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	2021
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
Data storage capacity	(Gbytes)			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)

(1) Analysis of the turbulence observations and comparison with CAT diagnostics implemented at the ECMWF

In collaboration with Peter Bechtold (see Bechtold et al., 2021) we will compare the HALO observations of the eddy dissipation rates measured during SouthTRAC with the IFS CAT products.

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

Further case studies are ongoing to analyse the meteorological situation during selected research flights. The goal is to understand the observed wave and turbulence events.

(3) High-resolution numerical simulation of selected cases

Based on the successful high-resolution simulation of the deep vertical propagation of mountain waves from the flow across the Auckland Island (Mixa et al., 2021) we will conduct similar numerical simulations for the flow past the Andes.

List of publications/reports from the project with complete references

1. Mixa, T., A. Dörnbrack, and M. Rapp, 2021: Nonlinear Simulations of Gravity Wave Tunneling and Breaking over Auckland Island, *Journal of the Atmospheric Sciences*, **78**, 1567-1582. https://journals.ametsoc.org/view/journals/atsc/78/5/JAS-D-20-0230.1.xml

2. Rapp, M., B. Kaifler, A. Dörnbrack, S. Gisinger, T. Mixa, R. Reichert, N. Kaifler, S. Knobloch, R. Eckert, N. Wildmann, A. Giez, L. Krasauskas, P. Preusse, M Geldenhuys, W. Woiwode, F. Friedl-Vallon, B.-M. Sinnhuber, A. de la Torre, P. Alexander, J. L. Hormaechea, D. Janches, M. Garhammer, J. L. Chau, J. F. Conte, P. Hoor, and A. Engel, 2021: SOUTHTRAC-GW: An airborne field campaign to explore gravity wave dynamics at the world's strongest hotspot. *Bulletin of the American Meteorological Society*, **102**, E871-E893. https://journals.ametsoc.org/view/journals/bams/102/4/BAMS-D-20-0034.1.xml

3. 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

4. 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

5. Wildmann, N., R. Eckert, A. Dörnbrack, S. Gisinger, M. Rapp, K. Ohlmann, A. van Niekerk, 2021: In-situ measurements of wind and turbulence by a motor glider in the Andes. *J. Atmos. Ocean. Techn*., **38**, 921-935; https://doi.org/10.1175/JTECH-D-20-0137.1

6. Pautet, P.-D., M. J. Taylor, D. C. Fritts, D. Janches, N. Kaifler, A. Dörnbrack, and J. L. Hormaechea, 2021: Mesospheric Mountain Wave Activity in the Lee of the Southern Andes, *Journal of Geophysical Research: Atmospheres*, **126**, e2020JD033268. https://doi.org/10.1029/2020JD033268

7. 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

Summary of selected results

(1) **Importance of gravity wave forcing for springtime southern polar vortex breakdown as revealed by ERA5** (Gupta et al., 2021)

