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Simulation of changes in the meridional circulation of the middle and upper atmosphere during transitional QBO phases

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ABSTRACT

3-dimensional numerical nonlinear model of general circulation of the middle and upper atmosphere (MUAM) is used to investigate reaction of the atmospheric circulation in the middle and upper atmosphere to changes in phases of equatorial stratospheric quasi-biennial oscillation (QBO). To estimate changes in transport of atmospheric gas species, residual meridional circulation (RMC) is calculated based on the modelled atmospheric hydrodynamic fields for easterly, westerly and transitional (so-called “easterly-shear” and “westerly-shear”) QBO phases. For this purpose, four 10-members ensembles of MUAM simulations have been obtained corresponding to the aforementioned QBO phases. To determine QBO phases, empirical orthogonal functions (EOF) are applied for the equatorial zonal wind profiles. Statistically significant results are obtained illustrating how changes in direction of equatorial stratospheric winds influence extratropical circulation. It is shown in particularly, that the strongest changes in thermal and dynamical conditions of the middle- and high-latitude stratosphere-mesosphere occur during easterly-shear QBO phase.

quasi-biennial oscillation, numerical modeling, residual circulation

1. INTRODUCTION

The phenomenon of quasi-biennial oscillation (QBO) of zonal flows is one of the important features of atmospheric dynamics[1,2]. QBO is observed at equatorial latitudes: the direction of the zonal wind changes to the opposite with the period varying between 22 and 34 months. Influence of equatorial QBO in the form of a quasi-two-year periodicity is observed in the composition of the atmosphere and in hydrodynamic fields also at middle and high latitudes and altitudes up to the thermosphere. Holton and Tan[1] analyzed the response of the extratropical circulation to the QBO and showed that it is particularly strong during northern winter, where the zonal mean westerly jet is weaker during the easterly QBO phase (eQBO) than that during the westerly QBO phase (wQBO). Gavrilov et al.[3] studied peculiarities of planetary wave (PW) and orographic gravity wave (OGW) interactions in the middle and upper atmosphere under easterly and westerly QBO phases during boreal winter. They showed that changes in QBO cause PW amplitude changes up to ±(30–90)% at middle and high northern latitudes. Recently, based on the numerical simulations Koval et al.[4] demonstrated how changes in the planetary waves (PW) structures promote spread of QBO effects to polar latitudes and to the thermosphere, through changes in the Eliassen-Palm (EP) flux and its divergence and through the formation of an eddy meridional circulation. They showed that the main contribution to the cooling of the polar winter stratosphere during the wQBO was associated with the weakening of wave activity.

2. METHODOLOGY

In this paper, we simulate effects of different QBO phases on atmospheric circulation, using the middle and upper atmosphere model (MUAM). This is a 3-dimensional nonlinear mechanistic numerical model[5]. The horizontal grid of the model is 5.625°x 5° in longitude and latitude, respectively. The MUAM uses a log-isobaric vertical coordinate $z = -H*ln(p/p_o)$, where p_o is the surface pressure and H is pressure scale height. To prepare background and initial conditions for the simulation, we use QBO phase determinations based on the decomposition of observed zonal flux variations with empirical orthogonal functions (EOF). This approach allows taking into account vertical evolutions of QBO phases and minimize uncertainties in determination of the QBO phases[4].

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In order to improve the statistical significance of the simulations, four series (ensembles) containing 10 calculations (“runs”) of the MUAM model are obtained for conditions typical for different QBO phases. These phases are determined as follows: the easterly phase (eQBO), transitional from easterly to westerly phase (westerly-shear phase, wsQBO), westerly (wQBO) and transitional from westerly to easterly phase (easterly-shear phase, esQBO). A detailed description of the peculiarities in QBO accounting in the MUAM based on EOF is presented in Koval et al. [4].

Table 1. Distribution of years by four QBO phases for January, obtained using EOF based on MERRA-2 reanalysis.

wQBO	esQBO	eQBO	wsQBO
1983, 1985, 1993, 1995, 1999, 2002, 2004, 2013	1981, 1986, 1991, 2007, 2009, 2011, 2014, 2016	1989, 1996, 1998, 2000, 2003, 2005, 2010, 2012	1980, 1990, 1992 ,1997 2001, 2006, 2008, 2015

Table 1 shows selected years for each of four QBO phases under consideration. Based on these sets of years, average zonal-mean distributions of zonal wind and temperature for all QBO phases were calculated and implemented into MUAM using nudging in the equatorial stratosphere (see [4] for details). Comparing of the simulated hydrodynamic fields with data from reanalysis of the meteorological information MERRA-2[6] shows good correlation. Our simulations are consistent also with the results of Rao et al. [7] who investigated the structure of stratospheric circulation based on 10 reanalyses of meteorological information and on numerical simulations.

