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The influence of orographic waves and quasi-biennial oscillations on vertical ozone flux in the model of general atmospheric circulation

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ABSTRACT

A parameterization of the dynamical and thermal effects of orographic gravity waves (OGWs) and assimilation quasi-biennial oscillations (QBOs) of the zonal wind in the equatorial lower atmosphere are implemented into the numerical model of the general circulation of the middle and upper atmosphere MUAM. The sensitivity of vertical ozone fluxes to the effects of stationary OGWs at different QBO phases at altitudes up to 100 km for January is investigated. The simulated changes in vertical velocities produce respective changes in vertical ozone fluxes caused by the effects of the OGW parameterization and the transition from the easterly to the westerly QBO phase. These changes can reach 40 - 60% in the Northern Hemisphere at altitudes of the middle atmosphere.

Keywords: atmospheric circulation, orographic waves, quasi-biennial oscillation, modeling, ozone flux

1 INTRODUCTION

One of the important factors of dynamical interactions between the lower and upper atmosphere is energy and momentum transfer by internal atmospheric waves. One of the major sources of atmospheric waves is the Earth’s topography [1]. Propagation of the orographic gravity waves (OGWs), generated at the Erath’s surface, into the middle and upper atmosphere can significantly affect the atmospheric general circulation as well as ozone transport in the middle atmosphere. Gavrilov and Koval [2] showed importance of the Earth’s rotation accounting the theory of stationary OGW. They developed a parameterization of dynamical and thermal effects of stationary OGWs, which are generated by the surface topography and propagate into the middle and upper atmosphere. This parameterization was implemented into a general circulation atmospheric model [3]. The authors showed that OGWs might produce substantial changes in the general circulation of the middle and upper atmosphere.

Ozone transfer between the stratosphere and troposphere has an effect on the total ozone distribution in the atmosphere and on its content in the troposphere (e.g., [4]). The main supposed mechanism of the global ozone transfer between the troposphere and the stratosphere is the ozone ascend at low latitudes and descend at the middle and high latitudes, which is initiated by the general circulation of the atmosphere [5]. The dynamical and thermal impacts of wave motions can change the general circulation of the atmosphere and thus have influence on the global ozone distribution.

Changes of the zonal wind direction near equator in the middle atmosphere, occurring nearly once in two years, the so-called quasi-biennial oscillations (QBO), can affect the general atmospheric circulation at middle and high latitudes (e.g. [6]). In this study, we focus on the sensitivity of vertical circulation and associated ozone fluxes to the dynamical and thermal effects of the OGW at different QBO phases. The sensitivity experiments are essential for better understanding of the roles of different factors in formation of global dynamical processes, in transport and mixing of atmospheric gas components and in dynamical coupling of different layers of the lower, middle and upper atmosphere.

2 NUMERICAL MODEL AND PARAMETERIZATIONS

For experiments studying dependencies of the atmospheric dynamics and ozone fluxes on OGW parameterization and changes in QBO phase, we use the Middle and Upper Atmosphere Model (MUAM) [7] simulating global atmospheric

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circulation. Gavrilov et al. [8] described briefly the main expressions and physical processes taken into account in the model. The horizontal grid spacing is 5°x5.625° in latitude and longitude, respectively. The model has 48 vertical levels the log-isobaric vertical coordinate covering altitude range from 0 to 135 km. The MUAM includes a three-dimensional distribution of the ozone mixing ratio, which takes into account the climatic (averaged for years 1996–2005) longitudinal ozone inhomogeneities [9].

As the MUAM does not involve entire mechanism forming QBO, this oscillation was assimilated from stratospheric meteorological data as it was proposed by Pogoreltsev et al. [10], who added terms into the MUAM equations for zonal wind and temperature, which are proportional to deviations of simulated zonal mean values from respective climatological values. Pogoreltsev et al. [10] used the UK Met Office meteorological assimilation data [11] for January during years 1992–2011 to analyze signs of deviations of annual-mean and climatological (averaged for 20 years) zonal velocities over the equator. The positive and negative deviations correspond to the westerly and easterly QBO phases, respectively. Pogoreltsev et al. [10] found maximum zonal velocity deviations at altitudes 30 – 35 km, selected years with different QBO phases and calculated average zonal-mean distributions of the zonal wind and temperature for the years with easterly and westerly QBO phases.

