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Possible Sources of Long-Term Variations in the Mid-Latitude Ionosphere

Ana G. Elias*

CONICET, Consejo Nacional de Investigaciones Cientificas y Tecnicas, Argentina

Universidad Nacional de Tucuman, Facultad de Ciencias Exactas y Tecnologia, Departamento de Fisica, Av. Independencia 1800, 4000 Tucumán, Argentina

Abstract: Trends in the upper atmosphere, together with the global warming of the lower atmosphere, are part of the global change of the Earth system. In the present work, which is focused in the upper atmosphere, long-term variations of the critical frequency of the ionospheric F2 layer, foF2, are studied in terms of the following possible causes: (1) long-term variations of the solar EUV radiation shown by the solar cycle length (SCL), (2) long-term variations in geomagnetic activity measured by the aa index, (3) the increasing greenhouse gases concentration in the lower atmosphere which would be producing a temperature decrease in the upper atmosphere, and (4) the Earth's main magnetic field secular variation, which implies changes in the dip angle (I) affecting the thermospheric neutral winds that move the conducting plasma of the ionosphere. For this purpose, foF2 time series of four mid-latitude stations were processed. After filtering the solar activity effect, the long-term variability of these time series and that of the mentioned possible trend sources, were analyzed. The study of trends in the upper atmosphere is an important contribution to one of the present focus of climate science that is the determination of the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants.

Keywords: Long-term trends, ionosphere, foF2, Solar cycle length, geomagnetic activity.

INTRODUCTION

Long-term changes in ionospheric parameters of time-scales longer than the 11 year solar activity cycle were analyzed by many authors that, after filtering the effects of solar activity, found long-term variations, or trends. These trends were attributed to solar EUV radiation changes [1, 2], geomagnetic activity variations [3-8], the increase of greenhouse gases concentration [9-14], and/or secular variations of the Earth's main magnetic field [15-19]. A description of these possible trend sources of the ionosphere is given in the following sections of the paper. Then, the data analysis is carried out using annual data of ionospheric F2 layer critical frequency, foF2, at 12 LT, together with solar and geomagnetic indices. Seasonal and diurnal variations will not be examined in the present paper. The last section includes the discussion and conclusions, stating the importance of atmosphere trend studies for the climate science.

SOLAR EUV RADIATION LONG-TERM VARIATION

The dependence of foF2 on solar EUV solar radiation is almost linear. It is well known the direct association of this ionospheric parameter to solar EUV proxies such as, the sunspot number, Rz, or the 10.7 cm solar flux, F10.7, with minor departures such as the saturation effect and the hysteresis [20-24].

*Address correspondence to this author at the Universidad Nacional de Tucuman, Facultad de Ciencias Exactas y Tecnologia, Departamento de Fisica, Av. Independencia 1800, 4000 Tucumán, Argentina; Tel: +54 381 4364093; Fax: +54 381 4364093; E-mails: anagelias@yahoo.com, aelias@herrera.unt.edu.ar

Friis-Christensen and Lassen [25] used SCL as a proxy of long-term total solar irradiance variations not shown by Rz or F10.7. Increasing SCL would correspond to decreasing solar irradiance and decreasing SCL, to increasing solar irradiance.

Adler *et al.* [1] argued that these variations shown by SCL should also appear in the solar radiation range responsible for ionization in the ionosphere, that is the EUV, so changes in the ionosphere related to SCL should also be seen. They found a close association between SCL and NmF2 after filtering the solar activity effect through Rz, and infer that SCL may provide also a measure of long-term EUV solar variability, but in this case increasing SCL would correspond to increasing EUV and decreasing SCL, to decreasing EUV. After this result SCL is used here as a proxy EUV trends not shown by common EUV indices (i.e. Rz and F10.7).

