Thermospheric parameters long-term variations retrieved from ionospheric observations in Europe

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Abstract
Recently developed method to retrieve thermospheric parameters ($T_{ex}$, O, O₂, and N₂) and the total solar EUV flux with $\lambda < 1050$ Å from routine $f_cF_1$ ionosonde observations has been applied to monthly median $f_cF_1$ data on Rome, Slough/Chilton, and Juliusruh stations to analyze long-term trends in the thermospheric parameters. For the first time exospheric temperature and neutral composition were obtained for June noontime conditions over the period of ~5 solar cycles. The retrieved parameter manifested solar cycle and long-term (some solar cycles) variations with a rising phase in 1965–1985 and falling phase in 1985–2008. The retrieved thermospheric parameters were shown to be close to the MSIS-86 model ones exhibiting very small (<1% per decade) and statistically insignificant linear trends estimated either over all 56 years or only over the years of solar minimum. No peculiarities in long-term variations in relation with the last deep solar minimum have been revealed. The source of the thermospheric parameter long-term trends is the Sun, i.e., they have a natural (not anthropogenic) origin and are mainly controlled by long-term variations of solar and geomagnetic activity.

1. Introduction
The contradiction between long-term trends of thermosphere temperature as well as mass density inferred from satellite drag measurements and those derived from ground-based incoherent scatter radars (ISR) is widely discussed in the literature [Emmert, 2015; Oliver et al., 2014, and references therein]. The trend in the thermospheric mass density estimated from satellite drag measurements over the 1967–2005 period is $-2.0 \pm 0.5$% per decade at 400 km altitude and the exospheric temperature trend is of $-1$ to $-2$ K per decade [Emmert, 2015], while the most recent estimates of the thermosphere temperature trends inferred from ISR observations are as follows: $-18$ K/decade for noontime exospheric temperature at Millstone Hill [Oliver et al., 2014], $-60$ K/decade at 350 km for daytime hours at Saint Santin/Nancay [Donaldson et al., 2010], $-10$ to $-15$ K/decade at $F_2$ layer heights for daytime hours at Tromso [Ogawa et al., 2014], and $-20$ K/decade at 350 km for daytime hours at Millstone Hill [Zhang and Holt, 2013]. In the last three cases the trends were estimated from ion temperature $T_i$ observations supposing that $T_n = T_i$. In the first case a six-parameter analysis by Oliver [1979] was applied to Millstone Hill ISR observations to find exospheric temperature and atomic oxygen concentration at 400 km long-term trends. Along with above mentioned trend in $T_{exo}$, Oliver et al. [2014] have estimated a very small trend in atomic oxygen density of $0.0 \pm 1.5$% per decade at 400 km altitude over the 1976–2013 period. A zero trend in the atomic oxygen density at 400 km under a strong decrease of the exospheric temperature automatically implies an increase of the atomic oxygen density at the turbopause level by $36.9 \pm 5.0$% over the 38 year period [Oliver et al., 2014]. The thermosphere neutral gas density at 400 km is mainly presented by atomic oxygen, so a zero trend in [O] implies a zero trend in mass density. Both large cooling rate in neutral temperature and a zero trend in the atomic oxygen estimated from ISR observations contradict satellite drag observations by Emmert [2015]. Therefore, an independent estimate of the thermospheric parameter trends would be interesting and useful in such contradictory situation.

Ground-based ionosonde observations are an ideal source of information for long-term trend analyses. These observations are technically simple; the same method of vertical ionospheric sounding is being used during the whole period of observations (for more than five solar cycles at some European stations), and the observations are being conducted round the clock in the same places and provide reliable information on the state of the ionosphere. The theory of the ionosphere formation is well developed by now (at least at middle latitudes), and it is possible to solve the inverse problem of aeronomy and to retrieve thermospheric parameters from routine ionospheric observations using the recently developed method by Mikhailov and...
Perrone [2016]. The method was tested using CHAMP/STAR neutral gas density measurements. It was shown that the proposed method provides better accuracy than the modern empirical model, MSISE-00 [Picone et al., 2002], and the uncertainty of the retrieved neutral gas density coincides with the announced absolute uncertainty (10–15%) of the neutral gas density observations with the CHAMP satellite [Bruinsma et al., 2004]. Therefore, it was concluded that the method could be used for trend analyses at three European stations, Rome, Slough/Chilton, and Juliusruh.

