Long-term trends of the F2-region at mid-latitudes in the Southern Hemisphere

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Abstract

The long-term variations in f_oF2 at Hobart (52.88°S, 147.32°E), Canberra (35.28°S, 149.13° E) and Christchurch (43.53°S, 172.64°E) stations, located in the mid-latitude zone in the Southern Hemisphere were analyzed using 1947-2006 years of the data. The saturation, solar and geomagnetic activity and seasonal effects were removed mainly by using 12-month running mean, linear and multiple regression (twofold regression) methods to find possible signatures of climate change in long-term trends in the f_oF2. The solar activity proxies, sunspot number, R_Z and F10.7 solar radio flux were used in regression to find the f_oF2 residuals at midday (12 LT) and midnight (00 LT) of the stations. The long-term trends obtained at 12 LT are more significant and consistent with the model results. The trends estimated with F10.7 solar flux are negative and the trends estimated with R_Z are positive (small and not significant). The f_oF2 decreased by 0.1–0.4 MHz for the 5 solar cycles period which could be mainly due to enhanced CO_2 in the troposphere that is cooling the upper atmosphere. Further research is needed to see if the f_oF2 trends are also affected by other factors such as thermospheric winds, neutral constituents, the secular variation of Earth's magnetic field, long-term changes in stratospheric ozone, solar and geomagnetic activities.

Keywords: Ionospheric f_oF2 trends, climate change, greenhouse gases, linear and multiple regression

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1. Introduction

Climate change is becoming evident on the Earth. The increase in sea level in Kiribati, Solomon Islands, Tuvalu, French Polynesia, Marshal Islands, Fiji and other South Pacific island countries (UNFCCC, 2017), the melting of the icebergs or reduction in glaciers, changes in rainfall patterns, and the increase in heat stored in oceans are all associated with climate change (MOE-NZ, 2018). The surface air temperature has increased in the 20th century by ~ 0.6 °C and this has mainly been initiated by an increase in the greenhouse gases (GHGs) concentration in the atmosphere (Solomon et al., 2007). This increase in GHGs concentration is considered to be primarily a factor responsible for the increase in global surface air temperature during the 20th century (Upadhyay and Mahajan, 1998). The changes in the various layers of the Earth's atmosphere may also be triggered by climate change. Roble and Dickinson (1989) did the first model calculations and suggested that the global warming of the Earth's lower atmosphere (troposphere), due to long-term increase in GHGs concentrations, would result in the cooling of the upper atmosphere starting from 50 km by infrared radiative cooling mainly by CO_2. This effect of GHGs has been referred to as "greenhouse cooling" (Manoff, 2009; Chilingar et al., 2008; Goessling and Bathiany, 2016). Rishbeth and Roble (1992) studied the cooling effect of the upper atmosphere by the GHGs (CO_2 and CH_4) and found that if CO_2 and CH_4 will double by mid-21st century, then this will cause global greenhouse cooling of the upper atmosphere. Due to this cooling effect, they predicted that the thermospheric temperature will be lowered by 30 to 40 kelvin (K), the air density will be reduced by 20 to 40% at heights between 200 to 300 km, critical frequency of F2-region (f_oF2) will decrease slightly by 0.5 MHz by mid-21st century and the virtual height (h_mF2) will be lowered by 10-20 km per century. The long-term changes and trends in the ionosphere can also confirm that the GHGs like, CO_2, CH_4 and NO_2 have increased over the decades by analyzing the f_oF2 data (Bremer et al., 2004). Throughout the 20th century, solar and geomagnetic activities have increased significantly and this could also affect the long-term trends in the ionosphere (Lastovicka et al., 2006). Hence, both anthropogenic, as well as solar and geomagnetic activities, could be responsible for long term trends in the ionosphere. Lastovicka et al. (2012) revealed that GHGs, mainly CO_2 was a primary factor responsible for the long-term trends of the ionosphere and the upper atmosphere.

The long-term trend in the ionospheric F2-region with different solar activity indices was studied by Mielich and Bremer (2013) using more than 100 ionosonde stations from Northern and Southern Hemispheric regions to find out the best solar index for long-term trend analysis in the f_oF2 and h_mF2 due to increasing greenhouse effect. The authors found that the F10.7 was a better solar activity index for trend estimation when compared with the sunspot number (R_Z). Several researchers have found that F10.7 is a better proxy over R_Z for removing the solar activity effects (e.g., Upadhyay and Mahajan, 1998; Danilov and Mikhailov, 1998; Mikhailov and Marin, 2000; Danilov, 2002; Danilov, 2003; Bremer et al., 2004; Yue et al., 2006; Lastovicka et al., 2006; Elias, 2011; Xian et al., 2012; Mielich and Bremer, 2013; Elias et al., 2014; Elias, 2014; Gordiyenko et al., 2014; Ogawa et al., 2014; Danilov and Konstantinova, 2015; Perna and Pezzopane, 2016; Thu et al., 2016). F10.7 reduces the error in trend analysis with similar or little uncertainty when compared with R_Z (Mielich and Bremer, 2013; Laštovička et al., 2014). Lastovicka and Jelinek (2019) reported that F10.7 describes 98% of the total variance of f_oF2. The authors also concluded that to find reliable long term trends for the upper atmosphere, adequately longer series of data must be used. For the11 year solar cycle, the f_oF2 would vary for the rising and falling parts with a fixed solar activity level which is termed as hysteresis effect (Huang, 1963; Rao and Rao, 1969; Elias, 2014). Hysteresis effect can play an important role in the long term ionospheric trends or time-series analysis as reported by many authors (Rao and Rao, 1969; Marin et al., 2001; Mikhailov and Marin, 2001; Adler and Elias, 2008). To avoid the hysteresis effect, Marin et al. (2001) and Mikhailov and Marin (2001) used only the ionospheric data around the solar maxima and minima to estimate the f_oF2 long term trends.

In this study, we present the long-term trends in the F2-region ionosphere, mainly in the critical frequency of F2-region (f_oF2) for the three stations; Hobart, Canberra and Christchurch, located in the mid-latitude zone in the Southern Hemisphere. The long-term trends for these three stations will be estimated and compared with the modeled results of (Roble and Dickinson, 1989; Rishbeth, 1990; Rishbeth and Roble, 1992) using F10.7 in the simple linear and multiple regression methods. The noise at wavelength, λ = 10.7 cm known as F10.7 will be used in the regression analysis for removing the solar activity effect from the raw f_oF2 data. The sunspot number, R_Z and F10.7 are both solar activity proxies, however, after performing the student's t-test and z-test to find the better solar proxy, it was found that F10.7 was a better solar proxy over R_Z. The data analysis and trend estimation will be done for 2 separate local times for all the stations at midday (12 LT) and midnight (00 LT).

2. Data and Analysis

Monthly mean values of f_oF2 at 12 LT and 00 LT were used from the three stations namely, Hobart (52.88° S, 147.32° E), Canberra (35.28° S, 149.13° E) and Christchurch

(43.53° S, 172.64° E). The ionospheric data were obtained from Damboldt and Suessmann (2012) database (ftp://ftp-out.sws.bom.gov.au/wdc/iondata/medians /Damboldt/). The solar activity index used in this study is the solar flux, F10.7 (taken from ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/monthly_ averages/solflux_monthly_average.txt). To remove the geomagnetic effects, the *Ap*-index was used which was obtained from ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES /KP_AP/MONTHLY.FMT and ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/ INDICES/KP_AP .

