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STYDYING ATMOSPHERE AND OCEANS FROM SPACE

Spatio-Temporal Variability of the Phase of Total Ozone Quasi-Decennial Oscillations

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Abstract—The SBUV/SBUV2 (65° S–65° N) and Bodeker Scientific (90° S–90° N) satellite databases have been used for composite and cross-wavelet analyses of the spatio-temporal variability of phase relations between a 11-year cycle of solar activity (SA) and quasi-decennial oscillations (QDOs) of total ozone content (TOC). For globally average TOC values, the QDO maxima coincide in phase with the solar-activity maxima, and amplitude variations of TOC correlate with those of the 11-year solar cycle. According to the analysis of amplitude and phase of QDOs for the zonal average TOC fields, a QDO amplitude is about 6–7 Dobson Units (DU) in the high northern and southern latitudes, and it does not exceed 2–3 DU in the tropic regions. The latitudinal TOC variations are distinguished by a delay of the quasi-decennial oscillation phase in the southern latitudes in comparison with the northern latitudes. The TOC maxima phase coincides with the SA maxima phase in the tropic regions; the TOC variations go ahead of the SA variations, on average, in moderate and high latitudes of the Northern Hemisphere; the TOC variations are behind the SA variations in the Southern Hemisphere. The phase delay between TOC QDO maxima in the northern and southern latitudes appears to increase in the course of time, and the TOC quasi-decennial variations in the Arctic and Antarctic subpolar regions occur approximately in an antiphase over the last two decades.

Keywords: total ozone content, quasi-decennial variations, cross-wavelet analysis, composite method, solar activity, and satellite data

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INTRODUCTION

The variability in total ozone content (TOC) is a topical problem due to the ozone effect on the radiation and chemical balance of the stratosphere and the attenuation of the biologically active UV radiation. The long-period variations in TOC and their relationship to the 11-year solar-activity (SA) periodicity have been studied in recent years with the help of the chemical–climatic models and statistical methods (for example, (Smyshlyaev et al., 2010, 2015; Gruzdev, 2014; Zvyagintsev et al., 2015; Chehade et al., 2014; Knibbe et al., 2014; Harris et al., 2015) and references in them). The SA contribution to long-period TOC variability is 2–3%, while the quasi-decennial oscillations (QDO) are almost consistent in phase with the SA variations (WMO, 2010). It should be noted that the multiple linear regression commonly used as a basic statistical method is not adequate in an analysis of phase shifts, especially when there is a great number of regressors. The composite method was used in (Visheratin, 2012) to analyze phase relationships between quasi-decennial oscillations of the total ozone content and the 11-year solar activity (SA) cycle. According to the comparison QDO TOC at the Arosa Station and the SA variations from 1932 to 2009 (17th–23rd SA cycles), until the 1960s, the QDO TOC maxima were behind and subsequently ahead of the SA maxima. As is known, the last 23rd SA cycle ending in 2009 was longer than the previous cycles by about 3 years, while the maximum of the current 24th cycle (2012–2014) also came with a delay. If there was a linear dependence between the variations of SA and QDO TOC, then the following ozone maximum also had to come with a delay. Meanwhile, according to the analysis results (Visheratin, 2016), the TOC maximum above Arosa Station was observed near the SA minimum in 2009, and the QDO TOC variations turned out to be close to an antiphase in relation to the SA variations.

The results obtained in (Visheratin, 2016) characterize the phase relations only for the single point located in the middle latitudes of the Northern Hemisphere. To verify these results, it seems logical to analyze the variability of the TOC quasi-decennial oscillations using a more expensive experimental material by independent methods for phase shift estimation.

The objective of the investigation is to study the spatio-temporal variability of the phase relationships between the 11-year SA cycle and quasi-decennial oscillations of the TOC by composite and cross-wavelet analyses based on the satellite data covering the entire globe and including the current 24th SA cycle.

