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Key Points:

- 93% of the column atomic oxygen content long-term variations are due to solar and geomagnetic activity
- The contribution of solar and geomagnetic activity to the $[O]_{col}$ variability decreases with years
- $[O]_{col}$ long-term variations have a natural origin

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Long-Term Variations of June Column Atomic Oxygen Abundance in the Upper Atmosphere Inferred From Ionospheric Observations

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Abstract For the first time, atomic oxygen column content $[O]_{col}$ has been inferred from June daytime monthly median f_oF_1 and f_oF_2 observations at Rome, Juliusruh, Sodankylä, and Boulder to analyze its long-term variations for the period of ~6 solar cycles. The analysis is interesting in the light of possible anthropogenic impact on the upper atmosphere. After the removal of solar and geomagnetic activity effects from the inferred $[O]_{col}$ variations, the residual linear trends are negative and statistically insignificant at middle latitudes. It is shown that ~93% (the corresponding correlation coefficient is 0.964 ± 0.03) of the whole $[O]_{col}$ variability is explained by solar and geomagnetic activity long-term variations and only ~7% may be attributed to other processes (reasons) including the anthropogenic impact. Solar and geomagnetic activity contributions to $[O]_{col}$ long-term variations decrease with time, and this may be related to the low solar activity epoch, which we have entered. The main conclusion is that the long-term variations of the atomic oxygen column content inferred from ionospheric observations are due to solar and geomagnetic activity; that is, they have a natural origin.

Plain Language Summary Anthropogenic impact on the upper atmosphere is increasing mainly via the CO_2 concentration increase. What is going on with atomic oxygen (the main constituent in the upper atmosphere) under this impact? Solving an inverse problem of aeronomy atomic oxygen long-term variations were retrieved from June daytime monthly median f_oF_1 and f_oF_2 observations for the period of ~6 solar cycles. The obtained results have shown that solar and geomagnetic activity contribute ~93% to the total $[O]_{col}$ variability at middle latitudes and only ~7% of $[O]_{col}$ variability may be attributed to other processes (reasons) including the anthropogenic impact. As we have entered the epoch of low solar activity the contribution of solar and geomagnetic activity to the $[O]_{col}$ variability decreases with years. The main conclusion is that the atomic oxygen column content long-term variations are due to solar and geomagnetic activity; that is, they have a natural origin.

1. Introduction

Atomic oxygen is the main thermospheric constituent above ~200 km responsible for neutral gas density variations at satellite heights. Ionospheric *F*-layer parameters are crucially dependent on atomic oxygen via its ionization by solar extreme ultraviolet (EUV) radiation and via the diffusion rate of O^+ ions. Direct observations of atomic oxygen require rocket and satellite mass spectrometer and optical measurements. On one hand, such observations are technically complicated (e.g., Russell et al., 2007), and expensive on the other hand, they are episodic and cannot tell us anything about long-term (for some solar cycles) changes in the atomic oxygen abundance. Using incoherent scatter radar (ISR) observations, it is also possible with some reservations to extract atomic oxygen and neutral temperature at F_2-region heights (Oliver, 1979), and Millstone Hill ISR observations analyzed for the period of 38 years gave a very small negative trend in atomic oxygen at 400-km height (Oliver et al., 2014).

The revealed long-term trends in thermospheric parameters are small (see the reviews by Emmert, 2015a; Laštovička, 2013, 2017) compared to diurnal and solar cycle variations and hardly are important from practical point of view, but such knowledge is important in the light of anthropogenic impact on the Earth's atmosphere. Continuous increase of CO_2 concentration in the Earth's atmosphere (https://www.co2.earth) should lead to cooling of the thermosphere with corresponding changes in thermospheric

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and ionospheric parameters as model simulations predict (Rishbeth & Roble, 1992; Solomon et al., 2018). Along with this anthropogenic impact on the upper atmosphere, there is a natural source related to solar and geomagnetic activity long-term variations (Mikhailov & Perrone, 2016a, 2016b; Perrone & Mikhailov, 2016).