IN order to study the OGW influence on atmospheric dynamics, the recently developed parameterization of dynamical and thermal effects of stationary OGWs [2] was implemented. To calculated vertical profiles of the total vertical wave energy flux and the associated accelerations of the mean horizontal winds by stationary OGWs with ground-based observed frequencies $\sigma = 0$, the parameterization uses wave polarization relations that take into account rotation of the atmosphere.

3 RESULTS OF THE OZONE FLUX CALCULATIONS

The performed calculations of the vertical velocities of the general circulation of the atmosphere make it possible to diagnose the corresponding vertical ozone fluxes using semiempirical three-dimensional ozone profiles included in the MUAM [9]. The mean vertical ozone flux F_{ozi} at the grid node with the number i is calculated with the expression [12]:

$$F_{ozi} = N_{ozi} w_i, \quad N_{ozi} = 10^{-6} \rho_i X_{ozi} N_A / \rho_0,$$

where w_i is the monthly mean vertical velocity, N_{ozi} is the ozone number concentration, ρ_0 is the ground density of the atmosphere at normal conditions, X_{ozi} is the zonal-mean ozone mixing ratio in ppm, and N_A is the Avogadro number

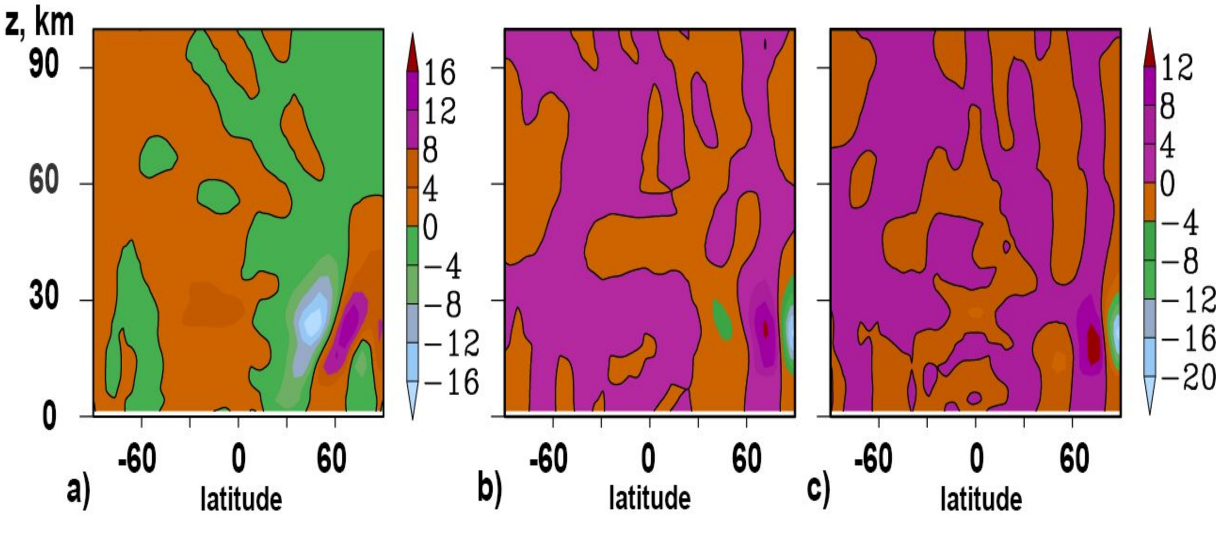

Figure 1. The simulated zonal-mean vertical ozone fluxes (in 10^{13} m^{-2}s^{-1}) for easterly QBO phase without OGW effects – (a) and the ozone flux differences (in 10^{13} m^{-2}s^{-1}) due to inclusion of OGW effects – (b) and change from easterly to westerly QBO phase – (c).

