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Earth magnetic field and geomagnetic activity effects on long-term trends in the F2 layer at mid-high latitudes

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Abstract

It is well known that the Earth magnetic field, as well as geomagnetic activity, presents long-term variations. Both phenomena affect the height of the F2 layer peak, hmF2, and the maximum electron concentration estimated by foF2. Experimental data of three mid-high latitude stations (Argentine Islands, Slough and Uppsala) were used to estimate foF2 long-term trends. These trends were compared with a theoretical approximation considering long-term variations in the Earth magnetic field, and also with a qualitative assessment of geomagnetic activity increasing trend effects. Although the agreement between experimental and theoretically approximated trends is not within a desired acceptance level, the ability of the Earth's magnetic field variations to produce trends in the F2 layer of the ionosphere may be an important result. Long-term trends in geomagnetic activity could possibly explain some discrepancies such as the seasonal pattern of Slough and Uppsala, with lesser negative trends in winter, and also the similarity in the trend pattern of both northern stations.

Keywords: Ionosphere; Long-term trend; foF2; Geomagnetic field; Dip angle

1. Introduction

Trends in ionospheric parameters has become a main subject since the beginning of the 1990's, when the study of upper atmosphere trends gained importance (Aikin et al., 1991; Roble, 1995; Ulich and Turunen, 1997; Jarvis et al., 1998). Some studies link ionospheric trends with the middle and upper atmosphere cooling due to an increase in greenhouse gases (Roble and Dickinson, 1989; Rishbeth, 1990; Hall and Cannon, 2002). A doubling in CO_2 concentration would produce a cooling of 30–40 K in the thermosphere, a 20%–40% decrease in air density between 200–300 km, a ~15−20 km lowering of the ionospheric F2 peak height (hmF2), and a worldwide decrease in the F2 critical frequency (foF2) less than 0.5 MHz (Roble and Dickinson, 1989; Rishbeth, 1990; Rishbeth and Roble, 1992). However, the global pattern of experimental hmF2 and foF2 of several worldwide stations over the last 40 years is highly complex and can hardly be reconciled with the greenhouse hypothesis (Bremer, 2001; Upadhyay and Mahajan, 1998; Mikhailov and Marin, 2000). Danilov and Mikhailov (1999) and Mikhailov and Marin (2000) with a new approach, obtained negative hmF2 and foF2 trends

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for several Northern-Hemisphere ionospheric stations and a dependence of the trend magnitude on geomagnetic latitude. Since more negative values were seen at higher latitudes they suggest that F2-layer trends might be related to long-term changes in geomagnetic activity and F2-layer storm mechanisms. Long-term changes in the dip angle (I), due to changes in the Earth's magnetic field, are also possibly the origin of hmF2 and foF2 trends (Foppiano et al., 1999). If the dip angle is changing then the $\sin(I)\cos(I)$ factor, which is associated with the effects of neutral winds on hmF2 (Rishbeth, 1998) will also change. The horizontal thermospheric wind U drives ions and electrons up during night and down during day, along the geomagnetic field lines at speed $U\cos(I)$. The vertical component $U\sin(I)\cos(I)$, raises during nighttime and lowers during daytime the F2-peak, increasing or decreasing the peak electron density. An increase in the $\sin(I)\cos(I)$ factor would produce: (a) an additional lowering of the F-region with a decrease in foF2, during daytime (when U blows from equator to pole), and (b) an additional raise of the region with an increase in foF2, during night (when U blows from pole to equator). A decrease in the $\sin(I)\cos(I)$ factor would produce the opposite effect. In this work, F2 critical frequency data, foF2, of three mid-high latitude ionospheric stations (Argentine Islands, Slough and Uppsala) where analized in order to elucidate a possible explanation for the daily and seasonal pattern of foF2 trends. Changes in Earth's magnetic field and in geomagnetic activity, which would induce foF2 trend values according to latitude, local time and season, were considered as possible mechanisms inducing the observed long-term trends.

