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Trends in the F2 ionospheric layer due to long-term variations in the Earth's magnetic field

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ABSTRACT

The Earth's magnetic field presents long-term variations with changes in strength and orientation. Particularly, changes in the dip angle (I) and, consequently, in the $\sin(I)\cos(I)$ factor, affect the thermospheric neutral winds that move the conducting plasma of the ionosphere. In this way, a lowering or lifting of the F2-peak (hmF2) is induced together with changes in foF2, depending on season, time and location. A simple theoretical approximation, developed in a previous work, is extended to a worldwide latitude–longitude grid to assess hmF2 and foF2 trends due to Earth's magnetic field secular variations. Compared to the greenhouse gases effects over the ionosphere, the Earth's magnetic field may be able to produce stronger trends which vary with season, time and location. However, to elucidate the origin of F2-region trends, long-term variations in the three possible known mechanisms should be considered altogether—greenhouse gases, geomagnetic activity and Earth's magnetic field.

1. Introduction

There are several mechanisms that may induce long-term variations, or trends, in ionospheric parameters. Some studies link these trends with the middle and upper atmosphere cooling due to an increase in greenhouse gases (Roble and Dickinson, 1989; Rishbeth, 1990; Upadhyay and Mahajan, 1998; Hall and Cannon, 2002). Others argue that trends in the ionosphere may be related to long-term changes in geomagnetic activity and to ionospheric storm mechanisms (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000). A third possible cause, suggested by Foppiano et al. (1999), and the one which will be analysed in the present work, is the Earth's magnetic field, generated in the Earth's core, which presents long-term variations in the field's strength and orientation (Bloxham and Gubbins, 1985; Hongre et al., 1998).

A simple mechanism through which trends in the Earth's magnetic field may affect the ionosphere is through changes in the dip angle (I) (Foppiano et al., 1999). In this case, the $\sin(I)\cos(I)$ factor, which is associated with the effects of neutral winds on hmF2 (Rishbeth, 1972, 1998; Rishbeth and Barron, 1960; Rishbeth and Garriott, 1969) will also change. The horizontal thermospheric wind U drives ions and electrons, up during the night and down during the day, along the geomagnetic field lines at speed $U\cos(I)$. U represents the meridional thermospheric wind along the geomagnetic field line. The vertical component $W = U\sin(I)\cos(I)$ raises the F2-peak during night time (when U blows from Pole to Equator) and lowers it during daytime (when U blows from Equator to Pole), increasing or decreasing the peak electron density. An increase in the $\sin(I)\cos(I)$ factor would produce an additional lowering of the F-region with a decrease in foF2, during daytime, and an additional raise of the region with an increase in foF2 during the night. A decrease in the $\sin(I)\cos(I)$ factor would produce the opposite effect.

In this paper, the approximations and models used in Elias and Ortiz de Adler (2006) are used to estimate the trends in hmF2 and foF2 in a worldwide latitude–longitude grid (Sections 2–4). In Section 5, a comparison is made between these trends and experimental results obtained by other authors. The discussion and conclusions of results are presented in Section 6, highlighting that being much simpler, the present approach gives a first picture comparable to that obtained using much more complex models (Yue et al., 2008; Cnossen and Richmond, 2008) and it adds one more hint to elucidate the origins of global changes in the upper atmosphere.

2. Earth's magnetic field variation effects over hmF2

To a first approximation, variations in the Earth's magnetic field may lead to changes in the vertical component of the

