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Examination of the solar cycle variation of *f*oF2 for cycles 22 and 23

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Abstract

The variations of monthly median noon values of *f*oF2 at Slough and Rome are examined by using different solar activity indices (solar flare index, relative sunspot number, solar flux at 2800 MHz, and Mg II index) for solar cycles 22 and 23 (1986–2006). We compared the dependence of *f*oF2 on solar activity indices by using a single regression analysis, and showed that qualitative similarity of the ionospheric *f*oF2 with the solar indices depends on the solar cycle. We found that hysteresis effect shows generally lower *f*oF2 for the rising branches compared with the falling branches of the two solar cycles, and the strength of the hysteresis effect varies from index to index as well as from cycle to cycle.

Keywords: Solar activity; Flare index; Ionospheric *f*oF2; Hysteresis

1. Introduction

The Sun emits a wide variety of radiations, originating in different parts of the solar atmosphere. Solar ultraviolet (UV) irradiance (115–420 nm) plays a dominant role in the temperature distribution, photochemistry, and overall momentum balance in the stratosphere, mesosphere, and lower thermosphere. However, ionospheric electron density is produced mainly by solar radiations (EUV, X-rays, etc.), which are generated by solar activity events. These radiations are known to show very definitive solar cycle variations. Consequently, electron concentration and critical frequency of F2 region (*f*oF2) are also expected to reflect these variations. Since there were no solar UV measurements during the early years of ionospheric research, traditionally, the smoothed monthly mean sunspot number (R12) was considered a primary index of solar activity for prediction of ionospheric parameters. The dependence of *f*oF2 on R is "poisoned" by the phenomenon of hysteresis, which has been known for a long time (Naismith and Smith, 1961; Naismith et al., 1961; Huang, 1963; Rao and Rao, 1969; Muggleton, 1969). However, several efforts have been made to introduce a new solar activity index for this prediction. Lakshimi et al. (1998) proposed to use EUV data for the long-term predictions of the monthly median ionospheric parameters. Kane (1992) reported that in the absence of solar EUV data, solar radio flux at 10.7 cm may be better than sunspot numbers when making ionospheric

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predictions. One of the goals of this study was to demonstrate which solar activity is more convenient for ionospheric predictions.

Ionospheric variations can be considered in time scales of (a) day-to-day, including 27-day solar rotation, (b) semiannual, (c) annual, and (d) solar cycle. In the present communication, examination is made only of the long-term (solar cycle) variations of solar activity indices and ionospheric parameter *f*oF2. We investigate the response of the ionosphere to the solar activity by using the flare index, the Mg II index, the solar radio flux at 10.7 cm, and the relative sunspot numbers during solar cycles 22 and 23. Three of these indices were used before to examine the relationships between the ionosphere and the solar activity. The flare index is used for the first time for cycles 22 and 23. We also try to determine the strength of hysteresis and its detailed course during the same period.

2. Data and methods

In the present study, the solar activity is represented by 12-month moving averages of the flare index, the composite Mg II index, the solar radio flux at 10.7 cm and the relative sunspot number. As well as in many studies in the solar–terrestrial field, solar flares are classified as one of the most important solar events affecting the Earth. Kleczek (1952) introduced the quantity $Q = it$ to quantify the daily flare activity over a 24-h period. He assumed that this relationship roughly gives the total energy emitted by the flare and named it ''flare index'' (FI). In this relation, ''i'' represents the intensity scale of importance of a flare in H_α and ''t'' the duration (in minutes) of the flare. The determination of Q has been explained previously (Özgüç et al., 2002, 2003). Calculated values are available for general use in NGDC (ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX/).

The relative sunspot number (Rz)—The daily data of the international sunspot numbers provided by the Sunspot Index Data Center of the Royal Observatory of Belgium were used for our analysis. These data represent the definitive relative numbers of the sunspots calculated on the basis of all observations available from different observatories.

Solar flux values (F10)—Daily measurements of the integrated emission from the solar disc at 2800 MHz (10.7 cm wavelength) have been made by the National Research Council of Canada since 1947. Values are available from the NGDC website.

The composite Mg II core-to-wing index (MG II)—This is a daily measurement of solar UV variability using the Mg II absorption feature at 280 nm. This index is a dimensionless quantity measuring mid-UV solar activity. We used the NOAA Mg II daily Index version 9.1.