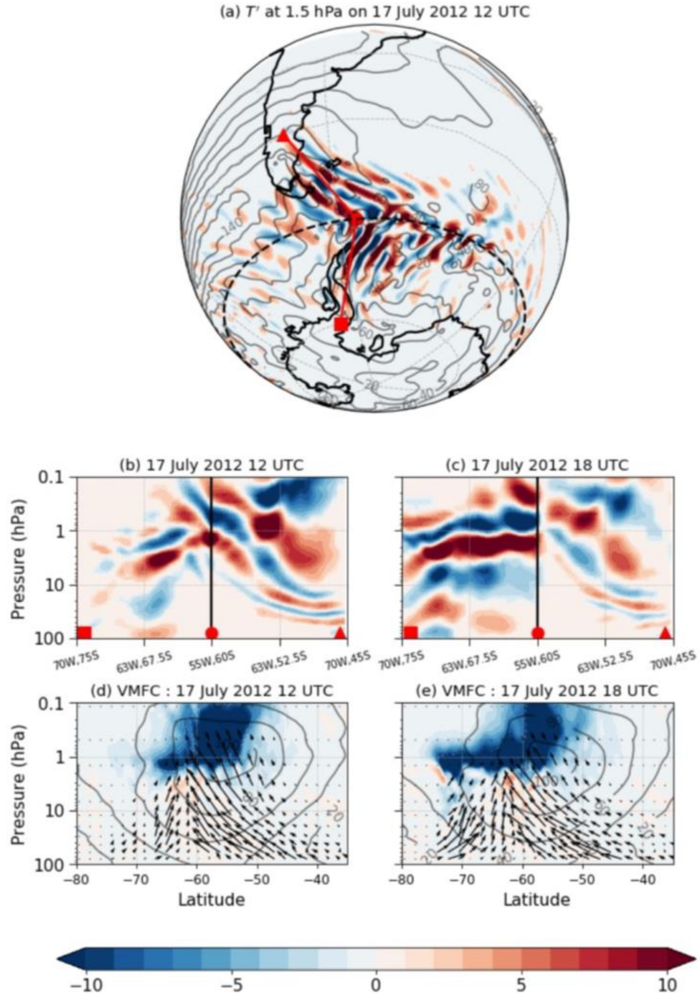

Figure 1. (a) Temperature perturbations (in K) and zonal winds (in m s^{-1}) at 1.5 hPa on 17 July 2012 in ERA5. (b)-(c) Temperature perturbation cross-section along the solid red line in subplot (a) showing the evolution of temperature perturbation at 12 UTC and 18 UTC on 17 July 2012. The red markers correspond to the respective locations along the red line in subplot (a). (d)-(e) Potential energy flux vectors (in arrows) for 12 UTC and 18 UTC on 17 July 2012 superimposed over VMFC (in color) with units of m s^{-1} day^{-1}. The black contours indicate zonal wind speeds. The subplots share the same colorbar but have different units. Contributions from zonal wavenumber 20 and below were filtered to calculate GW perturbations and geopotential perturbations Φ'.

Planetary waves and gravity waves are the key drivers of middle atmospheric circulation. Insufficient observations and inaccurate model representation of gravity waves limits our understanding of their stratospheric contributions, especially during the Antarctic polar vortex breakdown. This study employs the strength of the high-resolution ERA5 reanalysis in resolving a broad spectrum of gravity waves in southern midlatitudes and its ability to estimate their forcing during the breakdown period. Most of the resolved southern hemisphere gravity waves deposit momentum around 60°S over the Southern Ocean. Further, a zonal momentum budget analysis during the breakdown period reveals that the resolved gravity wave forcing in ERA5 provides as much as one-fourth of the wind deceleration at 60°S, 10 hPa. The parameterized gravity wave drag, mostly from non-orographic sources, provides more than half of the wind deceleration. Both findings highlight the key role of gravity waves in the vortex breakdown, and discuss possibilities for further stratospheric gravity wave analysis.

(2) Unusual appearance of mother-of-pearl clouds above El Calafate, Argentina (50° 21′ S, 72° 16′ W) (Dörnbrack et al., 2020)

Visual observations from the ground (Figure 2) and from a glider soaring in the lowermost stratosphere reveal the existence of mother-of-pearl clouds above El Calafate, Argentina in the lee of the Andes on 11 September 2019. The lenticular shape of the observed clouds resembles polar stratospheric clouds (PSCs) frequently observed over the Scandinavian mountains. However, the altitude of the PSCs remained uncertain by these visual observations. Moreover, the appearance of the PSCs is rather unusual considering the time - end of the austral winter - and the location at about 50°S being far away from Antarctica. Fortunately, two nearby crossings by the German research aircraft HALO (High Altitude Long Duration research aircraft) show evidence that the PSCs were located at about 26 km altitude. This estimate is based on the enhanced backscatter signal of airborne lidar observations. Here, we present the available observations and describe the overall meteorological situation that was related to the earliest sudden stratospheric warming so far recorded in the Southern Hemisphere. By using IFS operational analyses (Figure 3) and high-resolution numerical simulations we show evidence of mountain waves propagating up to the stratosphere responsible for generating the localized cold stratospheric temperature anomalies required for PSC formation.

Figure 2: Mother-of-pearl clouds west, south-west of El Calafate on 11 Sep¬tember 2019. The picture was taken from outside the city at the cabins belonging to Brillos Patagónicos, Calle 78 750, El Calafate (50.32°S, 72.26°W) at around 23 UTC. Photo taken by Marko Magister, Big Air Factory.