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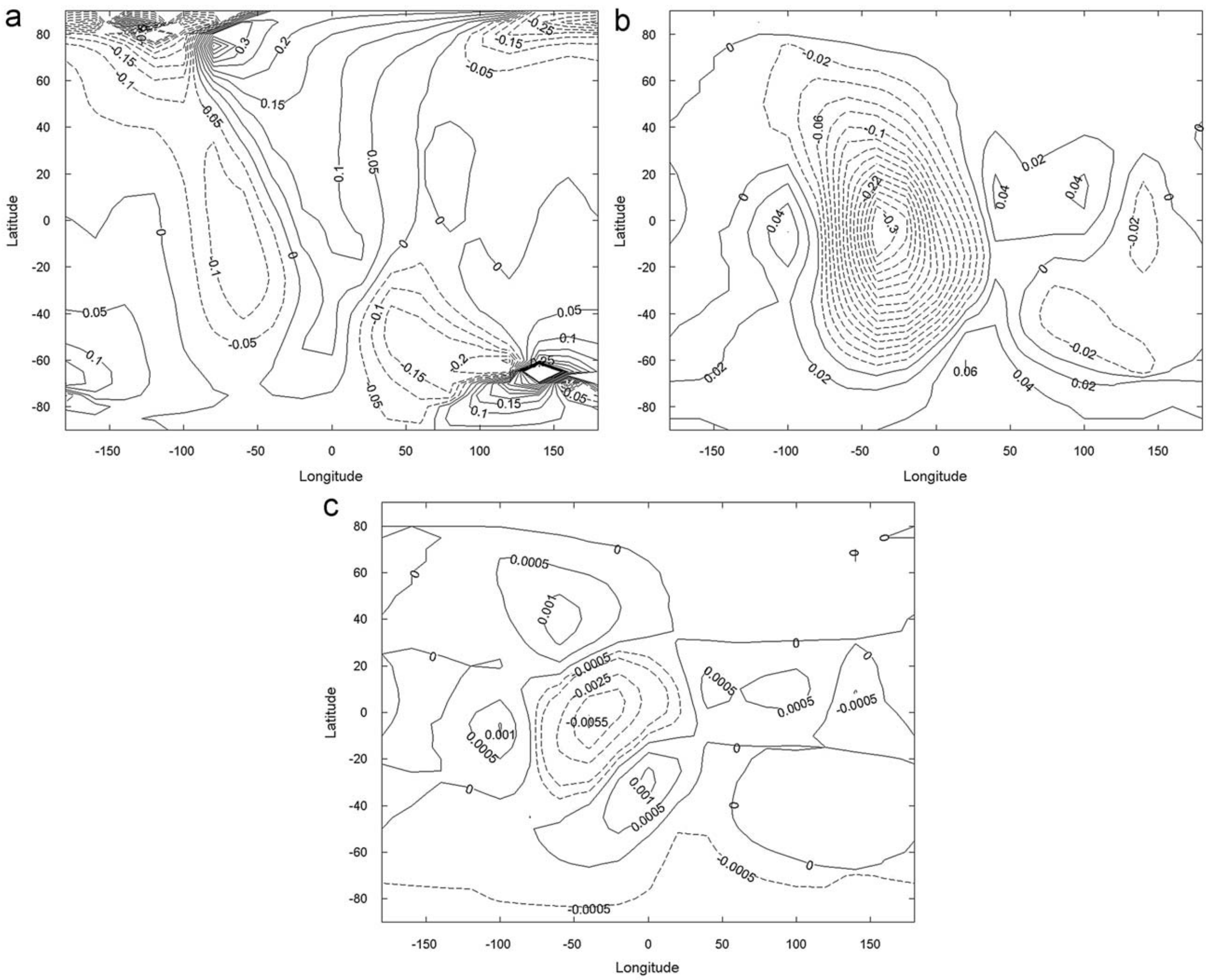

Fig. 1. (a) Declination trend (degrees/year), (b) dip angle trend (degrees/year) and (c) sin(I)cos(I) factor trend (1/year) estimated from the International Geomagnetic Reference Field IGRF, available from the National Space Science Data Center NSSDC, for the period 1950–2000. Dashed contours are negative values, solid contours are positive values.

thermospheric wind W as a result of variations in the dip angle I, which in turn induce variations in hmF2 and foF2. In the present analysis changes in the declination, δ, and in I will be considered, neglecting changes in the ExB drift through variations in the magnetic field B.

The behaviour of the F2-peak depends mainly on the interplay between photochemical and transport processes. In the absence of drift, standard theory (Rishbeth and Garriott, 1969) indicates that the height of the peak occurs where the loss coefficient β is comparable to the diffusion rate, D/H^2. D is the plasma diffusion coefficient. H is the scale height of the ionizable constituent given by kT/mg, which is about 53 T, in meters, considering that the ionizable constituent is atomic oxygen, T being the temperature.

The peak height is affected by vertical drift that may be caused by wind systems in the thermosphere or by electric fields. Here, the vertical drift considered, W, is given by $U\sin(I)\cos(I)$, where U represents the meridional thermospheric neutral wind (U_x) along the geomagnetic field line, that is $U_x\cos(\delta)$. The total vertical transport is then given by the diffusion plus the vertical drift (D/H+W). The level of the peak is altered, from the no-wind condition, by WH/D (Rishbeth, 1967, 1972, 1998; Rishbeth and Barron, 1960; Rishbeth and Garriott, 1969). Assuming an initial condition where the vertical drift is $W_i = U_x\cos(\delta_i)\sin(I_i)\cos(I_i)$ and a final state $W_f = U_x\cos(\delta_f)\sin(I_f)\cos(I_f)$, the peak shift results

$$\Delta z_m \approx \frac{\Delta hmF2}{H} \approx \frac{H\Delta W}{D} \quad (1)$$

z_m being the reduced peak height and $\Delta W = W_f - W_i$.

3. Earth's magnetic field variation effects over foF2

During daytime hours the peak electron concentration $NmF2$ is approximately given by

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

where $n(\mathrm{O})$ and $n(\mathrm{N_2})$ are the atomic oxygen and molecular nitrogen densities, respectively, at the peak level. Changes in $NmF2$ produced by changes in z_m may be obtained from $d(NmF2)/d(z_m) \propto 0.75\exp(0.75z_m)$, so that $d(NmF2)/NmF2 = 0.75\mathrm{d}(z_m)$.

