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SOLAR FLUX PROXIES AND MID LATITUDE IONOSPHERE

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ABSTRACT

Attempt has been made to compare the behaviour of ionosphere during the low and high activity of solar cycle 23. At the same time we have also studied the association of ionospheric behaviour with the solar radiation fluxes. We have selected a Japanese mid latitude station, Okinawa (26.3N, 127.8E) and taken the critical frequency of F2 layer (foF2) derived from ionosonde observations to compare the variability of ionosphere during low activity (2007) and high activity period (2003) of solar cycle 23. It was found that the values of foF2 were low during 2007 and extremely high during 2003, showing that ionospheric activity has a direct relationship with the solar activity. Three solar proxies namely F10.7 cm, EUV flux (26-34nm) and X-ray flux (1-8Å) have been considered and probed the association of $foF2_{2003}$ and $foF2_{2007}$ with these solar proxies. We found that EUV flux and X-ray flux correlate with the $foF2_{2003}$ and $foF2_{2007}$ much better than F10.7cm, during both the phases of the cycle. Therefore it is concluded that EUV and X-ray Flux are better solar proxies than F10.7 which have been widely used in previous studies. Moreover, the correlation of both fluxes (EUV and X-ray) is stronger with $foF2_{2003}$ than with $foF2_{2007}$.

KEYWORDS: Ionosphere, Solar Flux, Solar Proxies.

The ionosphere of earth is produced by the ionization of neutral atoms by the ultraviolet, extreme ultraviolet and X-rays of solar origin. These solar radiations undergo significant variations with the changes in the long term changes in the solar activity. Therefore, long term changes in these radiations cause the significant temporal variations in the ionosphere. Various researchers have observed that the ionosphere behaves differently during different solar epochs (Özgüe *et al*., 2008; Liu *et al*., 2011). Solar cycle variations of solar activity appear repeatedly, but vary from cycle to cycle (Chen *et al*., 2011).

The solar EUV radiations are known to follow the well defined solar cycle variations which significant changes in the ionosphere as reflected by the behaviour of various ionospheric parameters like electron density, critical frequency etc. As the observations of EUV and X-ray flux were not available during the early years of ionospheric research, the solar activity variations of ionosphere were studied by using some indirect proxies like sunspot number (Rz) or radio flux (F 10.7). Sunspot number and solar F10.7 cm radio flux were the most commonly used proxies for solar activity (Bilitza, 2000). The solar radio flux at 10.7cm (a proxy of the EUV radiation) is observed to follow the same variation pattern as of the sunspot number.

The studies carried out in the past have examined the solar activity variations of the ionosphere (Adler *et al*., 1997; Balan *et al*., 1994, 1996; Bilitza, 2000; Kane, 1992, 2003; Kouris *et al*., 1998; Liu *et al*., 2003, 2006; Richards, 2001; Richards *et al.,* 1994; Rishbeth, 1993; Sethi *et al*., 2002). These studies have found a strong control of solar activity variations on the ionospheric parameters like critical frequency of F2 layer (foF2), the peak electron density of the F region (NmF2), and the total electron content (TEC). These relations also pointed out some interesting features in the behaviour of ionospheric parameters with solar activity. In some of these studies the relation of monthly median values of foF2 and NmF2 with the smoothed sunspot number and F10.7 cm flux were explored. A linear relationship was found to exist between monthly median values of foF2 or NmF2 with sunspot number and F 10.7. However, this relation exists only for low values of sunspot number or F 10.7 and saturation occurs for high values. The saturation effect does not occur for monthly median values of foF2 or NmF2 but also with TEC (Balan *et al*, 1994) several reasons have been proposed for this saturation effect. According to Balan *et al*, (1994) it appears due to the non linear relation of EUV with F10.7. Subsequently, as they examined the relation of foF2 with EUV flux, they found the saturation effect does not exist (Balan *et al*. 1996). Later the saturation effect was also detected for the EUV flux also (Liu *et al*., 2003), which is thought to be caused by equatorial fountain effect and pre-reversal enhancements.

Moreover, the daily noon-time values of NmF2 or foF2 were found to exhibit either weak or no correlation with F10.7cm during a relatively short period (Rishbeth, 1993; Richards, 2001). The changes

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in the daily or hourly values of ionosphere which are large can have sources other than the solar activity (Forbes *et al*., 2000) which may badly affect the correlation. Therefore, the variation of daily values of ionospheric parameters with solar activity has to be examined carefully.

Another important attribute of the solar activity variations of the foF2 is seen with sunspot number. The foF2, at a given place at a constant value of the solar activity level i.e sunspot number Rz, is not same during the ascending and descending phase of solar cycle. consequently, if the variation of foF2 is studied over a complete cycle, the curves corresponding to ascending phase and descending phase do not overlap but form a loop like the hysteresis loop of magnetization and hence is termed as ionospheric hysteresis (Naismith and Smith, 1961; Huang, 1963; Rao and Rao, 1969; Smith and King, 1981).

