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foF2 long-term trends at the southern crest of the equatorial anomaly

Ana G. Elías [a,b,*], Nieves Ortiz de Adler [a]

[a] *Laboratorio de Física de la Atmósfera, Departamento de Física, Facultad de Ciencias Exactas y Tecnología,*
Universidad Nacional de Tucumán, Av. Independencia 1800, 4000 Tucuman, Argentina
[b] *Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Argentina*

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Abstract

Long-term trends in the electron density of the ionosphere for the period 1957–1986 is studied using foF2 monthly median hourly data measured at Tucuman (26.9°S, 65.4°W), a station located at the southern crest of the equatorial anomaly. The linear trend for each hour and each month is estimated after filtering out the effects of solar activity. For the intervals 0–2 LT and 9–23 LT, during equinoxes and summer solstice, the trend is negative. Statistically null or slightly positive trends are observed for the interval 3–8 LT for every season, and for every hour of winter months. The daily amplitude of foF2 decreases since 1957 due to the decreasing trend in the maximum daily values and almost null-trended minimum daily values. A rough estimate, based on the dip angle trend (which in Tucuman has increased during the 30-year interval at a rate of 0.35%/year), indicates that negative foF2 trends should be expected during daytime hours, and positive trends during night-time hours, behaviour observed in the foF2 data here analyzed.

Keywords: Ionosphere; foF2; Long-term trend; Dip angle variation

1. Introduction

Since the beginning of the 1990's interest has been focused on the study of upper atmosphere trends at time-scales longer than the well-known seasonal and solar activity cycles (Aikin et al., 1991; Clemesha et al., 1992; Roble, 1995; Taubenheim et al., 1997). Trends in ionospheric parameters is widely discussed in several publications (Givishvili and Leshchenko, 1995; Ulich and Turunen, 1997; Rishbeth, 1997; Danilov, 1998; Bremer, 1992, 1998, 2001; Upadhyay and Mahajan, 1998; Jarvis et al., 1998; Danilov and Mikhailov, 1999a, 2001; Sharma et al., 1999; Foppiano et al., 1999; Mikhailov and Marin, 2000, 2001).

Some studies link ionospheric trends with the stratosphere, mesosphere and thermosphere cooling due to an increase in greenhouse gases (Rishbeth, 1990; Roble and Dickinson, 1989). 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 and 300 km, a lowering of the ionospheric F2 peak height (hmF2), and a worldwide foF2 decrease less than 0.5 MHz (Rishbeth, 1990; Roble and Dickinson, 1989; Rishbeth and Roble, 1992). However, the global pattern of hmF2 and foF2 trends estimated from observations at several worldwide stations over the last 40 years is highly complex and can hardly be reconciled with the greenhouse hypothesis (Bremer, 1998; Upadhyay and Mahajan, 1998; Mikhailov and Marin, 2000, 2001).

Danilov and Mikhailov (1999a,b) and Mikhailov and Marin (2000) with a new approach, obtained negative hmF2 and foF2 trends for several Northern-Hemisphere ionospheric stations and a pronounced dependence of the trend magnitude on geomagnetic latitude (with more negative values at higher latitudes) indicating that F2-layer

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[*] Corresponding author. Address: Laboratorio de Física de la Atmósfera, Departamento de Física, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucumán, Av. Independencia 1800, 4000 Tucuman, Argentina. Tel.: +54 381 4210116; fax: +54 381 4364596.
E-mail address: anagelias@yahoo.com (A.G. Elías).

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trends might be related to long-term changes in geomagnetic activity and F2-layer storm mechanisms. They show that there exist periods with negative and positive foF2 trends, which correspond to the periods of long-term increasing or decreasing geomagnetic activity. A strong diurnal variation in the trend value is noticed for stations located at different latitudes which, according to Mikhailov and Marin (2000), is a strong argument against a greenhouse origin of such trends.

Long-term changes in the dip angle (I) are 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, 1967, 1998) will also change. The horizontal thermospheric wind U drives ions and electrons up (during night) or down (during day) along the geomagnetic field lines at speed $U\cos(I)$. The vertical component, or drift, $U\sin(I)\cos(I)$, raises (lowers) the F2-peak and increases (decreases) 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). So, the amplitude of foF2 diurnal variation should be decreasing and the amplitude of hmF2 increasing. Foppiano et al. (1999),