2. Data analysis

Monthly median values of F2 critical frequency, foF2, for the period 1957–1998, recorded at Argentine Islands (65.2°S, 64.3°W), Slough (51.5°N, 0.6°W) and Uppsala (59.8°N, 17.6°E) were analyzed, all of them around 55° of geomagnetic latitude. Data was arranged according to the different months and hours, which amounts to 288 series for each station. The foF2 trend was estimated with two methods: (1) a linear regression after filtering the solar activity effect on foF2, and (2) through a multiple regression analysis. In the first case, the solar activity variation was filtered out from the data series estimating the residuals of a linear fit between foF2 and a solar activity proxy (Rz or F10.7), that is

$$\Delta\text{foF2} \;=\; \text{foF2}_{\text{exp}} - \text{foF2}_{\text{mod}}, \tag{1}$$

where foF2_{exp} is the experimental data and foF2_{mod} is foF2 modeled through a linear regression with Rz or F10.7. Then, the linear trend (was estimated through least squares from

$$\Delta\ \text{foF2} = \alpha\ \text{time} + \beta. \tag{2}$$

The second method, estimates the trend from a multiple regression analysis where the independent variables considered were a solar activity proxy (Rz or F10.7) and time, that is

$$\begin{aligned}\text{foF2} &= \alpha\ \text{time}\ + \gamma\ \text{Rz} + \delta \quad \text{or}\\ \text{foF2} &= \alpha\ \text{time}\ + \gamma\ \text{F10.7} + \delta.\end{aligned} \tag{3}$$

Both methods, using Rz or F10.7, give similar trend values, α. Fig. 1(a) depicts α for each of the stations considered, estimated with method 2 and using Rz as a solar activity proxy in terms of month and local time. The significance level of trend estimations, shown in Fig. 1(b), is higher than 95% for the highest negative values in all the cases, and also for the highest positive values in the case of Argentine Islands. The percentage variation of foF2 per year presents a similar pattern to that of Fig. 1(a), ranging between $-0.030 \pm 0.006\%$/year and 0.015 ± 0.004 for Argentine Islands, -0.008 ± 0.002 to $0.004 \pm 0.001\%$/year for Uppsala, and -0.0030 ± 0.0008 to $0.0030 \pm 0.0008\%$/year for Slough.

Argentine Islands presents positive trends during nighttime and early morning hours for almost every season, while significant negative trends occur during the day for winter and equinoxes. Uppsala and Slough present the most negative trends during equinoxes for almost every hour, and null or positive trends only during some hours in winter.

3. Analysis of Earth's magnetic field variation effects over foF2

The Earth's magnetic field, generated in the Earth's core, presents long term variations in the strength and orientation of the field (Bloxham and Gubbins, 1985; Hongre et al., 1998). These variations lead to changes in the vertical component of the thermospheric wind W as a result of variations in the dip angle I, which in turn induce variations in hmF2 and foF2. As a first approximation, only changes in I will be considered, leaving for a future

