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Modeling Residual Meridional Circulation at Different Phases of the Quasi-Biennial Oscillation

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Abstract—The sensitivity of the residual meridional circulation (RMC) in the middle and upper atmosphere to the phase change of the quasi-biennial oscillation (QBO) of the low-latitude zonal wind in the stratosphere has been studied. Wind and temperature data obtained from a nonlinear numerical model of general circulation of the middle and upper atmosphere (MUAM) have been used to calculate the RMC. For the first time, statistically significant results have been obtained illustrating the change in wave-induced eddy flows in the extratropical strato–mesosphere at different QBO phases. Specifically, a general weakening of the eddy circulation in the Northern Hemisphere at the westerly QBO phase has been demonstrated, with the exception of the region located at midlatitudes in the altitude range of 50–60 km. The study of the RMC sensitivity to changes in QBO phases helps better understand the features of the dynamic interaction between tropical and extratropical latitudes, as well as different atmospheric layers that affect the circulation transport and mixing of long-lived atmospheric components.

Keywords: numerical modeling, residual meridional circulation, quasi-biennial oscillation

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1. INTRODUCTION

The circulation transport of gas species between the middle atmosphere and the troposphere affects the overall distribution of climatically active atmospheric gases. The main mechanism of the global transport of conservative admixtures [1] between the stratosphere and troposphere is the meridional Brewer–Dobson circulation (BDC) [2, 3], associated with global mass transport, when the tropospheric air enters the stratosphere in the tropics, then moves to the poles, and goes down at middle and high latitudes. At mesospheric heights, one traditionally considers the mesospheric meridional circulation implying the mass transport from the summer to the winter hemisphere [4].

It is known that, with the Eulerian mean meridional circulation, i.e., when meridional and vertical circulation flows are zonally averaged under the condition of stationarity and horizontal homogeneity of the hydrodynamic fields, the equations of dynamics have the feature that the eddy flexes of momentum and heat are compensated by advective fluxes of momentum and heat [5]. This feature does not allow the direct wave influence on the mean flow to be identified and diagnosed. In the Eulerian approach, the wave and mean fluxes are also compensated in the continuity equation for long-lived gases; thus, the use of the Eulerian mean meridional circulation is inefficient for calculating their transport [6].

To overcome this drawback, one traditionally uses alternative approaches to the analysis of the zonal-mean circulation, such as the mass (diabatic) circulation [7], the transformed Eulerian mean circulation [8], and the Lagrangian-mean circulation [9]. In this study, we used the approach in terms of the transformed Eulerian-mean circulation, first introduced in [8], which provides an efficient diagnostics of the wave effect on the mean flow and can assess the transport of gaseous admixtures in the meridional plane. This approach is based on the mean residual meridional circulation (RMC), which is a combination of eddy and advective mean transports. The residual circulation calculated using this approach makes it possible to estimate the mean flow fraction, whose contribution to the adiabatic change in air temperature is not compensated by the divergence of the wave-induced heat flux [10]. Atmospheric motions in the RMC at middle and high latitudes have a strong seasonal cycle with large interhemispheric differences. Specifically, to analyze the RMC structure, researchers introduce the concepts of tropical upwelling and extratropical downwelling in the stratosphere, which constitute an integral mass flux in the lower stratosphere and characterize the total strength of the RMC [11–13]. Here, the boundaries of the tropical upwelling region in the lower stratosphere (i.e., the latitudes where the vertical residual velocity changes its sign from positive to negative) are defined as turnaround latitudes [14]. In solstice seasons, the tropical upwelling region moves towards the summer hemisphere (see Fig. 4a in [15]).

