AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2017JA023909

Key Points:

- Mid-latitude foE long-term variations in ionosphere and thermosphere
- Long-term variations due to solar activity
- Long-term variations not due to CO_2 increase

Correspondence to:
L. Perrone,
loredana.perrone@ingv.it

Citation:
Mikhailov, A. V., L. Perrone, and A. A. Nusinov (2017), A mechanism of midlatitude noontime f_oE long-term variations inferred from European observations, *J. Geophys. Res. Space Physics*, *122*, doi:10.1002/2017JA023909.

Received 16 JAN 2017
Accepted 18 MAR 2017
Accepted article online 21 MAR 2017

A mechanism of midlatitude noontime f_oE long-term variations inferred from European observations

A. V. Mikhailov[1], L. Perrone[2], and A. A. Nusinov[3]

[1]Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Troitsk, Russia, [2]Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italia, [3]Fedorov Institute of Applied Geophysics, Moscow, Russia

Abstract Manually scaled June noontime monthly median f_oE values at three European stations Rome, Juliusruh, and Slough/Chilton were used to understand the mechanism of f_oE long-term variations. The 11 year running mean smoothed f_oE manifests long-term (for some solar cycles) variations with the rising phase at the end of 1960–1985 and the falling phase after 1985. A close relationship (even in details) between $(f_oE_{ave})_{11y}$ and $(R_{12})_{11y}$ variations with the correlation coefficient of 0.996 (absolutely significant according to Fisher *F* criterion) suggests that the Sun is the source of these $(f_oE_{ave})_{11y}$ long-term variations. After removing solar activity long-term variations the residual $(f_oE_{ave})_{11y}$ trend is very small (~0.029% per decade) being absolutely insignificant. This means that all $(f_oE_{ave})_{11y}$ variations are removed with one solar activity index, $(R_{12})_{11y}$, i.e., this means that long-term variations are fully controlled by solar activity. Theory of midlatitude daytime *E* region tells us that long-term variations of solar EUV in two lines $\lambda = 977$ Å (CIII) and $\lambda = 1025.7$ Å (HLyβ) and X-ray radiation with $\lambda < 100$ Å (both manifesting the same long-term variations with the rising phase at the end of 1960–1985 and the falling phase after 1985) are responsible for the observed $(f_oE_{ave})_{11y}$ variations. Therefore, the observed daytime midlatitude f_oE long-term variations have a natural (not anthropogenic) origin related to long-term variations of solar activity. No peculiarities in relation with the last deep solar minimum in 2008–2009 have been revealed.

1. Introduction

Long-term variations and trends in the ionospheric and thermospheric parameters have been extensively discussed in literature. The interest to this problem was initiated by *Roble and Dickinson* [1989]; *Rishbeth* [1990]; *Rishbeth and Roble* [1992], who predicted the ionospheric and thermospheric effects caused by the atmosphere greenhouse gas concentrations increase. Despite obvious contradictions with the observed ionospheric trends [*Perrone and Mikhailov*, 2016, and references therein], the greenhouse hypothesis is still very popular [*Laštovička et al.*, 2012; *Danilov and Konstantinova*, 2013; *Mielich and Bremer*, 2013; *Roininen et al.*, 2015]. It should be stressed that according to the *Rishbeth* [1990] estimates, under the doubled CO_2 increase scenario the cooling effect in the daytime *E* region should very small: a decrease in h_mE is about 2.5 km and an f_oE increase is about 0.5%. We are still far from the doubled CO_2 scenario having only a 20% CO_2 increase in the Earth's atmosphere [*Houghton et al.*, 2001]. Under a linear assumption this should give a decrease in h_mE by about 0.5 km and an f_oE increase by about 0.1%, but present-day *E* region trends are already larger these estimates. According to the last estimates by *Bremer* [2008], the mean global f_oE trend is 0.0013 MHz/yr, and the trend in h_mE is $-(0.029–0.068)$ km/yr. Under the accepted rate of CO_2 increase of 5% per decade, the cooling process has started ~40 years ago and this gives $-(0.029–0.068) \times 40 = -(1.16–2.72)$ km and $0.0013 \times 40 = 0.052$ MHz. Accepting an average noontime midlatitude $f_oE = 3.5$ MHz, one may obtain an f_oE increase by about 1.5%, and this is larger than 0.5%. The researchers realize these and similar discrepancies with f_oF_2 and f_oF_1 long-term trends and are telling only about a qualitative agreement with the CO_2 increase hypothesis [*Bremer*, 1998, 2008; *Laštovička et al.*, 2008, 2012; *Laštovička*, 2013].

Moreover, *Bremer* [2008] and *Bremer and Peters* [2008] see a relationship of f_oE trends with stratospheric ozone trends, although the theory of *E* layer formation does not show any ways of such impact of ozone on f_oE. One may think that both long-term variations reflect the variation of the third agent. Therefore, it is interesting to understand a real mechanism of f_oE long-term variations at least in the simplest (midlatitude noontime) conditions and to check if there are significant residual trends not related to long-term variations of solar activity.

