = q - \beta N - \mathbf{V} \cdot \nabla N. \qquad (3a)$$

Since the sun is the main source of the whole process, we look for an stationary solution with respect to the center of the sun. In this non-rotating frame, we have $\partial N/\partial t = 0$, and Eq.(3a) becomes

$$q - \beta N - \mathbf{V} \cdot \nabla N = 0. \quad (3b)$$

The numerical solution of Eq.(3b) is obtained for all heights, for each latitude-longitude pair. To obtain the finite difference solution to Eq.(3b) we use a forward difference approximation for the longitudinal derivative, central difference for the radial derivative, and neglect the north-south contribution of $\mathbf{V} \cdot \nabla N$. The value of the electron density at the site (i,k) of the longitude-height mesh is then given by

$$N(i,k) = \frac{1}{\beta + V_\phi/(r\Delta\phi)} \times \left\{ q + \frac{V_\phi}{r\Delta\phi} N(i-1,k) - \frac{V_r}{2\Delta r}\left[N(i-1,k+1) - N(i-1,k-1) \right] \right\}. \quad (4)$$

Here we adopt a system of spherical coordinates (r,θ,ϕ) representing the radial distance from the center of the earth, the co-latitude and the longitude, respectively. This system does not rotate with the earth, and $\phi = 0$ corresponds to midnight, local time. V_r and V_ϕ are the radial and zonal components of the plasma drift, and Δ_r and Δ_ϕ are the grid spacings in height and longitude. In Eq.(4), β, V_r, and V_ϕ are all evaluated at the site (i,k).

These equations are not solved alone. For each point on the earth, we get the new values for the electron density for all heights (from Eq.(4)), and use them in Equation (1) of Heelis et al. [1974], to obtain the new wind velocity.

All these calculations, i.e., for the momentum equation and electron density are done twice in longitude. The convergence is very good, so that both the wind and the electron density do not change appreciably if we continue the cycle beyond the second time. A profile of constant electron density, say $10^8 m^{-3}$ is used as an initial guess for the electron density profile at mid-night ($\phi = 0$), at the equator. The final solution is independent of this guess. For other latitudes the electron density is assumed to be the same as the equatorial value for the same longitude and height, i.e., there is no latitudinal variation of electron density. To consider any latitudinal variation, we would have to include diffusion along the magnetic field lines and the meridional electromagnetic drift, which would complicate the calculations. For this reason, we postpone that improvement for a future work.

We finally present a diagram to show the link between the calculations (Fig. 1). The two boxes on the right represent the contribution of the present work, while the other boxes represent essentially the model of Heelis et al. [1974]. We start the calculations in the left side, with the (1,-2) tide as main input and assuming that no current flows between the E- and F-regions. At this stage, the field aligned current density $\mathbf{j}_{//}$, and the normal to $\mathbf{B}$ current density, $\mathbf{j}_n$, at the boundary of these two regions are set to zero. As a result of the E-region dynamo, we get an initial electric field that maps into the F-region, causing a plasma drift, with a minor contribution to the F-region neutral wind, initially set to zero. This plasma drift enters the momentum equation for the neutral wind where it affects the calculation through collisions between ions and neutrals. The neutrals density *n(O)* and temperature *T* are given by Jacchia's [1977] model. The ion density comes from the continuity equation, expressed as Eq.(4) above, where a simple model for production and recombination together with the calculated plasma drift are used. Simultaneously with all this, the contribution of each grid point to the dynamo currents are being integrated (represented by the box on the bottom of the diagram). At last, from the non-divergence condition on the global currents in the F-region and

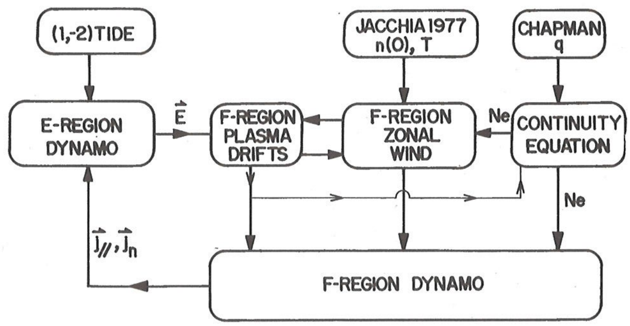

Figure 1 - Diagram indicating the coupling of the various calculations in the model.

