

RESEARCH ARTICLE

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Key Points:

- f_oF_2 at Phu Thuy presents an increasing trend
- Trend observed at noon is in agreement with the effect of the dip equator secular displacement
- Trend observed at night is in agreement with Earth's magnetic field inclination secular variation

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f_oF_2 long-term trend linked to Earth's magnetic field secular variation at a station under the northern crest of the equatorial ionization anomaly

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Abstract Long-term trend of the critical frequency of the F_2 ionospheric region, f_oF_2 , at Phu Thuy station (21.03°N, 105.96°E), Vietnam, located under the northern crest of the equatorial ionization anomaly, EIA, is studied. Annual mean data are analyzed at 04 LT and 12 LT for the period 1962–2002 using monthly median values and monthly mean values during magnetically quiet days ($am < 20$). In both cases we obtain similar trends at 4 LT and 12 LT, which we interpret as an absence of geomagnetic activity effect over trends. The positive trends obtained are not consistent with the negative values expected from greenhouse gases effect at this layer of the upper atmosphere. The increasing trend observed at 12 LT is qualitatively in agreement with the expected effect of the secular displacement of the dip equator over the EIA latitudinal profile. At 04 LT, when the EIA is absent, the positive trend is in qualitative agreement with the secular variation of the Earth's magnetic field inclination, I , and the consequent increase of the $\sin(I)\cos(I)$ factor at the corresponding location.

1. Introduction

Trends in ionospheric parameters have become a main subject since the beginning of the 1990s [e.g., Aikin *et al.*, 1991; Roble, 1995; Ulich and Turunen, 1997; Jarvis *et al.*, 1998].

A well-recognized source of trends in the upper atmosphere is the increase in greenhouse gases concentration (see Lastovicka *et al.* [2012] for a comprehensive review and references therein). Qian *et al.* [2009] performed a simulation using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model, doubling the CO_2 concentration from 365 ppmv to 730 ppmv, and observed changes in the F_2 layer maximum electron density (N_mF_2) and peak height (h_mF_2).

Among the natural possible sources of these trends is the long-term variation of geomagnetic activity. Clilverd *et al.* [1998] and Stamper *et al.* [1999] found that the geomagnetic activity in terms of the aa index was increasing throughout the twentieth century, and Clilverd *et al.* [2002] observed that the number of geomagnetic storms per solar cycle had also been increasing until it stabilized in the last few cycles. Long-term changes in the solar quiet-time day variation, Sq , have been found as well [Macmillan and Droujinina, 2007; Elias *et al.*, 2010; Shinbori *et al.*, 2014]. Variations in geomagnetic activity occur on short timescales from minutes to days and are responsible for a part of the large natural variability in the thermosphere-ionosphere system. A gradual, long-term change in the background level of geomagnetic activity could therefore cause a long-term trend in the upper atmosphere [Cnossen *et al.*, 2011].

Regarding secular changes of the Earth's main magnetic field, the possibility of ionospheric trends induced by these changes was suggested and analyzed by several authors [Foppiano *et al.*, 1999; Elias and Ortiz de Adler, 2006a, 2006b; Cnossen and Richmond, 2008; Yue *et al.*, 2008; Elias, 2009; Gnabahou *et al.*, 2013; Cnossen, 2014]. Among them, Gnabahou *et al.* [2013] considered the long-term trend of f_oF_2 at Ouagadougou, a West African equatorial station, linked to greenhouse gas increase and dip equator displacement, concluding that the latter cause was inducing the observed f_oF_2 trend.

From all these results we can conclude that the change in CO_2 concentration has contributed to long-term trends in the F_2 layer, but it is unlikely to be the unique cause.

In this work we analyze f_oF_2 long-term variation at Phu Thuy (21.03°N, 105.96°E), a station located at the northern crest of the equatorial ionization anomaly in the Asian sector, whose time variation was analyzed and extensively described by *Pham Thi Thu et al.* [2011]. The observed trend is considered in relationship with the Earth's magnetic field secular variation and the consequent dip equator secular displacement.

The paper is organized as follows. Section 2 describes the data and trend estimation. The Earth's magnetic field variation and the dip equator displacement as possible trend sources are analyzed in sections 3 and 4, respectively, followed by a comparison with other trend results in section 5 and the discussion and conclusions in section 6.