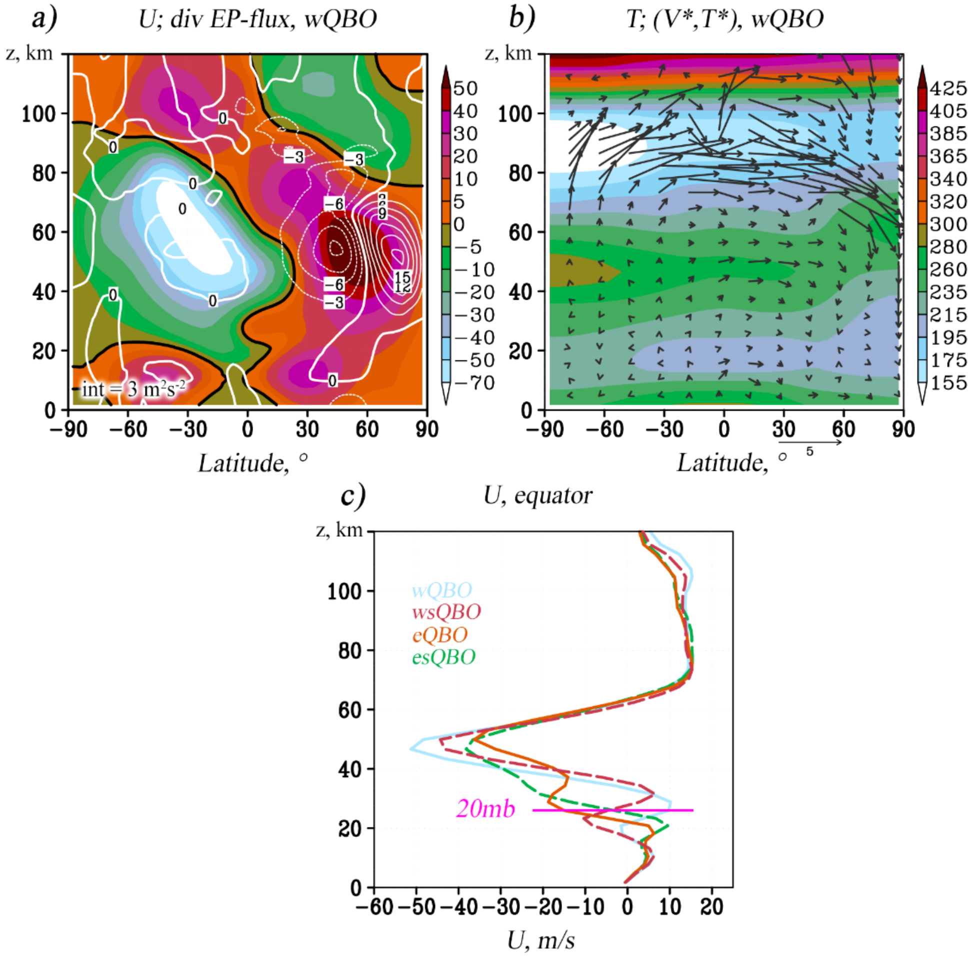

Figure 1. Latitude-altitude distribution of: (a) – zonal wind (shaded, m/s) and EP-flux divergence (contours, m^2/s^2); (b) – temperature (shaded, K) and RMC components (arrows, m/s, vertical component multiplied by 200); (c) – vertical profile of the equatorial zonal wind for all QBO phases.

3. RESULTS AND DISCUSSION

The top panels of Figure 1 show the latitude-altitude distributions of the zonal mean zonal wind (left) and temperature, obtained by the MUAM model for January for the wQBO. In general, the distributions correspond both to the reanalysis of meteorological information for years with the corresponding phase, and to semi-empirical models such as HWM-14[8] and NRLMSIS 2.0[9]. Contours in Fig. 1a show the divergence of the Eliassen-Palm flux (EP-flux) calculated using formulas (1,2) from [4]. EP flow divergence should be accompanied by an eastward acceleration of the zonal wind caused by PW energy transfer to the mean flow, while negative divergence (i.e., convergence) corresponds to a westward acceleration. Therefore, EP-flux components are useful tools for the analyzing the changes in zonal circulation and identifying possible PW contributions to its structure. Vectors in Fig. 1b show the calculated by formulas (4,5) from [4] residual meridional circulation (RMC). In terms of the Transformed Eulerian mean (TEM), the RMC is a superposition of advective and eddy meridional flows. The RMC is currently widely used to estimate the meridional transport of long-lived atmospheric components and passive species. In the stratosphere, the RMC represents branches of the Brewer-Dobson circulation[10], with ascending flows in the low-latitude region and descending flows at high latitudes, and the northern, winter circulation cell is much stronger than the southern, summer one. In the mesosphere and lower thermosphere, the transfer of air masses from their summer to winter hemisphere dominates.