Figura 1 *- Diagrama mostrando o acoplamento entre as diferentes fases do modelo.*

symmetry between hemispheres we get the currents at the boundary between the E- and F-regions. Here the calculations start again at the E-region dynamo (but this time with F-region effects included). The procedure is repeated until the plasma drift varies a few percent from the previous iteration.

EXPERIMENTAL INPUT

The experimental parameters of the dynamo calculations are the same used by Heelis et al. [1974], except for those used in the modifications discussed herein. These new parameters are: the peak production of ionization q_0, the height of this peak at noon, h_{q0}, and the recombination coefficient β at 300 km, for noon. The rate of production of ionization for a given local time and height is calculated as a Chapman profile [e.g., Rishbeth & Garriott, 1969] given by

$$q(z_{16}, \chi) = q_0 exp(1 - z_{16} - e^{-z_{16}} sec\chi),$$

where χ is the solar zenith angle. The maximum production rate for $\chi = 0$ is q_0. The reduced height of the atomic oxygen, z_{16}, is calculated with respect to the height h_{q0} of maximum production for $\chi = 0$, i.e. for twelve noon.

The coefficient for the loss of ionization of Eq.(3b) is given by

$$\beta = \beta_0 exp(-z_{32});$$

where β_0 is the value at 300 km and z_{32} is the reduced height of molecular oxygen, assumed to be the only molecular especies present. Since values for the parameters for the continuity equation vary a lot in the literature, we chose as standard the following:

$$\beta_0 = 7. \times 10^{-4} m^{-3} s^{-1}$$
$$q_0 = 7 \times 10^{-8} m^{-3} s^{-1}$$
$$h_{q0} = 180 Km.$$

SOME RESULTS

Now we show some results of calculations for different situations, to see how the F-region electron density, wind and the plasma drift adapt to each other.

In Fig. 2 we show the wind velocity, together with the vertical and zonal plasma drifts, for a height of 350km. The vertical drift is approximately constant in height, at least for these well behaved results due to weak or no pre-reversal enhancement of the zonal electric field. The zonal drift varies with height and, if we separate the results of the E-dynamo and F-dynamo, we can attribute this variation to the F-dynamo only. The contribution of the E-dynamo is practically constant in height.

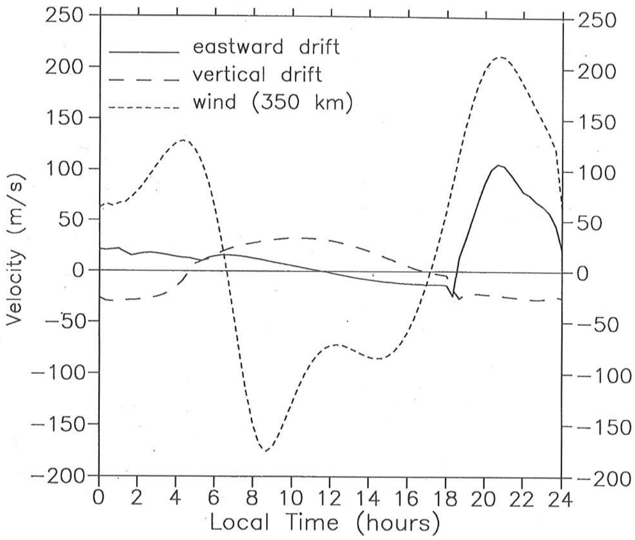

Figure 2 - Zonal drift, vertical drift, and wind for a height of 350 km, as function of local time.

Figura 2 *- Deriva zonal, deriva vertical e vento para altura de 350 km, em função do tempo local.*

In Fig. 3 three height profiles for the zonal drift are plotted for 20, 21, and 22 hours, Local Time. It is clear from this figure that the whole profile moves downwards with time. This can be explained as an effect of a downward motion of the F-layer, as is the case since the vertical drift is downwards at these times (Fig.2). We give more arguments in this respect below, when we discuss the behavior of the F-region electron density.

An interesting result are the electron density profiles for the F-region, which were obtained coupled with the plasma drifts and wind calculations. In Fig. 4 we show some of these profiles. The main features of these results are: a) Nighttime decrease in density and downward motion of the F-peak; b) Upward motion of the F-peak during the day, until around 15 LT and subsequent downward motion; c) Very little variation of the profiles between 12 and 15 LT. These features are better seen with help of a contour plot (Fig. 5) and a three dimensional diagram (Fig. 6).