The quasi-biennial oscillation (QBO) of equatorial zonal wind is an important characteristic of the middle atmosphere dynamics [16, 17]. The zonal wind reverses its direction with a frequency of almost two years. The QBO period varies from 22 to 34 months with an average of 28 months. The zonal wind speeds peak at altitudes of 20–30 km: around 20 m/s for an eastward zonal wind and around –30 m/s for a westward zonal wind. The boundary between the eastward and westward winds goes down with time at a rate of ~1 km/month. Although the QBO is a dynamic process occurring in the stratosphere near the equator, its effect as a quasi-biennial periodicity is observed in all hydrodynamic fields at all latitudes and heights [16, 18]. The study [19] concluded that the QBO effect at high latitudes may be associated with induced changes in the thermally balanced subtropical jet and the related refractive index, which limits the propagation of Rossby waves in the subtropics, increasing wave activity and global meridional circulation.

In this study, we simulate the general atmospheric circulation for January at the easterly and westerly phases of the QBO. Using wind and temperature data, we calculated the vertical and meridional components of the RMC, as well as the differences in the RMC components between the QBO phases, interpreted as a result of the dynamic effect of the QBO on the residual circulation. This is the first detailed study of the QBO effect on residual circulation (in particular, on the eddy contribution to the meridional circulation induced by planetary waves) up to lower thermospheric heights (up to 100 km) yielding statistically reliable results. The use of the Eulerian mean and residual meridional circulation makes it possible to estimate both the total circulation transport of atmospheric gases and the contribution of wave processes in the middle and upper atmosphere to this transport.

2. METHODOLOGY

To investigate the dynamic effect of QBO in the atmosphere, in this study we use the MUAM three-dimensional nonlinear mechanistic numerical model of the general circulation of the middle and upper atmosphere [20, 21], one of the most actively developed Russian models of wave atmospheric dynamics in recent years (see [22–26] and references therein). The MUAM model is based on the standard system of primitive equations in a spherical coordinate system [27]. The main parameters calculated by the model are the zonal, meridional, and vertical velocity components, as well as geopotential and temperature. The horizontal grid steps of the model are 5.625° by longitude and 5° by latitude. The vertical grid of the model is the log-isobaric coordinate $z = -H\ln(p/p_0)$, where p_0 is the surface pressure and $H = 7$ km. We used the model version with 48 vertical levels corresponding to the height range from the Earth's surface up to 135 km. The time step is 450 s. The MUAM model can reproduce quasi-stationary planetary waves propagating eastward and westward with periods of 2–16 days [28]. The model also parameterizes the dynamic and thermal effects of gravity waves of nonorographic origin [29, 30]. The thermal and dynamic effects of mesoscale orographic waves are taken into account using the orographic wave parametrization developed by Gavrilov and Koval [31]. The propagation of orographic gravity waves (OGWs) into a dissipative vertically inhomogeneous atmosphere leads to an energy exchange between the background flow and waves, as well as to the heating of the atmosphere due to the wave energy dissipation. To calculate total wave energy flux F_E, wave acceleration $a_{w\xi}$ along the ξ-axis directed along the horizontal wave vector $\mathbf{m}$, and the total velocity of the thermal effect ε_w generated by stationary OGWs with observed frequencies $\sigma = 0$, Gavrilov and Koval [31] obtained polarization relations, taking into account the rotation of the atmosphere, and obtained the following expressions:

$$
\begin{gathered}
F_E = -\frac{\bar{\rho} f^2 U^2}{2mk\bar{v}_\xi}; \quad k^2 = \frac{N^2}{\bar{v}_\xi^2}\left(1 - \frac{f^2}{m^2\bar{v}_\xi^2}\right)^{-1}, \\
a_{w\xi} = -\frac{k^2 U^2}{2\bar{v}_\xi}(\nu + K_z)\left(1 + \frac{1}{(\gamma - 1)\,\mathrm{Pr}}\right), \qquad (1) \\
\varepsilon_w = (\nu + K_z)\delta k^2 U^2, \quad \delta = \frac{f^2}{m^2}\frac{\partial}{\partial z}\left(\frac{\partial \bar{v}_\xi^2}{\partial z}\right)^{-1},
\end{gathered}
$$