2. Data Analysis

Hourly data of ionospheric F_2 layer critical frequency, f_oF_2 , has been recorded by the ionosonde at Phu Thuy (21.03°N, 105.96°E), Vietnam, since 1962. This observatory is located near the northern crest of equatorial ionization anomaly, EIA, in the Asian sector. The ionosonde data were almost continuously recorded by different ionospheric vertical sounders: IRX-Hungarian (1962–1966), AIC-Russian (1967–1994), IPS71-Australian (1994–2002), and Digital SKI02098-Japanese (2005–2010).

Annual f_oF_2 data at 04 LT and 12 LT were calculated for the period 1962–2002 (with no gaps) from monthly median values and also from monthly mean values considering only magnetically quiet days, using the condition $am < 20$. am is similar to Ap except that a more global distribution of stations are used. Its value is almost equal to aa , and the quietness limits can be extended to 30 [Joselyn, 1989]. The latter annual series is considered as free of geomagnetic activity effects, so by comparing both annual series trends it may be possible to detect if geomagnetic activity should be considered as a trend source in our case. This effect is not easy to detect or filter out since the ionospheric response to geomagnetic activity is highly complex due to the many physical processes involved.

In order to filter out solar activity effects, we took into account the period considered in the present analysis. As analyzed by *de Haro Barbas and Elias* [2015] and *Elias* [2014], solar cycle 19, for example, presents a strong maximum during which the ionosphere does not respond linearly to a further increase in EUV radiation. A kind of saturation takes place resulting in a breakdown of the linearity between f_oF_2 and EUV with consequent persistent negative residuals during this period. Even though we considered part of solar cycle 19, it is only the last 2 years with a solar activity level well below saturation. Regarding the end of the period here considered, we include the first half of solar cycle 23, for which the solar radio flux at 10.7 cm (2800 MHz), $F_{10.7}$, seems to be a better EUV proxy than R_z [Elias et al., 2014].

Given the above consideration, to filter out solar activity effect, we estimated f_oF_2 residuals (f_oF_2) from the linear regression between f_oF_2 and solar activity measured through $F_{10.7}$. That is

$$\Delta f_oF_2 = f_oF_2 - (a F_{10.7} + b) \quad (1)$$

where a and b are obtained from the regression between f_oF_2 and $F_{10.7}$ using least squares.

The linear f_oF_2 trend α is then assessed from

$$\Delta f_oF_2 = \alpha \text{ year} + \beta \quad (2)$$

being α in MHz/yr.

Figure 1 shows f_oF_2 residuals together with the linear trends for both f_oF_2 annual values considered at 4 LT and 12 LT. Absolute and percentage trend values are listed in Table 1. Local times were chosen according to the EIA strength effect on them (considering EIA strength as the crest-to-trough f_oF_2 ratio): at 12 LT it is strong, and at 4 LT it is almost absent [e.g., *Stolle et al.*, 2008; *Zhang et al.*, 2009].

The fact that trend values using monthly median values and using mean values during quiet days are similar points out that the geomagnetic activity may not affect the observed f_oF_2 trends for the period here considered.

The positive trends observed are not consistent with the expected decrease in f_oF_2 due to greenhouse gases increasing concentration. In fact, for a mean $\sim 0.5\%/yr$ increase in CO_2 occurred for the period here considered, a $0.003\%/yr$ decrease in f_oF_2 should be expected if we linearly extrapolate the results for a doubling in CO_2 concentration obtained by *Rishbeth* [1990] and *Rishbeth and Roble* [1992]. So, we considered the secular variations