The methodology used to determine the long-term trend in the F2-layer is very important because a minor or small error can give an insignificant or statically inconclusive long-term trend. The method used by some researchers (e.g. Bremer et al., 2004; Mielich and Bremer, 2013; Elias, 2014) was very clear as a detailed explanation was provided. We have used a similar methodology for long-term trend analysis by filtering the f_oF2 data. Similar methods have been used by several other researchers (e.g. Danilov and Mikhailov, 1998; Upadhyay and Mahajan, 1998; Danilov, 2002; Danilov, 2003; Bremer et al., 2004; Adler and Elias, 2008; Xian et al., 2012; Elias et al., 2014; Danilov and Konstantinova, 2015; Thu et al., 2016). The effects that were filtered from the input data were solar and geomagnetic activity effects, saturation and seasonal effects. Then using the linear regression least-square methods and multiple regression method, the long-term trend in f_oF2 was estimated.

The first step was to remove the seasonal effect present in the monthly mean f_oF2 data. However, for this research, we have also removed the seasonal effect in F10.7 and *Ap*-index monthly mean data. The seasonal effect is removed by applying 12-month running mean to f_oF2, F10.7 and *Ap*-index. The 12-month running mean reduces the data by 6 months in the beginning and by 6 months in the end. The second step was to remove the solar activity effect by using linear regression to obtain the residual using the similar relation used by (Bremer et al., 2004; Mielich and Bremer, 2013; Elias, 2014),

$$f_o\mathrm{F2}_{res} = f_o\mathrm{F2}_{exp} - f_o\mathrm{F2}_{mod} \quad (1)$$

Where $f_o\mathrm{F2}_{res}$ is the f_oF2 residual, $f_o\mathrm{F2}_{exp}$ is the experimental monthly mean f_oF2 values or the measured f_oF2 values. The $f_o\mathrm{F2}_{mod}$ is the modeled value obtained from the linear correlation between f_oF2 and the F10.7. The $f_o\mathrm{F2}_{mod}$ is obtained from the similar relations used by several researchers (e.g., Bremer et al., 2004; Mielich and Bremer, 2013; Elias, 2014),

$$f_oF2_{mod} = a + b\,F10.7_{12} \quad (2)$$

Where $F10.7_{12}$ is the 12-month running solar activity index and *a*, *b* are the correlation coefficients or regression constants which can be obtained from least-square methods.

The third step was to find the f_oF2 residual and adjust it with the time to obtain the long-term trend using the equation given by (Bremer et al., 2004; Mielich and Bremer, 2013; Elias, 2014),

$$f_oF2_{res} = xk + y \quad (3)$$

Where *x* and *y* are the regression constants and *k* is the trend in MHz/year which we are interested in. The fourth step was to remove the geomagnetic activity effect from the f_oF2 data. This was removed using the *Ap*-index in the multiple regression equation. A similar methodology and use of *Ap*-index were carried by some authors (e.g., Bremer, 1992; Mikhailov and Marin, 2000; Mielich and Bremer, 2013). The residual was found using equation (1) and the modeled f_oF2 was obtained using a similar equation given by (Bremer, 1992; Bremer et al., 2004; Mielich and Bremer, 2013),

$$f_oF2_{mod} = a + bF10.7_{12} + cAp_{12} \quad (4)$$

Where Ap_{12} is the 12-month running mean values of *Ap*-index and *c* is the regression constant.

Then using equation (3), the long-term trend in f_oF2 was determined. The saturation effect was removed by eliminating the values of F10.7 that do not exceed a certain value. When the results will be discussed, the clear method of removing the saturation effect will be addressed. Moreover, the solar proxy, sunspot number, R_Z or F10.7 to be used in this study was also confirmed statistically using the student's *t*-test formula by calculating the statistical *t* value using,

$$t = \frac{k}{\sigma} = \frac{k}{\frac{k}{\sqrt{n-1}}\sqrt{\frac{1}{y^2}-1}} = y\,\frac{\sqrt{n-2}}{\sqrt{1-y^2}} \quad (5)$$

Where σ is the standard deviation and *k* is the long-term trend, *y* is the correlation coefficient of regression between f_oF2 residual and duration of period and *n* is the years of data used.

Z-test was also carried out to compare a large amount of data using,

$$Z = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \quad (6)$$

Where, $\bar{x}_1$ and $\bar{x}_2$ are the mean of sample 1 and mean of sample 2, respectively. σ_1 and σ_2 are the standard deviation of sample 1 and sample 2, respectively. The n_1 and n_2 are the size of sample 1 and sample 2, respectively.

Using the student's *t*-test value of 1.96 and the statistical *t* value obtained using equation (5) was tested for its significance level for a better solar proxy. Another factor considered in long-term trend analysis was the duration of the data used. The longer the duration of the data, the better the trend estimation will be (Mielich and Bremer, 2013; Elias, 2014; Lastovicka and Jelinek, 2019). Hence, we have used around 55 to 60 years (more than 5 solar cycles) data for a better trend estimation in this study. The period before 1947 was not considered because the F10.7 data was only available from 1947 onwards. Moreover, using the student's *t*-test and *z*-test it was confirmed that F10.7 is a better solar activity index over R_Z for removing the solar activity effect from the long-term trends in f_oF2. Also, the analysis was done with and without saturation effects so that the regression, r^2 value was close to 1.0 or 100 %.

3. Results

3.1 Identification of Better Solar Proxy

A student's *t*-test was carried out using the formula (5) to compare which solar activity proxy was better to use in f_oF2 trend analysis. The null hypothesis was set that there is a difference between the F10.7 and R_Z data and F10.7 is better than R_Z for solar activity proxy using the significance level probability (*p*-value) of 0.05. The results of the test for both F10.7 and R_Z are given in Table 1. The null hypothesis was accepted if the *p*-value for the two-tail test was greater than 0.05 otherwise it was rejected. The *p*-value obtained was 0.99 which is much greater than 0.05, hence, we accept the null hypothesis. The residuals of f_oF2 with F10.7–*Ap*-index and R_Z – *Ap*-index for 12 LT were also tested using *t*-test and the results are given in Table 1. From this test, it is shown that the *p*-value is 0.0000087 which is much smaller than 0.05, hence, we reject our null hypothesis. Accepting the null hypothesis indicates that F10.7 is a better solar proxy than R_Z and rejecting the null means that there is no statistical difference in the F10.7 and R_Z data, if *Ap*-index is included in the regression analysis. *Z*-test was also carried out to compare a large amount of data using equation 6. The f_oF2 residuals with F10.7 and R_Z as indicators of solar activities and f_oF2 residuals using F10.7 and R_Z with *Ap*-index as an indicator of geomagnetic activities were carried out to know whether the two sets of data are statistically different and if F10.7 is better when compared with R_Z. The results from the *z*-test are given in Table 2 using the significance level at $p = 0.05$. The null hypothesis and the data samples used for the *z*-test were the same as *t*-test statistics.

After performing both the tests, it was shown that the f_oF2 residuals with F10.7 and R_Z have a *p*-value greater than 0.05 or 99.8 % significant, hence, the null hypothesis was accepted in both the statistical tests. However, if the *Ap*-index is introduced in the regression analysis along with F10.7 and R_Z for long-term trend estimation, then both the tests indicated that there should not be any statistical difference in their results, hence, the null hypothesis was rejected for both cases. Accepting the null hypothesis indicated that F10.7 is a better solar proxy indicator over the sunspot number, R_Z.