Replacing dz_m by Δz_m given in Eq. (1),

$$\frac{\Delta NmF2}{NmF2} \approx 0.75\ \frac{H\Delta W}{D}$$

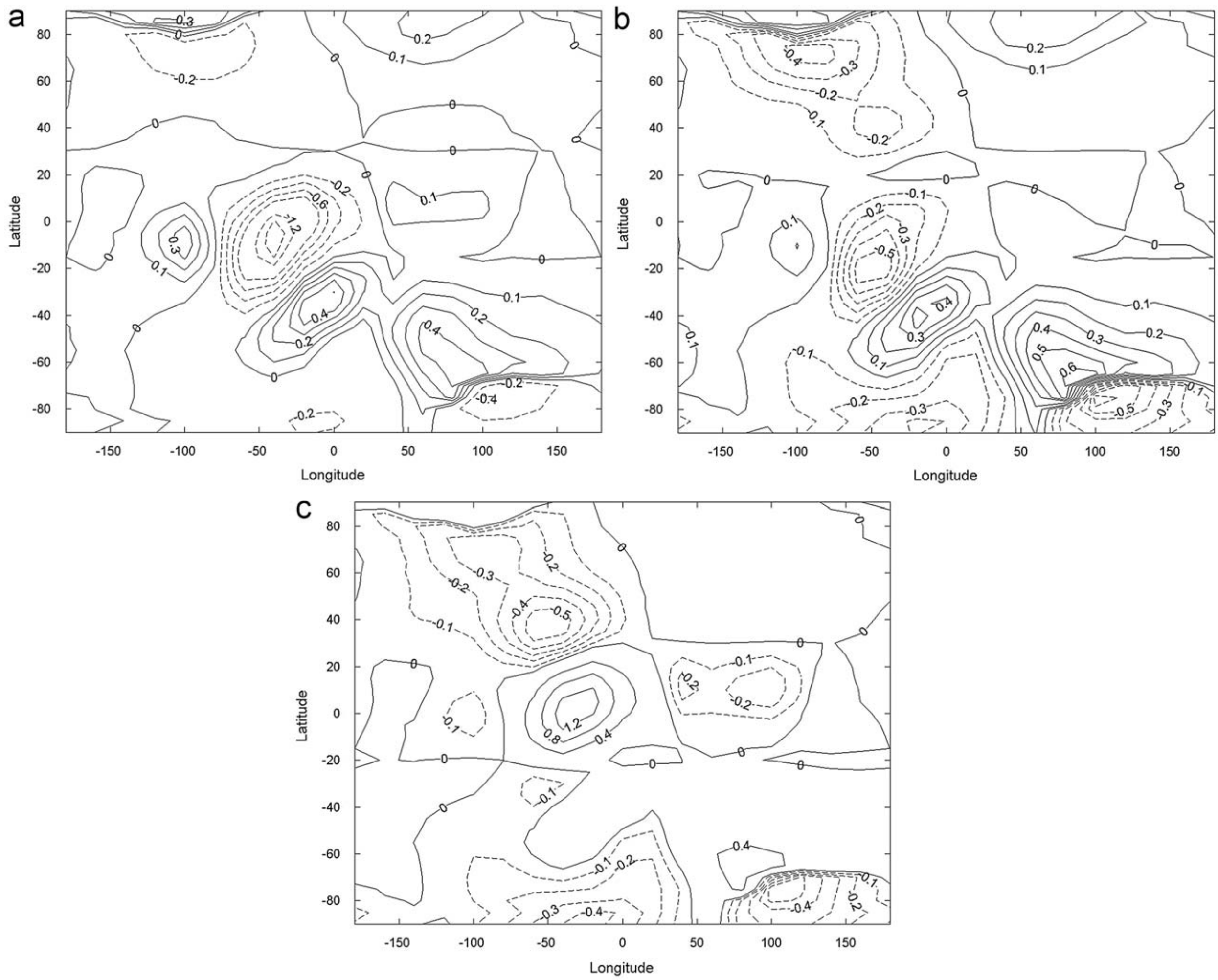

Fig. 2. hmF2 trend (km/year) calculated with Eq. (1) for (a) June, (b) September and (c) December. Variables in Eq. (1) – density, temperature, wind – were obtained for 12 LT and solar activity level corresponding to $F10.7 = 150$. Dashed contours are negative values, solid contours are positive values.

Since $NmF2 \propto foF2^2$, then

$$\frac{\Delta foF2}{foF2} = \frac{1}{2}\frac{\Delta NmF2}{NmF2} \approx 0.375\frac{H\Delta W}{D} \tag{2}$$

4. Assessment of hmF2 and foF2 variations

Variations in hmF2 and foF2 due to changes in the Earth's magnetic field were assessed from Eqs. (1) and (2) for all the globe at grid points spaced 5° intervals in latitude and 10° intervals in longitude. The initial and final conditions correspond to years 1950 and 2000, respectively. Temperature and density were obtained from Hedin MSIS86 model (Hedin, 1987), meridional thermosphere wind was calculated from HWM93 model (Hedin et al., 1996), and δ and I were obtained from the International Geomagnetic Reference Field IGRF, available from the National Space Science Data Center NSSDC. D is equal to kT/mv, where v is the ion-neutral atomic oxygen collision frequency given by $4 \times 10^{-17}\,T^{0.5}n(O)$ (Salah, 1993) with density given in m^{-3} and D in m^2/s. Noon local time, and a solar activity level given by $F10.7 = 150$ were considered. Wind, density and temperature values depend on solar activity level, so changes in $F10.7$ will induce changes in these parameters, and consequently in the final ionospheric trend values. Changes in the sign are not expected. The dependency of trends on solar activity will be analysed in detail in a later study.

