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LONG-TERM TREND OF THE IONOSPHERIC E-LAYER RESPONSE TO SOLAR FLARES

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Abstract. Using data from ground-based vertical sounding of the ionosphere (VS) at the station Moscow and five Japanese stations for the period from 1969 to 2015, we have examined the long-term response of the E layer to solar *X*-ray flares. The analysis relies on the previously developed method for estimating the ratio between rates of ionization by *X*-rays q_x and ultraviolet radiation q_u during flares. We confirmed the existence of a long-term (at least covering the 45-year observation period) increase in the proportion of *X*-rays in the total ionization rate of the ionospheric *E* layer, characterized by the ratio q_x/q, where $q = q_x + q$. The q_x/q ratio is shown to increase throughout the period of interest at a rate independent of the solar activity cycle. There is also no dependence of the q_x/q trend rate on the season, latitude (26°–56° *N*), and longitude (37°–28° *E*).

Keywords: ionospheric E layer, vertical sounding, solar flares, long-term trend.

INTRODUCTION

Ivanov-Kholodny et al. [1976] proposed a method for estimating the ratio between X-ray and ultraviolet solar radiation contributions to ionization of the ionospherшc E layer by its response to solar X-ray flares. An attempt to apply this method to assessing the seasonal variability of the ratio of proportions of the ionization rate by solar X-rays q_x and ultraviolet q_u radiation to E-layer ionization led the authors [Ivanov-Kholodny et al., 1977] to the conclusion that this ratio varies during the year. This circumstance gave grounds to the authors to conclude that control over the ratio q_x/q_u would make it possible to estimate the seasonal variability of the main gas components at E-layer heights. This method was therefore adopted in [Givishvili et al., 2005] for estimating the now long-term variations in flare phenomena, which make it possible to judge long-term variations in the gas composition of the lower thermosphere.

Results of the analysis of 68 flare events recorded at Moscow vertical sounding (VS) station from 1969 to 1990 indicated a long-term increase in the relative contribution of X-rays to the total ionization of the lower thermosphere in a height range 90–130 km. The question therefore naturally arose about the nature of the identified effect: whether it has a local or global character, and, in addition, whether there is any relationship between the q_x/q_u ratio and the latitude of the place of observation and season. The purpose of our work is to try to answer these questions.

1. TECHNIQUE FOR EVALUATING f_oE RESPONSE TO A FLARE

The contribution of X-rays to the total ionization of a region during a flare is estimated by the expression [Ivanov-Kholodny et al., 1976]

$$q_x / q = \left\{ \left[f_0\mathrm{E}^{\mathrm{B}} / f_0\mathrm{E} \right]^4 - 1 \right\} / \left\{ \left[J_{1-8}^{\mathrm{B}} / J_{1-8} \right]^P - 1 \right\}, \quad (1)$$

where $q=q_x+q_u$; $q_x/q=(q_x/q_u)(1-q_x/q)$; J_{1-8}^{B} is the X-ray intensity in a range 1–8 Å during a flare; J_{1-8} is the background intensity of the same radiation; P=0.25±0.10; f_0E is the critical frequency of the E layer. Since $q_x/q_u \propto q_x/q$, the ratio between rates of ionization by X-rays and ultraviolet radiation will be expressed hereinafter as q_x/q_u or q_x/q.

The assumption that it is possible to estimate any variations in the gas composition of the lower thermosphere from data on flare phenomena is based on the fact that solar emission in the 977 and 1026 Å lines affects only molecular oxygen; therefore, the rate of ionization q_u from this source anyhow depends on its concentration, i.e. $q_u \propto [O_2]$. Since X-rays interact with all atmospheric constituents, $q_x \propto \{[N_2]+[O_2]+[O]\}$.; hence it follows that the ratio q_x/q_u (identical to q_x/q) is equivalent to the parameter $\eta = \{[N_2]+[O_2]+[O]\}/[O_2]$. For certain heliogeophysical conditions, η is found from an empirical model of the atmosphere, in particular from the MSIS model [Hedin, 1991]. Thus, we get

$$q_x / q_u \propto \eta. \quad (2)$$

2. MEASUREMENT DATA ARRAY

To determine the latitude-longitude features of the effect of long-term variations in the E-layer response to solar flares, we have supplemented the VS data from the station Moscow, collected from 1969 to 1994, with f_oE measurements made at the network of Japanese VS stations (hereinafter referred to as Moscow and Japan) in Table 1. Moreover, the resumption of regular monitoring

