Regional specific features and temporal evolution of the quasi-biennial oscillation of total ozone (TO) in the atmosphere

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Abstract. This work presents results of the research on features of quasi-biennial oscillation (QBO) of total ozone content over the North Tien-Shan based on 35 year old (1980-2015) experimental database of Issyk-Kul high mountain monitoring station (lat. 42.62; long. 76.98; 1640 m.a.s.l.). It has been established that regional specific features and temporal evolution of QBO in total ozone (TO) are largely defined by interrelation - synchronizations of quasi-biennial and annual (seasonal) variations.

1. Introduction

The atmospheric ozone not only protects the biosphere from harmful Sun's ultraviolet radiation, but also plays one of the major roles in energy exchange processes between the different parts of the atmosphere. However, inter influence of atmospheric ozone evolution and global and regional climate changes in different time scales remains as one of the most important and not fully understood problems of atmosphere physics, meteorology and climatology. That is why experimental study of spatiotemporal ozone variations has scientific and applied value.

Monitoring of ozone and main greenhouse gases in Central part of the Eurasian continent has been conducted for more than 35 years at Issyk-Kul Station, located on the coast of the mountain lake Issyk-Kul (lat. 42.62; long.76.98; 1640 m.a.s.l.). There were received temporal series of TO, having unique duration for this region, which significantly complimented the measurement results of the monitoring network managed by the World Meteorological Organization (WMO).

The ozone content measurements are performed with the help of a spectrophotometer scanning set (SPS). Determination of a systematic measurements error and fitting TO values to the world ozonometric scale were conducted by simultaneous verification of TO measurements on SPS and spectrophotometer Dobson No. 108, located at Main Geophysical Observatory named after Voeikov A I, which is the national standard of Russia, as well as with SPS and spectrophotometer Brewer No. 44 (SPA "Typhoon"). The deviations in measurement results, obtained by the SPS, do not exceed 2 % from the world ozonometric scale. Comparative analysis of TO measurements at "Issyk-Kul" station and satellite measurements showed that the average relative deviation of TO between "Issyk-Kul" station and SBUV/SBUV2 satellite data for the period 1980-2013 made less than 1%.

Detailed description of measurement methods, set of measurement devices used at the research station Issyk-Kul, measurement results processing, analysis methods and detailed bibliography list on this subject are given in the works [1, 2, 3, 4].

Research in quasi-biennial oscillation (QBO) of total ozone were carried out by many scientists, particularly in works [5, 6]. This work contains the results of the research on features of quasi-biennial oscillation (QBO) development of total ozone over the North Tien-Shan based on 35 year old (1980-2015) experimental database of Issyk-Kul high mountain monitoring station (ISK 347). The interest in this research is due to the fact that powerful mountain ecosystems of Middle and Central Asia (the

Himalayas, Tien-Shan, Pamir-Alai, the Tibetan Plateau), making significant influence on the high-altitude jet streams, play an important role in spatial and temporal distribution of total ozone in the region [4].

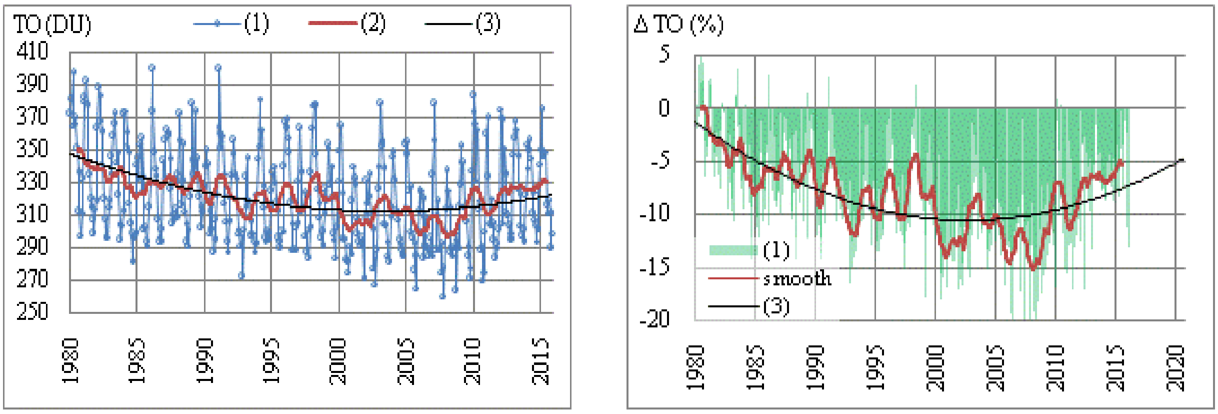
Due to the large volume of material presented in the article, informative and most significant results are shown in the form of graphs.

