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USE OF SPACE INFORMATION ABOUT THE EARTH

Quasi-Decadal Variations of Lower Stratosphere Meteorological Parameters and Total Ozone Global Fields Based on Satellite Data

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Abstract—This paper presents the results of an analysis of the phase relationships between the variations of solar activity (SA) with periods ranging from 8 to 13 years and the quasi-decadal variations (QDVs) of zonally and globally average values of total ozone (TO), and some parameters of the lower stratosphere at 50 and 100 GPa based on the NCEP-NCAR and satellite data. Analysis of the temporal and spatial variability of meteorological parameters and TO has been performed by Fourier, correlation and composite analysis for the period from 1979 to 2015 in the 90° S– 90° N latitudinal belt. The TO spectra have basic oscillations with periods of 116–140 months at all latitudes. The oscillations with periods of 87–96 months are also observed at the high southern latitudes. Significant oscillations of temperature and geopotential height with periods ranging from 95 to 102 and from 127 to 148 months are observed in the 90° S– 55° N latitudinal belt. The oscillations of the meridional and zonal wind velocity have periods within intervals of 85–100 and 120–150 months; their significance varies with altitude. The maxima of the TO QDVs advance the SA maxima by 20 months at the middle and high north latitudes and lag behind by 21 months at the high latitudes of the Southern Hemisphere. The lag between the SA and TO variations reverses its sign at 35°–40° S. On average, the phase of the QDVs of temperature and geopotential height within the 90° S–55° N latitudinal belt lags behind the SA variations approximately by one year and half a year, respectively. The phase relationships between the meridional and zonal wind variations and the 11-year SA cycle vary considerably with time and latitude. The quasi-decadal variations of the globally average TO values coincide with the SA variations.

Keywords: total ozone content, temperature, geopotential height, meridional and zonal wind, lower stratosphere, quasi-decadal variations, solar activity, satellite data, spectral and composite analysis

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INTRODUCTION

The temperature regime and dynamical processes in the stratosphere are largely determined by the variations of total ozone (TO). The problem of the long-term, and, particularly, quasi-decadal variations (QDVs) of TO and the relations between them and the 11-year cycle of solar activity (SA) has been considered in a great number of publications based on statistical methods and calculations using different models (Krivolutskiy et al., 2015; Smyshlyaev et al., 2016; Chiodo et al., 2014; Knibbe et al., 2014; Harris et al., 2015; *WMO*, 2014). The main mechanisms of the SA effect on the ozone content and other atmospheric parameters are related to a direct impact of the variations of UV radiation with wavelengths below 250 nm on stratospheric ozone (the "top-down" mechanism) and the radiation forcing of the tropical region in the visible and near-IR spectral ranges (the "bottom-up" mechanism) (Kodera and Kuroda, 2002; Haigh and Blackburn, 2006; Gray et al., 2010; Roy, 2013). The mechanisms associated with geomagnetic activity and variations of cosmic ray flux were considered in some works (Dergachev, 2015; Kovalenko and Zherebtsov, 2014; Jackman et al., 2016). The estimates obtained by different authors on the basis of climatic models show that along with the direct effect of the SA variations on ozone, a particular significance is attributed to the feedbacks associated with the temperature regime changes, the rates of chemical reactions, and the circulation characteristics of the atmosphere. According to the majority of recent publications and the WMO report (2014), the QDVs of TO conditioned by the SA variations are estimated to be about 2–3% and occur approximately in phase with the 11-year solar cycle. At the same time, it was previously shown (Visheratin, 2007, 2012, 2016) that the spectral composition of the TO variations may change both in space (with latitude) and in time; the TO QDV maxima can lead the SA maxima or lag behind them. Using the example of the Arosa station situated at the middle latitudes of the Northern Hemisphere (Visheratin, 2016), it was shown that the phase relationships between the SA and meteorological parameters of the lower stratosphere and troposphere also vary with time and altitude.

The aim of this work is to analyze the quasi-decadal variations of global fields of meteorological parameters and circulation characteristics of the lower stratosphere. The novelty of our work consists in our consideration of variations of zonal and meridional wind velocities, geopotential height, and temperature all over the Earth (90° N–90° S); the analyzed period (1979–2015) includes the "anomalous" 23th and current 24th cycles of solar activity. One of the aims of this work is to analyze the total ozone content data completed up to 2015.