The F2 layer critical frequency (*f*oF2) is one of the ionospheric parameters observed regularly by several observatories and it allows us to examine the relation of F2 layer with the solar activity indices. The monthly median noon values of *f*oF2 of the Rome (41.9N) and Slough (51.5N) ionosonde stations are used in our study.

In the present investigation, we considered only the long-term (solar cycle) variations. In this respect, to eliminate the complications due to seasonal effects, 12-month running means of *f*oF2 are calculated. We used the monthly median noon of *f*oF2 to examine the correlations between this ionospheric parameter and the solar activity indices for the time period of 1986–2006, which covers almost two solar cycles.

3. Results

Figs. 1 and 2 show the plots of the 12-month moving averages of solar indices and *f*oF2. We compared these indices with *f*oF2 values of the two stations, Slough and Rome, for the time period of 1986–2006, which covers almost two solar cycles. All these indices show a monotonic increase from the beginning of the two cycles to their maxima. Thereafter, all solar indices show clear two peaks in both cycles, but *f*oF2 shows multi-peaks during the maximum of cycle 22. In cycle 23, clear double peaks appear in Rome values (Figs. 1 and 2(d)). However, Slough *f*oF2 values show quasi-double peaks in the same period. The following may be noted:

- All solar parameters that we studied show two maxima with the first maximum higher than the second one at cycle 22.
- Only two solar parameters (Rz and FI) show two maxima during cycle 23 with the same behavior as cycle 22.
- F10 and MGII also show two maxima during cycle 23, but not like the other indices we examined, namely with the second maximum higher than the first one.

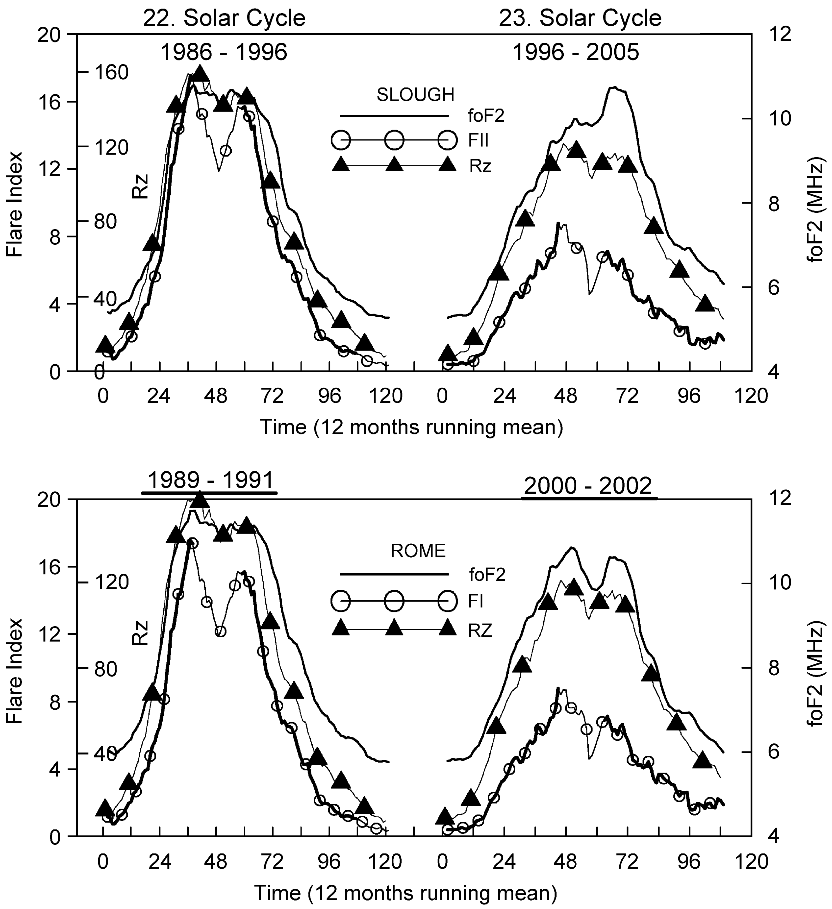

Fig. 1. Twelve-month moving average of flare index, sunspot number, and noon median *f*oF2 at Slough and at Rome for cycles 22 and 23 (1986–1996 and 1996–2005).