SCL is a parameter of long-term variation which has a periodicity of approximately 88 years that is the periodicity also observed in the magnitude of the maximum sunspot number named the Gleissberg period. The SCL series (see Fig. **1**) was obtained from Lassen and Friis-Christensen [26], and is available at http://web.dmi.dk/fsweb/solarterrestrial/sunclimate/SCL.txt. The assessment of the SCL time series is explained in Thejll and Lassen [27] and is briefly as follows:

SCL is assessed from the list of Rz. The cycle length is measured from minimum to subsequent minimum dates and also from maximum to subsequent maximum dates, resulting two lists of solar cycle duration. These measures are associated to the mid-cycle date. Following the procedure

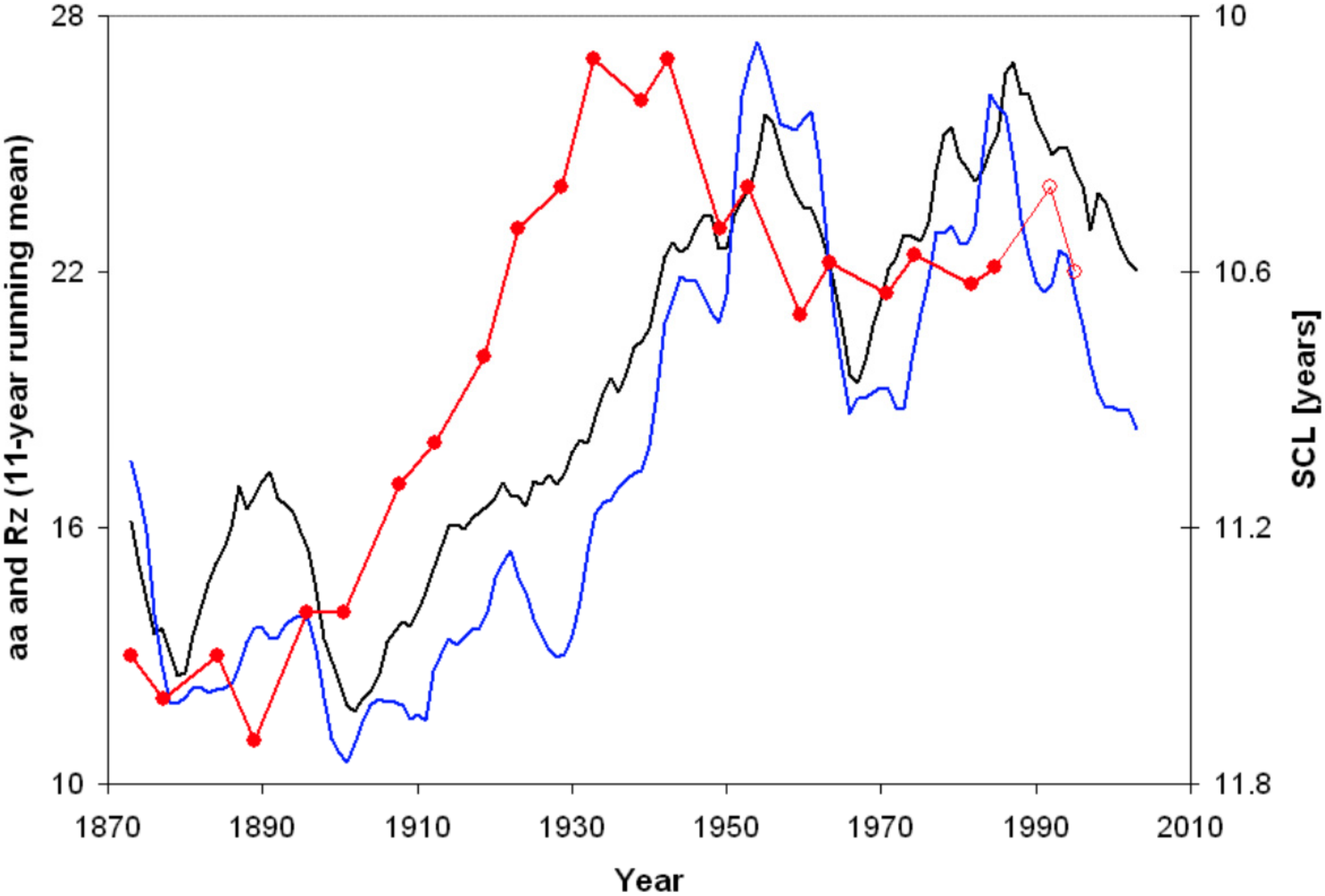

Fig. (1). Solar cycle length (SCL) in years after a 1-2-2-2-1 running mean (red line with solid circle – empty circles correspond to preliminary values), aa geomagnetic index after an 11-year running mean (black line) in nT, and Rz 11-year running mean (blue line) scaled to fit the aa axis.

introduced by Gleissberg [28] a 5-point filter is applied with the consecutive weights (1/8; 2/8; 2/8; 2/8 and 1/8) to each list of cycle lengths. This filter is usually referred to as the 12221 filter. Finally, the two lists of weighted cycle lengths are intercalated.