Table 1

Station coordinates, observation periods, and number of flares

Station	Latitude, N	Longitude, E	Period, years	Number of flares, n
Moscow	55.5	37.3	1969–2017	176
Wakkanai	45.4	141.7	1969–1986	124
Akita	39.7	140.1	1969–1984	35
Kokubunji	35.7	139.5	1970–2000	136
Yamagawa	31.2	130.6	1969–1986	56
Okinawa	26.3	127.8	1979–1986	10

of the ionosphere in Moscow since 2003 made it possible to involve new data on flare phenomena in the analysis.

Table 1 shows that the number of flare phenomena recorded changed noticeably from one measurement point to another. In some cases, this was due to technical reasons; in others, due to the degree of screening of the regular E layer by sporadic E_s layers; and in the third cases, due to differences in longitude. Because of this, the same flares at some stations occurred during daylight hours with a fairly well developed E layer; whereas at other stations, during twilight with a poorly developed E layer. Owing to the eight-hour time difference between Moscow and Japan, the series of flares, according to data from Japanese stations, practically does not intersect with the series of flares recorded in Moscow. Thus, a total of 176 cases of solar X-ray flares have been processed in Moscow and 361 in Japan. When the same flare was recorded at several Japanese stations simultaneously, the q_x/q values found from them were averaged. As a result, 243 q_x/q values have been used for the analysis.

2.1. Solar activity dependence of q_x/q

Figure 1 presents the estimated parameter q_x/q in Moscow (1969–2015) and Japan (1969–1994), calculated by Formula (1).

Firstly, we can see that in both regions absolute values of q_x/q are close. Secondly, a common feature in them is the obvious dependence on solar activity (SA), which can be expressed by

$$q_x / q = \left(q_x / q\right)_0 + a\, F10.7. \tag{3}$$

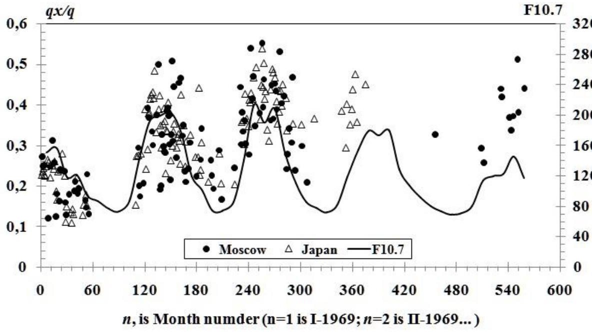

Figure 1. General dynamics of variations in the q_x/q ratio found from flares detected in Moscow and Japan, as well as monthly average values of F10.7

Table 2 lists coefficients of the linear relationship between q_x/q and F 10.7, determined for each solar cycle or half solar cycle.

For both regions, the coefficients a averaged over the entire measurement period are seen to be close. At the same time, the initial values of q_x/q for each SA cycle $(q_x/q)_0$ increase from cycle to cycle in both regions. Figure 2, a, b shows the dependences of q_x/q on F10.7 for incomplete solar cycle 20 and two complete SA cycles 21 and 22 in both regions. A noticeable cycle-to-cycle increase in the initial values $(q_x/q)_0$, as inferred from Moscow and Japan data, indicates the presence of an additional factor, apart from SA.

2.2. Season dependence

To analyze the season dependence of q_x/q, their monthly averages were reduced to the average level of solar activity for all cases of flare detection. Flare phenomena being rarely observed during periods of low solar activity (see Figure 1), this level corresponded to F10.7=170. Analysis has shown that seasonal variations in $(q_x/q)_{170}$ both in Moscow and Japan are not only close to each other, but, and that is what counts, they are small (Figure 3). An exception is the anomalously low value of $(q_x/q)_{170}$ in January for Moscow. This deviation is probably due to the small number of flare detections determined by the features of the development of the winter E layer at Moscow latitudes. At the same time, in both regions the ratio $(q_x/q)_{170}$ reaches its maximum in March, whereas in summer and fall it everywhere takes intermediate values.