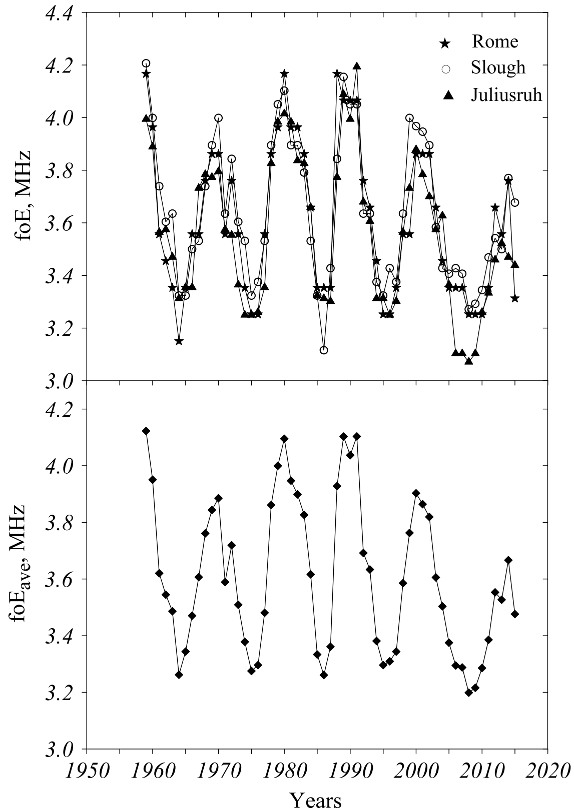

Figure 1. Reduced by solar zenith angle June noontime monthly median f_oE at (top) three stations and (bottom) averaged over three stations f_oE_{ave} variations.

The aims of our paper may be ormulated as follows: (1) to reveal long-term noontime f_oE variations using reliable (from manually scaled ionograms), monthly median f_oE values on three European ionosonde stations: Rome, Slough/Chilton, and Juliusruh for approximately five solar cycles including the period of the last deep solar minimum in 2008–2009; and (2) to reveal a physical mechanism responsible for the observed midlatitude daytime f_oE long-term variations.

2. f_oE Long-Term Variations

In our analysis, we used June noontime monthly median f_oE values at three European stations with the manual ionogram scaling: Slough/Chilton (51.5°N; 359.4°E), Juliusruh (54.6°N; 13.4°E), and Rome (41.9°N; 12.5°E). Ionospheric observations were taken from Space Physics Interactive Data Resource (SPIDR) (http://spidr.ngdc.noaa.gov/spidr/), Leibniz Institute of Atmospheric Physics-Field station Juliusruh (http://www.ips.gov.au/World_Data_Centre/1/3), from the Lowell Digital Ionogram DataBase (DIDBase) through Global Ionospheric Radio Observatory (GIRO) [*Reinisch et al.*, 2004], and directly from Rome ionosonde. Our retrieved solar EUV radiation is available only for June months; therefore, June f_oE observations were used in our analysis.

To simplify the analysis, the observed f_oE variations were reduced by the solar zenith angle using a well-known dependence $f_oE \sim \cos(\chi)^{0.3}$ [*Kouris and Muggleton*, 1973] or a more sophisticated expression by *Nava et al.* [2008], both giving the same result for the conditions in question. After such reduction the observed f_oE values turn out to be very close and can be averaged over three stations to give a f_oE_{ave} variation (Figure 1) for further analyses.

There is a discussion in the literature which index of solar activity should be used for long-term trend analyses [*Lastovicka*, 2013; *Mielich and Bremer*, 2013]. As long as we are working with f_oE_{ave}, a special analysis has been done to choose the index. Table 1 gives the correlation coefficients (CC) and standard deviations (SD) calculated for various indices of solar activity used in the regression: 12 month running mean sunspot number (R_{12}), monthly $F_{10.7}$ (F_{1mon}), 3 month $F_{10.7}$ (F_{3mon}), 12 month running mean $F_{10.7}$ (F_{12mon}), a half sum of F_{1mon} and F_{3mon}, and solar EUV with $\lambda < 1050$ Å retrieved from monthly median f_oF_1 [*Mikhailov and Perrone*, 2016a].

Table 1. Regression Results of June f_oE_{ave} Versus Various Indices of Solar Activity[a]

Index	R_{12}	F_{1mon}	F_{3mon}	F_{12mon}	½($F_{1mon}+F_{3mon}$)	EUV
CC	**0.968**	0.957	0.962	0.949	0.964	0.948
SD (MHz)	**0.065**	0.067	0.070	0.082	0.066	0.085

[a]Correlation coefficients and standard deviations are given. The best results are given in bold.

