What is happening with the Sun - and ionospheric impact?

Jan Lastovicka[1] and Dalia Buresova[2]

[1]Institute of Atmospheric Physics, Czech Academy of Sciences
[2]Institute of Atmospheric Physics

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Abstract

To model ionospheric climate and to study its long-term changes we need solar activity proxies, because long and homogeneous data series of solar ionizing flux are not available. Here we use solar activity proxies/indices F10.7, sunspot numbers, F30, Mg II, He II and solar Lyman-α flux, and yearly average foF2 values from six midlatitude ionospheric stations from four continents (Juliusruh, Pruhonice, Roma, Boulder, Kokubunji and Canberra) over 1976-2014. Main results are as follows: (1) Relationships among solar activity indices/proxies differ between solar cycles 21 and 22 (represented by years 1976-1995) on the one hand, and cycles 23 and 24 (represented by years 1996-2014) on the other hand. (2) Consequently the relationships between midlatitude foF2 and solar activity proxies also differ except for F30. (3) The variability of yearly values of foF2 at middle latitudes appears to be described best by solar activity proxies F30 and Mg II.

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Jan Lastovicka[1], Dalia Buresova[1]

[1]Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czech Republic

Corresponding author: Jan Lastovicka (`jla@ufa.cas.cz`)

Key points

- The relationships among solar activity indices/proxies differ between solar cycles 21 and 22 versus cycles 23 and 24.
- Consequently the relationships between midlatitude foF2 and solar activity proxies also differ except for F30.
- The variability of yearly values of foF2 at middle latitudes appears to be described best by the solar activity proxies F30 and Mg II.

Abstract

To model ionospheric climate and to study its long-term changes we need solar activity proxies, because long and homogeneous data series of solar ionizing flux are not available. Here we use solar activity proxies/indices F10.7, sunspot numbers, F30, Mg II, He II and solar Lyman- flux, and yearly average foF2 values from six midlatitude ionospheric stations from four continents (Juliusruh, Pruhonice, Roma, Boulder, Kokubunji and Canberra) over 1976-2014. Main results are as follows: (1) Relationships among solar activity indices/proxies differ between solar cycles 21 and 22 (represented by years 1976-1995) on the one hand, and cycles 23 and 24 (represented by years 1996-2014) on the other hand. (2) Consequently the relationships between midlatitude foF2 and solar activity proxies also differ except for F30. (3) The variability of yearly values of foF2 at middle latitudes appears to be described best by solar activity proxies F30 and Mg II.

Plain Language Summary

To model ionospheric climate and to study its long-term changes we need solar activity proxies, because long and homogeneous data series of solar ionizing flux are not available. To examine the stability of relationships among solar activity proxies, and between foF2 (ionospheric critical frequency) and solar activity proxies, and to search for optimum solar proxy for foF2 investigations, we use six solar activity proxies and yearly average values of foF2 from six midlatitude ionospheric stations over 1976-2014. The relationships among solar activity proxies differ between 1976-1995 and 1996-2014. Consequently the relationships between midlatitude foF2 and solar activity proxies also differ except for F30. The variability of yearly values of foF2 at middle latitudes appears to be described best by solar activity proxies F30 and Mg II.

1 Introduction

Several decade long homogeneous measurements of the solar EUV fluxes are not available, so various solar activity proxies (solar activity indices) must be used in long-term ionospheric studies. In the past, the relationships between solar activity proxies and ionospheric parameters were assumed to be stable with time. However, Lastovicka (2019) showed for three European stations that the relationship between foF2 (critical frequency of ionospheric F2 layer) and solar proxies F10.7 and solar Lyman- flux is clearly different in periods 1976-1995 and 1996-2014. This can hardly be caused by changes in the ionosphere; solar origin has to be searched for.

Lukianova & Mursula (2011) observed changed relation between sunspot numbers, solar EUV/UV radiation and the total solar irradiance during the declining phase of solar cycle 23. Clette & Lefevre (2012) reported a change of the relation between sunspot numbers and F10.7 since about 2000 and substantially smaller drop in F10.7 than in Mg II in the extreme solar minimum 2008-2009. Tapping & Valdes (2011) also reported changes of relations between solar proxies during the decline of solar cycle 23. Balogh et al. (2014) reported a change in the relationship between sunspot numbers and F10.7, and a drop of the sunspot formation fraction parameter (introduced by Livingstone et al., 2012) by ~40% during the solar cycle 23 compared to the quasi-stable level in cycles 19-22. Lastovicka (2019) found a different dependence of Mg II on F10.7 in 1979-1995 versus 1996-2014. Clette (2021) analyzed long data series of F10.7 and sunspot numbers and observed a jump in relation between them in 1980. Thus the relationships between various solar proxies need not be stable.