DATA AND METHODS OF ANALYSIS

Initial Data

To analyze the TO variations, we used the SBUV Merged Total And Profile Ozone Data Sets, Ver. 8.6, (Frith et al.) designated below as V86. This satellite database covered a region from 65° north latitude to 65° south latitude and a period from January 1979 to December 2015. We used the monthly average values of TO with a latitudinal step of 5° in our calculations. Some omissions (1–3 months) at the middle latitudes and seasonal gaps at the high latitudes in both hemispheres were completed by cubic interpolation. In addition, we used the Bodeker Scientific Combined Total Column Ozone Database (designated below as BS) for 1979–2011, covering the Earth's entire surface (90° N–90° S) with almost no omissions (Bodeker et al., 2013). On the basis of the NCEP–NCAR database (Kistler et al., 2001), the zonal mean monthly values of temperature (*Tm*), meridional (*Um*) and zonal (*Vz*) wind velocities, and geopotential height (*HP*) for the isobaric surfaces of 50 and 100 GPa were formed. The International Sunspot Number (Ri) was used as a solar activity index (WDC-SILSO, 2016).

Methods for Data Analysis

Spectral analysis of all initial series for the identical period of time (January 1979–December 2015) was performed using the Lomb–Scargle modified Fourier transform; the estimates of the oscillation significance in the spectral range for 8–13 years were obtained, according to the procedure described in (Scargle, 1982; Baluev, 2008). The analysis of the BS series was carried out for the period from 1979 to 2011. Preliminarily, we excluded the linear trend, annual oscillation, and its harmonics from all analyzed series except for the solar activity index. As an example, the initial time series and amplitude spectra for the 0°–5° N latitudinal belt are shown in Fig. 1.

To estimate the phase relationships between the series of TOC, meteorological parameters, and solar activity index, the filtration of the initial series was performed. For that, the arrays of Fourier transform coefficients obtained as a result of spectral analysis in a period interval of 8–13 years were used to form the time (composite) series containing only the oscillations in this spectral range by means of the inverse Fourier transform (Visheratin, 2007, 2016). For the periods of 8–13 years, the error of this method in determining the extremum positions of the composite series at the time axis is about half a year; at the ends of the composite series, the error increases approximately up to a year in some cases. The error in determining the extremum amplitudes is about 10% (Visheratin, 2016).

RESULTS OF ANALYSIS

The latitude-time behaviors of the QDVs of TO and the lower stratosphere parameters (LSPs) for the 90° S–90° N latitudinal belt are shown in Fig. 2. The TO QDVs are presented separately for the BS and V86 data, since they cover different time intervals and latitudinal regions. The QDVs of meteorological parameters for the levels of 50 and 100 GPa differ insignificantly, therefore, we present the data of analysis only for a level of 50 GPa.

In Fig. 2, the values of the lags (delays) corresponding to the maximum coefficients of correlation between the TOC, LSPs and Ri temporal series for each latitudinal region are presented. The values of the lags varied from –70 to 70 months. The lags were considered significant (at a level of 0.05) if, firstly, for a given latitudinal interval, the spectral components were significant (within an interval of 8–13 years) and, secondly, the coefficients of correlation between the QDVs of atmospheric parameters and SA were significant. It should be emphasized that the values of lags for each latitudinal region shown in Fig. 2 are the average value for the entire time interval analyzed in this work. For the shorter time periods and other time intervals, the values of lags and the phase relationships between the series may change. Therefore, it is complicated to estimate the real error for the presented values of lags, especially in cases when the phase relationships are nearly in counterphase (the lags are about 40–50 months). The errors of lags presented below are the root-mean-square deviations of the average lag for the broad latitudinal region. Let us consider in more detail the peculiarities of the temporal and spatial variability of the QDVs of TOC and lower stratosphere parameters.