We choose this SCL record since, although different smoothing of SCL give different results, SCL determination by other methods [29-31], is in general good agreement with the record used here.

GEOMAGNETIC ACTIVITY LONG-TERM VARIATION

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 [32, 33]. The energy deposition produces also an equatorward circulation. When it coincides with the quiet-time circulation, the gas with depleted atom-to-molecule ratio is brought toward low latitudes and so the negative phase extends equatorward. At middle latitudes, the storm-induced circulation increases the plasma upward vertical drift in the F2 layer and so leads to an uplifting of the layer [34, 35]. At lower latitudes, sometimes, the downwelling of the circulation leads to an increase of the atomic oxygen concentration and so to an increase in electron density [35]. It should be expected then that increasing geomagnetic activity would produce an foF2 decrease at high latitudes, with a lesser effect towards lower latitudes, and even a reversal at low latitudes with an foF2 increase final effect.

As a geomagnetic activity index, aa is used in the present work. This is a global geomagnetic activity index which measures the disturbance level of the Earth's magnetic field, and it is derived by two approximately antipodal observatories, originally Greenwich and Melbourne. At present these are Hartland observatory in the UK and Canberra observatory in Australia. The index, in nT units, is available back to 1868 from http://www.wdcb.ru/stp/data/geomagni.ind/aa/ and also http://isgi.cetp.ipsl.fr/source/indices/.

An 11-year running mean was applied to the annual aa values in order to filter out short-term variations. As can be seen in Fig. (**1**), and focusing on the period of the ionospheric data here analyzed, geomagnetic activity increased during 1940-1955, followed by a decrease until the end of 1960's, then an increase until the middle 1980's, and has been decreasing since then. The long-term variation of aa is similar to that of Rz, and shifted around 10 years with respect to SCL, as can be seen in Fig. (**1**).

INCREASING GREENHOUSE GASES CONCENTRATION

The amount of greenhouse gases in the atmosphere, such as CO_2 and CH_4, has been increasing during the past few decades [36, 37]. Current modeling studies indicate that the upper atmosphere may be sensitive to this increase. Brasseur and Hitchman [38] used a two-dimensional numerical model of the stratosphere and found that the net effect of increasing greenhouse gases is a cooling of the entire stratosphere and lower mesosphere, between 20 and 60 km. Roble and Dickinson [39], with a global mean model of the mesosphere, thermosphere and ionosphere between 60 and 500 km, estimate a mesosphere and thermosphere cooling of 10 K and 50 K respectively as the CO_2 and CH_4 mixing ratios are doubled.

Compositional redistribution and ionospheric structure alterations also occur in association with changes in the temperature profile. Theoretical studies examining the consequences of increasing greenhouse gases for the ionosphere, coincide that the F2 layer peak height, hmF2, and foF2 should decrease [40, 41]. Particularly, the decrease estimated for foF2 [41] is 0.2 - 0.5 MHz for a doubling of CO2. Since the greenhouse gases increasing concentration consists of a monotonic upward trend, this hypothesis is checked experimentally estimating, after a proper filtering, the linear trend of the data,

SECULAR VARIATIONS OF THE EARTH'S MAIN MAGNETIC FIELD

The possibility of ionospheric trends induced by the Earth's magnetic field secular variations was first suggested by Foppiano *et al*. [15], and followed then by other papers [16-19]. In fact, Earth's magnetic field, generated in the Earth's core, presents long term variations in the field's strength and orientation [42, 43].

