Project: **1097**

Project title: **Multiscale Dynamics of Atmospheric Gravity Waves**

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Report period: **2022-11-01 to 2023-10-31**

The project aims to enhance the comprehension of gravity wave (GW) dynamics and their subgrid-scale (SGS) parametrization in atmospheric models. In particular, GW generation mechanisms, GW interactions with the resolved flow, interactions of GWs with tracers and ice clouds, and codependencies with other SGS parameterizations are subject to the current research. While we continue to develop GW theory (e.g. Dolaptchiev et al., 2023; Achatz et al., 2023), numerical investigations are a major source of both detailed new insight and a major possibility to apply the findings to related problems. Our main tools beyond theoretical considerations are thus both idealized wave-resolving simulations, and GW parametrizations such as the developed Multi-Scale Gravity Wave Model, MS-GWaM. The latter is a transient GW parametrization implemented into a pseudo-incompressible flow solver (PincFlow, Schmid et al., 2021) as well as the high-top global model UA-ICON. Several results have been reported in peer-reviewed studies, among them the most recent insights on the wave impact on the global circulation, the quasi-biennial oscillation (QBO), and GW intermittency (Bölöni et al., 2021; Kim and Achatz, 2021; Kim et al., 2021). During the current allocation period and with the help of the DKRZ infrastructures the planned extension of these works, enabling 3-dimensional propagation of GWs, was finalized and submitted for publication by Kim et al. (2023) and Voelker et al. (2023). While the investigations concerning the implementation of orographic GWs, that is GWs excited by the flow over mountains, as well as the interaction with passive tracers and cirrus clouds have made progress in terms of implementation, and testing with idealized simulations, implementation into ICON / MS-GWaM is still undergoing. We will thus focus the present report on the submitted results.

1. MS-GWaM-3D: A 3-dimensional transient gravity wave parametrization in ICON

Within the current allocation period, we have concluded the implementation, tuning, and analysis of the 3-dimensional extension of MS-GWaM, MS-GWaM-3D. In particular, a retuning of the parametrization after changing our reference data set was done and a number of extended diagnostics were developed. The corresponding simulation results and analyses were then compared between MS-GWaM-1D (with columnar propagation only) and MS-GWaM-3D.

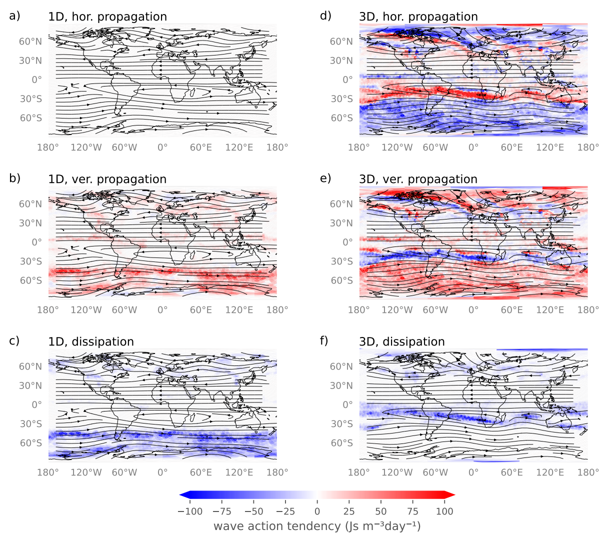

Figure 1: Wave action tendencies for MS-GWaM-1D (a-c) and MS-GWaM-3D (d-f) due to horizontal wave propagation (a, d), vertical wave propagation (b, e) and wave dissipation (c, f). All tendencies are 10-day averages for June 10-20 1991 at an altitude of $z \approx 25.1$ km. Additionally, streamlines of the horizontal wind are shown. Reproduced from Voelker et al. (2023).

We find that the contributions of the horizontal and vertical wave propagation to the wave action budget (Fig. 1) are of equal order of magnitude. This emphasizes the importance of including horizontal propagation. Moreover, it questions the validity of using columnar methods when, e.g., studying IGW distributions. Both methods do, however, perform as expected in reproducing the cold summer pole and the warm winter pole at altitudes ~ 85 km and ~ 60 km, respectively, in the climatological zonal mean. The corresponding wind reversals and the mesopause altitudes are reasonably predicted (not shown). We are thus confident that MS-GWaM-3D, as MS-GWaM-1D before it, covers some major effects of IGWs on the mean-flow dynamics, rendering MS-GWaM-3D a viable IGW parameterization. Including the horizontal propagation does, however, also introduce some important differences in the simulated climatology. In particular, the southern hemispheric winter jet is modified for MS-GWaM-3D. Possible explanations include the northward refraction of wave action near the Antarctic winter jet in MS-GWaM-3D as compared to MS-GWaM-1D. Both the 3D wave action tendencies (dipole structures in Fig. 1d and e) and the zonally averaged wave action fluxes (not shown) suggest that the 3D modulation causes IGWs to propagate northward and thus relate to a weaker gravity wave drag at high altitudes and similar latitudes. The refraction of waves into the jet may consequently result in a too strong zonal-mean zonal wind further south and at higher altitudes. These findings, among others, have been submitted in a corrsponding manuscript (Voelker et al., 2023).

