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A model of a perturbed ionosphere using the auroral power as the input

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RESUMEN

Este trabajo presenta un modelo semiempírico basado en la teoría desarrollada por Fuller-Rowell *et al* (1996). El modelo predice cambios en el cociente entre los valores observados y las medianas mensuales de la frecuencia crítica de la capa F2 ionosférica Φ (= foF2obs/foF2mm) durante condiciones perturbadas y requiere la historia temporal de las 30 horas anteriores del índice de potencia auroral (o del índice ap) del satélite TIROS/NOAA, afectado por un filtro. Encontramos que las dependencias estacionales, latitudinales y del tiempo local de la ionosfera perturbada están de acuerdo con el modelo.

PALABRAS CLAVE: Ionosfera perturbada, modelos ionosféricos.

ABSTRACT

This work presents a semi-empirical model based on the theory developed by Fuller-Rowell *et al.* (1996). The model predicts changes in the ratio between observed and monthly median values of the F2 ionospheric layer critical frequency Φ (= foF2obs/foF2mm) during perturbed conditions. It requires the time history of the previous 30 hours of the TIROS/NOAA auroral power index (or ap index) weighted by a filter. We determine seasonal, latitudinal, and local time dependencies of the perturbed ionosphere in good agreement with theory.

KEY WORDS: Perturbed ionosphere, ionospheric models.

INTRODUCTION

The ionospheric behavior during quiet conditions is well known and efficiently modeled. However, knowledge of ionospheric response during geomagnetic storms, and related process, remains incomplete. Currently no empirical storm-time correction algorithm shows improvement over climatological references models such as the International Reference Ionosphere (Bilitza, 1990). To predict the ionospheric response during storms is a priority task.

We present a semi-empirical model to predict Φ (= foF2obs/foF2mm) changes during perturbed conditions starting from the integral of the auroral power. The model is based on the theory developed by Fuller-Rowell *et al.* (1996).

Prölss (1993) and Fuller-Rowell *et al.* (1996) assumed that negative storm effects are due to regions in which the neutral composition has changed. The neutral "composition bulge" is produced by heating and upwelling of air by magnetospheric energy input at auroral latitudes. It moves to middle latitudes due to nighttime equatorward winds and it is brought into the dayside as Earth rotates.

Theoretically, the prevailing summer-to-winter circulation at solstice transports the molecular rich gas to mid and low latitudes in the summer hemisphere over the day or two following a storm, and thus explains the seasonal dependence. In the winter hemisphere, poleward winds restrict the equatorward movement of the bulge. Thus the altered environment in summer depletes the F-region mid-latitude ionosphere to produce a negative phase, while in winter mid-latitudes a decrease in molecular species, associated with downwelling, persists and produces the characteristic positive storm. The seasonal migration of the bulge is superimposed on the diurnal oscillation.

A first approximation to the empirical model

Ionospheric data was divided into six mid-latitude sectors, including Europe, N.E. Asia and North America in the north, and Africa, Australia, and South America in the south. Ionosonde observations from each sector were averaged, and the time series of the ratio of the storm time NmF2 to the monthly median was assembled. Based on theory we propose an empirical algorithm to represent the summer ionospheric response, including the regional variation. We assume that summer F-region ion densities are controlled by the magnitude and location of the thermospheric composition bulge

$$\Phi = a + b_1\left[\int P(0.6 + 0.4\sin(UT + \phi_1))dt\right] + b_2\left[\int P(0.6 + 0.4\sin(UT + \phi_1))dt\right]\sin(LT + \phi_2) \quad (1)$$

where P is the TIROS/NOAA power index, ϕ_1 is adjusted for each longitude sector for the first sine function which peaks at midnight, and ϕ_2 is adjusted for the second sine function to peak at dawn. The integral of P is over the previous 18 hours and is modulated by the sine function such that maximum weight is given for a longitude sector passing through the midnight sector. The constants a, b_1 and b_2 are obtained from multilinear regression.

The first term a is a quiet reference level. The second term reflects the development of the composition bulge as seen from a particular longitude sector. The third term represents the local time (LT) motion of the bulge. The phase is chosen so that more weight is given as a sector moves through the nightside.

Figure 1 shows an example of the fit for the storm of June 5, 1981. Storm time, x-axis, is referred to the beginning of the driven phase of the storm, and the y-axis is the prediction ratio of foF2. The horizontal line represents the IRI results, or monthly median (corresponding to magnetic quiet conditions), the full line is the actual data, and the broken line is the model output (perturbed conditions).

The prediction accuracy of the empirical algorithm was measured using the regional average of the root-mean-square-error (RMSE). In Figure 2 we obtain that some storms show an improvement over climatology, but the advantage is not consistent: averaged over the eighteen storm interval the first attempt at an empirical algorithm faired slightly worse than IRI.

