Final Report for Project **1139**

Project title: **Ozone-gravity wave interaction**

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# Final Report (30.12.2021)

*(1) Introduction*

Mesoscale gravity waves (GWs), with horizontal wavelengths of about 100 km to 2000 km, are produced in the troposphere and propagate upward to the stratosphere and mesosphere, where the increase of the GW amplitudes with height due to the decreasing density is usually described by exponential growth ($\sim e^{z/2H}$, where H is the scale height). Gravity wave breaking processes are an important driver of the time-mean circulation of the stratosphere and mesosphere (e.g., Andrews et al., 1986; Fritts and Alexander, 2003). Because of the limited spatial and temporal resolution, current general circulation models (GCMs) used for climate change studies do not resolve GWs or gravity wave breaking processes but still need a variety of gravity wave drag (GWD) parameterizations, where a spectrum of tropospheric GWs is prescribed. Recent Lidar measurements have shown that the increase in the amplitudes of gravity wave potential energy density (GWPED, which is proportional to the square of the GW temperature amplitudes $T'$) between middle stratosphere and upper mesosphere is much stronger during daylight than nighttime by a factor of about ~4 at summer midlatitudes and a factor of ~8 at mid-summer polar latitudes (Kaifler et al., 2015; Baumgarten et al., 2017, 2018). The related processes are not understood up to now and could significantly affect the circulation produced by high-altitude GCMs when incorporating into the GWD parameterizations.

The basic idea of the project is that ozone-temperature coupling might lead to a substantial amplification of the GW amplitudes in the upper stratosphere/lower mesosphere (USLM) region. The coupling between ozone-photochemistry and temperature is particularly strong in the upper stratosphere (Brasseur and Solomon, 1995) where the time-mean ozone mixing ratio is decreasing with height; therefore, an initial uplift of an air parcel must lead to a local increase in ozone and in the heating rate compared to the environment, and, hence, to an amplification of the initial uplift. The aim of the project was to provide a formulation of ozone-gravity wave interaction, based on standard equations describing upward propagating GWs in a background flow, which could be suitable for incorporating in a GWD, and to perform some test simulations with the Earth-System-Model MPI-ESM-MR (provided by the MPI-Met, Hamburg) to analyse the effect of this process on the time means and long-term changes in the circulation of the tropo-, strato- and mesosphere.

*(2) Outline of the project work*

At the beginning, the project work was designed for a project period of approximately two years. In a first step, standard solutions of upward propagating GWs were formulated including linear ozone-temperature coupling, providing quantification of the local amplification of the GW amplitudes at a specific level as well as of the cumulative amplification during the successive level-by-level propagation from the middle stratosphere to the upper mesosphere, where zonal means of temperature, zonal wind, ozone and ozone-related heating rate derived from the chemistry-climate model HAMMONIA were used as background (data provided by H. Schmidt, MPI Hamburg). These analytic first-guess solutions are formulated excluding other effects like small-scale diffusion, numerical noise or wave breaking processes to focus on the effects of ozone-gravity wave interaction only, which is necessary before introducing a suitable parameterization into a GCM.

The resulting effects of ozone-gravity wave coupling on the GW amplitudes are carefully analysed in dependence on the wave characteristics (internal frequencies, horizontal and vertical wavelengths), including daylight-nighttime conditions during the vertical propagation through the USLM region in case of small vertical group velocities. The results are briefly summarized in the next subsection and given in detail in the accompanying uploaded paper (Gabriel, 2021). Unfortunately, because of a strong delay during the last two years, the planned simulations were not finished within the two-year project period. Like other GCMs, the MPI-ESM-MR uses a prescribed tropospheric GW source spectrum and a variety of tuning parameters in the gravity wave drag (GWD) parameterizations, which particularly requires extensive test simulations when incorporating the process of ozone-gravity wave coupling, particularly because the effect is dependent on the characteristics of a specific initial GW. Some consequences on GWD parameterizations and expected effects on the time-mean circulation are briefly discussed below and in the uploaded paper (Gabriel, 2021). However, incorporating ozone-gravity wave coupling into high-altitude models like MPI-ESM-MR or HAMMONIA could be an interesting outlook for further project works.

*(3) Ozone-gravity wave coupling*

The basic process of ozone-gravity wave coupling is described in detail in the accompanying uploaded paper (Gabriel, 2021). Standard solutions of upward propagating GWs are formulated with and without linear ozone-temperature coupling, including an additional equation of a GW perturbation in ozone transport and ozone photochemistry. The linear coupling parameters are specified based on earlier concepts of ozone-temperature coupling in the USLM region (e.g., Brasseur and Solomon, 1995; Cordero et al. 1998, 2000; Nathan et al., 2007; Ward et al., 2010; Gabriel et al., 2011). Accordingly, the ozone-related heating rate perturbation $Q'$ is given as a first-order linear perturbation over the intrinsic wave period $\tau_i=2\pi/\omega_i$ ($\omega_i$ is the intrinsic frequency) in relation to the background, assuming the same sensitivity for both the slowly varying background and the mesoscale GW perturbation propagating within the background flow ($Q'=\mu'\cdot(Q_0/\mu_0)$ with $\mu'=\tau_i d_0\mu'/dt$). On the other hand, following Brasseur and Solomon (1995), a relative change in ozone $\Delta\mu_T/\mu_0$ due to a change in temperature $\Delta T$ is given by $\Delta\mu_T/\mu_0=-b_0(T_0)\cdot\Delta T$, where $b_0(T_0)$ describes the relation of the temperature-dependent reaction coefficients of ozone production and ozone loss; then, the GW-induced change in the source term is given by the change in temperature and the background temperature ($S'(T')=-\mu_0 b\cdot d_0\theta'/dt$, where $\theta'$ is potential temperature, $b=b_0\cdot(p/p_{00})^\kappa$ and $p_{00}$=1000 hPa).