The aims of the paper may be formulated as follows: (1) to retrieve neutral composition, temperature, and the total solar EUV flux with \( \lambda < 1050 \text{Å} \) for the whole available period of ionosonde observations at three ionosonde stations: Slough/Chilton, Juliusruh, and Rome; (2) to estimate thermospheric parameter long-term trends; and (3) to compare the obtained trends with the published thermospheric trend estimates.

2. The Idea of the Method

The method to retrieve thermospheric parameters from \( f_{\text{F}} \) observations is described by Mikhailov and Perrone [2016], but for convenience of reading we are giving here its idea and the limitations. The method is applied at middle latitudes where the \( F1 \) layer is produced by solar EUV radiation. Five hourly around noontime \( f_{\text{F}} \) observations are required as the input information. Using a standard scheme of photochemical processes, five unknown parameters, factors for the MSIS-86 [Hedin, 1987] model exospheric temperature \( T_{\text{ex}} \), concentrations [O], [O2], [N2], and a factor for the Nusinov [1992] model of total solar EUV flux with \( \lambda < 1050 \text{Å} \) are specified. The method can be used only around noon hours and mainly in summer when the \( F1 \) layer is well developed and reliably observed by ground-based ionosondes. For this reason the thermospheric parameters were retrieved for June when the number of gaps in \( f_{\text{F}} \) observations is minimal. The retrieved neutral composition is obtained at \( F1 \) layer heights, and then it may be reduced to any height in the thermosphere using the MSIS-86 model \( T_n(h) \) profile with the retrieved \( T_{\text{ex}} \) value. It should be stressed that the MSIS-86 neutral composition and temperature as well as the Nusinov [1992] model total solar EUV flux are used as the starting values in the fitting of five calculated \( f_{\text{F}} \) to the observed ones. At the output for each June of each year we get five independent factors for these initial model values, and these factors are supposed to reflect long-term variations in the thermospheric parameters and EUV responsible for the long-term variations in the observed \( f_{\text{F}} \). The fitting procedure is a problem of nonlinear programming [Himmelblau, 1972]. This is the main idea of our so called self-consistent approach to the analysis of thermospheric and ionospheric long-term variations.

3. Retrieved Thermospheric Parameter Variations

Monthly median \( f_{\text{F}} \) observations which can be used for our analysis are available for ~5 solar cycles at Rome (1957–2015), at Juliusruh (1958–2015), and at Slough/Chilton (1959–2015). It should be stressed that \( f_{\text{F}} \) monthly median values were obtained from manually scaled ionograms and may be considered as reliable ones. This was shown by testing of the method when the retrieved neutral gas densities were compared to CHAMP/STAR-measured ones [Mikhailov and Perrone, 2016]. Thermospheric neutral composition (O, O2, and N2) retrieved at heights of \( F1 \) layer was reduced to 300 km. We take 300 km rather than 400 km, usually used for mass density trend analyses [e.g., Emmert, 2015], for the following reason: The contribution of He to the neutral gas density may be essential at 400 km under solar minimum, but this contribution cannot be properly taken into account in our method.

The retrieved neutral composition and temperature are compared to the MSIS-86 thermospheric model [Hedin, 1987]. On the one hand, this is done for an additional control of our method performance. On the other hand, this is done to demonstrate that the retrieved and model thermospheric parameters manifest similar long-term variations indicating the origin of these variations.

