Project: **1097**
Project title: **Multiscale Dynamics of Atmospheric Gravity Waves**
Principal investigator: **Ulrich Achatz**
Report period: **2023-11-01 to 2024-10-31**

The overall project goal is the understanding of gravity wave (GW) dynamics and its use for the development of a state-of-the-art GW parameterization (GWP) for atmospheric models (Achatz et al., 2024). For this purpose we study GW generation mechanisms, GW interactions with the resolved flow, and interactions of GWs with tracers, turbulence and ice clouds. We have continued to develop GW theory (Dolaptchiev et al., 2023; Achatz et al., 2023), but intensive numerical investigations are also a major tool. We use idealized wave-resolving simulations, and GW parametrizations such as the Multi-Scale Gravity Wave Model (MS-GWaM). The latter is a transient GW parametrization implemented into a pseudo-incompressible flow solver (PincFlow, e.g. Jochum et al., 2024) as well as into the high-top global model UA-ICON (e.g. Voelker et al., 2024). Results that have been reported in peer-reviewed studies are, e.g., insights on the impact of GW transience and lateral propagation on GW intermittency, on the global circulation (e.g. Voelker et al., 2024), and on the quasi-biennial oscillation (QBO, Kim et al., 2024). In the following, we will focus on the two most recent key publications that have been enabled by DKRZ infrastuctures and we will describe partially preliminary results that have been obtained using those infrastructures in the implementation of an orographic wave source into MS-GWaM, on the interaction between GWs and turbulence, and on the GW impact on cirrus-cloud formation. For conciseness, we cite for the most part only own most recent manuscripts. More information can be found in the references therein.

Within the current allocation period, we have concluded the implementation, tuning, and analysis of the **3-dimensional extension of MS-GWaM**, MS-GWaM-3D, and the results have been published by Voelker et al. (2024). The corresponding simulation results and analyses were then compared between MS-GWaM-1D (with columnar propagation only) and MS-GWaM-3D. We find that the contributions of the horizontal and vertical wave propagation to the wave action budget are of equal order of magnitude. This emphasizes the importance of including horizontal propagation, that also introduces significant differences in the simulated climatology. In particular, the southern hemispheric winter jet is modified for MS-GWaM-3D. This seems to be due to the northward refraction of wave action near the Antarctic winter jet in MS-GWaM-3D as compared to MS-GWaM-1D, leading to a weaker gravity wave drag at high altitudes and similar latitudes.

With the purpose of a **more realistic representation of the impact of GWs on the QBO** we have configured and analyzed QBO simulations using ICON with MS-GWaM-3D and MS-GWaM-1D (Kim et al., 2024). The simulation using MS-GWaM-3D describes a realistic QBO with its easterly phase penetrating down to the lower stratosphere. In contrast, the simulation using MS-GWaM-1D exhibits an equatorial oscillation of much too long 3–4-year periods with much weaker and slower penetration of the easterly phase to the lower stratosphere (Fig.1 of the proposal). These differences in the tropical wind stem solely from lateral GW propagation. GWs with horizontal wavelengths larger than $\sim$300 km, generated by convection at around 15°N, propagate toward the equator through weak easterly mean flows in the lower stratosphere until they dissipate at $z \sim 24$ km in the QBO-easterly shear layer. They provide a significant amount of easterly-momentum forcing near the equator, contributing to the downward penetration of the easterly QBO phase and to the acceleration of the QBO. Hence, obliquely propagating GWs play a crucial non-negligible role in QBO dynamics.

For investigations on the **interaction between GWs and turbulence** we have coupled MS-GWaM in ICON with the operational turbulent-kinetic-energy (TKE) turbulence parameterization (Doms et al., 2021) by (i) including the production by GW shear as a source in the prognostic TKE equation and (ii) including damping of GW action by turbulent viscosity and diffusivity. In preliminary results we see a significant effect on the zonal-mean winds and temperatures in the middle atmosphere (not shown) and on the modeled TKE, and hence also mixing. Fig. 1 shows the ratio of the increase in the zonal mean TKE by the production via GW shear based on a comparison between eight January simulations using ICON/MS-GWaM with and without coupling between MS-GWaM and the TKE turbulence scheme. Passive tracers appear to be affected as well (also not shown). Consolidated results are to be obtained and reported in the next allocation period.