3.2 Long term f_oF2 trend at Hobart

The Hobart ionosonde station is located in the southern mid-latitude zone at the location 52.88° S, 147.32° E. The F10.7 was used as a main solar activity index in removing the solar activity effects from the f_oF2 data. The local time of Hobart is LT = UT + 10 hrs. The data used at 00 LT and 12 LT were from 1947 till 2006, however, there were some data gaps or the f_oF2 monthly data missing from the ionosonde station which were not included in the analysis. Also for the same months, the F10.7 and *Ap*-index were also removed for consistency in data analysis. Fig. 1(a-d) shows f_oF2 long-term trends estimation using F10.7, *Ap*-index and without removing the saturation effects at 00 LT for Hobart station. Panels a and b show the scatter plot of f_oF2 versus F10.7 solar flux and *Ap*-index, respectively. From the plots in panels a and b, it was clear that f_oF2 increases with the increase both in F10.7 and *Ap*-index, which gave a positive ionospheric effect of both solar and geomagnetic activities on f_oF2. From panel a, when the value of F10.7 reached 210, there was no increase in f_oF2 which showed the saturation in f_oF2 with F10.7 cm solar flux. The r^2 value was 0.9606 which around 98.0% correlation (r =0.9801) with f_oF2 and F10.7. The r^2 is the goodness to-fit-measure of the data for linear regression (Reisinger, 1997). The higher the r^2 value, the better the residuals will be (Jim, 2018). The saturation in f_oF2 against the *Ap*-index is marked in panel b, which shows that f_oF2 gets saturated for *Ap* ≥ 25. To filter the effects of solar activity (F10.7), the residuals in f_oF2 (f_oF2res) using equation (1) in which modeled f_oF2 was included using equation (3) is shown in Fig. 1(c). The long-term trend estimated using F10.7 was obtained as –0.004 MHz/year indicating that f_oF2 decreased by 0.23 MHz for the 57 years as shown in panel c. In panel d, the effect of both solar activity (F10.7) and geomagnetic activity (*Ap*) have been filtered by using the modeled f_oF2 equation (4) in equation (1). The long-term f_oF2 trend is obtained as –0.0013 MHz per year when the effects of both, solar and magnetic activities were removed. This was equivalent to a decrease in f_oF2 by 0.07 MHz for the 57 years. The f_oF2 data for F10.7 ≥ 210 and *Ap* ≥ 25 were not considered to remove the saturation effect from further analysis.

The same analysis as done for Fig. 1 was done using the equations (1) – (4) after removing the saturation effect and the results are shown in Fig. 2(a-d). The *Ap* < 25 was used in scatter plot and regression analysis which was considered to classify geomagnetic quiet days (Rangarajan and Barreto, 2000; NOAA, 2011), whereas, *Ap* < 20 has also been considered to classify geomagnetically quiet days (ISGI, 2013; Pham et al. 2016) which can be used for our future studies. After removing the saturation from F10.7 solar flux, the trend in f_oF2 was obtained as –0.0051 MHz per year or 0.08 MHz decrease for 56 years as shown in panel c whereas, the trend in f_oF2 residual with the F10.7 and *Ap*-index after removing the saturation effect was obtained as –0.004 MHz per year as shown in panel d. This also means that the f_oF2 decreased by 0.22 MHz for 56 years. Similar analysis as done for Fig. 1 was done using the equations (1) – (4) at 12 LT of the Hobart station. Initially, the analysis was done without removing the saturation effect in f_oF2 against F10.7 and *Ap*-index, results of which are shown in Fig. 3(a-d). Panels a and b shows the scatter plot of F10.7 solar flux and *Ap*-index and both the proxies increased along with f_oF2 portraying a positive solar and geomagnetic effect on the ionosphere. As the values of F10.7 reached 210, there was no increase in f_oF2 and the correlation between F10.7 and f_oF2 reduced indicating saturation had reached as marked in Fig. 3, panel a. The residual including saturation and the solar flux was analyzed and the trend was obtained as –0.0052 MHz per year which was a decrease in f_oF2 by 0.3 MHz for the 57 years as shown in panel c. The second residual was analysed including F10.7 and *Ap*-index and the trend was obtained as –0.0017 MHz per year indicating a decrease in f_oF2 by 0.09 MHz for the 57 years as shown in panel d. After removing the saturation effects and using F10.7 ≥ 210 and *Ap*-index ≥ 25, the results are shown in Fig. 4(a-d). The trend in f_oF2 obtained with F10.7 residual was –0.007 MHz per year and the trend obtained when *Ap*-index was included was found –0.0056 MHz per year as shown in panels c and d, respectively. This indicated that the f_oF2 decreased by 0.4 MHz and if the *Ap*-index was used in the regression then it decreased by 0.3 MHz for the 57 years.

3.3 Long term f_oF2 trend at Canberra

The geomagnetic location of Canberra station is at 35.28° S, 149.13° E, and the local time of Canberra is LT = UT + 10 hrs. The f_oF2 data was used during 1947-2006 for the analysis and data gaps for 00 LT and 12 LT were removed. The data for F10.7 and *Ap*-index were also removed for the months the f_oF2 was missing for consistency in data analysis. The 12–month running mean was calculated for f_oF2, F10.7, and *Ap*-index which was then used for long-term trend estimation at this station. However, the *Ap*-index was included in the data analysis so that the trends in f_oF2 with and without the *Ap*-index were compared even though the trend with *Ap*-index does not give a desirable trend as discussed in the literature.

Fig. 5(a-e) shows the long-term trends in f_oF2 at midnight (00 LT) for Canberra station. The panels a-c show the scatter plots of f_oF2 versus F10.7 and *Ap*-index which indicates that there was a positive effect of solar and geomagnetic activities on the F2-region ionosphere. The contribution of solar and magnetic activities on the long-term trends had been removed using F10.7 and *Ap*-index, respectively. The r^2 for f_oF2 against F10.7 at 00 LT without removing the saturation effect was obtained as 0.9556 as shown in panel a. After removing the saturation effects, which occurred at F10.7 < 217, the r^2 became 0.9604 which was around a 0.5% increase in the correlation between f_oF2 and F10.7 as shown in panel b. The long-term trend using the F10.7 solar flux in the regression was obtained as –0.0026 MHz per year which means that f_oF2 decreased by 0.15 MHz for the 59 years as shown in panel d. However, using the F10.7 and *Ap*-index in the regression gave the long-term trend as –0.0002 MHz per year as shown in panel e which seems to be very small. The long-term trend in f_oF2 at midday (12 LT) is shown in Fig. 6(a-e). The r^2 without removing the saturation effect was 0.9622 and after removing the saturation by eliminating the F10.7 values > 210, r^2 comes out to be 0.9701 which was around a 0.8% increase in the correlation between f_oF2 and F10.7 as shown in panels a and b, respectively. Panel c shows the regression between *Ap*-index < 25 and f_oF2 where the linear regression coefficients were used to find the residual and long-term trend. The long-term trend using F10.7 solar flux was obtained as –0.0072 MHz per year as shown in panel d. This trend indicates that the f_oF2 decreased by 0.42 MHz for the 59 years studied for this station. Also, the long-term trend using F10.7 and *Ap*-index obtained is –0.0032 MHz per year as shown in panel e, indicating f_oF2 decreased by 0.19 MHz for the 59 years.