Total Ozone Content

The feature of the TO QDVs is that they advance the SA variations at the middle and high latitudes of the Northern Hemisphere, occur approximately in phase with the SA variations in tropical regions, and lag behind the SA variations at the middle and high latitudes of the Southern Hemisphere (Visheratin, 2012, 2016). For comparison, Figs. 2a and 2b show the TO QDVs according to the BS data for a period from 1979 to 2011 and the V86 data covering a period from 1979 to 2015, i.e., the previous 24th cycle of solar activity with the maximum in 2012–2014. According to Fig. 2, the latitudinal distribution of the TO QDVs and the latitudinal behavior of the lags obtained from

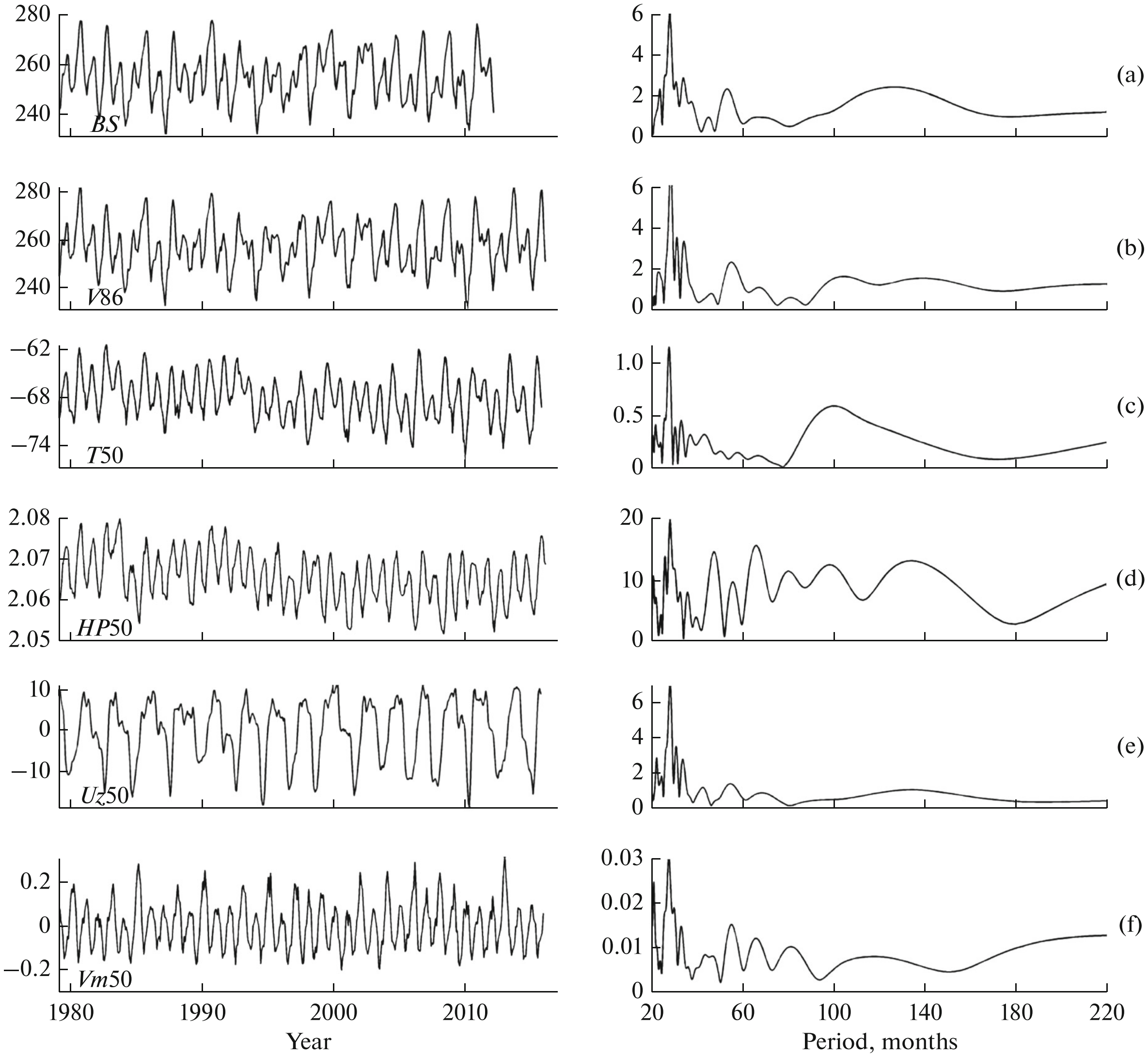

Fig. 1. Time series and spectra for the 0°–5° N latitudinal belt: (a) TO according to the BS data: time series (DU) for 1979–2011 (on the left), amplitude spectra (DU) for periods of 20–220 months (on the right); (b) the same for TO according to the V86 data for 1979–2015; (c) temperature time series (°C) and amplitude spectrum (°C) at a level of 50 mbar; (d) the same for the geopotential height (GPa, the values for the temporal series are reduced to 1/10000); (e) the same for the zonal wind velocity (m/s); (f) the same for the meridional wind velocity (m/s).