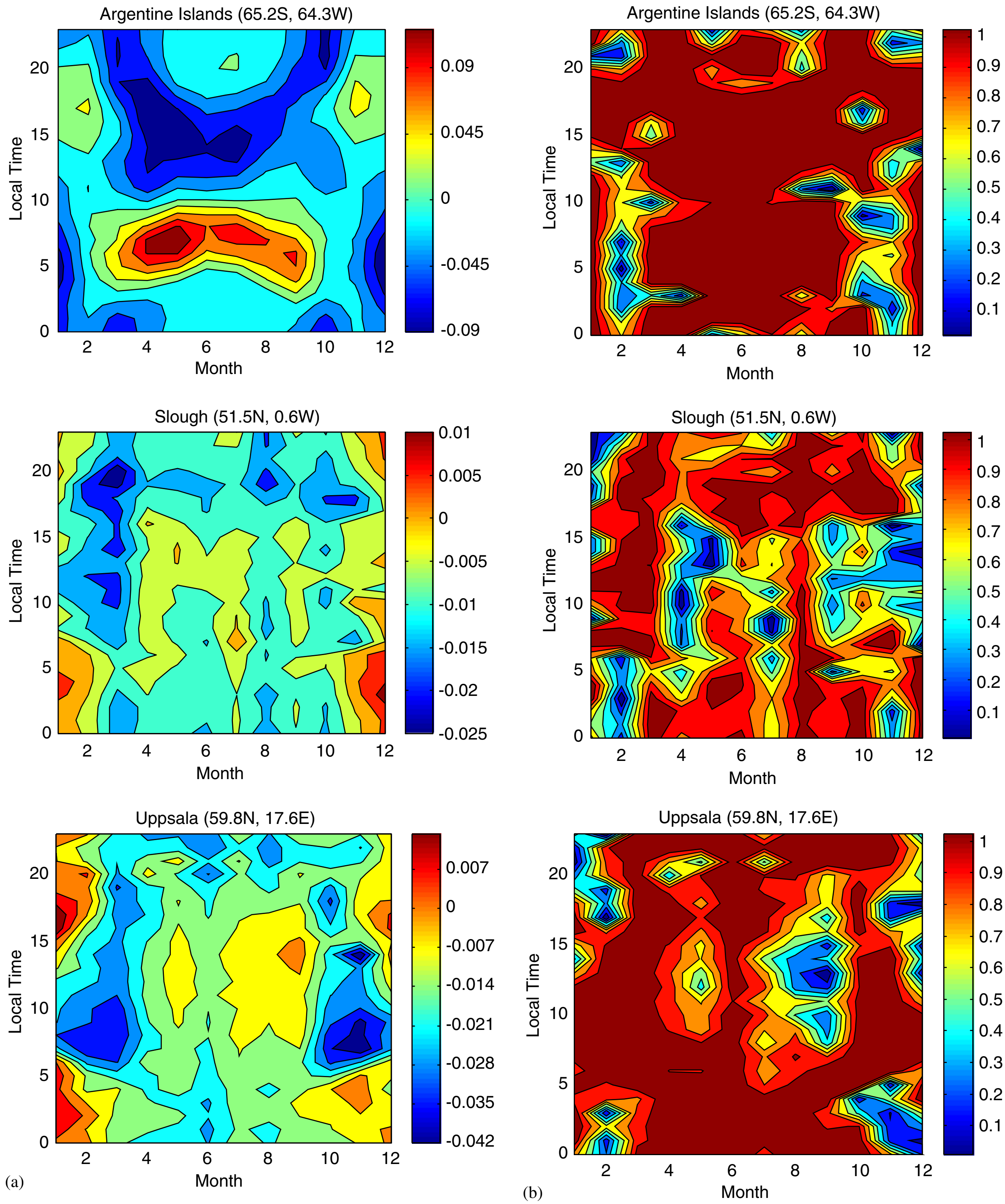

Fig. 1. (a). Linear trend, α, of foF2 in MHz/year, estimated from foF2 $= \alpha$ year $+ \gamma$ Rz $+ \delta$, for Argentine Islands, Slough and Uppsala, during the period 1957–1998, in terms of month and local time. (b) Significance level of trend values α in terms of month and local time.

work the effects of changes in the ExB drift through variations in the magnetic field B, which may play a significant transport role at the latitudes here analyzed.

The behavior of the F2-peak depends mainly on the interplay of photochemical with transport processes. The level of the peak is controlled by plasma diffusion and is affected by vertical drift which may be caused by wind systems in the thermosphere. A vertical drift W alters the level of the peak by approximately HW/D_m (Rishbeth and Garriott, 1969). H is the scale height given by kT/mg, which results 53 T in meters considering that the ionizable constituent is oxygen. $W = U\sin(I)\cos(I)$ where U is the meridional component of the neutral wind in the thermosphere and D_m is the plasma diffusion coefficient at the peak height. D_m, in m^2/s, can be estimated using a simple kinetic theory, which assumes that ion and neutral gas temperature are equal and electron temperature twice the ion temperature (a reasonable daytime condition) (Buonsanto et al., 1997; Omidvar et al., 1998):

$$D_m = \frac{4.4\times 10^{18}\sqrt{T}}{n(\mathrm{O})}, \tag{4}$$

where $n(\mathrm{O})$ is the atomic oxygen density in m^{-3} at the peak level.