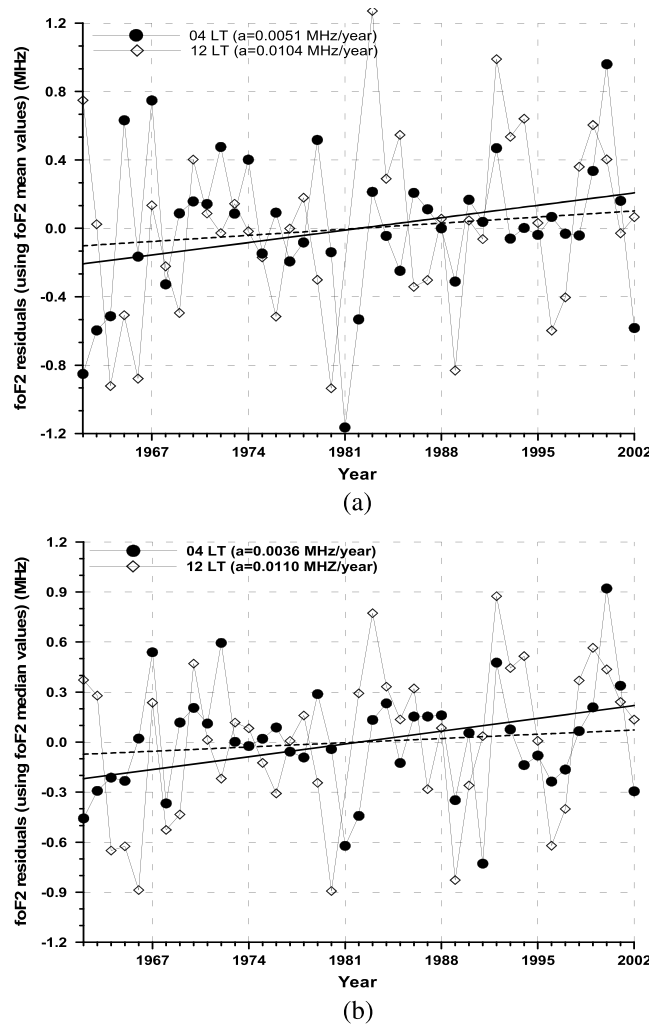


Figure 1. f_oF_2 residuals (MHz) at Phu Thuy (21.03°N, 105.96°E) obtained after filtering solar activity effect at 4 LT (filled circle) and 12 LT (empty lozenge) for (a) f_oF_2 annual mean considering only quiet days ($am < 20$) and (b) f_oF_2 annual mean assessed from monthly median data. Also shown are corresponding linear trends at 4 LT (dashed line) and 12 LT (solid line).

Table 1. f_oF_2 Trend Values for Phu Thuy (21.03°N, 105.96°E), for the Period 1962–2002, After Filtering Solar Activity Effect Through a Linear Regression With $F_{10.7}$, Estimating f_oF_2 Annual Values From Monthly Medians and From Monthly Mean of Quiet Days Only^a

Local Time	Trend Considering Annual f_oF_2 Mean of Monthly Median Values		Trend Considering Annual f_oF_2 Mean of Monthly Mean of Quiet Days	
	α (MHz/yr)	(%/yr)	α (MHz/yr)	(%/yr)
4	0.0036	0.07	0.0051	0.09
12	0.0110	0.09	0.0104	0.09

^aAbsolute trends, α (MHz/yr), and percentage trends, $(\alpha \times 100)/f_oF_{2\text{mean}}$ (%/yr).

of the Earth’s magnetic field, and the consequent dip equator displacement as possible “trend drivers”, taking into account that Phu Thuy, even though not under the region where the strongest effects of Earth’s magnetic field variations are occurring [Elias, 2009; Crossen and Richmond, 2008], it is under the EIA which is strongly controlled by the magnetic field and dip equator location.

3. Earth’s Magnetic Field Secular Variation

To explore the possibility of the Earth’s magnetic field as the main driver of f_oF_2 trends at Phu Thuy, the field at this location was estimated using the International Geomagnetic Reference Field, IGRF [Finlay et al., 2010]. Figure 2 shows its total intensity, F , and the magnetic inclination, I . Both, F and I , present an almost monotonic increase during the period of analysis.

The $\sin(I)\cos(I)$ factor, associated with the effects of neutral winds on h_mF_2 [Rishbeth, 1998], increases during the period considered as I does (see Figure 3). For midlatitudes the mechanism through which this factor affects the ionosphere peak height, h_mF_2 , and consequently f_oF_2 , is the following. 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 $U \cos(I)$. Then the vertical component, $U \sin(I)\cos(I)$, raises h_mF_2 during night and lowers it during day, resulting in an f_oF_2 increase at night or an f_oF_2 decrease during the day. So an increase in the $\sin(I)\cos(I)$ factor due to changes in I , as observed in Phu Thuy, would produce an additional lowering of the F region with a decrease in f_oF_2 during daytime (when U blows from equator to pole) and an additional rise of the region with an increase in f_oF_2 during the night (when U blows from pole to equator). A decrease in the $\sin(I)\cos(I)$ factor would produce the opposite effect.

