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Numerical simulations of the orographic waves impact on the vertical ozone fluxes in the middle atmosphere during stratospheric warming

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ABSTRACT

Numerical simulations have been performed to estimate sensitivity of ozone fluxes to the impact of mesoscale orographic gravity waves (OGWs) in the middle atmosphere at different phases of simulated stratospheric warming (SW) events during boreal winter. The numerical model of general circulation of the middle and upper atmosphere (MUAM) with implemented OGW parameterization has been used. The simulations demonstrate a weakening of the vertical ozone fluxes during and after simulated SW compared to the time intervals before SW, which corresponds to the changes in meridional mean circulation. The most significant differences in ozone fluxes due to OGW effects are obtained in the Northern Hemisphere. These differences are up to 20% at middle latitudes and may reach 100% at high latitudes. The results indicate a strong sensitivity of the meridional circulation and hence, the ozone fluxes to the influence of OGWs at different phases of simulated SWs.

Keywords: numerical modeling, ozone transport, stratospheric warming, orographic waves, atmospheric circulation

1. INTRODUCTION

Studies of dynamical interactions between different atmospheric layers have recently received increasing attention. These interactions significantly intensify during sudden stratospheric warming (SSW) events, which consist of substantial temperature increases (up to 30 – 40 K) at middle northern latitudes at altitudes 30 – 50 km and simultaneous decreases (or reversals) of the zonal-mean eastward flow. SSW development depends on breaking of planetary waves (PWs)[1,2,3]. During the recent years, plenty of studies are devoted to investigation of influence of SSWs on the formation of weather anomalies and climate changes[4,5,6,7]. Many SSW characteristics were analyzed from observations[8]. Changes in meridional mean circulation during different phases of stratospheric warming were recently studied by de la Cámara et al.[9], Koval et al.[10].

For the proper study of dynamical coupling in the atmosphere, accounting for energy and momentum transport by internal waves is required. One of the important sources of mesoscale waves are inhomogeneities of the Earth's surface[11]. Generation of orographic gravity waves (OGWs) by the surface inhomogeneities and transport of their energy can significantly alter the general circulation, and, hence, produce changes in the SSW development. Recently, Gavrilov et al.[12] developed and implemented a parameterization of dynamical and thermal effects of stationary OGWs into a mechanistic numerical model simulating general circulation at altitudes from the troposphere up to the thermosphere. They showed that OGWs could significantly affect the general atmospheric circulation in the middle and upper atmosphere.

Ozone concentration in the atmosphere depends primarily on the ozone transport between the stratosphere and troposphere[13]. Dynamical changes during the SSW events may also significantly affect the global ozone distribution[14]. Sensitivity of ozone transport to the effects of OGWs at different phases of quasi-biennial oscillation (QBO) of the low-latitude zonal flow was recently investigated by Gavrilov et al.[15]. It was shown that simulated changes in vertical velocities producing respective changes in ozone fluxes could reach 40 - 60% in the Northern Hemisphere in the middle atmosphere.

In the current study, we focus on the changes in the ozone fluxes at altitudes 0 – 100 km during time intervals before, during, and after the SSW simulated in the general circulation middle and upper atmosphere model (MUAM) with implemented three-dimensional ozone distribution model, with and without taking into account the OGW dynamical and thermal impact.

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2. THE NUMERICAL MODEL AND METHODOLOGY

In order to study the sensitivity of the atmospheric dynamics and ozone transport to the OGW propagation during SSW events, a three-dimensional mechanistic numerical model of general atmospheric circulation MUAM[16,17] is used. The horizontal resolution of the model is 36x64 grids along the latitudes and longitudes, respectively. The log-isobaric height with 48 vertical levels at the altitudes from the ground to 135 km is used. Pogoreltsev et al.[18] showed that inclusion of normal atmospheric modes into the MUAM could allow to simulate minor or major SSW events, so is considered as one of a few mechanistic GCMs able to reproduce major stratospheric warmings.