2. Results of total ozone content measurements at Issyk-Kul Station for the period 1980-2015

Figure1(a) shows the variations of average monthly TO values (curve 1) received from the data measured at "Issyk-Kul" Station (ISK 347). It also depicts the smoothed curve 2, that reflects inter annual TO variations, as well as the parabolic trend (curve 3):

$$(X(t) = 0.00044319 * t^2 - 0.249 * t + 347.09)$$

Figure 1(b) presents deviations of average monthly TO values (columns 1), expressed as a percentage to the average annual cycle of TO for year 1980. Curve "smooth" represents inter annual variations of the TO deviations, curve 3 is a polynomial trend of the second order, showing the TO evolution during the monitoring and coming periods. It shows that the depletion in the ozone layer was 11% on average during 1980-2005 and in the last decade its recovery has been observed. The data analysis revealed that the rates of the ozone layer depletion and recovery have seasonal dependence. It was established that the highest ozone depletion rates V= -1.79 DU/year (on linear trend for 1980-2005) and the highest recovery rates V= 5.13 DU/year (2005-2015) were observed in May.



(a). Average monthly (1), inter-annual (2) TO variations, parabolic trend (3)

(b). TO value deviations in % (1) relatively to TO values in 1980 and smoothed(smooth) and parabolic trend (3)

Figure 1. Temporal variations of total ozone content according to data measured at Issyk-Kul station (ISK 347).

Figure 2 shows the variations of inter-annual (1) and average annual (2) TO values with linear (3) and parabolic trends (4). The slopes of the linear trends ($X = X_0 + b \cdot t$) reflect the rates of the ozone layer depletion and recovery at different time intervals: for 1980 - 1985, value of b = -0.4 DU/mon.; 1984 - 1990, b = 0.18 DU/mon.; 1989 - 1994, b = -0.26 DU /mon.; 1993 - 1998, b = 0.14 DU /mon.; 1997 - 2006, b = -0.16 DU/mon.; 2006 - 2015, b = 0.29 DU/mon.

Note that in the observed long time TO variations (figure 2), there are deposits of natural (solar activity cycles, gravitational tidal forces, volcanism, the flux of galactic cosmic rays, etc.) and anthropogenic factors (Montreal protocol acts 1987), differentiation of which is a complex urgent problem that requires thorough research

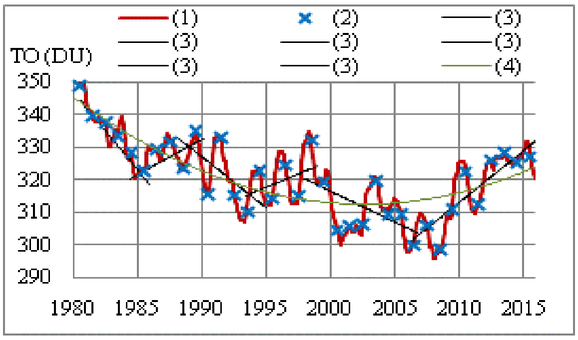


Figure 2. Variations of inter-annual (1) and average annual (2) TO values with linear trends(3) and parabolic trend(4)

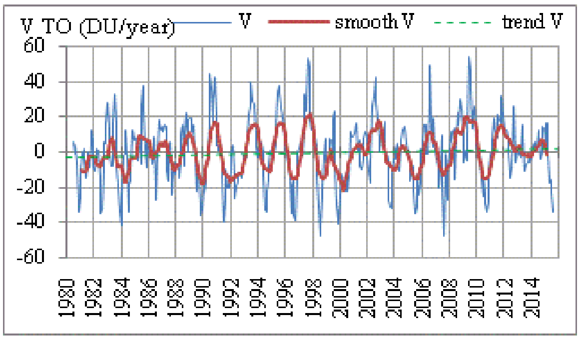


Figure3. Fluctuation of TO change rate (V) and its smooth (smooth V) for 13 months.

Figure 3 presents fluctuations of the TO change rate (V), obtained as a derivative from the inter-annual TO variations (figure 2). The linear trend (figure 3) shows that the TO change rate had negative values till 2002-2003, i.e. depletion of the TO was observed, and further it has positive values, i.e. the TO has been recovering.

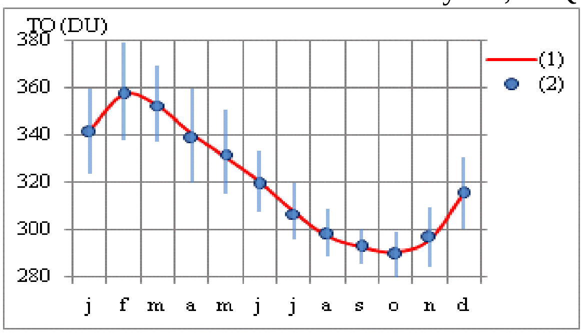
Figures 1, 2, 3 show that TO change is a complicated oscillatory process with distinct quasi-biennial oscillation. Oscillation amplitude of TO change rates (figure 3) varies within wide limits, and increase in magnitude of the amplitudes is observed at the beginning and its reduction at the end of the observation period (1980-2015) like the beating of amplitudes.