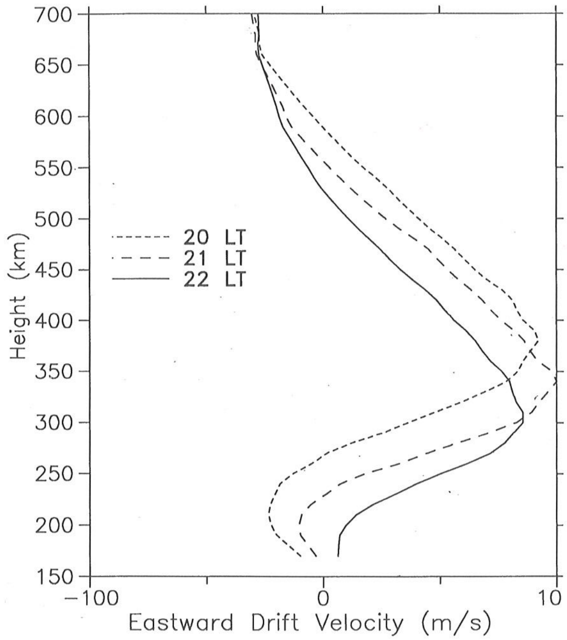

Figure 3 - Height profiles of zonal plasma drift for some local times.

Figura 3 - *Deriva zonal do plasma, em função da altura, para alguns tempos locais.*

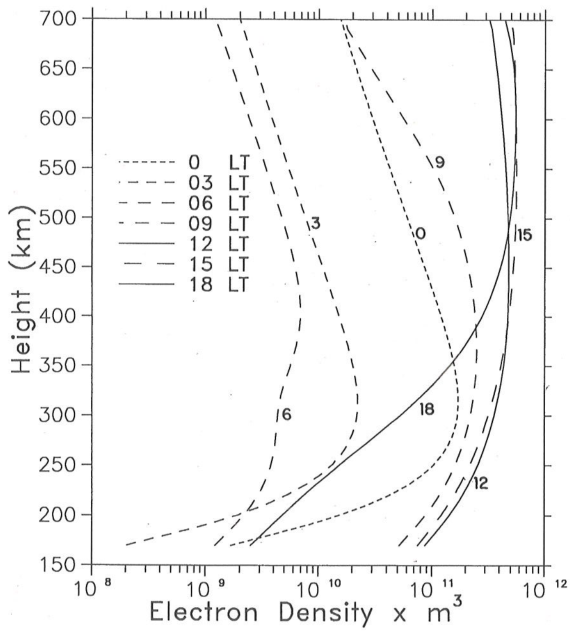

Figure 4 - Height profiles of electron density for some local times, with plasma drifts taken into account.

Figura 4 - *Densidade eletrônica, em função da altura, para alguns tempos locais, para o caso em que se considera derivas do plasma.*

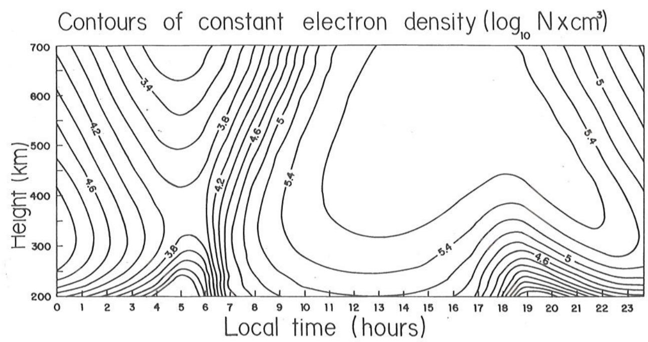

Figure 5 - Contours of constant electron density in the height-longitude plane. The labels on the iso-density lines represent the decimal logarithm of number density in cm^{-3}.

Figura 5 - *Curvas de nível de densidade eletrônica no plano altura-longitude. Os números sobre as linhas de iso-densidade representam o logaritmo decimal da densidade numérica em cm^{-3}.*

The nighttime effect of downward motion of the F peak can only be explained as being due to the downward plasma drift, since recombination is faster at lower heights and the effect of recombination would be to raise the F-peak. In this case, the decrease of electron density above the F-peak is mostly due to the diffusion of plasma to lower heights than to recombination, that is slower at these heights. To see where diffusion and recombination play their parts in the simulation, it is convenient to run the simulations for the case of no drifts at all (Fig. 7). In the non-rotating frame even in this case there is a drift: the co-rotation drift through which the plasma will follow the rotation of the earth. This drift is responsible for carrying plasma from the day to the night side. Due to this drift, the daytime electron density profiles are not "Beta Profiles", i.e., they can not be given by q/β [e.g, Rishbeth & Garriott, 1969]. This can be seen from Eq.(4), by setting $V_r = 0$ and $V_\varnothing$ = corrotation velocity.