Vertical transport of air particles during the general circulation of the atmosphere produces vertical ozone fluxes, which are important for the climate formation. The MUAM includes a three-dimensional distribution of the ozone mixing ratio, which takes into account the climatic spatial ozone structure, averaged over the years 1996 – 2005[19]. Ozone distribution is a combination of three semiempirical ozone distribution models: the ECMWF (project ERA_40)[20], GOME (Global Ozone Monitoring Experiment)[21] and the Berlin Model[22]. For examining the influence of OGWs on atmospheric dynamics, the parameterization of dynamical and thermal effects of stationary OGWs[23] was implemented into the MUAM. This parameterization performs calculations of vertical profiles of OGW amplitudes, total vertical wave energy flux and accelerations of horizontal wind produced by stationary OGWs. The parameterization uses method of "subgrid orography" that takes into account the Earth surface inhomogeneities with horizontal scales smaller than the horizontal grid of the MUAM.

The phases of stratospheric vacillations[16] of zonal wind influence the dates of stratospheric warming as well as their strength. In the MUAM, the changes in phases of stratospheric vacillations can be achieved by changing the starting day of the daily variations of solar heating during the model initialization. To obtain 12 pairs of the MUAM runs (with and without OGW parameterization, respectively), the starting day for the diurnal variability of the solar heating was shifted between 120th and 142nd model days[10].

3. RESULTS OF SIMULATIONS

The statistical confidence of the performed simulations is based a set of 12 pairs of the MUAM runs. The methods and approaches used to obtain ensembles of model runs were described in details by Koval et al.[10]. Numerical simulations show existence of minor or major SSW events at altitudes 20 – 60 km at high northern latitudes in all model runs in January-February. The dates of major and minor warming events were defined at altitudes up to 50 km similar to Koval et al.[10]. The term "sudden stratospheric warming" is usually associated with sharp temperature increases at the 10 hPa pressure level[24]. To differentiate warming events obtained in our model at higher altitudes from traditionally considered SSWs, we call them below as stratospheric warmings (SWs). We chose three 11-day intervals (referred thereafter as "before", "during" and "after") for the each SW date and averaged velocity and ozone flux differences for each time interval over 12 pairs of runs. The global atmospheric circulation can perform transport of atmospheric tracers, one of which could be atmospheric ozone. The mean vertical ozone flux F_{oz} was calculated using the equations from[15].

