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Dependence of long-term trends in foF2 at middle latitudes on different solar activity proxies

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Abstract

The most studied ionospheric parameter for long-term trends is foF2. The dominant factor of foF2 variability is the solar cycle, which is much stronger than the long-term trends. Therefore its effect in data must be removed. However, several decade long homogeneous measurements of the solar EUV fluxes are not available, so various solar activity proxies (solar activity indices) must be used. The aim of this paper is to study the impact of selection of different solar activity proxies on foF2 long-term trends and to find the best solar activity proxy for foF2 trends at middle latitudes. The results based on yearly average data of six midlatitude stations from four continents (1976–2014) and of six solar activity proxies show that the long-term trends in foF2 depend substantially on the solar activity proxy used, and the only solar proxy, which provides trends of the same sign for all stations and both sub-periods, is F30. Based on results of this paper and that of Laštovička and Burešová (2023), I can recommend F30 as the best solar proxy for studying long-term trends of foF2 at middle latitudes (at least for yearly average values).

Keywords: Ionosphere; Long-term trends; Solar activity proxies

1. Introduction

The most studied ionospheric parameter for long-term trends is foF2, because the global network of ionosondes provides foF2, some stations even very long data series, and because foF2 is important for ionospheric radio wave propagation in telecommunications and other systems. The dominant factor of foF2 climatological variability is the solar cycle, which is much stronger (by more than an order of magnitude on one-decade scale) than the long-term trends. Therefore its effect in data must be removed before studying long-term trends. However, several decade long homogeneous measurements of the solar EUV fluxes are not available, so various solar activity proxies (solar activity indices) must be used. Various solar activity proxies correspond to various parts of solar radiation spectrum; therefore it is possible that the use of different solar activity proxies results in somewhat different trends of foF2. An overview of trends in foF2 has recently been published by Laštovička (2022). The aim of this paper is to study the impact of selection of different solar activity proxies on foF2 long-term trends and to find the best solar activity proxy for foF2 trends at middle latitudes (much more long-term data series are available at middle than at low/equatorial and/or high latitudes).

Laštovička (2021a, 2021b) and Laštovička and Burešová (2023) used six solar activity proxies and they came to conclusion that F30 followed by Mg II are the best solar activity proxies for yearly average values of foF2 at middle latitudes, not the traditional proxies F10.7 and sunspot numbers R. This result is supported by the results of Dudok de Wit and Bruinsma (2017) that F30 is the best solar index for studying and modeling thermospheric neu-

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tral density. As for the ionosphere, Maruyama (2010), Lean et al. (2011), Perna and Pezzopane (2016), Gulyaeva et al. (2018) and Goncharenko et al. (2021) claim that Mg II is better for ionospheric studies than F10.7 or R but these authors did not consider F30 in analyses. Danilov and Konstantinova (2023) found for Juliusruh station the Lyman-α flux, Mg II and F30 to be better solar activity proxies than sunspot numbers and F10.7. Zossi et al. (2023) used 12 stations from Europe, Japan and Australia and found Mg II and F30 to be the best solar proxies for foF2. Nevertheless I will use all six solar proxies in further investigations to point out the difference in trend results due to applying different solar activity proxies.

Section 2 contains information about data and method, section 3 describes results, section 4 contains discussion of results, and the paper is closed by conclusions in section 5.

2. Data and method

Mid-latitude ionospheric critical frequency foF2 data obtained from a north–south chain of European stations Juliusruh (54.6°N, 13.4°W), Pruhonice (49.98°N, 14.55°E) and Roma (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) are used together with solar activity proxies F10.7 (solar radio noise at a wavelength 10.7 cm), F30 (solar radio noise at a wavelength 30 cm), R (sunspot number), Lα (solar H Lyman-alpha flux), Mg II (core-to-wing ratio of Mg II line), He II (solar flux in 26–34 nm dominated by the He II line at 30.4 nm). Re-calibrated sunspot numbers R is used (Clette et al., 2016). These data are analyzed over the period 1976–2014, divided into two sub-periods 1976–1995 and 1996–2014, because the dependence of foF2 on F10.7 was found to be clearly different in these two sub-periods for European stations (Laštovička, 2019) and Laštovička and Burešová (2023 – their Table 8) found some difference between sub-periods for all other four solar proxies except for F30.

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, which reduce the effects of large deviations, particularly effects of geomagnetic storms.