Therefore, the objective of this paper is to investigate the stability/instability of the relationships between solar activity proxies and the related stability/instability of the relationships between solar activity proxies and the main ionospheric parameter foF2 with focus on middle latitudes. The analyses will be carried out for yearly average values. Section 2 deals with data and method, section 3 with the relationships among solar activity proxies, section 4 with relationships between foF2 and solar activity proxies, and section 5 summarizes results in Conclusions.

2 Data and Methods

Six solar activity indices are used, F10.7, L (solar H Lyman-alpha flux), F30 (solar radio noise at wavelength of 30 cm), sunspot number R, Mg II and He II. Data are available over the whole period 1976-2014 except for Mg II available since late 1978. He II data are available only until April 2015, which is one of the reasons why our analysis terminates with the year 2014.

Ionospheric critical frequency foF2 data of six midlatitude stations are used: a north-south chain of European stations Juliusruh (54.6°N, 13.4°W), Pruhonice (49.98°N, 14.55°E) and Rome (41.8°N, 12.5°E), US station Boulder (40.0°N, 254.7°E), Japanese station Kokubunji (35.7°N, 139.5°E) and Australian station Canberra (35.3°S, 149.0°E). All data are studied separately over two periods, 1976-1995 and 1996-2014, because the dependence of foF2 on F10.7 is clearly different in these two periods (Laštovička, 2019). For the first period, data sets of yearly data of Juliusruh, Pruhonice, Rome, Boulder, Canberra and Kokubunji are complete. For the second period, data sets of yearly data of Juliusruh, Pruhonice, Rome, Canberra and Kokubunji are complete. The Boulder data set miss values for 2003 and 2012. The values of foF2 in 1989 and 1991 clearly suffered with the effect of saturation of their dependence on F10.7 (Laštovička, 2019). Therefore these two years have been excluded from analysis. The analysis focused on middle latitudes, because at low and high latitudes the availability of long (1976-2014) and high quality data series is much lower than at middle latitudes.

All ionospheric analyses are performed for noontime (11-13 LT) yearly average values. The yearly average values of ionospheric parameters are calculated as averages from monthly median values. This reduces effects of large deviations, particularly effects of geomagnetic storms. A simple linear regression, equation (1), has often been used to remove solar cycle effect, e.g. in calculating long-term trends in ionospheric parameters. As Laštovička (2021a, b) demonstrated for the above European stations, equation (1) with the optimum solar activity proxies describes a large majority of the total variance of ionospheric parameters for yearly values (99%); three non-European midlatitude stations provide the same result (Table 3). The linear correlation between yearly values of solar activity proxies reaches values 0.98-0.99. Therefore the simple linear regression, equation (1), may be used in all further analyses of relationships between individual solar proxies or between foF2 and solar proxies:

X = A + B * solar proxy (1)

where X is either foF2 or solar activity index, and solar proxy is either F10.7, or F30, or L , or R, or Mg II, or He II index of solar activity.

2.1 Solar Activity Index He II

Figure 1. The differences between observed and empirical model (equation (1)) values of He II, ΔHe II. Dashed lines are calculated from data for 1996-2014, black for He II as function of F30, green of F10.7. Full lines show ΔHe II values calculated from equation (1) based on data for 1996-2010, blue for He II as function of F30, red of F10.7. Horizontal long-dash line represents zero difference.

The results of Laštovička (2021b) indicate that there might be problems with He II index in years 2011-2014; these years substantially reduce the correlation between foF2 and He II. Figure 1 shows that the last four years display the largest deviations from the dependence of He II on F10.7 (red line) as well as on F30 (blue line). This may be considered to be evidence of some problems of He II in years 2011-2014. Therefore further analyses are carried out for 1996-2014 and also 1996-2010 (without 2011-2014).

3 Relationships among Solar Activity Proxies

Clette & Lefevre (2012) or Balogh et al. (2014) showed that the dependence of F10.7 on R (sunspot number) in the solar cycle 23 was different from that in previous period. Lastovicka (2019) found a different dependence of Mg II on F10.7 in 1979-1995 versus 1996-2014. Figure 2 is another example of different relationship between two solar proxies in 1979-1995 versus 1996-2014, here for sunspot numbers and F30.