2.3. Latitude-longitude dependence of q_x/q

To eliminate the possible influence of cyclic variations on the latitude-longitude structure of the q_x/q parameter distribution, we have analyzed the measurement data corresponding to the maximum phase of one solar cycle. The most optimal period in this sense falls within four years (1979–1982 with an average value of F10.7=208). The average q_x/q ratios for each of the years considered for each of the Japanese stations and for Moscow are listed in Table 3.

The q_x/q_u values averaged over four years of observations at all the measuring stations are shown in Figure 4. It seems to indicate a trend of an increase in q_x/q_u with latitude. It, however, manifests itself so weakly that it does not go beyond ±4.2 % relative to the

Table 2

Linear dependence of q_x/q on $F10.7$ within the SA cycle (half cycle)

SA cycle No.	Moscow					Japan				
SA	Period	n	$(q_x/q)_0$	a	R^2	Period	n	$(q_x/q)_0$	a	R^2
20 (0.5)	02.69–07.73	25	0.0965	0.0007	0.264	01.69–05.73	29	0.0173	0.0013	0.612
21 (1.0)	04.78–07.85	40	0.1160	0.0010	0.294	01.78–01.85	48	0.1457	0.0010	0.319
22 (1.0)	02.86–08.94	35	0.2243	0.0008	0.283	02.86–04.95	40	0.2167	0.0009	0.495
23 (0.5)	no observations					11.97–03.00	9	0.2157	0.0013	0.381
24 (0.5)	12.06–06.15	11	0.1833	0.0015	0.502					
	Average		**0.1550**	**0.0010**	**0.335**	**Average**		**0.1489**	**0.0011**	**0.452**

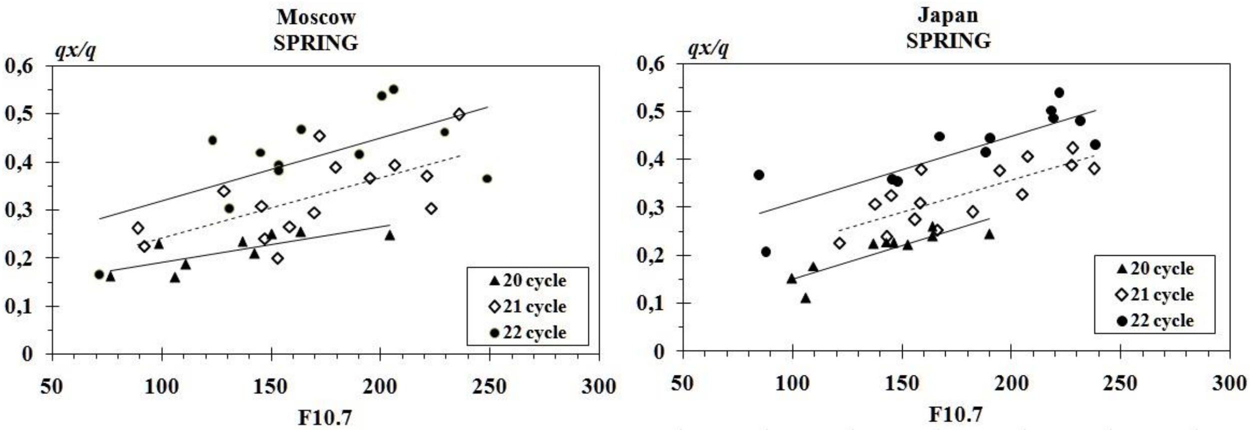

Figure 2. Dependence of q_x/q on $F10.7$ in solar cycles 20, 21, and 22 according to data from Moscow (*a*) and Japan (*b*)

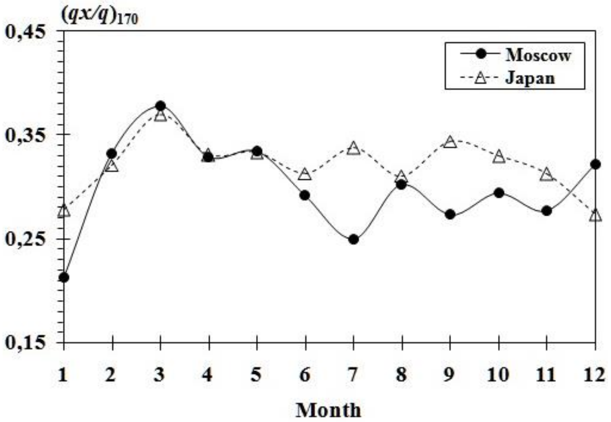

Figure 3. Seasonal variations of the ratio $(q_x/q)_{170}$ in Moscow and Japan

average value of *qx/q* equal to 0.347 for all the stations. According to the MSIS model, the latitudinal variation in the ratio of N_2, O_2, and O (parameter η) within the indicated boundaries are also hardly noticeable; hence there is no reason to expect any noticeable features to be detected in the spatial distribution of the parameter η either.