3.4 Long term f_oF2 trend at Christchurch

The geomagnetic location of the ionosonde station in Christchurch is 50.25° S and the local time of Christchurch is UT + 11 hrs. This station started operating in 1937 and was closed in 2011. Fig. 7(a-e) shows the long-term trends in f_oF2 at midnight (00 LT) for Christchurch station. The solar and magnetic activity contribution to the long-term trends has been removed using F10.7 and *Ap*-index, respectively. The r^2 for the regression between F10.7 and f_oF2 without removing the saturation was 0.9461 as shown in panel a and the r^2 for the regression between F10.7 and f_oF2 after removing the saturation effects caused by the F10.7 values > 209 was estimated as 0.9595 shown in panel b. Removing the saturation improves and increases the correlation between F10.7 and f_oF2 by 1.35%. Panel c shows that there was a positive effect on the F2-region ionosphere due to the geomagnetic activity, however, the correlation was very poor. The long-term trend using F10.7 solar flux was obtained as –0.0026 MHz per year indicating that f_oF2 decreased by 0.14 MHz for the 52 years as shown in panel d. The long-term trend using the f_oF2 residual obtained with F10.7 and *Ap*-index was –0.0004 MHz per year as shown in panel e. This indicated that the f_oF2 decreased by 0.02 MHz for the 52 years.

The long-term trend in f_oF2 for midday (12 LT) is shown in Fig. 8(a-e). The analysis conducted at 12 LT gave an r^2 value of 0.9647 without removing the saturation effect and after removing the F10.7 values > 217, the r^2 value improved to 0.9759 as shown in panels a and b, respectively. There was an approximately 1.1 % increase in regression value, r^2, indicating that the correlation between F10.7 and f_oF2 improved by 1.1 % after removing the saturation effects. The scatter plot of *Ap*-index versus f_oF2 is also shown in panel c. This scatter indicates that both the parameters increased positively, however, the correlation between them was poor because the r^2 was very low (0.0819). The long-term trend using the f_oF2 residual estimated with F10.7 solar flux was –0.007 MHz per year indicating that f_oF2 decreased by 0.36 MHz for the 52 years as shown in panel d. The trend estimated with F10.7 and *Ap*-index was obtained as –0.0016 MHz per year as shown in panel e. This trend indicates that f_oF2 decreased by 0.08 MHz for the 52 years studied.

A summary of f_oF2 long-term trends analysis at 00 LT (midnight) and 12 LT (midday) for all three stations (Hobart, Canberra and Christchurch) after removing the saturation effects and solar activity using F10.7 and geomagnetic activity using *Ap*-index is given in Table 3. From Table 3, it can be stated that the trend at 12 LT is more significant and desirable when compared with the trend at 00 LT estimated using F10.7. However, the trend in f_oF2 estimated using F10.7 and *Ap*-index at 12 LT and 00 LT did not give a significant trend. The trends −0.0002 MHz per year and −0.0004 MHz per year of Canberra and Christchurch, respectively, are very small, hence, *Ap*-index makes the trend statistically less significant. Also, the average decreasing rate in f_oF2 estimated using the mean long-term trends of Hobart, Canberra and Christchurch show a decrease between 0.1–0.4 MHz for more than 5 solar cycles data used in this study. This decreasing rate is possible if we use F10.7 solar flux in the regression models. However, if we include *Ap*-index in the regression models the f_oF2 decreasing rate becomes 0.08–0.2 MHz for 5 solar cycles.

4. Discussion

The f_oF2 long-term trend analysis in F2–layer ionosphere is one of the critical tasks of the upper atmosphere. The ionosphere is constantly affected by solar and geomagnetic activity, hence, to know the exact variations in the ionosphere due to climate change or anthropogenic activities, we have to remove any contributions of solar and geomagnetic activities from the long-term trend analysis of the ionosphere. The observed F10.7 solar flux values were used instead of the adjusted F10.7 values for the trend analysis (Lastovicka et al., 2008). The null hypothesis for the *t*-test and *z*-test was that F10.7 solar flux is a better solar activity proxy than sunspot number, R_Z. After performing the tests, the null hypothesis was accepted indicating that F10.7 is a better solar activity proxy. A similar test was performed by (Lastovicka et al., 2006; Mielich and Bremer, 2013; Elias, 2014) and found that F10.7 was better. The model trend results were obtained by Roble and Dickinson (1989); Rishbeth (1990); Rishbeth and Roble (1992) where the authors stated that by the middle of the 21st century, the greenhouse gases like CO_2 and CH_4 will double in the lower atmosphere and due to this the upper atmosphere will cool, hence, the f_oF2 will decrease by 0.2–0.5 MHz due to CO_2 doubling. Similar results have been obtained in this research where the f_oF2 was estimated to decrease by 0.1–0.4 MHz if F10.7 was used and 0.08–0.2 MHz if F10.7 with *Ap*-index were used in trend analysis as shown in Table 3. Using *Ap*-index in the regression analysis with F10.7 will not give a significant trend as it merely contaminates the regression results or it does not remove the solar and geomagnetic activity effects from the data (Bremer, 1992; Mikhailov and Marin, 2000; Mikhailov et al., 2002). The trends estimated with *Ap*-index are very small and of no practical importance statistically, in determining whether the ionosphere is affected by greenhouse gases or anthropogenic activities as shown in Table 3. Similar small trends were obtained by Mikhailov et al. (2002) where the authors have used *Ap*-index and stated that it did not remove the geomagnetic effects and it affected the trend analysis because the correlation between *Ap*-index and f_oF2 was very poor.

The trends at 12 LT with removed saturation effects are more significant when compared with the trends at 00 LT. The daytime trend slope is large and significant when compared with the nighttime trend because the electron density at night reduces by 25% when compared with the electron density in the daytime (Sharma et al., 1999). The trends estimated using F10.7 for this study are similar to the long-term trends obtained by (Mikhailov et al., 2002; Yue et al., 2006; Khaitov et al., 2012; Mielich and Bremer, 2013; Cnossen and Franzke, 2014; Gordiyenko et al., 2014; Elias et al., 2014; Danilov, 2015). The summary of their trends is given in Table 4. All these authors obtained significant negative long-term trends, whereas, the trend obtained by Mikhailov et al. (2002) was –0.00086 MHz per year which is very small because the authors used *Ap*-index in the regression model and removing the *Ap*-index from the regression model makes the trend significant (Mikhailov, 2006). Similar small trends are obtained for Canberra and Christchurch stations at 00 LT using *Ap*-index in the regression model as shown in Table 4.

Most of the authors used F10.7 to derive the long-term trends including Danilov (2015), where the author analyzed two different duration of data from Canberra station and estimated the long-term trend in f_oF2. Trends estimated using a longer duration of data are small when compared with the trends estimated using 1-2 solar cycles data as shown by Danilov (2015). The trend obtained by Cnossen and Franzke (2014) for the Hobart station is the same as the trend obtained in our study as shown in Tables 3 and 4, respectively. Mielich and Bremer (2013) compared their results with the model results and stated that the trends derived from the short duration of data series cannot be explained by the increasing greenhouse effects as it could have been affected by the thermospheric density reduction, solar and geomagnetic activities. The long-term trends are negative because of thermospheric cooling and a decrease in oxygen atom concentration in the thermosphere (Mikhailov et al., 2002: Danilov, 2015) or a decrease in thermospheric densities (Rishbeth and Roble, 1992) due to an increase in CO_2 concentrations. Qian et al. (2009) indicated that doubling of CO_2 will give a 40% reduction in the ionospheric maximum electron density (N_mF2) trend which results in f_oF2 decease by 0.008–0.009 MHz as also reported by Elias et al. (2014), where they concluded that the negative trend was mainly due to the anthropogenic means. Perrone and Mikhailov (2016) stated that the mid-latitude F2-layer was mainly controlled by geomagnetic activities which included the thermospheric winds and neutral compositions, hence, for 00 LT and 12 LT times, the authors obtained a negative long-term trend in f_oF2 and f_oF1. Recently, Cai et al (2019) using the electron density data for low and middle latitude stations obtained from Defense Meteorological Satellite Program satellites at 18

MLT found a mean trend with magnitude ranging from ~ – 2% to ~2% per decade, with clear seasonal, latitude and longitude variations. Our results for Hobart, Canberra and Christchurch at 00 LT without *Ap*-index are consistent with the trends obtained by the authors given in Table 4, except for the trends obtained by Mikhailov et al. (2002) which are similar to the trends obtained for Canberra and Christchurch at 00 LT when F10.7 and *Ap*-index were both used in the regression analysis were obtained as –0.0002 MHz per year and –0.0004 MHz per year, respectively. These trends are not statistically significant. The trends obtained at 12 LT for three stations for our study are –0.007 MHz per year when F10.7 was used and similar trends were obtained by Cnossen and Franzke (2014) and Khaitov et al. (2012). The results found by Mikhailov et al. (2002) indicated that the daytime (noon) trends are larger and significant when compared with the nighttime trends.