The emission mechanisms of EUV emissions are different from the F10.7 (Brekke, 1997; Floyd *et al*., 2005). Moreover, the EUV radiations are emitted from the higher regions of the sun (Lean et al., 2001). Consequently, neither F10.7cm nor the sunspot number can be regarded as an ideal proxy for EUV emission variability (Ivanov- Kholodny and Mikhailov, 1986; Lean *et al*., 2001). Hence, it turned out that F 10.7cm flux or sunspot number can never be a substitute for the EUV flux, which had been done earlier in the absence of EUV observations. Therefore, it is necessary to have EUV observations for studying the solar activity related variations of ionosphere.

Therefore, several efforts have been made to define new solar proxies which will adequate and ideal for representing ionospheric variations related to solar activity (laksmi et. al., 1998). Recently, significant variations of solar EUV irradiance have been described using its long term continuous measurements (Liu *et al*., 2006). Different models have been developed from these measurements (Richards *et al*., 1994; Tobiska *et al*., 2000). Most significantly Bilitza (2000) had advocated the continual measurement of the EUV for use in the IRI model. In most ionospheric models such as Xu *et al* (2008) solar activity indices like sunspot number and 10.7cm solar radio flux, were used rather the EUV due to their long term availability. However variation of sunspot number and F10.7 cm flux during different seasons near equator and low latitude in particular has not been investigated in detail.

However, the use of X-ray flux for the solar activity variations of the ionosphere has not been evaluated yet. In the present investigation we have made an attempt to compare the use of three different solar proxies for ionospheric predictions during low and high solar activity periods. We have compared the association of F10.7cm flux, which have been used in the past, with the solar EUV flux, used in recent studies and the solar X-ray flux which have not been used yet with the foF2. From our analysis, we conclude that EUV flux is the best fit proxy among the three, for solar activity variations of ionosphere.

EVENT SELECTION CRITERION

In order to investigate the association of ionospheric activity with the solar radiation fluxes and to compare the dependence of ionospheric activity on the solar X-ray flux, EUV flux and F10.7cm flux (used as a proxy in the past) we have considered the solar cycle 23. In the solar cycle 23, we selected two time windows: one of very high activity and another of very low activity. The year 2007 was taken as the low activity window because during 2007 the activity was extremely low and the sun went spotless for months together. The year 2003 was taken as the high activity window, during this year the solar cycle 23 had just entered the declining phase and the solar activity was very high. The selection of two such windows will allow us to compare the nature of association of ionospheric activity with the different types of solar fluxes during low and high solar activity.

To study the effect of solar radiative flux on the ionosphere, we have taken a mid latitude station. The ionosonde station of Okinawa (26.3N, 127.8E), Japan was selected for carrying out the present investigation. To characterize the ionospheric behaviour at Okinawa we have considered the ground based ionosonde observation and selected the Critical Frequency of F2 layer (foF2) as the parameter of study.

DATA SETS AND SOURCES

The solar emissions occur almost over the entire electromagnetic spectrum. Each of these emissions is characterized by a particular effect on the geospace. However, for investigations concerning ionospheric influences of solar activity, solar radiations at different wavelengths can be used, since these are the primary ionizing agents in the ionosphere and also reflect the solar activity variations. Sunspot number and solar F10.7cm radio noise, F10.7cm, are commonly used as proxies for solar activity induced ionospheric influences. For current study, we have used solar X-ray and EUV flux as solar activity proxies and compared these with proxy used in the past i.e. F10.7cm.

This X-ray sensors onboard GOES satellites provide high quality X-ray flux data with temporal resolution of 5 min and 1 min integrated in two pass bands 0.05-0.3 nm and 0.1-0.8 nm. The data is obtained from the NOAA's Space Environment Center (NOAA-SEC) at http://www.ngdc.noaa.gov/stp/GOES/. In our analysis we have used the 0.1-0.8 nm channel flux with 5min temporal resolution. The other bigger averages were constructed from it.

Similarly, the Solar EUV Monitor (SEM) onboard Solar and Heliospheric Observatory (SOHO) measures EUV flux, integrated in the two wavelength bands 26-34 nm (channel 1) and 1-50 nm (channel 0). The SEM data can be downloaded from web server at http://www.usc.edu/dept/space_science/semdatafolder/. The data provided on the website is in three time resolutions viz. 15 second, 5 min and 10 min as well as daily values. In our analysis we have used the hourly values in the channel 1 i.e. 26-34 nm, due to two reasons, firstly, because solar EUV photons are most important contributor to the lengthy ionospheric enhancements and secondly, due to the narrowness of this band it does not get saturated even during some large flares.

The solar radio flux at 2800MHz known as F10.7, used in the present investigation, is taken from the NGDC data server at http://www.ngdc.noaa.gov/stp with hourly time resolution.

The National Institute of Information and Communication (NICT), Japan has setup a network of five stations at Okinawa, Yamagawa, Kokubinji, Akita and Wakkanai where regular ionosonde observations are conducted. The data recorded and collected from all the five stations is freely accessible at http://wdc.nict.go.jp/IONO/HP2009/ISDJ/index/. The NICT has maintained a huge database of ionospheric data over Japan. The NICT Ionosonde data contains 15 minute and hourly as well as daily values both in manually scaled and automatic scaled mode and also their daily and monthly medians. The data is provided in the ASCII format. Moreover, the ionograms with a toolkit to view these ionograms can also be downloaded from the website. For the current investigation we have selected the Okinawa station only and downloaded the hourly values of Critical frequency of F layer ionosphere i.e foF2. We have also taken the hourly values and monthly means of the foF2 for our investigation.