where ν and K_z are the coefficients of kinematic and turbulent viscosity, respectively; m and k are the horizontal and vertical wave numbers, respectively; v_ξ is the wind velocity along the ξ-axis; ρ is atmospheric density; f is the Coriolis parameter; Pr is the effective Prandtl number; N is the Brunt–Väisälä frequency; $\gamma = c_p/c_v$ is the ratio of heat capacities; and δ is a coefficient depending on the vertical gradient of average horizontal velocity [31]. The calculated heat influxes generated by OGWs are added to the heat balance equation in the MUAM model, and the zonal and meridional components of the wave acceleration are added to the MUAM equations for the respective velocity components. The OGW parameterization allows one to most accurately—in comparison with the existing analogs (their review can be found in [32])—calculate the energy and dynamic contributions of OGWs taking into account the rotation of the atmosphere.

A detailed description of the processes and numerical schemes taken into account in the current version of the model can be found in [26].

Various Phases of QBO in MUAM. To reproduce the QBO in the MUAM model, Pogoreltsev et al. [28] proposed an additional term in the momentum equation for the zonal wind proportional to the difference between calculated and observed zonal-mean values at latitudes between 17.5° S and 17.5° N and at heights from 0 to 50 km. The reanalysis data of the UK Met Office [33] were used to choose individual years with westerly and easterly QBO phases and calculate the average zonal-mean distributions of the zonal wind and temperature for both QBO phases. It was shown that data for ten years are enough to record the reliable climatology of meteorological fields [34]. The temperature and geopotential fields obtained from reanalysis data of the UK Met Office and averaged over the chosen years are used in MUAM to initialize the model for reproducing the QBO phases.

Ensemble MUAM Calculations. Relatively small changes in the initial conditions can significantly affect the evolution of the modeled stratosphere [35]. Indeed, small variations in the structure and amplitude of planetary waves in the nonlinear model lead to mean flux changes affecting the conditions of their propagation. As a result, the stratospheric dynamics, after a sufficiently long integration over time, is characterized by significant variability and ensemble calculations of the general atmospheric circulation are required to ensure the statistical significance of model calculations.

The ensembles in the MUAM model are formed from separate calculations (runs) corresponding to different phases of mean-wind and planetary-wave vacillations in the middle atmosphere [36]. These phases are controlled in MUAM by changes in the date of diurnal solar heating variations and generation of normal atmospheric modes [21]. The initial and background conditions are taken to be identical for all model calculations.

To analyze the changes in the residual circulation at different QBO phases, we used ensembles of 12 pairs of MUAM model calculations for conditions characteristic of the westerly and easterly phases of the QBO. The ensemble data are statistically processed using the software package developed by the author [23] using standard criteria and automatically calculating the minimum required ensemble volume at which a 95% significance level of nonzero differences between the values is calculated for different QBO phases.

In this study, the **residual circulation** is understood in the context of the transformed Eulerian mean circulation [8]. The meridional and vertical components of the residual mean circulation can be obtained by standard formulas [8], which can be transformed to a form convenient for processing the simulated wind and temperature fields in the MUAM:

$$\overline{v}^* = \overline{v} - \frac{1}{\partial\overline{\theta}/\partial z}\left(-\frac{\overline{v'\theta'}}{H} + \frac{\partial\overline{v'\theta'}}{\partial z} - \frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial z}\frac{\partial^2\overline{\theta}}{\partial z^2}\right), \qquad (2)$$

$$\overline{w}^* = \overline{w} + \frac{1}{a\cos\varphi}\frac{1}{\partial\overline{\theta}/\partial z}$$
$$\times\left(-\sin\varphi\overline{v'\theta'} + \cos\varphi\left(\frac{\partial\overline{v'\theta'}}{\partial\varphi} - \frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial z}\frac{\partial^2\overline{\theta}}{\partial z\partial\varphi}\right)\right). \qquad (3)$$

Here, the overbars mean zonal averaging; the primes denote deviations from the zonal-mean values; v and w are meridional and vertical winds, respectively; θ is the potential temperature; φ is latitude; and a is the Earth's radius.