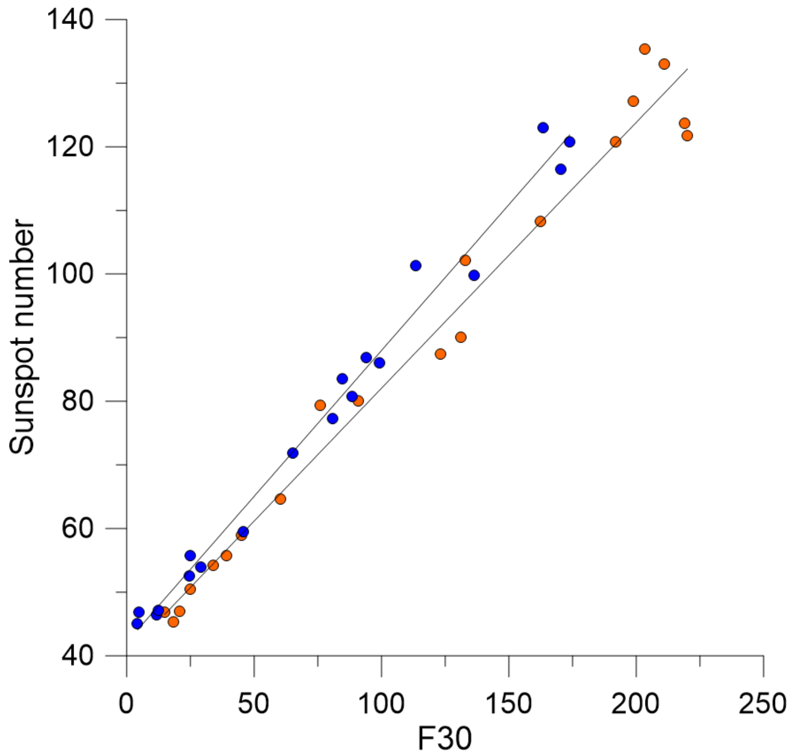

Figure 2. Dependence of yearly values of sunspot numbers on F30. 1996-2014 blue dots, 1979-1996 brownish dots.

Table 1 summarizes the ratios B2/B1 = B(1996-2014)/B(1976/1995), where B is the slope of solar activity dependence from equation (1), for relations between all solar activity proxies. For He II, values in parentheses are considered representative. The B2/B1 ratio is close to 1.00 (no change of relationship) for some pairs of solar activity proxies, namely Mg II – F30, He II – Mg II and L – He II. However, the B2/B1 ratio for majority of pairs of solar activity proxies differs from 1.00. For some of them the ratio differs clearly form 1.00, namely for pairs R – F30, F10.7 – F30, R – L and R – He II. Thus for majority (but not all) pairs of solar activity proxies the relationship between solar proxies differs between 1976-1995 (solar cycles 21 and 22) and 1996-2014 (solar cycles 23 and 24).

Table 1. 1996-2014 to 1976-1995 ratio of parameter B from equation Y = A + B*X for solar activity proxies; Y are solar indices on vertical axis, X on

horizontal axis; He II () – 1996-2010.

	F30 F10.7 Mg II R He II
L	1.07 0.95 1.10 0.98 (0.98)
He II	0.88 (0.96) 1.00 (1.06) 0.95 (1.02) 1.05
R	(1.10)
Mg II	0.88 1.03 0.91
F10.7	0.97 1.08
	0.89

The origin of these changes of relationships among solar activity proxies is not clear. It is likely related to the fact that different solar proxies are related to partly different parts of the solar irradiance spectrum and to different parts of the solar atmosphere. Mursula (2022) found that the solar spectral irradiance in the range from the near ultraviolet through visible to near infrared radiation changes its spectrum with time; some parts display positive, some parts negative and some parts no long-term trend over the period 2003-2019. Similar spectral changes in the EUV range (if they occur) could change the relationships between solar activity proxies. However, more investigations of this problem are necessary.

4 Relationships Between foF2 and Solar Activity Proxies

The question of stability or non-stability of the dependence of ionospheric parameters on solar activity proxies/indices is analyzed in terms of ratio B2/B1 = B(1996-2014)/B(1976/1995), where B is the slope from equation (1) for relations between foF2 and solar activity proxies. Table 2 summarizes the B2/B1 ratios for all six ionospheric stations and all six solar activity proxies. The B2/B1 ratio for F10.7 is clearly larger than 1.00, consistent with Lastovicka (2019); the same is valid for sunspot number R. The ratio is somewhat smaller for L but still clearly larger than 1.00. For He II and Mg II the ratio is in average still slightly larger than 1.00. However, for F30 it is in average equal to 1.00, i.e. the dependence of foF2 on F30 is the same in both periods. Thus for some solar activity proxies the relationship with foF2 changes substantially from 1976-1995 to 1996-2014, whereas for F30 it does not change at all.