The values retrieved at Slough/Chilton (as an example) for June, 12 LT exospheric temperature \( T_{\text{ex}} \) neutral gas density \( \rho \), and atomic oxygen [O] at 300 km altitude in a comparison with 3 month mean \( F_{10.7} \) index variations are given in Figure 1. This solar index is used to demonstrate a close relationship with thermospheric parameter variations. The correlation coefficient of 3 month \( F_{10.7} \) with \( T_{\text{ex}} \) is 0.983, and with \( \rho_{300} \) it is 0.988 under the absolute significance according to Fisher F criterion. For this reason 3 month \( F_{10.7} \) will be used to reduce the retrieved thermospheric parameters for trend analyses (see later text). Polynomial
approximations (solid lines) also manifest the closeness between 3 month $F_{10.7}$ and the retrieved thermospheric parameter variations. In the case of Slough/Chilton the correlation coefficients between approximated 3 month $F_{10.7}$ and the approximated parameter variations are: 0.989 for $[O]$, 0.998 for $\rho$, and 0.994 for $T_{ex}$. Therefore, after removing solar activity variations (presented by 3 month $F_{10.7}$) the residual trends in $T_{ex}$, $[O]$, and $\rho$ long-term variations should be very small (see later text).

Figure 1 (right column) gives the retrieved exospheric temperature $T_{ex}$, neutral gas density $\rho$, and atomic oxygen $[O]$ at 300 km versus MSIS-86 model values. To provide a correct comparison, MSIS-86 model monthly $T_{ex}$, $\rho$, and $[O]$ medians were calculated for each June of all years using the observed 3 h ap and daily $F_{10.7}$ indices for each day of June and 12 LT. Along with plots we provide some statistical metrics: mean relative deviation (MRD), the bias with respect to MSIS-86 model, and correlation coefficients between the retrieved and model values. The results are given in Table 1 for three stations.

The comparison (Table 1) of retrieved to model thermospheric parameters shows their closeness. One may note large correlation coefficients which are also absolutely significant according to Fisher F criterion and
small MRD ≈ 6% for $T_{\text{ex}}$ and 12–17% for $\rho$. This along with testing results on CHAMP/STAR observations given in Mikhailov and Perrone [2016] tells us that the proposed method gives reasonable results and the retrieved thermospheric parameters can be used for trend analyses.

4. Thermospheric Trends

To estimate the residual trends, solar and geomagnetic activity effects should be removed from the retrieved parameter variations. The most straightforward way is to use MSIS-86 as a reference model. The empirical MSIS-86 model does not “know” anything about either the CO$_2$ increase in the thermosphere or the intensification of eddy diffusion [Danilov, 2005, 2006; Danilov and Konstantinova, 2014] as the model is based on the observations mostly conducted in the 1970s and early 1980s and it is driven by two geophysical indices $F_{10.7}$ and $Ap$ which are proxies for solar and geomagnetic activity. Therefore, if there are any significant trends in the retrieved thermospheric parameters related to an anthropogenic activity during the last two to three decades, they should be seen with respect to the MSIS-86 model.

Figure 2 gives the retrieved $T_{\text{ex}}$ and $\rho_{300}$ long-term variations at Slough/Chilton and Rome stations reduced by MSIS-86. The residual variations are seen to manifest the solar activity dependence: all ups correspond to

![Figure 2](image_url)

Figure 2. Long-term variations of the retrieved and reduced by MSIS-86 $T_{\text{ex}}$ and $\rho$ values at 300 km altitude at Slough/Chilton and Rome stations. Straight line is the linear trend estimated over a 56 year time interval.
solar maxima, while all downs correspond to solar minima. It means that MSIS-86 underestimates the dependence on solar activity. Nevertheless, we have estimated linear trends using these reduced $T_{ex}$, $\rho_{300}$ and $[O]_{300}$ variations for various end years (Table 2).

The residual linear trends of the retrieved thermospheric parameters estimated over the selected years may be positive or negative, but in any case they are very small and statistically insignificant according to Fisher F criterion. Due to the residual solar activity dependence (Figure 2), the sign of the trend depends on the series length. The trends for all end years are seen to be small; the maximal are $\approx \pm$3% per decade for the period earlier than 1990, and even these maximal trends are statistically insignificant.

