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The best solar activity proxy for long-term ionospheric investigations

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Abstract

To select the best solar activity proxy is important for long-term trend or climatological studies of ionospheric parameters as well as for modeling. We deal with solar proxies for foF2 and foE analyses. The yearly average and monthly median values of foF2 and yearly values of foE of selected European stations with long and high-quality data series are used. Four solar proxies are utilized: F10.7, F30, Mg II and He II. Mg II and F30 are found to be the best solar proxies for both yearly and monthly foF2 values as well as for years of deep solar minima (2008–09, 2018–19). On the other hand, F10.7 is found to be the best solar proxy for yearly values of foE. The variability of yearly values of foF2 and foE is almost fully described by solar proxies and this relation is highly linear. Different solar proxies applied might result in somewhat different long-term trends of both foF2 and foE. All the results were derived for the European area.
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Keywords: Midlatitude ionosphere; Solar activity proxies

1. Introduction

The ionosphere is created mainly by the solar ionizing flux. However, long and homogeneous datasets of the solar ionizing flux required for long-term trend studies are not available. Therefore solar proxies have to be used. However, there are various solar proxies and their application leads to somewhat different results. So we have to select the best solar proxy.

The problem of the best solar proxy has been studied to some extent. In the past the sunspot number R was often used. Laštovička et al. (2006) and Mielich and Bremer (2013) came to conclusion that for investigating long-term trends in foF2, F10.7 is better than R but they used R values before their re-evaluation. However, Deminov et al. (2020) and Laštovička (2021) used re-evaluated sunspot numbers (e.g., Clette et al., 2016) and came to the same conclusion for foF2 as well as foE. F10.7 replaced R in most of more recent long-term trend studies. On the other hand, Perna and Pezzopane (2016) recommend Mg II index for description of foF2 behavior in the deep solar minimum 2008/2009. Laštovička (2021) used F10.7, Mg II, R and solar H Lyman-alpha flux and came to conclusion that the optimum solar proxy for yearly average values of foF2 is Mg II followed by F10.7, whereas F10.7 outperforms Mg II for foE, whereas R and Lyman-alpha flux perform less well, even though not poorly.

Lean et al. (2011) and Lastovicka et al. (2017) found Mg II to slightly outperform F10.7 for studying long-term changes of the global total electron content (G-TEC). Goncharenko et al. (2021) presented a new high-resolution empirical model for the ionospheric TEC based on data over 2000–2019. They used several solar proxies and based on daily values they found the solar EUV 0.05–105.05 nm flux from the FISM2 (Flare Irradiance Spectral Model) to be the best closely followed by Mg II. FISM2 is described by Chamberlin et al. (2020); it is based on SORCE XPS L4, SDO EVE, and SORCE SOLSTICE data, and extended in time using solar proxies like F10.7 or Mg II. However, non-extended FISM-2 flux are

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available only over a limited time interval. There are also other sophisticated solar EUV proxies like EUV flux proxy based on GOLD (Global-scale Observations of the Limb and Disk) observations (Schmöller et al., 2021) used in TEC analyses but they are available usually over time interval insufficient for long-term trend studies. Gulyaeva et al. (2018) recommend Mg II as the best solar proxy for ionospheric modeling. 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 mass density than F10.7. Vaishnav et al. (2019) used 12 different solar proxies and G-TEC derived from IGS maps over 1999–2017. They found that on time scales of 16–32 and 32–64 days, He II is the best solar proxy followed by Mg II, Lyman-alpha flux and F30 as the seconds, all with time delay of one day. Therefore it is necessary to check if He II and F30 perform better than Mg II and F10.7 for foF2 and foE long-term studies.

This paper is the final paper of series of three papers dealing with solar proxies for ionospheric studies. Laštovička (2019) found that the relationship between solar proxies is not stable with time; the dependence on solar proxies is steeper than before for foF2 after ~1996 and for foE after ~2000. Laštovička (2021) used solar proxies F10.7, F30, Mg II and solar H Lyman-aplha flux and found Mg II to be the best solar proxy for foF2 and F10.7 for foE. Here we extend these investigations by including two other solar proxies, which are potential candidates for the best proxy according to Dudok de Wit and Bruinsma (2017) – F30 - and Vaishnav et al. (2019) – He II. Moreover I analyze not only yearly average values as in my previous papers but for foF2 also monthly median values and conditions of very deep solar activity minima, when the ionosphere can behave in a specific way (e.g., Buresova et al., 2014).