After downloading all the data sets the datasheets were constructed in order to compare the variability of foF2 during two different solar activity phases and association of foF2 variability with different types of solar radiation flux. To compare the variability we have also derived the ratios of $foF2_{2003}$ and $foF2_{2007}$ as well as same for solar radiation fluxes and studied its variability. The correlation analysis of these ratios was then performed to access the magnitude of association between the two.

ANALYSIS AND RESULTS

We have conducted this study with two primary objectives. First, to compare the variability of ionospheric foF2 during the high and low solar activity. It is for this reason we selected 2003 and 2007 as the periods of our study. Because, during 2003 the solar activity was very high while during 2007 the solar activity was extremely low. Secondly, to compare the association of foF2 variability with different solar proxies. The solar proxies were selected in such a way as to compare the newly used proxies (X-ray and EUV Flux) with proxies used in the past (F 10.7cm flux).

Variability of foF2 During Low and High Solar Activity

In this section we will show the variability of foF2 at Okinawa during the low solar activity period 2007 and high solar activity period 2003 at different time scales and highlight the main differences. The hourly variability of the foF2 during all the months of the year at Okinawa is shown in Figure 1.

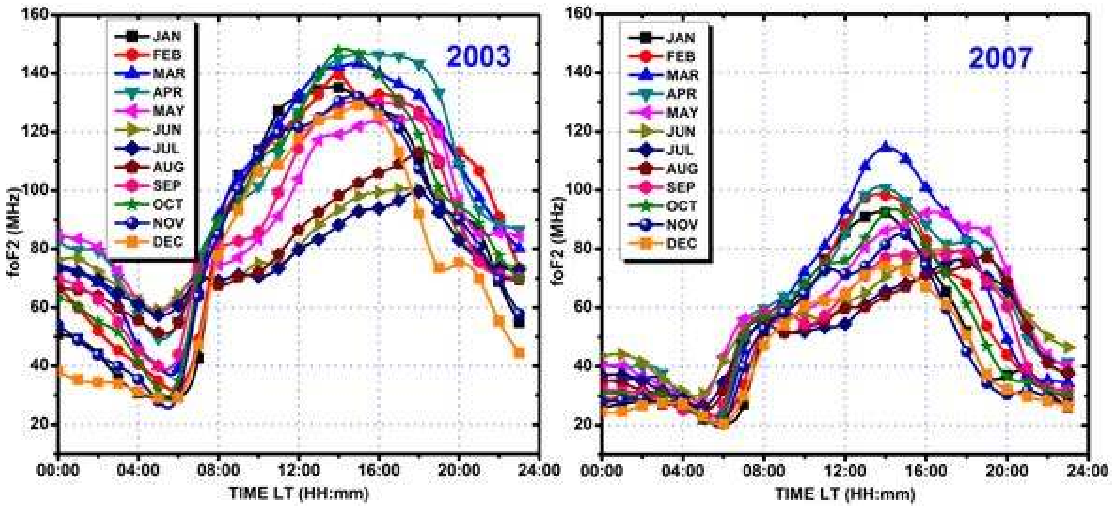

Figure 1: Comparison of hourly variability of foF2 over Okinawa during 2003 and 2007. Each curve represents hourly monthly median.

The two panels show the variability during the year 2003 and 2007. For both the years the hourly variability during all the twelve months have been shown by twelve different coloured lines. From the figure we notice a typical diurnal type of variability during both the years with occurrence of diurnal peak around 02:00 hrs LT. It can be easily noticed that the height of the diurnal peak is significantly different during the two years. The peak values of the foF2 during all the months of year 2003 are significantly greater than the corresponding peak values during the year 2007. The average peak value of the foF2 during the year 2003 was recorded to be 107.08 MHz while the average peak value of foF2 during the year 2007 was observed to be 76.22 MHz. Thus the difference in the average peak value during the two years comes out to be 30.86 MHz which is quite significant. Similarly, the average minimum value of foF2 during the year 2003 was observed to be 84.13 MHz while the average minimum value of foF2 during the year 2007 was observed to be 54.38 MHz. So, the difference in the average minimum value of foF2 during the two year comes out to be 29.75 MHz. So, the average difference between the values of foF2 during the two year is about 30 MHz. Therefore, we conclude that, although the nature of foF2 variability is similar during the low and high solar activity, but the magnitude of variability is different during the two phases of solar activity. The ionospheric activity is quite high during the high solar activity phase and low during the low solar activity phase, with almost 30% difference in the magnitude of activity. Hence, it follows that ionospheric activity is directly proportional to the solar activity.

The Figure 2 shows a contour map of foF2. The contour map has been constructed by plotting the hourly values of foF2 for all the months of each of the two years; 2003 and 2007. It shows the monthly variability of the hourly values. From the figure we notice a significant difference in the monthly variability of foF2 during the two years. The monthly variability of foF2 during the year 2003 follows a semi-annual pattern of variability. The first peak can be observed in the month of April while a second peak is observed during the month of October. The magnitude of second peak is stronger than the first peak with peak values 141 MHz and 127 MHz respectively. However, during 2007 a different behaviour can be observed from Figure 2. Although, the pattern reflects of a semi-annual pattern of variability, but the absence of the second peak can be clearly noticed. The first peak during 2007 occurs during the month of April, like during the year 2003. However, the second peak is completely absent. Hence, we conclude that during high solar activity the foF2 at Okinawa exhibits a semi-annual variability while during low solar activity the occurrence of second peak is completely absent.

