ANNALI DI GEOFISICA, VOL. 41, N. 4, October 1998

Some theoretical aspects of ionospheric storms at middle latitudes

Gustavo A. Mansilla (1) (2) **and José R. Manzano** (1) (2)
(1) *Laboratorio de Ionosfera, Universidad Nacional de Tucumán, Argentina*
(2) *Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina*

Abstract
Neutral wind effects in the F_2-region during geomagnetic storms are theoretically studied solving the continuity equation (with production and loss of electrons) by means of a numerical method. This study was made for storms with sudden commencement at different times of day and at different latitudes. The results show that the equatorward movements of neutral air produce either enhanced or depressed maximum electron density values which depend on the velocity of these winds when the perturbation occurs at diurnal hours. If the geomagnetic storm is present during the night, only enhanced values are observed.

Key words *ionospheric storms – continuity equation – neutral winds*

1. Introduction

Many papers have been published which demonstrate the important role played by thermospheric neutral winds in the behaviour of the peak electron density at the F_2-layer both in quiet and perturbed conditions. However, the majority of the studies performed during geomagnetic storms describe only qualitatively the spatial and temporal variations observed at F-region.

During the geomagnetic storms, the high-latitude heat input changes the meridional pressure gradient and drives a global circulation. Normally in quiet conditions, at middle latitudes, the winds blow toward the poles during the day and toward the equator at night. Poleward winds cause downward drift of plasma and tend to reduce the electron concentration, while equatorward winds cause upward drift and tend to increase the electron density. These effects vary with latitude and with magnetic declination. The increase in the pressure at high latitudes produces increased equatorward winds at night and reduced poleward winds by day (Jones and Rishbeth, 1971).

In this paper, the effects produced on the peak electron density both the velocity and the duration of the neutral winds developed in storms periods are discussed.

It must be mentioned that an east-west electric field in the presence of the geomagnetic field also causes a vertical movement of plasma but this mechanism of drift is not included in the analysis.

In order to do this study, the time-varing continuity equation for the maximum electron density has been solved using principles established by some authors which are given below. This study has been made for geomagnetic storms which occur both by day and by night at two different latitudes, assuming that the thermospheric winds propagate from high to

---

Mailing address: Dr. Gustavo A. Mansilla, Facultad de Ciencias Exactas y Tecnología, Laboratorio de Ionosfera, Instituto de Fisica, Universidad Nacional de Tucumán, Avda. Independencia 1800, 4000 - Tucumán, Argentina; e-mail: gusmans@herrera.unt.edu.ar

low latitudes at the different considered times.

Although the assumptions for the velocity and the duration of the disturbances used to compute the equation continuity are clearly rough approximations of the reality and consequently do not describe exactly the daily variations of the peak electron density during geomagnetic storms, this paper gives general quantitative features of this parameter which are useful in interpreting the behaviour of the perturbed real F_2-layer.

The calculations have been applied at medium-high geographic latitudes.

2. Theory

To compute the continuity equation the following assumptions have been made (Rishbeth, 1967; Jones and Rishbeth, 1971; Davies, 1974):

1) At any instant the F_2 peak has a height z_m and an «equilibrium» height z_b. In the absence of vertical drift, z_b is determined by the relation between the loss Γ and the rate of diffusion d (which are assumed to vary exponentially with height in the form: $\Gamma(z) = \Gamma_0 e^{-Kz}$ and $d(z) = d_0 e^z$

$$z_b = [\ln(\Gamma_0/d_0) - \ln L]/(K+1) \qquad (2.1)$$

where $L = \Gamma(z_b)/d(z_b)$ and K is the mass ratio of molecular nitrogen to atomic oxygen ($K = 1.75$).

2) The equilibrium height z_b is displaced due to a vertical drift velocity w to another equilibrium level z_{bw}, which is time-varying if the drift velocity w is time-varying (it is assumed that w is independent of height)

$$z_{bw}(t) = z_b + f(w) \qquad (2.2)$$

where $f(w)$ is related to the drift velocity by

$$f(w) = C_w w(t)/H d(z_b) \qquad (2.3)$$

being H the scale height of the ionizable gas (atomic oxygen) and $d(z_b) = d_0 \exp(z_b)$.

3) At any time the actual height z_m of the maximum electron density tends exponentially toward the equilibrium height z_{bw} with a time constant given by the diffusion rate d at the equilibrium level

$$dz_m/dt = C_z\, d(z_b)\, [z_{bw}(t) - z_m(t)]. \qquad (2.4)$$

4) The peak electron density N_m is determined by the relation

$$dN_m/dt = q_m - C_n N_m \Gamma_m \qquad (2.5)$$

where q_m is the production rate evaluated at level of the peak and $\Gamma_m = \Gamma_0 \exp(-K z_m)$.

