Project: **620**

Project title: **Vertical Propagation of Gravity Waves into the Middle Atmosphere**

Project lead: **Andreas Dörnbrack**

Report period: **2023-11-01 to 2024-10-31**

During the reporting period, computational time has primarily been used for simulations of deep gravity wave propagation events observed during the DEEPWAVE 2014 field campaign and for simulations of trapped waves in the lowermost stratosphere as observed during an aircraft campaign over Scandinavia. Published results can be found here: Binder and Dörnbrack (2024)[1] and Dörnbrack (2024)[2]. Nevertheless, a major part of the computational time went into new, still ongoing simulations for the PhD thesis of Michael Binder that deals with the airflow across the Andes mountains and the comparison of the numerical results with ground-based and airborne observations. The following, selected results are from Binder and Dörnbrack (2024) and form a methodological preparatory stage for further investigations during the ongoing PhD period of Michael Binder.

**Observing gravity waves generated by moving sources with ground-based Rayleigh lidars**

This section of the report sketches the main results of Binder and Dörnbrack (2024). It is a continuation and extension of Michael Binder's master thesis, which was described in the previous report. The study combines idealized numerical simulations with the EULAG model, analyses of ERA5 datasets, and evaluations of Rayleigh lidar measurements. Three overarching steps evolved: (1) Describe the appearance of gravity waves generated by a moving source under idealized conditions. (2) Identify these gravity waves in virtual measurements in ERA5. (3) Identify such waves in actual Rayleigh lidar measurements.

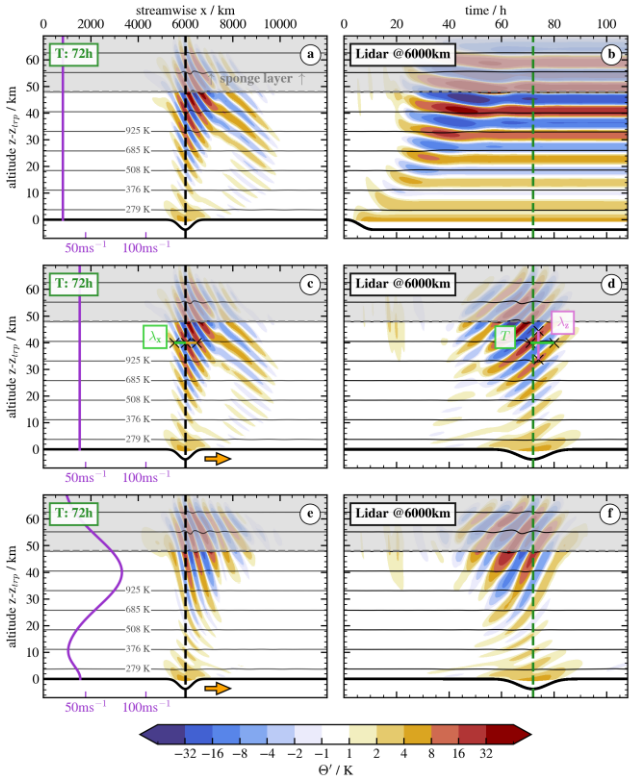


**Figure 1:** Vertical cross-sections (a, c, e) after t = 72 h with ambient wind profiles in purple and time-height diagrams (b, d, f) at the outlined position for three different EULAG simulations. The first simulation (a, b) features a stationary obstacle at the lower boundary and a constant wind profile. In the second simulation (c, d) the trough moves to the right with a constant speed of 13.88 $ms^{-1}$ and the wind is increased by the same amount. The last simulation (e, f) represents a simulation with a more realistic stratospheric wintertime wind profile.

Temperature measurements by zenith-pointing ground-based Rayleigh lidars are often used to detect middle atmospheric gravity waves. In these measurements, specifically time-height diagrams of temperature perturbations,

[1] Binder, M., & Dörnbrack, A., 2024: Observing gravity waves generated by moving sources with ground-based Rayleigh lidars. *Journal of Geophysical Research: Atmospheres,* **129**, e2023JD040156. https://doi.org/10.1029/ 2023JD040156

[2] Dörnbrack, A., 2024: Transient Tropopause Waves, *Journal of the Atmospheric Sciences*, **81**, 1647–1668, https://doi.org/10.1175/JAS-D-24-0037.1

stationary mountain waves are identifiable by horizontal phase lines. Vertically tilted phase lines, on the other hand, indicate that the wave source or the propagation conditions are transient. Idealized numerical simulations with the EULAG model illustrate that and how a wave source moving in the direction of the mean wind entails upward-tilted phase lines. This is visualized in Figure 1. The first row is a simulation of a mountain wave resulting in horizontally oriented phase lines in Panel (b). The second and third rows are simulations with a propagating source indicated by the orange arrows in (c) and (e). The wave source propagates towards the right (in the direction of the background wind), leading to upward-tilted phase lines. The inclination angle of the phase lines depends on the horizontal wavelength and the wave source's propagation speed. Stronger winds in the third row (Panel (e) and (f)) imply a smaller horizontal wavelength of the excited gravity waves and, therefore, steeper phase lines in Panel (f).