During day the peak electron concentration NmF2 is given by

$$\mathrm{NmF2} \approx \frac{q_m}{\beta_m} \propto \frac{n(\mathrm{O})}{n(N_2)} \propto \frac{e^{-z_m}}{e^{-1.75z_m}} \propto e^{0.75z_m}, \tag{5}$$

where $n(\mathrm{N2})$ and z_m are the density of molecular nitrogen and the reduced height, respectively. Note that the equation for determination of NmF2 takes into account only ionization and recombination, but not ambipolar diffusion. Changes in NmF2 produced by changes in z_m can be estimated by

$$\frac{\mathrm{dNmF2}}{\mathrm{d}z_m} \propto 0.75e^{0.75z_m} \tag{6}$$

so that

$$\frac{\mathrm{dNmF2}}{\mathrm{NmF2}} = 0.75\mathrm{d}z_m. \tag{7}$$

Considering that $\Delta z_m \approx H/D_m\Delta W$, Eq. (7) becomes

$$\frac{\Delta\mathrm{NmF2}}{\mathrm{NmF2}} \approx 0.75\frac{H}{D_m}\Delta W. \tag{8}$$

Since $\mathrm{NmF2} \propto \mathrm{foF2}^2$, then

$$\frac{\Delta\mathrm{foF2}}{\mathrm{foF2}} = \frac{1}{2}\frac{\Delta\mathrm{NmF2}}{\mathrm{NmF2}} \approx 0.375\frac{H}{D_m}\Delta W. \tag{9}$$

If it is assumed that changes in W are consequence of changes in the dip angle I, then $\Delta W = U_x\Delta[\sin(I)\cos(I)]$ (which results from $W = U\sin(I)\cos(I)$ assuming changes only in I). The value of $\Delta[\sin(I)\cos(I)]$ was estimated assessing the linear trend of the dip angle I over Argentine Islands, Slough and Uppsala with the International Geomagnetic Reference Field (IGRF), available from the National Space Science Data Center (NSSDC), and multiplying it by the length in years of the period considered. Fig. 2 shows the estimated dip angle and the factor $\sin(I)\cos(I)$ for each station in terms of time. During the period considered, the dip angle has decreased at Argentine Islands and Slough, and increased at Uppsala, by around 0.5%. The overall change in the factor $\sin(I)\cos(I)$ is around 1.5%, producing a 1.5% increase in W at Argentine Islands and Slough, and a 1.5% decrease at Uppsala.

Introducing in Eq. (9) the meridional wind estimated from Hedin HWM93 empirical model (Hedin et al., 1996), the neutral temperature and

