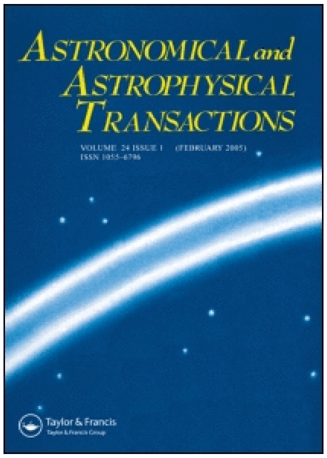

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QUASI-BIENNIAL RESPONSE OF THE UPPER ATMOSPHERIC TEMPERATURE ON THE SAME VARIATIONS OF THE SOLAR ACTIVITY

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On the basis of the data of the emission and radiophysical measurements some regularities of quasi-biennial oscillation (QBO) of the atmospheric temperature at heights of the mesopause and lower thermosphere are investigated. It is shown, that they are closely connected with quasi-biennial variations of solar activity and form within the limits of a cycle of solar activity the fading wave train of fluctuations. Such behaviour of the wave train can be good described by the Airy function. The wave train arises during an ending of previous cycle of solar activity. Within the maximum of solar activity the period of fluctuations is ~38 months and linearly ($r = -0.98$) decreases up to ~21 months to the end of a 11-year cycle.

Keywords: Solar activity; Quasi-biennial oscillation; Temperature; Mesopause; Lower thermosphere; Nightglow

1 INTRODUCTION

The existence QBO in a terrestrial atmosphere is known already enough for a long time (Angell and Korshover, 1962). The most detailed researches of their characteristics were carried out for troposphere and stratosphere. Labitzke (1987) and Labitzke and van Loon (1988) are established the connection between a type QBO and solar activity, and also a mode of circulation in the stratosphere.

Gruzdev and Bezverkhny (1999) using the spectral analysis of the high resolution by a method of wavelet-transformation have shown, that the QBO of speed of an equatorial wind at various altitude levels (from 20 up to 32 km) basically are shown as two prevailing modes with the periods 2 and 2.5 years, which replace each other, causing long-term changes of the QBO period.

Besides, the QBO of temperature at heights mesopause by the data of measurements of the hydroxyl emission are traced (Hernandez, 1976; Fukuyama, 1977; Fishkova, 1983; Neumann, 1990; Semenov and Shefov, 1996; 1999), and on the data of sounding E and

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F2 of ionospheric regions (Ivanov-Kholodny and Chertoprud, 1992; Antonova *et al.*, 1996; Ivanov-Kholodny *et al.*, 2000a,b) are revealed the QBO of f_0. The mechanism of formation the QBO in a middle atmosphere, as a consequence of the parametrical phenomenon in climatic system, was offered by Gledzer and Obukhov (1982). It is important to note, that the QBO may also present and in behaviour of solar activity (Schuster, 1906; Apostolov, 1985; Ivanov-Kholodny and Chertoprud, 1992; Antonova *et al.*, 1996; Ivanov-Kholodny *et al.*, 2000a,b). Thus the presence of close correlation between variations of an index of solar activity $F_{10.7}$ and variations of critical frequencies f_0 of layers E and F2 of ionosphere is marked.

In the given work the behaviour of temperature in the region of mesopause and lower thermosphere is analyzed with the purpose of the analysis of properties of the QBO and their connections with quasi-biennial variations of solar activity.

2 PROCEDURE OF MEASUREMENT

The measurements of variations of characteristics of the emissions of the hydroxyl, atomic sodium 589.3 nm, and atomic oxygen 557.7 nm were made at stations Zvenigorod (55.7° N, 36.8° E) and Abastumani (41.8° N, 42.8° E) with the help of the spectrographs (Galperin *et al.*, 1957) and photometers (Fishkova, 1983). Temperature and intensity of the hydroxyl emission was determined on spectra of its radiation with use of bands (5–2) and (8–3). The theory and methods for this can be found in (Chamberlain, 1961).

