Is There a Relationship Between Quasi-Biennial Atmospheric Variations and Changes in Temperature and Total Ozone in Antarctica?

Victor Frolkis and Andrey Kiselev

Abstract The correlation dependence between quasi-biennial oscillation at levels of 70, 50 and 30 hPa and the parameters of the Antarctic “ozone hole”, as well as air temperature at 70 hPa over Antarctica, is estimated. Both classical correlation analysis and the Hilbert transform were used as a research tool. The results obtained indicate that the hypothesis about the possible existence of a connection between the QBO and the state of the Antarctic “ozone hole” with a high degree of probability has no basis.

Keywords Quasi-Biennial oscillation · Total ozone · Hilbert transform

1 Introduction

The emergence and observed evolution of “ozone holes” over the past decades in the stratosphere of both hemispheres have become a relatively new and completely unexplored phenomenon. Unlike the “ozone hole” in the Arctic, which appears only from time to time and, as a rule, for a short period of time [1], the Antarctic “ozone hole” forms annually, and its characteristics have been seasonally fluctuating since the early 1990s without signs of a decrease in their amplitude until the mid-2010s [2]. Among the many mechanisms that determine the formation of the Antarctic “ozone hole” or contribute to it, a number of studies (see, for example, [3–6]) mention the quasi-biennial oscillation (QBO).

Such oscillations were first noticed in the 1950s in the course of observations in the equatorial stratosphere of the movements of clouds of nuclear explosions—products of the US hydrogen bomb tests carried out in those years on the Pacific Islands [5, 7, 8]. It was found that the direction of the zonal transfer of explosion products from

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the epicenter changes with sufficient regularity from west to east and back into the latitudinal band of 20°S–20°N in the layer from the tropopause (16–17 km) to the level of 30 km (10 hPa). At the same time, the change in the directions of zonal transport begins above the 30-km level and gradually descends to the tropopause in one to two years. This phenomenon is called the "quasi-biennial oscillation", it is accompanied by regular changes in the ozone content and air temperature into the mentioned above layer.

However, the relationship between the QBO and the evolution of the Antarctic "ozone hole" is not so obvious (both due to the remoteness of the regions where they occur, and because of the different time scales inherent in these phenomena). It should be noted that the hypothesis about the presence of such a connection, expressed at the end of the twentieth century (see above), was not developed in later publications. Thus, the question raised about the degree of impact of the QBO on the Antarctic "ozone hole" remains open today to a large extent.

This article is devoted to an attempt to test whether there is a correlation between the QBO and the Antarctic ozonosphere fluctuations. To this end, along with the classical statistical analysis, we used the Hilbert transform, which allows us to evaluate the "implicit correlation" between the declared phenomena.

2 Initial Data

In our work, we used the data on the average monthly values of the QBO given on the website http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html. Examples of observed equatorial sections show on Fig. 1. In general, there is a west–east transport characteristic of the equatorial stratosphere, which includes zones of reverse east–west zonal transport with a duration of 1–1.5 years. They originate in the middle stratosphere, descend in 2–2.5 years to the level of the tropopause, where they disappear in the general west–east flow. For more than 60 years of observations (from the beginning of 1953 to the end of 2018), approximately 28 such cycles of 2–4 years each have been noted. At the same time, the total zonal transport to the east is about twice as intense as the transport to the west. In general, the zonal transport rates change insignificantly during the entire observation period. The mechanism of this transfer, its dynamics, as well as its contribution to the formation and evolution of ozone in the stratosphere, have not yet been fully elucidated [9–11].

Data on the characteristics of the "ozone hole" and air temperature at a number of pressure levels in the Antarctic are taken from the website http://ozonewatch.gsfc.nasa.gov/. Figure 2 shows the values of the total ozone (TO) minimum and the area of the "hole", averaged over the periods indicated in the caption under the figure during its existence. The "ozone hole" here is defined as the area of positive difference between the value of 220 Dobson units (i.e., the conditional "climatic norm") and the area-average TO value for the indicated periods. In the twenty-first century, with the exception of the deviation in 2002, there are "stable" values of TO minima and "hole" areas with relatively small interannual fluctuations. The average area of the