the BS and V86 data demonstrate a good agreement. To the north from 45° N, the phase of the TO QDVs advances that of SA variations on average by 20 months; to the south from 75° S, it lags behind by 21 months. In the 30° S–30° N tropical region, the advance is 6–7 months; at about 35°–40° S, the lag reverses its sign. A relatively gradual change in the phase of the TO QDVs with latitude is violated in the Southern Hemisphere, in the Antarctic region. In this region (near 60° south latitude), an abrupt phase shift of the seasonal TO course occurs, which is related to the isolation of the Antarctica continent by the circumpolar vortex (Visheratin and Kuznetsov, 2016). It should also be noted that at the same time, the spectral structure of the TO variations in this regions changes. For the majority of the latitudinal regions, the TO variations occur mainly within an interval of 116–140 months, while in the regions located to the south, at 40°–45° S, the oscillations gradually shift to values of 140–145 months and the amplitude of the oscillation with a period of 87–96 months becomes larger. The maximum amplitudes of the TO QDVs, up to 7–8 DU (Dobson units), are observed at the high latitudes of the Northern Hemisphere; the minimum, 2–3 DU., in the equatorial region. For the globally average data, the phase of the TO variations approximately coincides with that of the SA variations.

Temperature and Geopotential Height

The latitudinal distributions of QDVs of temperature (Fig. 2c) and geopotential height (Fig. 2d) have similar features. At the high latitudes of the Southern