Atomic oxygen is totally produced and lost in the upper atmosphere (Banks & Kockarts, 1973); therefore, it is a convenient species to follow long-term changes in the thermosphere. Our recently proposed method by Perrone and Mikhailov (2018a) using summer noontime f_oF_1 and f_oF_2 observations provides a self-consistent set of the main aeronomic parameters (atomic oxygen in particular) responsible for the observed f_oF_1 and f_oF_2 long-term variations. Such observations are available for the period of ~6 solar cycles at some stations in Europe and America, and they can be successfully used for an analysis of atomic oxygen long-term trends. Our previous analyses concerned atomic oxygen long-term variations at a fixed height. The revealed negative [O] trend can explain a negative trend in f_oF_2, and qualitatively, it agrees with the negative trend in neutral gas density obtained on satellite drag observations (Emmert, 2015b). However, considering [O] variations at a fixed height, we have a combined effect of atomic oxygen and neutral temperature long-term variations and a correct separation of their contributions may be a problem. Therefore, here we will consider the total (column) atomic oxygen abundance above 70 km, which is independent on neutral temperature height profile. This analysis should show us what is going on with the atomic oxygen content in the course of ~6 solar cycles.

The aims of the paper may be formulated as follows:

1. Using the method by Perrone and Mikhailov (2018a) to consider long-term variations of the column atomic oxygen content at the ionospheric stations located in the European and American longitudinal sectors over the period of ~6 solar cycles.
2. To discuss the revealed variations of atomic oxygen column content in the light of CO_2 increase hypothesis and long-term variations of solar and geomagnetic activity.

2. Method and Results

There are two versions of the method by Perrone and Mikhailov (2018a), which are used depending on available observations in the F_1-region. When bottom-side Ne(h) profiles are available f_{o180} (critical frequency at 180-km height) can be used, but this is possible only using DPS-4 (Reinisch et al., 2004) observations. We are interesting in long-term variations for ~6 solar cycles; therefore, the only possibility is to consider f_oF_1 for summer season when F_1 layer is distinct on ionograms. Thus June near noontime (10-14) LT f_oF_1 and f_oF_2 observations were used to retrieve atomic oxygen [O] and exospheric temperature Tex at three European stations located at different latitudes Sodankylä (67.4°N; 26.6°E), Juliusruh (54.6°N; 13.4°E), Rome (41.9°N; 12.5°E), and Boulder (40.0°N; 254.7°E) with the latitude close to Rome one to compare two longitudinal sectors. European stations provide required observations since 1958 while Boulder—since 1962.

The applied method gives factors to MSIS-86 (Hedin, 1987) model neutral species concentrations and exospheric temperature. Normalized by this way the model atomic oxygen height profile is used to find the total column atomic oxygen content above 70-km height. It should be mentioned that the method uses MSIS-86 model neutral temperature at 120 km and the shape parameter S to specify the Bates (1959) Tn(h) profile. Keeping in mind that the internal structure of the MSIS-86 model is used in the method, there are doubts (e.g., Zhang et al., 2018) whether the inferred atomic oxygen column content differs from MSIS-86 one and does not just reproduce MSIS-86 model variations. Although the method was tested using CHAMP/STAR neutral gas density observations (Perrone & Mikhailov, 2018a) and it was shown to give the accuracy higher than modern thermospheric empirical models provide, we will give a comparison with MSIS-86 to demonstrate the difference (see later).

Solar and geomagnetic activity effects should be removed as much as possible from the retrieved atomic oxygen column content, $[O]_{col}$ to analyze its long-term variations. A comparison of various solar activity indices has shown that 3-month averaged $F_{10.7}$ (F_{3mon}) provides the best correlation and it was chosen for further analysis. June monthly Ap indices were used in the regression to remove geomagnetic activity effects.