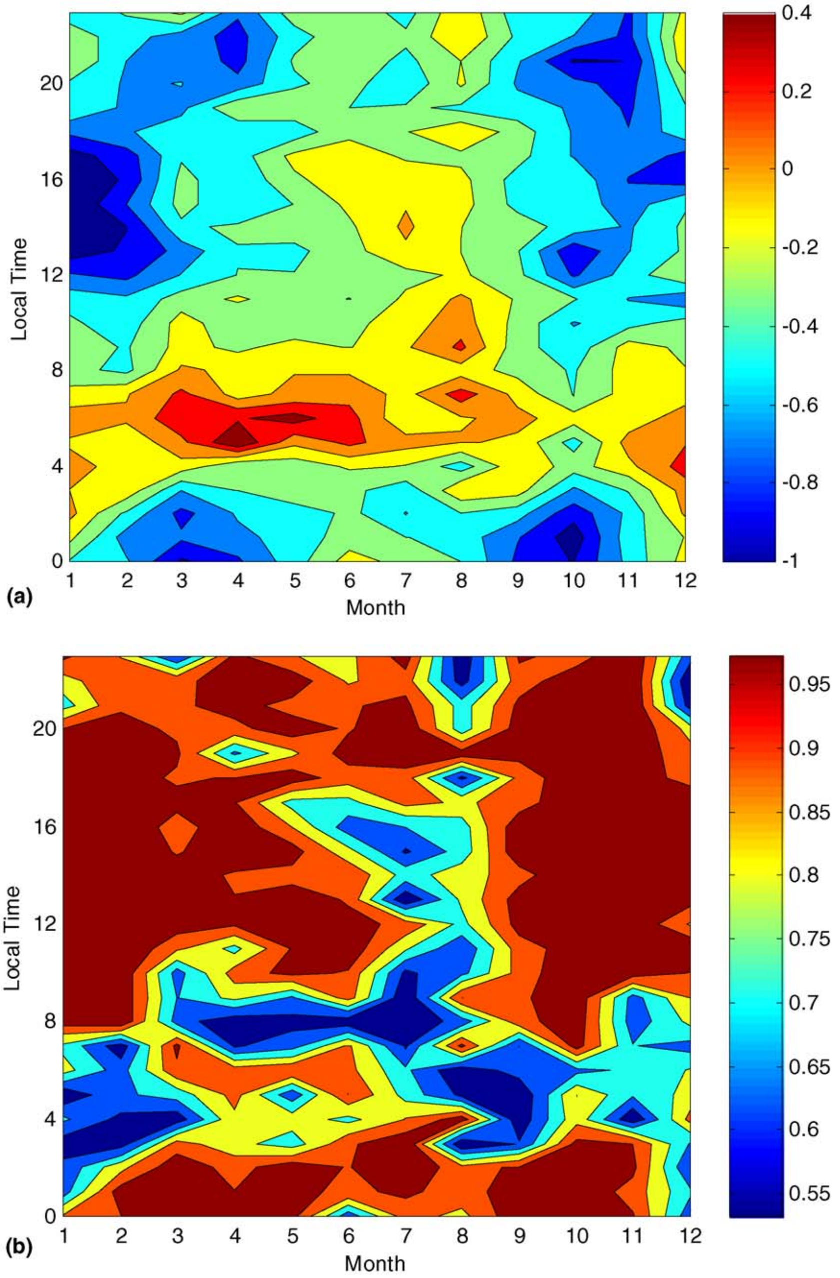

Fig. 1. (a) Percentage variation of foF2 per year (foF2 trend divided by the mean foF2 × 100) at Tucuman during the period 1957–1986. (b) Significance level of foF2 trend values estimated with the t-test.

analyzing foF2 and hmF2 data for Concepcion (36.8°S, 73.0°W) during the period 1958–1994 and 1958–1991 respectively, found that the trend behaviour is in agreement with the dip angle increase observed at that place.

Changes in both, geomagnetic activity and dip angle would induce trend values according to latitude and local time. The dip angle long-term variation was considered in this work as a possible explanation of the daily and seasonal pattern of foF2 trends found for Tucuman.

2. Data analysis

Monthly median hourly F2 critical frequency data, foF2, recorded at Tucuman (26.9°S, 65.4°W; 15.5°S, 3.8°E geographic and geomagnetic coordinates respectively) during the period 1957–1986 were analyzed. Arranging them according to the different months and hours amounts to 288 series.

Solar activity was filtered out from each time series estimating the foF2 anomalies, $\mathrm{foF2A} = \mathrm{foF2}_{\mathrm{exp}} - \mathrm{foF2}_{\mathrm{mod}}$, where $\mathrm{foF2}_{\mathrm{exp}}$ refers to the experimental foF2 value and $\mathrm{foF2}_{\mathrm{mod}}$ to the modelled value. $\mathrm{foF2}_{\mathrm{mod}}$ was estimated from a regression between the experimental value and solar activity measured through the sunspot number, Rz ($\mathrm{foF2}_{\mathrm{mod}} = aRz + b$). The linear trend α of foF2A in terms of time, was estimated then using minimum least squares from $\mathrm{foF2A} = \alpha t + \beta$.