The production rate follows the Chapman law

$$q_m = q_0 \exp[1 - z_m - \operatorname{ch}\chi \exp(-z_m)] \qquad (2.6)$$

where ch χ is the grazing incidence function (Chapman, 1931) which replaces sec χ when the solar zenith angle χ is near 90° (sunset and sunrise). The method described by Rishbeth and Garriott (1969) to compute ch χ has been used.

The parameters used in the eqs. (2.1)-(2.5) were

$q_0 = 5.3\ 10^8\ \mathrm{m^{-1}\ s^{-1}}$;
$\Gamma_0 = 0.015\ \mathrm{s^{-1}}$ (day); $0.002\ \mathrm{s^{-1}}$ (night);
$d_0 = 2.5\ 10^{-5}\ \mathrm{s^{-1}}$;
$L = 0.6$ (day); 0.15 (sunset; night);
$H = 50\ 10^3$ km;
$C_w = 0.9$ (day; night); 0.1 (sunrise);
$C_z = 0.5$ (day; night); 0.25 (sunrise);
$C_n = 1.25$ (sunrise; day); 1.6 (night).

The constants are dimensionless and change at different periods of the day. At night it is assumed that a source of ionization does not exist.

To evaluate z_m from eq. (2.4) it is assumed that the vertical drift w is independent of time and is given by (Davies, 1974)

$$w = U \operatorname{tg}\phi/(1 + 4\operatorname{tg}^2\phi) \qquad (2.7)$$

being U the horizontal wind velocity assuming it lies in the magnetic meridian and ϕ the geographic latitude.

The equation used for the height of peak at sunrise was

$$z_m(t) = \ln(\mathrm{ch}\,\chi) + C_z + C_w V \qquad (2.8)$$

where $V = w / [H d(z_b)]$.

Finally, the Runge-Kutta numerical method for resolution of differential equations with 30 min stepwise, has been used to solve eq. (2.5).

3. Results

All the calculations are carried out for equinox at 45° and 60° of geographic latitude. Resultant equatorward meridional speeds from 0 m/s to 150 m/s each 50 m/s have been considered. The first velocity value corresponds to the simplest case in which the quiet-poleward winds are cancelled by the equatorward winds produced by the increased pressure gradients due to the storm heating at high latitudes, a situation which is confirmed by observations in the daytime at middle latitudes (Buonsanto *et al.*, 1990). The remaining velocity values are typical for thermospheric winds blowing equatorward during geomagnetic storms; these have been obtained from observations and theoretical models (*e.g.*, Rishbeth, 1967; Prölss *et al.*, 1991; Fuller-Rowell *et al.*, 1994).

The sunrise and sunset periods were defined from the zenith angle χ; it takes values from 100° to around 80° during sunrise while it varies from 90° to 110° at sunset.

Figure 1 shows the behaviour of the peak electron density for different equatorward wind

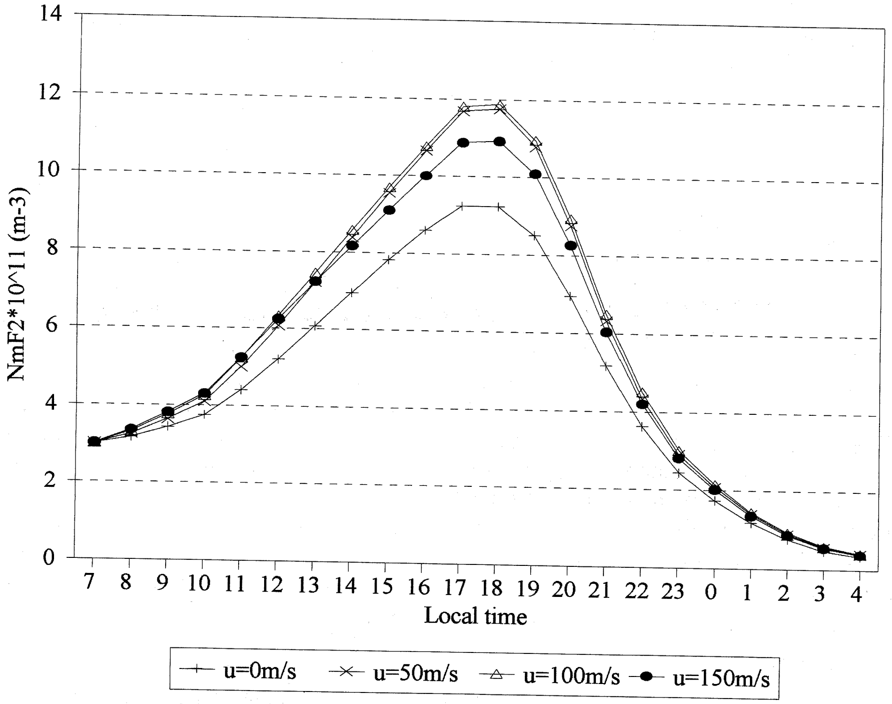

Fig. 1. Diurnal variation of peak electron density during a geomagnetic storm which produces equatorward winds from 07 to 17 LT at 60° of latitude.