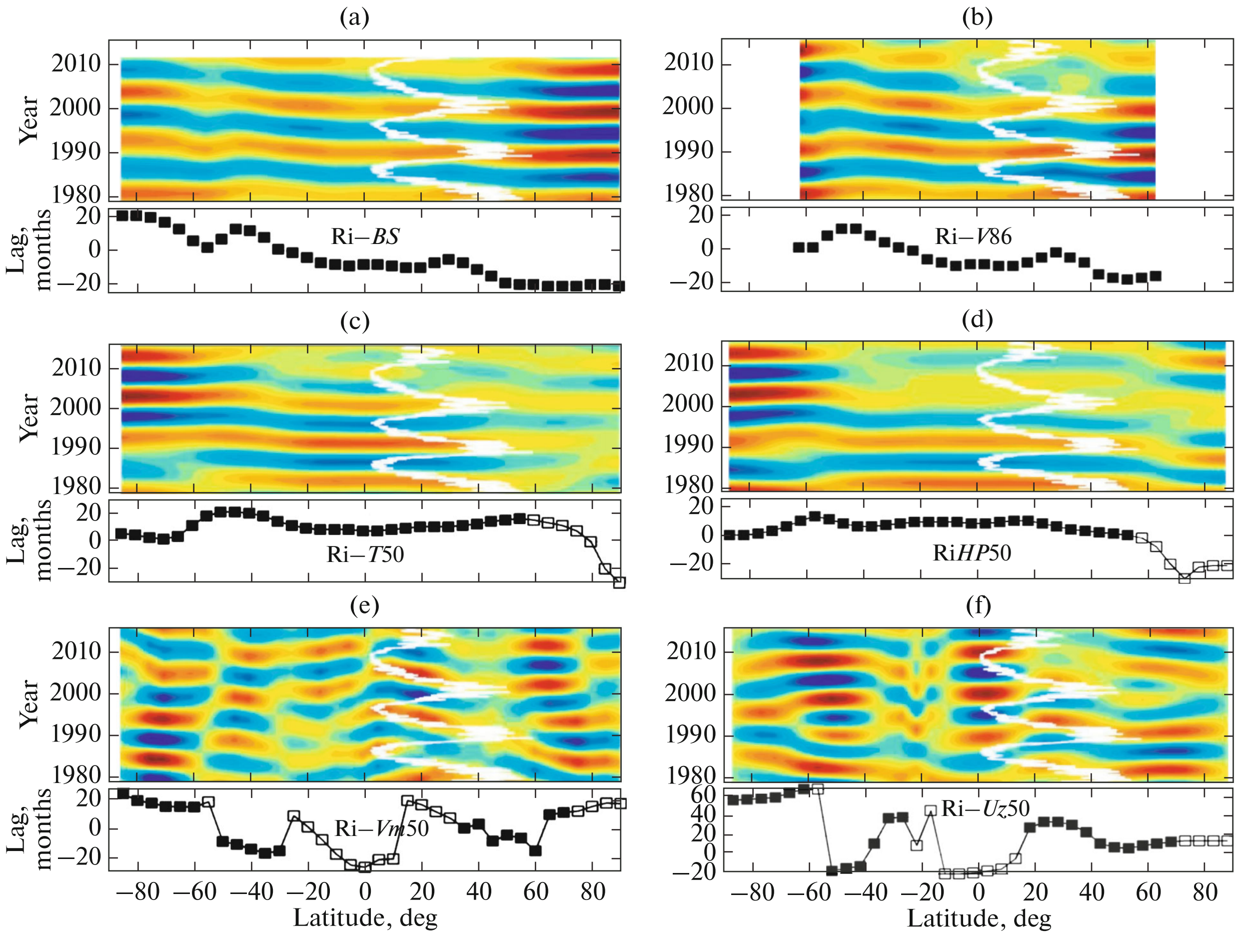

Fig. 2. Latitude-time quasi-decadal variations of TO (BS and V86 data), temperature (*T*50), geopotential height (*HP*50), meridional (*Vm*50) and zonal (*Uz*50) wind ((a), (b), (c), (d), (e), (f), respectively) (upper figs., rel. un.) and latitudinal behavior of lags (months) between the variations of solar activity index Ri and lower stratosphere parameters (lower figures). The values of lags correspond to the maximum coefficients of correlations between Ri and zonally average series of parameters. Positive lags mean that the SA variations advance those of atmospheric parameters. The values of lags significant at the 95% level are shown by filled squares. The white line on the upper figures shows the variations of solar activity index Ri.

Hemisphere, the variations of SA, *T*, and *HP* occur approximately in phase. At the high latitudes of the Northern Hemisphere, the variations of *T* and *HP* advance those of SA by 20–30 months. In the tropical region, the variations of temperature and geopotential height lag behind the SA variations by 9–10 months. The significant oscillations are located to the south from 55° N and their periods lie within intervals of 95–102 and 127–148 months. To the north from55° N, the QDVs of *T* and *HP* are insignificant. This phenomenon can apparently be explained by the fact that in this latitudinal belt, the amplitudes of quasi-biennial oscillations and those with periods of about 22–24 years increase and conceal the QDVs. A significant influence of the quasi-biennial oscillations at high northern latitudes and the difficulty in separating the solar signal in the temperature and geopotential fields were noted previously (Labitzke, 1987). On the whole, for a region from 90° south latitude to 55° north latitude, the average value of the temperature phase lag is 12 ± 4 months; for the geopotential height, the lag is smaller, namely, 6 ± 4 months for the same latitudinal belt. The maximum QDV amplitudes are observed at the high southern latitudes, their values are 0.9–1°C for the temperature and 50–55 gpm for the geopotential height. The minimum QDVs of temperature, 0.2–0.3°C, are observed in the 30°–55° N region; the minimum QDVs of geopotential height, 12–15 gpm, in the 35° S–55° N region. For the globally average data, the phases of QDVs of temperature and geopotential height lag that of the SA variations by two and nine months, respectively.

Meridional and Zonal Wind

The latitudinal distribution of the periods and amplitudes of the quasi-decadal oscillations of meridional and zonal winds, as well as their significance, change within large limits, which is illustrated in Figs. 2e and 2f. In the latitudinal distribution of the QDVs of meridional wind, we can separate some latitudinal intervals, in which the oscillation maxima are observed: near 60°–80°, 40°–45°, 5°–15° south latitude and 15°–25°, 60°–70° north latitude. Over the analyzed 36-year period, the shift of the centers of these regions to the lower latitudes is remarkable. It should be noted that the maximum positions of the *Vm* QDVs are likely related to the zones of wind direction changes. Within the 50°–70° S and 15°–50° N intervals, the main wind direction is southern (with a nearly antiphase seasonal behavior), while within the 15°–45° S interval, the wind is predominantly northern. In the 50°–65° N region, the wind changes its direction during a year, at that, the velocities of the north wind are maximal. The phase relationships vary from one interval to another. The meridional wind variations occur in antiphase with those of SA to the south from 60°S and advance the SA variations in the 20°–50° N interval. In the tropical regions, the lags are insignificant, which is associated with the insignificance of the correlation coefficients because of the growth of the amplitudes of quasi- biennial variations in this region and a relative smallness of amplitudes of the *Vm* QDVs (Fig. 1f). In different latitudinal regions, the *Vm* oscillation periods vary within intervals of 85–100 and 120–150 months. The amplitudes of *Vm* QDVs are maximum (up to 0.02 m/s) in the 70°–80° S region and minimum in the tropical regions (0.005—0.007 m/s).