The reasons for such results (predictions from the empirical algorithm are slightly worse than IRI) are related with two main assumptions. First, the model assumes a linear relationship between the integral of the power and the regional ionospheric response. Second, the assumption that the maximum in the energy inputs always occurs in the midnight sec-

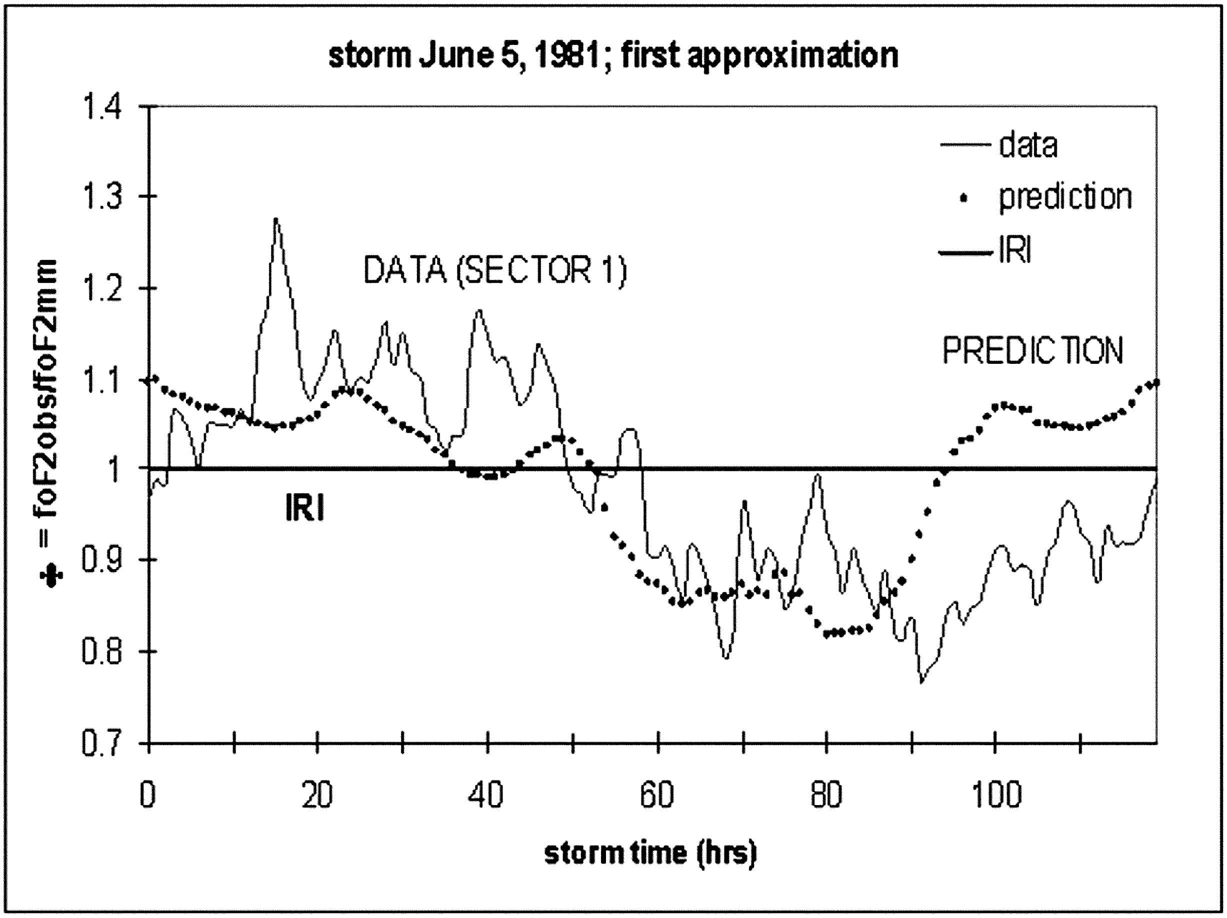

Fig. 1. First approximation fit to the June 5th, 1981 storm.