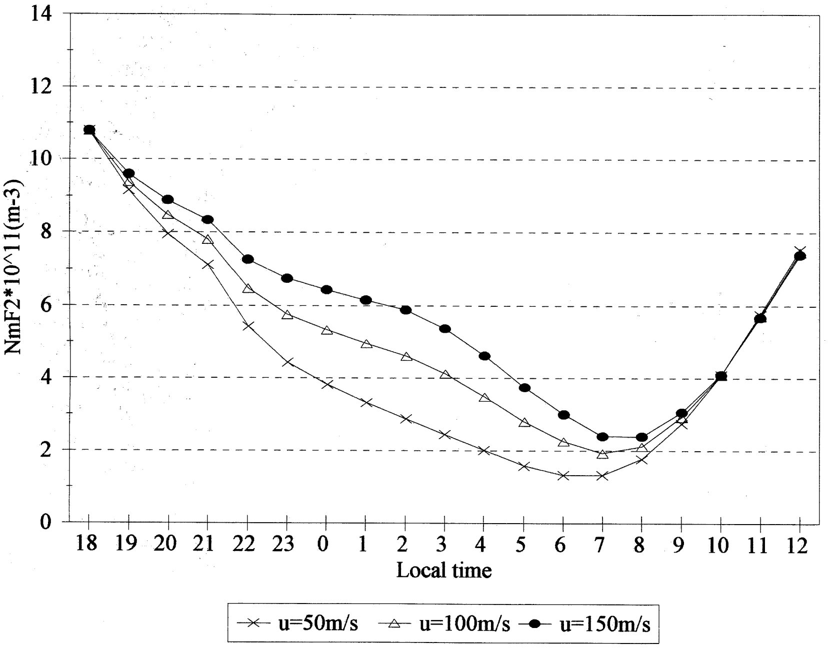

Fig. 2. Diurnal variation of peak electron density during a geomagnetic storm which produces equatorward winds from 18 to 02 LT at 60° of latitude.

speeds which blow from 07 LT to 17 LT at 60° of geographic latitude. It can be seen that electron density increases with velocity until 100 m/s (N_m values at this velocity are very close to corresponding 50 m/s) while for 150 m/s, it takes values below the corresponding values at 50 m/s and 100 m/s. In all cases the peak electron concentration rises up to 17 LT when the highest values are presented; a slow decay begins until around before dawn when the lowest values of electron density are observed. The recovery to undisturbed values around midnight is produced.

Figure 2 shows the time variation of N_m when the perturbation is applied from 18 LT until 02 LT next day at the same latitude. N_m increases as the velocity increases. The recovery to quiet values around 09 LT is produced.

Figure 3 is the same as fig. 1, but for 45° of geographic latitude. The largest increase in electron density takes place for the equatorward wind speed of 50 m/s; it decreases for higher wind velocities. For 150 m/s, there first occurs an enhancement of short duration from 08 LT to 12 LT followed by a marked decrease of the electronic concentration. The recovery is around local midnight for every wind velocity in the same way as at higher latitude.

Figure 4 presents the N_m behaviour when the winds flow from 18 LT, remaining until 02 LT next day. Similar behaviour to fig. 2 is seen, *i.e.* N_m values increase as the equatorward wind velocities increase.

In figs. 2 and 4 the electron density changes for $u = 0$ m/s are omitted because it is unlikely that the storm-time winds are cancelled with the quiet day winds at night.

A closer examination of all figures shows that electron density values by day decrease with increasing latitude; in contrast, for other velocities they decrease with latitude as well as at night.