3. Methods and results of analysis of quasi-biennial oscillation of total ozone (TO)

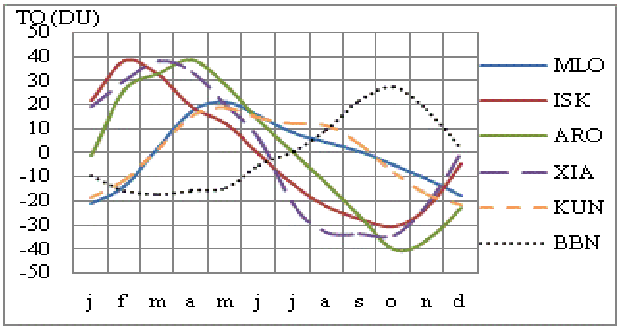
To study the quasi-biennial oscillation of total ozone, the following methods were used in this work:

1. The average annual cycle norm of TO (figure 4a) for the period 1980-2013, caused by the orbital motion of the Earth around the Sun, was subtracted from the temporal series of average monthly TO (figure 1). To improve the accuracy, unlike previously used method [1, 2, 3] in determining the “norm” of TO, instead of the linear trend, we subtracted a non-linear trend (inter-annual variations – figure 2) of TO.

2. The cleaning of temporal series of TO from long periodic oscillations with periods of T> 36 months was carried out in order to suppress influence of helio-geophysical and other processes, that have oscillations T more than three years, on QBO TO.



(a). TO norm for ISK 347 (2) versus the model (1)



(b). The relative norms: TO ISK 347; MLO 3; ARO 35; XIA 208; KUN 209; BBN 27.

Figure 4. (a) The TO norm (2) with standard deviations versus model (1) for ISK 347; (b) Comparison of relative norms of TO ISK 347, MLO 31, ARO 35, XIA 208, KUN209, BBN 27.

Figure 4(a) presents average annual (1980-2013) variations-norm of TO (2) in comparison to the model (1), received by us as a result of spectral Fourier analysis:

$$X(t) = \sum A_i \cos(\omega_i t + \varphi_i) + X_{mean} \qquad (1)$$

where: $\omega_i = 2\pi/T_i$; $T_1=12$, $A_1=31.57$, $\varphi_1=1.05$; $T_2=6$, $A_2=7.10$, $\varphi_2=0,86$; $T_3=4$, $A_3=2.95$, $\varphi_3=0.97$; X_{mean} = 320.81DU; T, A, φ correspondingly months, DU and rad.

Figure 4 presents the comparison of relative norms of TO, received with above mentioned method for the observation stations: ISK 347, MLO 31, ARO 35, XIA 208, KUN209, BBN 27 (table 1) (http://www.woudc.org/).These data further will be used for analysis of regional features of QBO of TO.

Table 1

Platform name	Platform id	Latitude	Longitude	Elevation (m)	Country	WMO region
ISSYK-KUL (ISK)	347	42.62	76.98	1640	KGZ	II
XIANGHE (XIA)	208	39.88	116.65	62	CHN	II
KUNMING (KUN)	209	25.03	102.68	1917	CHN	II
MAUNA LOA (MLO)	31	19.53	-155.57	3405	USA	V
AROSA (ARO)	35	46.78	9.68	1840	CHE	VI
BRISBANE (BBN)	27	-27.42	153.12	3	AUS	V

Figure 5 presents averaged (smoothed) values (remainders) of TO for three and thirteen months, received after subtraction of the annual cycle (norm) and non-linear trend (correspondingly curves 3 and 13). In the same figure, in order to demonstrate the features of interrelation between quasi-biennial oscillation of TO and quasi-biennial oscillation of equatorial zonal wind, the diagrams of temporal TO variations, zonal wind velocities V (QBO ZW) at the level of 20 hPa (13) (www.fu-berlin.de), as well as of temporal variation of solar activity index (F 10.7 – radio waves length 10.7 cm) were made (http://www.ngds.noaa.gov/stp/solar/flux.html/).