Thermospheric density trends derived from orbital drag were shown to be larger for solar minimum [Emmert, 2015]. For this reason we selected the years of solar minimum (1965, 1975, 1986, 1995, and 2008) to check the trends in the retrieved thermospheric parameters reduced with the MSIS-86 model. As long as we deal with the relative values we can put together data on three stations to increase statistics. The results are given in Figure 3 where the trends were estimated over all points (solid lines) and using only the lowest points at each solar minimum (dashes). The estimated linear trends per decade are given in plots for two point selections. The results are the same—linear trends are small and statistically insignificant.

Therefore, we may conclude that the reduction of the retrieved $T_{ex}$, $\rho_{300}$, and $[O]_{300}$ with the MSIS-86 model results in very small and statistically insignificant residual trends, whether all years or only the years of solar minimum are used. This result looks as an important one. The MSIS-86 model is driven by solar $F_{10.7}$ and geomagnetic $Ap$ indices. If the reduction of the retrieved thermospheric parameters with this model gives very small insignificant trends, one may conclude that the retrieved parameter variations are also controlled only by solar and geomagnetic activity.

Another interesting result is the behavior of the reduced values in the deep solar minimum in 2008 (Figure 3). The minimal points are on a line practically parallel to the $x$ axis, and the points in the deep solar minimum in 2008 do not exhibit any peculiarity unlike the results by Emmert et al. [2010] and

### Table 2. Linear Trends (in % per Decade) for Different End Years at Slough/Chilton and Rome

<table>
<thead>
<tr>
<th>End Year</th>
<th>$T_{ex}$</th>
<th>$\rho_{300}$</th>
<th>$[O]_{300}$</th>
<th>$T_{ex}$</th>
<th>$\rho_{300}$</th>
<th>$[O]_{300}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
<td>-0.1</td>
<td>-0.6</td>
<td>-0.7</td>
</tr>
<tr>
<td>2008</td>
<td>0.0</td>
<td>0.3</td>
<td>0.8</td>
<td>-0.5</td>
<td>-1.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>2002</td>
<td>0.3</td>
<td>1.3</td>
<td>1.8</td>
<td>0.0</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>1995</td>
<td>0.2</td>
<td>1.3</td>
<td>1.8</td>
<td>-0.6</td>
<td>-2.0</td>
<td>-1.8</td>
</tr>
<tr>
<td>1990</td>
<td>0.5</td>
<td>2.6</td>
<td>3.1</td>
<td>-0.9</td>
<td>-3.2</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

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**Figure 3.** Linear trends estimated over years of solar minimum using $T_{ex}$, $\rho_{300}$, and $[O]_{300}$ reduced with the MSIS-86 model for three stations. Linear trends in percent per decade are given in the plots: the first value, when all points were used (solid line); and the second value, when only the lowest points were used (dashed line).
Emmert [2015, Figure 2], where the solar minimum in 2008 is marked by a deep trough in $\ln(\rho/\rho_{\infty})$. This means that MSIS-86 properly works out the extreme conditions of 2008. However, Figure 2 indicates pronounced solar cycle dependence in the residual variations which should be removed as much as possible to estimate the residual trends over all years.

The retrieved thermospheric parameters manifest a good correlation with 3 month mean $F_{10.7}$ (Figure 4, left column); therefore, it is possible to delete these solar activity effects and to check the residual variations. If they bear the geomagnetic activity effects, they should be also removed. However, an addition of any $Ap$ indices (monthly, annually, or 11 year smoothed) to the regression practically does not affect the results. By analogy with the reduction using MSIS-86 we have reduced the retrieved $T_{ex}$, $\rho_{300}$, and $[O]_{300}$ dividing them by the regression with 3 month mean $F_{10.7}$ (Figure 4, right column). The reduction is seen to remove the dependence on solar cycle (Figure 2), and we have got just a scatter of points which again give a very small and statistically insignificant linear trend in all parameters (see later text).