In the present calculations we have a very small, or almost none "prereversal enhancement (PRE)" of the vertical drifts (Fig. 2). This is probably due to the over smoothing of the electron density profiles, so Eq.(4) can be numerically stable. For the cases including drifts, Eq.(4) is stable only if we use for N(i-1,k), the average value of N(i-1,k-1) and N(i-1,k+1) [Potter, 1980], which smooths too much the profiles. To avoid this problem, the only solution would be to solve the continuity equation in an implicit form, which would then forbid a self-consistent solution.

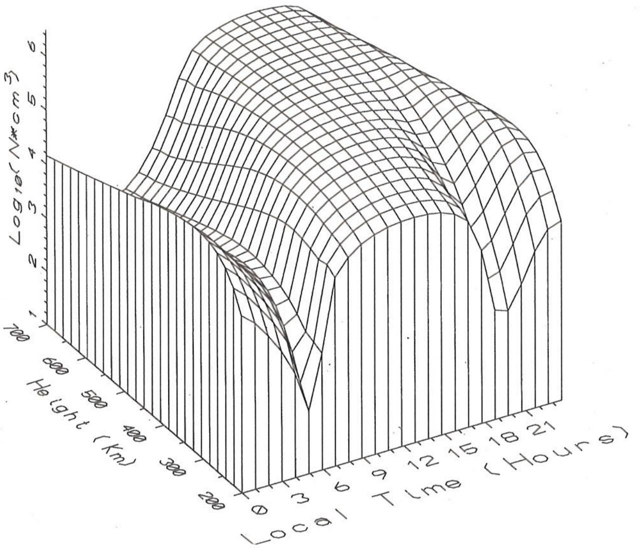

Figure 6 - Electron density as function of both local time and altitude.

Figura 6 *- Densidade eletrônica como função de tempo local e altura.*

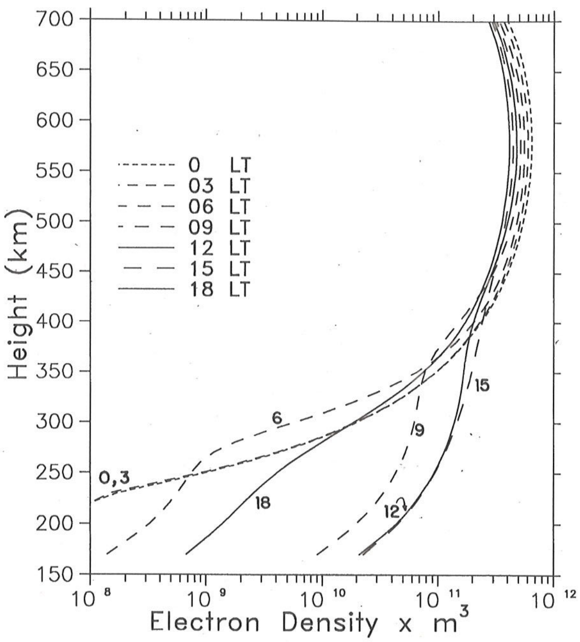

Figure 7 - Height profiles of electron density for some local times, for the no-drift case.

Figura 7 *- Densidade eletrônica em função da altura para alguns tempos locais, para o caso em que não há derivas do plasma.*

In experiments, the PRE is more pronounced for solar maximum conditions. This is not the case in our simulation, although we have used parameters for that phase of solar activity in the calculations. Another possible explanation for the absence of PRE in the calculations is the assumed symmetry between hemispheres and consequent simultaneous sunset at both hemispheres. Although the model deals with only one hemisphere, the symmetry is taken into account when calculating the E-region electron density. Batista et al. [1986] showed that the asymmetry between hemispheres is very important in dictating the behavior of the PRE.

CONCLUSIONS

We have shown that the electron density responds adequately to the calculated plasma drifts, for parameters not chosen in a rigorous manner, especially as it was done for the scale heights and recombination rate. For this reason, and also for not including plasma diffusion to other latitudes, we cannot expect that the calculations will agree too well with experiment. The value of these calculations is in their hint, for the first time in the literature, on how to solve the dynamo, momentum and continuity equations in coupled form. It is easy to see, from the material just presented, how to improve this or that feature, one at a time or in the whole.

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