Like in the case of the meridional wind, the phase of QDVs of zonal wind varies significantly with time from one zone to another. The oscillations in the zonal wind spectra are mainly concentrated in intervals of 85–105 and 120–150 months. With the exception of the tropical region, the zonal winds have predominantly a western direction with the maximum amplitudes of about 1 m/s in the 45°–70° S latitudinal belt and in the equatorial region. The amplitudes of the zonal wind QDVs are minimum (0.2–0.3 m/s) in the 30°–50° N region. The zonal wind variations occur in counterphase with those of SA to the south from 60° S; they advance the SA variations in the 40°–55° S interval and their phases are close in the 40°–50° N interval. In the Southern Hemisphere, there is apparently a double system of extrema—over the Antarctica and in the neighboring area (Fig. 2f). To the south from 60°–70° S, the amplitudes of oscillations with a period from 125 to 135 months are larger; to the north, they are comparable to the amplitudes of oscillations with periods of 96–105 months or smaller than these amplitudes. The insignificance of the lags in the tropical region has the same reasons as those for the meridional wind (Fig. 1e).

DISCUSSION

The above-presented results of the comparison of the phase relationships between the 11-year cycle of solar activity, the lower stratosphere parameters, and the total ozone content show that along with the positive lags, there are such latitudinal regions and time intervals, for which the lags are negative. If it is possible to find a physical explanation for the lags of the TO response to the SA variations (positive lags), it is quite complicated to imagine the mechanisms conditioning the advance of the quasi-decadal variations of TO relative to those of SA. One of the reasons of the TO modulation by the SA variations is, possibly, the decadal variations of the Brewer–Dobson circulation (Hood and Soukharev, 2012; WMO, 2014). According to current conceptions, ozone generated in the equatorial region is transported to the high latitudes due to the Brewer–Dobson circulation for several years (Weber, 2011).

A separate analysis of the influence of the direct and indirect effects of the solar radiation variation on the temperature regime, stratosphere composition, and circulation processes was performed by using the chemisty-climate models in the works (Smyshlyaev et al., 2005, 2010). The estimates of the indirect effects' influence (gas composition redistribution due to the changes in the temperature and rates of chemical reactions and due to the changes in the circulation conditioned by radiation heating) have shown that this influence has different signs in the middle latitudes of the northern and southern hemispheres. It is interesting that the latitudinal behavior of the TO lags (Fig. 2a) and that of the TO annual average response to the SA variations from the minimum to the maximum of the 11-year cycle (Fig. 7, Smyshlyaev et al. 2010) have common peculiarities. From the latitudes with the maximum positive response at 60° S, the values of the TO response are relatively gradually decreasing to the maximum negative responses approximately at 40°–60° N. The reverse from positive to negative values occurs in the 35°–40° S latitudinal belt, i.e., in the same region where the lag signs reverses from positive to negative. According to (Smyshlyaev et al. 2010), different signs of responses are likely associated with a considerable TO reduction in the middle and high latitudes during the first half of a year, when the TO is maximum in its annual behavior.

The problem of negative lags or advance of the TO QDVs relative to the SA maxima, can likely be solved by assuming (Visheratin, 2012) that the maximum TO response to the SA variations is related not to the average position of the SA maximum, but to the final phase of the SA rapid growth at the beginning of each cycle. Since the period of the maximum solar activity lasts for three-four years, the backward shift of the fixed points by 18–24 months will lead to the situation where for the data presented in Fig. 2a, at high northern latitudes, the TO and SA variations will occur approximately in phase, while at the high southern latitudes, the lag will be about 40 months, i.e. the delay will be less than a half-cycle. At such a shift, the negative shifts of temperature, geopotential height, and zonal wind will decrease or disappear.