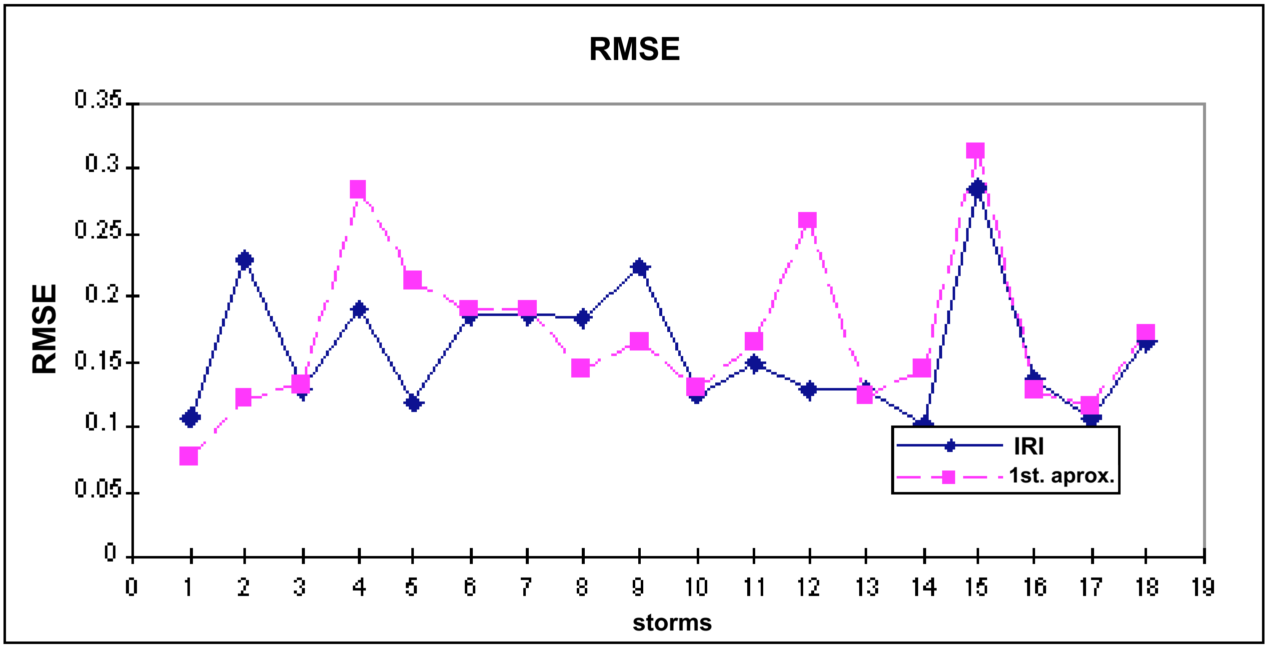

Fig. 2. Statistical comparison between the first approximation of the empirical model and the International Reference Ionosphere.

tor. If both are specified accurately and are captured in the model, then the regional ionospheric response can be produced. If, however, the forcing is predicted in the wrong sector (a sector where there is NOT the maximum of the gradient forcing the bulge of composition), the RMSE is worse than no specifying a regional dependence at all (Araujo-Pradere, 1998).

A second approximation to the empirical model

In order to improve our results we design a second approximation to the empirical model. The new design does not include the weighting of the auroral power by the local time sector during the driven phase of the storm (avoiding in this way the assumption that the maximum in the energy inputs always occurs in the midnight sector), but does retain the regional dependence in the migration of the composition bulge by the diurnal wind field. We also include two new features: an optimum shape of the auroral power filter (to consider the time history of the input and not a single value), and a non-linear dependence of the integral of the aurora power and the ionospheric response. Including all the features, the next algorithm describes the empirical model:

$$\Phi = a + b_1\left[X(t_0)\right] + b_2\left[X(t_0)\right]^2 + \ldots + c\left[X(t_0)\right]\sin(LT + \phi_1) \qquad (2)$$

where $X(t_0)=\int F(\tau)P(t_0-\tau)d\tau$, and $F(\tau)$ is the filter weighting function of auroral power, P, over the 30 previous hours (Figure 4). a, b_1 and b_2 coefficients adjust the fit to the non-linear relationship between the ionospheric response and the integral of the auroral power (Figure 3). The phase ϕ_1 is selected to peak at dawn.

The optimum shape and length of the filter shown in Figure 4 was obtained by multilinear regression technique, minimizing the mean square difference between the filter input (aurora power) and filter output (ionospheric ratios). A very good discussion about such techniques could be seen in Detman and Vassiliadis (1997). The power values have equal weight for the first 24 hours prior to the time of interest, and reduce to zero linearly between 24 and 30 hours. This implies that, at mid-latitudes, the ionosphere is dependent on geomagnetic or auroral activity up to 30 hours before the time that is being calculated.

In Figure 5 we show an example of fit using the second approximation of the semi empirical model. Data used is from the North America sector (sector 1). Similarly to Figure 1, x-axis is the storm time (beginning with the driven phase of the storm), and the y-axis is the prediction ratio of foF2. The horizontal line represents the IRI results, or monthly median, the full line is the actual data, and the broken line is the model output (perturbed conditions).

We conclude that the model is in good agreement with the actual data during the negative phase, while it is not good in the positive phase of the storm.

