SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2023
Project Title:	Gravity Waves and Turbulence over the Andes
Computer Project Account:	SPDESCAN
Principal Investigator:	Dr. Andreas Dörnbrack
Affiliation:	DLR Oberpfaffenhofen Institut für Physik der Atmosphäre Münchener Str. 20 **D – 82230 WESSLING** Germany
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Christian Kühnlein Dr. Inna Polichtchouk Dr. Nils Wedi Dr. Peter Bechtold
Start date of the project:	2021
Expected end date:	2023

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	500000	110000	500000	8000
Data storage capacity	(Gbytes)	80	80	80	80

Summary of project objectives (10 lines max)

In austral spring 2019, the SOUTHTRAC mission was conducted in South America. The SOUTHTRAC campaign was a joint atmospheric research project by German research centres and universities in close collaboration with partners from Argentina, Chile, and other international organizations. In late 2019, the German High-Altitude and Long-Range Research Aircraft (HALO) was relocated to Tierra del Fuego (Río Grande) at the southern tip of South America in order to perform atmospheric measurements of meteorological quantities and trace gases at southern hemispheric mid- and high-latitudes. The aircraft was equipped with a set of 13 instruments allowing a comprehensive study of the atmospheric state, composition and dynamical parameters by in-situ sampling and down-, up- and sideways-pointing remote sensing instruments. The extensive aircraft campaign was conducted in two phases taking place in September/October and November 2019, respectively, covering the late winter and spring season. The HALO measurements were accompanied by ground-based measurements (e.g., lidar, radar, radiosondes) and measurements on board a glider operating from El Calafate.

Of special interest for this special project are the airborne lidar measurements of internal gravity waves in the middle atmosphere by the Airborne Lidar for Middle Atmosphere research, the high-resolution flight level turbulence data collected by the Basis HALO Measurement and Sensor System on board the research aircraft HALO, and the wind and temperature observations from the glider. These different measurements shall be analysed and brought into a meteorological context.

Summary of problems encountered (10 lines max)

No problems encountered

Summary of plans for the continuation of the project (10 lines max)

This project will be finished end of the current year.

List of publications/reports from the project with complete references

1. Achatz, U., J. M. Alexander, E. Becker, H.-Y. Chun, **A. Dörnbrack**, L. Holt, R. Plougonven, I. Polichtchouk, K. Sato, A. Sheshadri, C. C. Stephan, A. van Niekerk, and C. J. Wright, 2023: Atmospheric Gravity Waves: Processes and Parameterization, *Bulletin of the American Meteorological Society*, submitted 28 May 2023

2. Gupta, A., R. Reichert, **A. Dörnbrack**, H. Garny, R. Eichinger, I.Polichtchouk, B. Kaifler, and T. Birner, 2023: Estimates of Southern Hemispheric Gravity Wave Momentum Fluxes Across Observations, Reanalyses, and Kilometer-scale Numerical Weather Prediction Models, *Journal of the Atmospheric Sciences*, under revision

3. Knobloch, S., B. Kaifler, **A. Dörnbrack**, and M. Rapp, 2023: Horizontal wavenumber spectra across the middle atmosphere from airborne lidar observations during a southern hemispheric SSW, *Geophysical Research Letters*, **50**, e2023GL104357. https://doi.org/10.1029/2023GL104357

4. **Dörnbrack, A**., 2023: Transient Tropopause Waves, *Journal of the Atmospheric Sciences*, submitted 20 January 2023, under revision.

5. Weimer, M., C. Wilka, D. E. Kinnison, R. R. Garcia, J. Bacmeister, M., J. Alexander, **A. Dörnbrack**, S. Solomon, 2023: A method for estimating global subgrid-scale gravity-wave temperature perturbations in chemistry-climate models. *Journal of Advances in Modeling Earth Systems (JAMES)*, under revision.

6. Woiwode, W., **A. Dörnbrack**, M. Geldenhuys, F. Friedl-Vallon, A. Giez, T. Gulde, M. Höpfner, S. Johansson, B. Kaifler, A. Kleinert, L. Krasauskas, E. Kretschmer, G. Maucher, T. Neubert, H. Nordmeyer, C. Piesch, P. Preusse, M. Rapp, M. Riese, U. Schumann and J. Ungermann, 2023: Non-orographic gravity waves and turbulence caused by merging jet streams. *Journal of Geophysical Research: Atmospheres*, **128**, e2022JD038097. https://doi.org/10.1029/2022JD038097

7. Witschas, B., **Gisinger, S.**, Rahm, S., **Dörnbrack, A.**, Fritts, D. C., and Rapp, M., 2023: Airborne coherent wind lidar measurements of the momentum flux profile from orographically induced gravity waves, *Atmospheric Measurement Technology*, **16**, 1087–1101, https://doi.org/10.5194/amt-16-1087-2023, 2023