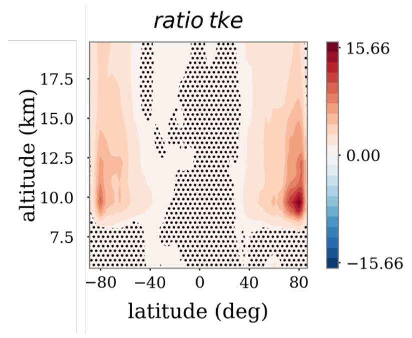

Figure 1: The increase in the January and zonal mean TKE in ICON by the production via GW shear, by coupling MS-GWaM with the TKE parameterization.

For studies of the **impact of GWs on cirrus clouds**, we have implemented a coupled approach to represent gravity wave (GW)-induced cirrus clouds. The two-moment ice scheme of Köhler and Seifert (2015) has been extended to include the effect of parameterized GWs on homogeneous ice nucleation ((Dolaptchiev et al., 2023, Kosareva et al., 2024, submitted to *GMD*). A comparison between the prototype parameterization and a time-integrated reference physics shows good agreement, proving the general validity of the approach. Further analysis has been conducted to assess the effect of the GW forcing on the ice number concentration, revealing a noticeable difference compared to a version of the scheme without GW impact (Fig. 2). Additional tests and further refinement of the scheme are still required, but the initial results indicate that the inclusion of GW-cirrus interactions has a significant impact on the ice number concentration.

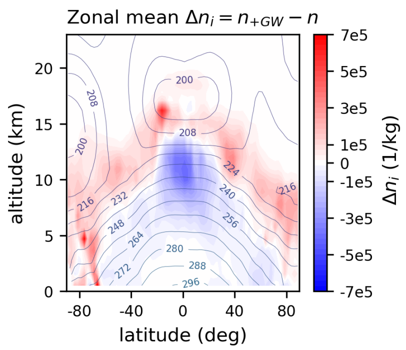

Figure 2: The impact of coupling MS-GWaM and ice physics on the zonal mean ice number concentration in ICON, shown as the difference from a control run without GW forcing after one week of computations.

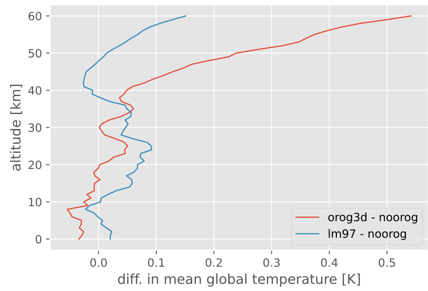

Figure 3: Altitude-dependent global mean temperature difference from a control run without orographic GWs (*noorog*) for two implementations of orographic GWs effects, including orographic GWs into MS-GWaM (*orog*) or describing them separately using Lott and Miller (1997, *lm97*).

MS-GWaM in ICON has hitherto parameterized non-orographic GWs due to convection and other background sources, while mountain waves have been described by the more conventional approach of Lott and Miller (1997, henceforth termed *lm97*) that does not take GW transience and lateral propagation into account. Two lines of investigation have been followed with the goal to **include the parameterization of orographic GWs into MS-GWaM**: (i) In the first of those an orographic-source formulation following linear theory has been implemented into PincFlow and tested against GW resolving simulations (Jochum et al., 2024). It is found that transience can have a significant impact on the interaction between mountain waves and resolved flow, and that MS-GWaM is able to capture this fairly accurately. In the second (ii) a Constrained Spectral Approximation (CSA) method has been developed and validated to provide a highly efficient Fourier decomposition of the subgrid-scale part of topography that fully respects the triangular grid structure of ICON and the physical and computational constraints of MS-GWaM (Chew et al., 2024). This decomposition has been used for the implementation of a mountain-wave source into ICON/MS-GWaM that is based on linear theory. First results involving all three GW sources (convection, background, orography) show results close to the previous setup using *lm97*. Figure 3 compares the mean global temperature differences between simulations using both setups (indicated as *orog* and *lm97*) against a simulation with orographic GW parameterization switched off (denoted as *noorog*).

Finally, the **code has also been re-factored for better usability by the climate modeling community**. The now available external shall be made part of the official ICON code maintained by DWD.

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