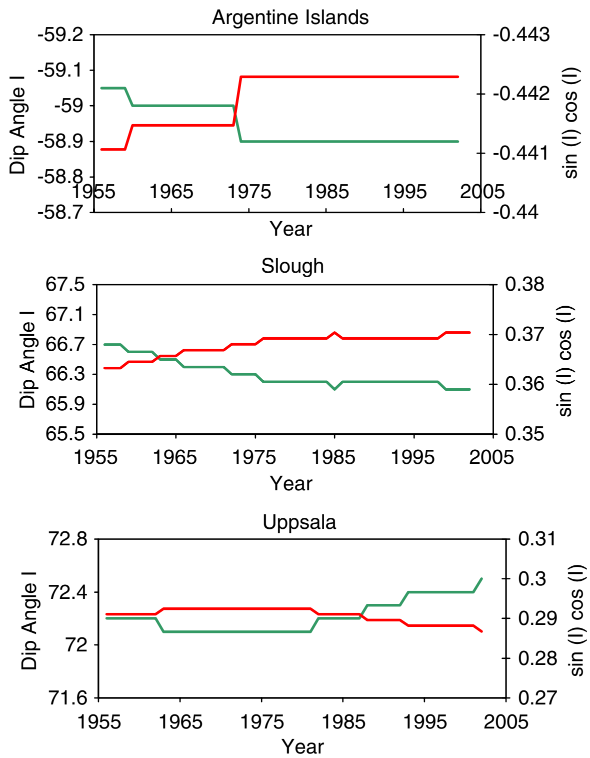

Fig. 2. Dip angle I (green line) and $\sin(I)\cos(I)$ factor (red line) for Argentine Islands, Slough and Uppsala in terms of time, assessed using the International Geomagnetic Reference Field IGRF, available from the National Space Science Data Center NSSDC.

n(O) values from Hedin MSIS86 (Hedin, 1987), the percentage change of foF2 per year, has been assessed. Fig. 3 shows the percentage change of foF2 per year between 6 and 18 LT, although Eqs. (8) and (9) are valid around noon, for the three stations analyzed. As a general picture, in the case of Argentine Islands there is a good agreement between theoretical and experimental trends.