Calculations of long-term trends were performed in three steps. First, the dependence of foF2 on solar proxies was calculated by linear regression, Eq. (1):

$$foF2 = A + B * \text{solar proxy} \quad (1)$$

This was already done by Laštovička (2021a, 2021b) and Laštovička and Burešová (2023), who also demonstrated that Eq. (1) with the optimum solar activity proxies describes 99% of the total variance of foF2 for yearly values and, therefore, such a simple linear regression may be used. Second, using Eq. (1) with parameters A and B calculated in the first step, model values of foF2mod were calculated for all individual years and all solar proxies. Third, using linear regression for foF2 residuals, Eq. (2):

$$foF2_{obs} - foF2_{mod} = C + D * \text{time} \quad (2)$$

where $foF2_{obs}$ is the observed value of foF2, the long-term trend represented by the trend coefficient D was calculated.

3. Results

First, two examples of dependence of foF2 trends on different solar activity proxies are shown. Fig. 1 show for Pruhonice, 1996–2014, long-term trends of foF2 derived with the use of solar activity proxies F10.7, F30 and Mg II. While application of F10.7 results in a negative trend, application of Mg II results in a weak negative trend, and application of F30 provides practically no trend (a negligible negative trend). Thus trends for different solar proxies used are clearly different.

Fig. 2 is another example, which however provides a different pattern of long-term trends compared to Fig. 1. The application of F30 reveals a negative trend, whereas application of Mg II provides a weaker positive trend and application of F10.7 provides a weak and insignificant positive trend.

Table 1 summarizes all trend coefficients for all six stations, all six solar proxies and separately for periods 1976–1995 and 1996–2014. Boulder 1996–2014 results are not reliable due to many data gaps (Laštovička and Burešová, 2023). Mg II* data are not available before 1979; He II** data in 2011–2014 do not look reliable (Laštovička and Burešová, 2023). The only solar proxy,

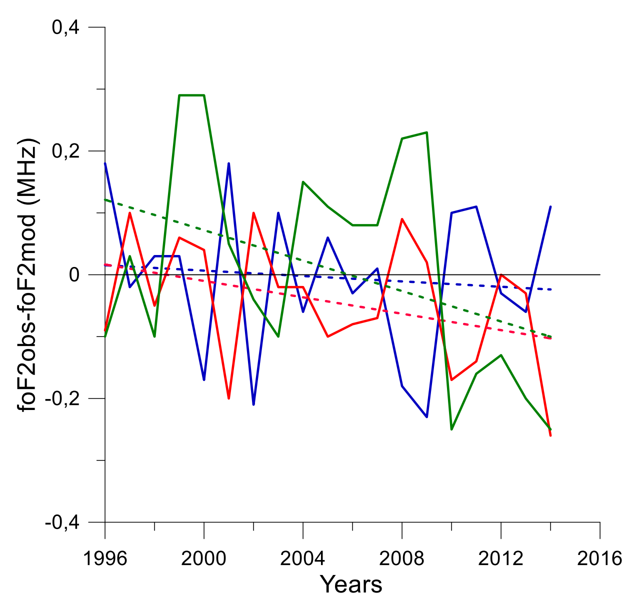

Fig. 1. Trends in foF2 in terms of foF2 residuals for Pruhonice, 1996–2014. Full lines – foF2 residuals; dashed lines – corresponding foF2 linear trends (fits). Green line with F10.7 applied to remove solar activity effect, red line with Mg II and blue line with F30. Long horizontal black thin line – zero level (no trend).

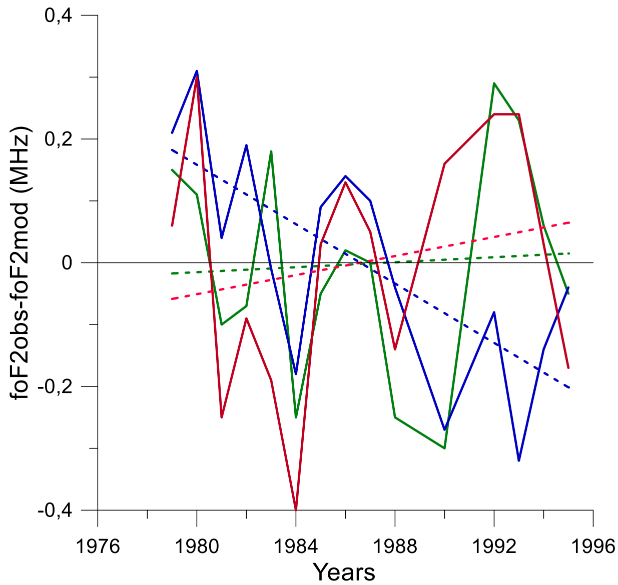

Fig. 2. Trends in foF2 in terms of foF2 residuals for Boulder, 1979–1995 (Mg II data series starts in late 1978). Full lines – foF2 residuals; dashed lines – corresponding foF2 linear trends (fits). Green line with F10.7 applied to remove solar activity effect, red line with Mg II and blue line with F30. Long horizontal black thin line – zero level (no trend).