Unlike the Eulerian mean circulation, the residual vertical velocity for time-averaged conditions is proportional to the resulting rate of diabatic heating. It can be interpreted as a diabatic circulation in the meridional plane [10], i.e., a circulation when the rising air volume is heated and the descending air is cooled, while their potential temperature adapts to the local environment. Thus, the time-averaged residual meridional circulation approximates the average movement of air masses and, therefore, unlike the common mean Eulerian circulation, it is an approximation of the average advective transport of gases. In our previous studies [22, 26], we have shown that the RMC calculated with this approach on the basis of MUAM calculation ensembles is very consistent by structure and magnitude with the meridional circulation calculated from observational or assimilated data.

3. RESULTS AND DISCUSSION

Figure 1a shows the latitude–altitude distribution of the RMC components for the easterly phase of the QBO, calculated by formulas (2) and (3) from wind and temperature fields for January, obtained from MUAM ensemble calculations. In the mesosphere above 50–60 km, a global meridional circulation cell can be detected with an upward flow at high and middle latitudes of the summer (Southern) hemisphere and a downward movement of air masses in the winter (Northern) hemisphere. In the stratosphere, one can see a deep branch of the Brewer–Dobson circulation, which is tropical upwelling and extratropical downwelling; in this case, the circulation cell in the Northern Hemisphere is much stronger than in the Southern Hemisphere [6].

In general, the distributions of the RMC components, similar to those shown in Fig. 1a correspond to the distributions obtained in [37], which were calculated using the Canadian Middle Atmosphere Model (CMAM). For the RMC analysis, we used not only model data, but also observational data obtained with the Microwave Limb Sounder (MLS) onboard the Upper Atmosphere Research Satellite (UARS); the distributions of the vertical and meridional compo-

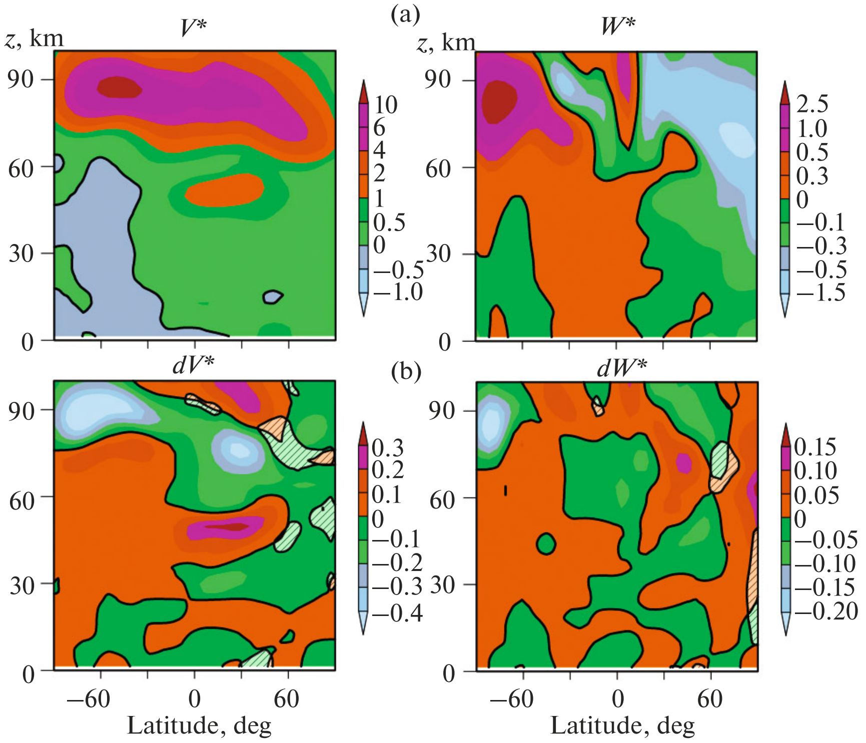

Fig. 1. Latitude–altitude distributions of the meridional (m/s, left) and vertical (cm/s, right) components of the RMC for the easterly phase of the QBO in January; (b) increments of the corresponding components due to the transition from the easterly to the westerly phase of the QBO. The solid lines and hatched areas indicate zero values and unreliable data, respectively.

nents of residual circulation presented in [38] are also consistent with our data. Good correlation with the data presented in Fig. 1a was also obtained in [39], which presents the RMC fields for the winter months in the Northern Hemisphere calculated with the Limb Infrared Monitor of the Stratosphere (LIMS) onboard the Nimbus-7 satellite.

