Project: **1097**
Project title: **Multiscale Dynamics of Atmospheric Gravity Waves**
Principal investigator: **Ulrich Achatz**
Report period: **2025-11-01 to 2026-10-31**

This project aims to advance the understanding of gravity wave (GW) dynamics and to apply this knowledge in a state-of-the-art GW parameterization for atmospheric models. In order to achieve this, GW generation mechanisms, their interactions with the resolved flow, and their coupling with tracers, turbulence, and ice clouds are studied. Building on our ongoing theoretical advancements, we complement analytical work with numerical investigations, which help to provide necessary verification and validation of our developments. These include idealized wave-resolving simulations as well as advanced GW parameterizations such as the Multi-Scale Gravity Wave Model (MS-GWaM). The idealized simulations are performed using our open-source idealized flow solver PinCFlow.jl [1] which includes an interactively coupled implementation of MS-GWaM. On the larger scale, MS-GWaM has been implemented and tested in ICON. Peer-reviewed studies have already yielded significant insights — for example, the influence of GW transience and lateral propagation on GW intermittency, global circulation patterns (Kühner et al., 2026), and the quasi-biennial oscillation. GW–turbulence coupling has been implemented and found to enhance turbulence throughout most of the atmosphere, leading to increased tracer mixing in the UTLS (Banerjee et al., 2026b). In this report, we focus on recent key publications that have been enabled by DKRZ computational infrastructure. We also present preliminary results obtained through these resources on further MS-GWaM developments and coupling to other physical parameterizations.

In the current allocation period, technical developments of the orographic GW source in MS-GWaM have been brought to the final stage. Necessary tuning runs have been successfully completed. Simulations for austral winters were then repeated for two versions of the SGS-orography schemes LM97 (Lott and Miller, 1997) and the new configuration MS-GWaM orog. Results show a **substantial reduction in the Antarctic winter stratospheric cold bias** relative to ERA5 by 56% at 10 hPa and 44% at 50 hP (see Fig.1). A corresponding manuscript is presently in writing.

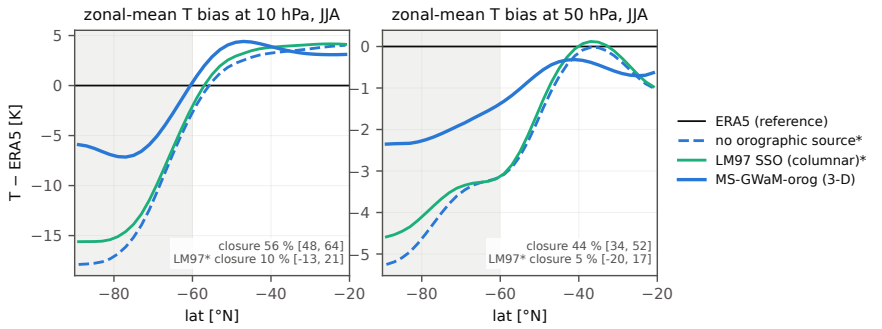


Figure 1: JJA zonal-mean temperature bias relative to ERA5 at 10 hPa (left) and 50 hPa (right), averaged over ten winters, for ICON without an orographic GW source (dashed), with the operational columnar orographic scheme (LM97, green), and with the new MS-GWaM orographic source and 3-D propagation (blue). The annotations give the fraction of the polar-cap (60–90 °S, shaded) bias that each scheme closes, with 95 % confidence intervals. Asterisks mark archived control runs, corrected for their reduced output levels.

Another aspect of MS-GWaM development focuses on analyzing GWs in the upper troposphere in high-resolution simulations, in order to derive more realistic lower boundary conditions. Procházková et al. (2026) show that the GW spectra have a complex structure in regions with strong zonal winds and exhibit greater variability in polar regions. The spectral variability can be represented well using a relatively small number of GW modes, although more modes are required in the mid-latitudes. Based on these results, a machine learning, flow-dependent model has been developed to diagnose the GW spectrum from the resolved flow for non-convective, non-orographic processes. Additional high-resolution R2B10 DYAMOND simulations were performed to expand the training dataset to cover additional months, and test the model on samples from different years and months. As is described in a corresponding manuscript, ready for submission soon, **the trained model can generate GW spectra for years and seasons outside of the training data**.