The objective of this study is to find the best solar proxies for long-term foF2 and foE investigations. Specifically answers to three questions are searched for:

(1) What is the best solar proxy for studying long-term evolution of yearly average values of foF2 and foE?

(2) What is the best solar proxy for reproducing foF2 yearly values in deep solar minima?

(3) What is the best solar proxy for season-representing monthly values of foF2 (January, April, July, October)?

For this purpose we use foF2 from three representative European ionospheric stations and foE with long and homogeneous data series, and four solar proxies F10.7, F30, He II and Mg II. Whereas for foF2 we will deal with all three questions, for foE we will only deal with question (1). For (2), July data on foE are less reliable due to the often presence of screening Es layer, i.e. missing foE. As for (3), foE recent data from the studied period suffer with data problems (Laštovička et al., 2016; Laštovička, 2019; Araujo-Pradere et al., 2019).

Section 2 describes data and methods used, section 3 deals with results and discussion for foF2, section 4 deals with results and discussion for foE, and section 5 contains conclusions.

2. Data and methods

The F2-layer critical frequency foF2 data of 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) and the E-layer critical frequency foE of Juliusruh and Slough/Chilton (51.5°N, 1.3°W) are used. Historical foF2 data were taken from http://www.ukssdc.ac.uk/wdcc1/iono_menu.html, more recent data from http://spidr.ionosonde.net/spidr and http://giro.uml.edu/ except for Rome, where data were taken from http://www.eswua.ingv.it/ingv/i_rom.php (Romano et al., 2008). Analysis is performed for noontime yearly average values, calculated as the average from monthly medians, which were calculated from daily medians over 11–13 LT (noontime). The analyzed period 1976–2014 is divided into two sub-periods, 1976–1995 and 1996–2014 for foF2, because the dependence of foF2 on solar proxies differs in the selected sub-periods for stations used here; the dependence is stronger for the second period (Laštovička, 2019). As for foE, Laštovička (2019) divided the period 1976–2014 into sub-periods 1976–1999 and 2000–2014 with a different dependence of foE on solar proxies. However, 2000–2014 suffers with data quality problems in late years (Laštovička et al., 2016; Laštovička, 2019), so only the period 1976–1999 is analyzed. Years 1989 and 1991 are excluded from foF2 analyses, because they suffer with saturation of dependence of foF2 on solar activity (Laštovička, 2019). For task (2) we use also data from the recent deep solar minimum, years 2018 and 2019.

Four solar proxies are used, F10.7, F30, He II and Mg II. F10.7 data were taken from ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-radio/noontime- flux/penticton/penticton_observed/tables/, F30 from ftp://ftpsedr.cls.fr/pub/previsol/solarflux/observation/, Mg II from http://www.iup.uni-bremen.de/UVSAT/Datasets/mgii. He II data were taken from the SOLID project database, /pub/projects/SOLID/database/l4/pddw.nc.

A simple linear regression (1), often used to remove solar cycle effect in calculating long-term trends in ionospheric parameters, is used in all further analyses:

$$X_{ion} = A + B * solar\ proxy \quad (1)$$

where X_{ion} is either foF2 or foE and the solar proxy is either F10.7, or F30, or He II, or Mg II.

3. Results and discussion – foF2

Equation (1) may be used only if it describes a large majority of total variance of ionospheric parameters studied. Table 1 presents the percentage of the total variance of yearly average values of foF2, calculated as

Table 1
Percentage of total variance of foF2 described by equation foF2 = A + B * solar proxy (F10.7, Mg II, F30 or He II) for yearly average values, and January, April, July and October median monthly values. I – 1976–1995, II – 1996–2019.

		F10.7					Mg II				
		Year	Jan	Apr	July	Oct	Year	Jan	Apr	July	Oct
Roma	I	98%	94%	94%	94%	97%	98%	95%	92%	98%	98%
	II	99%	95%	98%	89%	95%	100%	96%	97%	95%	98%
Pruhonice	I	98%	94%	95%	85%	93%	98%	96%	97%	91%	95%
	II	99%	98%	97%	84%	93%	100%	98%	98%	93%	94%
Juliusruh	I	99%	98%	91%	91%	95%	99%	98%	92%	95%	97%
	II	99%	97%	98%	88%	94%	99%	98%	97%	92%	95%
		F30					He II				
Roma	I	98%	95%	94%	98%	93%	97%	93%	92%	95%	98%
	II	99%	96%	98%	92%	94%	92%	97%	91%	89%	88%
Pruhonice	I	98%	96%	96%	91%	90%	95%	94%	87%	92%	92%
	II	99%	98%	98%	89%	93%	91%	96%	88%	86%	84%
Juliusruh	I	99%	98%	94%	95%	92%	97%	97%	90%	94%	93%
	II	100%	97%	99%	91%	93%	91%	97%	90%	84%	84%

