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	2022
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)

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

After completing the comparison paper of HALO eddy dissipation rate observations during SOUTHTRAC with the IFS CAT diagnostics (Dörnbrack et al., JGR 2022 under review), we will focus on new diagnostic tools to quantify the anisotropy in terms of ambient flow conditions. This investigation will be done in close collaboration with our colleagues from the Argentine national weather service as most of the data used so far were collected over South America during the SOUTHTRAC campaign. Furthermore, another case study is in preparation devoted to the small-scale intermittency of CAT events and the quantification of anisotropy based on 100 Hz flight level data from a research flight of HALO during SOUTHTRAC.

(2) High-resolution numerical simulation of the lateral propagation of non-orographic gravity waves into the polar night jet

Based on the case study about the excitation of non-orographic gravity waves by the stratospheric flow across a tropopause fold (Dörnbrack et al., JAS 2022), three-dimensional high-resolution simulations we will be conducted to investigate this process in more detail. For this purpose, a master thesis is in preparation that will be jointly supervised by Alexander Gohm from the University of Innsbruck and myself.

List of publications/reports from the project with complete references (members of the Special Project are highlighted)

1. Lachnitt, H.-C., P. Hoor, D. Kunkel, M. Bramberger, **A. Dörnbrack**, S. Müller, P. Reutter, A. Giez, T. Kaluza, and M. Rapp, 2022: Gravity wave induced cross-isentropic mixing: A DEEPWAVE case study. *Atmospheric Chemistry and Physics*, submitted 10 June 2022

2. **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*, under review.

3. **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*, accepted 21 June 2022

4. Voigt, C., J. Lelieveld, H. Schlager, J. Schneider, J. Curtius, R. Meerkötter, D. Sauer, L. Bugliaro, B. Bohn, J. N. Crowley, T. Erbertseder, S. Groß, Q. Li, M. Mertens, M. Pöhlker, A. Pozzer, U. Schumann, L. Tomsche, J. Williams, A. Zahn, M. Andreae, S. Borrmann, T. Bräuer, R. Dörich, **A. Dörnbrack**, A. Edtbauer, L. Ernle, H. Fischer, A. Giez, M. Granzin, V. Grewe, V. Hahn, H. Harder, M. Heinritzi , B. Holanda, P. Jöckel, K. Kaiser, O. Krüger, J. Lucke, A. Marsing, A. Martin, S. Matthes, C. Pöhlker, U. Pöschl, S. Reifenberg, A. Ringsdorf, M. Scheibe, I. Tadic, M. Zauner-Wieczorek, R. Henke, and M. Rapp, 2022: BLUESKY aircraft mission reveals reduction in atmospheric pollution during the 2020 Corona lockdown, *Bull. American Met. Soc*., submitted 1 October 2021, accepted 26 March 2022; (published online ahead of print 2022). Retrieved Jun 21, 2022, from https://journals.ametsoc.org/view/journals/bams/aop/BAMS-D-21-0012.1/BAMS-D-21-0012.1.xml

5. 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. https://doi.org/10.1029/2021JD035908

6. **Dörnbrack, A.,** S. D. Eckermann, B. P. Williams, and J. Haggerty, 2022: 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. 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

8. **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*

Summary of selected results

(1) Stratospheric mountain waves trailing across Northern Europe (Dörnbrack, 2021)

Planetary waves disturbed the hitherto stable Arctic stratospheric polar vortex in the middle of January 2016 in such a way that unique tropospheric and stratospheric flow conditions for vertically and horizontally propagating mountain waves developed. Coexisting strong low-level westerly winds across almost all European mountain ranges plus the almost zonally-aligned polar front jet created these favourable conditions for deeply propagating gravity waves. Furthermore, the northward displacement of the polar night jet resulted in a wide-spread coverage of stratospheric mountain waves trailing across northern Europe.