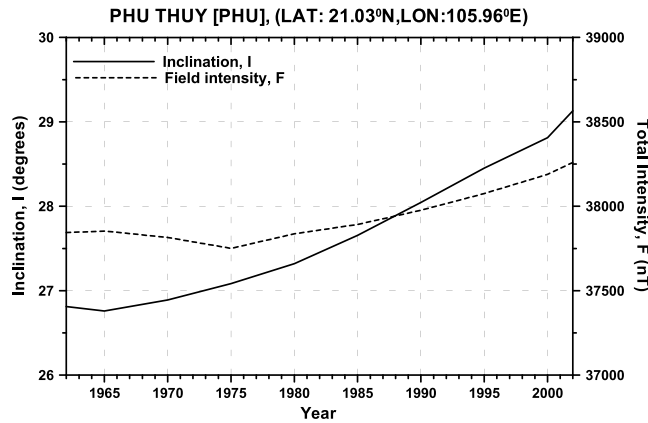


Figure 2. Inclination I in degrees (solid line) at 300 km height and total intensity of the Earth’s magnetic field, F , (dashed line) obtained from the International Geomagnetic Reference Field (IGRF) at Phu Thuy (21.03°N, 105.96°E).

netic field which makes the diffusion of the plasma mainly horizontal at the equatorial station. The vertical wind component is then small and so the trends of f_oF_2 and h_mF_2 should present a behavior like that of $\cos(D)\cos(I)$.

4. Secular Displacement of the EIA Latitudinal Profile

Secular variations of the Earth’s magnetic field also include the location of the magnetic equator (implicit in I variations), which is migrating with different directions and speed in different regions. For example, the maximum speed occurs at around 45° longitude, where the magnetic equator is moving northward, whereas it remains stable centered at 30°E, 120°E and 180°W, 80°W longitude, and is moving southward at around 80°E [Rangarajan, 1994; Rangarajan and Barreto, 2000]. This movement may affect equatorial ionospheric phenomena linked to the Earth magnetic field as it is the case of F_3 layer analyzed by Batista et al. [2002] and sporadic E layers studied by Abdu et al. [1996].

In our case, we consider that since the position of the trough and crests of the EIA depends on the magnetic equator location, then a movement of the magnetic equator should be followed by a movement of these positions, which in turn means changes in h_mF_2 and f_oF_2 . This should be an important factor at the location of Phu Thuy during 12 LT, located under the EIA northern crest. During 4 LT the EIA is almost absent, as already mentioned, so no effect of this phenomenon should be expected.

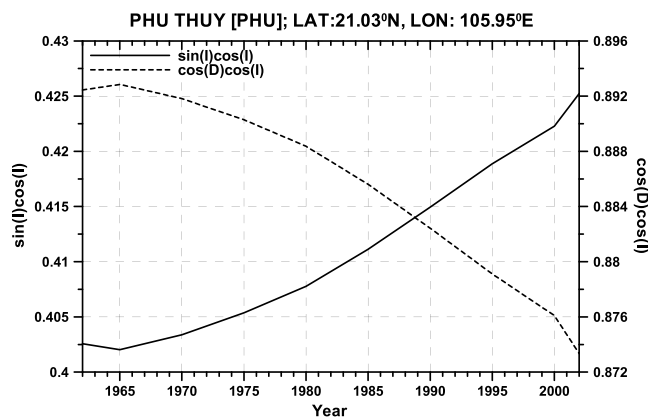


Figure 3. $\sin(I)\cos(I)$ factor (solid line) and $\cos(D)\cos(I)$ factor (dashed line). Inclination I and declination D obtained from the International Geomagnetic Reference Field (IGRF) at Phu Thuy (21.03°N, 105.96°E).

In the case of Phu Thuy, the increase observed in the $\sin(I)\cos(I)$ factor is expected to induce an f_oF_2 decrease during the day instead of the observed increase. Trend at 4 LT agrees qualitatively with the increase in the $\sin(I)\cos(I)$ factor.