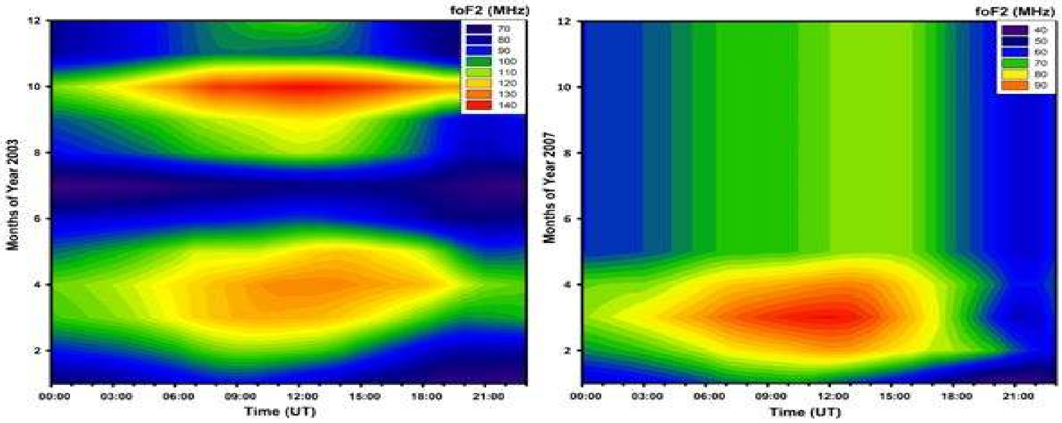

Figure 2: The hourly variability of foF2 over the Okinawa during the different months of year 2003 and 2007.

To compare the variability during two different phases we also derived the ratio of foF2 during 2003 and 2007 i.e. $foF2_{2003}/foF2_{2007}$. The monthly changes in the $foF2_{2003}/foF2_{2007}$ along with corresponding changes in foF2 during 2003 and 2007 is shown in Figure 3. It is double Y-axis plot, on one of the Y-axis shown by red colour we have plotted the values of foF2 for 2003 and 2007 as two separate curves; the red one is for 2007 and black one represents $foF2_{2003}$. The other Y-axis shown by blue colour represents the ratio $foF2_{2003}/foF2_{2007}$. From the figure we notice that the ratio follows a very typical pattern. During the initial months of the year the value of ratio is large indicating a large difference between the two. These months correspond to the first semi-annual peak. However, during the months of May, June and July the value of ratio is minimum indicating very small difference between the two. These months, particularly the month of June, correspond to the gap between the two semi-annual peaks. The value of ratio is larger during the ending months of the year. This is the indication of a significant difference between the variability of foF2 during two different solar activity phases. This is due to the opposite behaviour of foF2 variability during low and high solar activity. The opposite behaviour is manifested in the form of presence of second semi-annual peak during the high solar activity and absence of the peak during the low solar activity.

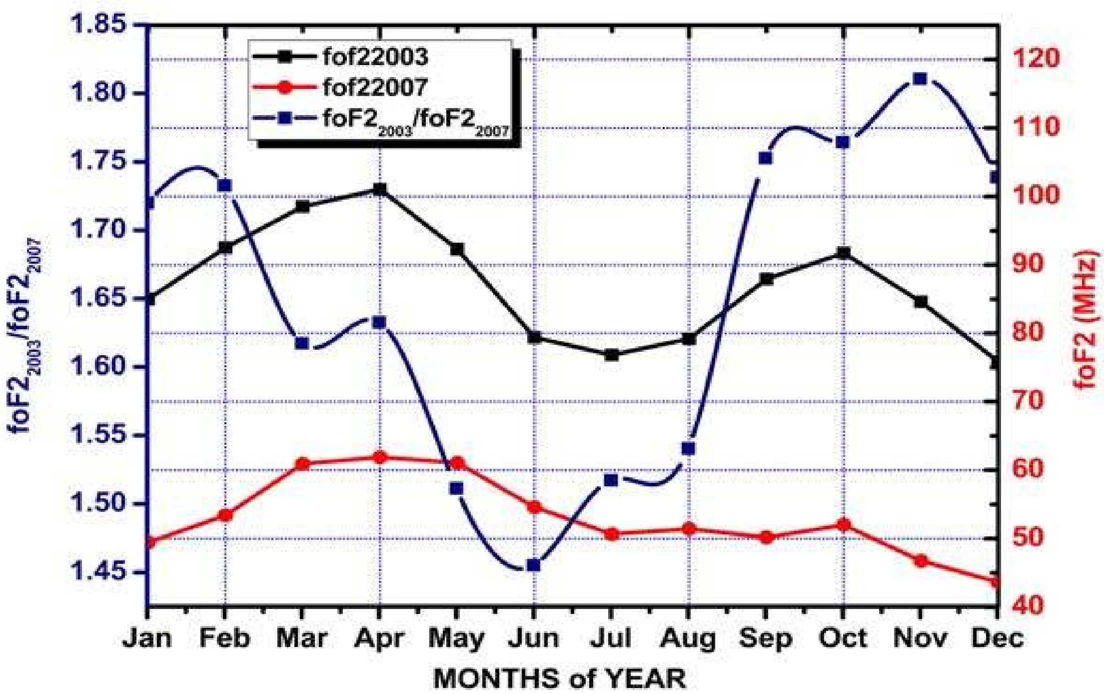

Figure 3: The monthly of variability of foF2 during 2003 and 2007 along with the corresponding variability of their ratio.