Besides, both empirical q_x/q_u and model η values, which characterize spatial variations in the gas composition of the upper atmosphere at the indicated heights, do not reveal any significant longitudinal effects either. For the regions separated from each other by eight time zones, long-term variations in q_x/q_u are almost the same.

2.4. General assessment of the long-term trend in q_x/q

Since the ratio q_x/q depends only to a small extent on the season, as well as on coordinates of the observation point, but correlates with solar activity and increases from SA cycle to cycle, the general dynamics of the long-term variability of q_x/q annual averages can be described by the expressions determined from observations

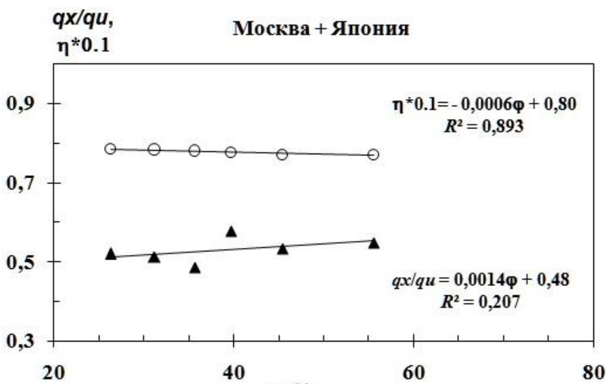

Figure 4. Latitudinal variation (dark triangles) in experimental q_x/q_u values averaged according to data from Moscow and Japan during the spring equinox (March, April, May); latitudinal dependence (open circles) of the ratio η={[N_2]+[O_2]+[O]}/[O_2], determined for 105–115 km heights on March 15, 1981 and station coordinates from Table 1 by the MSIS model [Hedin, 1991]

Table 3

Values of q_x/q obtained at different stations x during high solar activity

Year	q_x/q					
	Moscow	Wakkanai	Akita	Kokubunji	Yamagawa	Okinawa
1979	0.345	0.375	0.410	0.340	0.310	0.456
1980	0.300	0.350	0.364	0.340	0.350	0.272
1981	0.390	0.325	0.359	0.320	0.386	–
1982	0.364	0.339	0.329	0.325	0.306	0.315
Aver.	0.350	0.347	0.366	0.331	0.338	0.348

made over the period 1969–1994 in Moscow

$$(q_x/q)_M(t)=0.0068\cdot year+0.0012\cdot F10.7-13.343 \quad (4)$$

and in Japan

$$(q_x/q)_Я(t)=0.0076\cdot year+0.0012\cdot F10.7-14.934, \quad (5)$$

where *year* begins with 1969.

Figure 5, *a*, *b* illustrates the time variations in experimental (annual average) ratios $(q_x/q)_e$ and their calculated estimates $(q_x/q)_P$ found from Formulas (4), (5). Figure 5, *b* shows that in Japan there was an almost complete coincidence of $(q_x/q)_e$ and $(q_x/q)_p$. In Moscow after 2003, the difference between the experimental and calculated values of q_x/q was quite large, which had an effect on the difference in their linear trends. In Japan, it was 0.0074 /year; in Moscow, 0.0040/year. This may be due to two reasons. First, a noticeable decrease in solar activity and extremely rare cases of flare observations. So, for example, in 2004, one flare was recorded in Moscow; in 2010, two; in 2013, two; and after 2017, none. Second, a possible change in the spectrum of solar ionizing radiation that accompanies the general drop in its activity, observed in solar cycles 23 and 24. Anyway, the question remains open.