square of correlation coefficient. 98% and more of the total variance of yearly values of foF2 are described by equation (1) with Mg II, F30 and F10.7. This means that we may use Eq. (1), that the solar activity quite dominantly controls the yearly values of foF2, and that the dependence of yearly values of foF2 on solar activity is highly linear. He II performs less well than the other three solar proxies. Monthly values generally reveal somewhat lower percentage than yearly values, which is understandable. The monthly values are more sensitive to geomagnetic disturbances, to atmospheric waves and to other "meteorological" phenomena. The lowest percentage of the total variance occurs in July. This is probably due to much higher occurrence frequency of sporadic-E layer, which might screen the F2 layer, which results in lower number of foF2 data. Table 1 indicates that He II is not the best solar proxy; the other three proxies perform better. Mg II and F30 perform best. F10.7 performs slightly worse but the difference from Mg II and F30 performances is rather marginal.

The linear dependence on He II performs worse than the linear dependences with other three solar proxies. foF2 is proportional to square root from the maximum electron density NmF2. NmF2 is proportional to ionization rate, which is proportional to the intensity of ionizing radiation. This is simplification but it means that foF2 should be proportional rather to $(\text{He II})^{1/2}$ than to He II. However, the average percentages of total variance of foF2 described by He II and $(\text{He II})^{1/2}$ do not differ (not shown here).

Another way how to search for the best solar proxy is to calculate the mean absolute difference (averages irrespective of sign) between the observed and modeled (equation (1)) values of foF2. They are shown in Table 2 for the three better proxies F10.7, F30 and Mg II.

Table 2 clearly shows that F10.7 performs slightly worse than F30 and Mg II. Out of 30 yearly and monthly cases, in 24 cases it reveals the largest difference (worst performance), in no case F10.7 performs best and only in one case all three proxies perform equally. On the other hand, the performances of Mg II and F30 are in average equal. They are the best solar proxies. Again the performances for yearly values are better (smaller differences) for yearly values than those for monthly values for the same reasons as discussed with Table 1. Tables 1 and 2 perhaps indicate that Mg II is very slightly better than F30; on the other hand, Mg II is available since November 1979 only, whereas F30 is available since November 1957. The average yearly values of foF2 for Rome, Pruhonice and Juliusruh are 8.39, 7.61 and 7.63 for the first period, and 7.80, 7.29 and 7.08 MHz for the second period, respectively. Thus the mean absolute differences of yearly values shown in Table 2 are 2–3% of average values of foF2 for the first period and less than 2% for the second period.

Laštovička (2021) came to conclusion that Mg II is better solar proxy than F10.7 for yearly values of foF2. Lean et al. (2011) and Lastovicka et al. (2017) found Mg II to slightly outperform F10.7 for studying long-term changes of the global total electron content (G-TEC). Gulyaeva et al. (2018) recommend Mg II as the best solar proxy for ionospheric modeling. Dudok de Wit and Bruinsma (2017) claim F30 to be a more appropriate solar proxy for thermospheric mass density than F10.7. All these findings are consistent with our results on the best solar proxies Mg II and F30 for foF2. On the other hand, the result of Vaishnav et al. (2019) that for G-TEC on time scales of 16–32 and 32–64 days, He II is the best solar proxy followed by Mg II and F30, is not consistent with our results based on monthly values of foF2, which favor Mg II and F30 for foF2. However, it is necessary to mention that Laštovička (2021) found that the best solar proxies might differ for different ionospheric parameters.