Percentage variation of foF2 per year (foF2 trend divided by the mean $\mathrm{foF2} \times 100$) is depicted in Fig. 1(a) in terms of month and local time. During summer (December, January and February) and equinoxes, foF2A decreases from 0 to 2 LT and from 9 to 23 LT at a rate between 0.06 and 1%/year, that is approximately −0.006 to −0.12 MHz/year. During winter for every hour, and for the hour interval 3–8 LT for every month, trends are null or positive, reaching values of 0.4%/year, that is around 0.02 MHz/year. The significance level of foF2 trend values is shown in Fig. 1(b).

Decreasing trends during the day and increasing trends during the night should lead to a decrease in the amplitude of foF2 diurnal variation (difference between the maximum and the minimum monthly median hourly values). Fig. 2 shows foF2 daily amplitude linear trend during the 30-year period of data. A decreasing trend is obtained for every month.

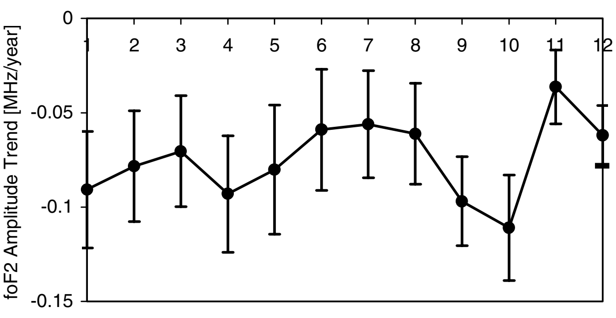

Fig. 2. foF2 daily amplitude trend for Tucuman during the period 1957–1986. Error indicated as vertical bar. All trend values are significant at more than a 95% level.

3. Theoretical analysis of increasing dip angle effects over foF2

The behaviour of the F2-peak at mid-latitudes depends on the interplay of photochemical processes 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 or electric fields. A vertical drift W alters the level of the peak by approximately WH/D_{m}, where H is the scale height of the ionizable constituent, that is atomic oxygen, and D_{m} the plasma diffusion coefficient at the peak height (Rishbeth, 1967; Rishbeth and Garriott, 1969). H is given by $kT/\mathrm{mg} = 53T$ in meters, where T is the temperature in Kelvin. The vertical drift is $W = U_x \sin(I)\cos(I)$ where U_x is the meridional component of the neutral wind in the thermosphere.

According to a simple kinetic theory, assuming that ion and neutral gas temperature are equal and electron temperature twice the ion temperature (a reasonable daytime condition), D_{m} can be estimated as

$$D_{\mathrm{m}} = \frac{4.4 \times 10^{18}\sqrt{T}}{n(\mathrm{O})}$$

where $n(\mathrm{O})$ is the atomic oxygen density in m^{-3} at the peak level and D_{m} results in m^2/s (Buonsanto et al., 1997; Omidvar et al., 1998).

For the day equilibrium layer the peak electron concentration NmF2 is given by

$$\mathrm{NmF2} \approx \frac{q_{\mathrm{m}}}{\beta_{\mathrm{m}}} \propto \frac{n(\mathrm{O})}{n(\mathrm{N}_2)} \propto \frac{\mathrm{e}^{-z_{\mathrm{m}}}}{\mathrm{e}^{-1.75 z_{\mathrm{m}}}} \propto \mathrm{e}^{0.75 z_{\mathrm{m}}}$$

where $n(\mathrm{N}_2)$ and z_{m} are the density of molecular nitrogen and the reduced height respectively at the peak level. Changes in z_{m} will produce changes in NmF2

$$\frac{\mathrm{dNmF2}}{\mathrm{d}z_{\mathrm{m}}} \propto 0.75\mathrm{e}^{0.75 z_{\mathrm{m}}}$$

so that

$$\frac{\mathrm{dNmF2}}{\mathrm{NmF2}} = 0.75\,\mathrm{d}z_{\mathrm{m}} \tag{1}$$

A change in ΔW, would induce changes in z_{m} equal to $\Delta z_{\mathrm{m}} \approx H/D_{\mathrm{m}}\Delta W$. So, Eq. (1) becomes

$$\frac{\Delta\mathrm{NmF2}}{\mathrm{NmF2}} \approx 0.75\frac{H}{D_{\mathrm{m}}}\Delta W \tag{2}$$