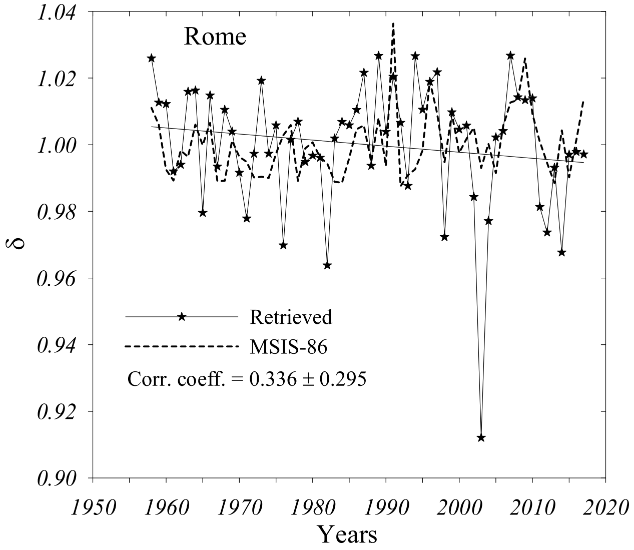

Figure 1. A comparison of the retrieved to MSIS-86 model δ=$[\mathrm{O}_{\mathrm{col}}]/([\mathrm{O}_{\mathrm{col}}]_{\mathrm{reg}}$ June noontime variations at Rome obtained after the removal of solar and geomagnetic activity effects from the column atomic oxygen variations. Straight line-linear trend estimated for the retrieved δ values over all years.

The most straightforward way is to use a regression

$$[\mathrm{O}]_{\mathrm{reg}} = b_0 + b_1\times F_{3\mathrm{mon}} + b_2\times \mathrm{Ap} \tag{1}$$

to remove solar and geomagnetic activity effects and to check if any significant residual trend is left in δ=$[\mathrm{O}]_{\mathrm{col}}/[\mathrm{O}]_{\mathrm{reg}}$ variations after the application of this regression.

Figure 1 gives a comparison of the inferred to MSIS-86 model δ=$[\mathrm{O}]_{\mathrm{col}}/[\mathrm{O}]_{\mathrm{reg}}$ variations obtained after the removal of solar and geomagnetic activity effects from the inferred column and MSIS-86 model atomic oxygen variations. It is seen that MSIS-86 only qualitatively reproduces the retrieved variations, but the magnitude of the inferred variations is much larger. The correlation coefficient between MSIS-86 and the retrieved δ values is small (0.336±0.295) although it is significant at the 99% confidence level. The difference between retrieved and MSIS-86 atomic oxygen column content, $[\mathrm{O}]_{\mathrm{col}}$, is significant at the 99% confidence level according to Student criterion. The MSIS-86 model underestimates geomagnetic activity effects in atomic oxygen variations, which are seen in the observed f_oF_1 and f_oF_2 used in our method. Three other stations demonstrate the same results.

Residual linear trends estimated over the retrieved δ=$[\mathrm{O}_{\mathrm{col}}]/[\mathrm{O}_{\mathrm{col}}]_{\mathrm{reg}}$ variations are negative (Figure 1) and statistically insignificant at three midlatitude stations, while at Sodankylä the trend is negative and significant at the confidence level of 99% according to Student criterion. This means that apart from solar and geomagnetic activity, some other process(s) contributes to atomic oxygen variations at Sodankylä (the auroral zone). This also follows from a comparison (Table 1) of the retrieved $[\mathrm{O}]_{\mathrm{col}}$ to the values found from the regression (1).

The correlation coefficients (r) in Table 1 are significant at the 99.9% confidence level, and r is the smallest at Sodankylä compared to other stations. The correlation coefficient averaged over three midlatitude stations is 0.964 ± 0.03. This means (according to the $R^2 = r^2$ definition) that solar and geomagnetic activities explain ~93% of the total (column) atomic oxygen variability at middle latitudes, while this is only ~84% at Sodankylä. Midlatitude 93% of the explained variability tells us that practically all atomic oxygen variations have a natural origin and only ~7% may be attributed to other processes including the anthropogenic impact. In principle, these residual 7% may not be associated to any physical process but may reflect the inaccuracy of the input data or the limitations of the applied method. Sodankylä manifests different from other three station results, and they will be discussed later (see section 3).