- *f*oF2 values of Slough show multi-peaks in cycle 22 and two peaks in cycle 23. However, the values of the second maximum relative to the first one are not alike.
- Rome *f*oF2 values also show the same behavior as Slough values. Thus, it is indicated that qualitative similarity with the solar indices depends on the solar cycle.

In our previous paper (Ataç and Özgüç, 2006), we found that in all solar activity indices that we studied the amplitude of the current cycle in the same time interval is distinctively weaker than the last one except the total solar irradiance. The average values of the activity indices as well as their standard deviations during the solar maximum and minimum phases for solar cycles 22 and 23 are given in Table 1. The ratio in the last column illustrates the amplitude differences from minimum to maximum between the two successive cycles for the four activity indices and for *f*oF2. As it can be seen from Figs. 1 and 2 the solar activity during the solar cycle 23 is weak but the amplitudes of the time variation of the Mg II index and *f*oF2 do not change during solar cycles 22 and 23.

In cycles 22 and 23 solar activity indices definitely had two peaks. *f*oF2 plots in Figs. 1 and 2 show that the time variation of this ionospheric parameter follows the solar activity cycles. However, in *f*oF2 plots multi-peaks are seen during the maximum of solar cycle 22, but in cycle 23 a double peak appeared very clearly.

In order to determine the relationships between *f*oF2 and the solar activity parameters, a single regression analysis was carried out for each station, and it was observed that the relationship is linear. This is demonstrated in Figs. 3–6 where the variations of *f*oF2 with the solar parameters are shown for cycles 22 and 23. These figures contain the observed data and the regression fits, correlation

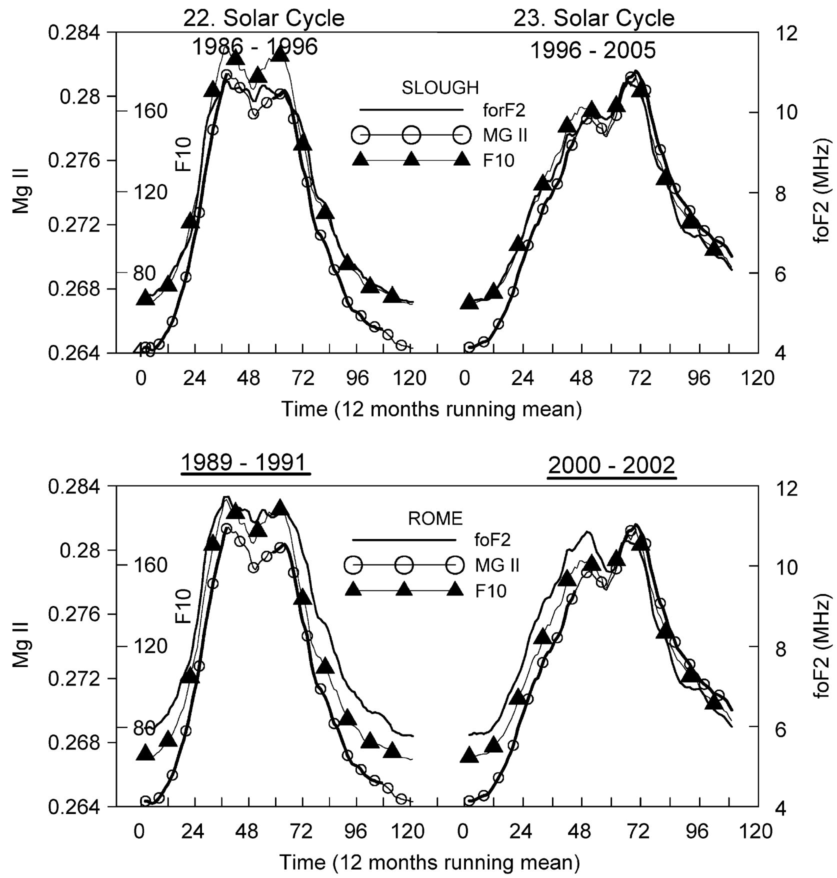

Fig. 2. Same as Fig. 1, but for solar flux values (F10) and Mg II core-to-wing index.