The "most stable" solar activity proxy is F30. Laštovička (2021a, b) found for the three European stations F30 and Mg II to be the best/optimum solar activity proxies for analyzing yearly average values of foF2. Now we shall analyze in the same way the relationship between foF2 and solar proxies for the other three stations, Boulder, Canberra and Kokubunji. Table 3 shows the percentage of the total variance of foF2 described by equation (1) for yearly average values of foF2 for Boulder, Canberra and Kokubunji. Table 3 supports Mg II and F30 as the optimum solar proxies. However, differences between percentages for

Table 2. 1996-2014 to 1976-1995 ratio of parameter B from equation (1) for

foF2 of all six stations for both periods and for all six solar activity proxies. Ratio higher than 1 means steeper dependence of foF2 on solar proxy in 1996-2014.

Proxy	Mg II	F30	F10.7	R	L	He II
Juliusruh	0.96	1.15	1.07	1.07	1.00	
Pruhonice	1.10	1.08	1.28	1.25	1.19	1.13
Roma	1.07	1.01	1.22	1.18	1.15	1.06
Boulder	0.98	0.93	1.05	1.07	1.02	0.96
Kokubunji	1.05	1.01	1.13	1.13	1.09	1.06
Canberra	1.02	0.98	1.10	1.12	1.05	1.02

different solar proxies in Table 3 are very small. Therefore one more criterion is used. Table 4 shows mean absolute differences (averaged irrespective of sign) with standard errors between observed and model (equation 1) values of foF2 in MHz for yearly average values. Table 4 displays the smallest differences between observed and model values of foF2 for F30 and Mg II and, therefore, it confirms as optimum solar activity proxies Mg II and F30. Perna and Pezzopane (2016) recommend Mg II for description of foF2 behavior in the deep solar minimum 2008/2009. Gulyaeva et al. (2018) recommend Mg II as the best solar proxy for ionospheric modeling. De Haro Barbas et al. (2021) analyzed foF2 from three Japanese stations and found Mg II to be better than L , F10.7 and R. However, these authors did not consider F30. Dudok de Wit and Bruinsma (2017) claim that F30, which correlates with Mg II better than F10.7, is more appropriate solar proxy for thermospheric density studies than F10.7.

Table 3. Percentage of the total variance of foF2 described by equation foF2 = A + B * solar proxy for yearly average values of foF2. I - 1976-1995, II - 1996-2014, * - 1979-1995, $^{\#}$ - 1996-2010. Bold – the highest described percentage. Lat – geographic latitude. Long – geographic longitude. Mlat – geomagnetic latitude (IGRF 1995).

	Lat Long Mlat	Mg II F30 F10.7 R L He II
Boulder I II	40.0N 254.7E 47.5N	**99%** 99% 98% 97% 97% **99%99%** 99%98%97%98% **98%** **98**% 97% 97% 98% 87% **99%$^{\#}$** **99%$^{\#}$** 99%$^{\#}$ 99%$^{\#}$ 99%$^{\#}$ 98%$^{\#}$

	Lat Long Mlat	Mg II F30 F10.7 R L He II
Canberra I II	35.3S 149.0E 43.1S	% 99% 98% 97% 98% **99%** 99%99%98%98%98% **100%** 99% 99% 99% 98% 91% **100%**# 99%# 100%# 100%# 98%# 99%#
Kokubunji I II	35.7N 139.5E 26.2N	**99% 99%** 98% 97% 98% **99%99%99%** 98%98%98% **99% 99% 99%** 99% 98% 93% **99%# 99%# 99%#** 99%# 98%# 99%#

Thus Mg II and F30 are the best/optimum solar activity proxies for analyses of long-term series of yearly values foF2, based on very long data series (1976-2014) from six midlatitude ionospheric stations from four continents. It should be mentioned that Laštovička (2021b) found the same optimum solar proxies for monthly median values of the three European

Table 4. Mean absolute differences (averaged irrespective of sign) with standard errors between observed and model (equation 1) values of foF2 in MHz for yearly average values for midlatitude stations. I - 1976-1995, II - 1996-2014, * - 1979-1995, # - 1996-2010. foF2av – average value of foF2 over the whole period in MHz. Bold – the smallest differences. Lat – geographic latitude. Mlat – geomagnetic latitude (IGRF 1995).