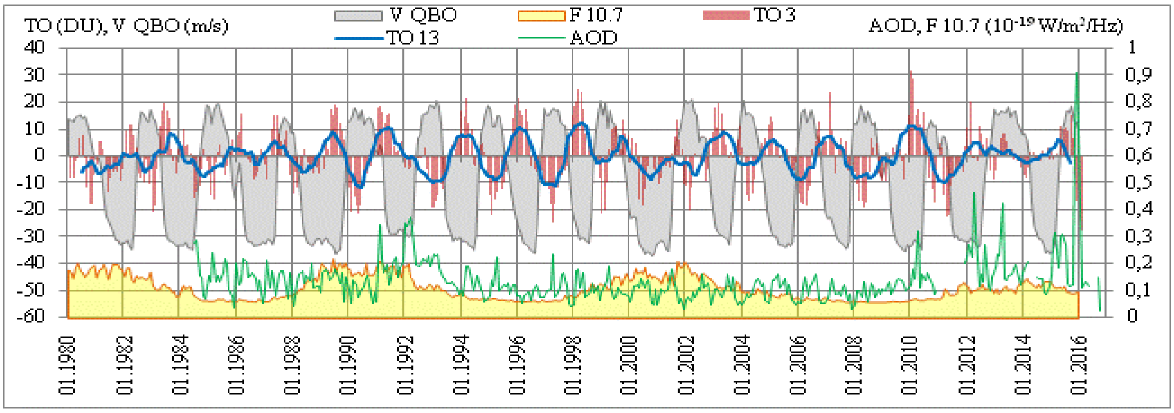
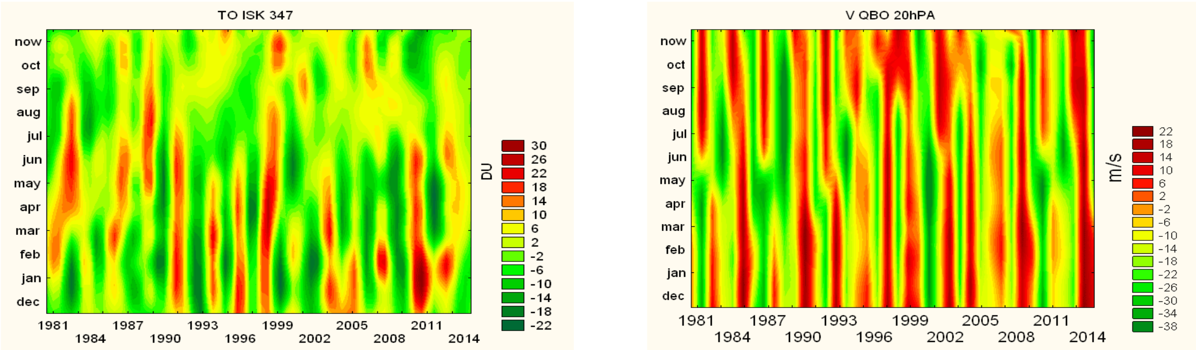


Figure 5. Correlation of quasi-biennial oscillation of TO (smoothed in three months -TO 3 and in thirteen months -TO 13) in DU with quasi-biennial oscillation of velocity (m/c) of Equatorial Zonal Wind (QBO) at the level of 20 hPa, with Solar Activity (Index F 10.7)and aerosol optical depth (AOD).

Correlation coefficient value, determined for QBO TO and QBO ZW, are equal to r= - 0.51 (for smooth 13, figure 5). The negative value of r means that when ZW changes its direction from western to eastern, TO increases and when oppositely, TO decreases. Changes in determined values of correlation coefficients between QBO TO (ISK) and QBO ZW year by year are presented in figure 8(a).



(a) TO ISK 347 **(b)** V QBO

Figure 6. Dynamics of seasonal dependence: a) QBO TOISK 347; b) QBO ZW

In figure 6, there are diagrams showing the dynamics of seasonal dependence of QBO TO (a) and QBO ZW (b). It can be seen in the figure that the effect of QBO ZW on QBO TO in winter and spring period is more significant than in summer and autumn period.

Analysis of TO and ZW correlation in comparison with the solar activity data of NOAA (http://www.ngds.noaa.gov/stp/solar/flux.html) and measured data on atmosphere's aerosol optic depth at Issyk-Kul station [7] (http://aeronet.gsfc.nasa.gov/) showed that pattern of interrelationship between TO and ZW gets destroyed in the years when aerosol content in the atmosphere is high (volcanic activity), as well as during the periods of magnetic polarity change of the Sun and its flare activity (up to r sign change). Excluding such periods (1991, 2000 and 2013) from the data processing, the relationship ratio increases and r reaches -0.68. Moreover, anomalies in correlation of TO and QBO were observed within the interval of 1986-1988 (figure 5), the reason of which can be related to the explosion of the nearest supernova (SN 1987A). Exclusion of this anomaly from time series results in increase of r up to - 0.78. It must be noted that such an anomaly of r for this time period was observed at other monitoring stations too (figures 5, 6, 7, 8).

3.1. Comparative analysis.

The data of Xianghe (XIA 208), Kunming (KUN 209), Arosa (ARO 35), Mauna Loa (MLO 31) and Brisbane (BBN 27) stations (http://www.woudc.org/data/products/totalozone/), which are located at different latitudes and longitudes, were processed using above mentioned method (table 1).

Figure 7 presents peculiarities of quasi-biennial oscillation of total ozone according to the data of stations ISK (347), MLO (31), ARO (35), XIA (208), KUN (209),BBN (27) (DU), quasi-biennial oscillations of Zonal Wind velocity (V QBO) at a level of 20 hPa (m/s) and solar activity (F 10.7 cm) for the period of 1980-2015. One can see that QBO TO observed at various stations differ by values of oscillation parameters and reaction to solar activity.

Figure 8, as an example, presents distribution of correlation coefficients for V QBO (20 hPa) and QBO TO arranged by the years for the stations ISK 347, MLO 31, ARO 35, XIA 208. Arithmetic average correlation coefficients of TO with V QBO made: a) <r> = - 0.6 for MLO 31; b)<r> = - 0.39 for ARO 35; c)<r> = - 0.52 for XIA 208; d) <r>= - 0.57 for ISK 347.

