Stability of solar correction for calculating ionospheric trends

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Abstract. Global climate change affects the whole atmosphere, including the thermosphere and ionosphere. Calculations of long-term trends in the ionosphere are critically dependent on solar activity (solar cycle) correction of ionospheric input data. The standard technique is to establish an experimental model via calculating the dependence of ionospheric parameter on solar activity from the whole analysed data set, subtract these model data from observed data and analyse the trend of residuals. However, if the solar activity dependence changes with time, the solar correction calculated from the whole data set may result in miscalculating the ionospheric trends. To test this, data from two European ionospheric stations – Juliusruh and Slough/Chilton – which provide long-term reliable data, have been used for the period 1975–2014. The main result of this study is the finding that the solar activity correction used in calculating ionospheric long-term trends need not be stable, as was assumed in all previous investigations of ionospheric trends. During the previous solar cycle 23 and the current solar cycle 24, the solar activity correction appears to be different from that for the previous period and the Sun seems to behave in a different way than throughout the whole previous era of ionospheric measurements. In future ionospheric trend investigations the non-stability of solar activity correction has to be very seriously taken into account, because it can substantially affect calculated long-term trends of ionospheric parameters.

Keywords. Ionosphere (mid-latitude ionosphere)

1 Introduction

The global climate change caused by the increasing concentration of radiatively active greenhouse gases affects not only the troposphere; it affects also the upper atmosphere, including the thermosphere and ionosphere, where it evokes long-term trends (e.g. Laštovička et al., 2012). However, to calculate the trends, the effect of the 11-year solar cycle must be removed from the data or at least very suppressed, as it is much stronger than the long-term trend, particularly for ionospheric quantities. Usually this is done by calculating the model of solar activity effect on the data from data themselves; after subtracting the solar contribution from the observed data the long-term trend is calculated from residuals. Another possibility is for example the multiple linear regression with simultaneous inclusion of solar activity and time, or some more sophisticated methods. Both these approaches are applied here and provide similar results. As Cnossen and Frantzke (2014) showed, the long-term trends of $f_{\text{0}F_2}$ and $h m F_2$ (critical frequency of ionospheric F2 region and its peak height, respectively) are highly linear, so the linear approximation is sufficient, and the same can be expected for corresponding parameters of the ionospheric E region, $f_{\text{0}E}$ and $h m E$. The solar activity effect has usually been removed or suppressed using solar activity proxies, particularly F10.7 (sunspot number is the worse option; see e.g. Mielich and Bremer, 2013), because decades-long homogeneous series of solar extreme ultraviolet (EUV) data are not available.

The last extremely long and deep solar minimum, particularly years 2008 and 2009, might create some problems in calculating long-term trends, because F10.7 is most probably unable to describe the large decrease of solar EUV flux in these years (e.g. Laštovička, 2013, and references therein; Solomon et al., 2010). The thermospheric density was anomalously low in 2008–2009, remarkably lower than that expected from F10.7 (e.g. Solomon et al., 2010). A similar problem was found for ionospheric parameters $h m F_2$ (e.g. Roininen et al., 2015) and $f_{\text{0}F_2}$ (e.g. Laštovička, 2013). Danilov and Konstantinova (2016) found some distortion of trends in $f_{\text{0}F_2}$ in these years; however, more recently the trend recovered back to the expected “trajectory”. Therefore, the original objective of this study was to examine whether
trends in the E region are distorted by this extreme solar min-
imum.

However, during this examination a more serious prob-
lem was detected, namely the possibility of change of the
solar activity correction necessary for trend investigations
during the examined period. Also Elias et al. (2014), when
studying long-term trends in foF2, found some changes of
trends during solar cycle 23, including the deep minimum
23/24, which they tentatively attributed to changes in the
solar EUV–F10.7 relationship. Moreover the Sun seems to
change its behaviour. Balogh et al. (2014; their Fig. 4) ob-
served an evident change of relationship between sunspot
number and F10.7 and a remarkable decrease of the sunspot
formation fraction parameter during solar cycle 23 and early
solar cycle 24. Therefore, the objective of this article was
to change its behaviour. Balogh et al. (2014; their Fig. 4) ob-
served an evident change of relationship between sunspot
number and F10.7 and a remarkable decrease of the sunspot
formation fraction parameter during solar cycle 23 and early
solar cycle 24. Therefore, the objective of this article was
to investigating the temporal stability of solar activity
correction in investigating ionospheric trends.