Lastovicka et al. (2006) reported that the long-term trends in the 20th century are predominantly because of geomagnetic and solar activities and the current trends are due to greenhouse effects. The authors also stated that the negative trends are due to changes in thermospheric densities. Lastovicka et al. (2006) did not conclude what was the main cause or drivers of long-term trends in f_oF2. The authors stated that they do not have enough information to decide whether the trends were due to global warming (greenhouse effects) giving thermospheric cooling or chemical contaminations from space vehicles, solar or geomagnetic effects.

Cnossen and Richmond (2008) studied the effects of changes in the Earth's magnetic field on the h_mF2 and f_oF2 parameters from 1957 to 1997 using the NCAR Thermosphere–Ionosphere–Electrodynamics General Circulation Model. They found substantial changes in the long-term trends of h_mF2 and f_oF2 over the Atlantic Ocean and South America, which they accounted for the changes in the Earth's magnetic field. Pham et al. (2016) studied the long-term variation of f_oF2 at Phu Thuy (21.03°N, 105.96°E) station in Vietnam 04 LT and 12 LT for the period 1962–2002 and reported that the secular variation of Earth's magnetic field inclination was responsible for the long-term trend in f_oF2 at 04 LT when equatorial ionization anomaly was absent. Mikhailov and Perrone (2018) used 5 solar cycle data (1958–2017) from European stations to find the long-term trends in h_mF2, f_oF1 and f_oF2. The authors found negative and latitudinal dependent trends in the ionospheric *F*1 and *F*2 regions which they attributed to a decrease in the ion drag. Also, they reported that there was a long-term decrease in solar and geomagnetic activity, hence, the ionospheric trends can also be attributed to a decrease in auroral heating. The negative trends derived in our study can mostly be due to enhanced CO_2 in the atmosphere and the cooling of the upper atmosphere when compared with the model results and the results of Bremer et al. (2004). Humans are one of the major contributors to releasing CO_2 through deforestation, burning forest and fossil fuels, and land-use changes. The release of CO_2 has to be minimized because it appears to be affecting our upper atmosphere and the most useful layer, the ionosphere. However, ionospheric long term trends still remain a challenging problem due to several different nature drivers of the trends with increasing concentration of CO2 being the main driver. Other drivers of the change include solar and geomagnetic activity, secular change in the Earth's main magnetic field, long-term changes in stratospheric ozone concentration and long term changes in atmospheric wave activity (Qian et al., 2011; Lastovicka et al., 2012; Kutiev et al., 2013). It would be interesting to examine how the ionosphere would respond if the current unprecedented low solar activity continues for further solar cycles (Courtillot et al., 2021).

5. Conclusions

The long-term trends of the f_oF2 for the F2-layer have been analyzed for the three mid-latitude stations in the Southern Hemisphere and the main findings of the study are summarised as follows:

- Removing seasonal, saturation, solar, and geomagnetic activity effects from the data helps in obtaining well-defined long-term trends, however, the hysteresis effect must also be considered.
- F10.7 is a better solar activity proxy when compared with the sunspot number, R_Z.
- The long-term trends of f_oF2 at midday (12 LT) are more significant when compared with the trends at midnight (00 LT) which can be due to the high electron density in the daytime ionosphere.
- The trends estimated for Hobart, Canberra and Christchurch using F10.7 solar flux at 12 LT is −0.007 MHz per year and is significant and comparable with other studies, whereas the trends at 00 LT for all three stations differ and are less significant but are comparable with the other studies.
- Using *Ap*-index in the regression model does not give a desirable trend and does not entirely remove the geomagnetic effects because the correlation between *Ap*-index and f_oF2 is very poor.
- The f_oF2 decreases by 0.1–0.4 MHz if F10.7 is used in trend analysis and 0.08–0.2 MHz if F10.7 and *Ap*-index are both used in regression models for the 5 solar cycles data.

- The long-term trends obtained for this study indicate that they could be mainly due to enhanced CO_2 in the troposphere that is cooling the upper atmosphere. The long-term trend in the F2-layer is still under discussion since there is no clear agreement about the main drivers of the trends. However, further research is needed to see how the f_oF2 is affected by the thermospheric winds, neutral constituents, the secular variation of Earth's magnetic field, long term changes in stratospheric ozone concentration, atmospheric wave activity and solar and geomagnetic activities.

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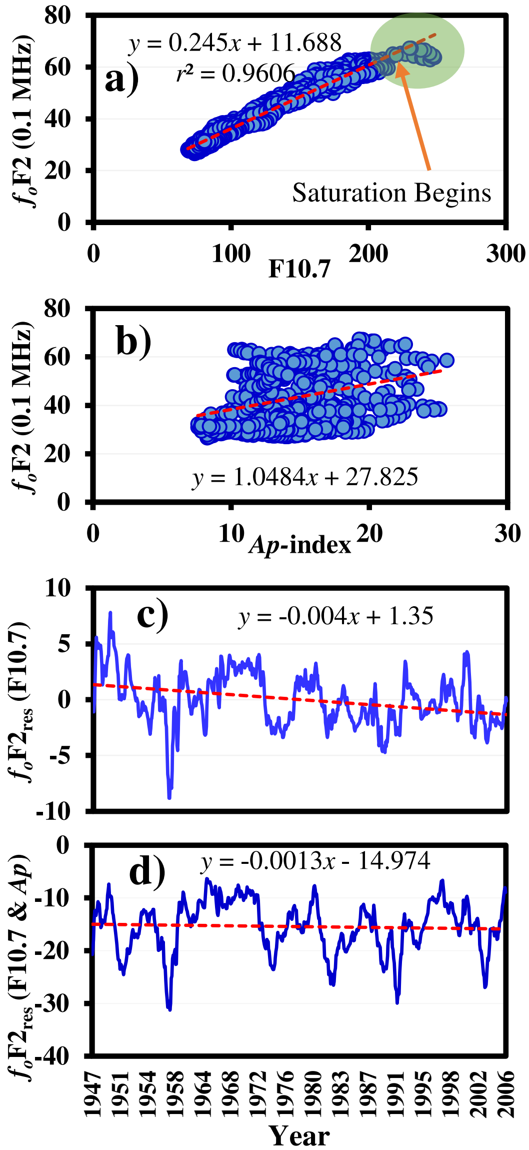

Fig. 1: The f_oF2 long-term trend estimation using F10.7 and *Ap*-index without removing the saturation effects at 00 LT for Hobart station. a) f_oF2 vs F10.7, b) f_oF2 vs *Ap*-index, c) f_oF2 residual (F10.7) vs time (year), d) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