The application of (1) gives the final residual trend, but it is interesting to follow the $F_{10.7}$ and Ap contributions separately. The coefficient b_2 in (1) (always negative) is by 2-4 times larger than b_1 (always positive), but $F_{3\mathrm{mon}}$ is much larger than Ap, so $F_{3\mathrm{mon}}$ provides the main contribution to $[\mathrm{O}]_{\mathrm{col}}$ variations. Two terms of the regression (1) are compared in Figure 2 for the Rome station, as an example (other stations manifest similar variations).

Figure 2 clearly indicates the solar cycle dependence of the two terms in the regression (1). The compensating contribution of geomagnetic activity is larger during solar maximum, for instance, in 1958, 1991, 2003, and it is small during solar minimum, especially in 1996 and 2008-2009.

Table 1
Correlation Coefficients Between the Retrieved $[O]_{col}$ and the Values Found From the Regression (1)

Station	Sodankylä	Juliusruh	Rome	Boulder
Corr. coeff.	0.919 ± 0.066	0.944 ± 0.046	0.969 ± 0.026	0.980 ± 0.017

Linear trends in Figure 2 indicate a decrease of solar and geomagnetic activity contributions with years; that is, the atomic oxygen column content is directed towards b_o (a constant value) at a given location and this looks as an interesting result. One may think that during the period of low solar activity in which we have entered (http://www.wdcb.ru/stp/data/solar.act/csa/Cycles%20of%20Solar%20Activity.en.pdf), the atomic oxygen abundance will stabilize at a constant level. The dependence of $[\mathrm{O}]_{\mathrm{col}}$ on solar activity (via $F_{3\mathrm{mon}}$) is mainly provided via O_2 dissociation above 100 km by solar radiation in Schumann-Runge continuum. In

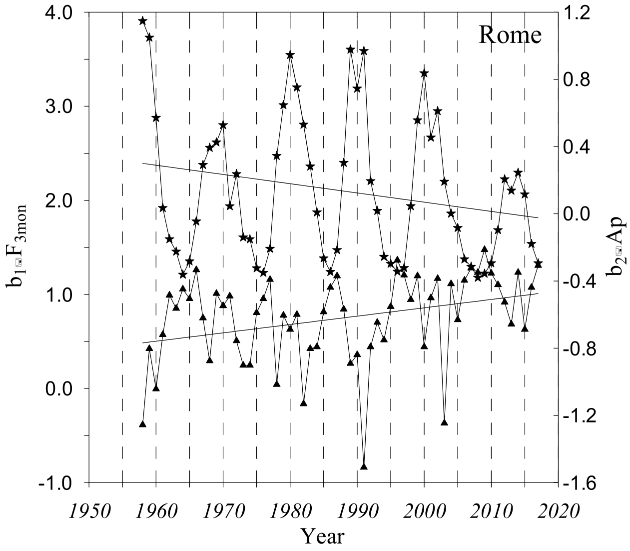

Figure 2. Variations of two terms in the regression (1). The asterisks represent the first term (left *y* axis); the triangles represent the second term (right *y* axis). The straight lines represent linear trends estimated over all years.

principle, eddy diffusion responsible for the atomic oxygen downward transfer with the subsequent loss in tree-body collisions may also depend on solar activity, but today such data are absent and only seasonal variations of eddy diffusion are discussed in the literature (e.g., Pilinski & Crowley, 2015; Qian et al., 2009).

The second term in (1) describes the dependence of atomic oxygen abundance on geomagnetic activity, and this dependence is related to global thermospheric circulation (Rishbeth, 1998; Rishbeth & Müller-Wodarg, 1999). After the removal of solar activity dependence using the regression coefficients of (1), we can analyze the residual $\Delta[\mathrm{O}]_{\mathrm{col}}$ variations, which are related to geomagnetic activity. An example of such 5-point smoothed $\Delta[\mathrm{O}]_{\mathrm{col}}$ variations (smoothed variations are more visual) is given in Figure 3 for Juliusruh and Rome in a comparison with smoothed June monthly Ap indices.