Figure 6 is like Figure 2, except for including the RMSE

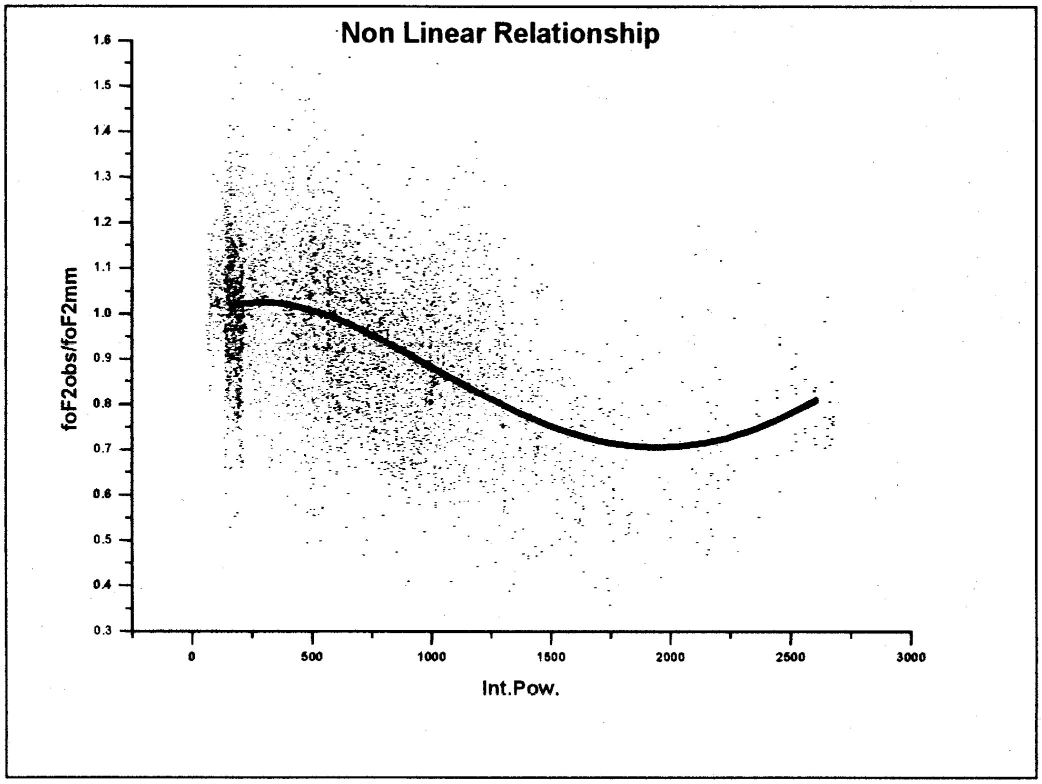

Fig. 3. Non-linear relationship between the ionospheric response (Φ) and the integral of the auroral power.

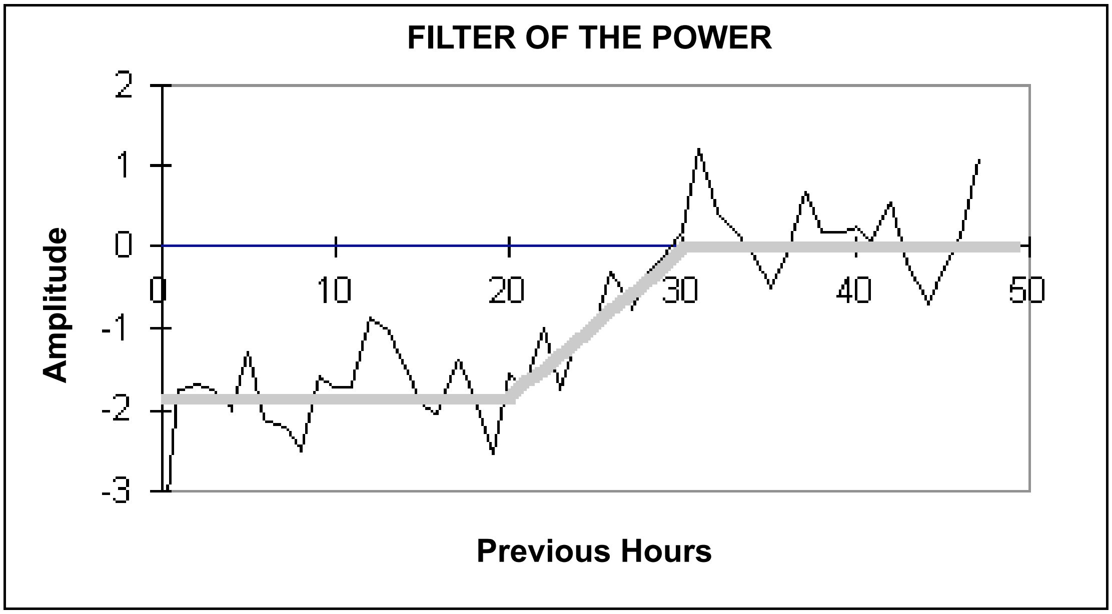

Fig. 4. Filter of the auroral power.