Fig. 1 shows the evolution of differences between observed and model (equation (1)) yearly values for Pruhonice, 1996–2014 (the period of smallest differences according to Table 2). F10.7-foF2 (green curve) displays evidently larger deviations from the zero difference level than the foF2 differences calculated with the other two solar proxies. On the other hand, the deviations from the zero difference level are in average comparable for F30

Table 2
Mean absolute differences (average calculated irrespective of sign) between observed and model (Eq. (1)) values of foF2 in MHz for Juliusruh, Pruhonice and Rome. * - only 1979–1995.

	foF2 Juliusruh			foF2 Pruhonice			foF2 Rome		
	F10.7	F30	Mg II	F10.7	F30	Mg II	F10.7	F30	Mg II
Year									
1976–1995	0.22	0.17	0.18*	0.22	0.17	0.19*	0.32	0.20	0.23*
	0.22*	0.16*		0.22*	0.14*		0.37*	0.22*	
1996–2014	0.14	0.11	0.12	0.15	0.11	0.09	0.17	0.12	0.10
January									
1996–2014	0.36	0.28	0.30*	0.47	0.39	0.38*	0.42	0.36	0.39*
	0.42*	0.28*		0.52*	0.43*		0.47*	0.38*	
1996–2014	0.32	0.35	0.30	0.24	0.21	0.21	0.40	0.35	0.35
April									
1976–1995	0.40	0.28	0.38*	0.29	0.28	0.21*	0.47	0.41	0.42*
	0.46*	0.30*		0.28*	0.25*		0.51*	0.44*	
1996–2014	0.18	0.18	0.18	0.30	0.22	0.25	0.26	0.25	0.26
July									
1996–2014	0.24	0.17	0.19*	0.31	0.26	0.22*	0.28	0.17	0.17*
	0.23*	0.17*		0.30*	0.23*		0.27*	0.15*	
1996–2014	0.22	0.21	0.16	0.31	0.24	0.22	0.35	0.25	0.20
October									
1976–1995	0.42	0.49	0.36*	0.34	0.48	0.39*	0.33	0.37	0.35*
	0.40*	0.44*		0.39*	0.53*		0.38*	0.39*	
1996–2014	0.44	0.31	0.37	0.48	0.34	.035	0.42	0.33	0.27

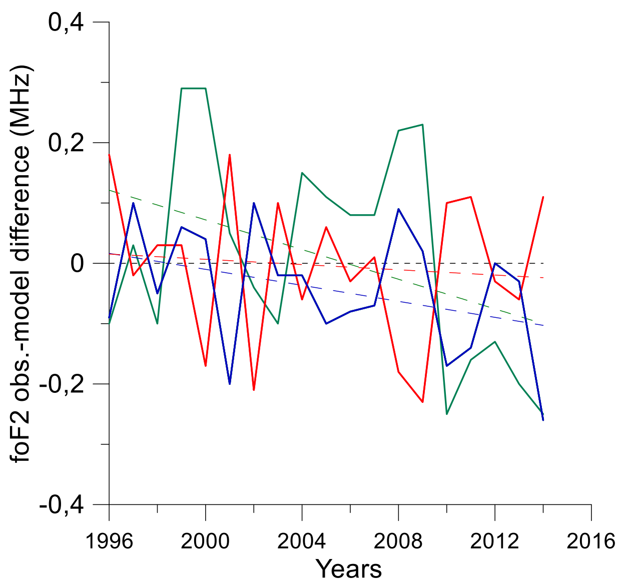

Fig. 1. Differences between observed and model (Eq. (1)) yearly values of foF2 for Pruhonice, 1996–2014. Green curve - solar activity proxy F10.7; blue curve – solar proxy F30; red curve – solar proxy Mg II; longer-dash colored lines – respective linear trends; short-dash black horizontal line – zero difference level. A negative difference means smaller observed than model value.

(blue curve) and Mg II (red curve), even though in individual years they can differ noticeably. This again supports Mg II and F30 as equally good and best solar proxies for yearly values of foF2.

Fig. 1 illustrates how important is the selection of solar activity proxy for long-term trends calculations. F10.7 (green curve) reveals a negative trend of foF2, Mg II (red curve) reveals a very weak negative trend of questionable reliability, and F30 (blue curve) provides essentially no trend. Thus trends calculated with different solar proxies might be different.

One of the tasks (see Introduction) is to answer question: What is the best solar proxy for reproducing foF2 yearly values in (deep) solar minima? Table 3 shows that "normal" solar minima 1976–1977, 1985–1986 and 1995–1996 reveal a comparable occurrence frequency of both positive and negative observation-model differences; in other words there is no systematic bias between model and observational foF2 values for these solar cycle minima. On the other hand, deep solar minima 2008–2009 and 2018–2019 display either negative differences or differences close to zero. The differences under the deep solar minimum conditions appear to be in average smallest for Mg II but F30 is only marginally worse, whereas F10.7 performs less well. This coincides with recommendations of Lean et al. (2011) to use Mg II instead of F10.7 for TEC in the deep solar minimum 2008–2009 and with the results of Perna and Pezzopane (2016), who recommended Mg II instead of F10.7 for foF2 from Rome in the deep minimum 2008–2009.