Table 1
Minimum to maximum variability of the solar activity indices and *f*oF2 during cycles 22 and 23

Cycles 22 and 23	1986 Minimum	1989–1991 Maximum	1996 Minimum	2000–2002 Maximum	Cycle 22/cycle 23 $(\text{Maximum–minimum})_{22}/(\text{maximum–minimum})_{23}$
10.7 cm Solar flux	66.63 (3.9)	183.38 (18.1)	64.81 (2.3)	162.18 (20.9)	1.20
Mg II index	0.264 (0.00052)	0.280 (0.0017)	0.264 (0.00036)	0.279 (0.0023)	1.07
Sunspot number	13.4 (9.9)	148.6 (23.2)	8.6 (5.3)	111.5 (19.4)	1.31
Flare index	1.2 (1.4)	14.9 (4.6)	0.4 (0.4)	6.3 (4.3)	2.32
*f*oF2-Slough (51.5N)	5.4 (0.5)	10.49 (2.2)	5.3 (0.4)	10.01 (2.2)	1.08
*f*oF2-Rome (41.9N)	6.1 (0.2)	11.2 (0.3)	5.8 (0.4)	10.26 (2.1)	1.14

Standard deviation values are given in parentheses.

coefficients, and the relations between *f*oF2 and the solar parameters.

Figs. 3–6 display the variations in the curves of the hysteresis between *f*oF2 and the solar activity indices for cycles 22 and 23. We may note that the hysteresis shows generally lower *f*oF2 for the rising branches compared with the falling branches of the two solar cycles. However, this is not the case in some individual indices for cycle 23.

4. Discussion

Being able to express aspects of solar activity by many indices, such as the sunspot number, the

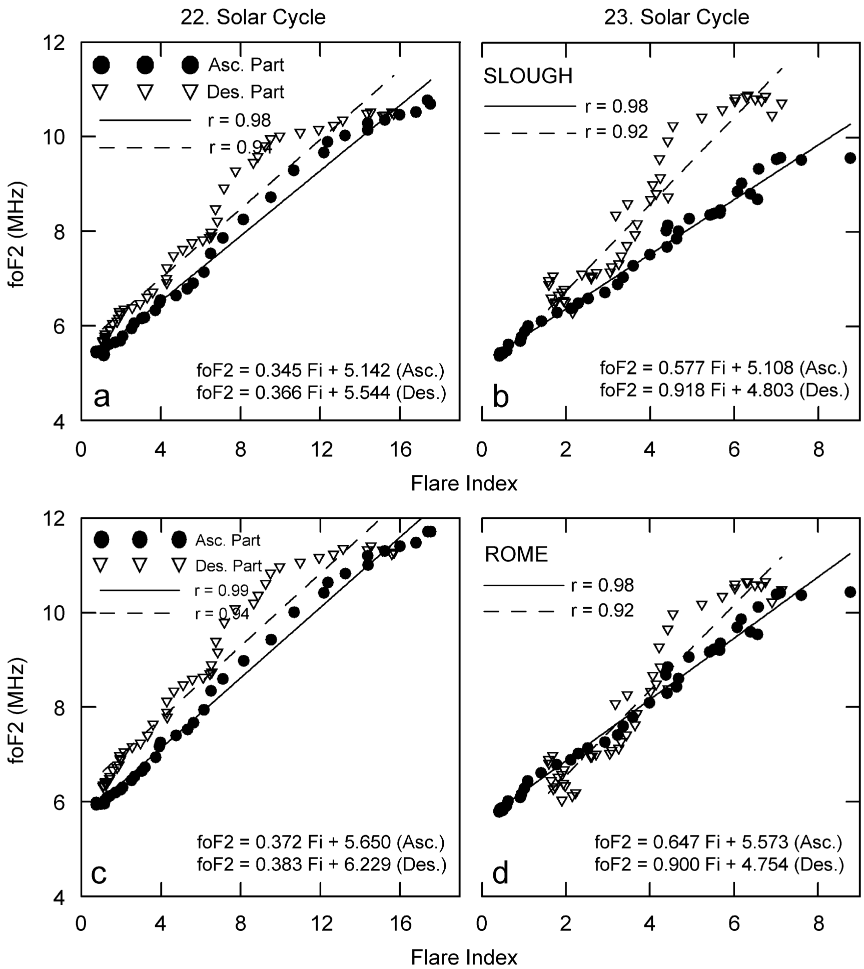

Fig. 3. Twelve-month moving average of noon median *f*oF2 at Slough and Rome versus flare index. Full dots refer to the ascending branches (1986–1989 and 1996–1999) of solar cycles 22 and 23, and empty triangles the descending branches (1991–1996 and 2001–2005). The single regression fits are shown as solid lines for the ascending branches and dashed lines for the descending branches of cycles 22 and 23.