8. 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

9. Lachnitt, H.-C., Hoor, P., Kunkel, D., Bramberger, M., **Dörnbrack, A.**, Müller, S., Reutter, P., Giez, A., Kaluza, T., and Rapp, M., 2023: Gravity-wave-induced cross-isentropic mixing: a DEEPWAVE case study, *Atmospheric Chemistry and Physics*, **23**, 355–373. https://doi.org/10.5194/acp-23-355-2023

10. **Dörnbrack, A.**, P. Bechtold, and U. Schumann, 2022: 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

11. **Gisinger, S.**, I. Polichtchouk, **A. Dörnbrack**, R. Reichert, B. Kaifler, N. Kaifler, M. Rapp, and I. Sandu, 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

Summary of selected results

(1) Not all Clear Air Turbulence is Kolmogorov − The fine-scale nature of atmospheric turbulence (Rodriguez Imazio et al. , 2023)

A strong clear air turbulence (CAT) event experienced by the German High-Altitude Long-Range (HALO) research aircraft during the Southern Hemisphere Transport, Dynamics, and Chemistry (SOUTHTRAC) campaign was investigated in a detailed case study. HALO encountered the CAT leeward of the southern Andes Mountains, where tropospheric airflow favoured vertically propagating mountain waves. These quasi-steady state mountain waves were refracted south-eastwards into the core of tropopause jet. Turbulence is quantified using spectral quantities and structure functions computed from in situ 100 Hz flight level data measured onboard HALO.

The detected CAT region exhibits strong patchiness, characterized by separated bursts in turbulent kinetic energy and energy dissipation rate (Figure 1). The high-resolution in situ observations reveal different turbulent scaling within each patch, in both spectra and structure functions, and following Monin and Yaglom's conversion law. One patch follows power laws with exponents − 1.71 ± 0.06, − 1.771 ± 0.006, and − 1.56 ± 0.05 for the velocity components w, v, and u respectively, while another patch has exponents − 2.17 ± 0.12, − 2.50 ± 0.08, and − 1.92 ± 0.09. These patches are mediated by a third patch with less clear scaling. While the patches can deviate from Kolmogorov scaling due to the anisotropy of the airflow, they still display evidence of CAT with enhanced energy dissipation rates.

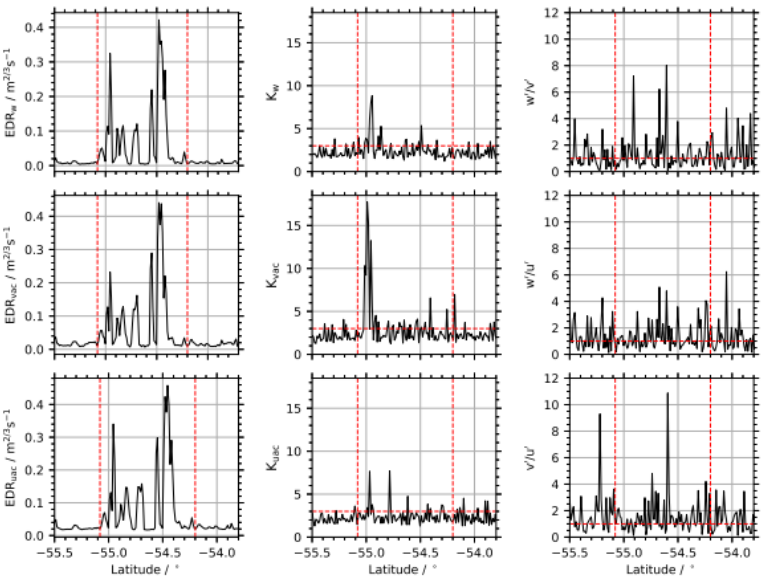

Figure 1: Energy dissipation rate (left column), kurtosis (middle column), and anisotropy measure (right column) as function of latitude for the three velocity components in aircraft-related coordinate system w, vac, uac from top to bottom, respectively. Red vertical lines frame the entire turbulence segment.

(2) Non-orographic gravity waves and turbulence caused by merging jet streams (Woiwode et al, 2023)

Jet streams are important sources of non-orographic internal gravity waves and clear air turbulence (CAT). Non-orographic gravity waves and CAT are analyzed during a merger of the polar front jet stream (PFJ) with the subtropical jet stream (STJ) above the southern Atlantic (Figure 2). Thereby, airborne observations covering the mesoscale and turbulent scale in combination with high-resolution deterministic short-term forecasts are combined. Coherent phase lines of temperature perturbations by gravity waves stretching along a highly sheared tropopause fold are simulated by the ECMWF IFS predictions. During the merging event, the PFJ reverses its direction from approximately antiparallel to parallel with respect to the STJ, going along with strong wind shear and horizontal deformation.