Section 2 describes data and methods used. Section 3, the
main part of the paper, contains the results and discussion.
The results are summarized in Conclusions (Sect. 4).

2 Data and methods

Since the long period 1975–2014 is investigated, high-
quality, continuous and long data series are needed.
Therefore, two European midlatitude ionospheric stations
are selected – Slough/Chilton (51.5° N, 1.3° W; geomag-
\( \Delta f_0E \); 1990–2005, stagnation or a mini-increase after jump-up; 2006–2014, rapid decrease. Whereas in the first two sub-periods residuals vary within \( \pm 0.1 \) MHz, in the third sub-period they fall to remarkably lower negative values. Originally the third interval was 2005–2014, but 2005 was a large outlier in residuals. Therefore, it remained only in 1990–2005, where it fits well.

Now the whole procedure, calculating the observational model with Eq. (1), then subtracting model values from observations and constructing the time development of residuals, is repeated separately for all three sub-intervals. Table 1 reveals an evident increase of percentage of total variance of \( f_0E \) explained by solar activity, on average about 93–94 %, except for Juliusruh, 2006–2014, when some oscillations appear (Fig. 2). Table 2 shows that solar coefficients \( B \) from Eq. (1) for the whole interval and for the three sub-intervals somewhat differ, although not much. The coefficients \( B \) in individual sub-intervals have been becoming smaller in recent years. This timing is in accord with the changes in solar activity mentioned in Introduction, which began during solar cycle 23.

The differences between solar coefficients \( B \) in different sub-intervals are relatively small, but their impact on time evolution of \( \Delta f_0E \) is substantial (Fig. 2). Figure 2 shows the behaviour of residuals after application of solar corrections separately in individual sub-intervals. The pattern is quite different from that depicted in Fig. 1; it is clear and physically plausible. In the beginning there is a slight negative trend, which turns into no trend in the mid-1990s in parallel with the change (levelling off or reversal) of trend in ozone at northern middle latitudes (Harris et al., 2008). The slight negative trend means a change by 0.05–0.06 MHz over 1975–1995, i.e. trend of about \(-0.03\)\(^{-\frac{1}{2}}\)(\(-0.025\)) MHz decade\(^{-1}\) for both stations.

Bremer (2008) analysed the trends in \( f_0E \) using data of 71 ionosondes located over the world. He received a weak but statistically significant average trend of \(+0.013 \pm 0.005\) MHz decade\(^{-1}\), but the histogram of trends used covers a range from \(-0.04\) to \(+0.07\) MHz decade\(^{-1}\). Thus our trends for Slough/Chilton and Juliusruh are within the range of trends found by Bremer (2008). Moreover, Tromsø in northern Norway also provides a negative trend in \( f_0E \) (Hall et al., 2007). Thus it looks like northern Europe is a region of negative trends in \( f_0E \).

The other approach used is to calculate trends by the multiple linear regression:

\[
\Delta f_0E = A + B \cdot \text{solar} + C \cdot \text{time},
\]

Table 3 presents the percentage of total variance of yearly values of \( f_0E \) accounted for by solar activity proxies and trend (Eq. 2) for the whole period and for three sub-periods, for Juliusruh and Chilton. It is evident that dividing the solar activity correction into three sub-periods increased the percentage of total variance described by solar activity variability and trend to 95 and 96 % for Juliusruh and Chilton except for Juliusruh, 2006–2014, where Figs. 1 and 2 display larger random-like variability.

Trend coefficients for Juliusruh and Chilton are shown for the whole dataset in Table 4 (sub-periods are too short to provide reliable trend coefficients). These trend coefficients for Chilton provide a decrease of \( f_0E \) over the analysed 40-year period to be 0.04–0.08 MHz, which agrees with estimate from Fig. 2, 0.05–0.06 MHz, but the latter decrease is realized in the first half of the studied period only. However, the Chilton trend coefficients from Table 4 are statistically insignificant. Trend coefficients given in Table 4 for Julius-

**Figure 1.** Residuals \( \Delta f_0E \) (0.01 MHz) after removal of solar activity (F10.7) influence (Eq. 1), yearly values, for Chilton (full line) and Juliusruh (dotted line).