A simple mechanism through which trends in the Earth's magnetic field may affect the ionosphere is through changes in the dip angle (I) [15]. The sin(I)cos(I) factor, associated with the effects of neutral winds on hmF2 [33, 44, 45] 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 Ucos(I). The vertical component Usin(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.

Using simple theoretical considerations, and with the help of empirical models, the expected foF2 trends were assessed worldwide by Elias and Adler [16] and Elias [17]. The region of strongest variations of foF2, lies between 10ºN and 30ºS in latitude and between 20ºE and 80ºW in longitude, which is also the region of strongest changes in I and sin(I)cos(I) factor. At the mid-latitude zone, corresponding to the locations of the ionospheric stations here analyzed, the expected trends due to changes in I, is not statistically significant different from cero.

DATA ANALYSIS

The ionospheric parameter foF2 of four mid-latitude stations, listed in Table **1**, were analyzed. The data was obtained from the World Data Centre for Solar-Terrestrial Physics at the Rutherford Appleton Laboratory (http://www.wdc.rl.ac.uk).

The solar activity effect was filtered out estimating the foF2 residuals from the regression between the experimental values and solar activity measured through the sunspot number, Rz, that is

$$foF2_{res} = foF2_{exp} - (a\ Rz + b)$$

The suffixes exp and res mean experimental and residual respectively. a and b are the coefficients of the linear regression between $foF2_{exp}$ and Rz. A 5-year running was applied then to the annual foF2 residual series in order to filter out short-term variations, which still persist.

Fig. (**2**) shows $foF2_{res}$ together with SCL and aa 11-year running mean. The linear trend of $foF2_{res}$, also shown in the figure, is (-0.11 ± 0.04) MHz/year for Sodankyla, (-0.06 ± 0.03) MHz/year for Uppsala, and not statistically significant different from cero for Moscow and Ottawa.

The expected foF2 trend value due to CO_2 increase can be estimated by linearly interpolating the value assessed by Rishbeth [40] and Rishbeth and Roble [41] for a doubling of CO_2. For a ~20% increase in CO_2, which occurs for the period here analyzed, the theoretical decrease of foF2 due to greenhouse effect results then 0.001 - 0.003 MHz/year. To obtain values of this order with statistical significance, longer time series than those now available are needed. However, two of the four stations, Sodankyla and Uppsala, present foF2 significant decreasing trends but much stronger than those expected from the greenhouse gases effect.

Table 1. Geographic and Geomagnetic Coordinates of the Studied Ionospheric Stations, and Available Period of foF2 Data

Station	Geographic		Geomagnetic		Period of Data
	Latitude (N)	Longitude (E)	Latitude (N)	Longitude (E)	
Sodankyla	67.4	26.0	63.6	120.8	1958-89
Uppsala	59.8	17.6	58.3	106.9	1957-98
Moscow	55.5	37.3	50.4	123.2	1957-98
Ottawa	45.4	284.1	56.4	352.7	1957-95