The estimations of temperatures for emissions 557.7 nm have been made on the basis of intensities of the 557.7 nm emission. There are a distinct correlation between the seasonal variations of the intensity ΔI_s (relative to mean annual value) and temperature ΔT_s, K, of the 557.7 nm oxygen emission (Semenov and Shefov, 1997; Shefov *et al.*, 2000), and $\Delta T_s/\Delta I_s = 0.3\,\mathrm{K}/\%$. Mean annual absolute intensity I_{MA} of this emission negatively correlates with mean annual temperature at 97 km T_{MA}, as a rate coefficient of the photochemical reaction of Barth's (1961) mechanism for excitation of the 557.7 nm emission has a negative dependence upon temperature (Starkov *et al.*, 2000). It enables to obtain a relationship

$$T_{\mathrm{MA}} = 196 - 0.097(t - 1972.5) - 0.080(\mathrm{F}_{10.7} - 130) \qquad (1)$$

The rms error of the mean annual temperature is about $\delta T(\mathrm{K}) \sim 0.36\ \delta I(\%)$ and $\delta T \leq 4\,\mathrm{K}$ for $\delta I \leq 10\%$.

The data about a temperature near 92 km are determined on the basis of the analysis of the behaviour of the atmospheric sodium emission. According to lidar measurements (States and Gardner, 1999) there is a satisfactory correlation between the sodium content in a layer and temperature in a maximum of its concentration. The reliability of this dependency between the southern and northern extreme high latitudes was presented by Plane *et al.* (1998). The data of long-term measurements of the seasonal variations of intensity of the sodium emission enable to execute their reduction to identical helio-geophysical conditions. It has enabled to obtain a dependence between intensity of sodium emission I_{Na} (Rayleigh) and temperature of an atmosphere at height about 92 km

$$T(92\,\mathrm{km}) = (185 \pm 0.8) + (0.20 + 0.01)I_{\mathrm{Na}},\ \mathrm{K} \qquad (2)$$

where the correlation coefficient r is 0.952 ± 0.020 (Shefov and Semenov, 2001).

The obtained temperatures and intensities of emissions correspond to local midnight. In this case the mean square root of the error of definition of absolute meanings of emissions intensity is ~5%. The error of definition of temperature is 2 K.

Material of research are the data of measurements of temperature at heights of 70–110 km obtained from incoherent-scatter spectral measurements with the help of EISCAT radar. The data accumulated during 1984–1994 for stations Tromsö (69.6° N, 19.2° E) were used. The particularities on a technique of realization of measurements of the ion temperature with the help of EISCAT radar and substantiation of its conformity to temperature T of neutral environment are presented by Kirkwood (1996).

For the analysis the data on temperature appropriate to local midnight in an interval of 22.00–02.00 LST were selected. To exclude influence geomagnetic disturbances the data at $Kp < 4$ were only used. Further on the basis of this material the monthly average meanings of temperature for heights 107, 97, 92 and 87 km were determined. These altitude levels were chosen as they correspond to heights of emissions OI 557.7 nm (97 km), Na 589.3 nm (92 km) and OH (87 km).

3 RESULTS

With the purpose of revealing the QBO at the analysis of time series the technique stated in (Ivanov-Kholodny and Chertoprud, 1992; Antonova *et al.* 1996; Ivanov-Kholodny *et al.*, 2000a,b) was used. Thus it was taken into account, that they have not strict harmonicity. Therefore, the passband of the used digital filter should not be too narrow. It was necessary to exclude the seasonal variations which have been not connected with solar activity, and also to exclude 11- both 22-year variations and long-term trend. In this case a filtration was reduced to calculation of the sliding average meanings for each month of an available number of monthly average meanings of temperature T, namely,