2. New findings on the interaction between GWs and the QBO

With the purpose of realistic representation of GWs and the QBO and, thereby, better understanding of their dynamics, we have configured QBO simulations using ICON with MS-GWaM-3D and MS-GWaM-1D and begun to integrate them since last year. They have been completed in the current allocation period, and their results have been documented in Kim et al. (2023) of which the key finding is briefly described below.

The simulation using MS-GWaM-3D describes a realistic QBO (see also Fig. 2 of the project request) with its easterly phase penetrating down to the lower stratosphere (Fig. 2, upper left). In contrast, the simulation using MS-GWaM-1D exhibits an equatorial oscillation of 3–4-year periods with much weaker and slower penetration of the easterly phase to the lower stratosphere, which results in the underrepresentation of the equatorial easterlies at $z = 24\,\mathrm{km}$ (Fig. 2, lower left). It also shows an excessive bias of summer-hemisphere easterlies at 10°–20°. Since the experimental configurations of the two simulations are identical up to GW propagation being either 1D or 3D, the observed differences in the tropical wind stem solely from lateral GW propagation. It is found from our experiment that GWs with horizontal wavelengths larger than $\sim$300 km can propagate substantial horizontal distances in the stratosphere. In particular, in the tropics, such far-distance propagation tends to occur under easterly mean flows with modest speeds and for waves carrying easterly momentum. Fig. 2 (right) shows an example of oblique propagation in the tropics, as parameterized by MS-GWaM-3D. GWs generated by convection at around 15°N propagate toward the equator through weak easterly mean flows in the lower stratosphere until they dissipate at $z \sim 24\,\mathrm{km}$ in the QBO-easterly shear layer. The obliquely propagating GWs provide a significant amount of easterly-momentum forcing near the equator, which contributes to the downward penetration of the easterly QBO phase and to the acceleration of the QBO. Similar events are found to occur at this QBO phase robustly in every cycle of the simulated QBO. The obliquely propagating GWs therefore play a crucial role in the QBO dynamics.

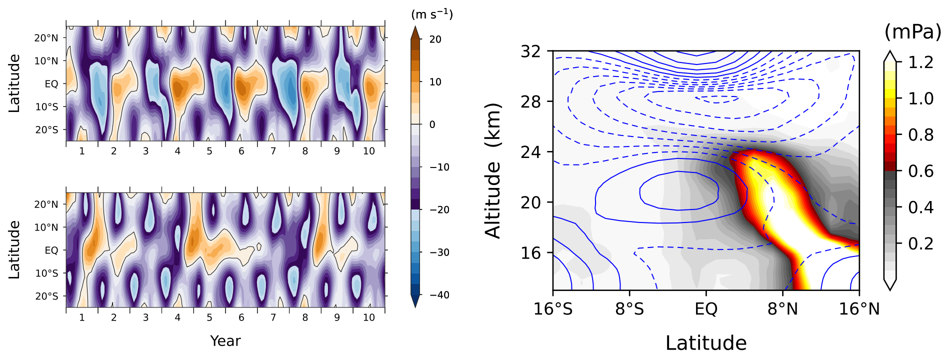

Figure 2: Zonal-mean zonal winds in the tropics at $z = 24\,\mathrm{km}$ ($p \approx 30\,\mathrm{hPa}$) in the QBO simulations using MS-GWaM-3D and MS-GWaM-1D (upper and lower left, respectively). In the simulation using MS-GWaM-3D, zonal-mean upward fluxes of easterly momentum due to gravity waves that are generated at 12–13 UTC 5 June in Year 5 (as an example) with horizontal wavelengths of 300–1000 km are plotted in the right panel (shading) along with the zonal-mean zonal wind (contours: negatives with dashed lines and non-negatives with solid lines, at the intervals of $5\,\mathrm{m\,s^{-1}}$).

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