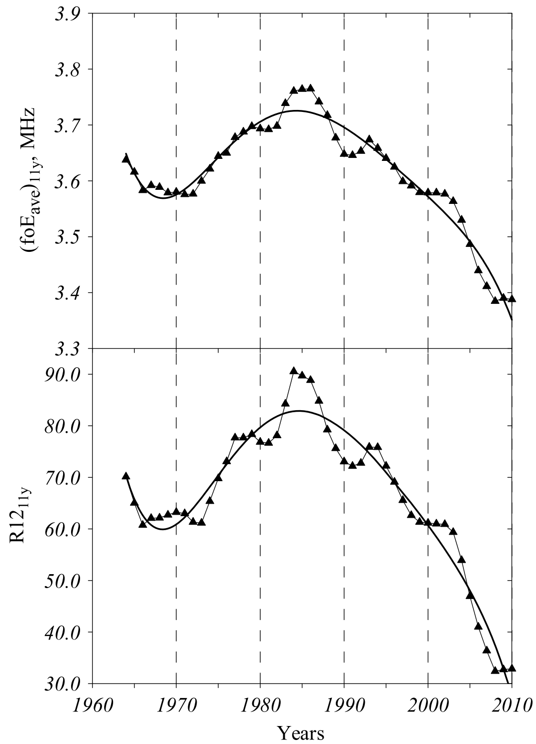

Figure 2. The 11 year running mean smoothed f_oE_{ave} and R_{12} variations. Solid lines—polynomial approximations.

Table 1 shows that all analyzed indices give close results with large and significant correlation coefficients; however, R_{12} turns out to be the best.

Our analysis has shown that meaningful results can be only obtained working with smoothed variations. Acceptable results provide 11 year running mean smoothing. Usual 11 year running mean smoothing applied to f_oE_{ave} results in variations given in Figure 2. This type of smoothing practically removes (as this is supposed) solar cycle variations (see Figure 1) leaving only the long-term variation with the rising phase in 1967–1985 and the falling phase after 1985. This peculiarity in the aeronomic parameter long-term variations was earlier revealed by *Mikhailov and Perrone* [2016a]. A close similarity even in details between $(f_oE_{ave})_{11y}$ and $(R_{12})_{11y}$ (Figure 2, bottom) variations with the correlation coefficient of 0.996 (absolutely significant according to Fisher *F* criterion) suggests that the Sun is the source of these $(f_oE_{ave})_{11y}$ long-term variations.

A linear trend in f_oE_{ave} long-term variations estimated over the rising phase is ~0.128 MHz per decade, while it is ~−0.144 MHz per decade over the falling phase. To get the final f_oE_{ave} trend $(R_{12})_{11y}$, variations should be removed from $(f_oE_{ave})_{11y}$ ones. We use a 3-D order polynomial regression to find relative deviations $\delta f = (f_{obs} - f_{reg})/f_{obs}$ (Figure 3).

The residual $(f_oE_{ave})_{11y}$ trend is negative and very small (~0.029% per decade) being absolutely insignificant according to Fisher *F* criterion. This means that all $(f_oE_{ave})_{11y}$ variations (Figure 1) are removed with one solar activity index, $(R_{12})_{11y}$, i.e., they are totally dependent on long-term variations of solar activity. Accepting noontime $f_oE = 3.5$ MHz, we may estimate the absolute $(f_oE_{ave})_{11y}$ trend ~-1.0×10^{-3} MHz per decade. It should be noted that our $(f_oE_{ave})_{11y}$ trend is by 10 times less and has different sign compared to the *Bremer* [2008] results.

Resuming the results of this morphological analysis, one may conclude that both solar cycle and long-term (for some solar cycles) f_oE_{ave} variations can be practically totally removed with one smoothed index of solar activity, $(R_{12})_{11y}$. This means that the observed variations of monthly median f_oE are mainly controlled by solar activity, presumably by solar EUV. Geomagnetic activity which possibly provides a small contribution may be also considered as a part of solar activity.

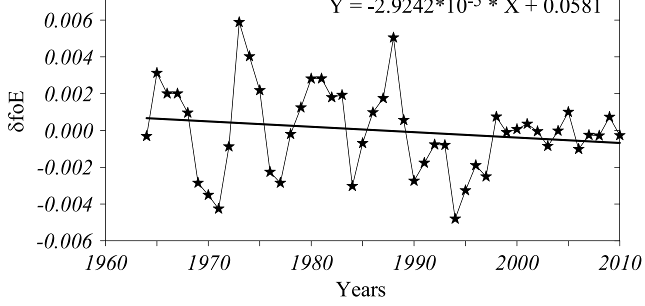

Figure 3. δf_oE after the regression of $(f_oE_{ave})_{11y}$ with $(R_{12})_{11y}$. The residual linear trend can be estimated from the regression given in the plot.