$$\begin{aligned}\Delta T(t_i) &= 0.256\ \{[T(t_i) - T(t_i - 12)] - [T(t_i + 12) - T(t_i)]\}\\ &= 0.256\ [2T(t_i) - T(t_i + 12) - T(t_i - 12)],\end{aligned} \tag{3}$$

where for time unit is accepted 1 month, i is a number of the member of a time series of monthly average meanings of temperature. Actually, it means a calculation of the second differences of elements of a time series. This transformation, otherwise, is an action of the digital linear filter with the module of amplitude-frequency characteristic

$$|G(f)| = \left|\frac{\sin^3(12\pi f)}{3\pi f}\right|, \tag{4}$$

were $f = 1/\tau$ is frequency, and τ is period of oscillations.

As shown in (Ivanov-Kholodny and Chertoprud, 1992; Antonova *et al.*, 1996), $|G(f)|$ reaches the maximum G_M at $\tau = 28.5$. The borders of half-width of the filter are determined by an inequality $19 \le \tau \le 57$ months. At $\tau = 1$, 2, 3, 4, 6 and 12 months $G(f) = 0$.

The calculated monthly average differences ΔT were smoothed by a method sliding average on 5 ordinates with weight 1:2:3:2:1.

The variations of temperature ΔT of emissions of the atomic oxygen 557.7 nm (~97 km), sodium (~92 km) and hydroxyl (~87 km) are shown by black circles on Figure 1. For comparison the data about ΔT on a basis of the interferometric measurements of temperature of

