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**Key Points:**

- A positive trend in the O+/Ne ratio (which corresponds to a negative trend in mean ion mass) and negative trend in Ti takes place at 175 km
- Routine incoherent scatter radar data cannot be used in long term trend analyses
- The revealed small Tex trends strongly contradict the results obtained from ISR observations

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# Long-term variations of exospheric temperature inferred from $f_oF_1$ observations: A comparison to ISR Ti trend estimates

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**Abstract** June noontime monthly median $f_oF_1$ ionosonde observations at Sodankylä (auroral zone), Juliusruh, and Rome (middle latitudes) were used to retrieve exospheric temperature, Tex long-term variations over the (1958–2015) period. After removing solar activity effects the residual linear trends were found to be small (0.05–0.6)% per decade and statistically insignificant at middle latitudes. Therefore, the revealed Tex long-term variations are mainly due to long-term variations of solar activity, i.e., they have a natural (not anthropogenic) origin. Large trends in ion temperature, Ti inferred from incoherent scatter radar (ISR) observations which the researchers identify with trends in neutral temperature, Tn may be related to the incoherent scatter method routinely based on a fixed model of ion composition ($O^+$/Ne ratio and mean ion mass, correspondingly) under varying geophysical conditions. Mean ion mass number manifests a negative trend at 175 km which should correspond to a negative trend in Ti contrary the results obtained below 200 km with ISRs. Therefore, routine ISR observations based on a fixed model of ion composition may be not appropriate for long-term trend analyses.

## 1. Introduction

The contradiction between long-term trends of the thermospheric temperature inferred from satellite drag measurements and those derived from incoherent scatter radar (ISR) observations is widely discussed in the literature [*Zhang et al*., 2016; *Emmert*, 2015; *Oliver et al*., 2014, and references therein]. The estimate from satellite drag measurements over the 1967–2005 period exospheric temperature trend is of −1 to −2 K per decade [*Emmert*, 2015], while the most recent estimates of thermosphere temperature trends inferred from ISR observations are −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 Tromsø [*Ogawa et al*., 2014], and −20 K/decade at 350 km for daytime hours at Millstone Hill *Zhang and Holt*, 2013]. A recent analysis by *Zhang et al*. [2016] of Sondrestrom and Chatanika/Poker Flat ISR observations has shown that the high-latitude long-term trend results are compared to those from the Millstone Hill midlatitude data set. At 250 km cooling at noon was between −10 and −30 K/decade. It should be stressed that only *Oliver et al*. [2014] have used a six-parameter analysis [*Oliver*, 1979] applied to Millstone Hill ISR observations to find exospheric temperature Tex and atomic oxygen concentration at 400 km long-term trends. The *Oliver* [1979] method should give real exospheric temperature Tex; however, it also gave a negative trend in Tex of −18 K/decade which is close to other Ti trends estimated from ISR observations [*Zhang et al*., 2016]. In all other cases trends in ion temperature were analyzed and it is supposed that Tn = Ti. Such Ti trends inferred from ISR observations manifest a strong dependence on height being positive below 200 km with a peak at ~175 km and increasingly negative at higher altitudes [*Zhang et al*., 2016, Figure 15]. This peculiarity below 200 km is presumably related to a well-known problem of ISR observations at $F_1$ region heights [*Waldteufel*, 1971; *Aponte et al*., 2007] where the ion composition (and consequently mean ion mass) changes from $NO^+$ and $O_2^+$ in the *E* region to $O^+$ in the $F_2$ region. The transition height varies with geophysical conditions, however, unchanged $O^+$/Ne models are used during the development of incoherent scatter (IS) observations (e.g., at Millstone Hill and European Incoherent Scatter (EISCAT) facilities). There is no reasonable physical explanation to such positive trend in Tn below 200 km. On the other hand, a negative trend in neutral temperature (supposing that Tn = Ti) increasing with height looks also questionable as the atmosphere above 300 km is practically isothermal and the trend should be height independent. Therefore, Tn trends inferred from ISR Ti observations should

be taken with caution as they hardly can be directly identified with the trends in neutral temperature. Such Ti trends are by 10 times larger than the Tn trends inferred from satellite drag measurements and they look as unreal ones supposing that Tn = Ti. Nevertheless, the problem still exists and further investigations are needed in this direction.

As an alternative to the two above mentioned approaches we have proposed a method [*Mikhailov and Perrone*, 2016a] to retrieve a self-consistent set of the aeronomic parameters (Tex is among them) from $f_oF_1$ ionosonde observations. 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 these observations are being conducted 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 during sunlit hours), and it is possible to solve the inverse problem of aeronomy and to retrieve the main aeronomic parameters responsible for the $F_1$ region formation from the routine ionosonde observations. A self-consistent set of the retrieved aeronomic parameters includes neutral composition (O, $O_2$, and $N_2$), exospheric temperature Tex, and the total solar EUV flux with $\lambda < 1050$ Å. The method was tested using CHAMP/STAR neutral gas density measurements. It was shown that the proposed method provided 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 the thermospheric trend analyses and this was demonstrated for three European stations: Rome, Slough/Chilton, and Juliusruh [*Mikhailov and Perrone*, 2016b]. It was shown that the exospheric temperature residual trends are very small and statistically insignificant, but they are close to the satellite drag trends estimated by *Emmert* [2015] and strongly contradict the results obtained from ISR observations.