The similarity between the $(q_x/q)_P$ values determined from annual average $F10.7$ for Moscow and Japan allows us to derive a generalized formula for the long-term trend in q_x/q, which characterizes the general dynamics of the variability of this parameter. Within the middle latitudes of the Northern Hemisphere, it will take the form

$$q_x / q(t) = 0.0072\,\text{год} + 0.0012\,F10.7 - 14/139. \quad (6)$$

3. DISCUSSION

Assessing the possible long-term consequences of the greenhouse effect for the gas composition of the atmosphere, Roble and Dickinson [1989] noted that a hypothetical twofold increase in the content of CO_2 and CH_4 can significantly reduce the concentrations of N_2, O_2, and O already from heights of 80 km. According to their estimates, the O_2 concentration at a height of 120 km should decrease by ~40 %; $[N_2]$, by ~30 %; and [O], by ~20 %. In [Rishbeth, 1990; Rishbeth, Roble, 1992], the consequences of variations in the critical frequency f_oE and the height of the E-layer maximum h_mE were estimated. Calculations have shown that the variations will primarily affect h_mE: it should decrease by ~2.5 km. The frequency f_oE would have increased, but only slightly, less than the measurement error of ±0.05 MHz [https://www.sws.bom.gov.au/IPSHosted/INAG/uag.htm].

From 1996 to 2002, no observations were made in Moscow due to lack of measuring equipment. To fill in the missing link in the series of continuous observations, the SA dependence of f_oE was determined in each SA decline and rise half-cycle from 1947 to 2020 with the formula

$$f_oE = (f_oE)_0 + a\,F10.7, \quad (7)$$

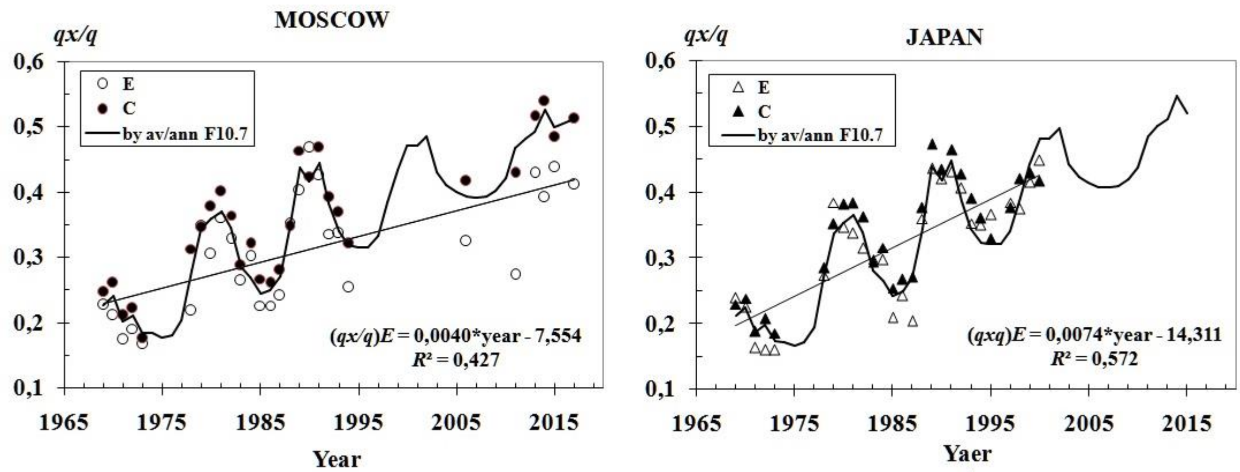

Figure 5. Experimental values of $(q_x/q)_e$ and $(q_x/q)_p$ calculated by Formulas (4), (5) for Moscow and Japan, as well as $q_x|q$ calculated by Formula (6) from annual average $F10.7$. Solid lines are linear trends of experimental $(q_x/q)_e$ in both regions

where $(f_oE)_0$ is f_oE at the beginning of each SA half-cycle; $F10.7$ is the current annual average solar activity index; a is the coupling coefficient of f_oE and $F10.7$. Thus, the f_oE values corresponding to the years in which no measurements were made were restored.

They showed that the dependence of f_oE on solar activity is high, but not absolute. Moreover, over time it changes, though slightly. In particular, over 74 years of observations, the coefficient a increased 1.13 times, with an average value of $F10.7$=123 over this time interval. This means that during the period of regular monitoring of the ionosphere the gas composition of the lower thermosphere changed in such a way that the E-region response to solar ionizing radiation became, on the whole, more and more pronounced.