Figure 3 manifests falling and rising phases in $\Delta[\mathrm{O}]_{\mathrm{col}}$ smoothed variations with minimum in ~1980 and maximum in 2000-2005. Naturally, linear trends ($\Delta[\mathrm{O}]_{\mathrm{col}} = b_0 + b_1 \times \mathrm{year}$) estimated separately over these phases will have different signs. But linear trends estimated over all available years are positive and significant at the confidence level >98% at Juliusruh, Rome, and Boulder. June smoothed $\mathrm{Ap}_{\mathrm{sm}}$ indices (Figure 3, bottom panel) also manifest distinct positive (1965-1985) and negative (1985-2010) phases with a tendency for a new positive phase after 2009. The linear trend in $\mathrm{Ap}_{\mathrm{sm}}$ estimated over all (1961-2015) years is negative and absolutely significant (the confidence level >99.9% according to Student criterion). The regression coefficients are $b_1 = -(8.01 \pm 4.03) \times 10^{-2}$ and $b_0 = (1.70 \pm 0.80) \times 10^{2}$. It should be stressed that the sign (negative) of this $\mathrm{Ap}_{\mathrm{sm}}$ trend does not depend on the starting year as it is determined by general decrease of geomagnetic activity after 1990 with the minimal low level in 2008-2009 (Figure 3). The anticorrelation between $\mathrm{Ap}_{\mathrm{sm}}$ and smoothed $\Delta[\mathrm{O}]_{\mathrm{col}}$ is well seen comparing ups and downs (numbers in the plot) in their variations.

After the removal from $[\mathrm{O}]_{\mathrm{col}}$, the dependences on F_{3mon} and Ap the residual trends are insignificant at the midlatitude stations in accordance with earlier results obtained after the direct application of the regression (1). The undertaken analysis has shown that long-term variations in the column atomic oxygen abundance are due to solar and geomagnetic activity long-term variations; that is, they have a natural origin.

3. Discussion

At present there are no long enough series of atomic oxygen observations in the thermosphere that could be used for a comparison with the obtained results. Only indirect methods can provide some information on long-term variations of atomic oxygen over a period of some decades. Ionospheric F_2 region is crucially dependent on atomic oxygen, and analyses of ground-based ionosonde N_mF_2 long-term variations firstly have indicated [O] long-term changes in the upper atmosphere (Danilov & Konstantinova, 2014; Givishvili & Shubin, 1995; Mikhailov, 2006). Incoherent scatter radar observations also can be used to infer atomic oxygen concentration at F_2-region heights (Oliver, 1979; Vickers et al., 2013). Oliver et al. (2014) have obtained at Millstone Hill a very small negative trend of 0.0±1.5% per decade in atomic oxygen density at 400-km altitude over the 1976-2013 period. However, this zero trend in [O] was accompanied by a very large trend of -18 K/decade in noontime exospheric temperature and this result contradicts satellite drag observations by Emmert (2015b). The problem of unreal Tex trends inferred from ISR observations was discussed by Perrone and Mikhailov (2018b). Wrong Tex ISR trends cast doubts on atomic oxygen long-term trends as well.

The aim of the undertaken analysis was to answer the question—what is going on with the atomic oxygen abundance in the thermosphere keeping in mind the anthropogenic CO_2 impact widely discussed in the literature. The only possibility to answer this question is to use ground-based ionosonde observations, which are available for ~60 years on some European and American stations. Our recently proposed method (Perrone & Mikhailov, 2018a) has allowed us to convert daytime monthly median f_oF_2 and f_oF_1 to atomic