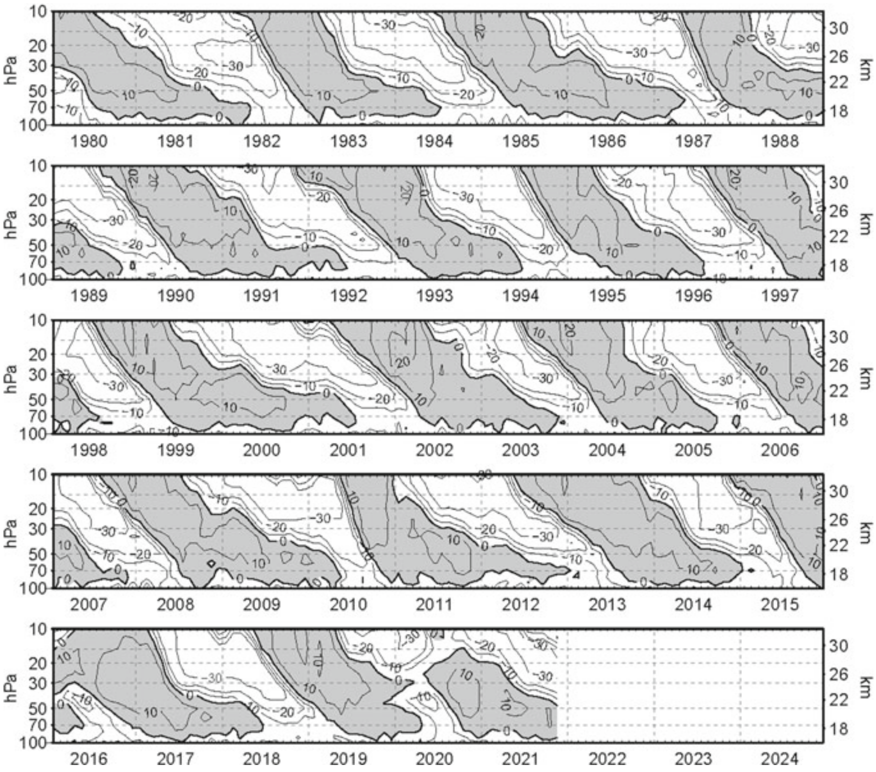


Fig. 1 Changes in the zonal component of wind speed in the layer 16–32 km above sea level in 1980–2019. Positive values refer to the west–east component. The western phase is shown in grey. According to http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html

"hole" over the past 40 years is 24.7 million km^2, which is 1.75 times the area of Antarctica itself (about 14.1 million km^2).

Figure 3 shows interannual deviations of the values of TO minima, "hole" area maxima and air temperature at the level of 70 hPa, corresponding to the date of TO minimum. It should be noted that the temperature is in the same phase with the TO minimum and in antiphase with the "hole" area, which is confirmed by the high values of the correlation coefficients: 0.83 and –0.84, respectively. There is also a negative correlation between the TO minimum and the area of the "ozone hole" with a coefficient of –0.94.

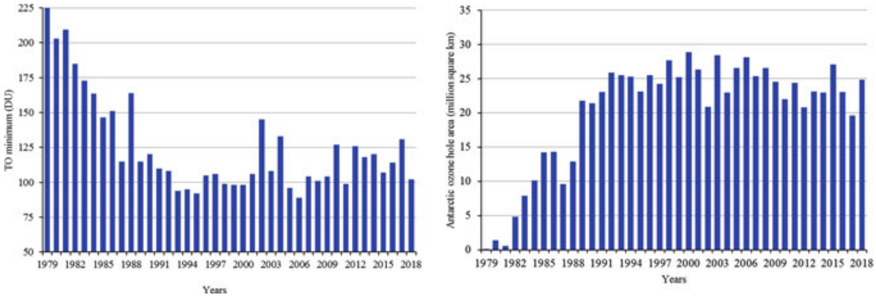
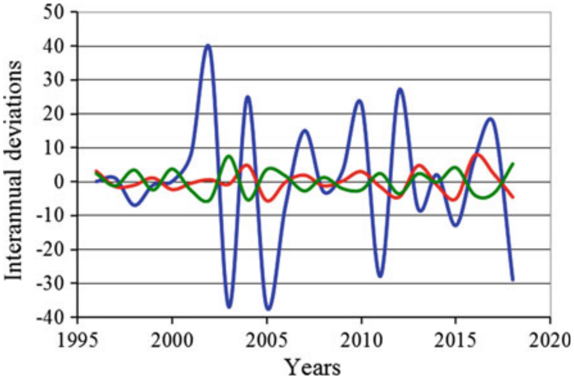


