Project: **1097**
Project title: **Multiscale Dynamics of Atmospheric Gravity Waves**
Principal investigator: **Ulrich Achatz**
Report period: **2021-11-01 to 2022-10-31**

The overall goal of this project is the improvement of the parameterization of subgrid-scale (SGS) internal gravity waves (GWs) and hence improved simulations of their effect on the resolved mean flow in atmospheric general circulation models. In this pursuit the transient GW parameterization MS-GWaM (Multi-Scale Gravity Wave Model) has been developed and implemented into a pseudo-incompressible flow solver (PincFlow) 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, JAS; Kim et al. 2021, JAS; Kim and Achatz 2021, GRL). These studies did, however, rely on the assumption of exclusively 1-dimensional (i.e. columnar) propagation of gravity waves. In the course of the last year a robust implementation of a 3-dimensional version of MS-GWaM, allowing for the lateral propagation of GWs, has been achieved and rigorously validated through this year. Moreover, improvements on the gravity-wave sources due to convection have been implemented and tested successfully. Manuscripts on the description of the 3D transient model (1), insights about the effects of the lateral propagation both on the QBO (2) and on (3) GW intermittency are currently in preparation. The report below details on the first two topics.

(1) Lateral propagation in MS-GWaM. While the implementation with correct lateral propagation was conducted in the last project period (see report 2021) we could validate the approach and conduct a first set of global realistic experiments (32 runs with 2 months model time each) as well as a range of short integrations with extended diagnostics. While simulated zonal-mean wind and temperature climatologies are in reasonable agreement with satellite climatology (URAP, not shown), we find various significant differences between simulations with (3D) and without (1D) lateral propagation. From these we highlight two examples in the following summary.

Key features of MS-GWaM are the vertical and horizontal transport of spectral wave-action density, characterizing the amplitude of the GW field, and its dissipation due to wave breaking. For a quantification of these processes we consider the corresponding wave-action budget. In particular we find that the horizontal divergence of the wave-action flux is of the same order of magnitude as both the vertical divergence and the dissipation term (Fig. 1). We can therefore conclude that the horizontal propagation has a significant influence and may not be neglected, in contrast to the present procedure in traditional GW parameterizatons.

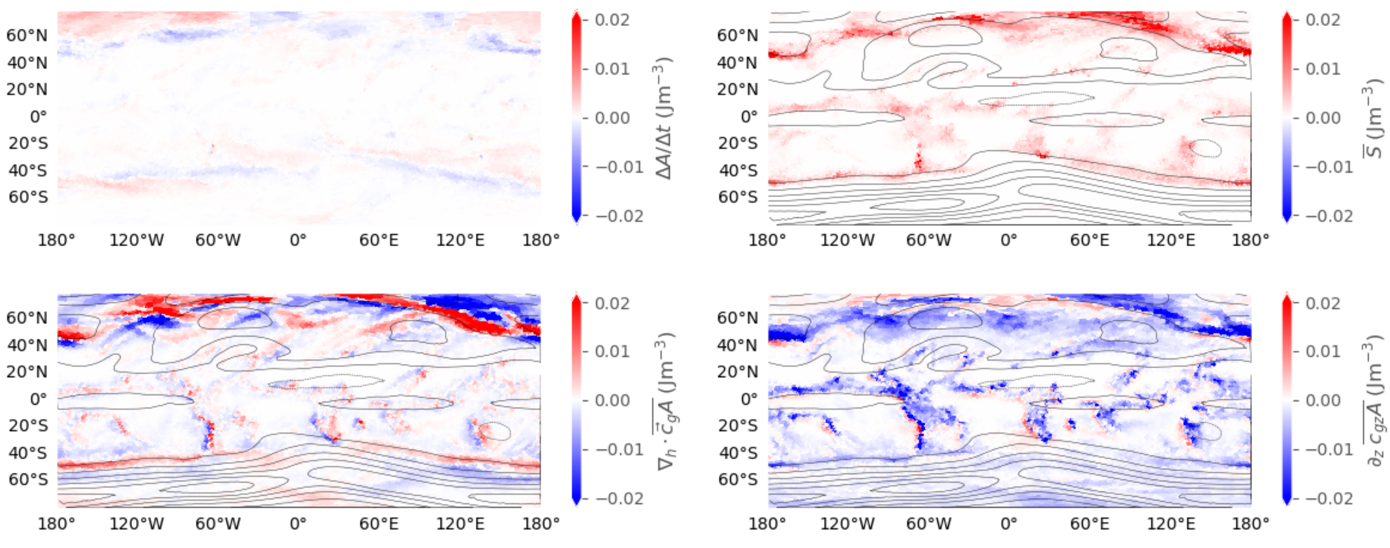

Figure 1: Contributions to the time-averaged wave action conservation as diagnosed from a 2-week integration (in June 1991) with MS-GWaM: (top left) the temporal change in the wave action, (bottom left) the horizontal and (bottom right) vertical components of the wave action flux divergence, and (top right) the wave dissipation, along with the mean zonal wind (black contours). The analysis has been done for the altitude $z \approx 20.2$ km.