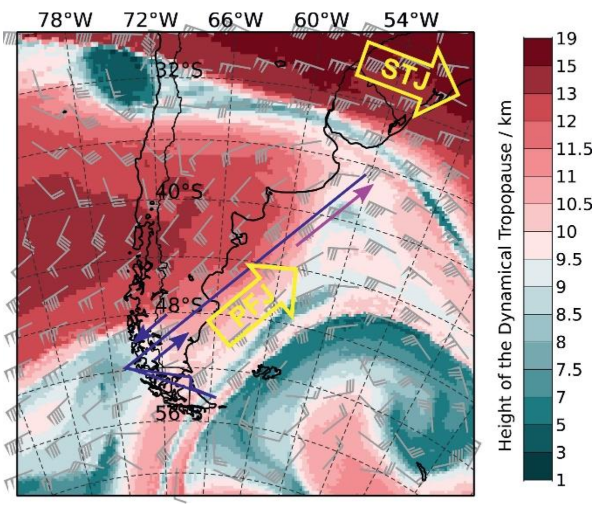

Figure 2: Upper-level atmospheric airflow during the merging event of the polar front jet (PFJ) and the subtropical jet (STJ) valid on 17 September 2019 02 UTC. Height of the −2 PVU surface as a proxy for the dynamical tropopause (km, colour-shaded; note the non-linear colour scale) and horizontal wind at the dynamical tropopause (short barbs 5 m s^{-1}, long barbs 10 m s^{-1}, triangles 50 m s^{-1}) from ECMWF ERA5 reanalysis. The HALO flight track is indicated schematically by a blue line. Magenta arrow: focus region of this study. Blue arrows: flight directions during the outbound and inbound legs.

Temperature perturbations in limb-imaging and lidar observations onboard the research aircraft HALO during the SOUTHTRAC campaign show remarkable agreement with the IFS data (Figure 3). Ten hours earlier, the IFS data show an "X-shaped" pattern in the temperature perturbations emanating from the sheared tropopause fold. Tendencies of the IFS wind components show that these gravity waves are excited by spontaneous emission adjusting the strongly divergent flow when the PFJ impinges the STJ. In situ observations of temperature and wind components at 100 Hz confirm upward propagation of the probed portion of the gravity waves. They furthermore reveal embedded episodes of light-to-moderate CAT, Kelvin Helmholtz waves, and indications for partial wave reflection. Patches of low Richardson numbers in the IFS data coincide with the CAT observations, suggesting that this event was accessible to turbulence forecasting.

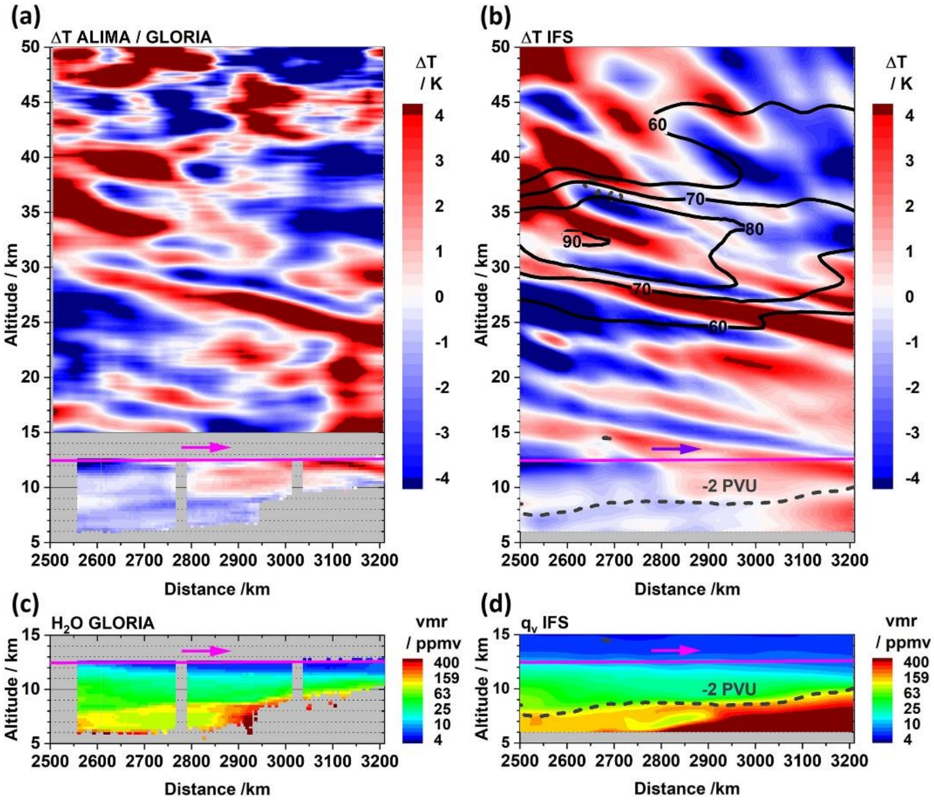

Figure 3: Observed and forecasted temperature perturbations. (a) Temperature perturbation calculated from ALIMA (above 15 km) and GLORIA (below 12.5 km). (b) Temperature perturbation calculated from IFS data. (c) GLORIA water vapor and (d) IFS specific humidity for the same flight section. HALO flight altitude (magenta solid line, all panels), selected isolines of horizontal wind speed (black solid lines in (b), in m s^{-1}), and dynamical tropopause (dashed dark gray lines in (b, d)).