Fig. 2 Left: The minimum value of TO in the “ozone hole” (Dobson units), averaged over the period September 21—October 16 of each year. Right: Area of the “ozone hole” (million km^2), average for the period September 7—October 13 each year. According to http://ozonewatch.gsfc.nasa.gov/meteorology

Fig. 3 Antarctic interannual deviations of the TO minimum (Dobson units)—blue line, temperatures at the level of 70 hPa (K)—red line and areas of the “ozone hole” (million km^2)—green line



3 Data Processing Method

At the first stage of the work, the existence of a correlation between the QBO (at the levels of 70, 50, and 30 hPa) and the characteristics of the “ozone hole” (its area and minimum TO values) was assessed using standard correlation analysis methods. The calculations showed the practical absence of a linear correlation (low and statistically insignificant values of the correlation coefficients) between the parameters of the above phenomena. Therefore, further an attempt was made to assess whether there is any “implicit correlation” between them. For this purpose, the time series describing the QBO, the temperature and the state of the “ozone hole” are presented as quasi-harmonic processes, and then the correlations are estimated not between the initial data, but between their amplitudes or phases.

To represent a signal as a quasi-harmonic oscillation (with time-varying amplitude and initial phase)

$$s(t) = a(t)\cos[\psi(t)] \tag{1}$$

it should be considered as a real part of some complex signal [12, 13],

$$s(t) = \mathrm{Re}\{z(t)\}, \tag{2}$$

in which the process is complemented by an arbitrary imaginary component $s_\perp(t)$,

$$z(t) = s(t) + is_\perp(t) = a(t)\exp[i\psi(t)], \tag{3}$$

where

$$a(t) = \sqrt{(s(t))^2 + (s_\perp(t))^2};\quad \psi(t) = \arccos\frac{s(t)}{a(t)},\ a(t) \neq 0;$$

$$\varphi(t) = \psi(t) - \nu_0 t;\quad a_m(t) = a(t)\exp[i\varphi(t)].$$

Here $a(t)$ is the amplitude envelope, $\psi(t)$ is the total phase, $\varphi(t)$ is the phase function, and $a_m(t)$ is the complex amplitude envelope of the signal $z(t)$; ν_0–fixed frequency, chosen arbitrarily; t is time.

The signal representation in the formula (2) can be implemented in an infinite number of ways due to the arbitrary choice of the imaginary component $s_\perp(t)$. However, it is clear that the quasi-harmonic signal obtained in this way must satisfy two natural requirements: (a) if the original signal $s(t)$ is harmonic, then its amplitude $a(t)$ and phase function $\varphi(t)$ (initial phase) must be constant; (b) the phase function $\varphi(t)$ should not change when the signal is multiplied by an arbitrary constant value.

The only way to select the imaginary component $s_\perp(t)$ of a complex signal $z(t)$ that satisfies the above conditions (a) and (b) is to use the Hilbert transform, which allows to define $s_\perp(t)$ as an orthogonal complement of the original signal

$$s_\perp(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{s(t')}{t - t'}dt', \tag{4}$$

in this case $z(t)$ is called an analytic signal.

Transformation (4) is a linear operator, which is the convolution of the original signal *s(t)* and the weight function $h(t) = \frac{1}{\pi t}$,

$$s_\perp(t) = h(t) * s(t). \tag{5}$$

Applying the complex Fourier transform, we find the frequency response $H(\omega)$ of the weight function *h*(*t*) of the Hilbert transform,

$$H(\omega) = \tilde{F}\{h(t)\} = \int_{-\infty}^{\infty} \frac{1}{\pi t} e^{-i\omega t}\, dt = -i \int_{-\infty}^{\infty} \frac{1}{\pi t} \sin(\omega t) dt = -i \cdot sign(\omega)$$
$$= \begin{cases} i,\ \omega < 0, \\ 0,\ \omega = 0, \\ -i,\ \omega > 0, \end{cases} \tag{6}$$

where $\tilde{F}\{\cdot\}$ is the symbol of the Fourier transform.