As for the parameter h_mE, it should be noted that the VS method determines not the true height of the layer maximum, but its equivalent height $h'E$. The difference between them is as follows. The parameter h_mE is found from measurements of the height distribution of N_e mainly in rocket experiments. They are used to develop empirical models of the ionosphere, e.g. [Fatkullin et al., 1981; Bilitza, 1997]. In the first model, h_mE is recognized as a variable that depends on a number of heliogeophysical conditions and varies within 108–115 km. In the IRI model, on the contrary, it is assumed that h_mE = 110 km, regardless of observation conditions. However, since this is not true, the variability of the current values of h_mE is estimated from data on $h'E$ corresponding to one or another heliogeophysical condition.

The results of expanding the time range of measurements and including the data on $h'E$ in them are presented in Figure 6 as annual average $h'E$ and $(f_oE)_{123}$, reduced to average $F10.7$=123 over the entire period of interest. Gaps in the $h'E$ data are caused not only by technical reasons, but also by the conditions of their archiving.

It can be seen that the mid-1950s was a turning point in the dynamics of long-term trends in both key parameters of the ionospheric E layer. In particular, the negative trend in $(f_oE)_{123}$ changed its sign in 1957 and still remains positive. Thus, in general, over 74 years of observations, the linear trend in the annual average frequency $(f_oE)_{123}$ was positive, but weak, and was $+1.13 \cdot 10^{-3}$ MHz/year. Ultimately, this led to an increase in $(f_oE)_{125}$ by no more than 0.1 MHz, whereas a decrease in $h'E$ and hence in h_mE was 3.5 km.

At the same time, the real content of CO_2 in the atmosphere in the second half of the 20th century increased from 315 to 415 ppm [https://techcrunch.com/2019/05/12/co2-in-the-atmosphere-just-exceeded-415-parts-per-million-for-the-first-time-in -human-history]. In other words, at the E-region heights the CO_2 concentration over the time interval of interest increased not by a factor of two, but no more than 1.32 times. Accordingly, any long-term variations in f_oE, not related to cyclic activity of the Sun, would not have been observed. Nonetheless, they are observed and can be explained neither by measurement errors nor by methods of processing and analyzing measurement data. They thus confirm the assumption that the solar ionizing radiation is dominant but not the only factor controlling the variability of the E-layer parameters.

In particular, this is clearly seen due to elimination of the influence of the SA cyclic variability on f_oE. The latter is achieved by 11-year averaging of both $F10.7$ and $(f_oE)_{123}$ by the moving average method, as well as by estimating the linear trend in the 11-year moving $(F10.7)_{11}$ and $((f_oE)_{123})_{11}$. Results of such an operation are presented in Figure 7. The trends in both parameters are seen to be significant, but have the opposite sign.

Mikhailov [2006] have concluded that the geomagnetic control over the long-term trends in f_oE is important. It is difficult to agree with this statement for the following reasons. First, even after strong geomagnetic disturbances, maximum deviations of f_oE from undisturbed values do not exceed 0.07 MHz [Beynon, Brown, 1959; Brown, Wynne, 1967; Ivanov-Kholodny, Nusinov, 1979]. Moreover, the aforementioned deviations were observed for only one or two days immediately after the peak of rare disturbances such as geomagnetic storms.

Second, the long-term variability of geomagnetic activity consists of periodic and chaotic components. The aperiodic factor is significant for time intervals limited to several years. The correlation coefficient between annual average $F10.7$ and the planetary index of geomagnetic activity K_p for the period from 1946 to 2015 was, therefore, only 0.492. When averaged by the 11-year moving average method, the stochastic component of the K_p index is eliminated. In this case, the correlation coefficient between $(F10.7)_{11}$ and $(K_p)_{11}$ sharply increases and becomes equal to 0.931 (Figure 8).

In other words, geomagnetic activity on large time scales depends on SA cyclic variations itself, and, since the solar factor is the main source of changes for both the geomagnetic field and the ionosphere, the conclusion about the existence of long-term control of geomagnetic activity over f_oE is obviously exaggerated. This was confirmed in [Bremer, 1992].

The method of joint analysis of data from ground-based measurements of the E-layer parameters and the results of satellite measurements of solar X-ray fluxes provides indisputable evidence of dramatic changes in the O_2 concentration occurring at heights of the lower thermosphere, but satellite measurements of X-ray fluxes have been carried out only since 1969. The contribution of this radiation to the total ionization rate can therefore be estimated with this method only since that time. They show that the trend in q_x/q contrasts sharply with that in $(f_oE)_{123}$ over their common time period. If $(f_oE)_{123}$ increased by less than 3 % (see Figure 6), q_x/q, according to Figure 5, a, increased from 0.22 to 0.40, i.e., approximately twofold.