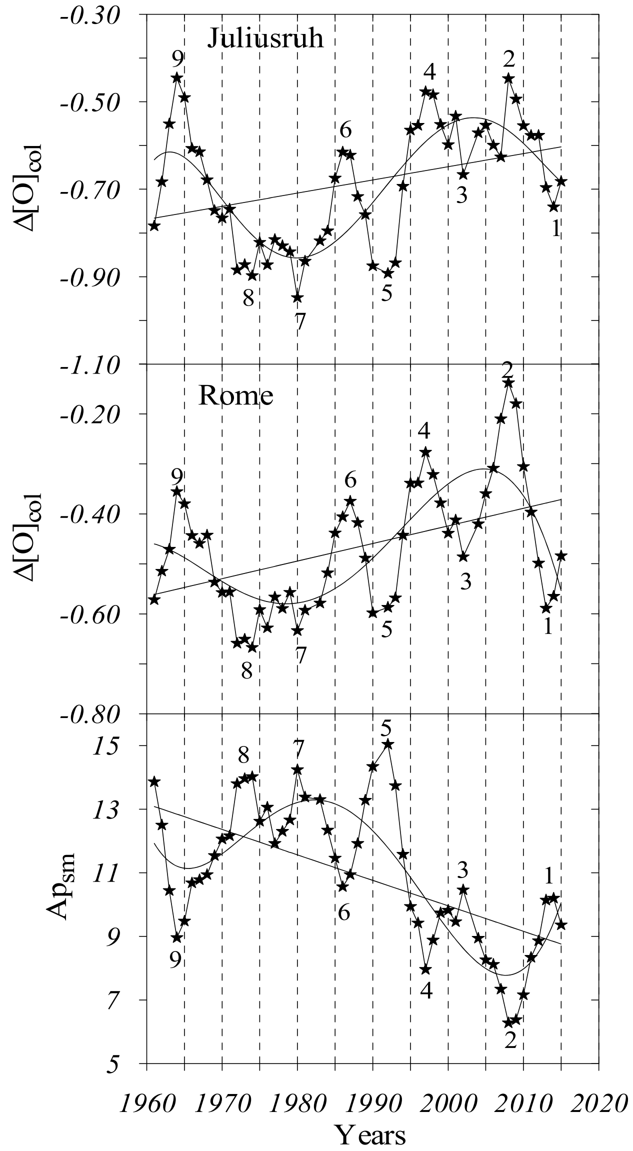

Figure 3. Five-point smoothed $\Delta[O]_{col}$ variations at Juliusruh and Rome are given in a comparison with smoothed monthly June Ap indices. The curves represent polynomial approximations, while the straight lines represent linear trends estimated over all years. Numbers indicate ups and downs in Ap_{sm} and $\Delta[O]_{col}$ variations (see text).

oxygen [O] and exospheric temperature Tex long-term variations at midlatitude (Juliusruh, Rome, and Boulder) and the auroral (Sodankylä) stations. The obtained factors to MSIS-86 model [O] and Tex were used to calculate the column $[O]_{col}$ content above 70 km (atomic oxygen is totally produced and lost above this height).

Under continuously increasing CO_2 abundance in the Earth's atmosphere with the rate of 5% per decade (https://www.co2.earth), statistically insignificant negative residual $[O]_{col}$ trends were obtained at midlatitude stations. It was found that ~93% of $[O]_{col}$ variations under June noontime conditions are due to solar and geomagnetic activity long-term variations. This result looks as a fundamental one as only ~7% of atomic oxygen variations may be attributed to other processes including the anthropogenic impact. These residual 7% may be also due to the inaccuracy of the input data or the limitations of the applied method.

Although atomic oxygen provides the main contribution to the total neutral gas density at F_2-layer heights a direct comparison of our results with satellite drag observations by Emmert (2015b) may not be correct for the following reasons. Satellite drag observations are globally averaged and automatically include different seasons, local times, latitudes, and longitudes, while our results are confined by June midlatitude noontime conditions. Moreover, neutral gas density comprises concentrations of other than [O] species: [He], [N], $[N_2]$, and $[O_2]$, and their contribution is different at 400 km (the height considered by Emmert) under solar maximum and minimum conditions. For instance, according to MSISE-00 (Picone et al., 2002), the atomic oxygen contribution to the total neutral gas density is ~77% under solar maximum and ~91% under solar minimum at 400 km at the Rome location in June noontime.

With above-mentioned reservations we may compare our results obtained at the midlatitude ionospheric stations with global satellite drag observations by Emmert (2015b) during the (1967-2005) period. As this was expected we have found statistically insignificant residual trends in $[O]_{col}$ at the three midlatitude stations estimated over this period. Emmert (2015b) has found a negative trend of $-2.0 \pm 0.5\%$ per decade in neutral gas density at 400 km. By fitting MSISE-00 model parameters to match the observed neutral gas density, he has related this trend to changes in neutral temperature and obtained a very modest Tex trend of -(0.7-1.1)K per decade (his Tab. 2). However, negative trend in neutral gas density at a fixed height may be due to either a decrease in Tex or to a decrease of the [O] abundance in the upper atmosphere. According to our results, one should not expect any statistically significant decrease in the total atomic oxygen abundance. Therefore, we should consider a decrease in Tex presumably related to thermospheric CO_2 cooling (Rishbeth, 1990; Rishbeth & Roble, 1992; Solomon et al., 2018).