That was a general conclusion not linked to a specific ISR facility and a period of observations. The analysis by *Ogawa et al*. [2014] of EISCAT (69.6°N; 19.2°E) measurements during a 33 year (1981–2013) period provides a good opportunity for such comparison using Sodankylä (67.4°N; 26.6°E) ionosonde observations. The EISCAT results indicate a cooling of 10–15 K/decade near the *F* region peak, the trend is zero around 400 km, and it becomes increasingly positive above 400 km height. The Sodankylä ionosonde provides manually scaled $f_oF_1$ data for the period overlapping the 33 year period analyzed by *Ogawa et al*. [2014], and this gives a possibility to make a comparison of the trend in Tex with the trend in Ti inferred from EISCAT observations.

Using a chain of ionosondes in the European sector, Sodankylä, Juliusruh, and Rome, it is possible to analyze latitudinal variations in the retrieved exospheric temperature long-term variations. The retrieved aeronomic parameters allow us to calculate long-term variations in ion composition and mean ion mass in the $F_1$ region which is crucial for the ISR method and to try to clear up the situation with the positive Ti trend below 200 km.

1. The aims of the paper may be formulated as follows: (1) to retrieve thermospheric neutral composition (O, $O_2$, $N_2$), exospheric temperature, Tex and the total solar EUV flux with $\lambda < 1050$ Å using all available monthly median summer $f_oF_1$ observations at Sodankylä (auroral zone) and to compare the obtained trends to midlatitude ones at Juliusruh and Rome ionosonde stations to check the latitudinal variations in the exospheric temperature long-term trends; (2) to compare the obtained Tex trends with the EISCAT trend in Ti [*Ogawa et al*., 2014]; and (3) to analyze long-term trends in ion composition and mean ion mass in the $F_1$ region in the auroral zone (Sodankylä) and at middle latitudes and to discuss the problem with the positive Ti trend below 200 km observed with the ISR method.

## 2. Method of Analysis

The undertaken analysis includes two steps: the first—a retrieval of a self-consistent set of aeronomic parameters from $f_oF_1$ ionosonde observations and the second—a method to extract long-term variations (trends) from the observed $f_oF_1$ and retrieved parameters.

The method to retrieve aeronomic parameters from $f_oF_1$ observations was described by *Mikhailov and Perrone* [2016a], but for a convenience of reading the main idea is repeated here.

We consider five observed $f_oF_1$ values for 10–14 LT and five unknown factors for: the MSIS-86 [*Hedin*, 1987] model exospheric temperature $T_{ex}$, concentrations [O], [$O_2$], and [$N_2$], as well as a factor for the *Nusinov* [1992] model of the total solar EUV flux with $\lambda < 1050$ Å. The transport processes are ignored, but a full scheme of photochemical processes for $O^+(^2D)$, $O^+(^2P)$, $O_2^+(X^2\Pi)$, $N^+$, $N_2^+$, and $NO^+$ ions at $F_1$ region heights is taken into account. Normally, the height of $F_1$ layer maximum is not available from routine ionosonde observations, but the theory of $F_1$ layer [e.g., *Ratcliffe*, 1972] tells us that the layer is formed in the transition area from a quadratic to a linear recombination law. This condition specifies $h_mF_1$ in our method as the observed $f_oF_1$ values should be prescribed to certain heights. The extraction of thermosphere parameters from ionospheric ones is a problem of nonlinear programming [*Himmelblau*, 1972]. The method can be only applied for the periods when $f_oF_1$ is explicitly present on ionograms; this takes place mainly in summer. June observations provide the minimum number of gaps, and June $f_oF_1$ data were used in our analysis. Sodankylä is located in the auroral zone ($\Phi = 66.9°$), but in summer during daytime sunlit conditions it exhibits itself as a typical midlatitude station as the auroral oval is located at $\Phi$ = 70–80° and $F_1$ layer is formed by solar EUV radiation.

During the retrieval process a complete set of ions is available; therefore, along with trends in the retrieved thermospheric parameters we will analyze long-term variations in ion composition, and in mean ion mass, only main ions $O^+$,$O_2^+$, and $NO^+$ will be considered. Such analysis is interesting in the light of positive Ti trends at $F_1$ region heights obtained from ISR observations [e.g., *Zhang et al.*, 2016].