Fig. 1 shows the variation per year of δ, I and the $\sin(I)\cos(I)$ factor. Figs. 2 and 3 depict ΔhmF2 in km/year and the foF2 percentage change per year, respectively, for June and December solstices, and September equinox. The region of strongest variations in hmF2 and foF2, reaching values of ± 1.3 km/year and ± 1%/year, respectively, lies between 10°N and 30°S in latitude and between 20°E and 80°W in longitude, which is also the region of strongest changes in I and $\sin(I)\cos(I)$ factor. This region presents also the highest seasonal variation, with changes even in the sign of the trend. At high latitudes, trends are similar for the different months analysed, so it can be said that seasonal changes should not be expected. Close to the magnetic poles, for September and in less degree for December (Figs. 2(b) and (c), and 3(b) and (c)), trend values are comparable to the strongest trends observed between 10°N and 30°S and between 20°E and 80°W. Around the magnetic poles, the declination presents the strongest rate of change. So, during these months, the declination long-term variation effects over ionospheric trends may be important. During June, trends close to the magnetic poles are relatively much smaller than during the other months in this region, and also than the June values of the region of strongest trends. This difference, clearly observed between September and June, is due to U_x seasonal variation. In fact, the trend pattern is determined by $\Delta W = U_x(\cos(\delta_f)\sin(I_f)\cos(I_f) - \cos(\delta_i)\sin(I_i)\cos(I_i))$ where the difference between brackets is the same for every month. It could be said that during September and December,