Variability of foF2 with Solar Radiation Fluxes

In this section we will examine the relationship of foF2 with solar radiation fluxes during the low and high solar activity phases. To characterize the solar flux we have taken solar flux in three different ranges viz X-ray, EUV and F10.7. The monthly variability of the X-ray flux, EUV flux, F10.7 cm and foF2 during 2003 and 2007 is shown in Figure 4. The Figure 4 compares the behaviour of flux parameters and foF2 during low solar activity and high solar activity. From the figure we find all the green curves corresponding to the low solar activity phase 2007 are significantly below the purple curves corresponding to high solar activity. Therefore, it becomes quite evident that when the solar activity is low the values of flux parameters as well as the foF2 are quite low and when the solar activity is high the values of flux parameters as well as the foF2 are also high. Hence, it can be well concluded that flux parameters and foF2 have a direct relationship with the solar activity.

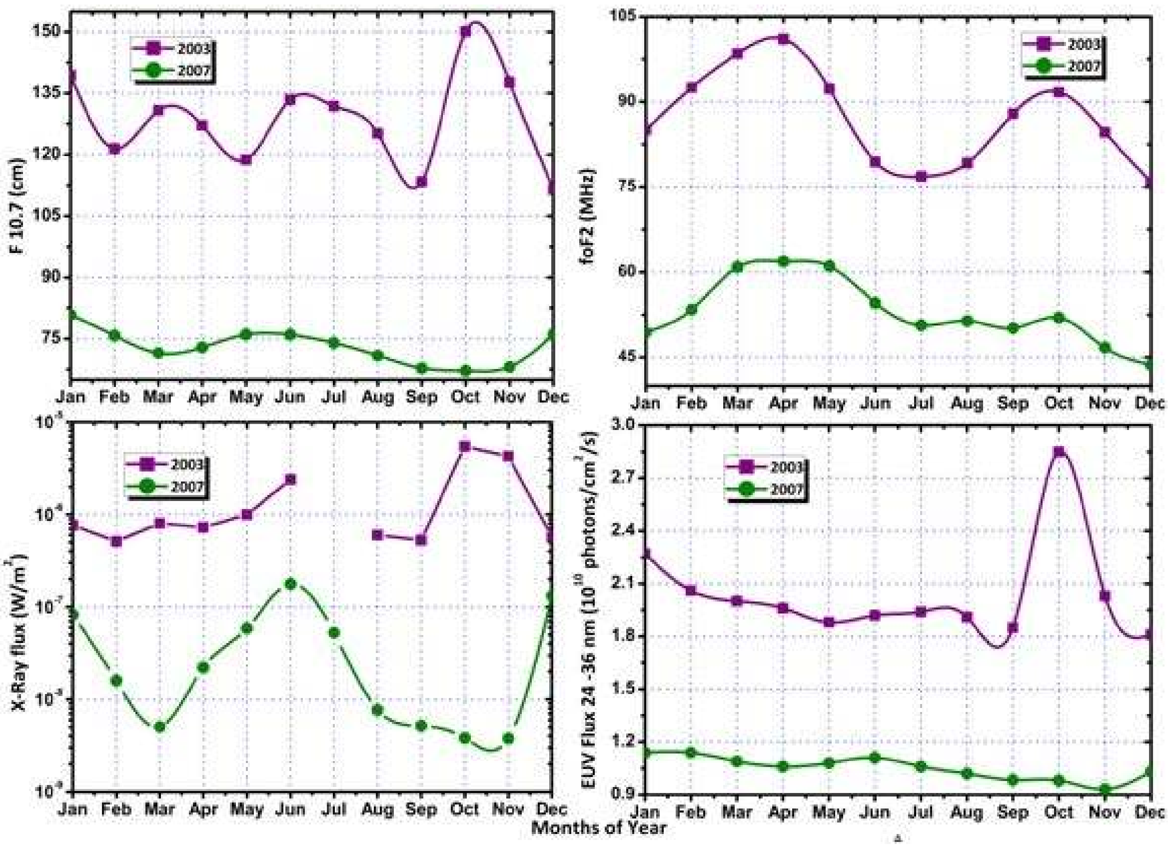

Figure 4: The comparison of monthly variability of three flux parameters and the foF2 during 2003 and 2007.