3. Physical Interpretation

The theory of *E* region may help understand some features of the revealed f_oE long-term variations (Figure 2). The midlatitude daytime *E* layer is mainly produced via the ionization of neutral O_2 by two close EUV lines $\lambda = 977$ Å (CIII) and $\lambda = 1025.7$ Å (HLyβ), which provide > 80% of the total ionization rate; the rest is produced by X-ray radiation with $\lambda < 100$ Å [*Ivanov-Kholodny et al*., 1976]. Therefore, the classical Chapman theory [*Chapman*, 1931] may be applied for estimates in this case [*Ivanov-Kholodny and Nusinov*, 1979] with a reservation that ≤ 20% of the total ionization rate is provided by X-ray radiation which ionizes all three neutral species: O, O_2, and N_2. Following *Ivanov-Kholodny and Nusinov* [1979], it is possible to write down

$$q_{m/\alpha_m}{}' = \frac{I_\infty \sigma^i \cos\chi}{\alpha' H \sigma^a e} \text{and} \quad f_oE \propto \left[\frac{I_\infty \sigma^i \cos\chi}{\alpha' H \sigma^a e}\right]^{0.25} \tag{1}$$

where q_m is the ionization rate at the *E* layer maximum, I_∞ is the incident ionizing flux, χ is the solar zenith angle, $\sigma^{i,a}$ are the ionization and absorption cross sections, α' is the effective dissociative recombination coefficient, and *H* is the molecular oxygen scale height both being constant with height.

Expression (1) shows that there are three parameters: α', *H*, and I_∞ which could be responsible for the revealed $(f_oE_{ave})_{11y}$ long-term variations (Figure 2).

The effective dissociative recombination coefficient α' depends on the $NO^+/O_2{}^+$ ratio which manifests a well-pronounced negative trend for the (1960–1985) period (*Danilov and Smirnova*, 1997; see also *Danilov*, 2002), and this could explain the positive trend in f_oE_{ave} (Figure 2) observed for the same period. Quantitative estimates seem to confirm this possibility [*Mikhailov*, 2006]. The $NO^+/O_2{}^+$ ratio is directly proportional to the [NO] concentration [*Danilov*, 1994]; therefore, a decrease in $NO^+/O_2{}^+$ corresponds to a decrease in [NO]. As a plausible mechanism for such [NO] decrease could be the intensified eddy diffusion that permits a vertical transfer of NO from *E* to *D* region [*Danilov*, 2002]. This is confirmed by the positive trend of electron concentration in the *D* region [*Danilov*, 2002], where the ionization of NO plays the dominate role. In his recent publications Danilov finds new confirmations for the intensification of eddy diffusion [*Danilov and Konstantinova*, 2014]. This means that one should expect a further decrease in [NO] and in the $NO^+/O_2{}^+$ ratio as well. Unfortunately, ion composition observations in the *E* region are not available for the period after 1985, and this suggestion cannot be checked. However, after 1985 the $(f_oE_{ave})_{11y}$ trend has changed the sign (Figure 2), and this contradicts the idea of the [NO] decrease. Therefore, other mechanisms should be considered to explain the observed f_oE_{ave} long-term variations.

Expression (1) shows that f_oE explicitly depends on T_o, but this dependence is very weak: $f_oE \propto T_o{}^{-0.05}$ and neutral temperature variations at *E* region heights provide a negligible contribution to f_oE variations. A weak dependence of f_oE on neutral temperature mentioned by *Ivanov-Kholodny and Nusinov* [1979], also by *Rishbeth* [1990], is due to the fact that *T* is present in two terms (equation (1)): in $H = kT/mg$ and in $\alpha' = \alpha_0 T^{-\beta}$ ($\beta \approx 1$), and this practically abolishes the temperature dependence.

In principle f_oE long-term variations may be due to the effective scale height H variations related to neutral gas vertical transfer rather than temperature changes. Such mechanism of N_mE variations was considered by *Mikhailov* [1983] and *Nusinov* [1988]. Downwelling of neutral gas should bring to a decrease of the $[O_2]$ effective scale height H and to an increase of f_oE, while upwelling should result in the opposite effect. Any observations on neutral gas vertical motion are absent. Model simulations by *Rishbeth and Müller-Wodarg* [1999, Figure 3] give a moderate upwelling (about 0.5 m/s) in a wide range of latitudes around noontime in June in the Northern Hemisphere. This cannot help us understand the revealed long-term $(f_oE_{ave})_{11y}$ variations (Figure 2) especially keeping in mind that the rising phase in 1965–1985 would need downwelling of neutral gas for the same June conditions. Therefore, we should consider the last possibility—long-term variations of the ionizing solar EUV radiation.

For our analysis we will use EUV with $\lambda < 1050$ Å retrieved from the observed monthly median f_oF_1 at the same ionosonde stations Slough/Chilton, Juliusruh, and Rome. The EUV model by *Nusinov* [1992] was applied during the retrieval procedure, but the EUVAC model by *Richards et al.* [1994] will be used for the cleanness of further analysis as this model has nothing to do with the retrieval process. The daytime midlatitude *E* region (as it was mentioned earlier) is formed by two EUV lines $\lambda = 977$ Å and $\lambda = 1025.7$ Å which provide > 80% of the total ionization; the rest is produced by X-ray radiation with $\lambda < 100$ Å. Our EUV flux was retrieved at F_1 layer heights where the *contribution* of X-ray to the total ionization rate is negligible. Therefore, the intensity of the two EUV lines in the retrieved flux may be taken in the same proportion as it is in the Extreme UltraViolet flux model for Aeronomic Calulations (EUVAC) model. Figure 4 gives the total EUV flux with