Figure 1b shows the differences in the meridional and vertical components of the RMC between the years with the westerly and easterly phases of the QBO, corresponding to the distributions in Fig. 1a. Both figures show significant positive and negative differences in the equatorial region at heights of 30–60 km, which correspond to significant (up to 40%) changes in the RMC.

In the MUAM equation of motion, the intensification of the polar vortex in the high-latitude northern stratosphere, observed in the westerly phase of the QBO [16], contributes to southward (negative) accelerations of the meridional circulation, slowing down the positive residual meridional velocity in the corresponding regions (Fig. 1, left panel), which, in turn, is interrelated with the weakening of the downward RMC component at high northern latitudes (Fig. 1b, right panel). Similar results in the lower stratosphere were obtained in [16], which analyzed the response of extratropical circulation to the QBO and showed that it is especially strong in the northern winter, when the eastward mean jet stream is weaker during the easterly QBO phase than during the westerly phase. The heights of mesosphere/lower thermosphere (MLT) regions are characterized by a general weakening of the RMC components in the westerly phase of the QBO, except for a small region at northern midlatitudes above 80 km.

The main changes in zonal velocity during the QBO occur in the low-latitude stratosphere [25]. In this region, the QBO can modify the waveguides along which planetary waves propagate. These planetary waves propagate to middle and high latitudes and to upper layers of the atmosphere, where they can interact with atmospheric circulation, thus spreading the effect from the QBO to other atmospheric layers and regions. In winter, sudden stratospheric warmings (SSWs) also have a significant effect on the structure of circulation in the middle atmosphere [40]: in the westerly phase of the QBO, the polar vortex is stronger and less disturbed, which leads to a decreased number of SSW events [18]. This behavior is also reproduced in the MUAM: out of 12 ensemble calculations, SSWs were observed in January 10 times in the easterly phase and 7 times in the westerly phase. The statistical significance of the calculated RMC increments (Fig. 1b) was assessed by testing the hypothesis of their difference from zero using the paired Student's t-test [23]. The monthly average increments of the RMC components at each latitude and height were obtained in the

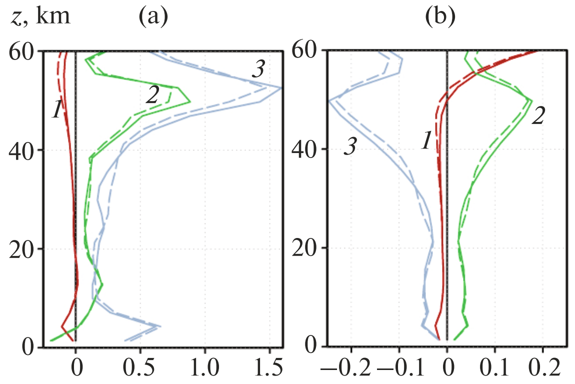

Fig. 2. (a) Meridional (m/s) and (b) vertical (cm/s) residual velocities along latitudinal belts 90° S–50° S, 50° S–15° N, and 15° N–90° N (lines *1*–*3*, respectively) for January according to MUAM data. Dotted and solid lines correspond to the easterly and westerly phases of the QBO, respectively.

MUAM model by averaging over 180 × 12 = 2160 (4-h data per month; an ensemble of 12 MUAM runs) differences of model fields pairs at each grid point. The areas with statistically insignificant increments at a 95% significance level are shaded.