The second step of our analysis is related to a method to extract long-term variations from the observed (e.g., $f_oF_1$) and from the retrieved parameters. Traditionally, monthly median values are taken, and using a regression with any solar activity index (sometimes magnetic activity index and *Ap* is added to a regression), solar cycle (11 year) variations are removed. Some questions arise at this step, which solar activity index (they are a lot) and which type of regression (linear or nonlinear) should be used. Depending on the choice, the resultant trends turn out to be different. At first solar cycle variations should be removed from monthly medians. A simple method allowing an easy control to extract ionospheric parameter long-term variations from routine monthly median ionosonde observations was described by *Perrone and Mikhailov* [2016]. However, depending on a parameter analyzed, the method may be slightly changed. For a convenience of reading we are giving its short description here. A regression of monthly median values of any parameter *f* with an index of solar activity, *S*, which is specially selected for the analyzed parameter

$$f_{\mathrm{reg}} = a_0 + a_1 S + a_2 S^2 \tag{1}$$

is used to find monthly relative deviations

$$\delta f = \left(f_{\mathrm{obs}} - f_{\mathrm{reg}}\right)/f_{\mathrm{obs}}. \tag{2}$$

The obtained $\delta f$ may be smoothed either using usual 11 year gate or running mean weighted smoothing with an 11 year gate according to the expression:

$$FS = \sum_{k=-5}^{0} F_k \times (6+k) + \sum_{k=1}^{5} F_k \times (6-k). \tag{3}$$

The type of smoothing depends on the analyzed parameter (see examples later).

First, we are considering $f_oF_1$ long-term variations. On one hand, $f_oF_1$ is the basic parameter in our analysis and it is important to know its long-term variations. On the other hand, the obtained $f_oF_1$ trends at different stations will be discussed later in relation with Ti trends at $F_1$ layer heights. A comparison of various indices of solar activity usually used in ionospheric parameter trend analyses is given in Table 1.

Table 1 shows that all indices provide a good correlation with monthly median $f_oF_1$ under the absolute significance according to Fisher *F* criterion but 3 month $F_{10.7}$ gives slightly better results, so this index was used in the regression (1).

## 3. $f_oF_1$ Trends

Using the earlier described method, long-term variations of $(\delta f_oF_1)_{11yw}$ (11 year running mean weighted) were obtained at Sodankylä (67.4°N; 26.6°E) and midlatitude stations: Juliusruh (54.6°N; 13.4°E) and Rome

**Table 1.** Correlation Coefficients Between June Noon Monthly Median $f_oF_1$ and Indices of Solar Activity Used in Ionospheric Parameter Trend Analyses[a]

| Station | $(F_{10.7})_{mon}$ | $(F_{10.7})_{3mon}$ | $(F_{10.7})_{12mon}$ | $(F_{10.7})_{11mon_w}$[b] | $R_{12}$ |
|---|---|---|---|---|---|
| Sodankylä | 0.94 | **0.95** | 0.93 | 0.93 | 0.93 |
| Juliusruh | 0.96 | **0.97** | 0.96 | 0.96 | 0.96 |
| Rome | 0.98 | **0.98** | 0.97 | 0.98 | 0.98 |

[a]The best result is given in bold.
[b]$(F_{10.7})_{11mon\ w}$—11 month running mean weighted smoothed $F_{10.7}$.

(41.9°N; 12.5°E) (Figure 1). Long-term $(\delta f_oF_1)_{11yw}$ variations manifest both positive and negative phases depending on the analyzed period. However, the linear trends in $(\delta f_oF_1)_{11yw}$ of ~−0.3% per decade estimated over all years are negative and statistically significant at 99% confidence level according to Fisher criterion.

This result contradicts the conclusion by *Bremer* [2008] who has found positive trends in $f_oF_1$ using worldwide ground-based ionosonde observations.

Although a negative trend in $(\delta f_oF_1)_{11yw}$ estimated over all years is obvious, a new (positive) tendency in $f_oF_1$ long-term variations is also seen after 2000–2005. It does not place at lower latitudes (Rome) but becomes more pronounced at higher latitudes especially at Sodankylä after 2000. The mechanism of such $f_oF_1$ long-term variations was described by *Mikhailov and Perrone* [2016a]. According to this mechanism, there is a competition between [O] and [O/$N_2$] which vary mainly antiphase. The change of sign in $f_oF_1$ long-term variations after circa 2000 is mainly due to an increase in the O/$N_2$ ratio which is larger at Sodankylä than at Rome. It was stressed by *Mikhailov and Perrone* [2016a] that the increase in $f_oF_1$ after 2000–2005 was a crucial argument against the $CO_2$ increase hypothesis in relation with the origin of ionospheric trends as the $CO_2$ abundance in the atmosphere continues to increase after 2000.