GW coupling to other atmospheric processes has been investigated, with a focus on GW–cirrus interactions. The necessary technical updates of the ICON base code and MS-GWaM have been completed, and the re-implemented coupling has been tested. This enables GW source separation diagnostics for further analysis. The results are consistent with previous findings and show a statistically significant increase in ice crystal number concentration when GW effects are included, particularly in the UTLS. An analysis of the probability density functions reveals that **GW influence leads to heavier tails in the ice number concentration distribution**.

[1] https://doi.org/10.5281/zenodo.17391579

To address the challenge of representing orographic GW sources, a new method, combining spectral transformation with dynamic compression through Elastic Mode Selection (EMS) ENUFFT, was developed and tested with PinCFlow.jl (Banerjee et al., 2026a). In idealized simulations for prescribed orography, **EMS achieved flow-dependent compression of GW launch spectra by at least 75% on average** while limiting power loss to 7%, demonstrating its potential for efficient and physically consistent GW parameterization. Alongside ICON/MS-GWaM development, PinCFlow.jl's orographic source remains a testbed for improvements and has recently been extended with a blocked-layer scheme consistent with MS-GWaM's spectral representation of SGS mountains. Ensemble Kalman Inversion is employed to calibrate the scheme's parameters and optimize its modification of MS-GWaM's mean-flow forcing. Initial tests show that **the blocked-layer scheme is able to correct mean-flow biases in the vicinity of high mountains**.

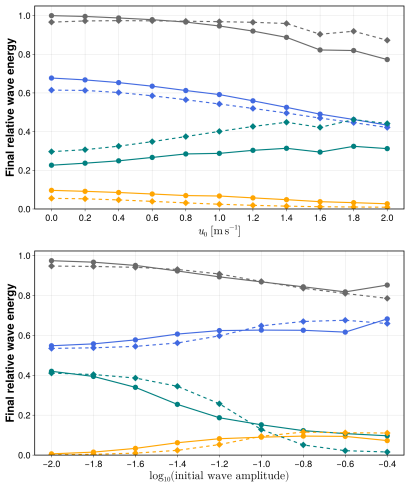


Figure 2: Validation of resonant wave-wave interactions for parametric subharmonic instability. Final relative modal energies as functions of (top) background-wind amplitude u_0 and (bottom) initial wave amplitude. Solid curves (circles) show coupled WKB-wave-wave simulations, while dashed curves (diamonds) show high-resolution WRS. Blue and teal denote the initialized modes, orange the generated mode, and gray their total diagnosed energy.

An additional development of MS-GWaM in PinCFlow.jl has focused on incorporating nonlinear resonant wave-wave interactions into its transient GW description. Building on the previous work on modulated triad interactions, and the wave-kinetic description of nonlinear spectral transfer, a coupled WKB-wave-wave interaction model has been developed and tested. Levante computing resources were used for high-resolution wave-resolving simulations (WRS), parameter-sensitivity studies, and systematic validation of the coupled model. Three configurations were investigated to assess different resonant interactions, focusing on nonlinear energy exchange sensitivity to background shear strength and initial wave amplitude. Figure 2 shows the final modal-energy distributions for the case with parametric subharmonic instability, comparing the coupled WKB simulations with WRS across a range of these parameters. The results show that **the model captures the main trends in modal-energy redistribution and the growth of the generated mode**, with generally better agreement in the weak-amplitude regime.

During the final quarter, the remaining resources will support production runs with coupled GW–ice microphysics, tests of a more accurate, stable treatment of the geographic poles, and further PinCFlow.jl development and validation. Within the reported period, some resources remained unused and expired due to a combination of delays in model development, code updates, and testing, delaying some production simulations. In addition, the newly introduced quarterly allocation scheme was also not fully accounted for in the initial planning. Together with long queue times, this limited resource use before quarterly expiration.

References

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