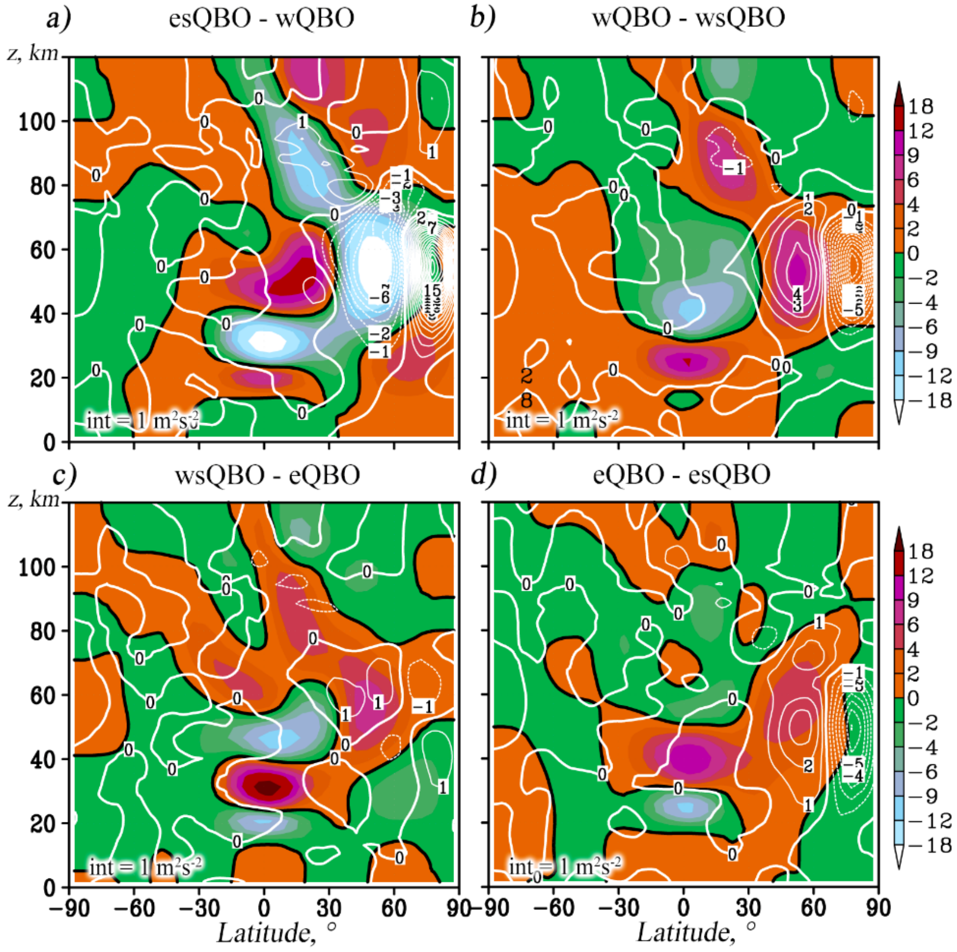

Figure 2 - Latitude-altitude distributions of: zonal wind increments with a successive change in QBO phases (filling, m/s); contours show increments of the EP-flux divergence (10^{-2} m^2/s^2/day).