Taking into account (6), the Fourier transform of the orthogonal complement $s_{\perp}(t)$ of the original signal *s(t)* is given by the expression

$$S_{\perp}(\omega) = \tilde{F}\{s_{\perp}(t)\} = \tilde{F}\{h(t) * s(t)\} = H(\omega) S(\omega),$$

where $S(\omega) = \tilde{F}\{s(t)\}$.

Thus, the spectrum of the analytical signal *z*(*t*) is determined by the relation

$$Z(\omega) = \tilde{F}\{z(t)\} = \tilde{F}\{s(t) + i s_{\perp}(t)\} = S(\omega) + iH(\omega)S(\omega) = \left\{ \begin{array}{c} 0,\ \omega < 0 \\ S(0),\ \omega = 0 \\ 2S(\omega),\ \omega > 0 \end{array} \right\}. \tag{7}$$

Formula (7) allows constructing the orthogonal complement $s_{\perp}(t)$, and, consequently, the analytical signal *z*(*t*), without using the Hilbert transform. Because

$$s(t) = \mathrm{Re}\{z(t)\} \text{ and } s_{\perp}(t) = \mathrm{Im}\{z(t)\},$$

then it follows:

- calculate the Fourier transform of the original signal *s*(*t*), $S(\omega) = \tilde{F}\{s(t)\}$;
- equate to zero the resulting spectrum in the region of negative frequencies, $\omega < 0$;
- multiply by two the spectrum in the region of positive frequencies, $\omega > 0$;
- apply the inverse Fourier transform to the non-negative part of the spectrum $\omega \geq 0$, $z(t) = \tilde{F}^{-1}\{Z(\omega)\}$.

As a result, we obtain an analytical signal *z*(*t*), the imaginary part of which is the orthogonal complement $s_{\perp}(t)$ of the original signal *s*(*t*). The convenience of this procedure is explained by the fact that, unlike the Hilbert transform, only the non-negative part of the spectrum is used.

Since the series under consideration are of finite length and equidistant, the continuous complex Fourier transform $\tilde{F}\{\cdot\}$ can be replaced by a discrete one. Note that in the discrete case, one can also directly calculate $s_{\perp}(t)$ from the following formula

$$s_{\perp}(m) = \frac{1}{\pi} \sum_{k=0, k \neq m}^{N} \frac{s(k)}{m-k}$$

however, in the case of a large data array, rather lengthy calculations will be required.

Such an algorithm is used when searching for synchronization between signals that are induced by stochastic systems. Since the signal is decomposed into amplitude and phase components, which are studied independently, this approach can make it possible to see the correlation between the signals, which may consist in the synchronism of the phase dynamics, even when there is no correlation between the signal amplitudes [12, 13].

Of interest to us are the following quantities (see (3)), the amplitude envelope $a(t)$, the total phase $\psi(t)$, also the phase function $\varphi(t)$ and the real part of the complex amplitude envelope $\text{Re}\{a_m(t)\}$. The amplitude envelopes describe how the amplitudes of the real and imaginary parts of the signal $z(t)$ change with time, the phase function $\varphi(t)$ characterizes the change in the phase of oscillations with time, taking into account the removal of the high-frequency component $\nu_0 t$ from the full phase function $\psi(t)$.

The above values are calculated for each of the characteristics considered in the work (QBO at levels of 70, 50, 30 and 10 hPa and the area of the "ozone hole" and the minimum TO values), based on the assumption that all the characteristics under study are presented in the form of a signal $z(t)$.

4 Results and Discussion

When evaluating the potential relationship between the evolution of the QBO and the Antarctic "ozone hole", it is necessary to take into account not only the fact that these phenomena take place at a considerable distance from each other, but also the difference in their characteristic time scales (several years and approximately one month per year, respectively). Therefore, the response of a signal coming from near-equatorial latitudes to the south polar region has a delay that can be several months. Taking into account the above, in order to check the presence of a "classic" linear relationship, the cross-correlation coefficients were calculated with a lag of 0–6 months (zero lag corresponds to the usual (without shift) correlation coefficient), see Table 1. The calculations were carried out for average monthly values, since it is such time scale have data on the QBO on the site http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html.