4. Results and discussion – foE

Table 4 shows that Eq. (1) can be well used for yearly average values, as it describes 99% of the total variance of foE with F10.7 for both stations Juliusruh and Slough/Chilton. It also reveals F10.7 as candidate for the best solar proxy for foE.

Another criterion is to use the mean absolute differences between observed and model (Eq. (1)) values of foE in

Table 3
Differences between observed and model (Eq. (1)) yearly values for the last five solar cycle minima and solar proxies F10.7, Mg II, F30 and He II. The extreme minima of cycles 23/24 and 24/25 are separated in the bottom part. A negative difference means smaller observed than model value.

	Roma				Pruhonice				Juliusruh			
	F10.7	Mg II	F30	He II	F10.7	Mg II	F30	He II	F10.7	Mg II	F30	He II
1976	−0.19		0.11	0.27	0.07		0.27	0.39	−0.04		0.19	0.35
1977	−0.04		0.09	0.11	−0.13		0.19	0.20	0.10		0.18	0.22
1985	−0.20	−0.09	−0.06	−0.36	−0.20	−0.17	−0.07	−0.34	−0.12	0.04	0.04	−0.19
1986	−0.24	0.01	0.09	0.11	−0.14	0	−0.01	−0.13	−0.07	0.14	0.09	0.02
1995	−0.09	−0.18	−0.01	−0.02	0.04	−0.06	0.06	0.12	−0.12	−0.16	−0.09	0.02
1996	−0.07	−0.02	0.11	−0.45	0.11	0.11	0.18	−0.27	−0.02	0.04	−0.04	−0.13
2008	−0.02	0.08	0.02	−0.05	−0.20	−0.07	−0.18	−0.27	−0.02	0.04	−0.04	−0.13
2009	−0.27	−0.13	−0.32	−0.28	−0.21	0	−0.23	−0.27	0.02	0.01	−0.05	−0.04
2018	−0.16	−0.14	−0.11		−0.22	−0.12	−0.15		−0.13	−0.11	−0.11	
2019	−0.22	−0.22	−0.15		−0.22	−0.14	−0.12		−0.22	−0.21	−0.17	

Table 4
Percentage of the total variance of foE described by equation foE = A + B * solar proxy (F10.7, Mg II, F30 or He II) for yearly values, 1976–1999. Values in brackets – values without year 1991.

	F10.7	F30	Mg II	He II
foE Juliusruh	99% (99%)	97% (97%)	97% (98%)	97% (97%)
foE Slough/Chilton	99% (99%)	97% (97%)	95% (98%)	96% (96%)

MHz for Juliusruh and Slough/Chilton, 1976–1999 in a similar way as for foF2 in Table 2. Table 5 shows the mean absolute differences for yearly average values of foE. When calculating these differences it was found that the Mg II Slough/Chilton for 1991 is an extreme outlier, 0.21, 6-times larger than the mean value. It is a consequence of combination of two factors: (a) foE Slough/Chilton values in 1991, which provide positive outliers for all solar proxies and (b) Mg II for 1991, which results in positive outliers for both Juliusruh and Slough/Chilton. Therefore the year 1991 is excluded. Values in brackets in Tables 5 and 4 are calculated without year 1991. The values in brackets are considered to be more reliable. Table 4 then supports F10.7 still as the best solar proxy but Mg II as the second best proxy. Table 5 also supports F10.7 as the best solar proxy for both stations but with Mg II and F30 as the second best proxies. Anyway He II performs slightly less well than the other three proxies. The average yearly values of foE for Juliusruh and Slough/Chilton are 3.10 and 3.18 MHz, thus the mean absolute differences of yearly values shown in Table 5 are about 1% of the average yearly values of foE.

Fig. 2 shows the evolution of the differences between observed and model (Eq. (1)) yearly values of foE for Juliusruh, 1976–1999. It again supports F10.7 (green curve) as the best solar proxy (the smallest differences). Fig. 2 reveals less difference between trends with different solar proxies than Fig. 1 for foF2. There is no visible trend of foE with solar proxy F10.7, particularly if we consider also 1991 value of the difference + 0.02. On the other hand, He II and less expressed F30 reveal some tendency to a negative trend in foE.