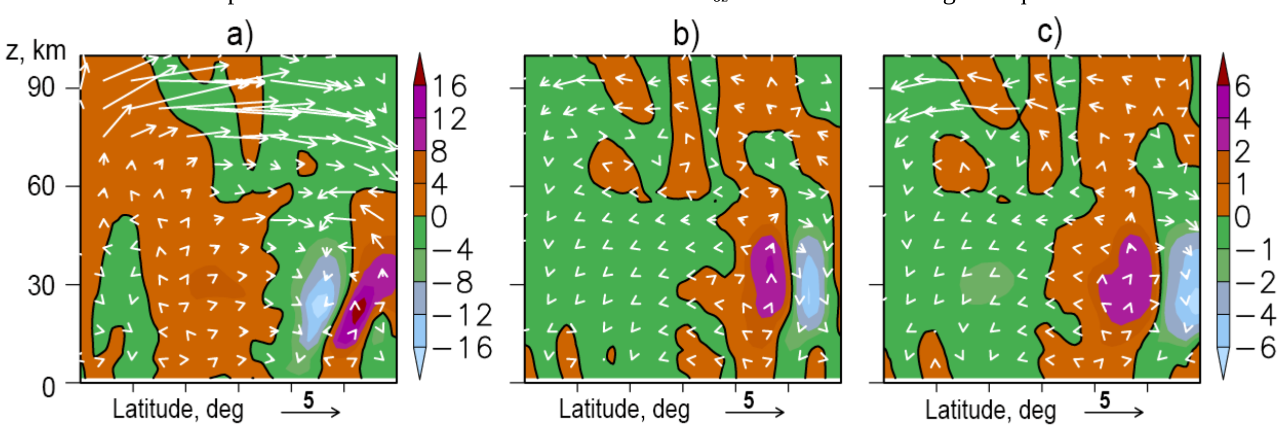

Figure 1. Zonal-mean velocity vector in the meridional plane in m/s (arrows) and associated F_{oz} in 10^{13} $m^{-2}s^{-1}$ (shaded), averaged over time intervals before SW (a) and differences between those quantities in time intervals during and before (b), also after and before (c) SW simulated with the MUAM. The vertical wind component is multiplied by 10^2. Solid contours correspond to zero levels.

Figure 1a shows zonal-mean velocity vector in the meridional plane in m/s (arrows) and vertical component of associated ozone flux (shaded), averaged over time intervals before SWs with inclusion of the OGW effects. The arrows illustrate global circulation cell from the Southern to the Northern Hemisphere above altitude of 60 km, the Brewer-Dobson circulation cell below 50 km and upward flows at the high-latitude Northern Hemisphere at altitudes 20 – 60 km. These circulation cells can significantly contribute to the ozone transport during the winter season. At altitudes above 60 km, the ozone fluxes (shaded in Figure 1a) are upward in the Southern Hemisphere and downward in the Northern Hemisphere. Below 50 km, the ozone fluxes are upward at low and high latitudes and downward at middle latitudes of both hemispheres in agreement with the of meridional mean circulation cells.

Shaded areas and arrows in Figures 1b,c show respective average differences in the zonal-mean vertical ozone fluxes and meridional flows between intervals during and after simulated SWs and respective intervals before SWs, which are averaged over 12 MUAM runs including OGW parameterization. The signs of F_{oz} differences in Figures 1b and 1c are generally opposite to the F_{oz} values in Figure 1a. Therefore, magnitudes of upward and downward ozone fluxes become smaller during and after simulated SW events, which corresponds to the changes in meridional mean circulation. The weakening of upward and downward ozone fluxes at altitudes 20 – 40 km at the middle latitudes of the Northern Hemisphere may reach 30% during SWs and 30 – 40% after simulated SW events. At altitudes above 70 km, the weakening of vertical ozone fluxes can reach 30 – 50% in Figures 1b and 1c compared to Figure 1a.