Figure 1a represents the simulated altitude-latitude distribution of the zonal-mean vertical ozone flux calculated for January, for the easterly QBO phase and without inclusion of the OGW parameterization. Above 50 – 60 km, there is a global cell of ozone flux with ascending ozone transfer in the Southern Hemisphere and descending one in the Northern Hemisphere. This correlates with existing knowledge about ozone transfer by the general atmospheric circulation (e.g., [5]). Below 50 – 60 km, additional ascending flux exists in Figure 1a at high latitudes of winter (Northern) hemisphere caused by the Polar Vortex and ascending flux in the middle and high latitudes of summer (Southern) hemisphere. Therefore, in Figure 1a one can observe areas of positive and negative ozone fluxes at middle and high latitudes of the Northern Hemisphere. This leads to the appearance of additional cells of ozone transport in the middle and high latitudes. In the Figure 1b are plotted zonal-mean vertical ozone flux differences (OFDs) occurred due to the inclusion of the OGW parameterization into the MUAM model. There are regions of positive and negative OFD values, which correspond to increases or decreases in vertical ozone fluxes. Figure 1c represents OFDs due to change from the westerly to the easterly QBO phase and shows substantial differences in vertical ozone fluxes in the Northern Hemisphere at altitudes 10 – 40 km (similar to Figure 1b) and their significant changes near the equator. In summer (Southern) Hemisphere OFD are smaller in Figure 1b. This can be explained by better conditions of OGW propagation and by the stronger influence of orographic waves on the general circulation of the atmosphere in winter hemispheres as compared to summer ones [2,3]. Differences in local vertical ozone fluxes in Figures 1b and 1c may change global ozone transfer.

Interesting feature of Figure 1 is general similarities of distributions in panels b and c for differences caused inclusion OGW effects and transition from westerly to easterly QBO phases, respectively. Similarity of these two different physical mechanisms is the additional drag of the eastward general circulation by stationary OGWs or westward stratospheric jets in the tropical stratosphere during the easterly QBO phase. The maximum zonal-mean OGW drag is located at latitudes 30-40°N and altitudes 0 – 50 km [13]. According to [10], the empirical QBO stratospheric flows are imposed in the latitude band between 17.5°S and 17.5°N at altitudes up to 50 km. OGW and QBO drags both affect the planetary waves, which try to compensate partly these drags. The planetary waves propagate upwards and may produce differences in meridional and vertical velocities.

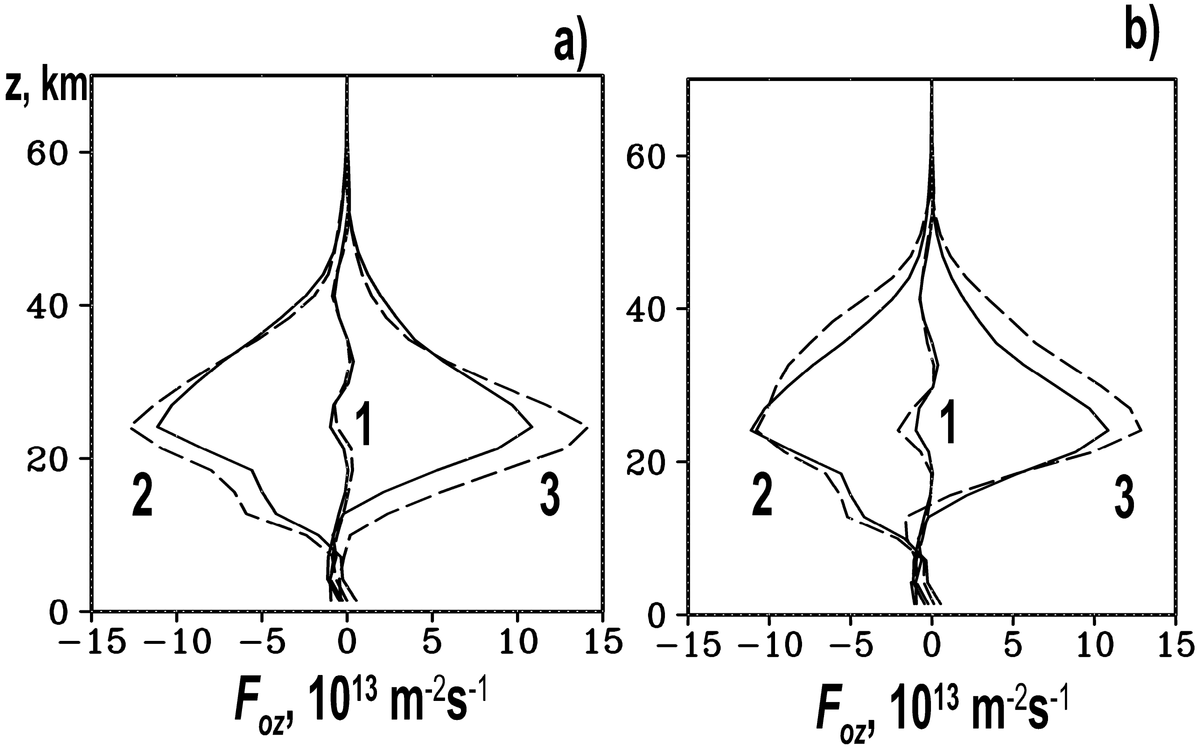

Figure 2. January-mean vertical ozone flux averaged over latitude belts 0 - 30° N – 1, 30 - 60° N – 2, 60 - 90° N – 3 for the easterly QBO phase without OGW effects (solid lines). Dashed lines show respective flux including OGW effects for easterly QBO (a), and the flux for the westerly QBO phase without OGW effects (b).