**Figure 2.** Residuals \( \Delta f_0E \) (0.01 MHz) after removal of solar activity (F10.7) influence (Eq. 1) separately for the three sub-periods 1975–1990, 1990–2005, and 2005–2006, yearly values, for Chilton (full line) and Juliusruh (dashed line).
Table 2. Solar coefficient $B$ from Eq. (1) for yearly values of $f_oE$ for the whole period and for three sub-periods, for Juliusruh and Chilton (values separated with a slash).

<table>
<thead>
<tr>
<th></th>
<th>F10.7</th>
<th>Foα</th>
</tr>
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<tbody>
<tr>
<td>1975–2014</td>
<td>$0.0053 \pm 0.0003$</td>
<td>$0.0003 \pm 0.0003$</td>
</tr>
<tr>
<td>1975–1990</td>
<td>$0.0050 \pm 0.0003$</td>
<td>$0.0004 \pm 0.0004$</td>
</tr>
<tr>
<td>1990–2005</td>
<td>$0.0045 \pm 0.0003$</td>
<td>$0.0002 \pm 0.0002$</td>
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<tr>
<td>2006–2014</td>
<td>$0.0038 \pm 0.0011$</td>
<td>$0.0006 \pm 0.0006$</td>
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</tbody>
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Table 3. Percentage of total variance of yearly values of $f_oE$ accounted for by solar activity proxies and trend (Eq. 2) for the whole period and for three sub-periods, for Juliusruh and Chilton (values separated with a slash).

<table>
<thead>
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<th></th>
<th>F10.7</th>
<th>Foα</th>
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<tbody>
<tr>
<td>1975–2014</td>
<td>0.92/0.94</td>
<td>0.91/0.94</td>
</tr>
<tr>
<td>1975–1990</td>
<td>0.97/0.96</td>
<td>0.95/0.96</td>
</tr>
<tr>
<td>1990–2005</td>
<td>0.95/0.98</td>
<td>0.93/0.95</td>
</tr>
<tr>
<td>2006–2014</td>
<td>0.78/0.96</td>
<td>0.85/0.96</td>
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</tbody>
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Table 4. Trends (MHz/decade) of $f_oE$ calculated from Eq. (2), for Juliusruh and Chilton (values separated with a slash).

<table>
<thead>
<tr>
<th></th>
<th>F10.7</th>
<th>Foα</th>
</tr>
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<tbody>
<tr>
<td>1975–2014</td>
<td>$-0.03/-0.01$</td>
<td>$-0.04/-0.02$</td>
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</table>

Table 5. Percentage of total variance of yearly values of $f_oF2$ accounted for by F10.7 (Eq. 1) for the whole period and for three sub-periods for Chilton.

<table>
<thead>
<tr>
<th></th>
<th>F10.7</th>
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<tbody>
<tr>
<td>1975–2014</td>
<td>0.97</td>
</tr>
<tr>
<td>1975–1990</td>
<td>0.99</td>
</tr>
<tr>
<td>1990–2005</td>
<td>0.95</td>
</tr>
<tr>
<td>2006–2014</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Juliusruh and Chilton (values separated with a slash). Trends (MHz/decade) of $f_oE$ calculated from Eq. (2), for Juliusruh and Chilton (values separated with a slash). Trends calculated via approach with Eq. (1) over the period 1975–1996 with solar proxy F10.7 provide trends for Chilton of $-0.011 \pm 0.008$ ($\sigma$) and for Juliusruh of $-0.019 \pm 0.005$ MHz decade$^{-1}$. The trend is more significant for Juliusruh (at more than 3$\sigma$ level), because Juliusruh values evolve in a smoother way over 1975–1996 than Chilton values. These trend coefficients provide a decrease of $f_oE$ from 1975 to 1996 by 0.025 MHz for Chilton and 0.041 MHz for Juliusruh, which is somewhat less than estimates from Fig. 2 (0.05–0.06 MHz).