for the second approximation to the empirical model. A statistical analysis using the RMSE values for the eighteen storm intervals, including the new design of the empirical model shows a significant improvement over the first approximation and the monthly median values (IRI). The second approximation reduces the variance to values around 0.13, close

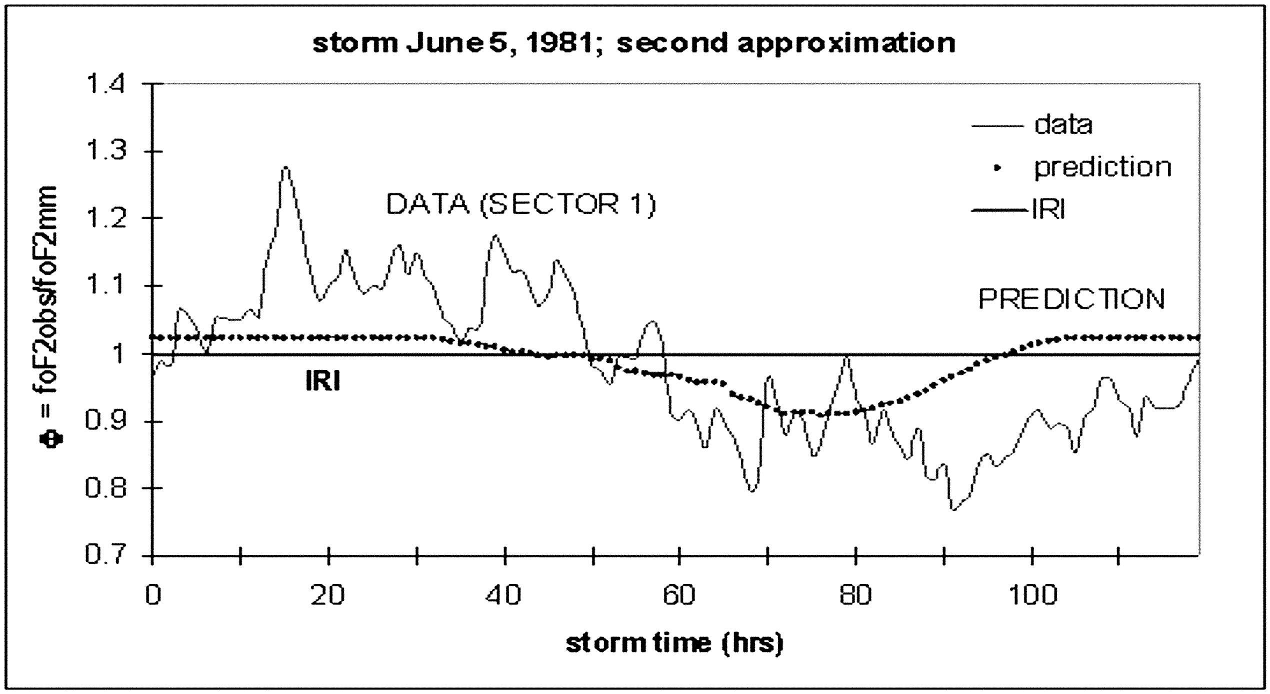

Fig. 5. Empirical model second approximation fit to the June 5th, 1981 storm data.