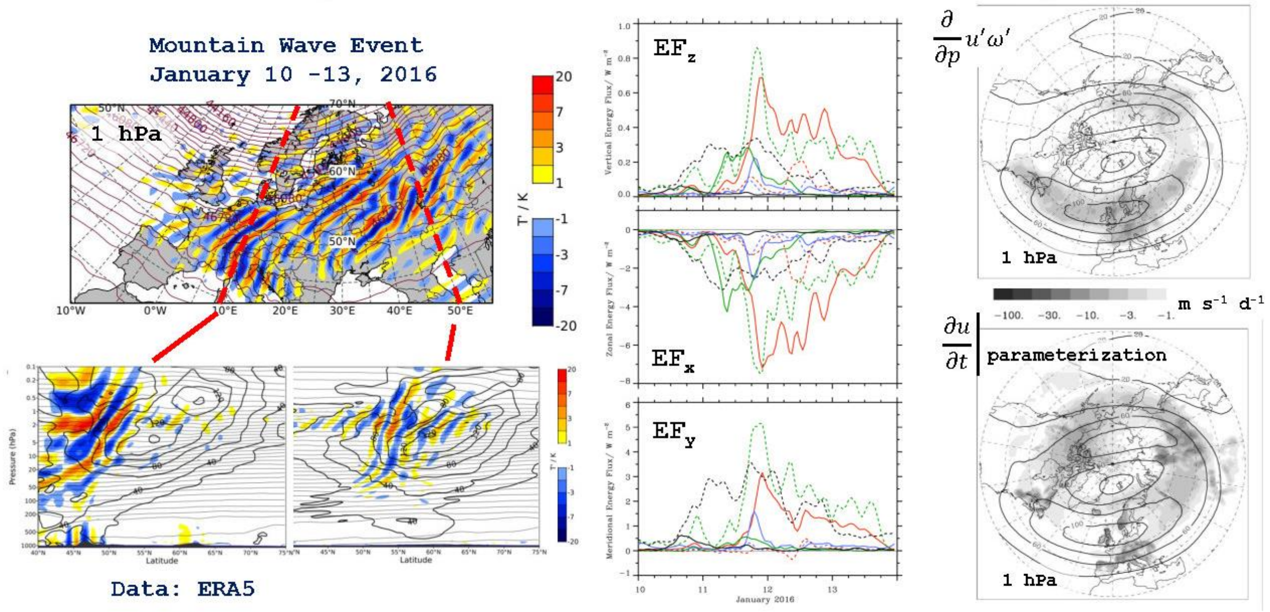

Figure 1: Left column: Stratospheric temperature perturbations associated with the excitation of mountain waves by the strong tropospheric airflow across the main middle European mountain ranges during the period 11 to 13 January 2016. In the vertical sections, the polar-night jet is visible into which the mountain waves are refracted. Middle column: Temporal evolution of the vertical and horizontal wave energy fluxes at 1 hPa for a couple of control areas enclosing the different mountain ranges. Right column: The resolved and parameterized gravity wave drag for the considered period from ERA5 reanalysis data. For a detailed and more complete description, see Dörnbrack (2021).

The particular meteorological setting was analysed by investigating the tropospheric and stratospheric flows based on the ERA5 data, see Figure 1. The potential of the flow for exciting internal gravity waves from non-orographic sources is evaluated across all altitudes by considering various indices to indicate flow imbalances as divergence δ, the Rossby numbers Ro and Ro_ζ as well as the residuum of the non-linear balance equation ΔNBE. The analysed gravity waves are described and characterized. The main finding of this case study is the exceptionally vast extension of the mountain waves trailing to high latitudes originating from the flow across the mountainous sources that are located at about 45°N. The magnitudes of the simulated stratospheric temperature perturbations attain values larger than 10 K and are comparable to values as documented by recent case studies of large-amplitude mountain waves over South America. The zonal means of the resolved and parameterized stratospheric wave drag during the mountain wave event peak at $-$ 4.5 m s^{-1} d^{-1} and $-$ 32.2 m s^{-1} d^{-1}, respectively, see right column in Figure 1.