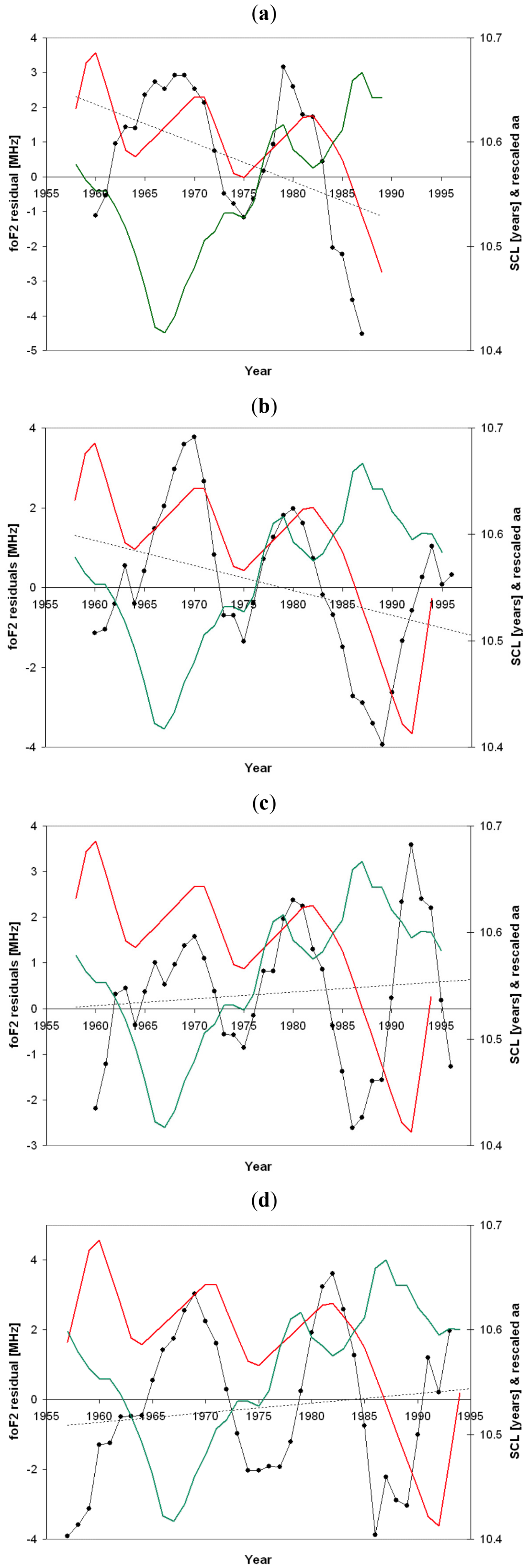

Fig. (2). SCL in years (red line), aa 11-year running mean (green line) rescaled to fit the SCL axis, foF2 residuals ($foF2_{res}$) in MHz after a 5-year running mean (black line with filled circle), and $foF2_{res}$ linear trend (dotted line) for (**a**) Sodankyla (67.4ºN, 26.6ºE), (**b**) Uppsala (59.8ºN, 17.6ºE), (**c**) Moscow (55.5ºN, 37.3ºE), and (**d**) Ottawa (45.4ºN, 284.1ºE).

Regarding the EUV long-term variation shown by SCL, an in-phase relation is apparent from Fig. (**2**), as shown by Adler *et al*. [1] for three other ionospheric stations. For Sodankyla and Uppsala, the correlation coefficient between $foF2_{res}$ and SCL is 0.52 and 0.56 respectively. However, for the other two stations, the correlation coefficient is only ~0.15.

In the case of geomagnetic activity, the expected anti-correlation is noticed from Fig. (**2**). The correlation coefficient between $foF2_{res}$ and aa 11-year running mean is -0.64 for Sodankyla and Uppsala, -0.45 for Ottawa, and -0.19 for Moscow. An explanation for the decrease of the correlation coefficient for decreasing latitudes may be that the strongest effects of geomagnetic storms are seen at higher latitudes.

DISCUSSION AND CONCLUSIONS

In this study, trends in the ionospheric parameter foF2 are analyzed, through the study of $foF2_{res}$ which consists in the deviations of the real data from a model which takes into account only the changes described by Rz. Four liable factors, leading to deviations from the model and to long-term variations, are changes in solar EUV not properly presented by Rz variations, long-term changes of geomagnetic activity resulting in long-term trends of aeronomical parameters, increasing greenhouse gases concentration leading to a cooling at ionosphere heights, and secular variations of the Earth's main magnetic field.

Rz, usually used in empirical ionospheric models, does not allow to completely eliminate the dependence of ionospheric parameters on solar activity. So it seemed reasonable to think of a remaining dependence on SCL as a proxy of solar activity variations not shown by Rz. However, from the cases here analyzed, any concluding remark was obtained regarding SCL. Probably the remaining effect of Rz on foF2 masks other variation patterns. In fact, the filtering process here applied to foF2, do not completely remove the Rz effect, as can be seen in Fig. (**3**) which shows $foF2_{res}$ and the annual Rz. Some decadal variation linked to the solar cycle is still present in $foF2_{res}$.

Regarding geomagnetic activity, according to Mikhailov and Marin [4] and other papers by Mikahailov and Danilov [3, 5-8], periods with negative and positive foF2 trends correspond to the periods of increasing or decreasing geomagnetic activity with the turning points around 1955, and the end of the 1960s and 1980s, where foF2 change their trend signs. This behavior is seen in all the stations here analyzed (see Fig. **2**). So, it can be concluded that geomagnetic activity trends do induce detectable trends in foF2. And the linear downward trend detected for two stations may be the result of the general increasing trend of aa.