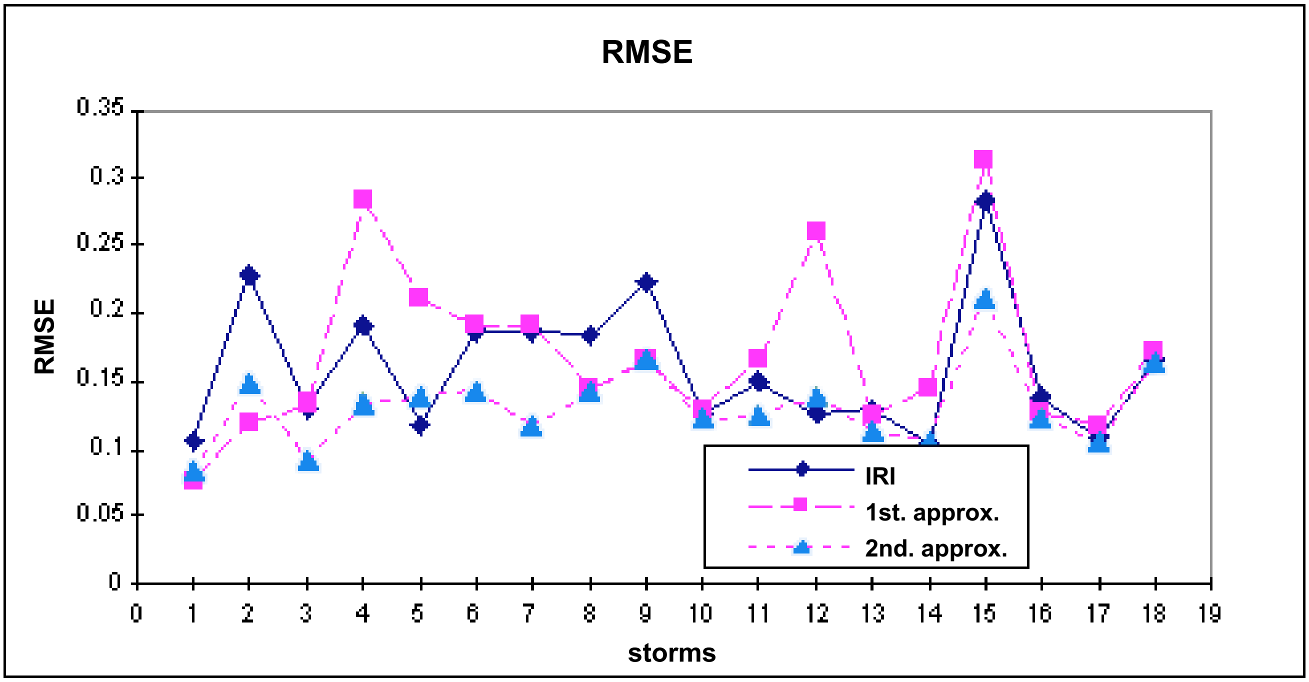

Fig. 6. Statistical comparison between both approximation of the empirical model and the International Reference Ionosphere.

to the quiet-time reference level (0.12756). This level was obtained from the variability of the data around the monthly median during quiet conditions.

These statistical results assure us the validity of our second approximation to the empirical model.

In order to improve the model, we introduce ionospheric storm data dependency.

Figure 7 presents the local time dependency of the non-quiet ionospheric behavior. This figure represents the latitude dependence on the global neutral wind field. Maximum

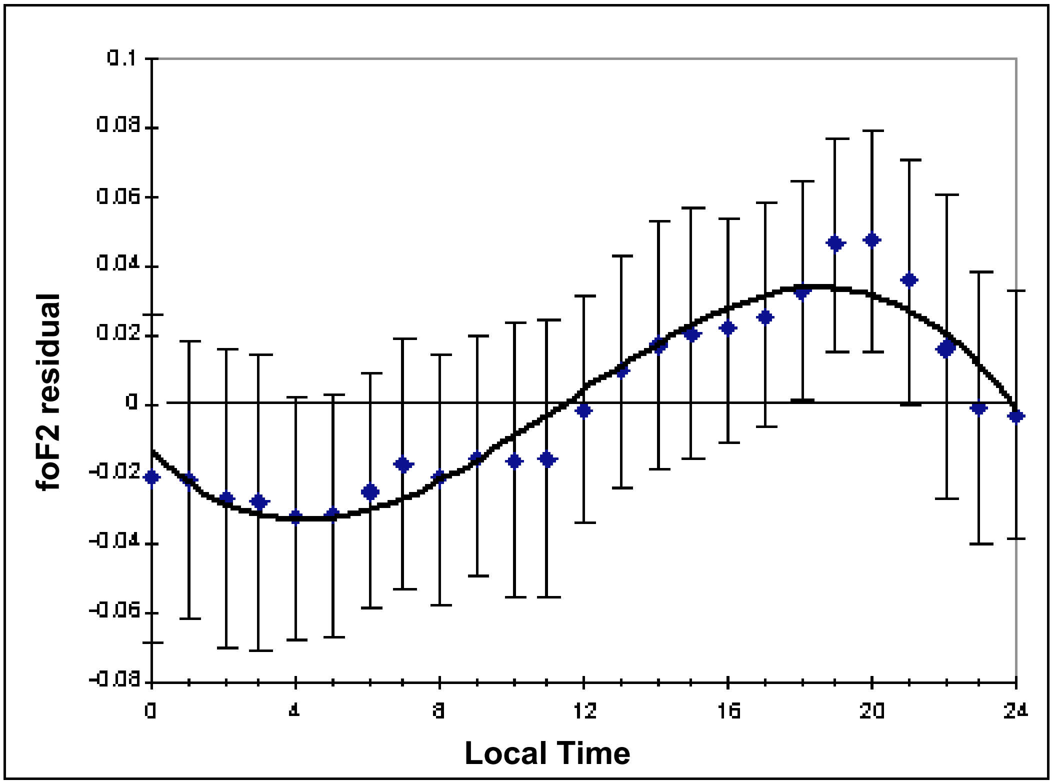

Fig. 7. Local time dependency of the perturbed ionospheric response.

equatorwards winds are at midnight, and the minimum of concentration (NmF2) is near 0600 local time. Maximum poleward winds at noon show a maximum of concentration at 1800 local time (Fuller-Rowell *et al*., 1998).