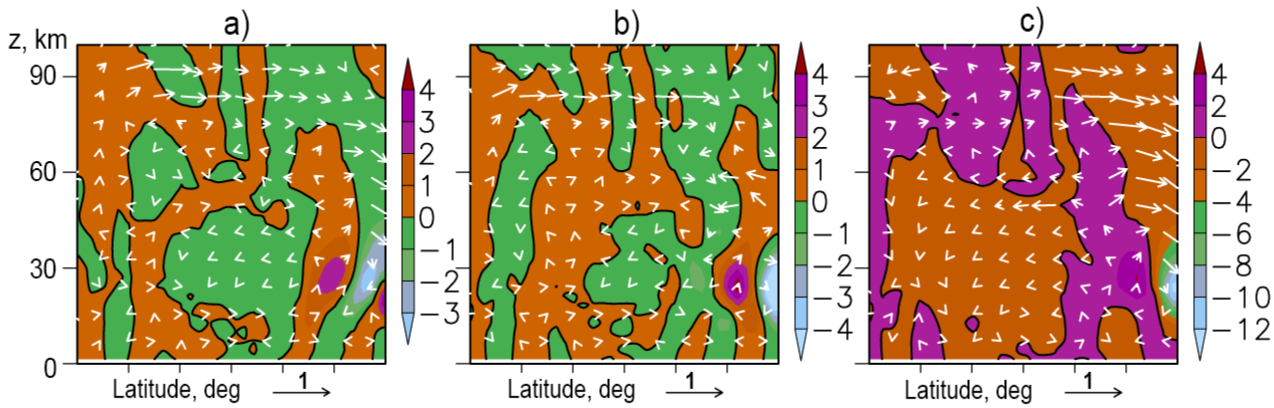

Figure 2. Average differences in F_{oz} in 10^{13} $m^{-2}s^{-1}$ (shaded) and in velocity vectors in the meridional plane in m/s (arrows) before (a), during (b) and after (c) simulated SW events due to inclusion of OGW dynamical and heating effects into MUAM. The vertical wind component is multiplied by 102. Solid contours correspond to zero levels.

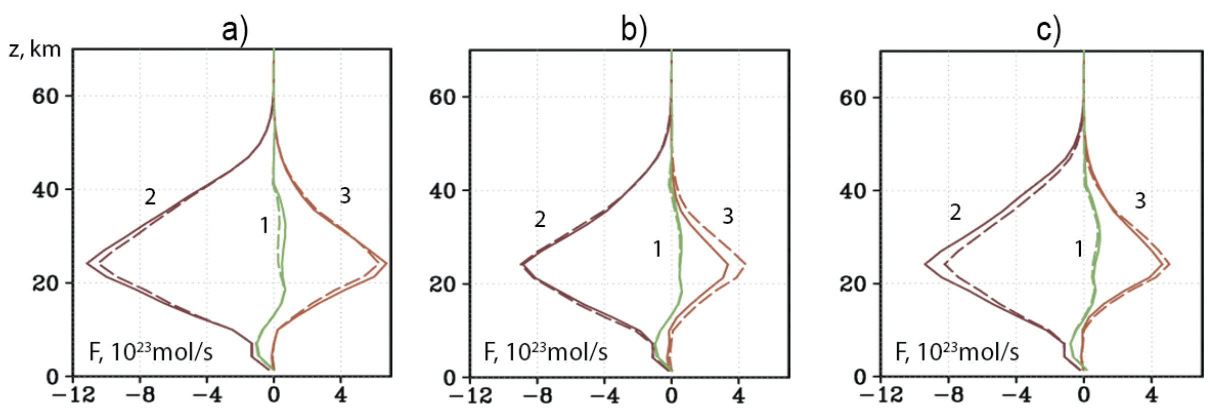

Figure 3. Total vertical ozone fluxes in 10^{23} mol/s integrated over areas of latitude bands 0 - 30ºN (1), 30ºN – 60ºN (2) and 60ºN – 90ºN (3) for time intervals before (a), during (b) and after (c) simulated SSW. Solid and dashed lines correspond to simulations including and excluding OGW effects.

Figures 2(a-c) show F_{oz} differences in F_{oz} and in zonal-mean meridional flows simulated in the MUAM with and without inclusion of OGW dynamical and heating effects in time intervals before, during and after simulated SW events. The most significant differences in F_{oz} are obtained at altitudes 20 – 40 km of the Northern Hemisphere. At different phases of simulated SW, magnitudes of F_{oz} differences may reach 15 – 20% at the middle latitudes and up to 100% near the North Pole. In the Southern (summer) Hemisphere, the meridional velocity and ozone flux differences are smaller in Figure 2. This can be explained by better conditions for OGW propagation and by the stronger influence of OGWs on the general circulation of the atmosphere in the winter hemisphere compared to the summer one[12].

The differences in Figure 2 indicate a strong sensitivity of the meridional circulation and hence, the ozone fluxes to the influence of OGWs at different phases of simulated SWs. One of the reasons for this behavior could be significant changes in amplitudes of planetary-scale waves SW due to the OGW impact. In addition, the Coriolis force in the MUAM equation of motion makes the negative (directed westwards) zonal accelerations created by OGWs, which decelerates the mean eastward atmospheric flow, to correspond to the negative differences in meridional velocity at middle latitudes of the Northern Hemisphere.