which provides trends of the same sign for all stations and both periods, is F30 with a negative trend of foF2. F10.7 and Lα provide comparable number of positive and negative trends. Mg II and sunspot numbers R display both positive and negative trends but positive prevail. The result for He II is peculiar and difficult to interpret. Thus the results obtained with F30 appear to be most reliable as all stations provide the same sign of trends.

Table 2 present the trend coefficients D (MHz/decade) from Eq. (2) with standard errors 1σ for all six midlatitude stations and the solar activity proxy F30 for periods 1976–1995, 1995–2014 and 1976–2014. The trend coefficients for the whole period 1976–2014 are between those for sub-periods 1976–1995 and 1996–2014 except for Rome, where all trend coefficients are equal within error bars (standard errors). However, standard errors for 1976–2014 are much smaller than for both sub-periods mainly due the double length of period 1976–2014; this makes all trend coefficients for 1976–2014 statistically significant at 2σ and even higher levels. Another evident feature of Table 2 is systematically stronger trends in the period 1976–1995 than in 1996–2014.

4. Discussion

Danilov and Konstantinova (2023) found for Juliusruh a diurnal and seasonal variation of long-term trend in foF2. Diurnally the trend was clearly stronger during daytime than at night, seasonally during winter than summer. I study trends near noon, i.e. diurnally in the period of stronger trend. Seasonally I study trends in yearly average values, i.e. this trend is expected to be between stronger wintertime and weaker summertime trends. On the other hand, the trends derived from yearly values are more reliable in terms of statistical significance than trends based on foF2 values in individual months (e.g., Laštovička, 2021b). Monthly values are more affected by geomagnetic disturbances and effects of meteorological origin; e.g. a negative effect of geomagnetic storms dominates in summertime foF2, whereas the role of a positive effect is substantially more important in winter than in summer, and in yearly values of foF2 the negative and positive effects partially compensate each other.

The results presented in this paper clearly demonstrate that different solar activity proxies used result in different long-term trends of yearly values of foF2, in some cases even in different sign of trends. I consider and recommend

Table 1
The trend coefficients D (MHz/decade) from Eq. (2) with standard errors 1σ for all six midlatitude stations and solar activity proxies F10.7, F30 and Mg II for periods 1976–1995 and 1996–2014.

1976–1995						
	F10.7	F30	Mg II*	R	Lα	He II
Juliusruh	−0.14 ± 0.10	−0.30 ± 0.06	0.08 ± 0.13	−0.04 ± 0.10	−0.25 ± 0.17	−0.27 ± 0.15
Pruhonice	−0.04 ± 0.12	−0.20 ± 0.10	0.28 ± 0.13	0.01 ± 0.17	−0.01 ± 0.16	−0.17 ± 0.18
Roma	0.09 ± 0.15	−0.08 ± 0.10	0.28 ± 0.23	0.15 ± 0.20	0.02 ± 0.17	−0.04 ± 0.18
Boulder	0.05 ± 0.06	−0.23 ± 0.08	0.17 ± 0.13	0.01 ± 0.07	−0.03 ± 0.11	−0.10 ± 0.10
Kokubunji	−0.02 ± 0.07	−0.24 ± 0.11	0.09 ± 0.11	−0.04 ± 0.10	−0.03 ± 0.10	−0.17 ± 0.09
Canberra	0.04 ± 0.10	−0.20 ± 0.08	0.18 ± 0.12	−0.09 ± 0.18	−0.13 ± 0.15	−0.07 ± 0.13
1996–2014						
	F10.7	F30	Mg II	R	Lα	He II**
Juliusruh	0.10 ± 0.07	−0.04 ± 0.06	0.08 ± 0.06	0.24 ± 0.13	0.11 ± 0.08	0.36 ± 0.10
Pruhonice	−0.12 ± 0.07	−0.02 ± 0.05	−0.07 ± 0.04	0.18 ± 0.07	0 ± 0.09	0.28 ± 0.09
Roma	−0.08 ± 0.11	−0.07 ± 0.06	−0.02 ± 0.05	0.14 ± 0.08	−0.07 ± 0.05	0.39 ± 0.12
Boulder	0.30 ± 0.10	0.15 ± 0.11	0.25 ± 0.09	0.37 ± 0.11	0.25 ± 0.11	0.34 ± 0.13
Kokubunji	0.03 ± 0.10	−0.19 ± 0.08	−0.09 ± 0.07	0.05 ± 0.08	−0.12 ± 0.11	0.21 ± 0.13
Canberra	0.09 ± 0.08	−0.04 ± 0.06	0.10 ± 0.05	0.15 ± 0.05	0.01 ± 0.10	0.21 ± 0.05