(2) Clear Air Turbulence observed across a tropopause fold over the Drake Passage - A Case Study (Rodriguez Imazio et al., 2022)

This case study documents an aircraft encounter with clear-air turbulence (CAT) that occurred over the remote Drake Passage. Exceptional atmospheric conditions are known to exist there as low-pressure systems regularly pass through the passage. During a research flight conducted as part of the SOUTHTRAC campaign in November 2019, moderate to severe turbulence was detected using flight-level observations of wind and temperature with a frequency of 10 Hz. The vertical distribution of atmospheric variables is provided by a high-resolution radiosonde profile launched from the Argentinian research station Marambio.

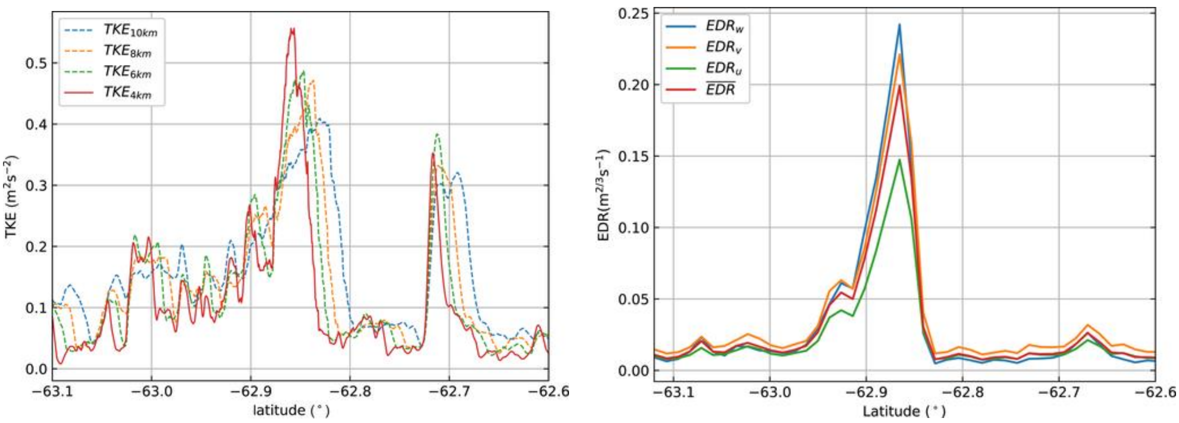

Figure 2: Left; Specific turbulent kinetic energy derived from different subleg lengths as indicated by the different colors and line styles, along HALO's flight path through the CAT encounter. Right: Cubic root of the energy dissipation rate (EDR=$\varepsilon^{1/3}$) for all wind components in an aircraft-related coordinate system and the geometric mean $\overline{\text{EDR}}$ calculated from all wind components, along the same flight path.

In addition, the results of global (IFS) and regional (WRF) numerical weather prediction models are used to provide the meteorological context and to derive quantities, such as the cubic root of the energy dissipation rate EDR = $\varepsilon^{1/3}$, commonly used to predict CAT for aviation, see Figure 2. Two different analysis techniques are used to quantify the EDR associated with the CAT event: EDR values derived from spectral methods are contrasted with the EDR results computed from second- and third-order structure functions. Both methods show that the event exhibits the characteristic feature of the bursty and intermittent nature of turbulence in the upper troposphere and lower stratosphere. Flow anisotropy is large outside the mixing regions of the CAT patch.

(3) Stratospheric gravity waves excited by propagating Rossby wave trains – A DEEPWAVE case study (Dörnbrack et al., JAS 2022)

Stratospheric gravity waves observed during the DEEPWAVE research flight RF25 over the Southern Ocean are analysed and compared with numerical weather prediction (NWP) model results from the ECMWF. The unique research flight RF25 went as far south as 63°S and observed stratospheric gravity in the vicinity of the polar night jet (Figure 3). The quantitative agreement of the NWP model output and the airborne tropospheric and lower-stratospheric observations is remarkable. The high-resolution NWP models are even able to reproduce qualitatively the observed upper-stratospheric gravity waves detected by an airborne Rayleigh lidar (Figure 4).