The cause explaining the long-term (climatic scale) variations in the E-layer parameters and the ratio q_x/q is most likely to be associated with a decrease in the O_2 content in the upper atmosphere, since only this process explains the entire set of consequences, namely, the increase in q_x/q and $(f_oE)_{123}$ with the simultaneous decrease in $h'E$. In this case, the rate of $[O_2]$ decrease obviously exceeds the estimates, made in [Roble, Dickinson, 1989], attributed to a doubling of the CO_2 concentration in the atmosphere.

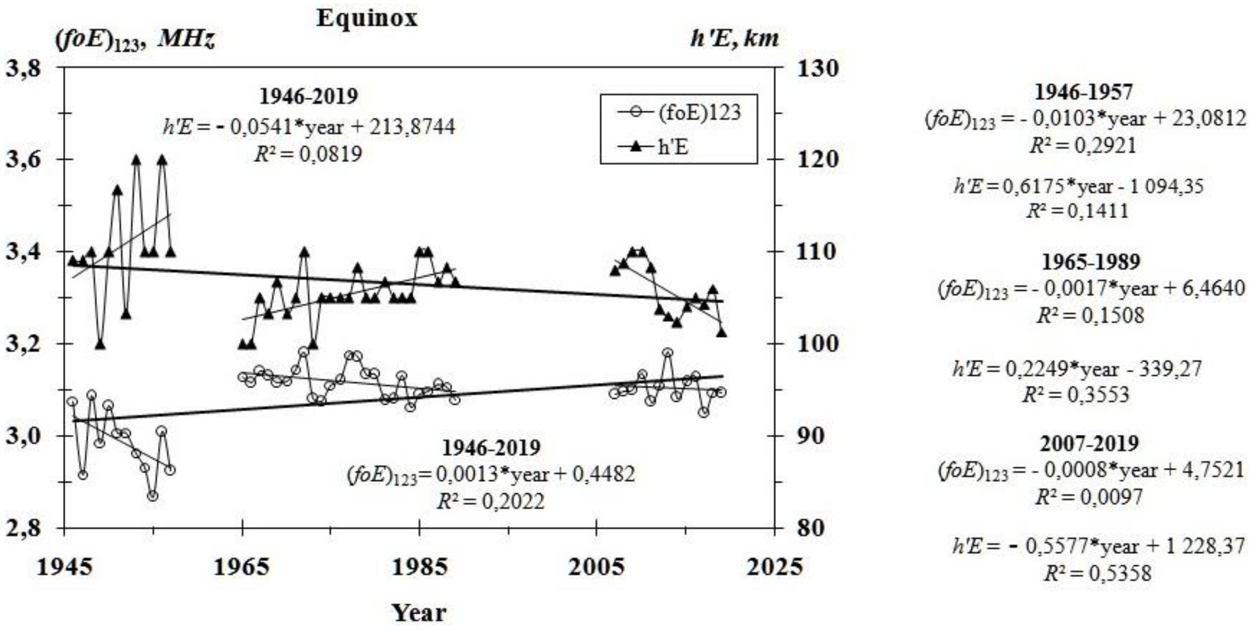

Figure 6. Linear trends in $(f_o\text{E})_{123}$ and h'E for three time periods and in general for the entire observation period in Moscow