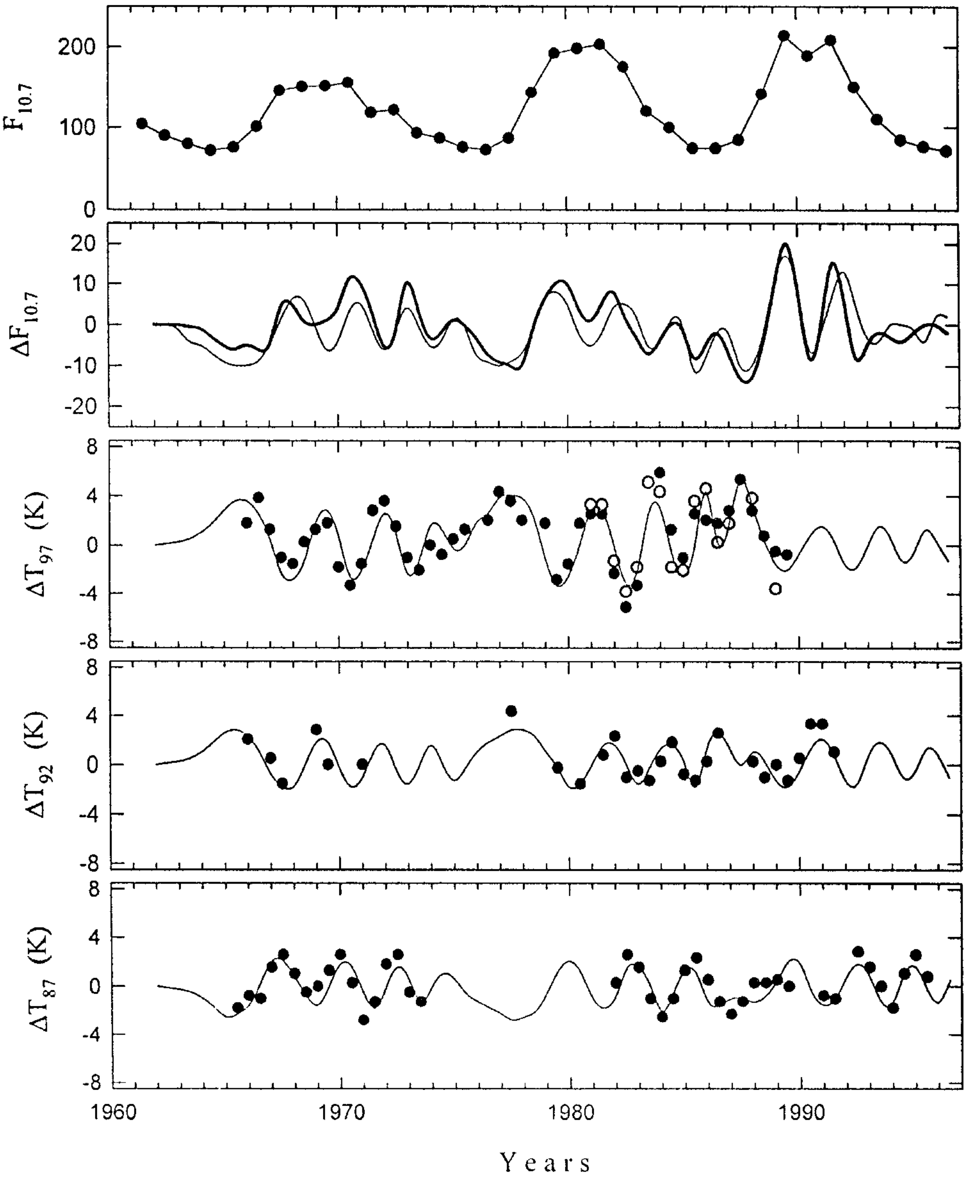

FIGURE 1 QBO of the temperature ΔT at heights 97, 92, and 87 km according to spectrophotometric measurements of the emissions of the atomic oxygen 557.7 nm, atomic sodium 589.3 nm, and hydroxyl, respectively (black circles). Hollow circles show the data of the interferometric temperature measurements in Yakutsk by Yugov *et al.* (1997). In top the mean annual variations or the $F_{10.7}$ are shown and its quasi-biennial variations of $\Delta F_{10.7}$ (Ivanov-Kholodny *et al.*, 2000a) marked by thick solid line. Thin lines are approximations by Airy function.

emission 557.7 nm in Yakutsk (62.0° N, 129.7° E) – hollow circles (Yugov *et al.*, 1997) simultaneously are shown. It is possible to note the satisfactory consent between these ΔT and their represented temporaly behaviour.

The variations of ΔT for the period 1985–1993 (black circles) are shown on Figure 2, inside which there is a maximum of the 22nd cycle of solar activity (1989–1991), obtained on the basis of the data EISCAT radar at heights 107, 97, 92 and 87 km.