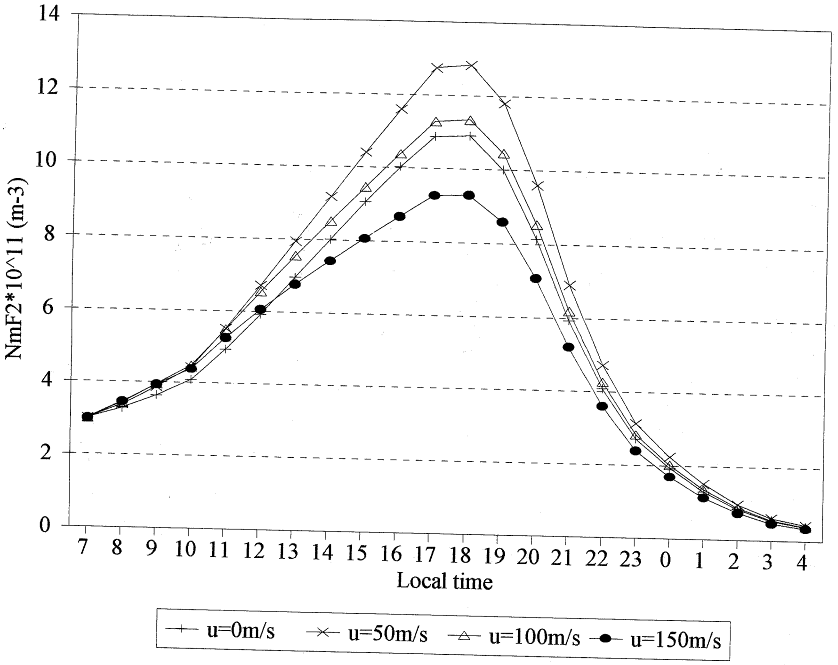

Fig. 3. As in fig. 1, for 45° of latitude.

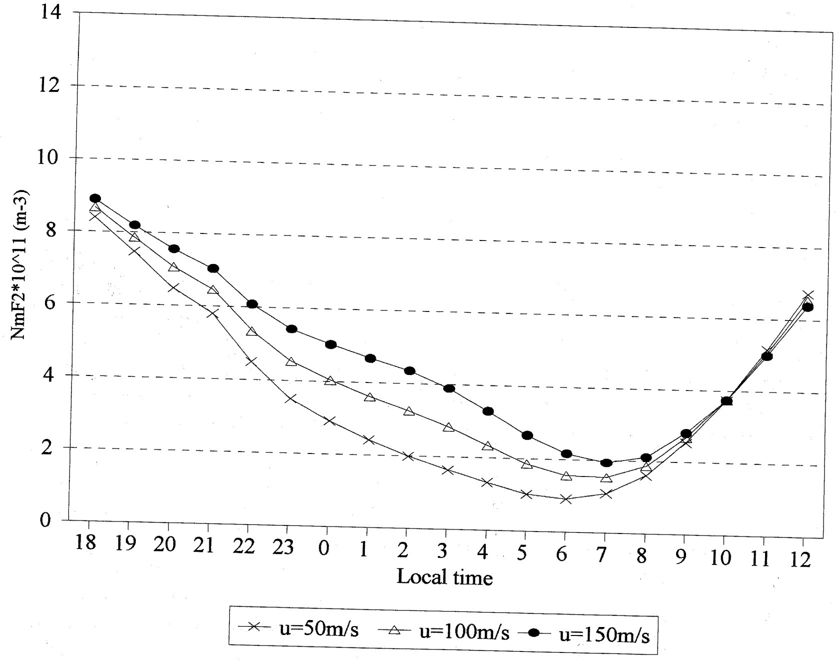

Fig. 4. As in fig. 2, for 45° of latitude.

4. Discussion

The initially global-scale equatorward winds, driven by the increase in Joule heating and particle injection at auroral latitudes during a geomagnetic storm push ionospheric layers to greater altitudes where the recombination is lower producing enhancements in F_2 layer electron concentration (called positive storm effects). The winds developed in high-latitudes transport nitrogen rich-air from low to high heights (into F region) by convection, distributing this nitrogen-rich air over much of the high and middle latitude regions. The upwelling of gas changes the chemical composition which produces the depressions in electron density (called negative storm effects).

It is reasonable to assume that the greater wind speeds are the consequence of a more intensified heat input at high latitude, which will give rise to faster changes in the meridional circulation generating also faster changes in the neutral composition and therefore in the appearance of negative effects. The lowest peak electron density values shown in fig. 3 for 150 m/s may be explained in this way. The negative effects observed by day, a few hours after the commencement of the storm should be a consequence of a substantial injection of energy at polar regions which generate fast meridional winds. Therefore, the negative effects will present more quickly the greater the magnetospheric energy input at high latitudes.