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

$$\frac{\Delta\mathrm{foF2}}{\mathrm{foF2}} = \frac{1}{2}\frac{\Delta\mathrm{NmF2}}{\mathrm{NmF2}} \approx 0.375\frac{H}{D_{\mathrm{m}}}\Delta W \tag{3}$$

If it is assumed that the changes in W are consequence of changes in the dip angle I, then $\Delta W = U_x \Delta[\sin(I)\cos(I)]$. The value of $\Delta[\sin(I)\cos(I)]$ was estimated assessing the

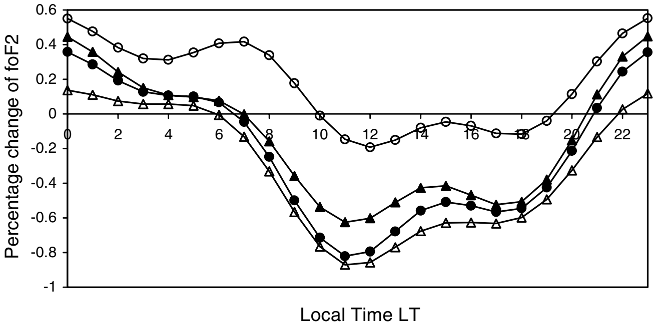

Fig. 3. Theoretical assessment of the percentage change of foF2 ($\Delta foF2/foF2 \times 100$) per year for a 0.3%/year change in the meridional thermospheric wind in terms of local time for January (empty circle), March (filled circle), July (empty triangle), and September (filled triangle). *Note:* $\Delta foF2/foF2$ has been estimated with an approximation valid for daytime hours. So the LT outside the range $8 < LT < 18$ are qualitative.

trend of the dip angle I over Tucuman (26.9°S, 65.4W) with the International Geomagnetic Reference Field (IGRF, model available at http://nssdc.gsfc.nasa.gov/space/model/magnetos/igrf.html). At this location during the period 1957–1986, the dip angle has increased from 21.5 in 1957 to 23.8 in 1986 which implies an increase of 10% and an overall increase of 8% in the factor $\sin(I)\cos(I)$. This would produce an increase of 0.3%/year in W.

The meridional wind velocity was estimated from Hedin HWM93 empirical model (retrievable from NSSDC ftp site) (Hedin et al., 1996), and temperature and density values from Hedin MSIS86 (Hedin, 1987). Introducing the meridional wind, neutral temperature and $n(O)$ values in Eq. (3), the percentage change of foF2 per year, has been estimated and plotted in Fig. 3, where every hour is shown although Eqs. (2) and (3) are only valid around noon. There are negative foF2 trends between 8 and 20 LT (ranging from 0.04 to 1%/year) and positive trends during the rest of the hours (reaching values of 0.55%/year). Negative trends are greater during winter months (June, July, August) than summer and equinoxes, and positive trends are greater during summer months.

4. Discussion and conclusions

Increase in CO_2 concentration and long-term changes in the dip angle would be possible causes to explain long-term trends in the ionosphere.

A doubling in CO_2 concentration should produce an foF2 decrease less than 0.5 MHz. In the period 1957–1986, CO_2 has had an increase of 15% (IPCC, 1995). If a linear change in foF2 with increasing CO_2 is assumed, then foF2 should decrease around 0.04 MHz during the 30 years here analyzed, while the mean observed decrease in Tucuman is around 2 MHz.

Using some approximations and models, the interesting Foppiano idea that the observed trend may be a result of the dip angle (I) trend was developed. The horizontal wind lifts (or lowers) the F2-layer plasma along the magnetic field lines inducing changes not only in hmF2, but in foF2 as well, since the layer comes to regions of lower (higher) recombination. Since in the daytime the horizontal wind blows poleward, the F2 layer should go down and foF2 should decrease. That is what should happen if there is a trend in I such that $\sin(I)\cos(I)$ increases with time.

The negative foF2 trend during day, null or positive trends during night-time hours and decreasing trends in foF2 daily amplitude, qualitatively support the possibility of dip angle trends inducing foF2 trends. A rough theoretical assessment of the expected foF2 variations in response to the observed dip angle trend at Tucuman, agree with the daily pattern of foF2 trends and with the percentage foF2 changes, but experimental trends are greater during summer while theoretically estimated trends are greater during winter.

The seasonal and hourly patterns of foF2 trends obtained at Tucuman (located at the southern crest of the equatorial anomaly) are similar to those obtained for Concepcion (located on the poleward slope of the anomaly) by Foppiano et al. (1999). Trend values are bigger in the case of Tucuman which presents a stronger decrease in the $\sin(I)\cos(I)$ factor.

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