* only 1979–1995;
** only 1996–2010.

Table 2
Long-term trend coefficients (MHz/decade and %/decade) calculated for foF2 with F30 for all six midlatitude stations and periods 1976–1995, 1996–2014 and 1976–2014.

Period	Juliusruh	Pruhonice	Rome	Boulder	Kokubunji	Canberra
1976–1995	−0.30 ± 0.06 −3.9%	−0.20 ± 0.10 −2.6%	−0.08 ± 0.10 −0.95%	−0.23 ± 0.08 −3.0%	−0.24 ± 0.11 −2.6%	−0.20 ± 0.08 −2.5%
1996–2014	−0.04 ± 0.06 −0.5%	−0.02 ± 0.05 −0.3%	−0.07 ± 0.06 −0.9%	0.15 ± 0.11 2.0%	−0.19 ± 0.08 −2.3%	−0.04 ± 0.06 −0.5%
1976–2014	−0.13 ± 0.02 −1.8%	−0.04 ± 0.02 −0.5%	−0.10 ± 0.03 −1.2%	−0.15 ± 0.04 −2.0%	−0.21 ± 0.03 −2.2%	−0.11 ± 0.02 −1.4%

F30 to be the best solar proxy for studying long-term trends of foF2 at middle latitudes: (1) The total variance of yearly values of foF2 and average absolute deviations of foF2 from the linear dependence on solar activity proxies indicate F30 and Mg II as the best solar proxies (Laštovička, 2021b; Laštovička and Burešová, 2023). (2) The average dependence of foF2 on solar proxies is the same in periods 1971–1995 and 1996–2014 only for F30, even though for Mg II the difference is rather small (Laštovička and Burešová, 2023). (3) F30 is the only solar proxy which provides for all six stations the same sign of long-term trends of foF2 (negative trend). Mg II provides trends of both signs but predominantly positive. In this context it should be mentioned that model calculations (e.g. Qian et al., 2008) also provide a negative trend of foF2, even though with comment that hmF2 is close to the boundary between positive and negative trends in electron density. Modeling by Solomon et al. (2018) provides the NmF2 trend −1.2 %/decade for 1972–2005. This corresponds to foF2 trend 0.6%/decade; such a trend is near the lower boundary of observational trends of foF2 0.5–2.2 %/decade for F30, 1976–2014 (Table 2). Direct quantitative comparison with model results should be done with care – the observational trends may include not only effects of CO_2 but also some influence of other trend drivers as the secular change of the Earth's magnetic field etc.

Table 2 reveals stronger trends for the period 1976–1995 than 1996–2014. However, this result should be considered with caution because both periods are relatively short for determination quite reliable trends, which is reflected in larger standard errors compared to 1976–2014. Moreover, Danilov and Konstantinova (2023) analyzed the period 1996–2022 for Juliusruh and they found that in the last 5–7 years the foF2 trend was much stronger than before; this could increase the trend for 1996–2022 compared to that for 1996–2014 and reduce the difference between trends revealed by Table 2.

5. Conclusions

Analysis of long-term (1976–2014) data on foF2 from six midlatitude stations from four continents, focused on long-term trends of foF2 calculated with the use of six different solar activity proxies, revealed the following main results:

1. Long-term trends in foF2 depend on the solar activity proxy used; with different solar activity proxies they might be even of opposite sign.
2. The only solar proxy, which provides trends of the same sign for all stations and both sub-periods, is F30 with a negative trend of foF2, not F10.7, sunspot number or Mg II.
3. Based on the results of this paper and of Laštovička and Burešová (2023), I can recommend F30 as the best solar proxy for studying long-term trends of foF2 at middle latitudes (at least for yearly average values).

Future research should try to make a similar study for low and high latitudes (depending on data availability) and also examine the long-term trends in total electron content based on sufficiently long data series.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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