Under a double CO_2 increase scenario, the thermosphere should cool by ~50K (Rishbeth, 1990; Rishbeth & Roble, 1992). Today, we have a 28% CO_2 increase in the Earth's atmosphere comparing to the 1960 level with 320 ppm (https://www.co2.earth). Therefore, in the case of a linear dependence, one may expect a 14 K decrease in the exospheric temperature. Under the accepted rate of CO_2 increase 5% per decade the cooling process has started ~50 years ago and this gives the cooling rate of ~2.8 K per decade. This coincides with the estimate by Solomon et al. (2018) based on model simulations. On the other hand, the cooling rate ~1K per decade obtained from satellite drag observations (Emmert, 2015b) gives the Tex decrease of ~5 K only and

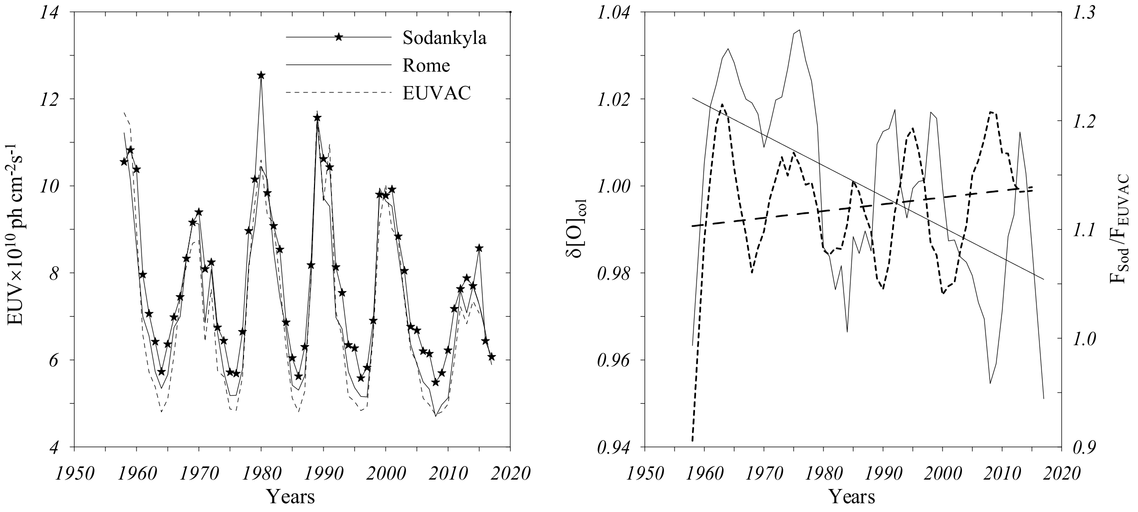

Figure 4. Retrieved total solar extreme ultraviolet (EUV) flux at Sodankylä and Rome in a comparison to the EUVAC model (left panel). Sodankylä $\delta[O]_{col}$ (solid) and Sodankylä/EUVAC ratio solar EUV flux (dashes). The straight lines represent linear trends estimated over all years.

this is much less than is expected from the 28% CO_2 increase. This means that satellite drag observations (the only direct way for today to check the CO_2 concept) do not confirm the predicted CO_2 thermosphere cooling although everywhere the opposite is stated.

The application of the regression (1) to our inferred Tex also results in a very small (<0.1% per decade) negative and statistically insignificant residual Tex trends at midlatitude stations.

Therefore, small negative Tex trend of ~1K per decade obtained from satellite drag observations (Emmert, 2015b) may be resulted from an incomplete removal of solar and geomagnetic activity effects from neutral gas density observations. After the removal of these effects, one should not expect any significant residual trends in the thermospheric parameters.