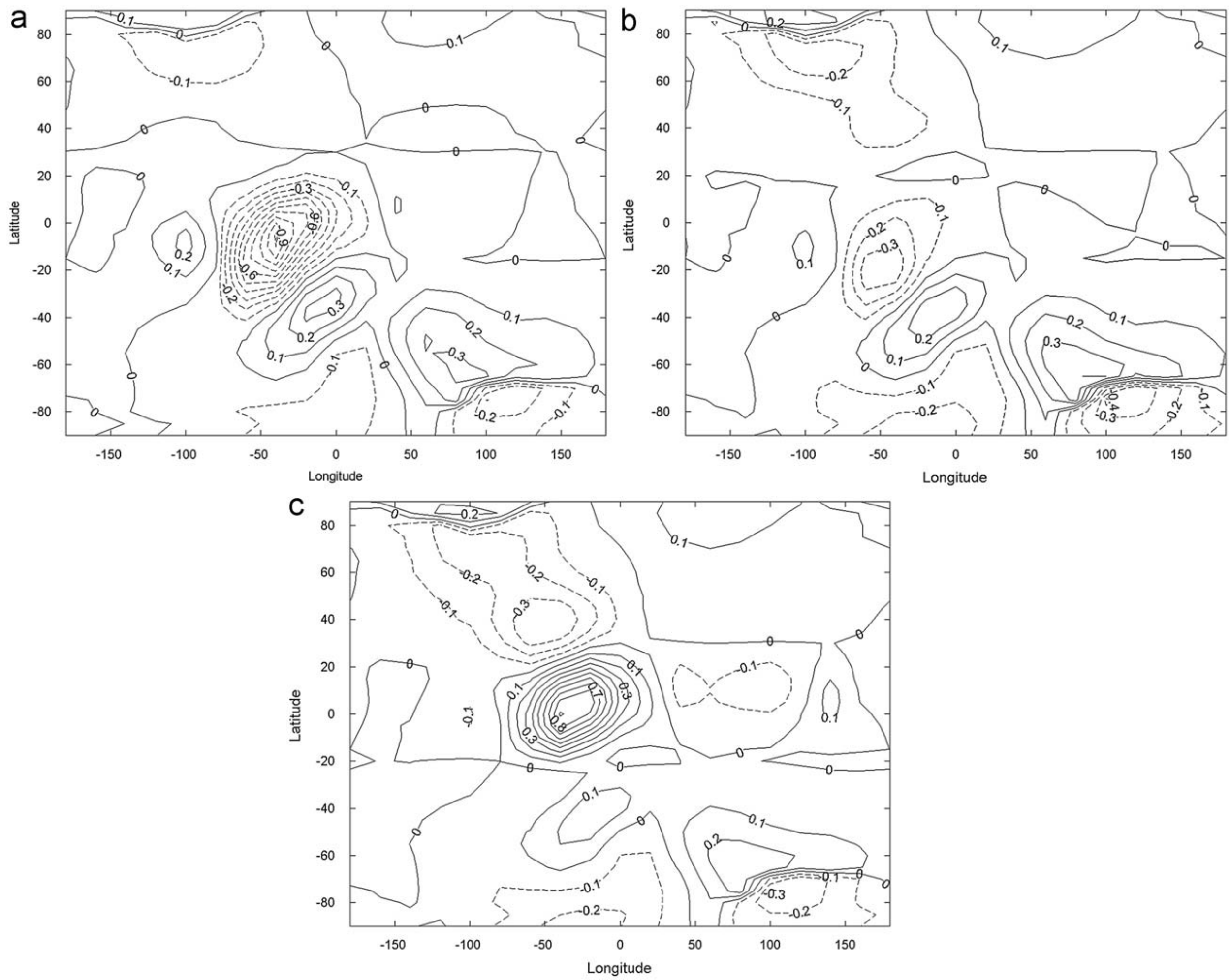

Fig. 3. foF2 percentage trend (%/year) calculated with Eq. (2) for (a) June, (b) September, and (c) December. Variables in Eq. (2) – density, temperature, wind – were obtained for 12 LT and solar activity level corresponding to $F10.7 = 150$. Dashed contours are negative values, solid contours are positive values.

Table 1
Observed noon hmF2 trends (km/year) – published by [1]Ulich and Turunen (1997), [2]Bremer (1992), [3]Xu et al. (2004), [4]Sharma et al. (1999), [5]Foppiano et al. (1999) and [6]Jarvis et al. (1998) – and trends assessed with Eq. (1).

Station	Lat. °N	Long. °E	June (or NH summer)		September (or equinox)		December (or NH winter)	
			Observed	Assessed Eq. (1)	Observed	Assessed Eq. (1)	Observed	Assessed Eq. (1)
[1]Sodankyla	67.4	26.7	−0.55	0.02	−0.15	0.03	−0.40	0.03
[2]Juliusruh	54.6	13.4	−0.12	0.01	−0.14	−0.01	−0.45	−0.05
[3]Kokubunji	35.7	139.7	−0.6	0.00	−0.5	0.00	−0.2	0.01
[4]Ahmedabad	23.0	72.6	−0.22	0.01	−0.56	−0.01	−0.16	−0.05
[5]Concepcion	−36.8	−73.0	−0.5	−0.20	−0.5	−0.20	−0.5	−0.10
[6]Port Stanley	−51.7	−57.8	−0.4	0.01	−0.1	0.01	−0.2	0.01
[6]Arg. Island	−65.2	−64.3	−0.15	−0.06	−0.2	−0.08	−0.9	−0.08

Note: Sharma et al. (1999) gave seasonal values.

U_x geographical pattern enhances the factor $\cos(\delta_f)\sin(I_f)\cos(I_f) - \cos(\delta_i)\sin(I_i)\cos(I_i)$ at high latitudes with respect to June.

5. Comparison with experimental results

Only hmF2 results are compared to experimental results since percentage values were obtained in the case of foF2. The comparison of foF2 will be done in a future study converting percentage trends to absolute trends with mean foF2 values obtained from the International Reference Ionosphere model.

Two types of comparisons are made. First, single trend values obtained and published by authors that present results separately for each season or month are considered, so they can be easily compared with the values obtained in the present work. Second, a regional pattern of positive and negative trends determined by Bremer (1998) is compared with the pattern here obtained for the same region.