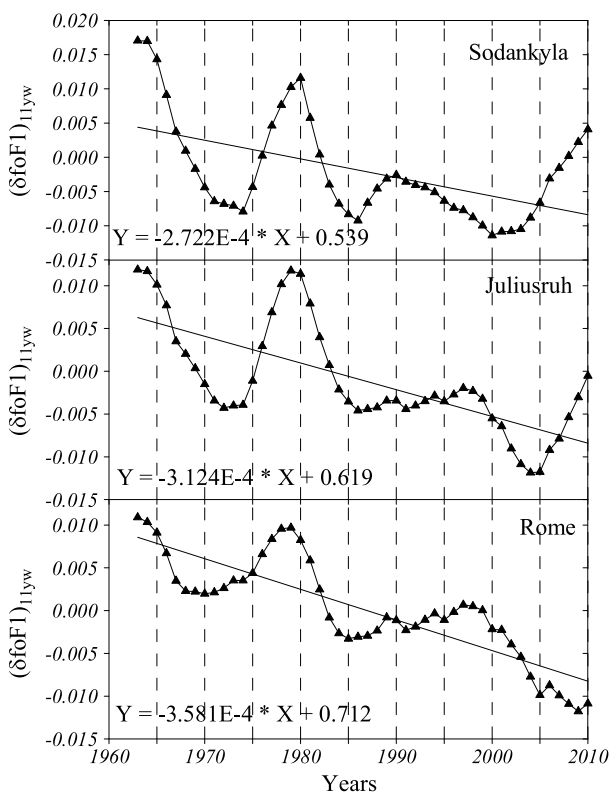


**Figure 1.** Long-term $(\delta f_oF_1)_{11yw}$ variations at three European stations located at different latitudes. Straight lines are linear trends estimated over all years with available $f_oF_1$ observations. Expressions in plots are given to quantify the trends. The error bars indicate the $\pm 1\sigma$ uncertainties.

## 4. Tex Trends

Using the method by *Mikhailov and Perrone* [2016a] exospheric temperature, Tex, and neutral composition and solar EUV were retrieved from the observed June daytime $f_oF_1$ at the three stations. We are discussing only Tex variations.

Testing of various solar activity indices (same as in Table 1) for a regression with Tex has shown that 3 month $F_{10.7}$ also provides better results compared to other indices and it was used in the regression (1). The retrieved exospheric temperature Tex in a comparison with monthly median MSIS-86 model Tex variations is given in Figure 2 (left column). To provide a correct comparison MSIS-86 model, monthly Tex 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.

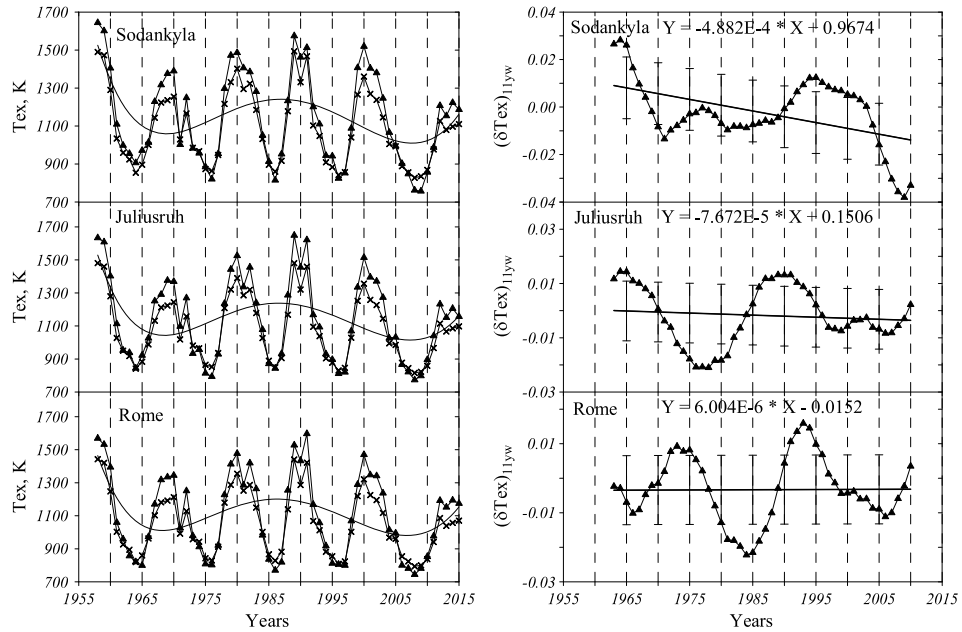


**Figure 2.** (left column) Retrieved (triangles) for June, 12 LT exospheric temperature at Sodankylä, Juliusruh, and Rome. Monthly median MSIS-86 model Tex variations are given for a comparison (crosses). Solid lines—polynomial approximations of the retrieved Tex. (right column) δTex variations after the regression of Tex with $(F_{10.7})_{3mon}$ and linear trends estimated over all years (expressions are given in plots). The error bars indicate the ±1$\sigma$ uncertainties.

Polynomial approximations indicate long-term Tex variations with the rising phase in 1967–1985 and the falling phase after 1990 reflecting the corresponding long-term variations in solar activity. A comparison of the retrieved Tex to the model MSIS-86 monthly median Tex variations shows their closeness with the correlation coefficient of ~0.99; however, the absolute values may differ especially during solar maximum (Figure 2).

The correlation coefficients of 3 month $F_{10.7}$ with Tex are large: 0.975 at Rome, 0.983 at Juliusruh, and 0.981 at Sodankylä under the absolute significance according to Fisher $F$ criterion. Therefore, after the regression of Tex with $(F_{10.7})_{3mon}$ and 11 year weighted smoothing the residual $(\delta Tex)_{11yw}$ variations should be small (Figure 2, right column). Although $(\delta Tex)_{11yw}$ demonstrates both increasing and decreasing phases, the magnitude of these variations is small ~±2%. The linear trends estimated over all years are also very small and statistically insignificant at Rome and Juliusruh. At Sodankylä the trend is significant at the 99% confidence level being also very small <0.5% per decade. This means that practically, all Tex variations retrieved for June noon conditions can be removed using a regression with one solar activity index, $(F_{10.7})_{3mon}$, i.e., solar activity practically totally controls Tex variations.