As can be seen from Table 1, in most cases the correlation coefficient does not exceed several hundredths and is statistically insignificant. Its highest values are reached between the TO minimum/"hole" area and the QBO at the level of 70 hPa, with the latter being delayed by three months, but even here it remains extremely low. Thus, it can be concluded that, within the framework of standard correlation analysis, the hypothesis of a number of authors about the influence of the QBO on the formation of the Antarctic "ozone hole" is not confirmed (see, for example, [3, 4]).

Below are the results of calculations made using the Hilbert transform and their analysis. Thus, an attempt was made to identify and evaluate whether there is any

Table 1 Values of the cross-correlation coefficient at lags of 0–6 months between the TO minimum/“hole” area and QBO at levels of 70, 50, and 30 hPa

Lag (months)	TO minimum			“Hole” area		
	QBO (70)	QBO (50)	QBO (30)	QBO (70)	QBO (50)	QBO (30)
0	0.002	0.051	–0.031	0.037	–0.049	0.019
1	0.090	0.077	0.010	–0.046	–0.052	–0.012
3	0.152	0.110	0.006	–0.099	–0.056	0.003
4	0.117	0.116	–0.029	–0.086	–0.068	0.040
5	0.035	0.075	–0.049	–0.010	–0.054	0.036
6	–0.042	0.025	–0.007	0.072	–0.038	–0.018

correlation between the characteristics of the Antarctic “ozone hole” and the QBO at different altitude levels.

Figure 4 shows the amplitudes $a(t)$ of the analytical signal (see (3)), determined by the QBO, with a monthly step, starting from January 1986, at altitudes of 70, 50, 30, and 15 hPa. Calculations show that the amplitude fluctuations become more regular and are characterized by a large range as the height increases.

Figure 5 demonstrates the correlation coefficients of the amplitudes of the QBO values at three altitude levels and the amplitudes of either the TO minima (Fig. 5a) or the area of the “ozone hole” (Fig. 5b). Since the Hilbert transform involves the study of processes that perform harmonic oscillations, it is not surprising that their correlation dependences are also subject to oscillations. Such a cyclicity with a period of approximately one year is typical for all those shown in Fig. 5 correlations. Here and below, the date of January 1, 1986 is chosen as the starting point of reference. The maxima of the correlation coefficients of QBO amplitudes and TO minima are “shifted” relative to the reference point by about nine months, which corresponds to the time of the emergence and development of the Antarctic “ozone hole”, which falls on September–October. As is known, its formation is associated with the winter/spring blocking of the meridional transport by the circumpolar vortex and the destruction of ozone over Antarctica in chemical reactions (see, for example, [1, 2]). The fact that the highest, although statistically insignificant, correlation coefficients in the “classical” analysis (see Table 1) are achieved with a three-month lag can be attributed to the fact that the characteristic time of air mass transfer from the equator to the poles is 2–4 months. But for the aforementioned nine-month shift, it is hardly possible to find justification in the form of any physical (circulation) atmospheric process with a characteristic time of about 9 months. In this case, the cyclicity with a period of one year of the correlation coefficients is entirely due to the very fact of the annual phenomenon of the “ozone hole”. This is indirectly indicated by the fact that the three peaks of the correlation coefficients in Fig. 5a for 36 months have almost the same height, not reacting in any way to the change in the QBO phase during this time. Comparison of the curves in the left (a) and rigth (b) parts of Fig. 5 again reminds us that the amplitudes of the TO minima and the area of the “ozone hole” are in antiphase.