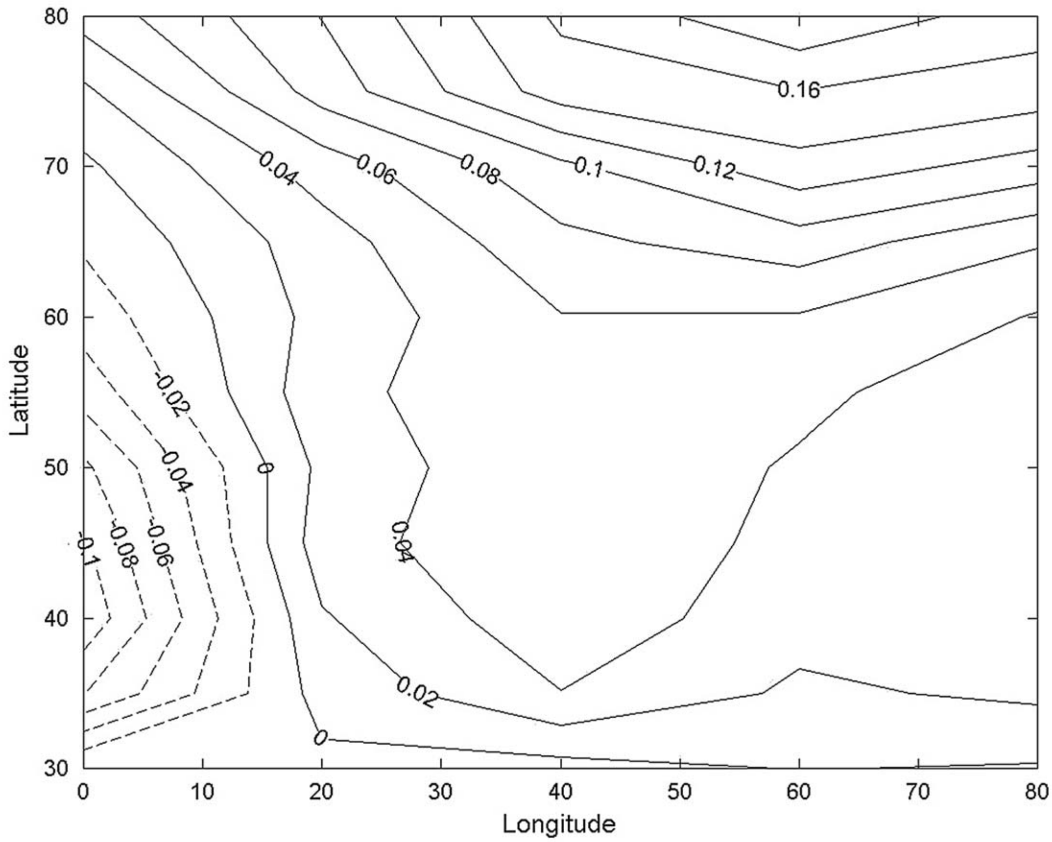

Fig. 4. hmF2 trend (km/year) calculated with Eq. (1) for December for the region comprised between 0° and 80°N, and 0° and 80°E. Dashed contours are negative values, solid contours are positive values.

Table 1 presents the values of hmF2 noon trends assessed with Eq. (1) and experimental trends for Sodankyla (67.4°N, 26.7°E) calculated by Ulich and Turunen (1997), Juliusruh (54.6°N,13.4°E) by Bremer (1992), Kokubunji (35.7°N, 139.5°E) by Xu et al. (2004), Ahmedabad (23.0°N, 72.6°E) by Sharma et al. (1999), Concepcion (36.8°S,73.0°W) by Foppiano et al. (1999), and Port Stanley (51.7°S, 57.8°W) and Argentine Islands (65.2°S, 64.3°W) by Jarvis et al. (1998). In the cases where experimental values were not listed by the mentioned authors, they were obtained from the figures. The seasonal pattern is not uniform for all the stations neither in the observed nor in the theoretical case. Only in the case of Concepcion, a location that is close to the region of strongest trends according to the results here shown, it seems to be some agreement in the seasonal behaviour between observed and theoretical trends, but not in the trend absolute values. This suggests that although the Earth's magnetic field is able to produce trends in the ionosphere, other factors (greenhouse gases increase and geomagnetic activity long-term variation) may be more important in trend generation. The situation should be different for the region between 10°N and 30°S in latitude and between 20°E and 80°W in longitude, where, especially at the centre of the region, much stronger trends are expected due to changes in the Earth's magnetic field. Adler et al. (2002) estimated the mean annual hmF2 trend at Tucuman (26.9°S, 65.4°W), a site that lies within the region of strong trends here expected. A decrease of 0.2 km/year was obtained which should be compared to −0.6, −0.4 and −0.1 km/year obtained for this location with Eq. (1) for June, September and December, respectively. Something that should be pointed out is that stations at high latitudes, such as Sodankyla and Argentine Islands, present stronger downward trends than Tucuman and Concepcion, contrary to what is expected based on the Earth's magnetic field mechanism. Jarvis et al. (1998) also present a trend estimation for Argentine Islands due to changes in the Earth's magnetic field using the SUPIM model. Their values are of the same order of magnitude as those presented here for that site, so at high latitudes the Earth's magnetic field is not enough to produce the observed trends.

At high latitudes, the effect of long-term variations in geomagnetic activity over the ionosphere is expected to be stronger (Field and Rishbeth, 1997). So, possibly at these latitudes, hmF2 and foF2 trends are mainly linked to this mechanism as proposed by Danilov and Mikhailov (1999) and Mikhailov and Marin (2000).

Fig. 4 corresponds to a portion of Fig. 2(c), which includes the region analysed by Bremer (1998). Only December is shown because, as already mentioned, trends in this region present almost no variation with season. Bremer (1998) observed that hmF2 and foF2 trends show marked differences for the longitudinal regions west or east of 30°E in Europe. At longitudes west of 30°E trends are in general negative, while east of 30°E trends are generally positive. This behaviour is outlined in Fig. (4), but with the zero-trend line at 20°E.

