REQUEST FOR A SPECIAL PROJECT 2024–2026

MEMBER STATE: GERMANY

Principal Investigator[1]: Dr. Andreas Dörnbrack

Affiliation: DLR Oberpfaffenhofen, Institut für Physik der Atmosphäre

Address: Münchener Str. 20
D – 82230 WESSLING
Germany

Other researchers: Dr. Sonja Gisinger
Dr. Andreas Schäfler
Dr. Antonia Englberger

Project Title: Gravity Waves and Turbulence in the Free Atmosphere and the Atmospheric Boundary Layer

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** DESCAN	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2024	
Would you accept support for 1 year only, if necessary?	YES ☐	NO ☒

Computer resources required for project year:		**2024**	**2025**	**2026**
High Performance Computing Facility	[SBU]	500000	500000	500000
Accumulated data storage (total archive volume)[2]	[GB]	100	100	100

EWC resources required for project year:		**2024**	**2025**	**2026**
Number of vCPUs	[#]	24	24	24
Total memory	[GB]	350	350	350
Storage	[GB]	1000	1000	1000
Number of vGPUs[3]	[#]	2	2	2

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

This special project aims at combining high-resolution ground-based and airborne observations with IFS operational forecasts and analyses, with reanalyses, and with results from numerical modelling. The base of our measurements are airborne in-situ observations of the atmospheric wind and temperature in the upper troposphere and lower stratosphere as well as ground-based and airborne remote-sensing observations of temperature in the middle atmosphere. The goal is to analyse the properties of internal gravity waves and of turbulence in the stably stratified atmospheric airflow. A new aspect of our research will be the numerical simulation of the stably stratified atmospheric boundary layer where similar turbulent bursts are observed as in the free atmosphere. The challenge for numerical modelling is to achieve the needed high spatial and temporal resolutions. Furthermore, in this project we want to address the transition to modern computer architectures by applying the newly developed FVM of ECMWF to selected problems.

The project is structured into four parts.

(1) Analysis of turbulence observations by the German research aircraft HALO and comparison with CAT diagnostics implemented at the ECMWF

In Dörnbrack et al. (2022a), we compared the in-situ flight-level turbulence observations during the SouthTRAC campaign with the CAT index as implemented in the current operational IFS forecasts (Bechtold et al., 2021). In the coming years, the comparison will be extended to other aircraft campaigns of the German research aircraft HALO, where similar turbulence data are available in different geographical regions of the world. In addition to these comparisons, the spread of the CAT predictions in the IFS ensemble will be evaluated.

(2) Meteorological analysis and comparison of our observations with different IFS products

In addition to the airborne observations, ground-based Rayleigh lidar measurements of temperature perturbations in the middle atmosphere have been conducted during the recent years since November 2017 (Reichert et al. 2022). They reveal a large spectrum of frequencies and vertical and horizontal wavelengths of the observed gravity waves. An understanding of these different wave modes in the middle atmosphere is still lacking. Especially, the link of the observed gravity wave activity to possible sources in the troposphere as well as in the stratosphere is difficult to establish as 3D data of wind and temperature in high spatial and temporal resolution and covering larger areas are missing. Therefore, the meteorological analyses and forecasts of the various IFS products will fill this gap. Successful examples applying this approach to combine observations with IFS data can be found in the following papers: Dörnbrack (2021), Gupta et al. (2021), Gisinger et al., (2022), Dörnbrack et al. (2022b). Cases similar to these will be investigated further.

(3) High-resolution numerical simulation of selected cases

Idealized numerical simulations will complement the combined analysis of the observational data and the IFS output (e.g., Dörnbrack et al., 2020, Binder, 2023). The geophysical flow solver EULAG is used to simulate the flow over the mountain ranges or over propagating tropopause depressions where ground-based or airborne middle atmosphere lidar measurements are available. In the project, the extensive numerical simulations will be continued to study the middle atmospheric gravity waves for a series of different geographical locations and atmospheric conditions.

The computer hours will mainly be spent for numerical simulations with the geophysical flow solver EULAG. Tests with a version covering the altitude range from the surface to 180 km reveal about 2000 SBUs for a 2D simulation of the 2D flow over an isolated mountain ridge. As different parameters of the numerical scheme and the atmospheric background conditions have to be varied, I expect about 200 000 SBU per year for the necessary runs. Furthermore, planned 3D simulation will increase the computational effort. A rough estimate gives about 300 000 SBU which sum up to the applied 500 000 SBUs. Note: Currently, since I have no experience with the new ATOS computer yet, these figures are based on the former CRAY computer and have to be scaled.

(4) Turbulence in the stably stratified boundary layer over complex terrain

Besides the turbulence in the free atmosphere (see Section (1) and Rodriguez Imazio et al., 2022, 2023), turbulence in the stably stratified atmospheric boundary layer (ABL), especially over complex terrain, is a current research topic. The various dynamical processes are not fully understood and very difficult to simulate with large-eddy simulation (LES) codes (e.g., Maronga & Li, 2022). This is due to a very fine resolution required to represent the resolved turbulent motions, which has very small eddy sizes in comparison to convective or neutral cases. Furthermore, internal gravity waves interact with the mechanically produced turbulence. Another important aspect is that the subgrid-scale model of the LES must account for the anisotropy of turbulence caused either by the complex terrain or by nighttime surface cooling. The required fine grid resolution results in very large computational costs for stably-stratified ABL flows.