Coming back to the obtained results, we remind that Sodankylä (an auroral station) indicates different from midlatitude stations $[O]_{col}$ variations. The residual $[O]_{col}$ trend obtained after the regression (1) is negative and statistically significant at the confidence level of 99%. This indicates that other processes not taken into account in our method contribute to [O] variations. The first candidate is particle precipitations. The retrieved total solar EUV flux at Sodankylä is systematically larger compared to midlatitude stations. An example is given in Figure 4 (left panel) for Sodankylä in a comparison to Rome and the EUVAC model (Richards et al., 1994).

The Sodankylä-Rome difference in EUV is seen to increase comparing years of solar minimum. While the retrieved EUV at Rome decreases following the decreasing solar activity after 1985-1990, EUV at Sodankylä remains practically unchanged in solar minima. The difference between two stations is not practically seen during solar maximum. Such variations may tell us about the existence of a permanent background particle precipitations ionizing *F* layer. The contribution of this particle ionization is not essential compared to solar EUV one under solar maximum, but it is distinct in solar minimum when solar EUV ionization is at the minimal level, especially in 2008-2009. Therefore, under decreasing solar activity after 1985-1990, the contribution of particle ionization is increasing. A decrease of the atomic oxygen total content is an efficient way to compensate this extra ion production as the method fits calculated N_mF_2 and N_mF_1 to the observed ones. Figure 4 (right panel) explains this process. Using EUVAC model as a reference, we have calculated the Sodankylä/EUVAC flux ratio (dashes in Figure 4) and compared this ratio to Sodankylä $\delta[O]_{col}$ variations (solid line in Figure 4). A positive linear trend in the EUV ratio is compensated by a negative trend in $\delta[O]_{col.}$ Therefore, a significant negative trend in the atomic oxygen abundance at Sodankylä is not real but is induced by our method, which does not take into account the ionization produced by particle precipitations.

4. Conclusions

Using the recently developed method by Perrone and Mikhailov (2018a) and June daytime monthly median f_oF_1 and f_oF_2 observations at Rome, Juliusruh, Sodankylä, and Boulder, long-term variations of atomic oxygen column content $[\mathrm{O}]_{\mathrm{col}}$ above 70 km have been analyzed for the period of ~6 solar cycles. This has been done for the first time. The obtained results may be formulated as follows.

1. After the removal of solar and geomagnetic activity effects from the inferred $[\mathrm{O}]_{\mathrm{col}}$ variations, the residual linear trends are negative and statistically insignificant at three mid-latitude stations, while at Sodankylä (the auroral zone) the trend is negative and significant at the confidence level of 99%.
2. The averaged over three midlatitude stations correlation coefficient between the retrieved and model (described with the regression (1)) $[\mathrm{O}]_{\mathrm{col}}$ variations is 0.964 ± 0.03. This means (according to the $R^2 = r^2$ definition) that solar and geomagnetic activities explain ~93% of the total (column) atomic oxygen variability at middle latitudes; that is, practically, all atomic oxygen variations have a natural origin and only ~7% may be attributed to other processes (reasons) including the anthropogenic impact. In principle, these residual 7% may just reflect the inaccuracy of the input data or the limitations of our method.
3. Solar and geomagnetic activity contributions to $[\mathrm{O}]_{\mathrm{col}}$ long-term variations decrease with time; that is, the atomic oxygen column content is directed toward a constant equilibrium value at a given location. This may be related to the low solar activity epoch, which we have entered (http://www.wdcb.ru/stp/data/solar.act/csa/Cycles%20of%20Solar%20Activity.en.pdf).
4. The peculiarities of $[\mathrm{O}]_{\mathrm{col}}$ long-term variations at Sodankylä (the auroral zone) may be related to particle precipitations, which are not taken into account in the retrieval method. Therefore, the inferred strong and significant $[\mathrm{O}]_{\mathrm{col}}$ residual trend is not real one but is induced by the method.
5. The main conclusion is that the inferred from ionospheric observations long-term variations of the atomic oxygen column content are due to solar and geomagnetic activity; that is they have a natural origin.

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