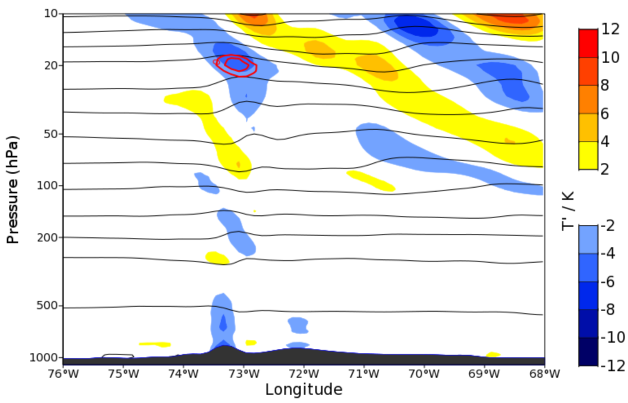

Figure 3: IFS Temperature perturbation T' = T_{1279}-T_{106} (K, colour shaded), ΔT_{ice} = -1 K and 0 K (red contour lines, see text) and logarithm of Θ (increment 0.075) at 50.5°S on 11 September 2019 18 UTC (bottom row).

(3) Nonlinear Simulations of Gravity Wave Tunneling and Breaking over Auckland Island (Mixa et al., 2021)

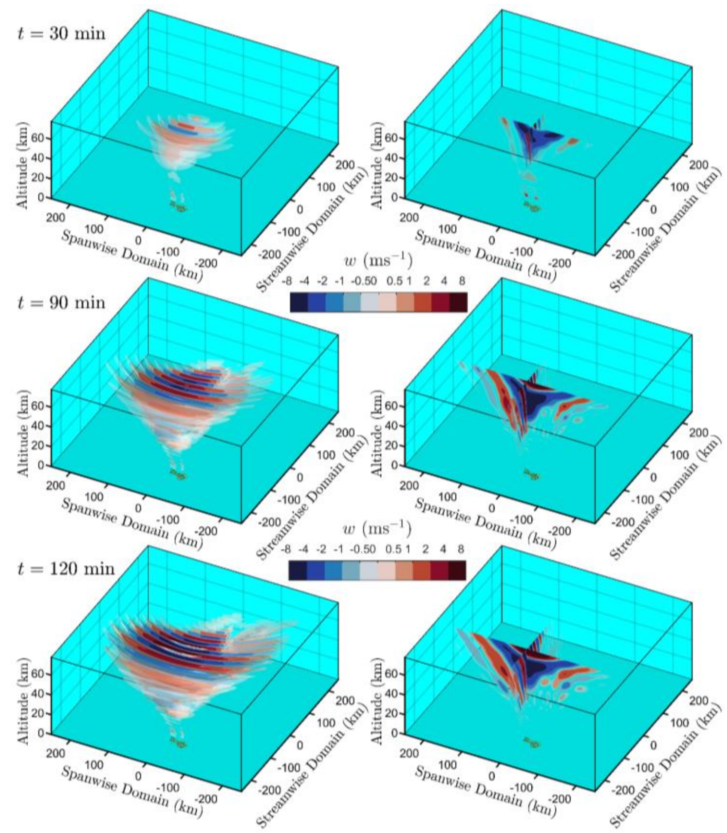

Figure 4: Time evolution of the simulated 3D vertical velocity field shown at elapsed times of 30 min (top), 90 min (middle), and 120 min (bottom). The 3D gravity wave phase structure is presented as both 1) a series of isosurfaces, plotted on a logarithmic scale with increasing opacity for higher values (left column); and 2) intersecting vertical slices through the domain at (x, y) = (-130,-25) km for 30 min and (x,y) = (-90,10) km for 90 min and 120 min (right column).

Horizontally dispersing gravity waves with horizontal wavelengths of 30 to 40 km were observed at mesospheric altitudes over Auckland Island by the airborne advanced mesospheric temperature mapper during a DEEPWAVE research flight on 14 July 2014. The 3D nonlinear compressible model EULAG is used to determine which propagation conditions enabled gravity wave penetration into the mesosphere and how the resulting instability characteristics led to widespread momentum deposition. Results indicate that linear tunnelling through the polar night jet enabled quick gravity wave propagation from the surface up to the mesopause, while subsequent instability processes reveal large rolls that formed in the negative shear above the jet maximum and led to significant momentum deposition as they descended. This study suggests that gravity wave tunnelling is a viable source for this particular case and other deep propagation events reaching the mesosphere and lower thermosphere.