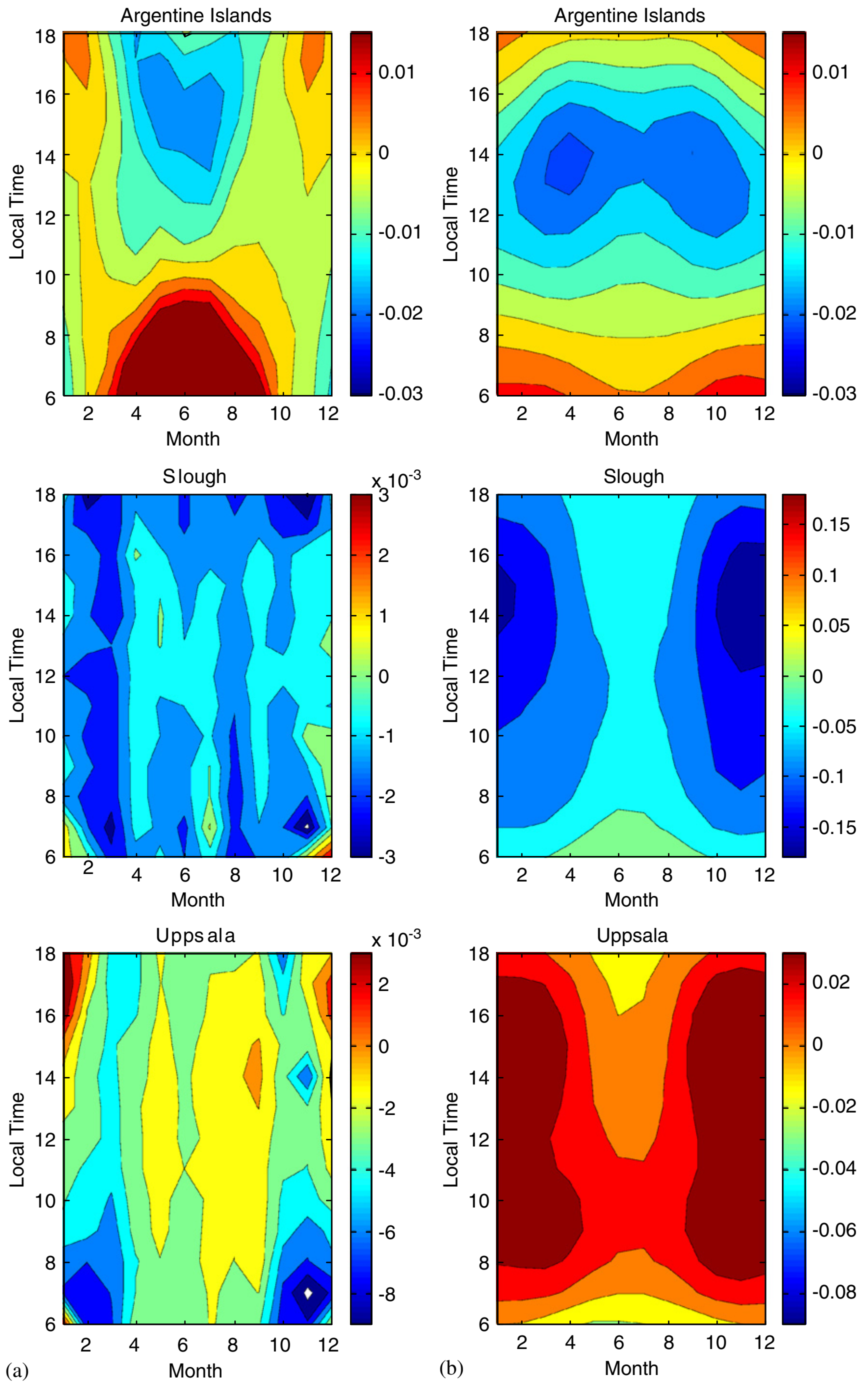

Fig. 3. (a) Percentage variation of foF2 per year (foF2 trend divided by the mean foF2 × 100) during the period 1957–1998 and (b) the corresponding theoretical assessment considering changes in the meridional thermospheric wind due to the dip angle trend, in terms of month and local time. *Note*: The theoretical assessment follows from an approximation valid for daytime hours.

For Slough there is agreement in the trend pattern but not in the magnitude order of trend values, while for Uppsala theoretical and experimental trends have quite opposite behaviors.

To make a more strict comparison, Fig. 4 shows the experimental and theoretical percentage foF2 trend values (as in Fig. 3) but only for 12 LT, in terms of month (11 LT and 13 LT behave very similarly). In the case of Argentine Islands, except for the months of June and July, there seems to be a kind of coherence between both curves. For Slough, there is agreement in the trends sign and also in the trend pattern from January to August, but the theoretical trend values are an order of magnitude greater than the experimental ones. In the case of Uppsala, one of the curves looks like the mirror image of the other.

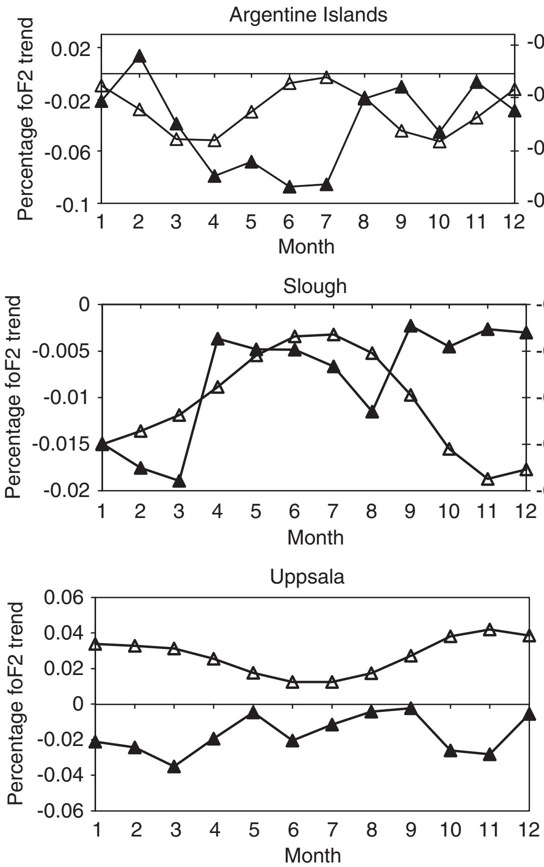

Fig. 4. Percentage variation of foF2 per year (foF2 trend divided by the mean foF2 $\times$ 100) during the period 1957–1998 for 12 LT (filled triangles) and the corresponding theoretical assessment (empty triangles) considering changes in the meridional thermospheric wind due to the dip angle trend, in terms of month.