	Lat Mlat foF2av	Mg II F 30 F10.7 R L He II
Boulder I II	40.0N 47.5N 7.66 7.41	**0.17**±0.11 0.20±0.13 0.24±0.15 0.30±0.23 0.29±0.21 0.17* **0.15*** 0.20* 0.26* 0.30* 0.28* 0.20±0.13 **0.20**±0.12 0.22±0.18 0.21±0.22 0.21±0.17 0.17# **0.16**# 0.15# 0.16# 0.17# 0.20#

	Lat Mlat foF2av	Mg II F 30 F10.7 R L He II
Canberra I II	35.3S 43.1S 7.85 7.35	**0.14**±0.13 0.17±0.13 0.21±0.13 0.25±0.20 0.19±0.18 **0.15*** **0.11*** 0.16* 0.20* 0.23* 0.16* **0.11**±0.08 **0.12**±0.08 0.15±0.13 0.11±0.11 0.20±0.11 **0.09**$^{\#}$ **0.10**$^{\#}$ 0.10$^{\#}$ 0.08$^{\#}$ 0.16$^{\#}$ 0.16$^{\#}$
Kokubunji I II	35.7N 26.2N 9.10 8.30	±0.12 0.22±0.16 0.24±0.21 0.29±0.22 0.27±0.22 **0.18*** 0.21* 0.24* 0.27* 0.28* 0.25* **0.12**±0.11 0.17±0.13 0.19±0.11 0.15±0.10 0.22±0.15 **0.13**$^{\#}$ 0.18$^{\#}$ 0.21$^{\#}$ 0.14$^{\#}$ 0.23$^{\#}$ 0.20$^{\#}$

stations. F30 is the only solar proxy which provides the same dependence of foF2 on solar proxy for 1976-1995 and 1996-2014 but this dependence changes only slightly for Mg II. F30

is available over longer time interval than Mg II (not available before November 1978). Dudok de Witt and Bruinsma (2017) recommend F30 as the best solar activity proxy for studying the thermospheric neutral density. Therefore we can recommend F30 as the optimum solar activity proxy and Mg II as the second one for analyzing yearly (probably also monthly) values of foF2 at middle latitudes (particularly for analyses of long data series), not traditionally used parameters F10.7 and sunspot numbers. As concerns daily values of foF2, we cannot exclude different result; this is also the case for other ionospheric parameters. Preliminary results for foE favor rather F10.7 (Laštovička**,** 2021b).

5. Conclusions

We analyzed yearly average values of solar activity proxies and foF2 measured at six midlatitude ionospheric stations from four continents over the periods 1976-1995 and 1996-2014. The main results are as follows:

1. The relationships among different solar activity proxies very predominantly change from solar cycles 21 and 22 to solar cycles 23 and 24. The origin of these changes is not well understood.

2. The relationship between foF2 and solar activity proxies between the periods 1976-1995 and 1996-2014 did not change for F30, changed a little for Mg II and He II, changed more for L , and it changed quite clearly for F10.7 and sunspot numbers.

3. The optimum solar activity proxies F30 and Mg II describe 99% of total variance of yearly values of foF2; they are better than traditional F10.7 and sunspot numbers.

4. F30 is available over longer period than Mg II. Taking into account all above findings, we recommend F30 as the best solar activity proxy for examining yearly values (particularly long series) of foF2, and Mg II as the second one.

It would be interesting to carry out similar study for low latitudes. However, we found in data bases only two stations without substantial data gaps, which cover the whole period 1976-2014, Okinawa and Townsville, which are from the same longitudinal sector. Other stations cover only the first or the second sub-period. Moreover, preliminary results show that equation (1) is oversimplification for low latitudes and a multi-parameter regression has to be used, and that at equatorial latitudes rather He II is the optimum solar proxy. A broader investigation and data mining are necessary in future for low/equatorial latitudes.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data used in this study are publicly available on the following websites. Solar activity indices were taken from: F10.7 (observed) - https://lasp.colorado.edu/lisird/data/noaa_radio_flux/, F30 - https://solar.nro.nao.ac.jp/norp/data/daily/, F - https://lasp.colorado.edu/data/timed_see/composite_lya/version3/, Mg II - http://www.iup.uni-bremen.de/UVSAT/Datasets/mgii, sunspot numbers R were taken from https://sidc.be/silso/datafiles, He II - from the SOLID project database https://projects.pmodwrc.ch/solid-visualization/makeover/index.php?type=proxy&waveStart=215&waveEnd=215&dateStart=1970-01-01&dateEnd=2014-12-31, with the option: Proxies > Data selections > He II > Download.

Ionospheric foF2 data were taken from: http://www.ukssdc.ac.uk/wdcc1/iono_menu.html, http://giro.uml.edu/didbase / (click on station list and select station), http://www.eswua.ingv.it/ewphp/landing.php?doi=hf, sws.bom.gov.au/World_Data_Centre/1/3, and wdc.nict.go.jp/IONO/HP2009/ISDJ/index-E.html.

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