After examining the daily variation of foF2 with flux parameters during low and high solar activity phases we also investigated the same on monthly scale. The monthly variability of foF2 with monthly variability of three flux parameters during 2003 and 2007 is shown in Figure 5. The bottom panels show the variability of three flux parameters along with the corresponding changes in the foF2 during the low solar activity period 2007 and the top panels show the same during the high solar activity period 2003. From the figure we notice that the monthly variability of foF2 follows a very good association with the monthly variability of X-ray flux and F 10.7 during both the years. During few months, particularly June and July 2003 as well as March 2003, we find a disagreement of X-ray flux and EUV flux with the foF2. Moreover, the disagreement is more during high solar activity period 2003 than the low solar activity period 2007. However, the monthly variability of foF2 follows a very good association with the monthly variability of EUV flux during both the years. We do notice any disagreement between the two, unlike with X-ray flux and F 10.7. Thus we conclude that foF2 exhibits a very strong association with EUV flux during both types of solar activity.

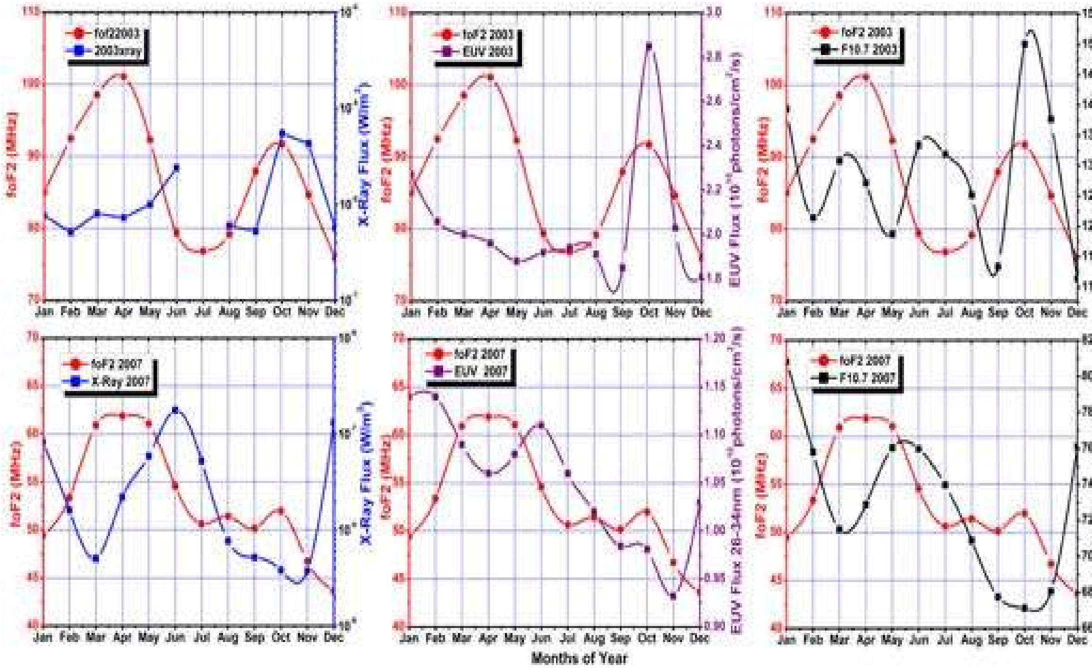

Figure 5: The monthly variability of foF2 with the corresponding variability of three flux parameters during 2003 and 2007 over Okinawa.

In order to compare the variability of foF2 as well as of X-ray flux, EUV flux and F10.7 during 2003 and 2007, we derived the corresponding ratios and investigated the variability of these ratios. In otherwords, we derived the ratio of $foF2_{2003}$ and $foF2_{2007}$ i.e. $foF2_{2003}/foF2_{2007}$ and X-ray $flux_{2003}$/X-ray $flux_{2007}$, EUV $flux_{2003}$/EUV $flux_{2007}$ and $F10.7_{2003}/F10.7_{2007}$ and then investigated the monthly variability of these ratios. The monthly variability of the ratios of foF2 and flux parameters is shown in Figure 6. From the figure we notice the high to low activity ratio of all the three flux parameters, particularly, X-ray flux and EUV flux, does not undergo a significant change, except during the month of October and November, during which a large increase in the ratios of all the three flux parameters undergoes a large increase indicating a large deviation in the flux values of 2003 and 2007. The simple reason for this large deviation is that the October 2003 was dominated by some giant solar flares. The ratio of foF2 follows a typical variability. The value of ratio is more during the months of January and February and starts decreasing from the month of March and assumes a least value during the month of June. From the month of June the value of ratio again starts increasing and becomes maximum during the ending months of the year. The variability of ratio of foF2 is much consistent with the variability of ratios of EUV flux and X-ray flux than with the ratio of F10.7 flux. The value of ratio of EUV flux and X-ray flux is least during the month of June and so is the ratio of foF2, similarly the value of ratio of these two types of fluxes is maximum during the month of October and so is the value of ratio of foF2. Although, the maximum value of ratio of F10.7 corresponds to the maximum value of ratio of foF2, but the minimum value of ratio of F10.7 does not correspond to the minimum value of ratio of foF2. Therefore, we conclude that the variability of foF2 is much strongly correlated with variability of EUV flux and X-ray flux than with the variability of F10.7. So, instead of F10.7 the better solar proxies for ionospheric studies are EUV flux and X-ray flux.