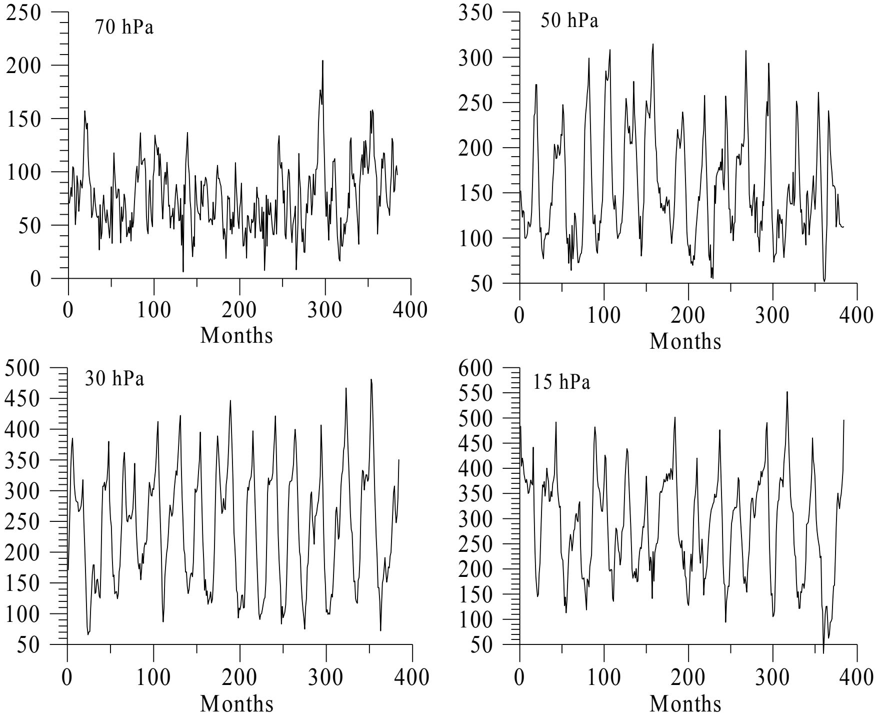


Fig. 4 Amplitudes $a(t)$ of the analytical QBO signal with a monthly step starting from January 1986 at altitudes of 70, 50, 30, and 15 hPa

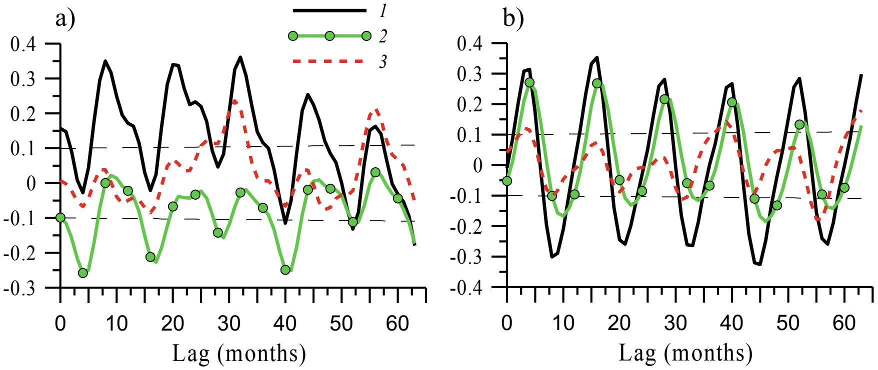


Fig. 5 Time variation of the correlation coefficient between the QBO amplitudes at the levels of 70 (1), 50 (2), 30 hPa (3) and either the TO minimum (**a**) or the “hole” area (**b**). The dashed lines indicate the 95% confidence interval in which the correlation coefficient is not statistically significant

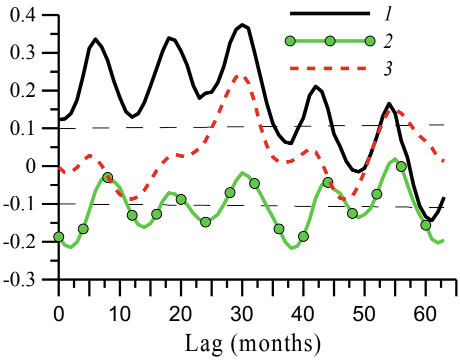


Fig. 6 Time variation of the correlation coefficient between the QBO amplitudes at levels 70 (1), 50 (2), 30 hPa (3) and temperature at the level 70 hPa. The dashed lines indicate the 95% confidence interval in which the correlation coefficient is not statistically significant

It should be noted that all the correlation coefficients shown in Fig. 5 are relatively small (do not exceed 0.4) and often statistically insignificant (here and below, the statistical significance was determined by the Student's t-test), and their values are the smaller, the higher the level under consideration is located. Their greatest values fall on the altitude level of 70 hPa (about 18 km), in the vicinity of which the vertical profile of ozone concentration in the polar regions has its maximum.

Figure 6 confirms the presence of a strong dependence between TO minima and temperature at the level of 70 hPa, characterized by high coefficients in the framework of the "classical correlation analysis" (see above). The correlation coefficients between the QBO amplitudes at three altitude levels and the temperature at the level of 70 hPa are of the same order of magnitude and have a similar curve configuration as the correlation coefficients in the top row of Fig. 5.