All analyzed by *Zhang et al*. [2016] ISR observations demonstrate positive Ti trends below 200 km with a well-pronounced peak around 175 km both in Western and Eastern longitudinal sectors (their Figure 12). From ionospheric physics point of view such Ti variations look rather strange. But it is known that ISR observations crucially depend on the accepted model of the mean ion mass [*Waldteufel*, 1971; *Beynon and Williams*, 1978; *Aponte et al*., 2007]. The problem arises at $F_1$ region heights where ion composition (and consequently mean ion mass) changes from $NO^+$ and $O_2^+$ in the $E$ region to $O^+$ in the $F_2$ region. Similar problem takes place with the transition from $O^+$ to the lighter ions of $H^+$ and $He^+$ in the topside ionosphere. The transition height varies with geophysical conditions; however, unchanged $O^+$/Ne models are used in the routine development of ISR observations (at least at Millstone Hill and EISCAT facilities). Mean ion mass is subjected to large changes during severe geomagnetic storms when $F$ region is enriched with heavy $NO^+$ and $O_2^+$ ions and routine ISR observations (mainly Ti and Te vertical profiles) should be corrected [*Mikhailov and Foster*, 1997; *Mikhailov and Schlegel*, 1997]. The magnitude of long-term variations of the thermospheric parameters is not that large as during geomagnetic storms; however, such variations take place with the corresponding changes in ion composition and mean ion mass. It should be stressed that analyzing ionospheric and

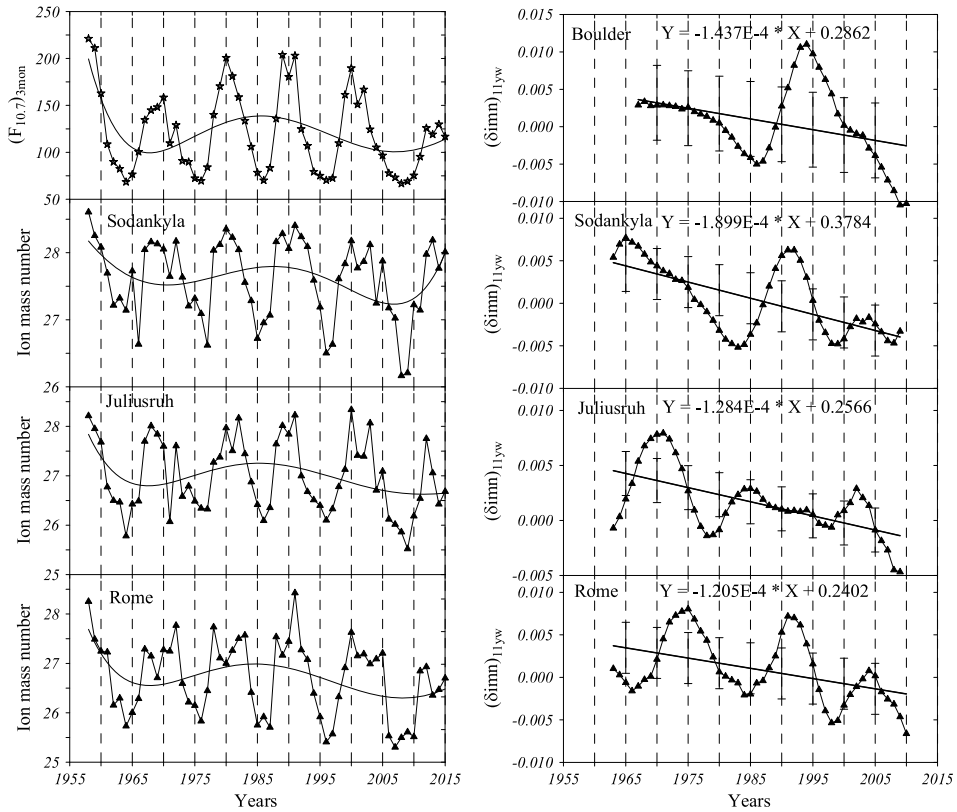


**Figure 3.** (left panel) Calculated long-term variations of the mean ion mass number at 175 km along with $(F_{10.7})_{3mon}$. Lines —polynomial approximations. (right column)—11 year mean weighted smoothed δ(ion mass number) at four stations. Straight lines—linear trends estimated over all years (corresponding expressions are given in plots). The error bars indicate the $\pm 1\sigma$ uncertainties.

thermospheric long-term trends, we deal with very small deviations (practically, we work at the level of noise); therefore, even small variations in mean ion mass may be crucial for Ti trends obtained from ISR measurements.