Earlier, the RMC changes in different phases of the QBO were analyzed by processing the UK Met Office meteorological assimilation database [33]. For example, Fig. 5 in [41] shows the RMC increments, which, accurate to a factor of "−1" (since that study considers the differences between the easterly and westerly phases), have a similar structure to the distributions calculated in this work. Previous studies [42] also showed that the impact of planetary waves on the RMC increases in the easterly phase of the QBO, which contributes to the RMC acceleration in the stratosphere. This is also confirmed by our calculations; specifically, they reveal a significant weakening of the amplitude of a stationary planetary wave with zonal number 1 (SPW1) in the mid- and high-latitude stratosphere of the Northern Hemisphere in the westerly phase, accompanied by an increase in the polar vortex, which is consistent with theory [4]. Similar tendencies of changes in the residual circulation at different phases of the QBO are reported in [43].

To analyze in more detail the RMC changes in the stratosphere, we considered its meridional and vertical components averaged over different latitudinal intervals (Fig. 2). The entire latitudinal range was divided into three intervals between the turnaround points: the latitudes where the stratospheric residual vertical wind changes its sign. Classical studies (for example, [14]) commonly assume turnaround points at an altitude of 70 hPa when studying the meridional circulation in the troposphere and lower stratosphere. In our study of the middle and upper stratosphere, the turnaround points are calculated in the altitude range of 10–50 km. Using this approach, we obtained regions of tropical stratospheric upwelling region between 50° S and 15° N (lines *2* in Fig. 2b) and extratropical downwelling to the poles from these latitudes (lines *1* and *3* in Fig. 2b).

The abovementioned vertical flows are shown in Fig. 2b. Comparing the solid and dotted lines corresponding to the easterly and westerly phases of the QBO, one can see the RMC changes in the range of 20–30 km with a weakening of circulation in the upwelling and downwelling zones in the westerly phase of the QBO in comparison with the easterly phase. The respective changes in the RMC meridional component are shown in Fig. 2a. The range of 50–60 km is characterized by the opposite effect: an increase in the RMC in the westerly phase.

Wave-Induced Eddy Circulation. The differences between the residual and Eulerian components of meridional velocity describe the so-called eddy circulation, which describes the contribution to the nonzonal motions generated mainly by tides and planetary waves [4]. Figure 3a shows the meridional and vertical components of the eddy circulation in the easterly phase of the QBO. The right panel of Fig. 3a shows that atmospheric waves create strong upward flows in midlatitudes of the Northern Hemisphere, which form a poleward meridional wind at high latitudes with a maximum at heights of 40–50 km (left panel, Fig. 3a) as well as downward flows near the North Pole (right panel, Fig. 3a). This is consistent with the existing theory [4, 6], showing that regions of eddy flows are created by SPWs propagating upward from the northern troposphere along waveguides [44]. These waveguides are located in the northern (winter) stratosphere, which contributes to the propagation of SPWs at these altitudes and the occurrence of significant eddy circulation. This eddy contribution is generally directed oppositely to the mean Eulerian circulation in the stratosphere and along it in the MLT region [45]. The peak values of the eddy components in Fig. 3a can significantly exceed the residual circulation components in the corresponding plots in Fig. 1a. This confirms the conclusions that the eddy components are largely compensated by the zonal-mean Eulerian circulation.

The right panel of Fig. 3b shows that the westerly phase of the QBO is characterized by an increased upward eddy velocity in northern midlatitudes at heights of 40–50 km. This causes positive increments of the meridional component (left panel, Fig. 3b) at latitudes below 60° N and at corresponding heights. At high latitudes (see Fig. 3), the downward eddy component weakens in the westerly phase of the QBO, which is also accompanied by a weakening of the meridional component in this region. In general, these processes contribute to the weakening of the RMC observed in Fig. 1b in the westerly phase of the QBO. In the southern (summer) strato–mesosphere, SPWs do not propagate [25], and the general structure of the eddy component of circulation reflects the structure of SPW waveguides. At heights above 50 km, these waveguides