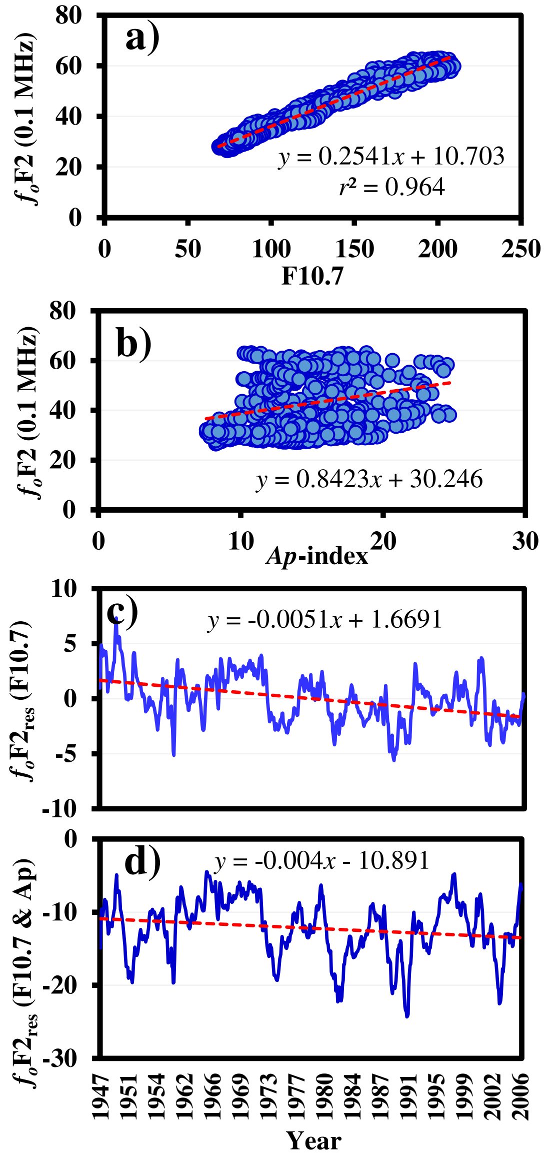

Fig. 2: The f_oF2 long-term trend estimation using F10.7 and *Ap*-index after removing the saturation effects at 00 LT for Hobart station. a) f_oF2 vs F10.7, b) f_oF2 vs *Ap*-index, c) f_oF2 residual (F10.7) vs time (year), d) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

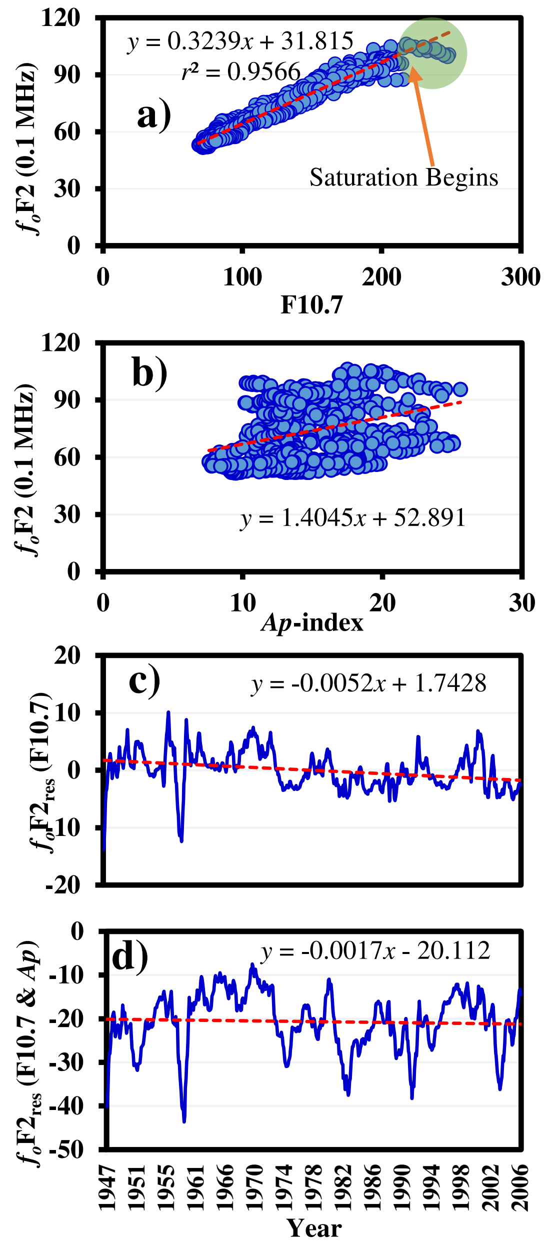

Fig. 3: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index without removing the saturation effects at 12 LT for Hobart station. a) f_oF2 vs F10.7, b) f_oF2 vs *Ap*-index, c) f_oF2 residual (F10.7) vs time (year), d) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

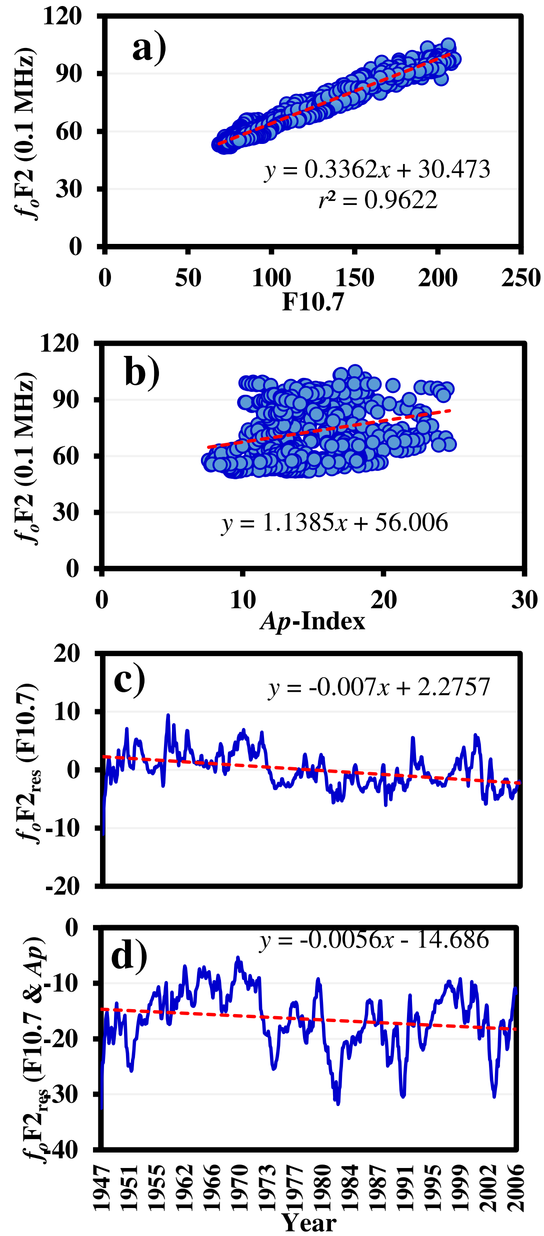

Fig. 4: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index after removing the saturation effects at 12 LT for Hobart station. a) f_oF2 vs F10.7, b) f_oF2 vs *Ap*-index, c) f_oF2 residual (F10.7) vs time (year), d) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