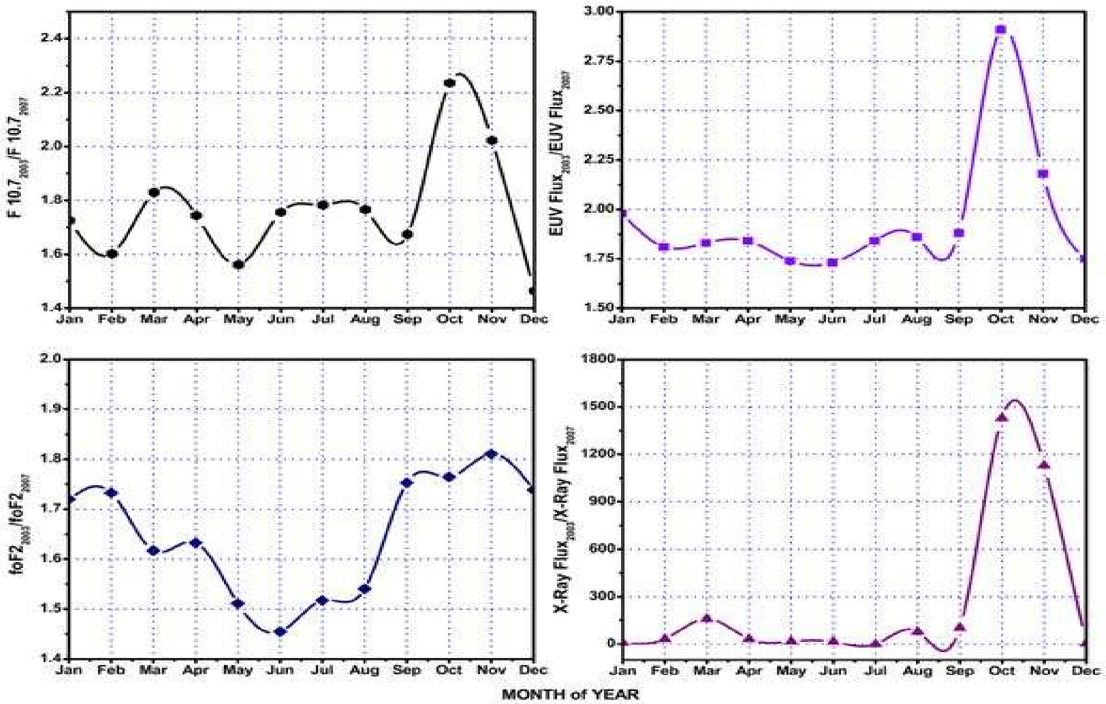

Figure 6: The monthly variability of the ratio of three flux parameters and foF2.

Finally, to quantify the magnitude of association of three types of flux parameters during low and high solar activity with the foF2, we constructed the scatter plots of these parameters as well as their ratios and performed the single regression analysis. First we derived the correlation of foF2 with F10.7, EUV flux and X-ray flux separately for 2003 and 2007. Figure 7 shows the scatter plots and correlation of foF2 with F10.7, EUV flux and X-ray flux during 2003 and 2007. From the figure we find that foF2 exhibits the strongest correlation with EUV flux and least correlation with F10.7 during both the years. The correlation coefficients of foF2 with F 10.7, X-ray flux and EUV flux during the year 2003 are 0.10, 0.58 and 0.66 respectively. Similarly, the correlation coefficients of foF2 with F 10.7, X-ray flux and EUV flux during 2007 are 0.05, 0.57 and 0.56 respectively. From the values of correlation coefficients we conclude that foF2 exhibits a very good correlation with EUV flux and X-ray flux and a very weak correlation with F 10.7 flux during both the years. However, the magnitude of correlation is comparatively stronger during the high solar activity period 2003.

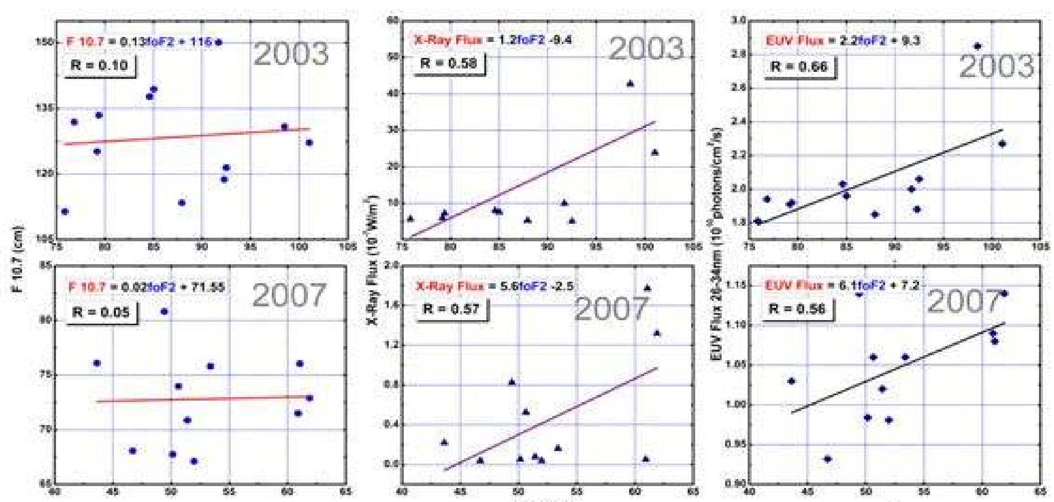

Figure 7: The scatter plot and correlation of foF2 with three flux parameters during 2003 and 2007.