The retrieval method by *Mikhailov and Perrone* [2016a] comprises a complete set of pertinent processes to calculate the whole ion composition and such results are available for the (1958–2015) period. Therefore, we can check whether the calculated long-term variations of the mean ion mass at $F_1$ region heights correspond to a positive Ti trend observed below 200 km with the ISR method. We are considering only three major ions $O^+$, $NO^+$, and $O_2^+$ at 175 km where according to ISR observations the maximal positive Ti trend is observed [*Zhang et al*., 2016]. It should be stressed that in our approach we have a self-consistent set of the main aeronomic parameters (neutral composition, temperature, and the ionizing solar EUV flux); therefore, the calculated long-term variations in ion composition reflect the corresponding long-term variations in the aeronomic parameters retrieved from the observed $f_oF_1$ variations.

Calculated long-term variations of the mean ion mass number at 175 km are given at Figure 3 (left column). Similar to other retrieved thermospheric parameters [*Mikhailov and Perrone*, 2016b] mean ion mass number manifests both solar cycle and long-term (for some solar cycles) variations due to corresponding variations in solar activity (cf. $(F_{10.7})_{3mon}$, Figure 3). Naturally, mean ion mass number increases during high solar activity when the upper atmosphere at 175 km is enriched with heavy molecule species ionized by solar EUV. Long-term variations in the mean ion mass number are also seen with the rising phase in 1967–1985 and the falling phase in 1985–2008. Even a visual analysis of the interminima mean ion mass number variations shows its decrease after the solar minimum in 1985 (Figure 3, left column).

To estimate long-term trends in mean ion mass number, solar activity variations should be removed as much as possible from the calculated variations in Figure 3. By analogy with our earlier analysis a proper index of

**Table 2.** Correlation Coefficients Between the Calculated Ion Mass Number and Some Indices of Solar Activity[a]

| Station | $(F_{10.7})_{mon}$ | $(F_{10.7})_{3mon}$ | $(F_{10.7})_{12mon}$ | $(F_{10.7})_{11mon_w}$[b] | $R_{12}$ |
|---|---|---|---|---|---|
| Sodankylä | 0.79 | **0.81** | 0.80 | 0.80 | 0.81 |
| Juliusruh | 0.87 | **0.88** | 0.85 | 0.86 | 0.86 |
| Rome | 0.80 | **0.82** | 0.81 | 0.82 | 0.82 |

[a]The best result is given in bold.
[b]$(F_{10.7})_{11mon_w}$—11 month running mean weighted smoothed $F_{10.7}$ according to (3).

solar activity should be selected (see Table 2). All tested indices provide close results with the correlation coefficients being absolutely significant according to *F* criterion, but 3 month $F_{10.7}$ turns out to be the best, and it was used for the regression.

The results of this regression analysis are given in Figure 3 (right column) with corresponding linear trends estimated over all years. The trends are negative and small—(0.12–0.19)% per decade, but they are statistically significant at the 99% confidence level according to *F* criterion.

The obtained negative trend in mean ion mass implies a negative trend in ion temperature, Ti as ISR ion-line observations are sensitive to the Ti/$m^+$ ratio, where $m^+$ is mean ion mass [*Beynon and Williams*, 1978]. In this case the ISR routine data development with an unchanged model of $O^+$/Ne (and $m^+$ correspondingly) overestimates real Ti resulting in a positive Ti trend at 175 km. This could be the explanation of the abnormal Ti long-term variations at $F_1$ layer heights observed with ISRs.

Figure 4 (left column) gives long-term variations of the $O^+$/Ne ratio at 175 km at the three stations. Even a visual analysis without removing the solar activity dependence manifests a positive trend after circa 1980 comparing interminimum changes in the mean ion mass number.