Table 3 gives the estimated linear trends per decade for the retrieved parameters after reducing them with the two methods. The trends were estimated over a 56 year time interval with the end year, 2015. The reduction using the regression with 3 month $F_{10.7}$ gives slightly better results (less SD); however, in both cases the residual trends are very small and statistically insignificant according to Fisher F criterion.

Summarizing the results of undertaken analysis, one may conclude that the retrieved $T_{ex}$, $\rho_{300}$, and $[O]_{300}$ do not manifest any significant long-term trends contrary to the results obtained on satellite drag measurements and those derived from incoherent scatter radars. However, it should be stressed that this conclusion has been obtained using only June noontime ionosonde observations in Europe.
5. Discussion

The interest in long-term trends in the ionosphere and thermosphere has been stimulated by Roble and Dickinson [1989], Rishbeth [1990], and Rishbeth and Roble [1992] who predicted the ionospheric and thermospheric effects of the atmosphere greenhouse gas concentrations increase. According to their estimates under a doubled CO$_2$ scenario the thermosphere should cool by ~50 K. We are still far from this situation having only a 20% CO$_2$ increase in the Earth’s atmosphere [Houghton et al., 2001]. Therefore, in the case of a linear dependence one may expect a 10 K decrease in the exospheric temperature. Under the accepted rate of CO$_2$ increase 5% per decade the cooling process has started ~40 years (3.74 decades) ago and this gives the cooling rate of 2.67 K/decade. Doubling CO$_2$ will need 14.21 decades, and this gives the cooling rate of 3.52 K/decade. This is much smaller than neutral temperature trends inferred from incoherent scatter radar measurements [Oliver et al., 2014; Donaldson et al., 2010; Zhang and Holt, 2013; Ogawa et al., 2014] which look as unreal ones. The satellite drag $T_{ex}$ trend based on adjusting MSISE-00 model parameters to the observed mass density perturbations [Emmert et al., 2010] is very small ~ −1 K/decade [Emmert, 2015, his Table 2], but the upper value of cooling rate −2 K/decade [Emmert, 2015] is close to the above given estimate of the cooling rate over ~4 decades especially taking the thermosphere cooling of 30–40 K [Rishbeth and Roble, 1992] instead of 50 K under the doubled CO$_2$ scenario.

Our method gives also very small (0.1–0.2 % per decade) and statistically insignificant trends in $T_{ex}$ (Table 3 and Figure 3). Under an average exospheric temperature of 1000 K such trends correspond to a cooling rate of 1–2 K/decade at Rome and Juliusruh, i.e., close to the satellite drag estimates, and this seems to confirm the CO$_2$ increase hypothesis. However, our retrieved trends in neutral gas density at 300 km are 0.3–0.7% per decade (Table 3) and this is much less than the satellite drag estimate of −2.0 ± 0.5% per decade at 400 km altitude.