The correlation of high to low activity ratio of foF2 with the high to low activity ratios of three flux parameters is shown in Figure 8. The Figure 8 represents the conclusion of the study effectively. From the left panel of the Figure 8 we find that $foF2_{2003}/foF2_{2007}$ exhibits a very good correlation with EUV $flux_{2003}$/EUV $flux_{2007}$ with correlation coefficient calculated as 0.51. In this panel of the Figure 8 we also find that scatter of the data points is less. From the centre panel of Figure 8, we find that $foF2_{2003}/foF2_{2007}$ exhibits a moderate correlation with X-ray $flux_{2003}$/X-ray $flux_{2007}$ and the correlation coefficient is 0.41. Here we also find more scatter in the data points. From the right panel of the Figure 8 we notice a weak correlation between $foF2_{2003}/foF2_{2007}$ and $F10.7_{2003}/F10.7_{2007}$ and the correlation coefficient is 0.14. In this panel we also notice a significantly large scatter of data points. Therefore, we conclude that the association of foF2 is stronger with EUV flux than with X-ray flux and F10.7 flux.

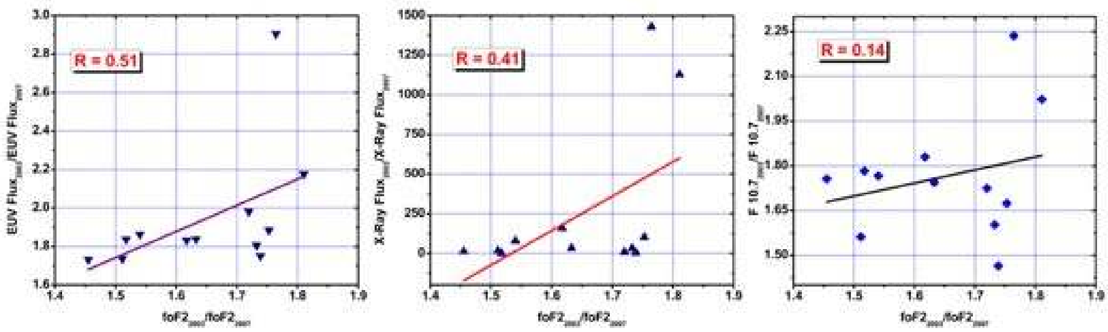

Figure 8: The single regression analysis of foF2 ratio with the ratios of three flux parameters.

CONCLUSION

We made a comparative study of mid-latitude foF2 variability during low and high solar activity as well as probed the association of foF2 variability with three different solar proxies

- Although the nature of diurnal variability of foF2 is similar during the low and high solar activity, but the magnitude of variability is different during the two phases of solar activity. The peak values of foF2 are quite high during the high solar activity phase and low during the low solar activity phase, with almost 30% difference in the magnitude. Hence, it follows that ionospheric activity is directly proportional to the solar activity.
- During high solar activity the foF2 at Okinawa exhibits a semi-annual variability, the first peak occurs in the month of April and the second peak is observed in the month of October. However, during low solar activity the occurrence of first peak is observed in the month of April, the second peak is absent.
- The value of ratio, $foF2_{2003}/foF2_{2007}$, is largest during the ending months of year (Sep. to Dec.) indicating a significant difference between the variability of foF2 during two different solar activity phases. This is due to the opposite behaviour of foF2 variability during low and high solar activity. The opposite behaviour is manifested in the form of presence of second semi-annual peak during the high solar activity and absence of the peak during the low solar activity. However, during the months of May, June and July the value of ratio is minimum indicating very small difference between the two. These months, particularly the month of June, correspond to the gap between the two semi-annual peaks.
- From our analysis we also conclude that the daily variability of foF2 has a stronger association with the flux parameters during the high solar activity period than the low solar activity period. Moreover, among the three different flux parameters the association of foF2 is more consistent with X-ray flux and EUV flux than with the F10.7cm flux during both types of solar activities. The strongest association of foF2 was found to exist with the EUV flux, irrespective of low or high solar activity.
- The correlation coefficients of foF2 with F 10.7, X-ray flux and EUV flux during the year 2003 are 0.10, 0.58 and 0.66 and during 2007 are 0.05, 0.57 and 0.56 respectively. Hence, it follows that foF2 exhibits a very good correlation with EUV flux and X-ray flux and a very weak correlation with F 10.7 flux during both the years. However, the magnitude of correlation is comparatively stronger during the high solar activity period 2003.

- The correlation coefficients of $foF2_{2003}/foF2_{2007}$ with EUV $flux_{2003}$/EUV $flux_{2007}$, X-ray $flux_{2003}$/X-ray $flux_{2007}$ and $F10.7_{2003}/F10.7_{2007}$ are 0.51, 0.41 and 0.14 respectively. Therefore, it follows that the ratio of foF2 exhibits a good correlation with ratio of EUV flux and X-ray flux and an extremely insignificant correlation with the ratio of F10.7 flux.

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