If we consider the results of Yue et al. [2008] who conclude that at equatorial stations f_oF_2 follows the trend of $\cos(D)\cos(I)$, D being the magnetic declination, again a negative trend at midday should be expected according to the negative $\cos(D)\cos(I)$ trend observed at Phu Thuy (see Figure 3). Yue et al. [2008] argument is based on the configuration of the geomag-

The geographic location of the magnetic dip equator for the period 1956–2002 was obtained from the IGRF, considering the positions where the vertical component of B and I are zero. At the longitude of Phu Thuy, the dip equator presents a southward secular displacement of 0.026°/yr as can be noticed in Figure 4 which shows the time variation of the dip equator geographic latitude at the longitude of Phu Thuy.

To qualitatively assess the movement of the northern EIA crest, we calculated f_oF_2 at 12 LT for different latitudes at the geographic longitude of Phu Thuy with the International Reference

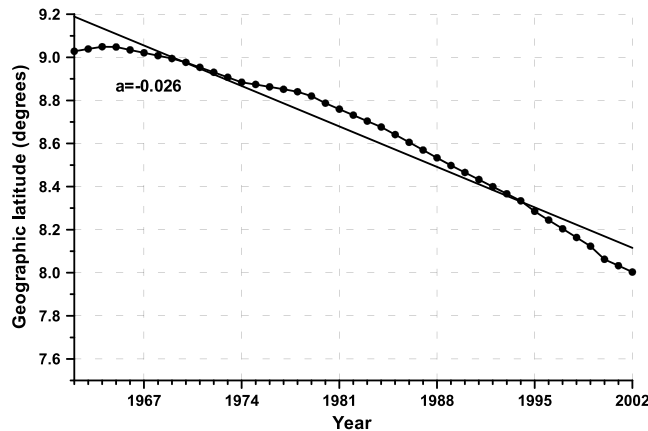


Figure 4. Variation of the geographic latitude of the dip equator (filled circle) at the geographic longitude of Phu Thuy station (105.96°E) together with its linear trend (solid line).

an increase in f_oF_2 during the period 1962–2002. Note that this trend value is not equal to the dip equator trend (~ -0.026). A reason could be that International Reference Ionosphere (IRI) model does not take completely into account the secular displacement of the dip equator, or the EIA latitudinal profile displacement does not behave as a “rigid body” as we assumed.

In order to obtain a rough estimation of the expected f_oF_2 increase at 12 LT at Phu Thuy, IRI2012 model f_oF_2 output for daily data was used. Monthly f_oF_2 values are calculated from these daily data, and then yearly mean f_oF_2 values are obtained from monthly mean ones. The yearly mean trend obtained is 0.0032 MHz/yr that corresponds to $\sim 0.027\%/yr$, one third of the value obtained with experimental data (shown in Table 1). In order to assess if it is greater enough to surpass the decreasing trend expected from the increase in the $\sin(l)\cos(l)$, the simple formula proposed by Elias [2009], valid for middle latitudes at noon, was used

$$\frac{\Delta f_oF_2}{f_oF_2} \approx 0.375 \frac{H \Delta [U_x \cos(D) \sin(l) \cos(l)]}{D_c} \quad (3)$$

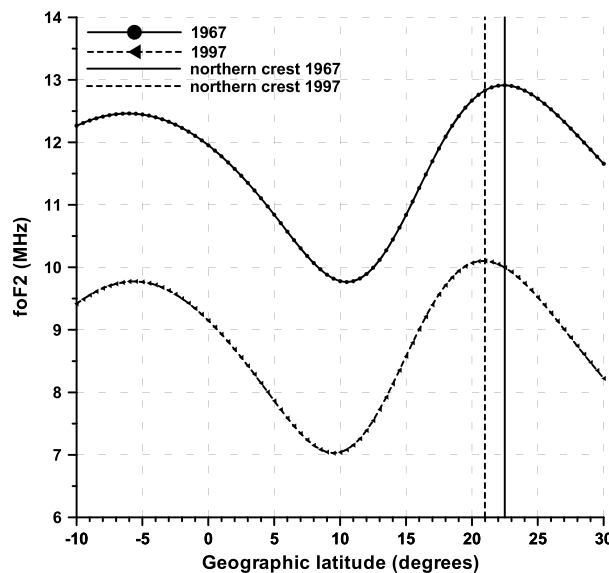


Figure 5. f_oF_2 latitudinal profile at the geographic longitude of Phu Thuy (105.96°E) obtained with International Reference Ionosphere model, IRI2012, in 1967 (filled circle) and 1997 (filled triangle) at 12 LT.