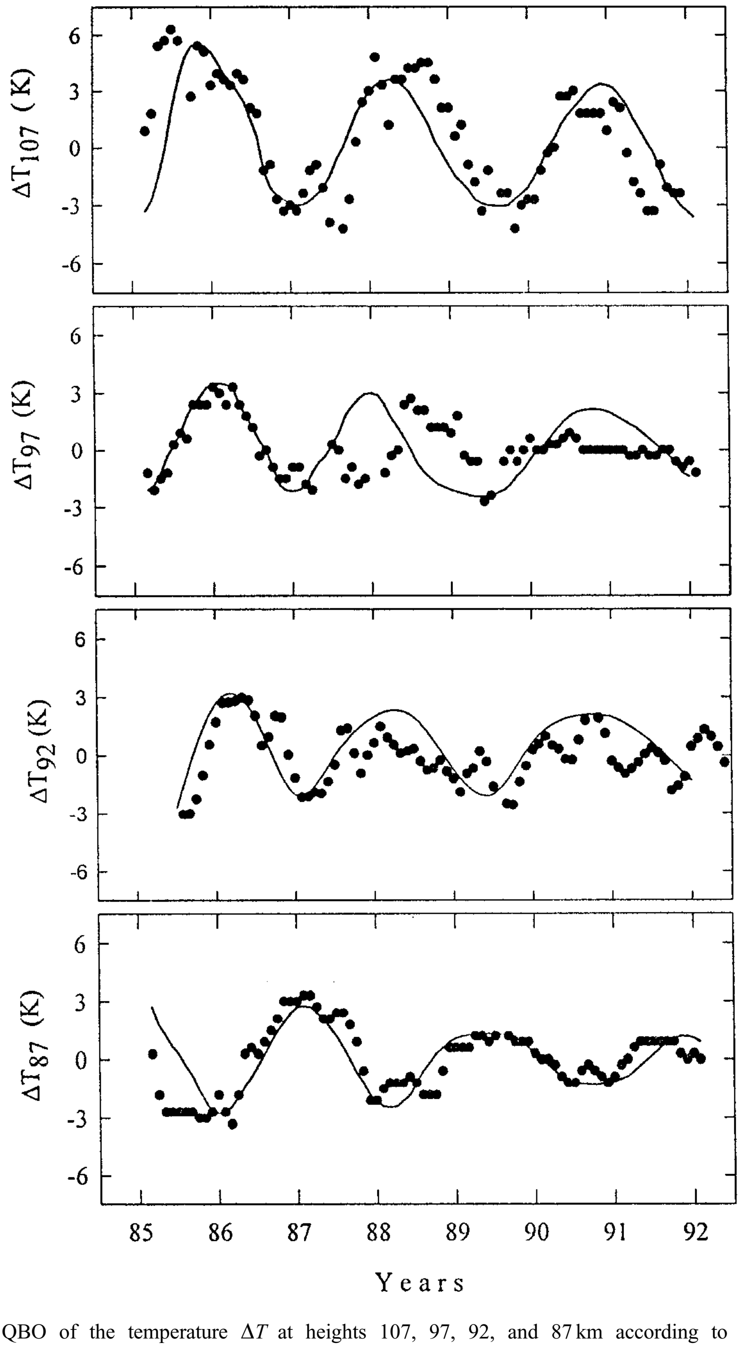

FIGURE 2 QBO of the temperature ΔT at heights 107, 97, 92, and 87 km according to EISCAT radar measurements. Black circles are measured data, solid line is an approximation by Airy function.

4 DISCUSSION

In prevailing number of previous researches of behaviour of the QBO of parameters of lower thermosphere the reveal of regularity of the investigated characteristics and correlations with the accompanying geophysical phenomena and with solar activity was carried out by spectral analysis of long-term series. Only in a few works the attempt is made to reveal character of the QBO during the several consecutive periods, namely, in variations of equatorial stratospheric circulation (Fedorov *et al.*, 1994), in variations of cosmic rays in stratosphere (Okhlopkov, 1998a,b) and in behaviour of critical frequencies of reflection in layers E and F2 of the ionosphere (Antonova *et al.*, 1996; Ivanov-Kholodny *et al.*, 2000b) within of a 11-year solar cycle. In last cases there is a close correlation between the QBO of solar activity (index $F_{10.7}$) and ionospheric parameters (Ivanov-Kholodny *et al.*, 2000a,b). How follows from these data, quasi-biennial variations of $\Delta F_{10.7}$ form a characteristic wave train of fluctuations the most distinct displaying in the beginning of each 11-year period (a thick line in a Fig. 1). Results represented in a Figures 1 and 2, reveal similar character of behaviour of variations for temperature at heights of 87–107 km.

It is important to emphasize, that the wave train of the QBO has a fading character, the amplitudes and periods which are maximal in the beginning of a cycle and decrease to its end.

Such regularity of behaviour is satisfactorily described by Airy function Ai(x) (Abramowitz and Stegun, 1964; Olver, 1974). It is the decision of the differential equation

$$y'' - xy = 0, \tag{5}$$

which describes the process of propagation of the internal waves in the atmosphere and ocean of the rotating planets (Desaubies, 1973). For positive meanings of argument

$$\mathrm{Ai}(x) = \left(\frac{1}{3}\right)x^{1/2}\left[\mathrm{I}_{-1/3}\left(\frac{2}{3}x^{3/2}\right) - \mathrm{I}_{1/3}\left(\frac{2}{3}x^{3/2}\right)\right], \tag{6}$$

for negative meanings

$$\mathrm{Ai}(-x) = \left(\frac{1}{3}\right)x^{1/2}\left[\mathrm{J}_{-1/3}\left(\frac{2}{3}x^{3/2}\right) + \mathrm{J}_{1/3}\left(\frac{2}{3}x^{3/2}\right)\right], \tag{7}$$

where J and I are Bessel functions.