Thus, presented analysis results show significant correlation of QBO in total ozone with quasi-biennial oscillations of zonal wind (ZW) average velocity in the equatorial stratosphere, as well as peculiarities of narrowness and dynamics manifestation of this relationship of QBO in total ozone depending on Solar variability and latitude and longitude coordinates of monitoring stations. Relationship patterns of TO and ZW get destroyed in the years when aerosol components in the atmosphere have high values (volcanic activity), as well as during the periods of magnetic polarity change of the Sun and its flare activity, up to r sign change.

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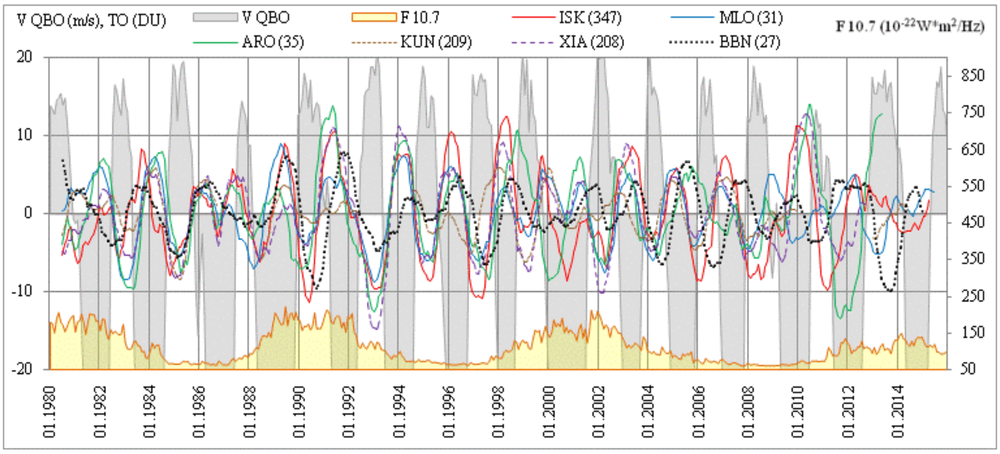
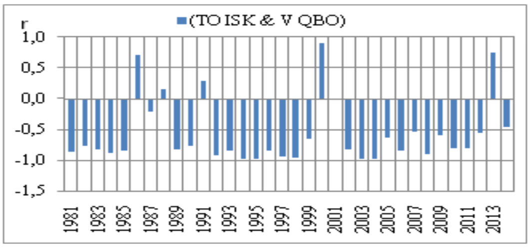
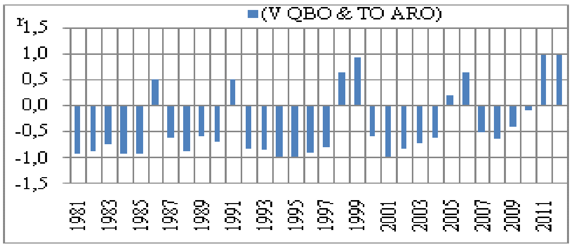


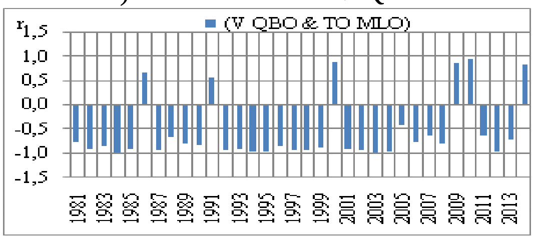
Figure 7. Comparison of quasi-biennial oscillations of TO of the stations ISK 347, MLO 31, ARO 35, XIA 208, KUN 209, BBN 27 in DU with quasi-biennial oscillations of the zonal wind velocity (m/s) (V QBO) at a level of 20 hPa.



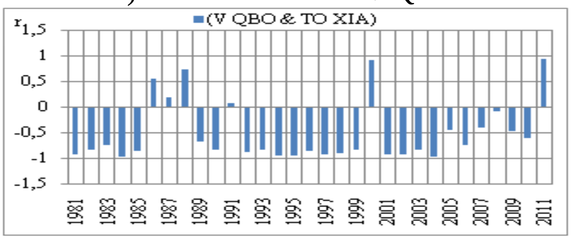
a) TO ISK &V QBO



b) TO ARO &V QBO



c) TO MLO & V QBO

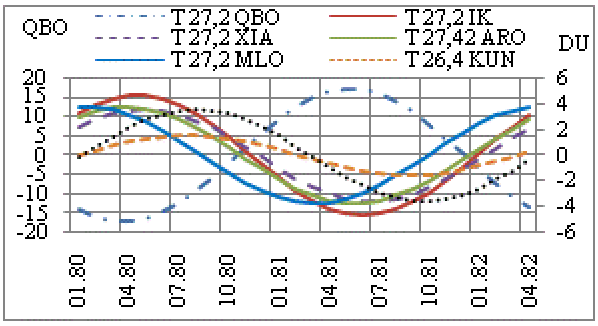


d) TO XIA & V QBO

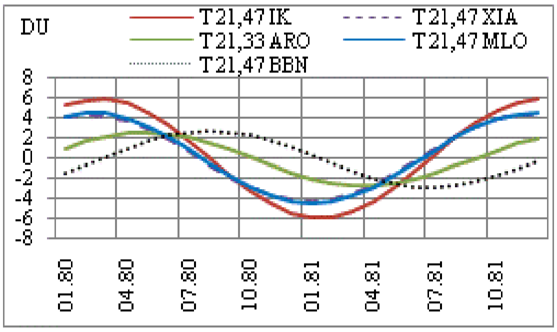
Figure 8. Distribution of correlation coefficient values for V QBO (20 hPa (m/c)) and QBO in total ozone arranged by the years: (a) ISK 347 (<r>= -0.57); (b) ARO 35 (<r>= -0.39); (c) MLO 31 (<r>= -0.6); (d) XIA 208 (<r>= -0.52).