DATA AND ANALYSIS METHODS

Initial Data

For investigation purposes, we used the merged satellite database containing the TOC measurements obtained by the BUV/SBUV/SBUV2 equipment (SBUV Merged Total and Profile Ozone Data, Version 8.6, hereinafter, V86) recommended by the developers for analyzing long-period ozone-field variability (Labow et al., 2013; McPeters et al., 2013; Frith et al., 2014). The last update of this database (Release 4) contains the average monthly TOC values from January 1970 to June 2014. Since the data before 1978 contain significant omissions, our investigation has involved monthly average zonal mean TOC values with a step of 5° for the full years from January 1979 to December 2013 (http://acdb-ext.gsfc.nasa.gov/Data_services/). Small omissions (1–3 months) in the middle latitudes and seasonal gaps in the region of 60°–75° in both hemispheres were filled using cubic interpolation (Visheratin and Kuznetzov, 2016). In addition, for an analysis of the TOC variations in the polar and subpolar latitudes, we have used the Bodeker Scientific Combined Total Column Ozone Database (hereinafter, BS) covering the entire globe (Bodeker et al., 2005, 2013). When developing this database, in order to fill the measurement gaps, the authors used the data from different satellite and ground-based instruments and linear interpolation into the data grid points. The latest version of this database (Version 2.8) covers the period from January 1979 to August 2012 (ftp://ftp.bodekerscientific.com). In this study, we use the monthly average TOC values with a step of 5° in latitude for the period from January 1979 to December 2011. It should be noted that other integrated ozone databases have been developed to date, but they cover shorter time periods (Tummon et al., 2015, Harris et al., 2015). The Arosa monthly mean TOC values were obtained from (WOUDC, 2014). The international sunspot number (WDC-SILSO, 2015) has been used as a SA index (hereinafter, Ri).

Data Analysis Methods

The linear trend and the seasonal component have been preliminarily excluded from all analyzed series except for the SA index. The composite and the cross-wavelet analyses have been used to assess the phase relationships between the TOC series and the SA index in the region of 8–13 years. The composite method is based on identifying particular-frequency oscillations in the frequency region and the time (composite) series formation by means of the inverse Fourier transform (Visheratin, 2012, 2016). The errors of this method have been estimated by model calculations using the Monte Carlo method. In particular, in the analysis of quasi-decennial oscillations, the position of the composite series extrema on the time axis is determined with an error of less than 6 months, while, at the ends of the composite series, the error occasionally increases to about 1 year. The determination error of the extrema amplitudes is about 10%; at the ends of the series, the oscillation amplitudes are commonly underestimated due to specific features of the Fourier transform limited along the series length.

The second method used in this paper is the cross-wavelet analysis proposed in (Torrence and Compo, 1998; Grinsted et al., 2004). At the first stage, it involves wavelet transformation of the analyzed series using the Morlet function. At the second stage, the cross-correlation spectrum is calculated and a joint magnitude and phase relations between two series are estimated. The advantage of this method lies in the ability to determine the correlation degree and phase relationships between two series for different periods and time intervals, and also to assess the significance of correlation relationships taking into account the red-noise processes.

ANALYSIS RESULTS AND DISCUSSION

Comparison of the Satellite and Ground-Based TOC Measurements

In (Visheratin, 2016), the phase relations between the TOC quasi-decennial variations and the SA were determined for the Arosa Station located in the middle latitudes of the Northern Hemisphere (46.8° N). To validate these results, we used satellite data averaged in the latitudinal region of 45°–50° N. The QDO TOC values based on the Arosa and V86 data are compared in Fig. 1. As follows from a comparison of the composite series containing the oscillations in the range of 8–13 years (Fig. 1a), the TOC quasi-decennial oscillations inferred from the satellite and ground-based data are relatively well-consistent in both oscillation amplitude and phase.

The QDO TOC maxima are, on average, ahead of the solar-cycle maxima, and this lead increases in the course of time. The last QDO TOC minimum observed in 2004–2005 was ahead of the SA minimum in 2009 by 4–5 years, while the following TOC maximum fell on 2010–2011 and was also ahead of the last SA maximum in 2013–2014. Figure 1b shows the results of cross-wavelet analysis of phase relationships between the sunspot index Ri and TOC inferred from the satellite data. In the period range of 100–140 months, until 1995–2000, the TOC variations were ahead of the SA variations by about 45° (the arrows point rightwards and downwards). Further on, the lead increases to about 90°, which is about 30 months for the oscillation period of 120 months. It should be noted that the composite (Fig. 1a) and cross-wavelet (Fig. 1b) analyses results are in good agreement with each other,