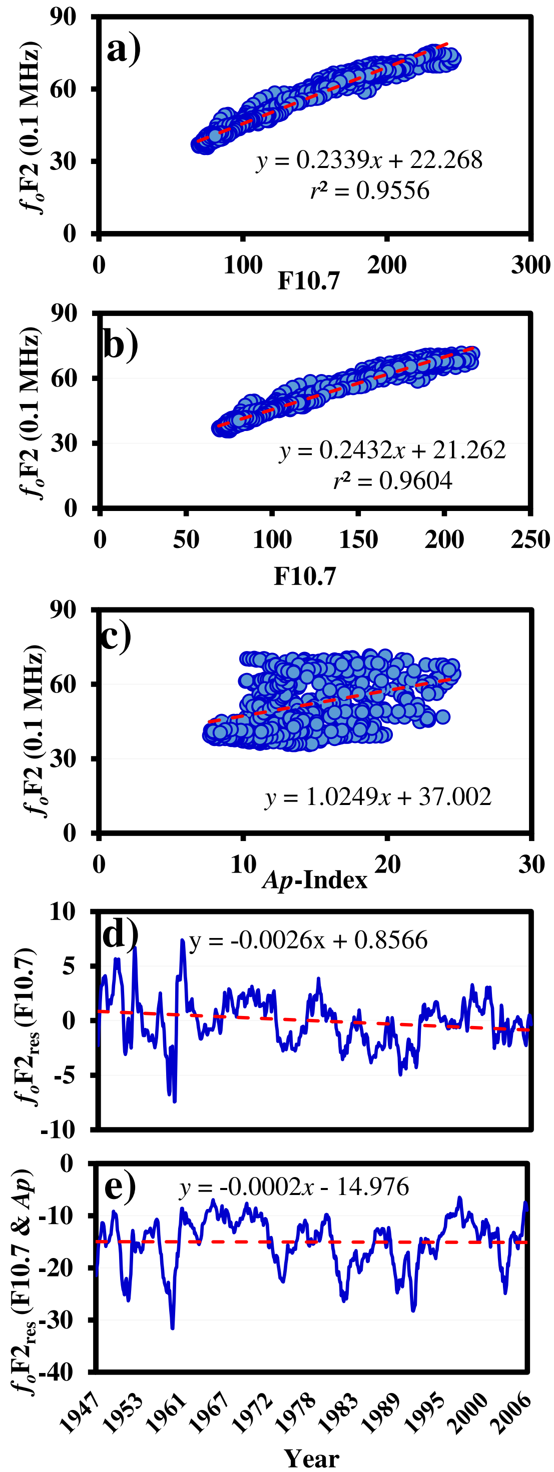

Fig. 5: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index at 00 LT for Canberra station. a) f_oF2 vs F10.7, b) f_oF2 vs F10.7 < 217, c) f_oF2 vs *Ap*-index < 25, d) f_oF2 residual (F10.7) vs time (year), e) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

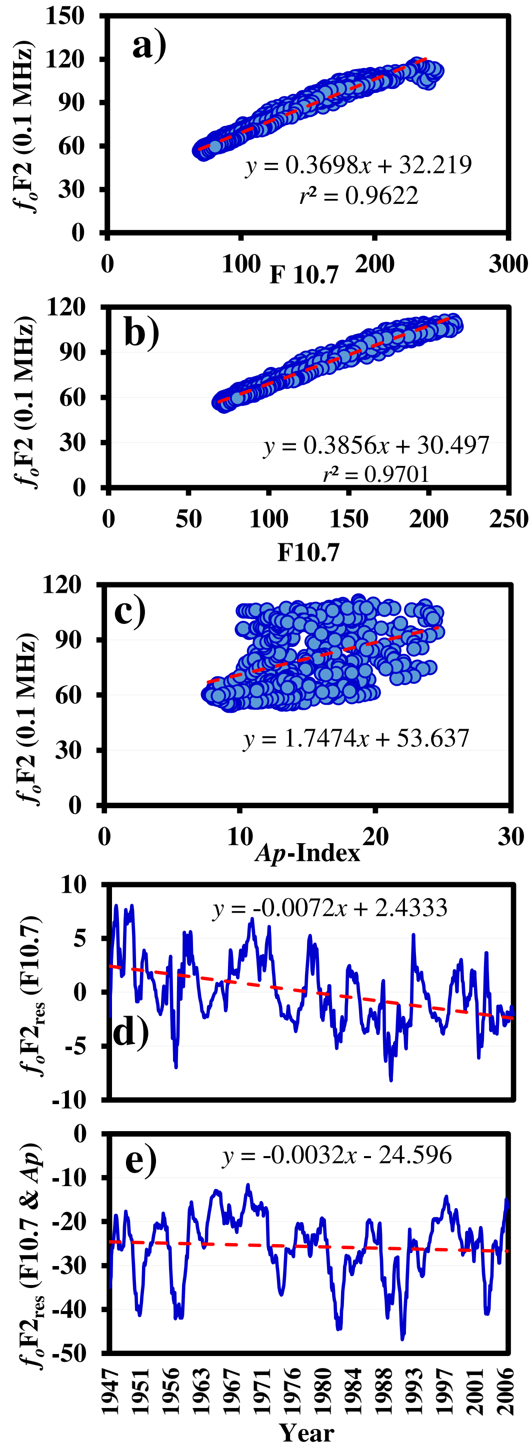

Fig. 6: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index at 12 LT for Canberra station. a) f_oF2 vs F10.7, b) f_oF2 vs F10.7 < 220, c) f_oF2 vs *Ap*-index < 25, d) f_oF2 residual (F10.7) vs time (year), e) f_oF2 residual (F10.7 & *Ap*-index) vs time (year).

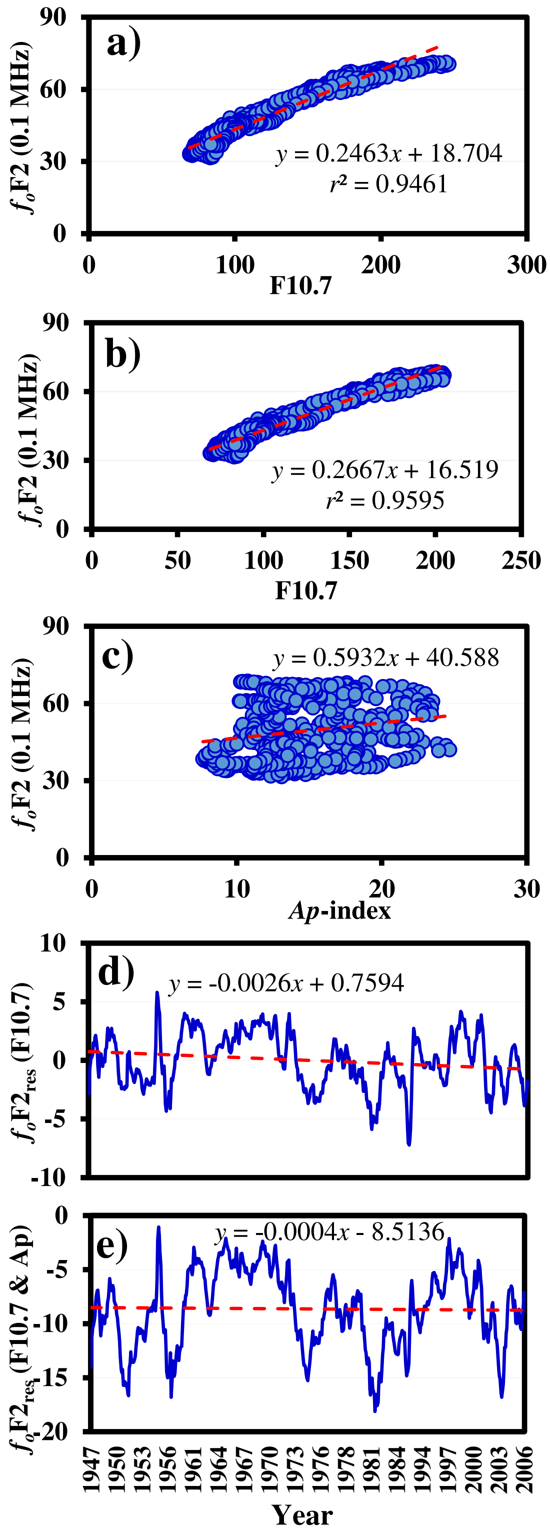

Fig. 7: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index at 00 LT for Christchurch station. a) f_oF2 vs F10.7, b) f_oF2 vs F10.7 < 209, c) f_oF2 vs *Ap*-index < 25, d) f_oF2residual (F10.7) vs time (year), e) f_oF2residual (F10.7 & *Ap*-index) vs time (year).