2800 MHz radio flux, flare index, Mg II index, etc., are useful for studying the Sun's long-term behavior and its interaction with our near Earth space environment. Long-term predictions of the critical frequency have traditionally been based on the relationship between the predicted ionospheric parameters and 12-month running mean of the sunspot number (R12). The dependence of *f*oF2 on Rz (or R12) is "poisoned" by the phenomenon of hysteresis, which has been known for a long time. For a given station and a constant value of the solar activity indices, *f*oF2 differs for the ascending and the descending parts of the 11-year solar cycle. In this connection, we investigated the solar cycle variation of *f*oF2 by using the solar flare index and the composite Mg II core-to-wing index, relative sunspot number, and the 2800 MHz radio flux.

The examination of the correlation between the monthly median noon values of *f*oF2 and several indices of solar activity showed that independently from the kind of index and location, significant hysteresis is present during cycles 22 and 23. Although the phenomenon of the ionospheric hysteresis between *f*oF2 and R12 has been known for a long time, a linear relationship between these two parameters is used in forecasting and in long-term trend estimations. According to our findings the hysteresis magnitude varies non-systematically with the solar cycles, so the inclusion of the hysteresis into the long-term ionospheric predictions seems not suitable.

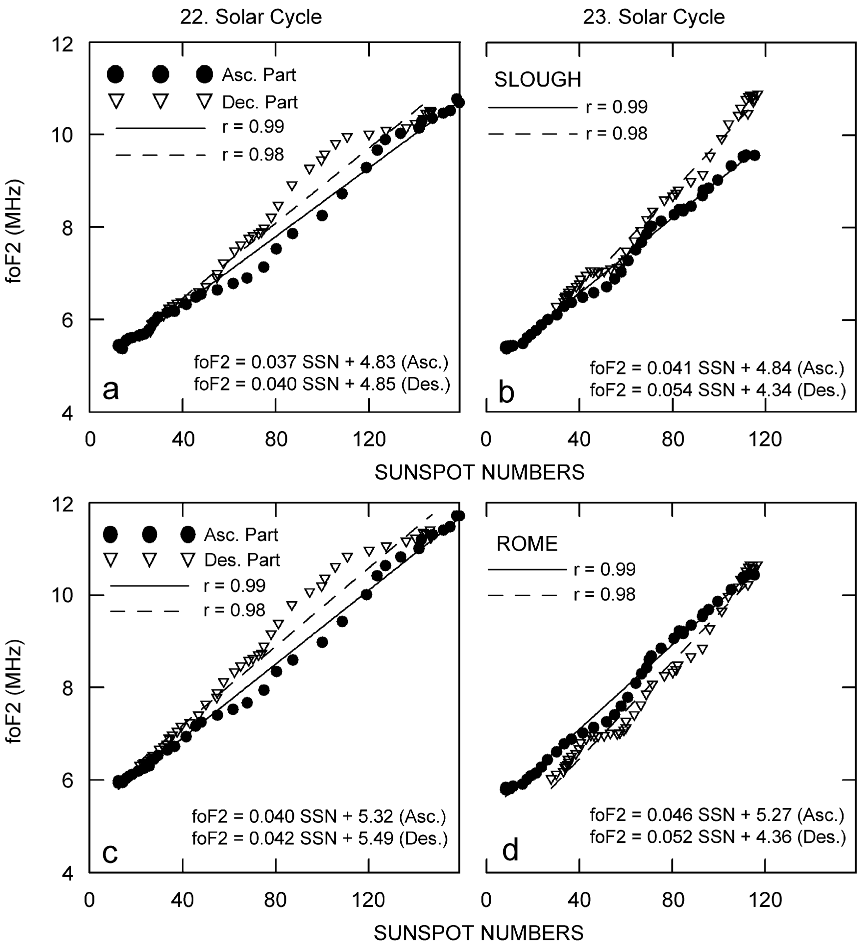

Fig. 4. Same as Fig. 3, but for relative sunspot numbers.