4. Discussion and conclusions

The effects over foF2 due to long-term trends in the Earth's magnetic field were assessed considering the thermospheric neutral wind variations due to dip angle changes. Changes in the ExB drift through variations in the magnetic field B (which may play a significant transport role at the latitudes here analyzed) and long-term variations in T and n(O), due to CO_2 increasing trend for example, were not taken into account. These assumptions allowed us to use the simple expression $\Delta z_m \approx H/D_m \Delta W$.

Although the agreement between experimental and assessed long-term trends is not within a desired acceptance level, we find as an important result, the ability of long-term trends in the Earth's magnetic field to produce trends in the F2 layer of the ionosphere.

Geomagnetic activity, another possible mechanism causing foF2 trends, has been increasing since the beginning of the century with a local minimum in solar cycle 20 (Lockwood et al., 1999; Cliverd et al., 2002). The ionospheric response to geomagnetic activity is highly complex due to the many physical processes involved. However, there are underlying trends that are useful in characterizing the ionosphere response to storms in a relatively simple way (Fuller-Rowell et al., 2000; Araujo-Pradere et al., 2002). During geomagnetic storms a large amount of energy is deposited into the thermosphere at high latitudes. This leads to an increase of the neutral gas temperature and variations of the neutral composition with a decrease of the atom-to-molecule ratio at heights of the F2 region. Both factors contribute to a decrease of the electron concentration in the high latitude ionosphere (Prolss, 1993; Rishbeth, 1998). This effect, which implies an foF2 decrease, is strongest during summer, followed by equinoxes (Field and Rishbeth, 1997). If geomagnetic activity long-term trend were the origin of foF2 trend patterns it should be expected similar patterns at high latitude stations and weakest trends during winter. Accordingly, foF2 trend pattern of Slough and Uppsala are similar and present, on average, lesser negative trends during winter. In the case of Argentine Islands there are significant positive trends during winter morning hours not expected at high latitudes from an increasing trend in geomagnetic activity. For noon hours, where experimental trends are negative for almost every month, geomagnetic activity, like the deep angle, cannot explain the greatest winter values (as can be seen in Fig. 4).

Long-term trends in geomagnetic activity could possibly explain, in the case of Slough and Uppsala, the seasonal pattern, with lesser negative trends in winter. It would also explain the similarity in the trend pattern of both northern stations in terms of month and local time.

A doubling in CO_2 concentration should produce an foF2 decrease less than 0.5 MHz. In the period 1957–1998, CO_2 has had an increase of 16% (Keeling and Whorf, 2005). If a linear change in foF2 with increasing CO_2 is assumed, then foF2 should decrease around 0.04 MHz during the 40 years here analyzed, while the mean observed decrease was greater than 1 MHz. However, greenhouse cooling could possibly explain the seasonal pattern at Argentine Island during noon hours at least. According to Hall and Cannon (2002) results, who have analyzed foF2 data at Tromsø (69°N, 19°E) during the period 1935–2001, trend values are around zero in summer and most negative in late winter. They explained this seasonal dependence by the arguments of Rishbeth (1990) and the proposition that greenhouse cooling is responsible for long-term variations in temperature, O and N_2 densities in the ionosphere.

A quantitative assessment of geomagnetic activity effects over foF2 trend and the addition of the ExB drift effect remains to be done, but it seems that, compared to CO_2 long-term trend, the Earth's magnetic field and geomagnetic activity trends may be able to produce stronger trends in foF2 and also to explain some seasonal and daily variation patterns in trend values. We cannot rule out the greenhouse cooling effect over the ionosphere, and some theoretical assessment should be done taking into account these three possible mechanisms altogether.

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