Ionosphere model, IRI2012, available at http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html [Bilitza et al., 2014]. Figure 5 shows the typical yearly mean f_oF_2 latitudinal profiles in 1967 and in 1997 at 12 LT at the geographic longitude of Phu Thuy (105.96°E) obtained with IRI2012.

Figure 6 presents the latitude of the northern crest assessed from annual f_oF_2 latitudinal profile calculated with IRI2012 at 12 LT, together with the latitudinal position of Phu Thuy. The linear trend of the northern crest latitude (dashed line) has a slope of ~ -0.014 which is approaching Phu Thuy. This approach should induce

where D_c is the plasma diffusion coefficient and depends on temperature and neutral density, H is the scale height of the ionizable constituent given by kT/mg , and U_x represents the meridional thermospheric neutral wind. The derivation of this equation is explained in detail in Elias and Ortiz de Adler [2006a, 2006b] and Elias [2009] and is valid for local time around noon. The required data of neutral components were obtained from the NRLMISISE-00 [Picone et al., 2002], and the meridional thermosphere wind was calculated from the HWM93 model [Hedin et al., 1996]. The mean percentage trend obtained for Phu Thuy, during 1962–2002, is $\sim -0.01\%/yr$.

Although it indicates a lower trend value than that expected from the movement of the dip equator, the

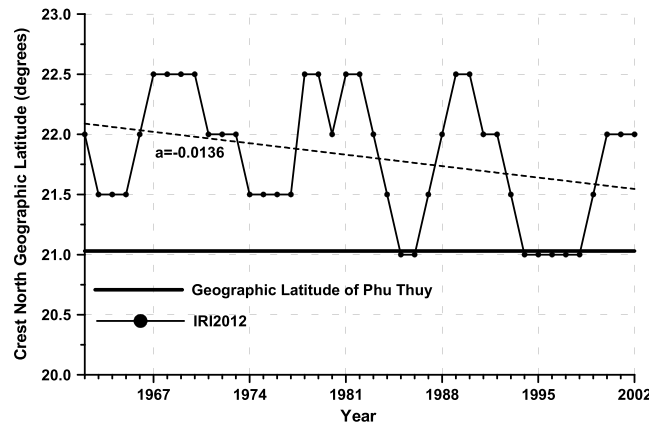


Figure 6. Latitude of the northern anomaly crest during 1962–2002 obtained with IRI2012 at the geographic longitude of Phu Thuy (105.96°E) at 12 LT. The black horizontal line indicates the geographic latitude of Phu Thuy. Slope of the linear approximation of the latitude of northern crest is -0.0136 (dashed line).

is qualitatively consistent with a decrease due to greenhouse gases increase, but of greater magnitude. Regarding the Earth’s magnetic field variation, on one side the $\sin(l)\cos(l)$ factor decreases during the whole period considered and should induce an f_oF_2 increase during the day instead of the observed decrease. On the other side, the dip equator is approaching Ouagadougou with a consequent f_oF_2 decrease due to the northward EIA displacement at this longitude. This mechanism would strengthen the greenhouse effect, as opposed to the situation of Phu Thuy where the greenhouse and EIA displacement have opposite effects.

In this same work, results of Huancayo (12.0°S, 284.7°E) and Phu Thuy obtained by *Upadhyay and Mahajan* [1998] and *Pham Thi Thu et al.* [2011], respectively, are also explained in terms of the EIA latitudinal profile displacement. Huancayo is in a similar geographic situation as Ouagadougou, being an equatorial ionospheric station north of the dip equator, but in the Southern Hemisphere. The dip equator is moving away from the station, so an increase in f_oF_2 should be expected. The 0.017 MHz/yr trend obtained by *Upadhyay and Mahajan* [1998] is then qualitatively in agreement with the displacement of the EIA trough, and also with the decrease of the $\sin(l)\cos(l)$ factor at the corresponding location.