The analytic solutions for a specific level in the ULSM reveal that the intrinsic frequency of an initial prescribed GW perturbation decreases if ozone-temperature is included, and that the accompanying amplitude increases as far as the intrinsic frequency decreases, suggesting local amplitude amplifications during daylight of up to 5 to 15% for low-frequency GWs (periods $\geq$4 hours). Subsequently, for horizontal and vertical wavelengths $L_k\geq$500 km and $L_m\leq$5 km, an analytic approach of the upward level-by-level propagation shows that the cumulative amplification at upper mesospheric altitudes leads to much stronger amplitudes during daylight than nighttime, i.e., in the GW perturbations by a factor of ~1.5 to ~3, and in the GWPED by a factor of ~3 to ~9, where the latter can quantitatively explain the over-exponential growth during daylight observed by Kaifler et al. (2015) and Baumgarten et al. (2017, 2018).

Overall, the results suggest that incorporating ozone-gravity wave coupling in numerical models either with resolved or parameterized GWs might lead to significant improvements of the models. The vertical momentum flux terms $F_{GW}=\rho_0(u'w')$ related to the GWs can be derived from local profiles $T'$ if the background is known, i.e., by $F_{GW}=\rho_0 E\cdot(k/m)$ where E denotes the GWPED (Ern et al., 2004). Therefore, the amplification of the GWPED amplitudes must lead to the same amplification of $F_{GW}$ and, if the GWs do not break at lower levels, of the associated gravity wave drag via $GWD=-\rho_0^{-1}\partial F_{GW}/\partial z$, suggesting that ozone-gravity wave coupling can efficiently contribute to the wave-driven meridional mass circulation particularly in the polar summer stratosphere and mesosphere. Considering observed long-term changes in upper stratospheric ozone derived from satellite measurements (e.g., Sofieva et al., 2017; WMO, 2018), additional sensitivity tests have shown that, for horizontal and vertical wavelengths $L_k\geq$500 km and $L_m\leq$5 km, a decrease in upper stratospheric ozone of ±10% results in a change of ±10% to ±20% in the upper mesospheric GWPED (Gabriel, 2021). Conclusively, long-term changes in stratospheric ozone might have a significant effect particularly on the mesospheric circulation.

*(4) Outlook*

Current GCMs usually use a prescribed tropospheric source spectrum of GWs with different wave characteristics and a variety of tuning parameters in the GWD parameterizations forcing the middle atmospheric circulation (e.g., Fritts and Alexander, 2003), where the extreme low temperatures observed in the summer upper mesosphere provide an important benchmark for the quality of the upwelling branch and the associated adiabatic cooling produced by the models (e.g., Hofmann et al., 2010). GCMs particularly indicate significant changes in the time-mean circulation of the upper mesosphere due to the stratospheric ozone loss over Antarctica during southern spring and early summer via the induced changes in the GWD (Smith et al., 2010; Lossow et al., 2012; Lubi et al., 2016). The results shown in Gabriel (2021) suggests that including ozone-gravity wave interaction into GCMs might lead to a substantial improvement of the used GWDs and the associated processes driving the summer mesospheric circulation, and that long-term changes in stratospheric ozone might have a stronger effect on the middle atmospheric circulation than expected up to now.

Overall, it is recommendable to incorporate the described process of ozone-gravity wave coupling in the GCMs; however, some conceptual problems arise when incorporating in a GWD, requiring some extended formulations. Generally, state-of-the-art GWD parameterizations consist of (1) a wave source spectrum with specified amplitudes and phase speeds (or wavelengths and frequencies) at a launch level in the troposphere, (2) the straight upward propagation of the GWs conserving its momentum flux (conservative growth with height), and (3) nonlinear gravity wave breaking and dissipation mechanisms if a critical level is reached (defined by u-c=0, where u is the zonal wind and c is the phase speed), or if the amplitudes exceed a specific threshold. First, considering (1), including ozone-gravity wave coupling needs sufficient information on the initial GW characteristics because the effects depend on these characteristics (e.g., information of the phase speed is not enough, wavelengths and frequencies are needed). Further, the successive change in the intrinsic frequency of a specific GW at each level of the USLM region suggests calculating the momentum flux level by level, considering that each point of a propagating wave front at a specific level is the source of a new wave at this level (Huygens principle), i.e., the approach of straight upward propagation of the GWs must be modulated towards an upward level-by-level propagation for each prescribed GW. Finally, nonlinear gravity wave breaking and dissipation mechanisms will change significantly if ozone-gravity wave coupling is included, because the change in the intrinsic frequency leads to a change in the critical level, and because the amplitudes increase with height over-exponentially; these changes could lead to the necessity for some more or less improved tuning of the GWD depending on the used model.

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