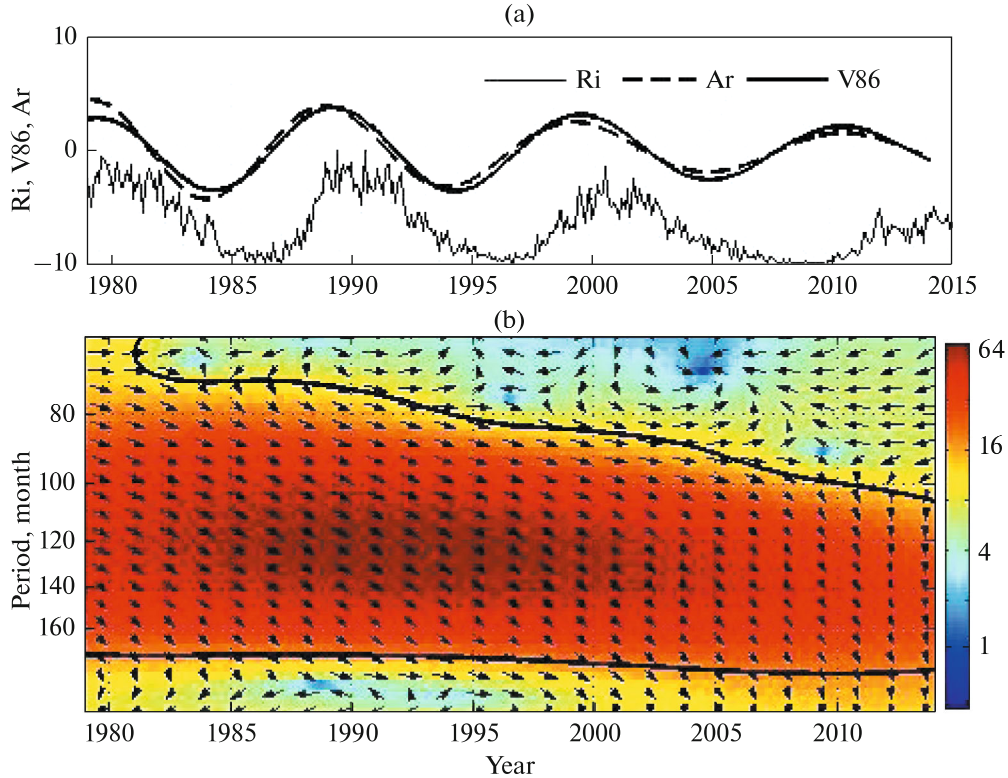

Fig. 1. (a) TOC composite series in the range of 8–13 years based on the V86 data (latitudinal belt 45°–50° N) and the Arosa (Ar) Station data. The QDO TOC values are given in DU. The SA index Ri (r.u.) is given below; (b) cross-wavelet analysis of the V86 and Ri series. Color scale, r.u. The thick solid line limits the area with a confidence probability of 95%. Arrows indicate the phase relationships (rightwards, oscillations occur in the phase; leftwards, in the antiphase; downwards, TOC variations are ahead of SA by 90°; upwards, behind the SA phase by 90°).

confirming the conclusion on time variability of the phase relationships between QDO TOC and SA.

The QDO TOC values inferred from the satellite and ground-based data on three stations located in the Asian Region were compared in (Visheratin et al., 2017). The phase relationships are different between the 11-year SA cycle and ozone variations inferred from the satellite and ground-based data obtained at the stations located in the north and south of the studied region. The oscillation phase for the Kunming Station located in the subtropic region is similar to that of the 11-year solar cycle, while the TOC oscillations are ahead of the solar-cycle variations at the Huang He and Issyk-Kul stations located in the north of the studied region. The zonal mean total ozone values will be considered below to analyze the latitudinal distribution of QDO TOC.