Moving to the ionospheric trends which should reflect the thermospheric trends at least at middle latitudes during daytime hours, we see a contradiction with the CO$_2$ increase hypothesis [Perrone and Mikhailov, 2016; Mikhailov and Perrone, 2016]. The most essential ionospheric effect of CO$_2$ cooling should be seen in $h_mF_2$ decrease. According to Rishbeth [1990] under the CO$_2$ doubled scenario $\Delta h_mF_2 = -20$ km for midnight and −17 km for noontime. Under a 20% CO$_2$ increase (the present-day level) and assuming a linear dependence, one should expect a 3.5–4 km decrease in $h_mF_2$ over ~4 decades. The most successful NCAR TIME-GCM model simulations by Solomon et al. [2015] give an average $h_mF_2$ decrease of 1.13 km per decade, so four decades should result in ~4.5 km decrease, i.e., close to the above given estimate. This also coincides with the results of TIE-GCM model simulations by Cnossen [2014] for a ~28% increase in CO$_2$ concentration. A fairly uniform decrease in $h_mF_2$ of about 5 km was found, and this was not statistically significant everywhere. Therefore, recent model simulations with the current abundance of CO$_2$ in general confirm quantitatively the first estimates by Rishbeth [1990] of the $h_mF_2$ decrease. On the other hand, the observed $h_mF_2$ trends turn out to be larger than the predicted trend for a 20% CO$_2$ increase. The analysis of Sodankylä observations for the period 1957–2014 gave a 30 km $h_mF_2$ decrease [Roininen et al., 2015]. Cnossen [2014] model simulations have also shown “very clearly how little influence the increase in CO$_2$ concentration has had on $f_p F_2$,” and this contradicts the commonly accepted $f_p F_2$ trends [Perrone and Mikhailov, 2016]. Therefore, the CO$_2$ increase hypothesis cannot unambiguously explain at the quantitative level both ionospheric and thermospheric trends, while the geomagnetic control concept seems to indicate a solution [Mikhailov and Perrone, 2016].

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Table 3. Linear Trends Along With the Standard Deviation (±SD) in Percent per Decade Estimated Over a 56 Year Time Period With the End Year 2015 for the Retrieved Thermospheric Parameters$^a$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rome</th>
<th>Juliusruh</th>
<th>Slough/Chilton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reduction With MSIS-86</td>
<td>Reduction With the Regression</td>
<td>Reduction With MSIS-86</td>
</tr>
<tr>
<td>$T_{ex}$</td>
<td>−0.12 ± 6.3</td>
<td>+0.03 ± 3.6</td>
<td>−0.11 ± 5.4</td>
</tr>
<tr>
<td>$\rho_{300}$</td>
<td>−0.60 ± 17.5</td>
<td>−0.29 ± 13.2</td>
<td>−0.71 ± 14.3</td>
</tr>
<tr>
<td>[$O_{300}$</td>
<td>−0.68 ± 11.8</td>
<td>−0.44 ± 11.6</td>
<td>−0.24 ± 8.4</td>
</tr>
</tbody>
</table>

$^a$Neutral gas density and atomic oxygen concentration are taken at 300 km. The reduction was made in two ways: with the MSIS-86 model and the regression with 3 month mean $F_{10.7}$. 

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References for AGU publication are included in the text, and the figure numbers are as follows: Figure 3.
The retrieved thermospheric parameter linear long-term trends at 300 km estimated over a 56 year time interval were shown to be small (<1% per decade) and statistically insignificant. This conclusion is valid either all years or when only years of solar minimum were analyzed (Figure 3), while the satellite drag mass density trends [Emmert, 2015] were found to be 2 times larger under solar minimum. This conclusion can be checked from the other end. Keeping in mind small variations in $F_{10.7}$ from one solar minimum to another and low level of geomagnetic activity in general during solar minima, it is possible to compare trends in the retrieved and model thermospheric parameters as they are without any reduction on solar and geomagnetic activity and to understand the absence of trends in the retrieved parameters after the reduction (Figure 3).

Figure 5 illustrates the retrieved and model $T_{ex}$, $\rho_{300}$, and $[O]_{300}$ variations at Rome as an example over five solar minima. Two to three years in the vicinity of each minimum with the minimal values in the thermospheric parameters were used in Figure 5. Figure 5 shows that both retrieved and model thermospheric parameters manifest negative trends. According to our analysis all trends are statistically significant with the confidence level 90–95%.

The trend in $F_{10.7}$ is small and insignificant, while the trend in $Ap$ is significant at the 95% level; however, the absolute $Ap$ values are seen to be small. Nevertheless, the negative trends in MSIS-86 model thermospheric parameters should be attributed to these trends in $F_{10.7}$ and $Ap$ as the model is driven by these indices. Figure 5 indicates that the trends (line slopes) are close for the retrieved and model values, and this explains the absence of trends in the retrieved parameters after their reduction with the MSIS-86 model (Figure 3). MSIS-86 absolute $[O]$ and $\rho$ values are seen to be larger than the retrieved ones, but this is due to larger $T_{ex}$ in MSIS-86 (Figure 5).