Jarvis (2008) confirmed the longitudinal differences in F-region trends across Europe observed by Bremer (1998) by showing an east–west gradient in trend, between 3°W and 70°E and suggests a driver related to a stationary wave-like feature linked to tidal effects. He rules out the secular change in the magnetic field through the analysis of its effects over foE, which enters the equation to assess hmF2 in terms of M3000(F2), and does not consider the effect over meridional winds. The results shown here suggest that the trend's east–west gradient can be noticed considering only long-term variations in the Earth's main magnetic field. From Fig. 4 a difference in hmF2 trend 0.08 km/year is obtained between the locations of Moscow and the location of Juliusruh. Which mean 0.8 km per decade, much less than the result obtained by Jarvis (2008) which is around 10 km per decade. Although the trend absolute values may not suffice to produce the observed trends, this can be a mechanism that should interact or may be added to other factors able of producing stronger trends.

6. Discussion and conclusions

Long-term trends in the ionosphere F2 region are analysed in this work in terms only of secular changes in the Earth's magnetic field. These changes, like long-term variations in geomagnetic activity, are able to produce trends in foF2 and hmF2, which vary with local time, season and location. An increase in greenhouse gases concentration is expected to produce a global decrease in foF2 and hmF2 instead, although recently Qian et al. (2008) have given an explanation for positive and negative hmF2 trends based on increased greenhouse gases mechanisms only.

During 1950–2000, CO_2 concentration has increased 20%. If we linearly extrapolate the 20 km lowering of hmF2 assessed by Rishbeth (1990) as a consequence of a doubling in CO_2 concentration, then a 0.04 km/year decreasing trend in hmF2 should be expected for the period 1950–2000. This value is even much lower than the values expected from long-term variations in the Earth's magnetic field.

Theoretical analyses of ionospheric trends produced by the Earth's magnetic field variation have also been recently published by Yue et al. (2008) and Cnossen and Richmond (2008). They coincide with the present results in the region where greatest trends should be expected and also in the ability of the magnetic field changes to produce trends in the ionosphere that depend on local time, season and location.

Yue et al. (2008) use a mid- and low-latitude ionospheric theoretical model which solves plasma continuity, motion and energy equations while Cnossen and Richmond (2008) use the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model. The trend pattern obtained in this work is similar to that obtained by Cnossen and Richmond (2008), in sign and relative values. Fig. 5 shows hmF2 noon trend values for June estimated with Eq. (1), between 1997 and 1957 (the period Cnossen and Richmond (2008) have analysed), to make a direct comparison. The trend values here obtained are comparable to those shown in their Fig. 5 (bottom). The extension and location of the region of strongest negative trends is similar to the one they present for 12 UT, but absolute trend values are closer to their 0 UT values. It should be taken into account that they use universal time while here local time is considered. In their case time is different for each time zone. Changes at 0° longitude for 12 UT and at 180° for 0 UT obtained from their Fig. 5 can be directly compared to corresponding changes in the present Fig. 5. This is shown in Fig. 6 in the case of 0° longitude. In both cases (changes assessed by Cnossen and Richmond (2008) and those obtained here) the strongest negative trends are seen around 0° latitude. The curves differ in the location of positive trends which is around 30°N in the case of Cnossen and Richmond and around 30°S in this case. For this particular longitude, looking separately at changes in the upward component of the horizontal wind parallel to the magnetic field estimated by Cnossen and Richmond (2008) (which they call $\nu_{n,par,v}$ and are shown in their Fig. 8, bottom right) and changes in the vertical component of the ExB drift (shown in their Fig. 9, bottom right) it can also be concluded that changes in the $\nu_{n,par,v}$ seem to be a more important factor than