Figure 8 shows the seasonal and latitudinal dependencies of the perturbed ionosphere response. As expected by the theory, the equinoxes do not show any particular behavior. We can see a clear tendency to show deepest negative phase to greatest values of the integral of the power, which corresponds to highest rate of recombination because the fresh molecular mass in the bulge of composition.

The other two intervals in Figure 8, May – June – July (mid panel), and November – December – January (low panel) have a more complex interpretation. The picture in summer hemisphere of both panels is very clear, deepest negative phase corresponds to greatest values of the power. The change in the negative phase is due to the depletion of N_2 related with the composition bulge, and since the movement of the bulge coincides with the general tendency of the wind field, there is not any mixed behavior.

The winter hemisphere behavior during perturbed conditions of both groups of storms (Figure 8, mid and low panel) is more complex. Now the movement of the bulge and the general tendency of the wind field are in opposite sense, creating a “border line” around 45°. Between the Equator and this border there is a positive phase related with O increases, while in winter high latitudes we can see the opposite feature: a negative phase related with the increment of N_2. Under both conditions there is a consistent tendency to show deepest negative phase in high latitudes, and highest positive phase in low latitudes, corresponding to greatest values of the integral of the auroral power.

DISCUSSION

The model can be extended by substituting the integral of the power by an integral of the three hourly magnetic index “ap” as the input. The weighting function was obtained by singular value decomposition (Detman and Vassiliadis, 1997) and its shape is similar to those obtained for auroral power (Figure 9). The statistical analysis shows a slight improvement using the new filter with the second approximation over the second approximation and the auroral power filter.

CONCLUSION

An empirical formula has been developed to account for the summer hemisphere mid-latitude ionospheric response