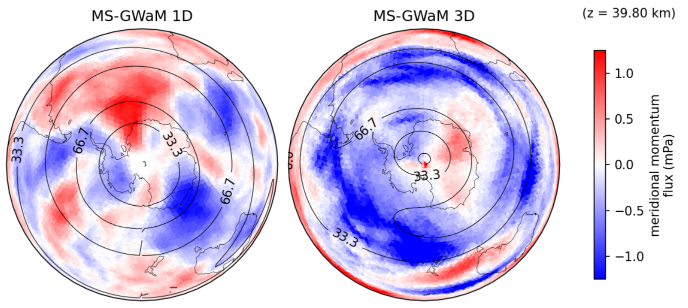

Figure 2: Meridional momentum fluxes for the 1D implementation (left panel) and the 3D implementation (right panel) near the Southern polar vortex averaged over June 1991 at an altitude $z \approx 39.8$ km.

Moreover, the GW dynamics is strongly bound to the horizontal distribution of the mean flow, quite in contrast to the result from 1D simulations. As an example we show the meridional GW momentum flux near the southern polar vortex averaged over June 1991 (Fig. 2). The two different implementations (1D and 3D) yield quite different results. The 1D case exhibits a column-wise meridional momentum flux that is independent of a polar vortex which is centered around the geographic pole. In contrast, the 3D parameterization leads to a slightly shifted polar vortex and a wave refraction into the jet. This agrees with typical observational findings (e.g. Hindley et al. 2020, GRL).

Two manuscripts describing these results and related effects on GW momentum-flux intermittency are currently in preparation (Völker et al. 2022, Kim et al. 2022).

(2) Lateral GW propagation and the QBO. QBO simulations using ICON/MS-GWaM have been investigated since last year. Particularly in this year (a) we have begun using the 3D variant of MS-GWaM, (b) we have introduced an additional large-scale component of the convective GW source (taking into account the contribution of mesoscale convective systems), (c) and we have introduced a new scale-selective vertical damping of divergence in the ICON dynamical core. The latter is to control vertical noise detected in our runs where the existing 2nd-order vertical numerical diffusion had to be suppressed for simulations of the vertically fine QBO structure. Following these modifications, both the strength of the GW source and a few parameters of the ICON dynamical core (e.g. vertical + horizontal damping of divergence) had to be adjusted within the course of several tens of sensitivity runs for 3–6 years each. This task required considerable computational resources: ∼1.3 million node hours of Levante Compute (exceeding the granted amount of ∼0.27 million node hours) had to be used due to (a) a large number of sensitivity runs and (b) a larger number of ray volumes (∼40,000 per model-grid column) as compared to the usual setup of 3D MS-GWaM, required here for simulations of the tropical QBO. Thanks to DKRZ's allowance for the exceeding resources, we have been able to identify a configuration that simulates the QBO with reasonable ICON-dynamics/GW-source parameters.

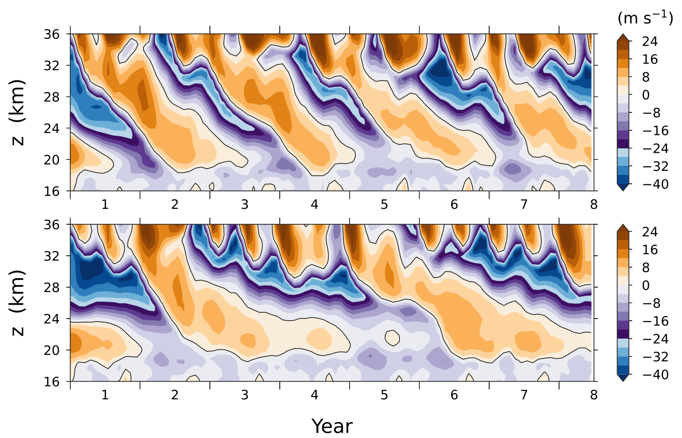

Figure 3: Time–height cross-sections of zonal mean zonal winds in the tropical stratosphere (5°N–5°S) simulated using ICON with (top) 3D MS-GWaM and (bottom) steady-state columnar GW parametrization.

Figure 3 (top) shows the zonal-mean zonal wind simulated using the final configuration set up from the sensitivity runs. The oscillation exhibits realistic magnitudes of both westerlies (∼15 m/s) and easterlies in the middle stratosphere (∼35 m/s), while the easterlies below $z \sim 24$ km are somewhat weaker than in the real atmosphere. The latter may be due in part to an under-representation of westward propagating planetary-scale equatorial inertia-gravity waves. To investigate the effect of 3D transient processes of GWs, this result is compared to that from the simulation using a steady-state columnar GW parameterization where the same wave sources have been employed (Fig. 3, bottom). A considerably longer (unrealistic) period of the oscillation is found in that run, associated with slower/weaker descents of the easterly phase. Interestingly we also find (not shown) that GWs originating from the summer side of the tropics tend to propagate equatorward in 3D MS-GWaM, thereby inducing the necessary westward force and stronger descent of the easterlies. This essential process could not be described in the 1D setup of conventional GW parameterizations. A corresponding manuscript (Kim et al. 2022) is currently in preparation.