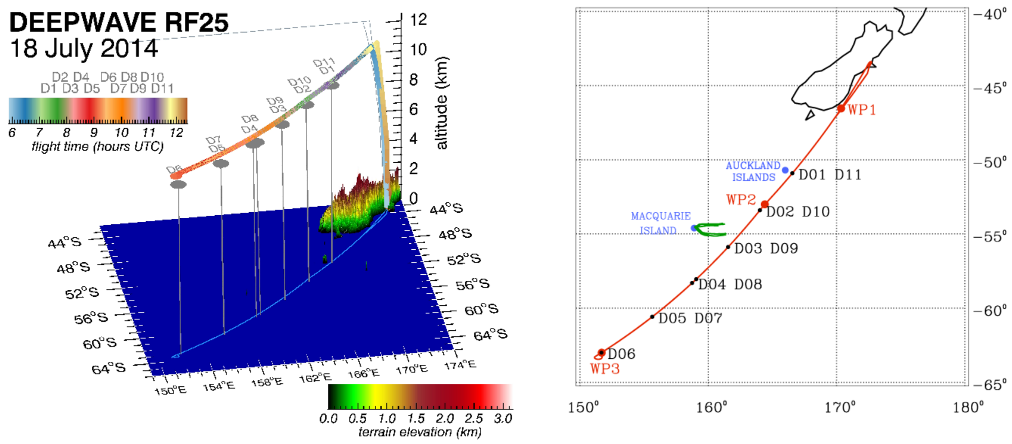

Figure 3: 3D and top view of the trajectory of the GV research flight RF25 on July 18, 2014, showing the launch positions of the eleven dropsondes (marked by D1 to D11) and the waypoints WP1, WP2, and WP3. Flight time, and terrain elevation of the remote South Island of New Zealand are indicated in the left panel. The total flight distance is about 3100 nautical miles. The green lines starting at Macquarie Island are the trajectories of the seven radiosondes launched from 17 July 2014 00 UTC to 19 July 2014 00 UTC (right panel).

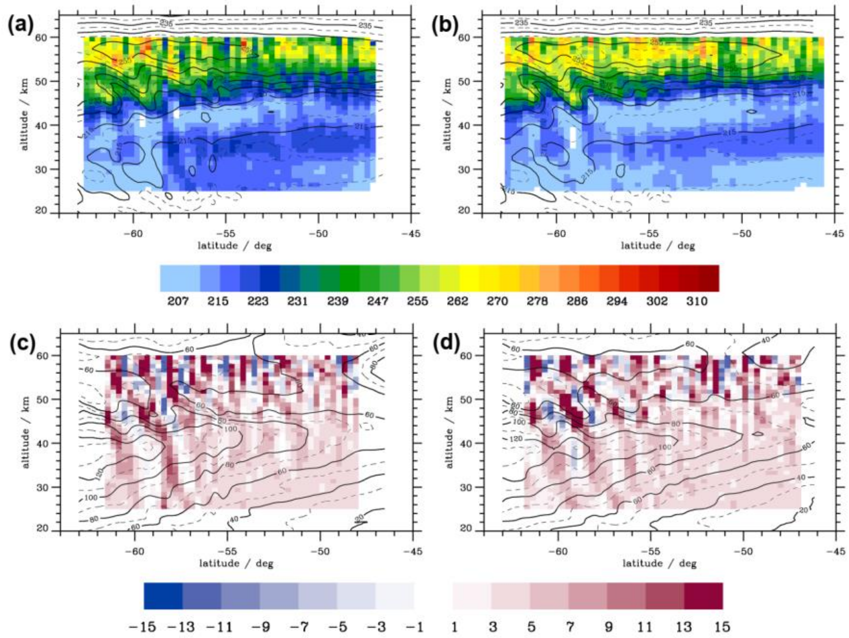

Figure 4: (a, b) GV Rayleigh lidar temperature (K, color coded) and IFS temperature (K, black contour lines) and (c, d) temperature perturbations T’ from the Rayleigh lidar (K, color coded) and IFS horizontal wind (m s^{-1}, black contour lines) for the outbound (a, c) and inbound (b, d) legs of RF25. Data: 180 s mean values of the Rayleigh lidar observations and HRES IFS.