QDO of Zonal Mean and Globally Averaged TOC Series

The QDO amplitude and phase variability for zonal mean TOC series based on the V86 data is shown in Fig. 2a. The highest QDO amplitudes, up to 6–7 DU, are observed in the high northern and southern latitudes. In the tropical regions, the QDO amplitudes do not exceed 2–3 DU. The latitude course of the QDO TOC amplitude corresponds approximately to the latitudinal amplitude distribution of the TOC seasonal variations, with the minimum in the equatorial region and the maximum in the high latitudes. The TOC maxima phase is consistent with the SA maxima phase in the tropical regions. Previously, a close coincidence of the TOC and SA variation maxima in the 25° S–25° N tropical zone was noted in an analysis of the extensive experimental material in (Fioletov et al., 2002).

A latitudinal distribution of the TOC variations is characterized by a delay of the oscillation maximum phase in the southern latitudes relative to the northern latitudes. In the northern moderate and high latitudes, the TOC variations start being ahead of the SA variations in the course of time, while, in the southern latitudes, the QDO TOC maxima are behind the SA variations. This conclusion is consistent with the results obtained earlier in an analysis of the shorter term TOMS data for 1979–2005 and TOMS-SBUV for 1979–2009 (Visheratin, 2012). The QDO TOC phase delay upon moving from the north to the south can likely be explained by the delay in latitude of the annual oscillation maximum phase. Meanwhile, it should be noted that, according to (Gruzdev and

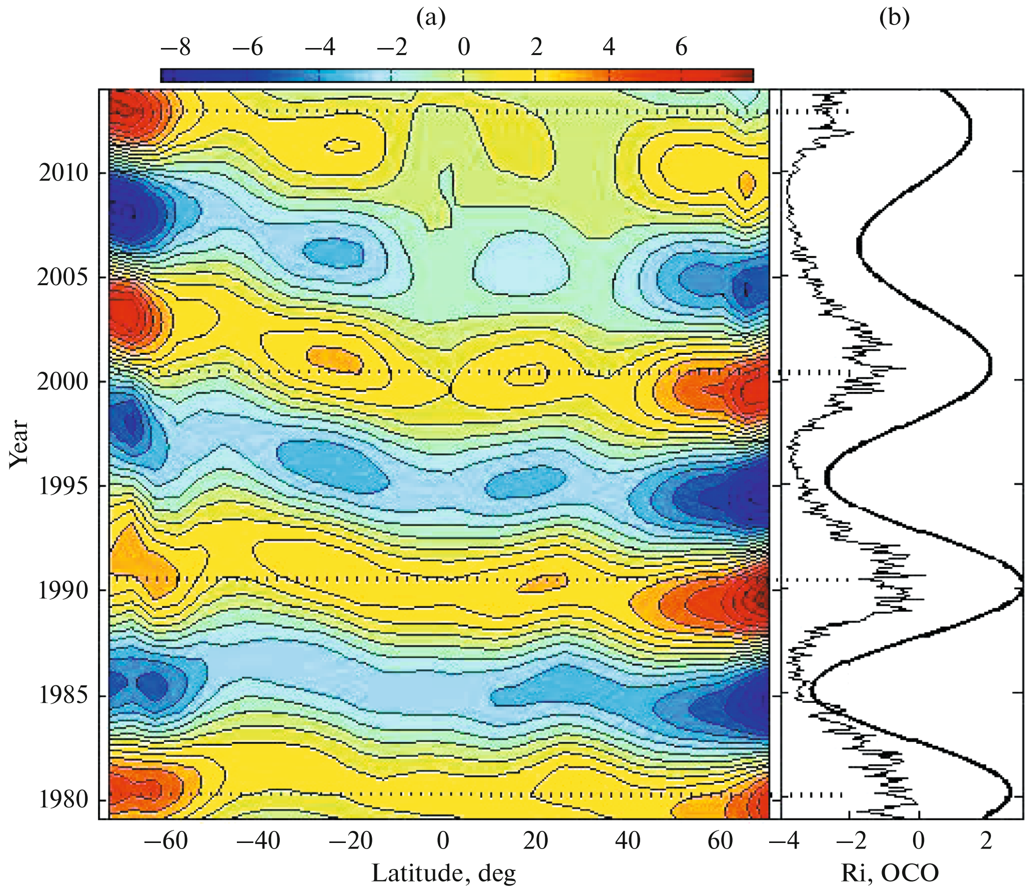

Fig. 2. (a) Quasi-decennial variations of the TOC average zoned series based on the V86 data; (b) globally averaged QDO TOC (DU) and solar spot index Ri (r.u.). Dashed–dotted lines are drawn through the SA maxima.