In previous work, we successfully simulated the well-known GABLS test case (Beare et al., 2006), which serves as reference case for LES of the stable ABL flow. We conducted the simulations with the geophysical flow solver EULAG in LES configuration. Since the grid resolution approaches 1 m in all three spatial directions, very high computational costs are incurred. To circumvent this limitation, we propose for GPUh to simulate the same GABLS case using the newly developed finite volume model (FVM, Kühnlein et al., 2019) in a much more efficient way on GPU. First results using FVM for regional applications have been obtained recently by Nicolai Krieger at the ETH Zürich. Since EULAG and FVM are based on similar numerical solution schemes, and FVM can also be run in CPU mode, it is a prefect case to study the computational cost of high-resolution stably stratified LESs on GPU, with the goal of applying FVM in GPU mode in future studies. Therefore, we request also access to the European Weather Cloud and a limited number of GPUs.

Beare, R. J., et al., 2006: An intercomparison of large-eddy simulations of the stable boundary layer. *Boundary-Layer Meteorology* **118**, 247-272.

Kühnlein, C., Deconinck, W., Klein, R., Malardel, S., Piotrowski, Z. P., Smolarkiewicz, P. K., Szmelter, J., and Wedi, N. P.: FVM 1.0: A nonhydrostatic finite-volume dynamical core for the IFS, *Geosci. Model Dev*., **12,** 651–676, https://doi.org/10.5194/gmd-12-651-2019, 2019.

Maronga, B. and D. Li, 2022: An investigation of the grid sensitivity in large-eddy simulations of the stable boundary layer. *Boundary-Layer Meteorology* **182**, 251-273.

Published papers related to the project:

1. Bechtold, P., M. Bramberger, **A. Dörnbrack**, L. Isaksen, M. Leutbecher, 2021: Experimenting with a clear air turbulence (CAT) index from the IFS. *ECMWF Technical Memorandum* **874**. https://doi.org/10.21957/4l34tqljm

2. Binder, M., 2023: *Non-orographic gravity waves above propagating tropopause depressions -- Idealized numerical simulations*. Master thesis. Department of Atmospheric and Cryospheric Sciences, University of Innsbruck.

3. **Dörnbrack, A**., Kaifler, B., Kaifler, N., Rapp, M., Wildmann, N., Garhammer, M., Ohlman, K., Payne, J., Sandercock, M., and E. Austin, 2020: Unusual appearance of mother-of-pearl clouds above El Calafate, Argentina (50° 21′ S, 72° 16′ W). *Weather*, **75,** 378-388. https://doi.org/10.1002/wea.3863

4. **Dörnbrack, A.,** 2021: Stratospheric mountain waves trailing across Northern Europe. *Journal of the Atmospheric Sciences*, ***78***, 2835-2857. https://doi.org/10.1175/JAS-D-20-0312.1

5. **Dörnbrack, A**., P. Bechtold, and U. Schumann, 2022a: High-resolution aircraft observations of turbulence and waves in the free atmosphere and comparison with global model predictions. *Journal of Geophysical Research: Atmospheres*, **127**, e2022JD036654. https://doi.org/10.1029/2022JD036654

6. **Dörnbrack, A**., S. D. Eckermann, B. P. Williams, and J. Haggerty, 2022b: Stratospheric gravity waves excited by propagating Rossby wave trains – A DEEPWAVE case study. *Journal of the Atmospheric Sciences*, ***79***, 567-591. https://doi.org/10.1175/JAS-D-21-0057.1

7. **Gisinger, S**., Polichtchouk, I., **Dörnbrack, A**., Reichert, R., Kaifler, B., Kaifler, N., et al., 2022: Gravity-wave-driven seasonal variability of temperature differences between ECMWF IFS and Rayleigh lidar measurements in the lee of the Southern Andes. *Journal of Geophysical Research: Atmospheres*, **127**, e2021JD036270. https://doi.org/10.1029/2021JD036270

8. Gupta, A., T. Birner, **A. Dörnbrack**, and I. Polichtchouk, 2021: Importance of gravity wave forcing for springtime southern polar vortex breakdown as revealed by ERA5. *Geophys. Res. Lett*., **48**, e2021GL092762. https://doi.org/10.1029/2021GL092762

9. Reichert, R., B. Kaifler, N. Kaifler, **A. Dörnbrack**, M. Rapp, and J. L. Hormaechea, 2021: High-Cadence Lidar Observations of Middle Atmospheric Temperature and Gravity Waves at the Southern Andes Hot Spot. *Journal of Geophysical Research: Atmospheres*, **126**, e2021JD034683. https://doi.org/10.1029/2021JD034683

10. Rodriguez Imazio, P., **Dörnbrack, A**., Urzua, R. D., Rivaben, N., & Godoy, A., 2022: Clear Air Turbulence observed across a tropopause fold over the Drake Passage - A Case Study. *Journal of Geophysical Research: Atmospheres*, **127**, e2021JD035908.

11. Rodriguez Imazio, P., Mininni, P. D., Godoy, A., Rivaben, N., & **Dörnbrack, A**., 2023: Not all clear air turbulence is Kolmogorov—The fine-scale nature of atmospheric turbulence. *Journal of Geophysical Research: Atmospheres*, **128,** e2022JD037491. https://doi.org/10.1029/2022JD037491