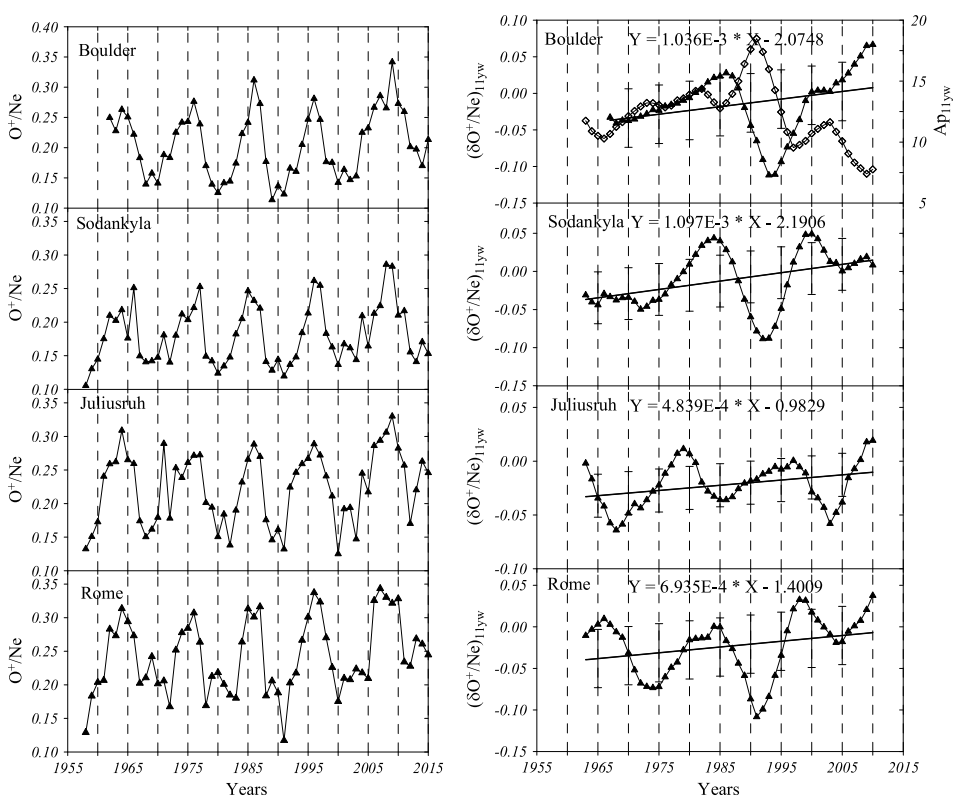


**Figure 4.** (left column) Long-term variations of the $O^+$/Ne ratio at 175 km. (right column) $\delta(O^+/Ne)_{11yw}$ long-term variations. Straight lines—linear trends estimated over all years (corresponding expressions are given in plots). Open squares —$Ap_{11yw}$ variations (right column, top).The error bars indicate the $\pm 1\sigma$ uncertainties.

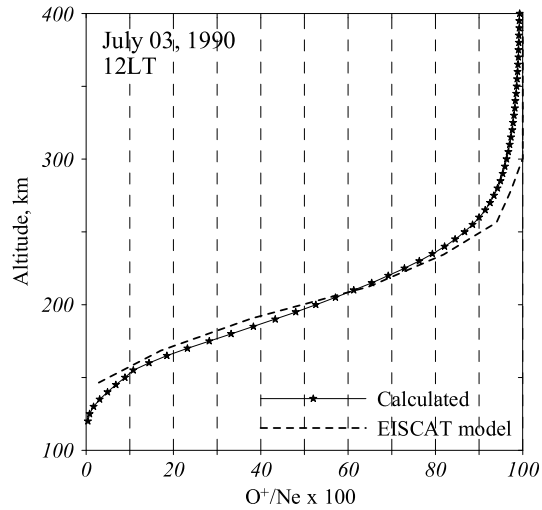


**Figure 5.** A comparison of the calculated $O^+$/Ne profile for summer noon conditions to the standard one which is used at EISCAT during routine data development. The standard model is seen to imply 100% of $O^+$ ions above 300 km height while, in fact, there are ~5% of molecule ions in the vicinity of the $F_2$ layer maximum. Therefore, instead of mean ion mass number 16 we have 0.95 × 16 + 0.05 × 30 = 16.7.

The $O^+$/Ne varies antiphase with solar activity (presented by 3 month $F_{10.7}$ indices) with the correlation coefficients of ~−0.85. After the regression with $(F_{10.7})_{3mon}$11 year mean weighted smoothed $\delta(O^+/Ne)$ along with linear trends estimated over all years are given in Figure 4 (right column). All linear trends are positive and statistically significant according to Fisher criterion with the 99% at Sodankylä, >95% at Juliusruh and >90% at Rome confidence levels.

The residual positive trend in $(\delta O^+/Ne)_{11yw}$ may be related to the negative trend in $Ap_{11yw}$ (Figure 4, right column, top). Also, the deep trough in $(\delta O^+/Ne)_{11yw}$ long-term variations observed after circa 1990 may be related to the strong increase in geomagnetic activity in that period (squares in Figure 4). The mechanism of this dependence is known—an increase of geomagnetic activity decreases the $O/(N_2 + O_2)$ ratio at a fixed height decreasing the $O^+$/Ne ratio. The absence of this trough at Juliusruh needs a special consideration.

Summarizing this part of our analysis, it is possible to conclude that long-term variations in ion composition ($O^+$/Ne ratio) and correspondingly in mean ion mass really exist and should affect the results of ISR observations used for long-term trend analyses.

## 5. Discussion

The undertaken analysis has shown that large negative Ti trends obtained from ISR observations (which researchers incline to identify with trends in neutral temperature) may be related to the ISR method which routinely uses the unchanged model of ion composition ($O^+$/Ne profile) and correspondingly the unchanged model of mean ion mass. Figure 4 (left column) shows that solar cycle $O^+$/Ne variations are rather large reaching (2–3) times at a fixed height 175 km; moreover, this ratio manifests long-term variations; however, this is not taken into account during the routine development of ISR measurements. Ion-line ISR observations are sensitive to the $Ti/m^+$ ratio, where $m^+$ is the mean ion mass [*Beynon and Williams*, 1978]. The negative trend in mean ion mass at $F_1$ region heights retrieved from $f_oF_1$ observations should result in a negative Ti trend if this negative trend in mean ion mass was taken into account during the development of ISR observations. But fixed mean ion mass was used which gave overestimated Ti values and a positive Ti trend in the $F_1$ region [*Zhang et al.*, 2016].