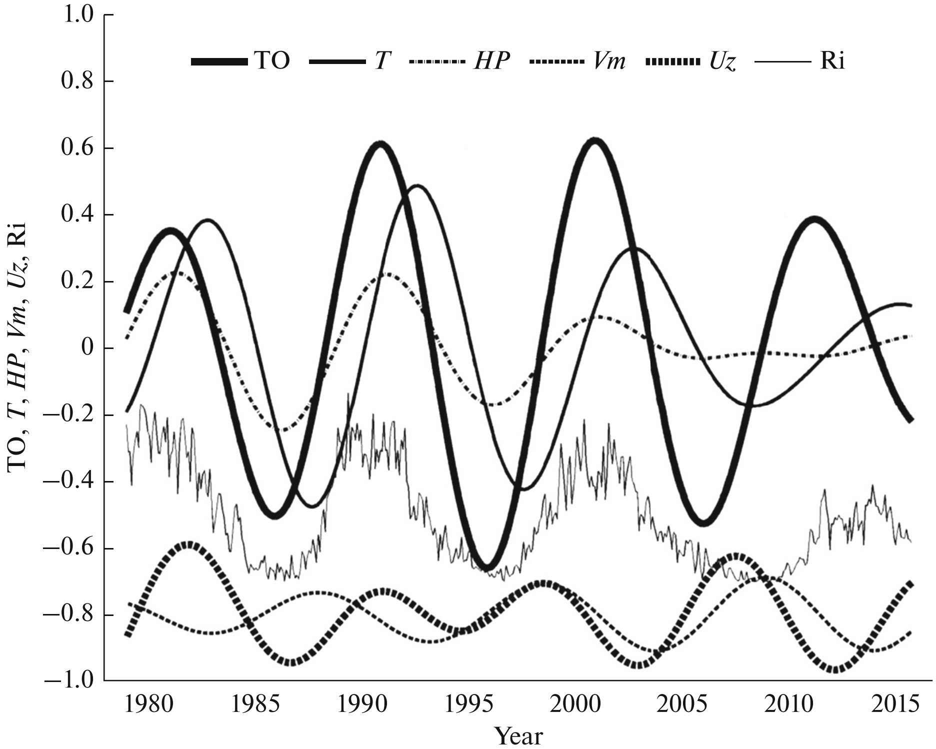

Fig. 3. Quasi-decadal variations of TO and lower stratosphere parameters in the 35°–40° S latitudinal belt. For a better visibility, the values of TO (DU) and zonal wind (*Uz*, m/s) are reduced to one fifth and to a half, respectively; geopotential height (*HP*, gpm) and meridional wind (*Vm*, m/s) are multiplied be factors 10 and 15, respectively. The graphs for the wind velocities are shifted along the ordinate axis. The solar activity index Ri (rel. un.) is also shown.

The phase shift of the QDVs of a parameter, that has its proper decadal variations, relative to the phase of a forcing action (in particular, SA) may also be obtained with the help of the forced oscillator model (Gusev and Martin, 2012; Visheratin, 2012) due to the reverse of the sign of the difference between the frequencies of the forced oscillation and self-oscillation. However, to use this model for the spatially dispersed series (latitudinal belts), it is necessary to fit the frequency of the self-oscillation of the atmospheric parameter and some other parameters for each latitudinal belt. Weng, 2012, proposed a model consisting of a sum of "multiplicative" parts. It is interesting that in this model, the QDVs of the atmospheric parameter may both lag and advance the variations of the forcing parameter (solar activity), at that, the response's sign and amplitude significantly depend on small changes in the amplitude of the annual oscillation of the atmospheric parameter. Similar to the model discussed previously, several parameters require fitting.