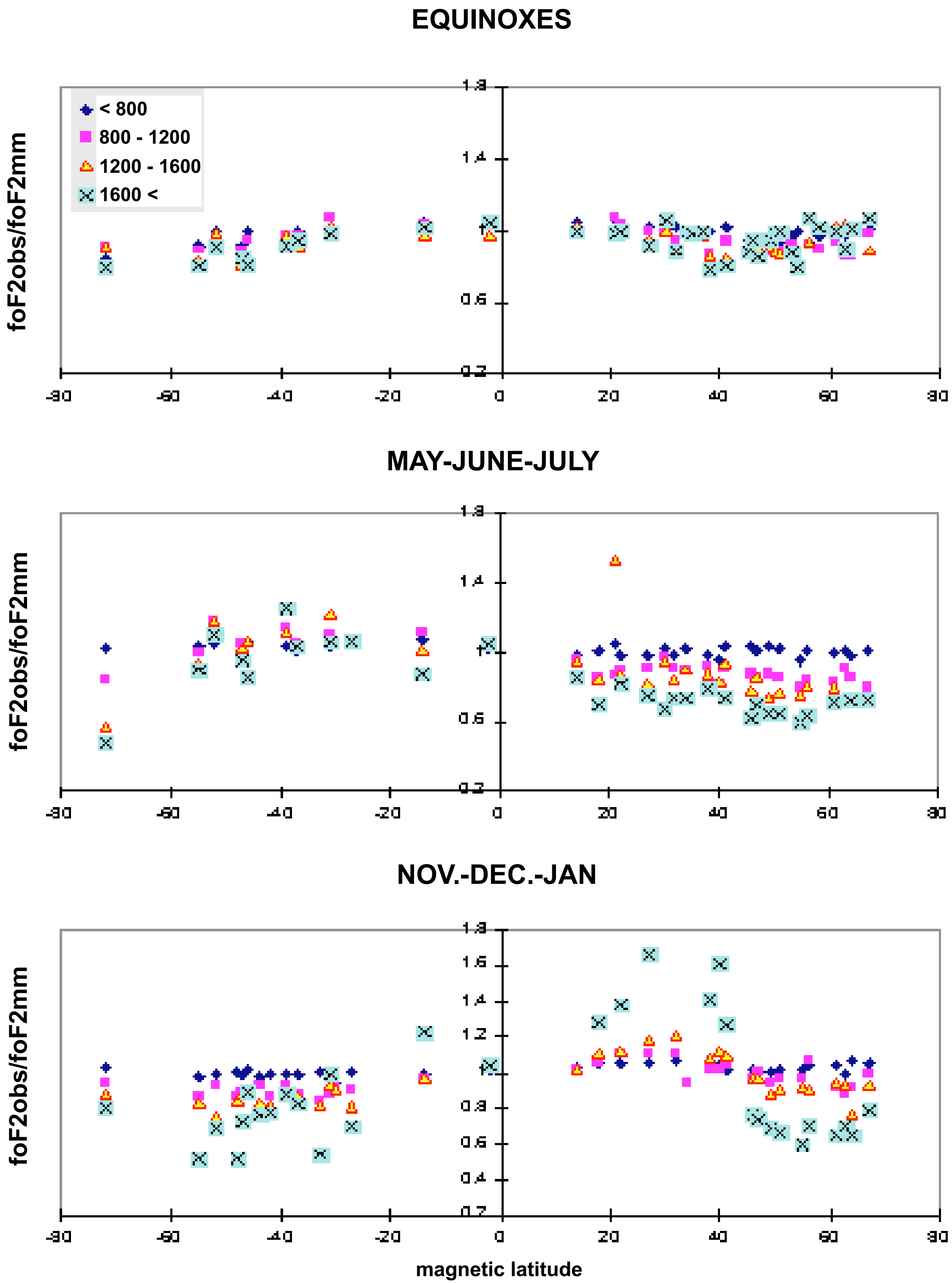

Fig. 8. Seasonal and latitudinal dependencies of the perturbed ionospheric response.

as a definition of the time history of the previous 30 hours of the TIROS/NOAA power index weighted by a filter. The formula can be used to predict the departure of the ionospheric F2 peak density from the appropriate quiet-time reference, during a geomagnetic storm. Several dependencies obtained of the perturbed ionosphere response are in good agreement with the theory.

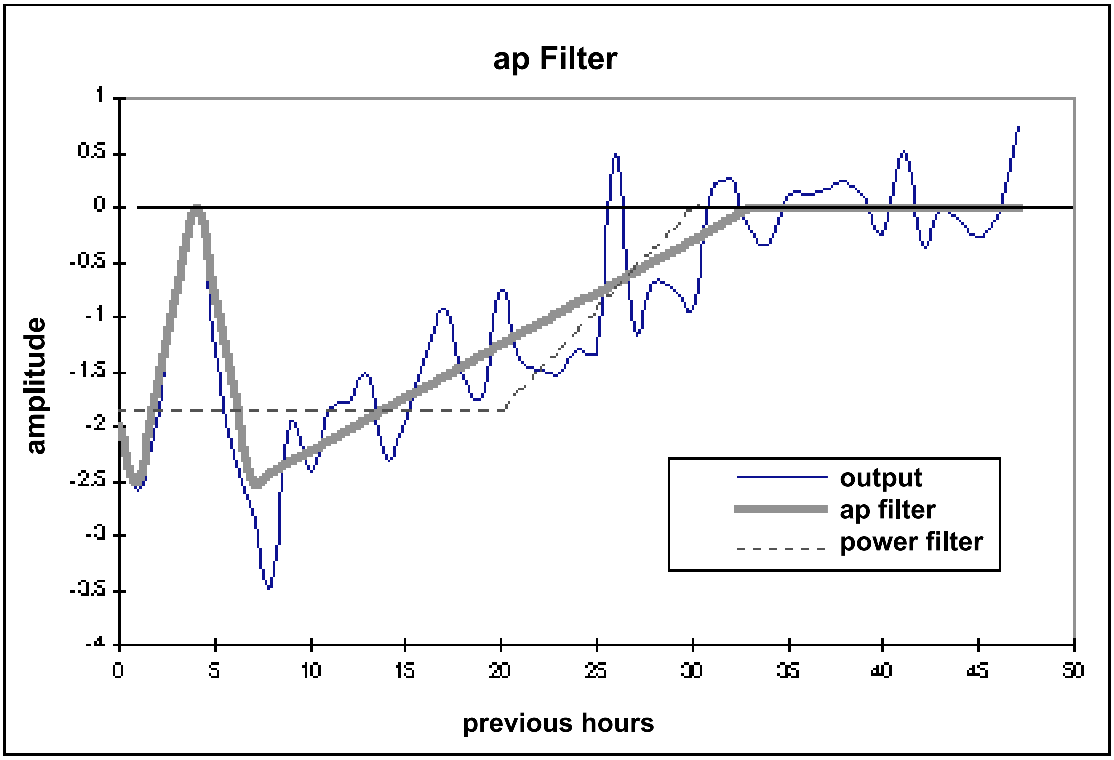

Fig. 9. Filter obtained for ap index.

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