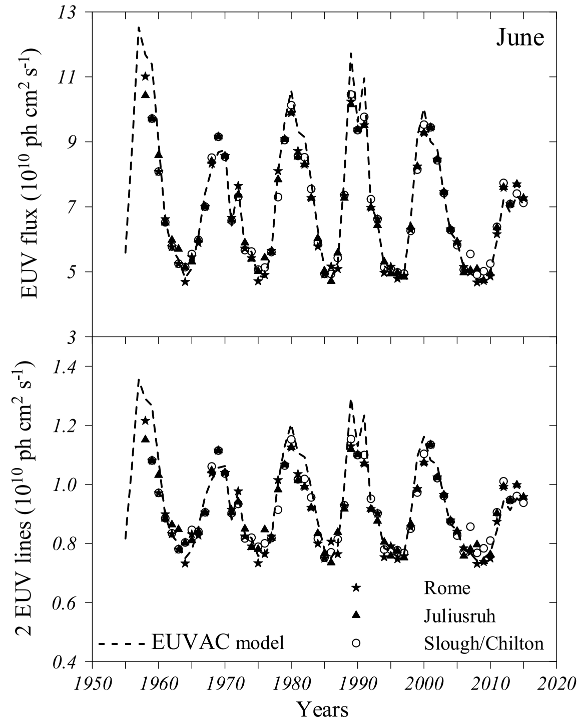

Figure 4. The retrieved at (top) the three stations total EUV flux with $\lambda < 1050$ Å and (bottom) the intensity of two EUV lines with $\lambda = 977$ Å and $\lambda = 1025.7$ Å. EUVAC model is given by dashes.

$\lambda < 1050$ Å retrieved at the three stations and the summary intensity in the two EUV lines with $\lambda = 977$ Å and $\lambda = 1025.7$ Å.

The results of Figure 4 seem to be interesting. First, the retrieved EUV flux variations are seen to be close at the three stations (as this is supposed to be) although they are not related by any means. Second, the retrieved EUV variations turn out to be very close to the EUVAC model variations. It should be reminded that the EUVAC model had nothing to do with the retrieval process. These results tell us that the method by *Mikhailov and Perrone* [2016a] to retrieve aeronomic parameters from observed foF1 values does work and provides reasonable results not only in a comparison with the CHAMP/STAR (Spatial Triaxial Accelerometer for Research) neutral gas density observations as it was shown earlier but on solar EUV flux variations as well. This may be considered as an additional confirmation of the efficiency of the proposed method.

To understand the origin of $(f_oE_{ave})_{11y}$ long-term variations (Figure 2), we should consider long-term variations of two ratios: $(EUV_{2\ lines})/H$ and (X-ray)/H (see (1)). The thermospheric model MSIS-86 [*Hedin*, 1987] with the retrieved Tex [*Mikhailov and Perrone*, 2016b] was used to find neutral temperature variations at 110 km in the expression for the scale height, $H = kT/mg$. We consider 110 km as an average height of the daytime *E* layer maximum in summer. It should be noted that temperatures T_{110} found by this way differ from the original MSIS-86 model values. Our analysis has shown that the variations of H at 110 km are very small and practically do not affect the $EUV_{2\ lines}$ and X-ray long-term variations. Therefore, we will consider $EUV_{2\ lines}$ and X-ray long-term variations as they are without the H term.

X-ray radiation is not available either from our retrieved EUV [*Mikhailov and Perrone*, 2016a] or from the EUVAC model [*Richards et al.*, 1994]. For this reason X-ray emission was taken from the *Nusinov* [1992] model where $F_{10.7}$ is the only driving parameter for X-rays. However, to keep the succession with the earlier morphological analysis (Figure 2), we take $(R_{12})_{11y}$ as the index of solar activity. According to equation (1), we should analyze $(EUV_{2\ lines})^{0.25}$ and (X-ray)$^{0.25}$ long-term (11 year smoothed) variations. A comparison of $[(EUV_{2\ lines})^{0.25}]_{11y}$ and $[(\text{X-ray})^{0.25}]_{11y}$ with $(f_oE_{ave})_{11y}$ and $(R_{12})_{11y}$ manifests their similarity (Figure 5).

The correlation coefficients of $(f_oE_{ave})_{11y}$ with $[(EUV_{2\ lines})^{0.25}]_{11y}$ is 0.931 and 0.952 in the case of $[(\text{X-ray})^{0.25}]_{11y}$, both being absolutely significant. $[(EUV_{2\ lines})^{0.25}]_{11y}$ and $[(\text{X-ray})^{0.25}]_{11y}$ also manifest the similarity in their variations with $(R_{12})_{11y}$—the absolutely significant correlation coefficients are 0.936 and 0.949, correspondingly. All this tells us that solar EUV and X-ray long-term variations are the main cause of the observed $(f_oE_{ave})_{11y}$ long-term variations. This is not surprising as the midlatitude daytime *E* region is known to be controlled by solar ionizing radiation.