Figure 2 reveals the January-mean vertical ozone fluxe F_{oz} averaged for different latitude belts 0 – 30º N, 30 - 60º N and 60 - 90º N for the easterly QBO without OGW effects (solid lines). One can see that at altitudes of the maximum of ozone number concentration 20 – 30 km the main ascending $F_{oz} > 0$ exists at high latitudes of the Northern Hemisphere, which are approximately equal to descending $F_{oz} < 0$ at middle latitudes. Dashed lines in Figure 2a show respective vertical ozone fluxes for the easterly QBO simulated with the OGW parameterization included into the MUAM. They show that dynamical and thermal OGW effects substantially (up to 20 – 30 %) increase absolute values of ascending and descending F_{oz} at middle and high Northern latitudes. In Figure 2b, dashed lines show F_{oz} simulated for the westerly QBO phase without OGW effects. Absolute values of these ozone fluxes are by 10 – 20 % larger above altitudes 20 – 25 km than those for the easterly QBO phase.

Figure 3a shows the horizontal distribution of the vertical ozone flux at altitude 25 km calculated with the MUAM for the easterly QBO phase without OGW effects and averaged over January. The main downward ozone fluxes occur over Siberia, while upward ozone fluxes exist over North America and Greenland. Figures 3b and 3c reveal ozone flux increments caused by OGW effects for the easterly QBO phase and by changes in QBO phase without OGWs. There are areas of positive and negative differences in the ozone flux corresponding to the regions of enhancement or weakening of the vertical wind. Maximum increases in ozone fluxes occur in the both Figures above Siberia and North-West of Canada, while maximum decrease is observed over North Atlantic. Peak differences of the ozone flux in Figures 3b and 3c can reach 40 - 60% of the flux peak values shown in Figure 3a.

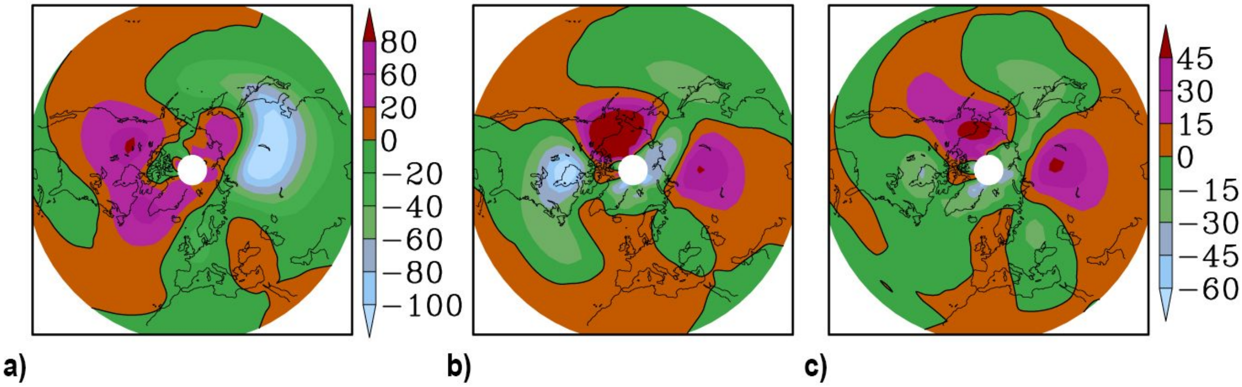

Figure 3. North polar stereographic projection of the simulated mean vertical ozone fluxes (in 10^{13} $m^{-2}s^{-1}$) in January for easterly QBO phase without OGW effects – (a) and the ozone flux differences (in 10^{13} $m^{-2}s^{-1}$) due to inclusion of OGW effects – (b) and change from easterly to westerly QBO phase – (c)

4 CONCLUSION

In this study, we performed numerical experiments with the MUAM model simulating the general circulation in the middle atmosphere using ten-year average meteorological information and three-dimensional ozone distribution. We focused on the sensitivity of the vertical ozone fluxes in the middle atmosphere to inclusions of recently developed parameterization of OGW dynamical and thermal effects at different QBO phases for understanding the role of the processes associated with dynamical coupling between different atmospheric layers in the MUAM general circulation models. The numerical experiments were performed for the background and initial conditions typical for the westerly and easterly QBO phases in the equatorial atmosphere.