4. Regional specific feature of quasi-biennial oscillation of total ozone (QBO TO)

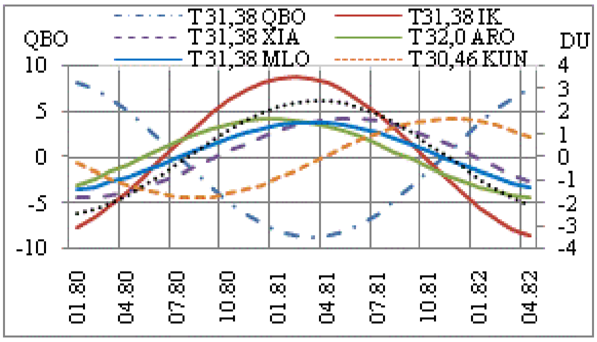
Features of significant harmonics of QBO TO and QBO ZW components were found out by using Fourier and wavelet analysis for time series of TO and ZW. The relation of periods, amplitudes and phases of significant harmonics of the analyzed oscillations are presented in figure 9. The comparison of harmonics parameters of QBO TO and QBO ZW for Issyk-Kul station revealed significant harmonics (main) in fluctuation of QBO TO with periods of T_m= 34.0; 31.4; 29.1; 27.2; 25.5; 24.0 (months), where T values match harmonics periods of quasi-biennial oscillations of zonal wind velocity (QBO ZW). Moreover, QBO TO also had “additional” significant harmonics with periods of T_{ad}= 21.47; 20.40; 19.43; 18.55; 22.60 (months).