4. Discussion

We live in the atmosphere of the Sun, and the state of the Earth's upper atmosphere is totally dependent on solar activity (geomagnetic activity may be considered as a part of solar activity), and it is not related to

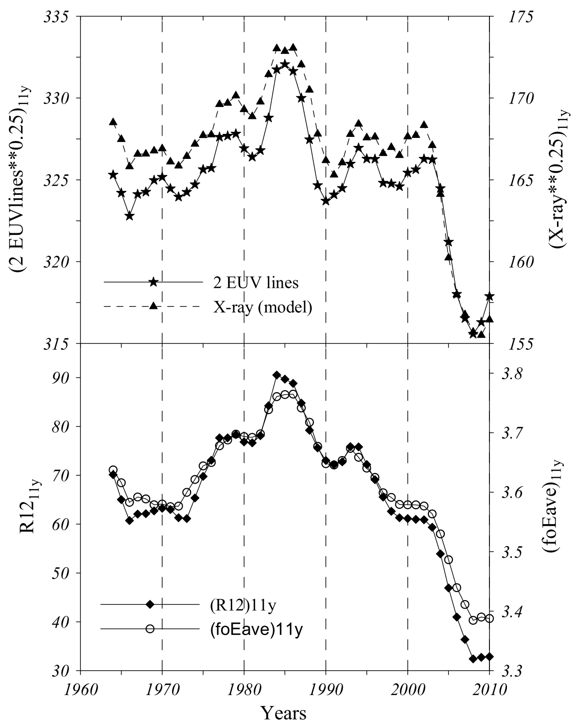

Figure 5. (top) $(\mathrm{EUV}_{2\ \mathrm{lines}})^{0.25}$ and $(\text{X-ray})^{0.25}$ 11 year smoothed variations; (bottom) $(R_{12})_{11y}$ and $(f_oE\mathrm{ave})_{11y}$ variations.

the CO_2 increase. The present paper has once again confirmed this conclusion with respect to midlatitude noontime f_oE long-term variations: solar EUV and X-ray are the main sources of these variations.

It has been repeatedly stressed that only smoothed (normally 11 year smoothing is applied) observations could be used for long-term trend analyses. As an example, it may be considered the recent paper by *Laštovička et al.* [2016]. The main result of their 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." This means that the ionosphere reacts differently to solar activity during various historical periods. The formation mechanism of the midlatitude daytime f_oE is well determined, and no peculiarities in the f_oE long-term variations were revealed according to the results of our analysis. Therefore, one may think that the conclusion by *Laštovička et al.* [2016] is related to the method of data development. *Laštovička et al.* [2016] analyzed annual mean f_oE calculated from daily medians at 10–14 LT; however, the method of f_oE averaging is not described in their paper. It may be shown that using the same regression with one solar activity index $(R_{12})_{11y}$ for all historical epochs, it is possible to remove all f_oE long-term variations and to obtain the residual trend which is absolutely insignificant. This result looks reasonable from a physical point of view as the ionosphere is obeyed by the laws, and such laws for the midlatitude daytime *E* region were established long ago. According to the results of our main analysis, the f_oE long-term variations are due to long-term variations of solar EUV and X-ray radiations which reflect the long-term variations of solar activity. The long-term (for some solar cycles) variations with the rising phase before 1985 and the falling phase after 1985 show not only the retrieved solar EUV flux (Figure 4) but also the thermospheric parameters [*Mikhailov and Perrone*, 2016b], and this looks reasonable from a physical point of view. Right now we cannot say anything on the mechanism of solar activity long-term variations, but the magnetic moment of the solar dipole shows similar long-term variations with the rising phase before 1985 and the falling phase with a sharp decrease of the magnetic moment after 1985 [*Obridko and Shelting*, 2009, Figure 1].

It is interesting to note that such long-term variations related to solar activity, the researchers revealed earlier but did not pay attention to that fact. For instance, *Danilov* [2008, Figure 8] clearly demonstrates such variations with a minimum attention the end of 1960, the rising phase till 1980–1985, and the falling phase after 1985. He just did not remove the long-term solar activity variations the latter is possible to do working with 11 year running mean values. A similar situation takes place with long-term variation of the total ozone [*Bremer*, 2008, Figure 11].