In the case of Phu Thuy, *Pham Thi Thu et al.* [2011] obtain a positive 0.025 MHz/yr trend which is greater than the value obtained here due to the solar activity filtering is done using R_z as a solar proxy instead of $F_{10.7}$. There is an underestimation of EUV in the case of R_z during the maximum solar cycle 23, which systematically results in positive residuals after the filtering tilting the trend upward [*Elias et al.* 2014].

Elias and Ortiz de Adler [2006a] analyzed f_oF_2 at Tucuman (26.9°S, 65.4°W), which has a similar situation to that of Phu Thuy but in the EIA southern crest. They obtained a negative trend during daytime in agreement with the variation expected from the $\sin(l)\cos(l)$ factor increasing trend during the period 1957–1986. Effects due to the EIA displacement that should also be expected at this station would be almost null considering that the displacement of the EIA southern crest at the position of Tucuman obtained with IRI model consists of an approach followed by a departure.

Elias and Ortiz de Adler [2006b] analyzed three midlatitude to high-latitude stations: Argentine Islands (65.2°S, 64.3°W), Slough (51.5°N, 0.6°W), and Uppsala (59.8°N, 17.6°E), for the period 1957–1998, all of them distant from the EIA. For the first two stations an increase in the $\sin(l)\cos(l)$ factor is compatible with the mean decreasing f_oF_2 trends observed around noon. In the case of Uppsala, an f_oF_2 decrease is observed during noon, incompatible with a decreasing $\sin(l)\cos(l)$ factor at this station but qualitatively in agreement with the increasing CO_2 concentration. The nighttime behavior is in qualitative agreement with the $\sin(l)\cos(l)$ factor in the cases of Argentine Island and Uppsala. The decrease in the case of Slough could be attributed to CO_2 increase. We can notice that day and nighttime trends for the three stations can be explained in terms of greenhouse gases increase or $\sin(l)\cos(l)$ factor secular behavior, unlike the case of Phu Thuy.

difference is not significant to arrive to any conclusion. In addition, although both “theoretical trends” obtained agree in sign, with those expected from each process, both values are lower than the experimental trend, around 1 order of magnitude less.

5. Comparison With Other Trend Results

Gnabahou et al. [2013] analyzed annual f_oF_2 data, for 12 LT, measured at Ouagadougou (12.4°N, 358.5°E), a West African equatorial station, for the period 1966–1998. As in the case of Phu Thuy, this station is under the EIA effect. A 0.015 MHz/yr decreasing trend is obtained ($\sim 0.2\%$ /yr decrease), which

6. Conclusion

In the present work, we obtain an increasing f_oF_2 trend at Phu Thuy station at 4 LT and at 12 LT, which is not in agreement with the expected decrease for the increasing concentration of greenhouse gases. Geomagnetic activity as a trend factor has been discarded based on the similar trend values obtained using monthly median values and mean values during quiet days. The positive trend at 12 LT (~ 0.01 MHz/yr, which means a $\sim 0.1\%$ /yr) is in qualitative agreement with the expected increasing trend at Phu Thuy location due to the secular displacement of the EIA latitudinal pattern, following the dip equator secular movement. This would imply that the effect of the secular variation on the EIA due to the secular displacement of the dip equator may be strong enough at noon to counteract the negative effect expected due to the $\sin(I)\cos(I)$ factor increase. At 4 LT, the positive trend (~ 0.004 MHz/yr, which means 0.07% /yr) is in qualitative agreement with the increasing trend expected from the increase of the $\sin(I)\cos(I)$ factor at the corresponding location.

In an attempt to estimate theoretically both expected trend values, the IRI2012 model, which takes into account the secular displacement of the dip equator, and rough theoretical approximations were used. Even though we obtain agreements regarding trend's sign, the values obtained are not sufficient to corroborate our experimental results. The quantitative difference may be due to the models and approximations that we use do not consider the trends and variations expected in neutral concentration, winds, and temperature surely occurring as a consequence of the dip equator migration and the Earth's magnetic field variation. In fact, equation (3), for example, should be a self-consistent equation needing more complicated solution methods.

However, we sustain that at the location of Phu Thuy, the Earth magnetic field secular variation is the more likely forcing of the observed f_oF_2 trends.

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