Only positive effects are seen at night using this model, which are larger at greater velocities and at lower latitude. Although negative phases at night are often seen, increased electronic concentration at night has been observed and possible explanations have been suggested (Oliver and Hagan, 1991; Burnside *et al.*, 1991); the numerical simulations presented here indicate that these positive effects could be mainly due to an uplifting of plasma to higher altitudes. This modeled ionospheric response is in agreement with recent observations (Prölss, 1993), confirming the realism of these assumptions.

The effects of a magnetospheric electric field E normal to the geomagnetic field in this simple approximative procedure used to compute the continuity equation have been neglected. In fact, a horizontal eastward electric field E produces a vertical plasma drift velocity $E/B \cos I$, where B is the Earth's magnetic field and I is the magnetic dip. At low latitudes, the $\boldsymbol{E}\times\boldsymbol{B}$ drift may be more important than the vertical motion produced by meridional winds. So, this paper has examined only the ionospheric behaviour at medium-high geographic latitudes; in a detailed study of ionospheric storms both winds and electric field effects should be included as a whole.

On the other hand, it is necessary also to include an ionization night source and to take into account the temporal and latitudinal variations of these winds, for which a source heat at auroral latitudes is necessary. Thus, improved models require elaborations which consider at least the elements mentioned above.

There are models to compute maximum electron density during geomagnetic storms which are very complex and do not consider all involucred processes, and the physics of the problem is not always easy to extract. The results obtained in this paper are approximate, but they are useful to give both some features of positive and negative phases expected to occur in the middle-high geographic latitudes F_2-layer during geomagnetically perturbed periods in a simple way.

It is well known that negative effects can be explained by meridional winds; however this study suggests that these effects are more intensified the greater the propagation velocity of these winds even if they blow equatorward. The storm-time winds will produce major negative storm effects by day during large magnetic disturbances. Moreover, the enhanced electronic concentration values observed by day and at night may be calculated.

In brief, due to competition of different processes in the magnetosphere-ionosphere-thermosphere system, each storm shows an individual face, for that reason it is difficult to obtain precise models to compute the peak electron density which includes all involucred factors. Neverthless with this simple model, even with a number of limitations, we can predict and explain some local ionospheric responses observed during geomagnetic storms. At night as mentioned previously the effects predicted by this model are quite limited, and to solve this difficulty more accurate elaborations are required.

REFERENCES

BUONSANTO, M.J., J.C. FOSTER, A.D. GALASSO, D.P. SIPLER and J.M. HOLT (1990): Neutral winds and thermosphere/ionosphere coupling and energetics during the geomagnetic disturbances of March 6-10, 1989, *J. Geophys. Res.*, **95**, 21033-21050.

BURNSIDE, R.G., C.A. TEPLEY, M.P. SULZER, T.J. FULLER-ROWELL, D.G. TORR and R.G. ROBLE (1991): The neutral thermosphere at Arecibo during geomagnetic storms, *J. Geophys. Res.*, **96**, 1289-1301.

CHAPMAN, S. (1931): The absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating earth. II. Grazing incidence, *Proc. Phys. Soc. London*, **43**, 483-501.

DAVIES, K. (1974): Studies of ionospheric storms using a simple model, *J. Geophys. Res.*, **79**, 605-613.

FULLER-ROWELL, T.J., M.V. CODRESCU, R.J. MOFFETT and S. QUEGAN (1994): Response of the thermosphere and ionosphere to geomagnetic storms, *J. Geophys. Res.*, **99**, 3893-3914.

JONES, K.L. and H. RISHBETH (1971): The origin of storm increases of mid-latitude *F*-layer electron concentration, *J. Atmos. Terr. Phys.*, **33**, 391-401.

OLIVER, W.L. and M.E. HAGAN (1991): Simulation of a gravity wave over the middle and upper atmosphere radar, *J. Geophys. Res.*, **96**, 9793-9800.

PRÖLSS, G.W. (1993): Commom origin of positive ionospheric storms at middle latitudes and the geomagnetic activity effect at low latitudes, *J. Geophys. Res.*, **98**, 5981-5991.

PRÖLSS, G.W., L.H. BRACE, H.G. MAYR, G.R. CARIGNAN, T.L. KILLEEN and J.A. KLOBUCHAR (1991): Ionospheric storm effects at subauroral latitudes: a case study, *J. Geophys. Res.*, **96**, 1275-1288.

RISHBETH, H. (1967): The effect of winds on the ionospheric F_2-peak, *J. Atmos. Terr. Phys.*, **29**, 225-238.

RISHBETH, H. and O.K. GARRIOTT (1969): *Introduction to Jonospheric Physics* (Academic Press), 95-96.

(received December 20, 1997;
accepted May 2, 1998)