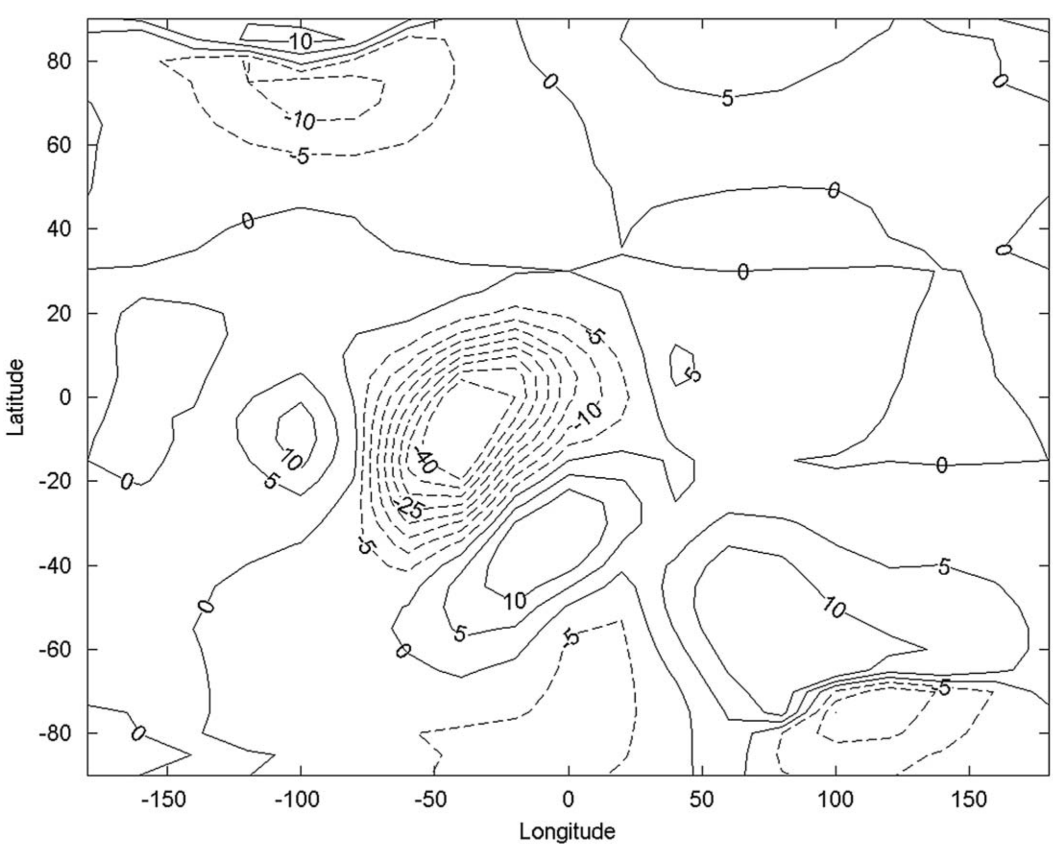

Fig. 5. hmF2 change (km) calculated with Eq. (1) for June between 1997 and 1957. Variables in Eq. (1) – density, temperature, wind – were obtained for 12 LT and solar activity level corresponding to $F10.7 = 150$. Dashed contours are negative values, solid contours are positive values.

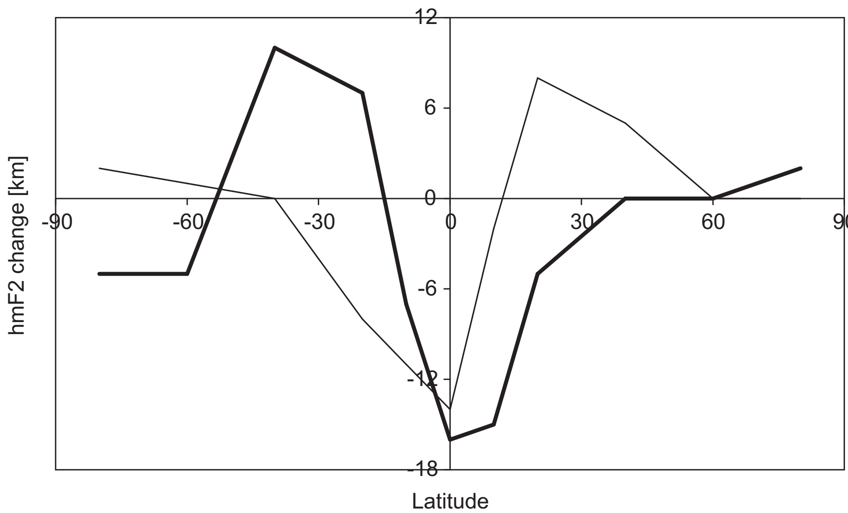

Fig. 6. hmF2 change (km) calculated with Eq. (1) for June between 1997 and 1957 (solid enhanced line) at 0° longitude, and hmF2 change assessed by Cnossen and Richmond (2008) obtained from their Fig. 5 – bottom right – at longitude 0° (solid line).

changes in ExB drift in causing hmF2 long-term variation. In the case of 180° longitude, hmF2 changes oscillate close to cero in the case of Cnossen and Richmond and the present case.

Like Cnossen and Richmond (2008) and Yue et al. (2008), the present work demonstrates on a theoretical basis that secular changes in the Earth's magnetic field do induce trends in the F-region ionosphere. Using simple theoretical considerations, and with the help of empirical models to assess some variables, the expected hmF2 and percentage foF2 trends were assessed worldwide. This simple approach can give us a first picture, comparable to that obtained using much more complex models. It should be taken into account that the present analysis does not consider several factors, such as long-term variations in the wind strength, neutral composition and temperature (Keating et al., 2000; Emmert et al., 2004). Although this disadvantage, the approach presented here allows to visualize, in a first approximation, the role of the variables considered. Regarding the lack of considering ExB drift variations, Cnossen and Richmond (2008) conclude that the changes in the vertical ExB drift are less important than the changes in δ and I.

The comparison between modelled and experimental values is complex in this case. Although experimental values may have the last word, they involve a statistical analysis to extract linear trends after filtering procedures, which ends in trend values highly influenced by the method used (Lastovicka et al., 2006, 2008). However, it would be interesting to obtain experimental trends over the region where the strongest trends are expected according to the present analysis.

Since the Earth's magnetic field does not seem to explain the experimental trends obtained by many authors, one may think that adding the other factors that are able to induce ionospheric trends, a better theoretical picture should be obtained. So, to elucidate the origin of the F2-region trends, long-term variations in the three possible known mechanisms should be considered altogether – greenhouse gases, geomagnetic activity and Earth's magnetic field – and their interaction.

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