Figure 6 gives the retrieved 11 year running mean atomic oxygen concentration at 200 km and the EUV flux with $\lambda < 1050$ Å in a comparison with ($F_{10.7}$)$_{11y}$ long-term variations. The retrieved EUV variations are given in a comparison with the EUVAC model [Richards et al., 1994] ones. The EUVAC model has nothing to do with our method retrieving aeronomic parameters from $f_{\nu}, F_1$ observations, but the closeness between the retrieved and model EUV variations is obvious. This may be considered as an absolutely independent checking of the proposed method. All these along with the testing results on CHAMP/STAR neutral gas density observations [Mikhailov and Perrone, 2016] tell us that the method provides reliable information on thermospheric parameters and solar EUV. In particular, a sharp decrease in EUV and $[O]$ variations after ~2000 with the absolute minimum reached in 2008 may be considered as a reaction to analogous variation of $F_{10.7}$. Note that the last two available years (2009–2010) manifest a tendency for an increase in the analyzed parameters.
All this tells us that the source of the thermospheric parameter long-term variations is in the Sun rather than in the Earth’s atmosphere. A support for this conclusion may be found in the magnetic moment of the solar dipole which demonstrates the same type of 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]. A relationship between large-scale solar magnetic field and sunspot cycles was shown by Makarov et al. [2001]. According to Wang et al. [2000] the large-scale magnetic fields determine the interplanetary magnetic field. On the other hand, it is well established that geomagnetic activity is driven by the solar wind. Therefore, negative trends in neutral temperature and gas density widely discussed in the literature may be related with the falling phase in solar activity.

6. Conclusions

The main results may be formulated as follows.

1. A new recently developed method to retrieve thermospheric parameters and the total solar EUV flux with λ < 1050 Å from routine ionosonde observations was applied to June monthly median noontime f_F1 observations at three European stations: Rome, Slough/Chilton, and Juliusruh. For the first time, the exospheric temperature, thermospheric neutral composition, and solar EUV were obtained over the period of five solar cycles. The retrieved thermospheric parameters were compared to the MSIS-86 thermospheric model ones, and their closeness was demonstrated. A closeness was also shown between the retrieved and the EUVAC model EUV long-term variations.

2. Two reduction methods—with the MSIS-86 model as a reference and using a regression with 3 month F_10.7—were applied to the retrieved thermospheric parameters. The reduction of the retrieved T_ex, ρ_300, and [O]_300 with the MSIS-86 model results in very small and statistically insignificant residual trends. Keeping in mind that MSIS-86 is driven by solar F_10.7 and geomagnetic Ap indices, one may conclude that the retrieved parameter variations are also mainly controlled by solar and geomagnetic activity. The reduction using the regression with 3 month F_10.7 also gives very small and insignificant trends according to Fisher F criterion.

3. A special analysis of solar minimum conditions has also shown very small and insignificant trends in the thermospheric parameters, while the satellite drag mass density trend was found to be 2 times larger than the average one [Emmert, 2015]. No peculiarities in relation with the last deep solar minimum discussed in the literature [Emmert et al., 2010; Solomon et al., 2010; Emmert, 2015] have been revealed. This means that the empirical thermospheric model MSIS-86 which was used as a reference properly works out the extremely low solar and geomagnetic activity conditions of 2008–2009.

4. Answering the question formulated in section 1, it is possible to conclude that the proposed method provides the trend in neutral temperature which is close to the satellite drag estimate by Emmert [2015] and strongly contradicts the results obtained from ISR observations.

5. Summarizing the results of our analysis, it is possible to conclude that long-term variations of the thermospheric parameters retrieved from monthly median f_F1 observations have a natural (not anthropogenic)
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