With relation to greenhouse gases, many authors have estimated foF2 long-term trends for different ionospheric stations [3, 5, 8, 11-14]. They found a variety of different values ranging from -0.029 to 0.017 Mhz/year, and arrived to the conclusion that a change of greenhouse gases concentration is not sufficient to explain these different trends, which in addition are characterized by alternation of phases of decay and rise against the background of its general increase (or decrease). It seems that, in addition, the trend values depend on the estimation method, as stated by Jarvis *et al*. [46] and Lastovicka *et al*. [47]. From the data here analyzed, it can be said that Sodankyla and Uppsala, present foF2 decreasing trends in agreement, but much stronger, than trends expected from the greenhouse gases effect. Moscow and Ottawa do not present detectable trends, which does not contradicts the hypothesis of ionosphere trends induced by greenhouse gases. In fact, as already stated, the expected trends are really small and need much longer time series in order to be detected with a desirable statistical significance.

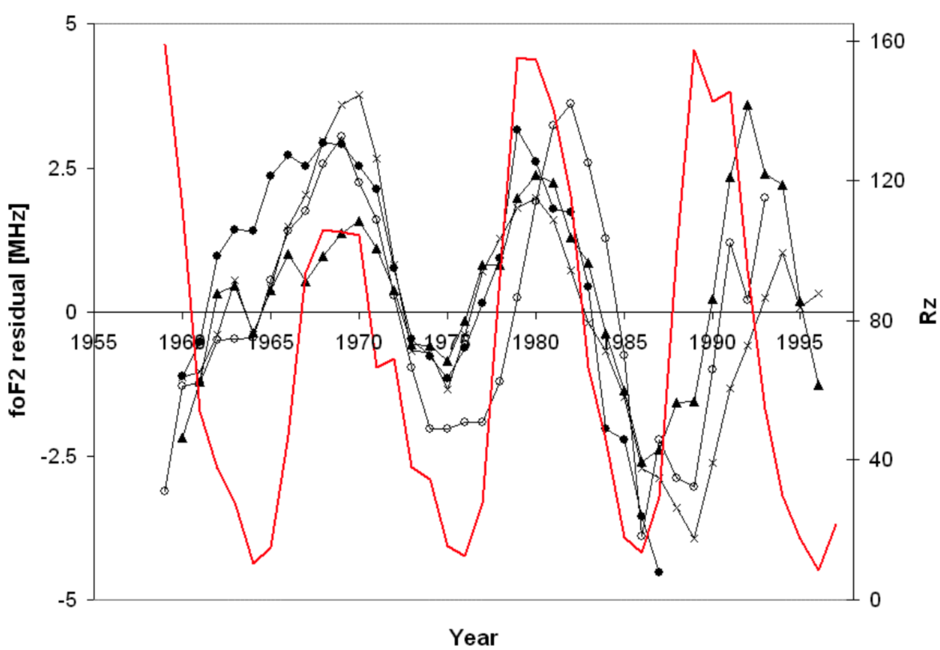

Fig. (3). foF2 residuals ($foF2_{res}$) in MHz after a 5-year running mean for Sodankyla (filled circle), Uppsala (cross), Moscow (filled triangle), and Ottawa (empty circle), together with the annual sunspot number, Rz (red line).

In conclusion, although the sources of long-term variations considered here are all capable of inducing ionospheric trends, any of them fully explain the observed trends in the experimental data considered. There might be other factors such as trends in thermospheric winds and neutral constituent variations affecting the ionosphere which were not considered. The subject of trends in the ionosphere is still under debate and there is not yet any agreement about the main mechanism responsible for the trends observed.

Why is it important to understand and measure the low, middle and upper atmosphere trends during the last decades? We live in the Earth and we want to understand and predict the atmosphere behavior which is essential for human life. And, in the present context, an understanding of the atmosphere variations is an essential focus of climate science, which is seeking to determine the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants [48].

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