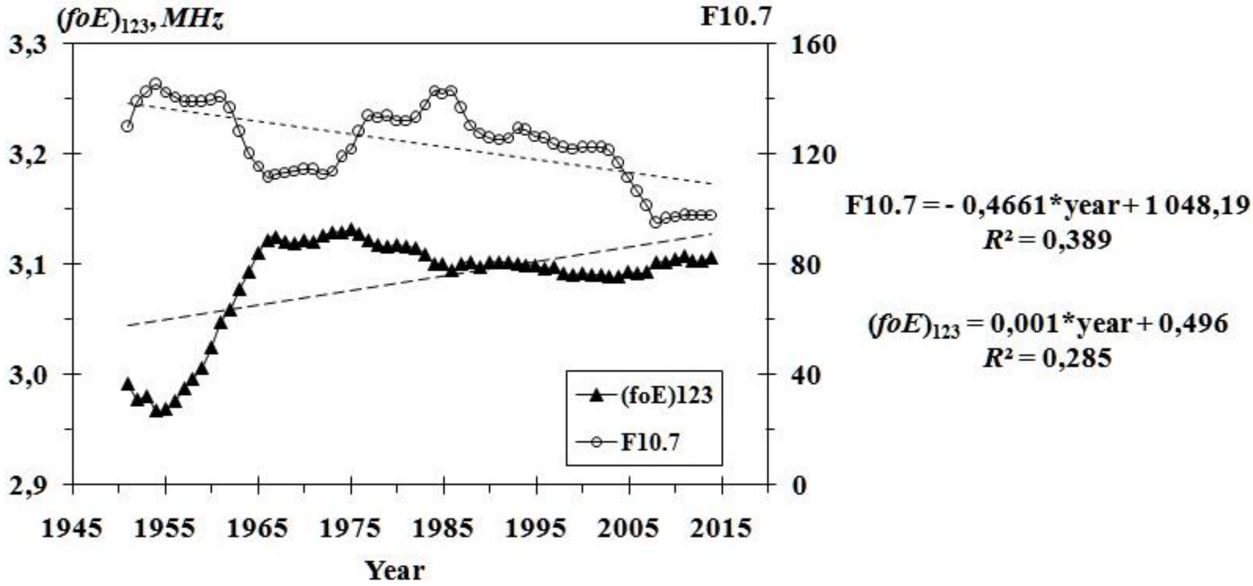

Figure 7. 11-year moving averages of $F10.7$ and $(f_o\text{E})_{123}$ according to monitoring data from Moscow, as well as their linear trends

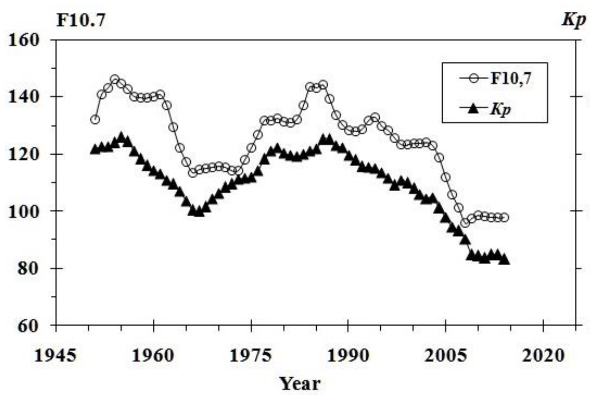

Figure 8. 11-year smoothed indices of solar $F10.7$ and geomagnetic K_p activity

That said, the above estimates of the rate of decrease in the O_2 content at the heights above the turbopause level require clarification as based on a simplified scheme of photochemical reactions.

CONCLUSION

Conclusions about the trends in q_x/q, $(f_o\text{E})_{123}$, and h'E can be formulated as follows.

1. Data from ground-based VS measurements and satellite measurements of solar X-ray fluxes have shown that in the region covering the range of latitudes 26°–56° N and longitudes 37°–128° E the q_x/q ratio has approximately doubled since 1969.

2. In the region, neither noticeable longitudinal nor latitudinal features were found in the rate of increase in

q_x/q. Seasonal variations were also weakly pronounced.

3. Extension of the time range of measurements by the VS method at the station Moscow to 74 years confirms the fact of an increase in $(f_oE)_{123}$ as a whole. Nevertheless, its linear trend was small and insignificant. It is important, however, that its sign was opposite to the solar activity trend, *F*10.7. The *h*′E trend was great and significant.

4. Signs of the trends in $(f_oE)_{123}$ and *h*′E were opposite and corresponded to the predicted changes caused by the greenhouse effect, yet their amplitudes were many times higher than the actual increase in the CO_2 content in the atmosphere.

5. The coincidence of the signs of the $(f_oE)_{123}$ and q_x/q trends, as well as their opposite to the sign of the *h*′E trend, suggests that they are based on a common cause — a decrease in the O_2 concentration that controls the critical frequency and the height of the E-layer maximum.

At the same time, these conclusions give rise to two questions awaiting to be answered.

1. What is the real rate of O_2 decrease?

2. What happened in the mid-1950s which dramatically changed the sign and magnitude of the trend in $(f_oE)_{123}$ and *h*′E?

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