*Ogawa et al.* [2014] did not consider $F_1$ region heights, but their Ti trends are of −10 to −15 K/decade around $F_2$ layer maximum for daytime hours. It should be noted that their estimates are the minimal compared to Ti trends obtained at other ISR facilities. Nevertheless, even these trends are also too large supposing that Tn = Ti. They may be also related to mean ion mass variations. Figure 5, taken from *Mikhailov and Kofman* [2001], gives a comparison of the calculated $O^+$/Ne profile for summer noon conditions to the standard one which is used at EISCAT during routine data development. The standard model is seen to imply 100% of $O^+$ ions above 300 km height, while, in fact, there are ~5% of molecule ions in the vicinity of the $F_2$ layer maximum. Therefore, instead of mean ion mass number 16, we have 0.95 × 16 + 0.05 × 30 = 16.7.

Smaller mean ion mass in the ISR method results in smaller Ti values compared to real ones, and this may explain underestimated Ti values around $F_2$ layer maximum [*Ogawa et al.*, 2014]. The share of molecular ions decreases with height (Figure 5) and mean ion mass number $\mu$ approaches 16. At 400 km the ionosphere is

totally composed of $O^+$ ions with $\mu$ = 16 and the ISR method should give correct Ti values. Exactly the same altitude variations manifest the Ti trend obtained at EISCAT [*Ogawa et al*., 2014, Figure 3]: the largest negative trend takes place around 320 km, then it decreases with height reaching zero at 400 km, and then it becomes positive increasing with height. Zero Ti trend at 400 km [*Ogawa et al*., 2014] where $\mu$ = 16 corresponds to our very small Tex trends (Figure 2). Therefore, EISCAT observations can give reasonable Ti trends which are comparable to our Tex trend estimates (Figure 2) as well as to satellite drag Tex trends [*Emmert*, 2015] but only at heights where the ionosphere is really composed of $O^+$ ions as it is supposed in the ISR method.

A positive increasing with height Ti trend above 400 km [*Ogawa et al*., 2014] may be related to decreasing mean ion mass due to lighter ions of $H^+$ and $He^+$. The routine EISCAT method uses $\mu$ = 16, while real mass number is less than 16 and $\mu$ decreases with height. The larger mean ion mass used in the ISR method the larger Ti values, i.e., the ISR method overestimates real Ti. This explains the positive increasing with height Ti trend [*Ogawa et al*., 2014, Figure 3]. The situation with the topside ionosphere is the same as we discussed in relation with the $F_1$ region (see earlier). The height dependence of the Ti trend may be explained this way, but a trend means a variation in time. Therefore, by analogy with the $F_1$ region mean ion mass should also demonstrate long-term variations in the topside. There is a significant negative Tex trend at Sodankylä (Figure 2) especially after 1995; therefore, the topside ionosphere should subside and will be enriched with lighter ions of $H^+$ and $He^+$ at any fixed height, and this will result in a positive and increasing with height Ti trend in ISR observations exactly what was revealed by *Ogawa et al*. [2014, Figure 3].

According to *Rishbeth and Edwards* [1989], the daytime $F_2$ layer mainly follows a constant pressure level; therefore, under decreasing Tex an ~5% of molecular ions will be always present in the $F_2$ layer maximum, and the ISR method based on $\mu$ = 16 will always underestimate Ti values. It should be stressed that small effects related with mean ion mass in the ISR method are not important, in practice, when we deal with the absolute values of Ti, Te, and Ne, but they become essential when we consider long-term variations of these parameters.

Thus, the peculiarities with Ti trends obtained from ISR measurements may be related to models of ion composition used in the routine ISR method when the model $O^+$/Ne profile is taken unchanged under varying geophysical conditions. Therefore, the long-term trends obtained on the basis of such ISR observations will differ from the trends obtained with other (satellite drag or ionosonde observations) methods.

## 6. Conclusions

The results of undertaken analysis may be summarized as follows.

1. The Tex long-term variations inferred from $f_oF_1$ summer (June) noontime observations at the latitudinal chain of European stations over the (1958–2015) are practically totally controlled by solar activity long-term variations. After removing solar activity effects the residual Tex trends were found to be very small (0.05–0.6)% per decade.
2. The revealed small Tex trends are closer to the Tex trends inferred from satellite drag observations [*Emmert*, 2015] and contradict the results obtained from ISR observations [*Zhang et al*., 2016; *Oliver et al*., 2014].
3. Large and physically unreal Ti trends obtained from ISR observations which the researchers incline to identify with Tn trends may be related to the routine IS method using a fixed model of ion composition ($O^+$/Ne ratio and mean ion mass, correspondingly) under varying geophysical conditions.
4. Our analysis based on the consideration of June daytime conditions tells us that routine ISR observations based on a fixed model of ion composition ($O^+$/Ne ratio) under varying geophysical conditions may be not appropriate for long-term trend analyses. This result is the first indication that such problem does exist with ISR observations. In the future such analysis should be extended to other seasons when a corresponding method to retrieve thermospheric parameters from $F_1$ layer observations is developed.

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