5. Conclusions

Manually scaled June noontime monthly median f_oE values at three European stations Rome, Juliusruh, and Slough/Chilton were used to understand the mechanism of f_oE long-term variations. The following was shown:

1. The 11 year running mean smoothed f_oE manifest long-term (for some solar cycles) variations with the rising phase at the end of 1960–1985 and the falling phase after 1985. This peculiarity in the aeronomic

parameter long-term variations was earlier revealed by *Mikhailov and Perrone* [2016a]. A close similarity even in details between $(f_oE_{ave})_{11y}$ and $(R_{12})_{11y}$ variations with the correlation coefficient of 0.996 (absolutely significant according to Fisher *F* criterion) tells us that the origin of these $(f_oE_{ave})_{11y}$ long-term variations is the Sun.
2. After removing this long-term solar activity variation (presented by index $(R_{12})_{11y}$) the residual $(f_oE_{ave})_{11y}$ trend is very small (~0.029% per decade) being absolutely insignificant according to Fisher *F* criterion. This means that all $(f_oE_{ave})_{11y}$ variations are removed with one solar activity index, $(R_{12})_{11y}$, i.e., these variations are totally dependent on the long-term variations of solar activity.
3. Theory of daytime midlatitude *E* region formation tells us that such f_oE long-term variations are due to long-term variations of solar EUV in two lines $\lambda = 977$ Å (CIII) and $\lambda = 1025.7$ Å (HLyβ) and X-ray radiation with $\lambda < 100$ Å, both manifesting the same long-term variations with the rising phase at the end of 1960–1985 and the falling phase after 1985. Therefore, the observed daytime midlatitude f_oE long-term variations have a natural (not anthropogenic) origin related to the long-term variations of solar activity.
4. No peculiarities in relation with the last deep solar minimum in 2008–2009 have been revealed.

Acknowledgments
The Juliusruh data are kindly provided by Leibniz institute of Atmospheric Physics station Juliusruh, Germany. The authors thank SPIDR (http://spidr.ngdc.noaa.gov/), IPS (http://www.ips.gov.au/World_Data_Centre/), and the Lowell DIDBase through GIRO (http://giro.uml.edu/) for providing the ionospheric data. The Rome data are provided by Istituto Nazionale di Geofisica e Vulcanologia (http://www.eswua.ingv.it/).

References

Bremer, J. (1998), Trends in the ionospheric *E* and *F* regions over Europe, *Ann. Geophysicae.*, *16*, 986–996, doi:10.1007/s00585-998-0986-9.

Bremer, J. (2008), Long-term trends in the ionospheric E and F1 regions, *Ann. Geophysicae*, *26*, 1189–1197, doi:10.5194/angeo-26-1189-2008.

Bremer, J., and D. Peters (2008), Influence of stratospheric ozone changes on long-term trends in the mesosphere and lower thermosphere, *J. Atmos. Sol.-Terr. Phy.*, *70*, 1473–1481, doi:10.1016/j.jastp.2008.03.024.

Chapman, S. (1931), The absorption and dissociative or ionizing effect of monochromatic radiation in a atmosphere on a rotating Earth, *Proc. R. Soc. Lond.*, *43*(1), 26–45 and 43(5), 483–501, doi:10.1088/0959-5309/43/1/305.

Danilov, A. D., and A. V. Konstantinova (2013), Trends in the *F*2 layer parameters at the end of the 1990s and the beginning of the 2000s, *J. Geophys. Res. Atmos.*, *118*, 5947–5964, doi:10.1002/jgrd.50501.

Danilov, A. D. (1994), Ion chemistry of the lower thermosphere, *J. Atmos. Terr. Phys.*, *56*, 1213–1225, doi:10.1016/0021-9169(94)90059-0.

Danilov, A. D. (2002), Overview of the trends in the ionospheric E and F2 regions, *Phys. Chem. Earth*, *27*, 579–588, doi:10.1016/S1474-7065(02)00040-2.

Danilov, A. D. (2008), Long-term trends in the relation between daytime and nighttime values of *fo*F2, *Ann. Geophysicae*, *26*, 1199–1206, doi:10.5194/angeo-26-1199-2008.

Danilov, A. D., and A. V. Konstantinova (2014), Reduction of the atomic oxygen content in the upper atmosphere, *Geomagn. Aeron.*, *54*, 224–229, doi:10.1134/S0016793214020066.

Danilov, A. D., and N. V. Smirnova (1997), Long-term trends of the ion composition in the *E* region, *Geomag. Aeronom.*, *37*(N4), 35–40.

Hedin, A. E. (1987), MSIS-86 thermospheric model, *J. Geophys. Res.*, *92*, 4649–4662, doi:10.1029/JA092iA05p04649.

Houghton, J. T., Y. Ding, D. J. Groggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (2001), *Climate Change: The Scientific Basis, Contribution of WG I to the 3rd Assessment Report of the IPCC*, Univ. Press, Cambridge.

Ivanov-Kholodny, G. S., and A. A. Nusinov (1979), Formation and dynamics of the daytime mid-latitude ionospheric *E*-layer [in Russian], *Transactions of IAG*, *37*, 128.

Ivanov-Kholodny, G. S., L. N. Leshenko, and I. N. Odintzova (1976), Relationship between X-ray and ultraviolet radiations of solar flares in the ionization of the ionosphere E-region [in Russian], *Geomag. Aeronom.*, *16*, 246–250.

Kouris, S. S., and L. M. Muggleton (1973), Diurnal variation in the E-layer ionization, *J. Atmos. Terr. Phys.*, *35*(133–139), 1973.

Laštovička, J. (2013), Trends in the upper atmosphere and ionosphere: Recent progress, *J. Geophys. Res. Space Physics*, *118*, 3924–3935, doi:10.1002/jgra.50341.