Figure 7 is constructed by analogy with Fig. 5 with the only difference that instead of the amplitudes, it shows the full phases of the phenomena under consideration – the QBO and minima of the TO/"ozone hole" area.

According to our calculations, there is no connection between the full phases of the above phenomena, which is confirmed by both very low correlation coefficients and their statistical insignificance.

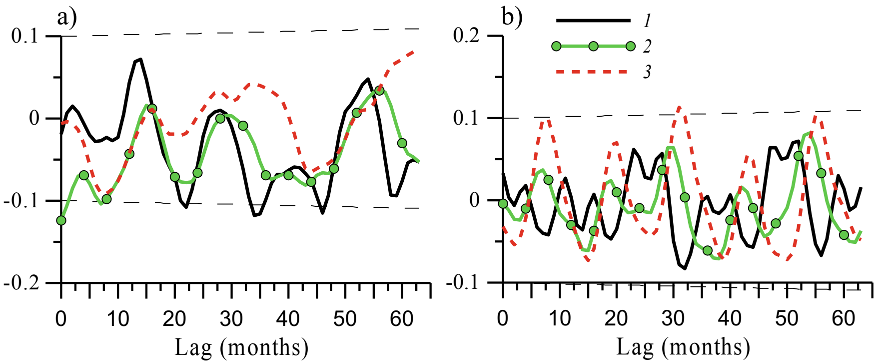


Fig. 7 Time variation of the correlation coefficient between the total QBO phases at levels of 70 (1), 50 (2), 30 hPa (3) and either the TO minimum (**a**) or the "hole" area (**b**). The dashed lines indicate the 95% confidence interval in which the correlation coefficient is not statistically significant

5 Conclusion

The discovery of the Antarctic "ozone hole" in the mid-1980s gave a powerful impetus over the next decades to a comprehensive study of the ozonosphere, as well as to the introduction of ozone-saving international restrictions regulated by the Montreal Protocol and its amendments. The protection of the ozone layer at that time topped the "rating" of global environmental and climate problems, but has recently given way to measures to counter and adapt to anthropogenic climate change. However, in this context, studies of the ozonosphere remain relevant, since ozone (primarily tropospheric one) is one of the most important greenhouse gases that determine the rate of global warming (see, for example, [14, 15]).

The phenomenon of the Antarctic "ozone hole" has a number of features, of which we will highlight two. First, ozone losses in Antarctica occur regularly (annually) and are much larger than those in other regions, including the Arctic. As a result, their "signal" is easier to isolate and process using modeling or statistical analysis. Second, a significant role in the formation of the TO field in Antarctica is played by atmospheric dynamic processes on a planetary scale—the transfer of ozone-rich air masses from northern latitudes to the southern polar region, which is interrupted in spring with the formation of a circumpolar vortex. This circumstance gives reason to assume that the evolution of the "ozone hole" depends on periodic large-scale circulation processes, including the QBO.

The fact that the phenomena considered here take place at a considerable distance from each other obviously makes it necessary to take into account the time shift for the QBO. However, the values of cross-correlations calculated by us turned out to be extremely low and statistically insignificant (see Table 1), which indicated that there was no connection between the QBO and the parameters of the Antarctic "ozone hole" in the framework of the classical correlation analysis. But such a conclusion can hardly be considered exhaustive, since it excluded only the presence of a linear relationship between phenomena that are essentially non-linear in nature. That is why we made an attempt to check whether there is a more complex, non-linear dependence between the QBO and the characteristics of the “ozone hole”, as well as the air temperature over Antarctica. As a tool for such an assessment, the Hilbert transform was used, which represents the studied periodic processes in the form of harmonic oscillations.

Our results showed that with this approach, the correlation dependence for the amplitudes of the characteristics under consideration turned out to be rather low (<0.4), and for the total phases it was completely absent. As we known, a significant correlation does not guarantee the existence of causal relationships, but is only a sufficient condition for their existence. Indirect considerations (for example, the “insensitivity” of the correlation coefficients to the change in the QBO phases), on the one hand, and the absence of clear physical mechanisms indicating any influence of the QBO on the state and evolution of the Antarctic ozonosphere, on the other hand, indicate that the hypothesis of a possible connection between the QBO and the characteristics of the Antarctic “ozone hole” is, with a high degree of probability, unfounded.

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