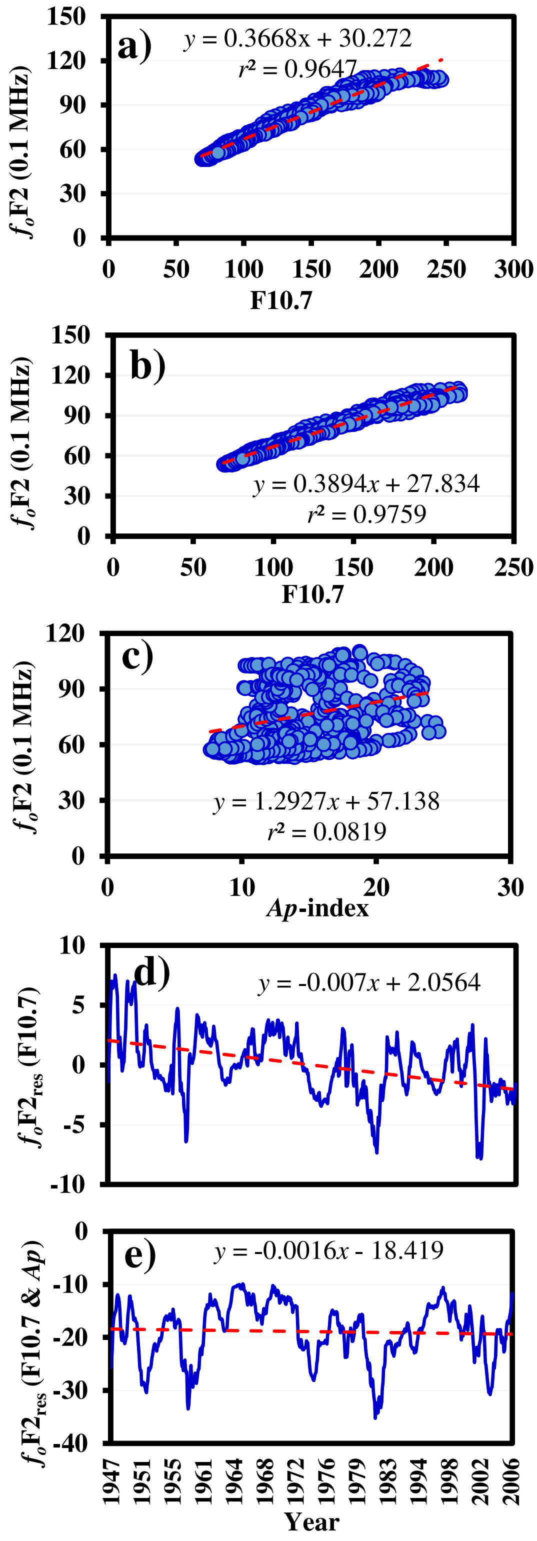

Fig. 8: The f_oF2 long-term trends estimation using F10.7 and *Ap*-index at 12 LT for Christchurch station. a) f_oF2 vs F10.7, b) f_oF2 vs F10.7 < 217, c) f_oF2 vs *Ap*-index < 25, d) f_oF2residual (F10.7) vs time (year), e) f_oF2residual (F10.7 & *Ap*-index) vs time (year).

Table 1: Student's *t*-test performed with f_oF2 residuals using F10.7 and R_Z as solar activity indicators and *Ap*-index assuming unequal variance at 12 LT for Hobart station**.**

	Residual (F10.7)	Residual (R_Z)	Residual (F10.7 with *Ap*-index)	Residual (R_Z with *Ap*-index)
Mean	-0.002552374	-0.002233739	-16.48396756	-17.8769586
Variance	8.622134382	8.957208603	28.76136856	34.73140194
Observations	647	657	647	657
Hypothesized Mean Difference	0		0	
df	1302		1294	
t Stat	-0.001940592		4.465332934	
P(T<=t) one-tail	0.499225965		4.34549E-06	
t Critical one-tail	1.646024795		1.646032041	
P(T<=t) two-tail	**0.99845193**		**8.69097E-06**	
t Critical two-tail	1.961787672		1.961798957	

Table 2: *Z*-test performed for f_oF2 residuals using F10.7 and R_Z as solar activity indicators and *Ap*-index assuming unequal variance at 12 LT for Hobart station**.**

	Residual (F10.7)	Residual (R_Z)	Residual (F10.7 with *Ap*-index)	Residual (R_Z with *Ap*-index)
Mean	-0.002552374	-0.002233739	-16.48396756	-17.8769586
Known Variance	8.622134832	8.957208603	28.76136856	34.73140194
Observations	647	657	647	657
Hypothesized Mean Difference	0		0	
z	-0.001940592		4.465332934	
P(Z<=z) one-tail	0.499225816		3.99722E-06	
z Critical one-tail	1.644853627		1.644853627	
P(Z<=z) two-tail	**0.998451632**		**7.99443E-06**	
z Critical two-tail	1.959963985		1.959963985	

Table 3: Summary of f_oF2 long-term trends for Hobart, Canberra and Christchurch stations at 00 LT and 12 LT using the solar activity index, F10.7 and geomagnetic activity index, *Ap*-index.

Station	Long-term trends at 00 LT in MHz per year using;		Long-term trends at 12 LT in MHz per year using;	
	F10.7	F10.7 and *Ap*-index	F10.7	F10.7 and *Ap*-index
Hobart	−0.0051	−0.004	−0.007	−0.0056
Canberra	−0.0026	−0.0002	−0.007	−0.0032
Christchurch	−0.0026	−0.0004	−0.007	−0.0016
Average f_oF2 decreasing rate	−0.1	−0.08	−0.4	−0.2

Table 4: Summary of f_oF2 long-term trends of various authors given in MHz per year.

Authors/Journals	Duration of data used	Long-term trend in MHz per year
Danilov (2015)	1985-2009	−0.047 for Canberra station
	1958-2009	−0.004 for Canberra station
Gordiyenko et al. (2014)	1957-2012	−0.0038
Elias et al. (2014)	1964-1994	−0.018 to −0.009
	1964-2008	−0.004 to −0.003
Cnossen and Franzke (2014)	1960-2005	−0.007 for Hobart Station
Mielich and Bremer (2013)	1948-2009	−0.003 to 0.0038
Khaitov et al. (2012)	1937-2011	−0.008 to −0.014
Yue et al. (2006)	1948-2005	−0.005
Mikhailov et al. (2002)	1971-1999	−0.00086