Brasser, 2007), the annual ozone-variation maxima at various latitudes can be in both phase and antiphase with the SA variations, and the phase relationships can vary with time. The variability of the phase relationships can also be noted between variations in the ratio of the ozone mixture and periodic SA oscillations in (Gruzdev, 2014) in the course of an analysis of the SBUV/SBUV2 data for 1978–2003.

According to the model calculations (Smyshlyaev et al., 2010), changes in the total ozone content from the minimum to the maximum of the 11-year solar cycle are largely dependent on the processes in the lower and middle stratosphere. Meanwhile, the indirect SA variation effects (changes in the atmosphere radiation, temperature, chemical-reaction velocity, and circulation processes) become more critical for the TOC seasonal–latitudinal variability. In the case of middle latitudes and average annual ozone contents, the effect of the SA variation from the minimum to the maximum has a positive sign in the Southern Hemisphere and a negative sign in the Northern Hemisphere.

According to Fig. 2a, a phase delay between QDO TOC grows with time in the middle and high latitudes of different hemispheres. Interpreting the time-growing phase delay is difficult and requires further studies. It should be just noted that the higher phase shift between QDO TOC in different hemispheres correlates with the lower SA level in the last solar cycles.

The QDO TOC phase shift between the Southern and Northern hemispheres, with averaging of the zonal mean values, should lead to phase shift compensation. Temporal variations in the average global QDO TOC values are shown in Fig. 2b. According to it, the quasi-decennial variation maxima coincide in phase with the SA variations for the globally averaged TOC values. A similar conclusion was made earlier (Bekoryukov et al., 2009) in an analysis of the globally averaged TOC values inferred from the ground-based measurement data on the period from 1964 to 2006. In (Zvyagintsev et al., 2015), on the basis of the satellite data for the period of 1979–2014, it was also concluded that the globally averaged TOC variations upon the exclusion of the trend component were mainly dependent on the 11-year solar-cycle modulation.

QDO TOC in the Polar Latitudes

The maximum TOC values are observed in the middle and high latitudes due to the ozone transfer