The linear correlation between the solar activity indices and *f*oF2 is very strong during the ascending and descending branches of the two cycles (Figs. 3–6). The slope of their linear fits shows variations from cycle to cycle, as well as index to index. Solar ionizing flux, meteorological influences, and solar wind conditions are the origins of changes in state of the ionosphere. All of these effects are dependent on local time, latitude, and season (Forbes et al., 2000). To avoid the seasonal variation we applied a 12-month running mean to the time series of solar activity indices and *f*oF2. In spite of this, in Figs. 3–6 one can see that the hysteresis magnitude is high in different solar cycles depending on different ionospheric stations. So, we conclude that this phenomenon is due to the latitude and meteorological influences as well as solar wind conditions. This conclusion is supported by the results of Forbes et al. (2000).

The hysteresis effect in ionospheric parameters, such as *f*oF2, may be compatible with a geomagnetic control for each solar cycle. Geomagnetic disturbances are accompanied by large changes in the ionospheric F2 layer. Although the ionospheric response to geomagnetic activity is highly complex due to the many physical processes involved, there are underlying trends that are useful in characterizing the ionosphere response to storms (Fuller-Rowell et al., 2000; Araujo-Pradere et al., 2002; Rishbeth and Field, 1997; Field and Rishbeth, 1997). Taking into account that geomagnetic activity is higher on average during the descending phase of the solar cycle than during the ascending phase, a clockwise or counter-clockwise hysteresis should be expected at a location depending on its prevalent negative or positive ionospheric storms. This implies negative or positive hysteresis magnitude, respectively.

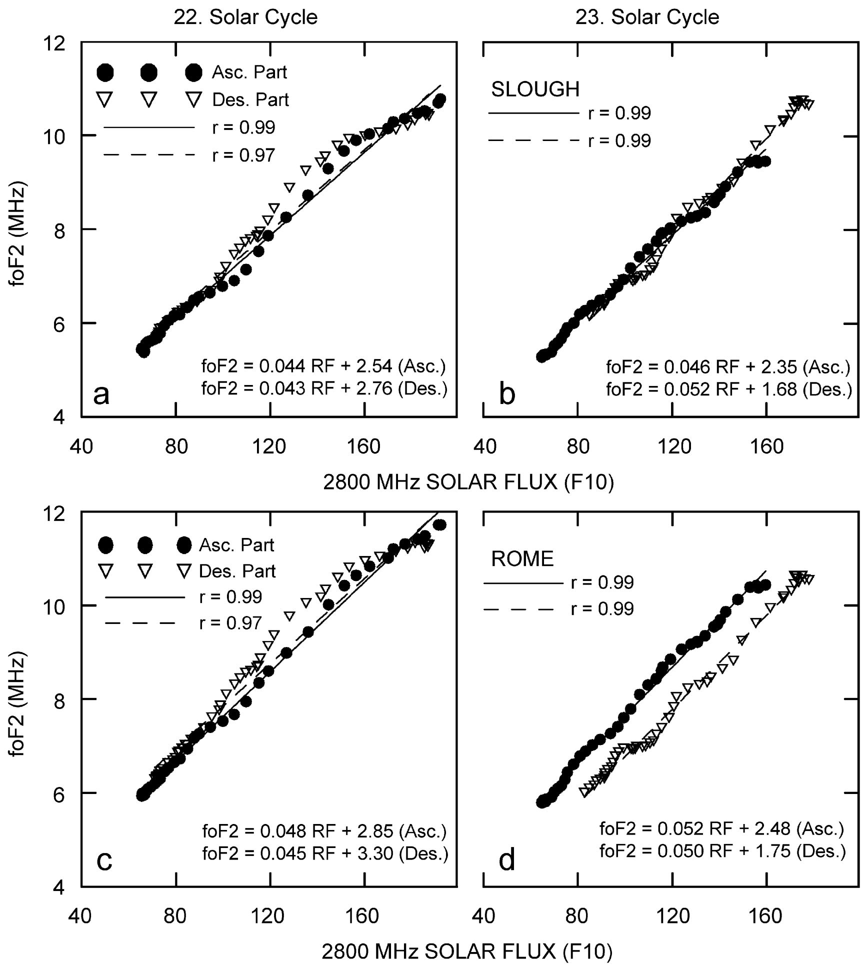

Fig. 5. Same as Fig. 3, but for 2800 MHz solar flux.