For calculation the tables (Abramowitz and Stegun, 1964) and also formulas can be used

$$\mathrm{Ai}(x) = \mathrm{c}_1 f(x) - \mathrm{c}_2 g(x), \tag{8}$$

where

$$f(x) = 1 + \left(\frac{1}{3!}\right)x^3 + \left(\frac{1\cdot 4}{6!}\right)x^6 + \left(\frac{1\cdot 4\cdot 7}{9!}\right)x^9 + \cdots, \tag{9}$$

$$g(x) = x + \left(\frac{2}{4!}\right)x^4 + \left(\frac{2\cdot 5}{7!}\right)x^7 + \left(\frac{2\cdot 5\cdot 8}{10!}\right)x^{10} + \cdots, \tag{10}$$

$$\mathrm{c}_1 = \frac{3^{-2/3}}{\Gamma\left(\frac{2}{3}\right)} = 0.35503, \quad \mathrm{c}_2 = \frac{3^{-1/3}}{\Gamma\left(\frac{1}{3}\right)} = 0.25882. \tag{11}$$

In this case for the description of process of variations of $\Delta F_{10.7}$ the argument $x = 3 - \Delta t$, where $\Delta T = t - t_0$ are years concerning the moment of a beginning of the wave train t_0. As $\mathrm{Ai}(3) \leq 0.008$, *i.e.* practically is equal to zero, though Ai(x) asymptotic tends to zero at

$x \to \infty$, it is possible to accept, that the beginning of the wave train corresponds to $x = 3$. Therefore

$$\Delta \mathrm{F}_{10.7} = -22\mathrm{Ai}(3 - \Delta t). \tag{12}$$

On the Figure 1 the thin line shows an approximation of long-term variations of $\Delta \mathrm{F}_{10.7}$ in view of mutual imposing of consecutive cycles. As can be seen, the wave train of the QBO arises at the end of a previous 11-year cycle and during an interval of the 11-year period the five maxima are contained. In an initial phase of a maximum of solar activity the period is ~38 months and in a phase of a minimum is ~21 months, linearly ($r = -0.98$) decreasing with a rate -1.7 month per year. Correlation coefficient between measured and calculated of an approximating values of $\Delta \mathrm{F}_{10.7}$ is 0.805 ± 0.042. As it is possible to conclude from the available data the value in minimum $-\mathrm{Ai}\ (-1) = -0.54$, is apparently, corresponds to the moment of a minimum of the mean annual $\mathrm{F}_{10.7}$ in a 11-year cycle. It in turn can give the basis for the forecasting estimations of a forthcoming solar cycle.

It is necessary to note, that for the first time Schuster (1906) has assumed about existence of the QBO in solar activity. This problem was investigated for a long time (*e.g.* Apostolov (1985), Antonova *et al.* (1996); Ivanov-Kholodny *et al.* (2000b)). However, it must be emphasized that the obtained regularities of the QBO of the solar activity differ from what are described by Apostolov (1985), and Fedorov *et al.* (1994), namely, during a 11-year cycle the periods of variations monotonously decrease, instead of are increased. The wave train of the QBO arising during the ending of the previous solar cycle does not terminate with the beginning of the following wave train and some time continues to exist simultaneously with new wave train. An example it can serve the first and second maxima in the beginning of the 90-th years, which are the sum with the sixth and eighth maxima of the previous wave train, respectively. The fifth and seventh maxima of the previous wave train are completely contaminated by the first and second minima of the subsequent wave train, respectively. The variations of an interval of time between occurrence of the consecutive wave trains, apparently, cause the observable changes of a ratio of amplitudes of maxima in the wave train.