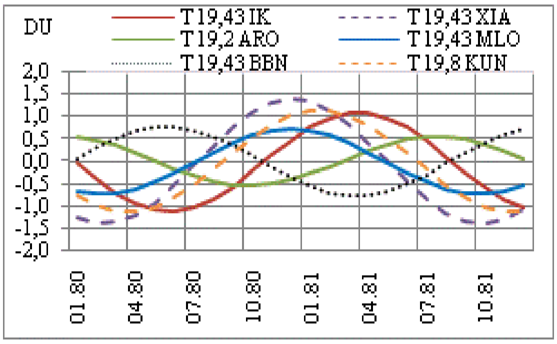
a)T 27.2



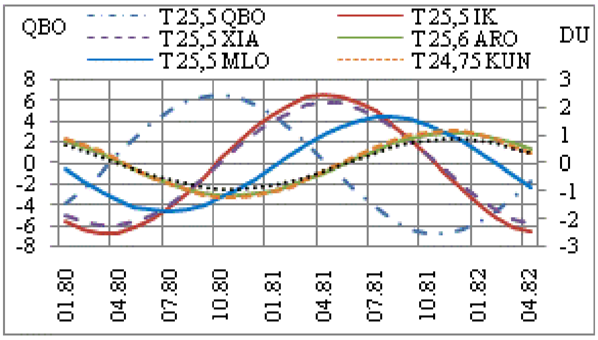
b)T 21.47



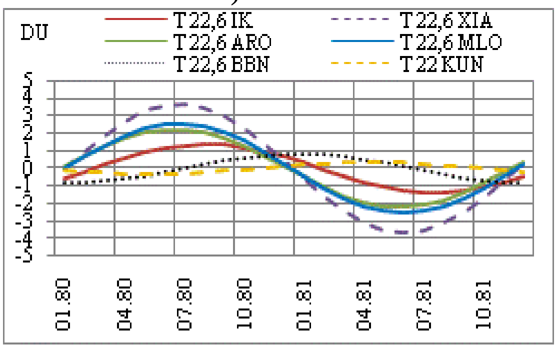
c)T 31.38



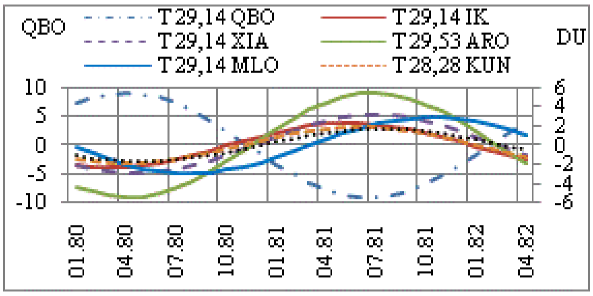
d)T 19.43



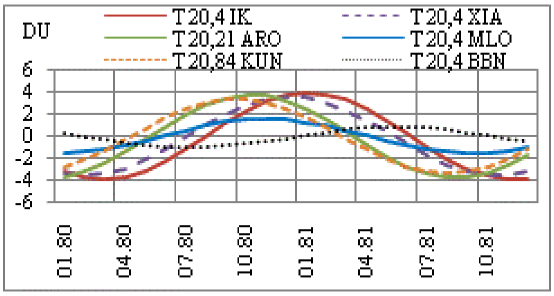
e)T 25.5



f)T 22.6



g)T 29.14



h)T 20.4

Figure 9. Relationship of QBO TO harmonics' amplitudes and phases with periods, coinciding with the harmonic periods of ZW: a) T = 27.2; c) T 31.38; e) T= 25.54; g) T= 29.17; and "additional" harmonics of QBO TO with periods of b) T = 21.47; d) T 19.43; f) T = 22.6; h) T= 20.4

Analysis of received data gives grounds to assume that the "additional" harmonic arises as a result of mutual synchronization of the "main" harmonics in QBO with annual harmonics (12 months). Then, the frequency of the resulting oscillation at mutual synchronization of two oscillations, as known [8], can be determined using equation: $\frac{1}{T_T} = \left(\frac{1}{T_1} - \frac{1}{T_2}\right)$

For our case: $\frac{1}{T} = \left(\frac{1}{12} - \frac{1}{27.2}\right) = \frac{1}{21.47}$ $\frac{1}{T} = \left(\frac{1}{12} - \frac{1}{29.14}\right) = \frac{1}{20.40}$

$\frac{1}{T} = \left(\frac{1}{12} - \frac{1}{31.38}\right) = \frac{1}{19.43}$ $\frac{1}{T} = \left(\frac{1}{12} - \frac{1}{34.0}\right) = \frac{1}{18.55}$ $\frac{1}{T} = \left(\frac{1}{12} - \frac{1}{25.5}\right) = \frac{1}{22.60}$

Comparison of the above calculated T_T with the periods of T_{ad}, obtained from the spectral analysis of experimental data, showed that they match to the third decimal point. Such a good match between the theoretically calculated T_T and T_{ad} values, determined from experimental data of Issyk-Kul station, confirms our assumption about the nature of "additional" harmonics, resulting from mutual synchronization of QBO with the annual cycle.

As one would expect, "additional" harmonics in QBO TO with similar values of T periods, but with different values of the amplitudes (power) and phases were identified for other monitoring stations too: Xianghe (XIA 208), Kunming (KUN 209), Arosa (ARO 35), Mauna-Loa (MLO 31). These differences, obviously, are due to the fact that TO annual cycle (figure 4(b)), as well known [9], has a longitude and latitude dependence, which is caused by the orbital motion of the Earth around the Sun.

The analysis of QBO TO at other stations, including Brisbane (BBN 27) station, located in the southern hemisphere, has also shown that regional and evolutional specifics of QBO TO are mostly defined by synchronization of quasi-biennial oscillation with annual oscillations. Figure 9 shows, as an example, relationship ratio of QBO TO harmonics' amplitudes and phases with periods, coinciding with the harmonic periods of ZW: a) T = 27.2; c) T 31.38; e) T= 25.54; g) T= 29.17; as well as "additional" harmonics in QBO TO with periods: b) T = 21.47; d) T 19.43; f) T = 22.6; h) T= 20.4 for some monitoring stations.

It is established that some observed particularities of temporal evolution of QBO in total ozone (figure 3 and 5.) are due to the superposition of "additional" harmonics. For example, for the data of Issyk-Kul station (ISK 347), a superposition of harmonics with periods of 21.47 and 20.4 months gives the beating with a period of 34.1 years: $\frac{1}{T} = \left(\frac{1}{21.47} - \frac{1}{20.4}\right) = \frac{1}{409.3}(mon.) = \frac{1}{34.1}(years)$.

Figure 10 (a) shows the resulting oscillations, received during superposition of "additional" harmonics with periods: T=21.47; 20.40; 19.43; 18.55; 22.60 months, and resulting oscillations, obtained during superposition of "main" harmonics with periods:T=34.0; 31.4; 29.1; 27.2; 25.5;24.0 months of QBO TO (figure 10 b).

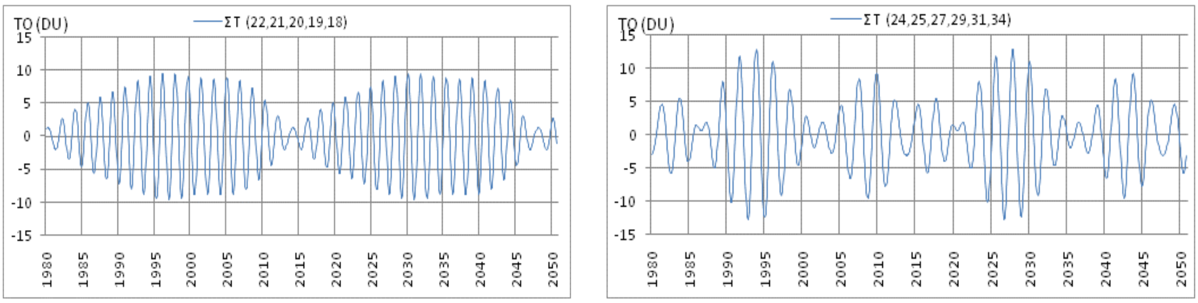
Figure 11 shows a good match between the experimental data ISK 347 (figure 5) and the model, obtained by adding "main" and "additional" harmonics of QBO TO.