The values of lags presented in Fig. 2 are the average estimates over the entire 1979–2015 period. The detailed analysis of the temporal behavior of the QDVs of TO and meteorological parameters shows that the phase relationships between them and the SA variations change not only with latitude but also with time. As an example, the QDVs of TO and other parameters for the 35°–40° S are shown in Fig. 3. The TO maxima approximately coincide with the end of the SA maximum phase in the 21th–23th cycles and with the beginning of the SA maximum phase in the 24th cycle. In the equatorial zone, an additional TO maximum (in counterphase) is observed in the 2005–2009 period. For the longest TO series (Arosa station), the phase relationships between the SA variations and the TO QDVs are such (Visheratin, 2016) that up to 1960, the TO QDV maxima lagged behind the corresponding SA level maxima; within a period of the 1970s (the 20th SA cycle), nearly synchronous variations were observed, while during the consequent solar cycles, they started to advance the SA maxima.

The phase relationships between the variations of other low stratosphere parameters presented in Fig. 3 and those of SA are different. These differences are most likely related to the fact that the variability of meteorological and circulation parameters is determined not only by a direct effect of the SA variations but also by the TO variations. According to Fig. 3, the temperature maxima lag behind the TO maxima by approximately two–three years and are in antiphase with the zonal wind variations. These relationships vary with latitude and likely with altitude. The phase variations from –90° to 90° between the 11-year SA cycle and the ozone mixture ratio in the middle stratosphere were noted in (Gruzdev, 2014); they are supposedly related to the dynamic processes. In (Gray et al., 2013), it was found that the variations of equatorial stratopause temperature advance those of SA. One of the possible explanations proposed by the authors is the existence of feedbacks related to the ocean temperature variability and the generation of tropospheric waves propagating from the troposphere to the stratosphere. For the middle latitudes of the Northern Hemisphere (Arosa station) the phase relationships between the SA and temperature, meridional and zonal wind velocities, and geopotential height vary with altitude (20–925GPa) (Visheratin, 2016).

The variability of phase relationships with time might be explained by the fact that for all considered parameters, the spectral composition of oscillations in a range of 8–13 years contains a "short-period" (85–105 months) and a "long-period" (120–140 months) components. The long-period oscillation has approximately the same period as that of the SA oscillations (Visheratin, 2012), whereas the short-period component may be conditioned by the self-oscillations of the atmosphere–ocean system or the second harmonic of the nutation period (18.6 years) of variations of coming solar radiation (Fedorov, 2015). The variability of the amplitudes (and frequencies) of these oscillations can generate the interferential effects that may influence the variations of the phase and amplitude of the resulting temporal series of atmospheric parameter.

CONCLUSIONS

We performed an analysis of the phase relationships between the QDVs of SA and the QDVs of zonally average (with a 5° latitudinal step) and globally average values of some parameters of the lower stratosphere and the QDVs of TO in the 90° S–90° N latitudinal belt. Our analysis of the time and temporal variability of the global fields of the QDVs of meteorological parameters and TO by the Fourier methods, as well as the correlation and composite analysis, have shown that the phase relationships between the QDVs of SA and those of zonally average parameters of the lower stratosphere can vary considerably with altitude, which is related to the variability of the spectral composition of oscillations within an interval of 8–13 years with latitude. Over a period of 1979–2015, in the TO spectra in all latitudinal regions, the fundamental oscillation has a period of 116–140 months; at the high southern latitudes, the amplitude of oscillations with periods of 87–96 months increases. In the spectra of temperature and geopotential height (50 and 100 GPa), the significant oscillations with periods of 95–102 and 127–148 months are located in the 90° S– 55° N latitudinal belt. The meridional and zonal wind oscillations have periods within intervals of 85–100 and 120–150 months, whose significance changes with altitude. The phase of the TO QDVs advances that of the SA variations on average by 20 months at the northern middle and high latitudes and lags behind them by approximately the same value at the southern high latitudes. The lags reverse their sign from negative to positive approximately in the 35°–40° S region. The significant coefficients of correlation between the SA and temperature and between the SA and geopotential height are observed in the 90° S–55° N latitudinal belt. As distinct from the case of TO, no noticeable shift of the QDV phase with altitude was observed. In this latitudinal belt, the phase of temperature lags behind that of SA on average approximately by one year; the phase of geopotential height, by six months. The phase relationships between the QDVs of meridional and zonal wind and the11-year SA cycle vary considerably with time and latitude. The globally average QDVs of TO coincide in phase with those of SA. On the whole, the comparison of phase relationships shows that the periods of variations of the total ozone and atmospheric parameters are shorter than that of solar activity, which is likely conditioned by the interference of oscillations within intervals of 85–105 and 120–140 months in the majority of the considered series.

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