Results of numerical experiments show that global-scale vertical ozone fluxes in the MUAM are very sensitive to OGW dynamical and thermal effects, as well as to the changes in QBO phase. The largest increments in ozone flux are observed at high latitudes of the Northern Hemisphere where the flux changes can reach 40-60% at the altitudes of the maximum of the ozone layer. At the same time, taking into account the OGW effects and changing QBO phases, can have a similar effect on vertical circulation in the middle atmosphere.

Used prescribed unchanged ozone distribution may be used for ozone flux diagnostics during relatively short time intervals in the lower stratosphere and troposphere, where photochemical ozone sources are generally weak (e.g., [14]). Simulations of ozone concentrations and fluxes for longer periods and at higher altitudes require interactive chemistry-dynamic models.

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REFERENCES

[1] Gossard, E. E. and Hooke, W. H., [Waves in the atmosphere], Elsevier Sci. Publ. Co., Amsterdam-Oxford-New York (1975).

[2] Gavrilov, N. M., and Koval, A. V., "Parameterization of mesoscale stationary orographic wave impact for usage in numerical models of atmospheric dynamics," Izvestia. Atmos. Oceanic Phys. 49(3), 244-251 (2013).

[3] Gavrilov, N. M., Koval, A. V., Pogoreltsev, A. I. and Savenkova, E. N., "Numerical simulation of the response of general circulation of the middle atmosphere to spatial inhomogeneities of orographic waves," Izvestia. Atmos. Oceanic Phys. 49(4), 367-374 (2013).

[4] Danielsen, E. F. and Mohnen, J., "Project Dustorm report: Ozone transport, in situ measurements and meteorological analyses of tropopause folding," J. Geophys. Res. 82, 5867-5877 (1977).

[5] Holton, J. R., Curry, J. A. and Pyle, J.A. (eds.), [Encyclopedia of Atmospheric Sciences], London, Academic Press (2003).

[6] Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquard,t C., Sato, K. and Takahashi, M., "The quasi-biennial oscillation," Rev. Geophys. 39(2), 179 – 229 (2001).

[7] Pogoreltsev, A. I., Vlasov, A. A., Froehlich, K. and Jacobi, Ch., "Planetary waves in coupling the lower and upper atmosphere," J. Atmos. Solar-Terr. Phys. 69, 2083-2101 (2007).

[8] Gavrilov, N. M., Pogoreltsev, A. I. and Jacobi, Ch., "Numerical modeling of the effect of latitude-inhomogeneous gravity waves on the circulation of the middle atmosphere," Izvestia. Atmos. Oceanic Phys. 41(1), 9 – 18 (2005).

[9] Suvorova, E. V. and Pogoreltsev, A. I., "Modeling of nonmigrating tides in the middle atmosphere," Geomagn. Aeronomy 51(1), 105-115 (2011).

[10] Pogoreltsev, A. I., Savenkova, E. N. and Pertsev, N. N., "Sudden stratospheric warmings: the role of normal atmospheric modes," Geomagn. Aeronomy 54(3), 357-372 (2014).

[11] Swinbank, R. and O'Neill, A., "Stratosphere-troposphere assimilation system," Mon. Weather Rev. 122, 686–702 (1994).

[12] Gavrilov, N. M., Koval, A. V., Pogoreltsev, A. I. and Savenkova, E. N., "Numerical simulation of the influence of stationary mesoscale orographic waves on the meridional circulation and ozone fluxes in the middle atmosphere," Geomagn. Aeronomy 54(3), 381–387 (2014).

[13] Gavrilov, N. M., Koval, A. V., Pogoreltsev, A. I. and Savenkova, E. N., "Simulating influences of QBO phases and orographic gravity wave forcing on planetary waves in the middle atmosphere," Earth Planets Space 67, 86 (2015).

[14] Garny, H., Grewe, V., Dameris, M., Bodeker, G. E. and Stenke, A., "Attribution of ozone changes to dynamical and chemical processes in CCMs and CTMs," Geosci. Model Dev. 4, 271–286 (2011).