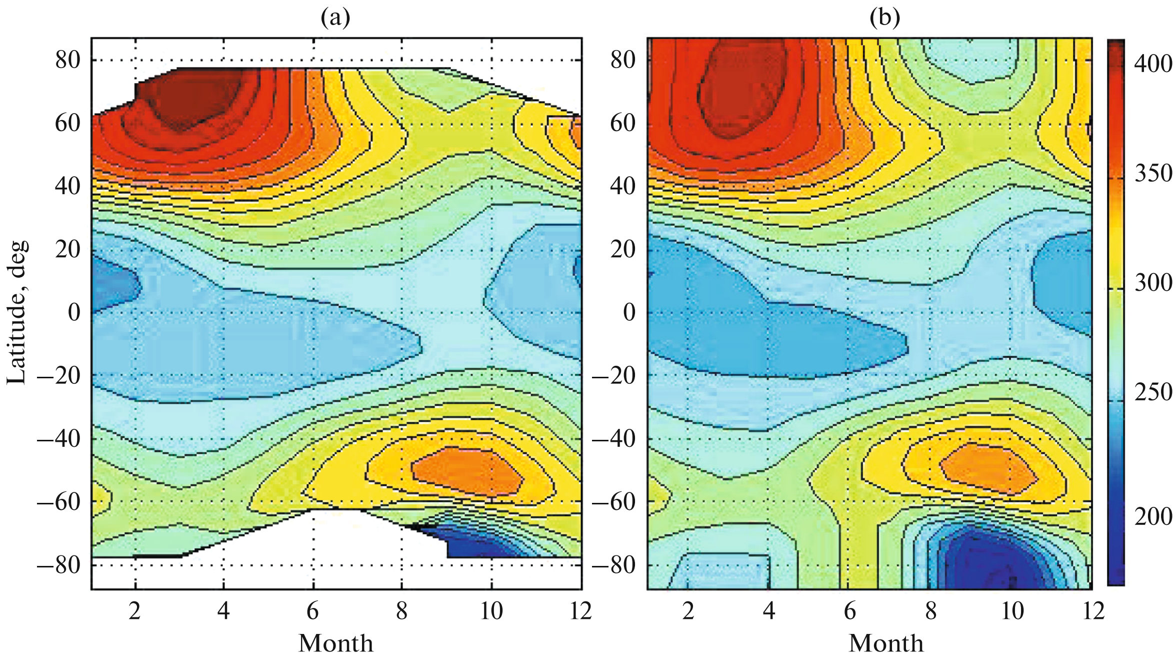

Fig. 3. Seasonal–latitudinal variations in TOC based on the V86 (a) and BS (b) data for the period of 1979–2011. Color scale, DU.

from the tropical stratosphere under meridional circulation. However, the SBUV and TOMS measurements are not carried out during the polar night, and the Bodeker Scientific Combined Total Column Ozone Database (BS) has been used to estimate the TOC variabillty in the high latitudes. Figure 3 shows V86 and BS latitudinal–seasonal variations averaged over the same period of time (1979 to 2011). The calculation results are in good agreement in the tropic and midlatitude regions (Visheratin and Kuznetzov, 2016). According to the BS data, the seasonal course in the southern subpolar latitudes is characterized by a low secondary minimum in February–March and a coincidence of this minimum with a maximum in the high northern latitudes.

According to Fig. 3, the TOC extrema occur in the subpolar regions. The quasi-decennial variations of the average total ozone in the latitudinal belts of 75°–90° N and 75°–90° S are compared in Fig. 4. The composite (Fig. 4a) and cross-wavelet analyses (Figs. 4b, 4c) results are in a relatively good agreement. The TOC variations in the Arctic Region are similar to those in the middle latitudes of the Northern Hemisphere (Fig. 1), but the phase shift between QDO TOC and SA in recent decades is more significant and close to an antiphase.

In the Antarctic Region, the QDO TOC maximum phase in 1990–2005 fell on the decay phase of the SA, while the minimum phase fell on the growth phase; however, the last TOC minimum in 2009 was close to the SA minimum. Similar specific features were also observed for the lower latitudes (Fig. 2). As follows from Fig. 4a, in recent decades the quasi-decennial oscillations of the TOC in the Arctic and Antarctic regions have occurred almost in an antiphase.

CONCLUSIONS

The spatio-temporal variability of the phase relationships between the 11-year SA cycle and quasi-decennial oscillations of TOC has been analyzed by composite and cross-wavelet analyses on the basis of the SBUV/SBUV2 (65° S–65° N) and Bodeker Scientific (90° S–90° N) databases. The TOC quasi-decennial variations in the range of 8–13 years inferred from the satellite data in the latitudinal belt of 45°–50° N are in a relatively good agreement with the ground-based data of the Arosa station in both oscillation amplitude and phase. The last QDO TOC minimum observed in 2004–2005 was ahead of the SA minimum in 2009 by 4–5 years, while the following TOC maximum falling in 2010–2011 was also ahead of the last SA maximum in 2013–2014.

The maxima of the quasi-decennial variations are consistent in phase with those of the SA variations for the globally averaged TOC values. According to the analysis data on the latitudinal course of QDO amplitude and phase for the zonal mean TOC series, the QDO amplitudes reach 6–7 DU in the high northern and southern latitudes and they do not exceed 2–3 DU in the tropic regions. The maximum phase of TOC coincides with that of SA in the tropic regions. The latitudinal course of the TOC variations is characterized by a delay in the quasi-decennial oscillation phase in the southern latitudes relative to the northern latitudes. The