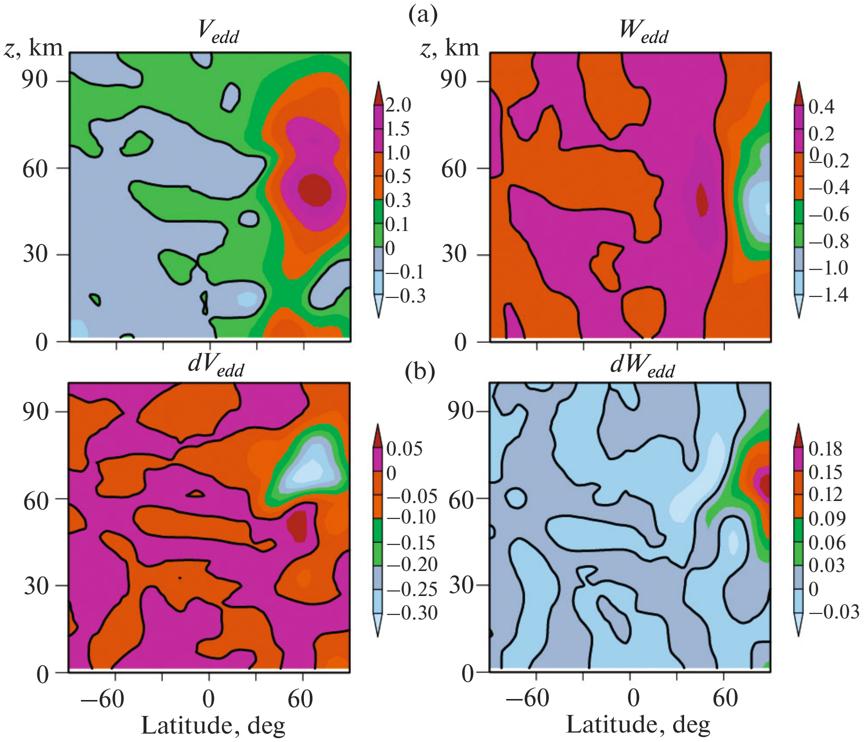

Fig. 3. Same as in Fig. 1, except for wave-induced eddy circulation.

cross the equator and can propagate into the Southern Hemisphere. This confirms the hypothesis that SPW propagation from the northern winter stratosphere along waveguides extending to the Summer Hemisphere at heights above 50–60 km can change the eddy and residual circulation in the MLT region of the Southern Hemisphere.

4. CONCLUSIONS

In this study, we use an approach to calculating the transformed Eulerian mean circulation to diagnose the wave effect on the mean flow and estimate the transport of gas species in the meridional plane. This approach considers the so-called mean residual meridional circulation (RMC), which is the sum of the eddy and advective mean transports. The time-averaged RMC approximates the resulting movement of air masses and, unlike the common Eulerian mean circulation, is a convenient tool for estimating the transport of conservative pollutants in the atmosphere.

The results of ensemble calculations of the general atmospheric circulation using the MUAM model for the initial and background conditions corresponding to the easterly and westerly phases of the QBO are used as the initial wind and temperature data for RMC calculations.

The results of numerical experiments have shown a significant RMC sensitivity to a change in the QBO phase in both the tropical and extratropical regions of the atmosphere. Differences in meridional and vertical residual velocities can reach up to 30–40%. Here, the weakening of the upward and downward branches of the RMC in the middle stratosphere in the westerly phase is accompanied by their strengthening in the upper stratosphere, which is associated with a local increase in the eddy circulation in this region. In the Southern Hemisphere, a change in the RMC is observed only at MLT heights, which is associated with the specific features in the SPW propagation in the summer hemisphere with a major effect on the eddy circulation structure.

The general structure of the eddy component of circulation reflects the structure of SPW waveguides. In this case, the peak values of the eddy components of meridional circulation can significantly exceed the residual circulation components in the corresponding regions of the atmosphere, which indicates that the vortex components are largely compensated by the zonal-mean Eulerian circulation. The westerly phase of the QBO is characterized by enhanced eddy circulation at northern midlatitudes in the range of 40–50 km and its general weakening in other regions of the Northern Hemisphere, which is explained by the weakening of the activity of SPWs in the middle and high northern latitudes and the polar vortex intensification.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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