For the further analysis of the changes in the ozone fluxes in the middle atmosphere due to the OGW impact, we considered vertical ozone flux at different latitudinal bands. Low-latitude bands have larger areas than the high-latitude bands, which can influence the total ozone flux. Figure 3 reveals the integral vertical ozone fluxes over areas of latitude bands 0 – 30ºN, 30ºN – 60ºN and 60ºN – 90ºN (marked as 1 – 3, respectively) before, during and after simulated SWs (a-c, respectively) including and excluding OGW impact (solid and dashed lines, respectively). Substantial fluxes are observed at altitudes of the ozone concentration maxima (20 – 30 km). Considerations of Figure 3 show that the largest total ascending ozone fluxes in northern winter season are produced by the Polar Vortex at high latitudes of the Northern Hemisphere (lines 3). Largest descending ozone fluxes occur at middle latitudes of the Northern Hemisphere (lines 2). High-latitude upward ozone fluxes in the Northern Hemisphere become smallest during simulated SWs, then recover but remain smaller after SWs compared to those before SWs in Figure 3. Comparisons of solid and dashed lines in Figure 3 show that OGW influence can change the ozone vertical fluxes up to 10 – 15%. At high latitudes, the total ozone flux between 60º and 90º increases due to OGW before SW and decreases during and after the event. Between 30º and 60º, the most remarkable increase of total ozone flux occurs after SW.

4. CONCLUSION

Numerical simulations of the general atmospheric circulation in altitude range 0 – 100 are performed for the boreal winter using the MUAM model with implemented three-dimensional ozone distribution. The changes in the ozone transport in the middle atmosphere during 11-day time intervals at different phases of SW events are studied. Recently developed OGW parameterization scheme is implemented into the MUAM in order study sensitivity of vertical ozone fluxes to the OGW thermal and dynamical impact. In order to obtain sufficient statistical confidence, the results of numerical simulations have been averaged over 12 pairs of the MUAM runs with and without OGW parameterization.

The results of analysis show a weakening of the vertical ozone fluxes (up to 30 – 40%) in time intervals during and after simulated SWs compared to the values before the events. The most significant differences in the vertical ozone fluxes are obtained at altitudes 20 – 40 km at middle and high latitudes of the Northern Hemisphere. At altitudes above 70 km, the weakening of vertical ozone fluxes can reach 30–50%

At different phases of simulated SW, the most significant differences in F_{oz} due to OGW impact are obtained at altitudes 20 – 40 km at middle and high latitudes of the Northern Hemisphere. In the Southern Hemisphere, the meridional velocity and ozone flux differences are smaller due to features in OGW propagation in the summer middle atmosphere. The differences in F_{oz} indicate a strong sensitivity of the meridional circulation and the ozone fluxes to the influence of OGW at different phases of simulated SWs.

Considerations of different latitude bands in the Northern Hemisphere show that the largest total ascending ozone flux in northern winter season are produced by the Polar Vortex at high latitudes of the Northern Hemisphere, while largest descending ozone flux occurs at the middle latitudes. Upward ozone flux at high latitudes of the Northern Hemisphere becomes smallest during simulated SW, then recovers but remains smaller after SW compared to that before SW. OGW influence can change the ozone vertical flux up to 10 – 15% at different latitude bands.

The performed numerical experiments are important for understanding the contributions of different factors to formation of transport and mixing of long-lived atmospheric gas components by the global circulation. Our study shows that the global meridional circulation and ozone transport in the middle atmosphere may significantly vary due to OGW dynamical and thermal effects. We carried out the diagnostics of only mechanistical ozone transport by atmospheric circulation, because the MUAM does not simulate photochemical processes in the atmosphere. The use of predefined ozone distributions in the model may give correct results of ozone fluxes diagnostics only for relatively short time intervals in the stratosphere and troposphere, where the photochemical ozone sources are weak.

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