The approximations of the temperature variations of an atmosphere at heights of 87–107 km by Airy function (Figs. 1 and 2) are shown by thin lines. Correlation coefficients between the measured values of ΔT and calculated on the basis of approximations

$$\Delta T_{107} = 8\ \mathrm{Ai}(3 - \Delta t), \mathrm{K}, \tag{13}$$

$$\Delta T_{97} = 7\ \mathrm{Ai}(3 - \Delta t), \mathrm{K}, \tag{14}$$

$$\Delta T_{92} = 5\ \mathrm{Ai}(3 - \Delta t), \mathrm{K}, \tag{15}$$

$$\Delta T_{87} = -5\ \mathrm{Ai}(3 - \Delta t), \mathrm{K}, \tag{16}$$

are presented in the Table I. As can see, there is a high degree of the validity of chosen approximations. It is necessary to note, that the values of numerical coefficients in the presented above formulas probably can depend on parameters of a specific cycle of solar activity. It requires the further analysis on the basis of a material of the greater duration.

It is necessary to note, that the negative correlation between ΔT_{97} and $\Delta \mathrm{F}_{10.7}$ and positive correlation between ΔT_{87} and $\Delta \mathrm{F}_{10.7}$ are in agreement with correlation between I and $\mathrm{F}_{10.7}$ obtained on long-term observation of 557.7 nm and OH emissions (Semenov and Shefov, 1996; 1997; 1999; 2000).

As well as for $\Delta \mathrm{F}_{10.7}$ the period of temperature fluctuations is maximal in the beginning of a 11-year's cycle (~38 months) and decreases within a minimum ~21 months. It differs from

TABLE I Correlation Coefficients r and rms σ_r Between ΔT Values According to Measurements and Calculations.

	Radar measurements		*Emission measurements*	
z, km	r	σ_r	r	σ_r
107	0.707	0.055		
97	0.444	0.097	0.836	0.039
92	0.696	0.061	0.825	0.061
87	0.708	0.055	0.754	0.067

conclusions by Fedorov *et al.* (1994) for conditions of stratosphere at heights ~20 and 24 km, though the data presented in this paper, testify to the maximal periods within a maximum of solar activity and reduction them within a minimum. It is interesting to note, that the QBO of pressure in an atmosphere at heights of 5–26 km (Okhlopkov, 1998b) occurred in opposite phase with the QBO of $\Delta F_{10.7}$.

Thus, the quasi-biennial variation of temperature of an atmosphere at heights of 87–107 km are caused by appropriate QBO of solar activity. It means their conditionality by the variations of the solar UV radiation absorbed at heights of the lower thermosphere. Excitation of such fluctuations is obviously connected to the mechanism of a 11-year cycle of solar activity and is a consequence of dynamic processes in the interior of the Sun.

It is important to note that similar periodic structures (1.6–3 years) in the long-term cycle variations (7–16 years) of chromospheric emissions apparently take place for the stars of the F6–K7 spectral classes as it is possible to reveal in the data published by Baliunas *et al.* (1995) and Frick *et al.* (1997).

5 CONCLUSION

The carried out analysis has allowed to establish, that the QBO of the temperatures at heights of mesosphere and lower thermosphere regularly are present at high and middle latitudes and they are closely connected with the QBO of the solar activity. The amplitude of temperature variations at middle and high latitudes and at heights of 87–107 km reached values ~6 K and decreased during a solar cycle. The revealed variations have character of the wave train of fluctuations with decreasing amplitude and period and are present from a beginning of each 11-year period of solar activity. For the first time is shown, that the character of the QBO behaviour is described by properties of the Airy function. It testifies that the QBO occurrence in the solar activity is caused by wave processes in convective zone of the Sun.

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