Özgüç et al. (1998) showed that to use flare index than any other solar index may be more adequate. They found this result only for solar cycle 21. However, the results for cycles 22 and 23 do not support this conclusion.

In a very recent study Kane (2006) showed that most of the solar parameters as well as the $(f\mathrm{oF2})^2$ show two maxima, with the second maximum higher than the first maximum. He also found that the magnitudes of the second maxima relative to the first one were different for different solar indices. We found the same result with our parameters. Therefore, we may add the flare index and the two stations (Slough and Rome) results into his conclusion, since the data set of that study does not contain the flare index and those stations.

*f*oF2 changes differ from location to location, indicating that direct linear relationship with solar intensities is not maintained, and complex effects of other parameters are involved (Kane, 2006). Our results support this conclusion.

5. Conclusion

This paper investigated the dependence of *f*oF2 on the solar activity. Four solar activity indices, namely flare index, relative sunspot number, solar flux at 10.7 cm, and Mg II index as well as Slough and Rome *f*oF2 noon medians are used. These indices and *f*oF2 data provide a good opportunity to study the solar activity variability in the ionosphere. The conclusions can be drawn as follows:

- The linear correlation between the solar activity indices and *f*oF2 is very strong during the ascending and descending branches of the two cycles (Figs. 3–6). The slope of their linear fits shows variations from cycle to cycle, as well as

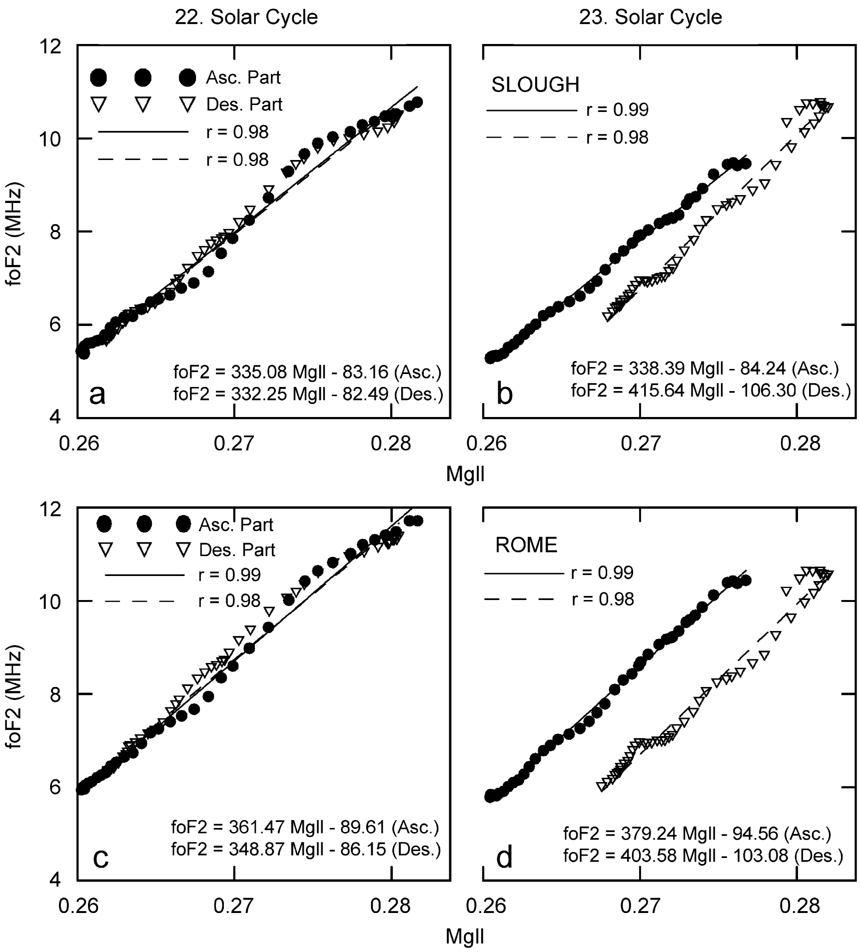

Fig. 6. Same as Fig. 3, but for Mg II core-to-wing index.

index to index. So, we conclude that hysteresis is due to the latitude and meteorological influences as well as solar wind conditions.

- The hysteresis magnitude varies non-systematically with the solar cycles, so the inclusion of the hysteresis into the long-term ionospheric predictions seems not suitable.

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