$$X(t) = \sum A_i \cos(\omega_i t + \varphi_i)$$

where

Table 2 Harmonic parameters

#	1	2	3	4	5	6	7	8	9	10	11
T	34,00	31,38	29,14	27,20	25,50	24,00	22,67	21,47	20,40	19,43	18,55
A	1,22	3,64	2,33	4,58	2,60	2,85	1,25	5,80	3,89	1,21	0,34
φ	1,04	0,21	0,96	1,97	0,79	2,42	1,31	3,03	0,07	0,84	0,90



a) The oscillation amplitude beats with period of b) The superposition of "main" harmonis of TO

T~34 years, received by adding “additional” harmonics of TO with T=21.47; 20.40; 19.43; 18.55; 22.60 (mon.)

with T=34.0; 31.4; 29.1; 27.2; 25,5; 24.0 (mon.)

Figure 10. The model of quasi-biennial oscillation beats in TO for ISK347 in comparison to:
(a) The oscillation amplitude beats with period of T~34 years, received by adding “additional” harmonics of TO with T_{ad}=21.47; 20.40; 19.43; 18.55; 22.60 (mon.).
(b) The superposition of “main” harmonis of TO withT_m=34.0; 31.4; 29.1; 27.2; 25.5; 24.0(mon).

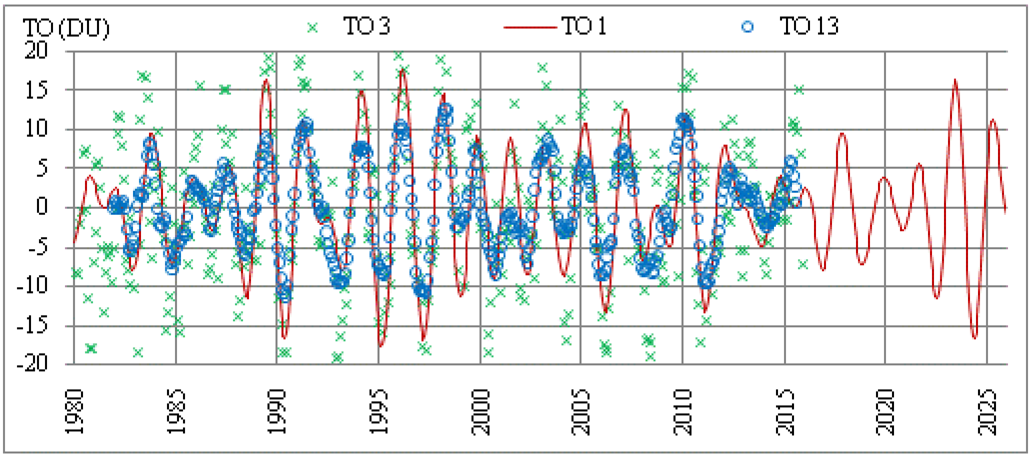


Figure 11. The QBO TO amplitude beats and comparison of experimental data of ISK 347 with the model.

The given data shows that the observed decrease in the amplitude excursion of QBO TO in recent years is due to the transition to the new long-period (34 year) regime of atmospheric circulation.

The period and beating mode of total ozone time series for other stations are different from the data obtained at ISK station. This is due to the dependence of the value of "additional" harmonics of total ozone on latitude and longitude.

Thus, the model calculation results allow describing the existing experimental data with sufficient accuracy and make forecast estimates for the expected TO changes in the atmosphere (in the future).

On the basis of detailed analysis of above mentioned experimental data, we found out, that regional and evolutional specific features of QBO TO, to a significant degree, are defined by mutual interaction of synchronization of quasi-biennial and annual (seasonal) oscillations.

5. Conclusion

Based on analysis of long-term (1980-2015) experimental data of Issyk-Kul station, in comparison with the data from other stations, there were defined specific features of quasi-biennial oscillation (QBO) of total ozone content over the North Tyan-Shan.It is established that the regional specific feature and temporal evolution of QBO in total ozone, to a significant degree, are resulted by the synchronization of quasi-biennial and annual (seasonal) oscillations.

It was found, that experimentally observed QBO TO amplitude beats are based on superposition of “additional” harmonics of QBO TO, produced as a result of mutual synchronization of quasi-biennial and annual (seasonal) oscillations. Calculations revealed that the minimum in QBO TO amplitude excursion over North Tien-Shan was reached in 2015 and new 34-years period of ozone layer variations started.

It is shown that the pattern of the relationship between TO and ZW breaks down in the years when the value of aerosol content in the atmosphere is high (volcanic activity), as well as during the periods of Magnetic Polarity change of the Sun and its flare activity, up to the change of the correlation coefficient r sign, and moreover, the degree and duration of the disturbance have regional features.

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