On this basis, the goal was to identify and characterize non-orographic gravity waves (NOGWs) from propagating sources, e.g., upper-level jet/front systems, in simulated, so-called virtual lidar observations (step 2) and actual Rayleigh lidar measurements (step 3).

In step 2, compositions of selected atmospheric variables from a meteorological forecast or reanalysis (here ERA5) are thoughtfully combined to associate NOGWs with processes in the troposphere and stratosphere. Figure 2 shows this composition for a virtual observation over the Southern Ocean. Upward-tilted phase lines indeed dominate the time-height diagram (Panel (a) after July 17, 12:00 UTC) during the passage of an upper-level trough (see Panels (e) and (g)) and have a high similarity with phase lines in the idealized simulation in Figure 1(f). The upper-level trough could be a potential propagating gravity wave source that leads to this upward-tilt.

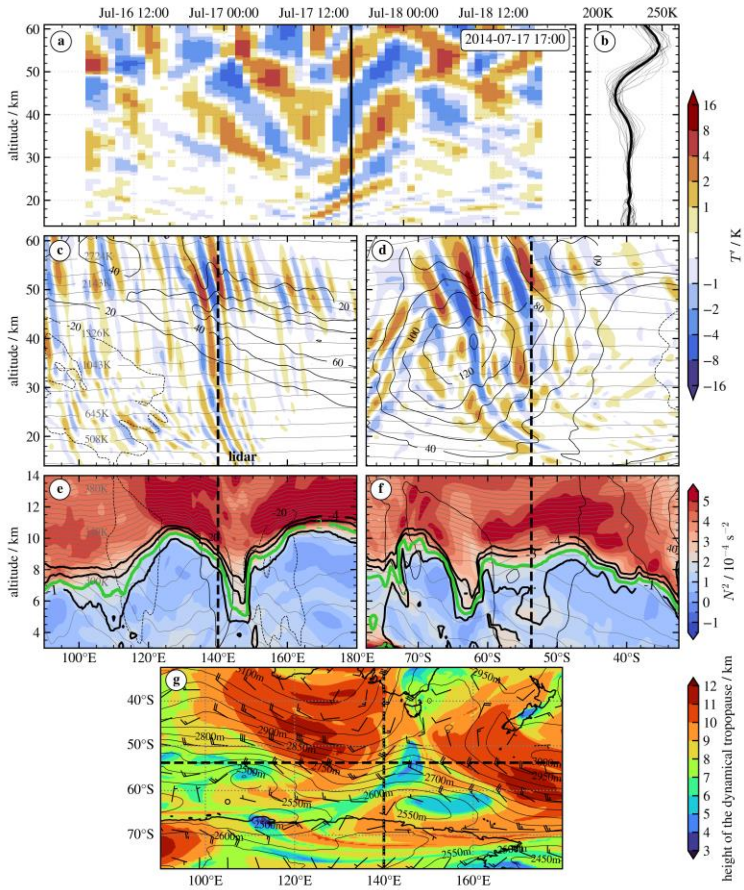


**Figure 1:** ERA5 overview for a location over the Southern Ocean (53.75°S, 140°E) during research flight RF25 of the DEEPWAVE campaign. Panel (a) emulates the measurement of a vertically staring ground-based Rayleigh lidar. Panels (c) and (d) are vertical sections of stratospheric T ′ and Panels (e) to (g) provide an overview of the synoptic conditions at the tropopause level. The black vertical line in (a) marks the timestamp (July 17, 2014, 17 UTC) for (c)-(g) and dashed lines in (c)-(g) highlight the location of the virtual lidar and profiles in (a) and (b).

In step 3, two selected observational periods of the COmpact Rayleigh Autonomous Lidar (CORAL) in the lee of the southern Andes were investigated. However, upward-tilted phase lines in these measurements are mainly associated with mountain waves in transient background wind conditions and not with a propagating gravity wave source. One night-time measurement by CORAL coincides with the passage of an upper-level trough, but large-amplitude mountain waves superpose the small-amplitude NOGWs in the middle atmosphere and complicate the identification of gravity waves from a propagating source.