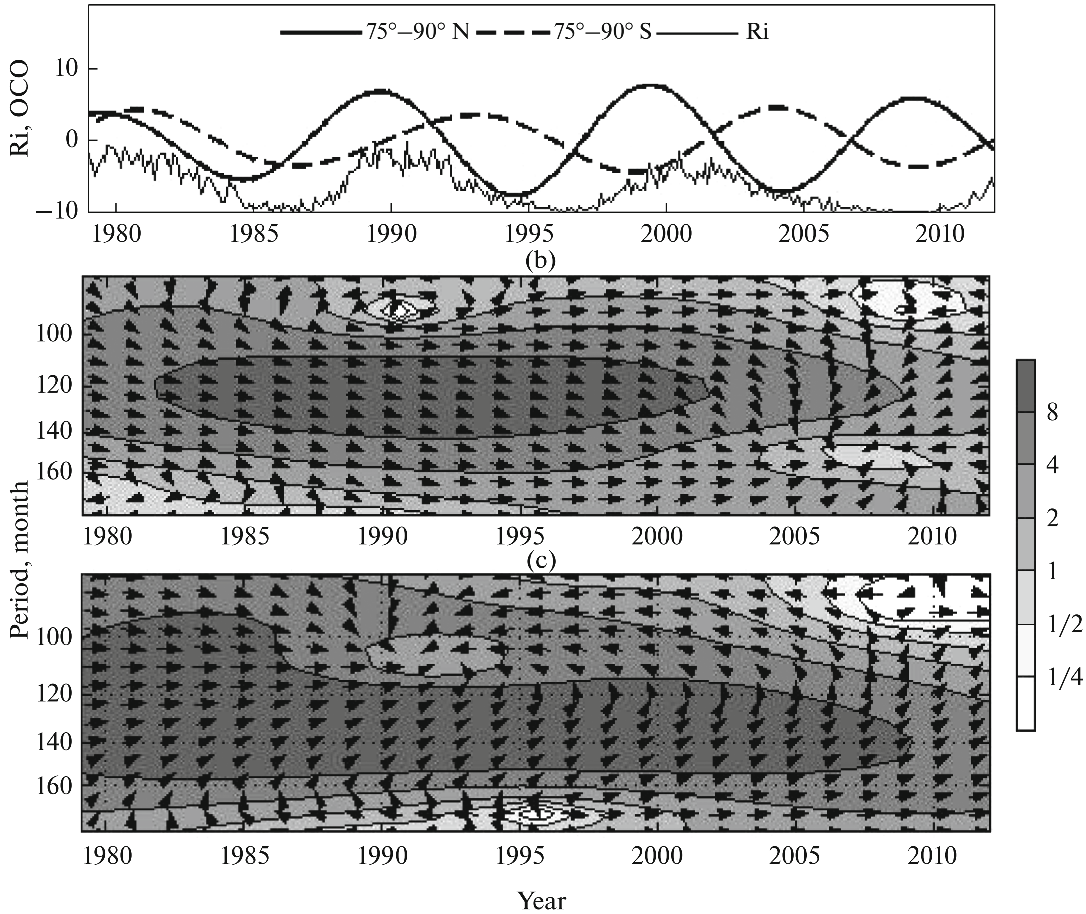

Fig. 4. (a) QDO TOC based on the BS data averaged for the latitudes of 75°–90° N and 75°–90° S (DU) and SA variations Ri (r.u.); (b, c) cross-wavelet analysis data on TOC and Ri for 75°–90° N and 75°–90° S, respectively. Confidence level in the period range of 120–130 months exceeds 90%. Arrows indicate the phase relationships (rightwards, TOC and Ri oscillations occur in the phase; leftwards, in the antiphase; downwards, TOC variations are ahead of Ri by 90°; upwards, they are behind by 90°).

TOC variations are ahead of the SA variations, on average, in moderate and high latitudes in the Northern Hemisphere, and they are behind the SA variations in the Southern Hemisphere. In the course of time, the phase delay grows between the QDO TOC maxima in the northern and southern latitudes.

The QDO TOC variations in the Arctic and Antarctic regions are similar to those in the middle latitudes of the Northern and Southern hemispheres. In the Antarctic Region, the QDO TOC maximum phase in 1990–2005 fell on the decay phase of the SA, the minimum phase fell on the growth phase, and the last QDO TOC minimum in 2009 was similar to the SA minimum. In the last two decades, the TOC quasi-decennial oscillations in the Arctic and Antarctic regions have occurred almost in the antiphase.

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