Laštovička, J., R. A. Akmaev, G. Beig, J. Bremer, J. T. Emmert, C. Jacobi, M. J. Jarvis, G. Nedoluha, Y. I. Portnyagin, and T. Ulich (2008), Emerging pattern of global change in the upper atmosphere and ionosphere, *Ann. Geophysicae*, *26*, 1255–1268, doi:10.5194/angeo-26-1255-2008.

Laštovička, J., S. C. Solomon, and L. Qian (2012), Trends in the neutral and ionized upper atmosphere, *Space Sci. Rev.*, *168*, 113–145, doi:10.1007/s11214-011-9799-3.

Laštovička, J., D. Burešová, D. Kouba, and P. Križan (2016), Stability of solar correction for calculating ionospheric trends, *Ann. Geophysicae*, *34*, 1191–1196, doi:10.5194/angeo-34-1191-2016.

Mielich, J., and J. Bremer (2013), Long-term trends in the ionospheric F2 region with different solar activity indices, *Ann. Geophysicae.*, *31*, 291–303, doi:10.5194/angeo-31-291-2013.

Mikhailov, A. V. (1983), Possible mechanism for the in-phase changes in the electron densities in the ionospheric E and F2 regions, *Geomagn. Aeron.*, *23*, 455–458.

Mikhailov, A. V. (2006), Trends in the ionospheric E-region, *Phys. Chem. Earth*, *31*, 22–23, doi:10.1016/j.pce.2005.02.005.

Mikhailov, A. V., and L. Perrone (2016a), Geomagnetic control of the midlatitude daytime f_oF_1 and f_oF_2 long-term variations: Physical interpretation using European observations, *J. Geophys. Res. Space Physics*, *121*, 7193–7203, doi:10.1002/2016JA022716.

Mikhailov, A. V., and L. Perrone (2016b), Thermospheric parameters long-term variations retrieved from ionospheric observations in Europe, *J. Geophys. Res. Space Physics*, *121*, 11,574–11,583, doi:10.1002/2016JA023234.

Nava, B., P. Coisson, and S. M. Radicella (2008), A new version of the NeQuick ionosphere electron density model, *J. Atmos. Sol.-Terr. Phys.*, *70*, 1856–1862, doi:10.1016/j.jastp.2008.01.015.

Nusinov, A. A. (1988), Deterministic model of mid-latitude and equatorial E-layer (Description and comparative characteristics of the accuracy) [in Russian], *Ionosph. Researches*, *44*, 94–97.

Nusinov, A. A. (1992), Models for prediction of EUV and X-ray solar radiation based on 10.7-cm radio emission, in *Proceedings Workshop on Solar Electromagnetic Radiation for Solar Cycle 22*, edited by R. F. Donnely, pp. 354–359, NOAA ERL. Boulder, Colo., July.

Obridko, V. N., and B. D. Shelting (2009), Anomalies in the evolution of global and large-scale solar magnetic fields as the precursors of several upcoming low solar cycles, *Astron. Lett.*, *35*(4), 247–252, doi:10.1134/S1063773709040045.

Perrone, L., and A. V. Mikhailov (2016), Geomagnetic control of the midlatitude f_oF_1 and f_oF_2 long-term variations: Recent observations in Europe, *J. Geophys. Res. Space Physics*, *121*, 7183–7192, doi:10.1002/2016JA022715.

Reinisch, B. W., I. A. Galkin, G. Khmyrov, A. Kozlov, and D. F. Kitrosser (2004), Automated collection and dissemination of ionospheric data from the digisonde network, *Adv. Radio Sci.*, *2*, 241–247, doi:10.5194/ars-2-241-2004.

Richards, P. G., J. A. Fennelly, and D. G. Torr (1994), EUVAC: A solar EUV flux model for aeronomic calculations, *J. Geophys. Res.*, *99*, 8981–8992, doi:10.1029/94JA00518.

Rishbeth, H. (1990), A greenhouse effect in the ionosphere?, *Planet. Space Sci.*, *38*, 945–948, doi:10.1016/0032-0633(90)90061-T.

Rishbeth, H., and I. C. F. Müller-Wodarg (1999), Vertical circulation and thermospheric composition: A modelling study, *Ann. Geophys.*, *17*, 794–805, doi:10.1007/s00585-999-0794-x.

Rishbeth, H., and R. G. Roble (1992), Cooling of the upper atmosphere by enhanced greenhouse gases—Modelling of thermospheric and ionospheric effects, *Planet. Space Sci.*, *40*, 1011–1026, doi:10.1016/0032-0633(92)90141-A.

Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?, *Geophys. Res. Lett.*, *16*, 1441–1444, doi:10.1029/GL016i012p01441.

Roininen, L., M. Laine, and T. Ulich (2015), Time-varying ionosonde trend: Case study of Sodankylä h_mF_2 data 1957–2014, *J. Geophys. Res. Space Physics*, *120*, 6851–6859, doi:10.1002/2015JA021176.