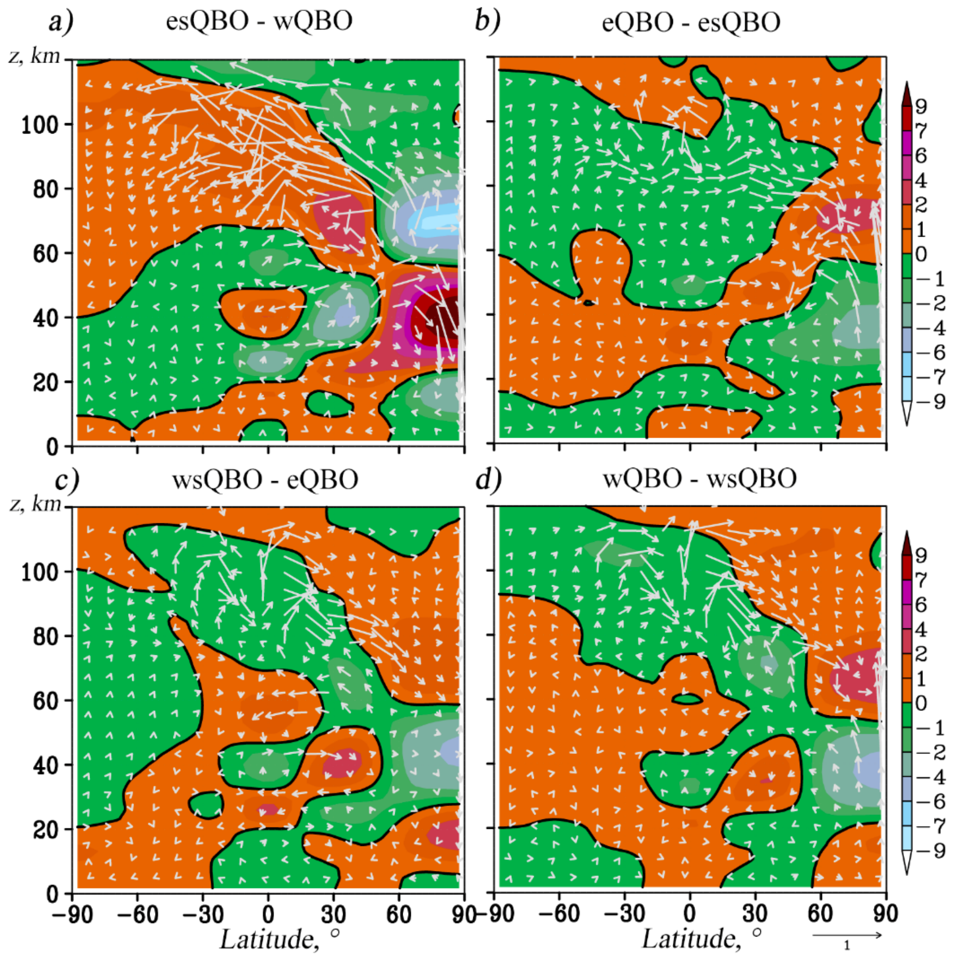

Figure 3 - Latitude-altitude distributions of temperature increments with a successive change in the QBO phases (shaded, K); increments of the RMC component (arrows, m/s, vertical component multiplied by 200).

Figure 1c shows profiles of the zonal mean zonal wind averaged over the equatorial region (± 2.5°) for the four QBO phases considered. As shown by Koval et al. [4], the QBO phase is determined by the direction of the main component of the expansion of the equatorial zonal wind field according to the EOF at a level of 20 mb (indicated in Fig. 1c by the pink line): it is clearly seen that at this level the zonal wind is directed eastward and westward for the wQBO and eQBO, respectively. For the transitional phases the wind speed it is close to zero, while its sharp change towards the next phase is observed.

Shaded areas in Fig. 3 show the distributions of increments of the zonal-mean temperature according to the results of numerical simulation with a successive change in the phases of the QBO. In particular, Fig. 3a shows a significant increase in temperature in the subpolar stratosphere and cooling of the mesosphere (above 60 km) during the esQBO transition phase (from westerly to easterly), compared to the wQBO. During the next three phases (Figs. 3b-d), reverse processes are observed: cooling of the subpolar regions of the stratosphere and heating of the regions above and below this area. At the same time, these processes are much weaker than in Fig. 3a, which is explained by their longer duration.

The statistical significance of the increments shown in Figs. 2 and 3 was calculated using a paired Student's t-test applied to the above-mentioned ensembles of 10 model runs for each QBO phase. The calculations showed statistically significant increments of zonal wind and temperature at the 95% significance level in all areas where they exceed ±0.5 m/s and ±1 K, respectively.

The arrows in Fig. 3 show the components of the RMC increments for the corresponding QBO phases. As in the case of temperature changes, these increments are maximum during the QBO transition phase depicted in Fig. 3a. In most areas in Fig. 3, the increase and decrease in the vertical component of the RMC is accompanied, respectively, by adiabatic cooling and heating. However, in the low-latitude lower thermosphere (above 70 km), one can notice areas of descending increments of the vertical residual wind, accompanied by cooling, in Fig. 3b-d, and the opposite effect in Fig. 3a. The change in the temperature of these regions is mainly due to the change in the meridional component of the RMC, respectively, accelerating or slowing down the meridional transfer of cold air masses from the summer lower thermosphere (see Fig. 1b)

According to the classic theory of thermal wind, the thermal component of the zonal wind is proportional to the meridional temperature gradient. At the same time, in the Northern Hemisphere, an increase in the meridional temperature gradient should correspond to a decrease in the zonal wind speed. Indeed, a strong increase in the meridional temperature gradient in the stratosphere of the Northern Hemisphere during the esQBO transitional phase in Fig. 3a is accompanied by a significant weakening of the zonal jet stream in this region in Fig. 2a. Thus, a warmer and weaker Polar vortex during the esQBO phase can provide better conditions for the onset of SSW events during this phase. However, further studies are required to confirm this hypothesis.

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