5. Conclusions

This paper finalizes a series of papers (Laštovička, 2019; 2021) dealing with dependence of ionospheric parameters, particularly of foF2, on solar activity proxies using a long data series (1976–2014) for selected European ionosonde stations and six solar activity proxies. The main relevant conclusions of the previous two papers based on yearly average values and four solar proxies are as follows:

(a) The dependence of foF2 on solar activity proxies differs in periods 1976–1995 and 1996–2014, for foE it differs in periods before and after 2000.
(b) Solar proxies the sunspot numbers and solar H Lyman-alpha flux perform less well than Mg II and F10.7 for foF2 and less well than F10.7 for foE.

Table 5
Mean absolute differences (average irrespective of sign) between observed and model (Eq. (1)) values of foE in MHz for Juliusruh and Slough/Chilton, 1976–1999. * - only 1979–1999. Values in brackets – values without year 1991.

	F10.7	F30	Mg II*	He II
foE Juliusruh	0.018 (0.018)	0.026 (0.027)	0.034 (0.029)	0.037 (0.036)
foE Slough/Chilton	0.029 (0.026)	0.034 (0.033)	0.038 (0.029)	0.041 (0.037)

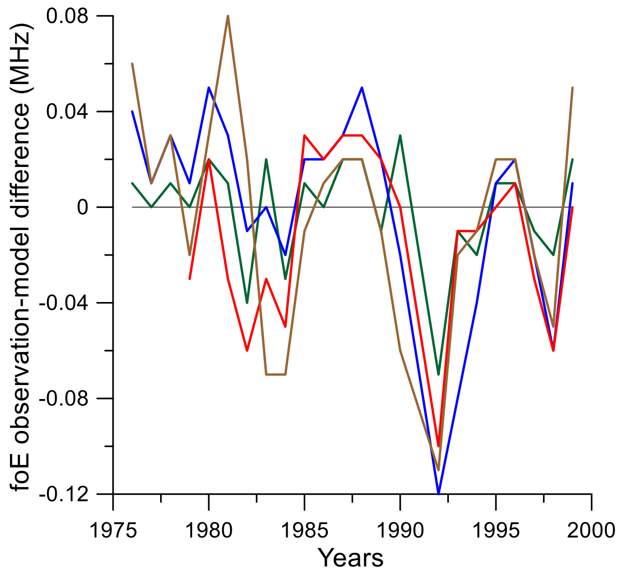

Fig. 2. Differences between observed and model (Eq. (1)) yearly values of foE for Juliusruh, 1976–1999. Green curve - solar activity proxy F10.7; blue curve – solar proxy F30; red curve – solar proxy Mg II; brown curve – solar proxy He II; black horizontal line – no difference level. A negative difference means smaller observed than model value.

(c) The best solar proxies and the relative roles of various solar proxies might be different for different ionospheric parameters.
(d) The yearly average values of ionospheric parameters are very dominantly controlled by solar activity represented by proxies even under assumption of simple linear dependence.

In this paper we used two other solar proxies, F30 and He II, together with Mg II and F10.7 and for foF2 also monthly median values and values from one more extreme solar activity minimum, 2018 and 2019. The main results on solar proxies suitable for fof2 and foE studies, reached in this paper, are as follows:

(1) The best solar proxies for both yearly average and monthly median values of foF2 are Mg II and F30 followed by F10.7. He II performs less well.
(2) The best solar proxy for the yearly average values of foE is F10.7 followed by Mg II and F30. He II performs less well.
(3) The foF2 yearly average values in years of deep solar minima, 2008–09 and 2018–19 are reproduced best again by Mg II and F30.
(4) The dependence of foF2 and foE on solar proxies is highly linear; the linear dependence reproduces large majority of variability of particularly yearly values of both foF2 and foE (~99% of total variance for the best solar proxies).
(5) Selection of the right solar proxy is important for foF2 and foE long-term trend studies. The trends with different solar proxies applied might be different (Fig. 1); the best solar proxies tend to reveal weaker trends than the other solar proxies.

The results were obtained for Europe and noontime (11–13 LT). However, it might be expected that they are valid at least for middle latitudes in general.

The reason for different most suitable solar proxies for different ionospheric parameters could be that various ionospheric layers are ionized by different parts of solar spectrum. It should be mentioned that the best solar proxies might in principle be different for yearly, monthly and daily average values of ionospheric parameters; our results are derived for yearly and partly monthly values.

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