Table 2 shows values of solar coefficients $B$ from Eq. (1). They all are statistically quite significant, which is not surprising because the percentage of total variance of $f_oE$ accounted for by solar activity variability is around 90% and more (Table 1). It is interesting that such relatively mild changes of solar activity correction (particularly for Chilton) can quite change the pattern of $f_oE$ residuals, changing Fig. 1 into Fig. 2. The solar coefficients are somewhat (although not much) decreasing with time. Such systematic change seems to be of solar origin. For example, when we look at the behaviour of the sunspot formation fraction parameter (Balogh et al., 2014; their Fig. 4), it evidently begins to decrease in the late 1990s and it is decreasing continuously until 2010 (end of the data series). Thus the period 1975–1990 is not impacted by this solar behaviour change, the period 1990–2005 is affected partly and the period 2005–2014 seems to be fully affected, which coincides with changes of solar coefficient in Table 2. On the other hand, changes of $f_oE$ sensitivity to solar activity are similar for F10.7 and Fo (proxy of solar EUV flux versus spectral line from the soft end of EUV range). So it may be that there are also some changes of ionospheric sensitivity, although it is difficult to say what their physical origin could be. First of all, solar physics should answer the question of what is happening with the Sun.

In the case that our study were limited only to the period 1975–2005, then Fig. 1 would indicate a slight positive tendency (if any, rather none) for Juliusruh, whereas Fig. 2 would indicate a slight negative tendency. This illustrates how important it is to check/test and consider non-stability of solar correction in long-term ionospheric trend studies.

The stability of solar correction has been examined above only for $f_oE$. Let us now look at $f_oF2$. Chilton and Juliusruh data provide quite similar results. Therefore only those for Chilton are presented. An approach based on Eq. (1) applied to $f_oF2$ is used. Table 5 shows that almost all variance (95–99%) of $f_oF2$ is accounted for by solar activity variability. However, even in such a situation there are some changes of solar correction in individual sub-periods with some impact on $f_oF2$ residuals. Figure 3 shows evolution of $f_oF2$ when only one solar correction is applied for the whole period,
whereas Fig. 3 perhaps indicates some slight insignificant negative trend of $\Delta f_{\text{F2}}$, Fig. 4 clearly displays no trend. Thus there is some (slight) impact of changes of solar correction on evolution of $f_{\text{F2}}$ residuals. Figure 4 also displays no effect of change of ozone trends in the mid-1990s on trends in $f_{\text{F2}}$. Unfortunately, the pattern of $f_{\text{F2}}$ residuals in Figs. 3 and 4 is “poisoned” by two outliers in 1991 and 1992, which largely compensate each other, so they do not affect trend. However, they affect scatter of data and therefore slightly lower the value of percentage in Table 5 for the period 1990–2005.

4 Conclusions

Data of two European ionospheric stations – Juliusruh and Chilton – which provide long-term reliable data, have been used for the period 1975–2014. The main result of this study is the finding that the solar activity correction used in calculating ionospheric long-term trends need not be stable, as was assumed in all previous investigations of ionospheric trends. During the previous solar cycle 23 and the current solar cycle 24, the solar activity correction appears to be different from that for the previous period and the Sun seems to behave in a different way than throughout the whole previous era of ionospheric measurements. Whether it is related to the generally low level of solar activity in the 21st century compared to the second half of the 20th century remains an open question. Anyway, in future ionospheric trend investigations the non-stability of solar activity correction has to be very seriously taken into account, because it can substantially affect long-term evolution and calculated trends of ionospheric parameters (compare Figs. 1 and 2).

5 Data availability

Ionospheric data are available at the Rutherford Appleton Laboratory database (http://www.ukssdc.ac.uk/wdcc1/iono_menu.html), SPIDR database (http://spidr.ionosonde.net/spidr), and the digisonde database GIRO (http://giro.uml.edu/), and solar Lyman-alpha data at http://lasp.colorado.edu/lisird/lya/.

Author contributions. Jan Laštovička did most of the work, Dalia Burešová and Daniel Kouba helped with data mining, and Peter Krížan helped with data evaluation.

Competing interests. The authors declare that they have no conflict of interest.

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References