The usage of high-resolution ERA5 data - partially capturing the long internal gravity waves - enabled a thorough interpretation of the particular event. The main result of this case study is that the observed and modelled gravity waves are excited by the stratospheric flow past a deep tropopause depression belonging to an eastward-propagating Rossby wave train. This results in wave patterns resembling hydrostatic mountain waves, see Figure 5. In the reference frame of the propagating Rossby wave, these vertically propagating hydrostatic gravity waves appear stationary; in reality, of course, they are transient and propagate horizontally at the phase speed of the Rossby wave. The subsequent refraction of these transient gravity waves into the polar night jet explains their observed and modelled patchy stratospheric occurrence near 60°S, see Figure 6. The combination of both unique airborne observations and high-resolution NWP output provides evidence for the one case investigated in this paper. As the excitation of such gravity waves persists during the quasi-linear propagation phase of the Rossby wave's life cycle, a hypothesis is formulated that parts of the stratospheric gravity wave belt over the Southern Ocean might be generated by such Rossby wave trains propagating along the midlatitude waveguide.

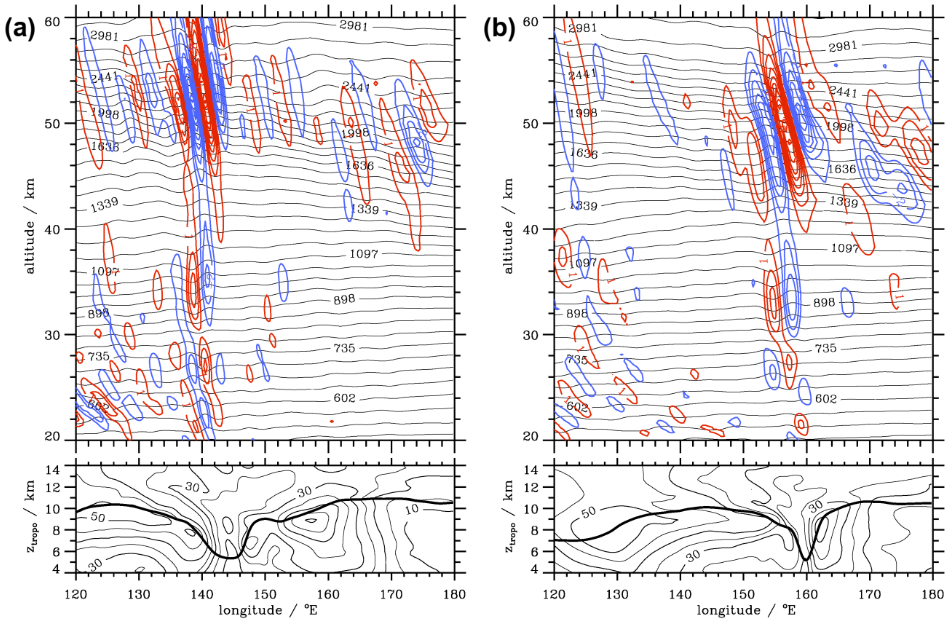

Figure 5: Temperature perturbations T'_{ERA5} (K, red and blue contour lines) and potential temperature (K, black lines in logarithmic scaling) along 55°S on 17 July 2014 15 UTC (a) and 18 July 2014 09 UTC (b). The bottom panels depict the height of the dynamical tropopause (thick black lines, meridional average from 52.5°S to 57.5°S) and the horizontal wind (m s-1, thin black lines) at the same instances. Data: One hourly ERA5 data.

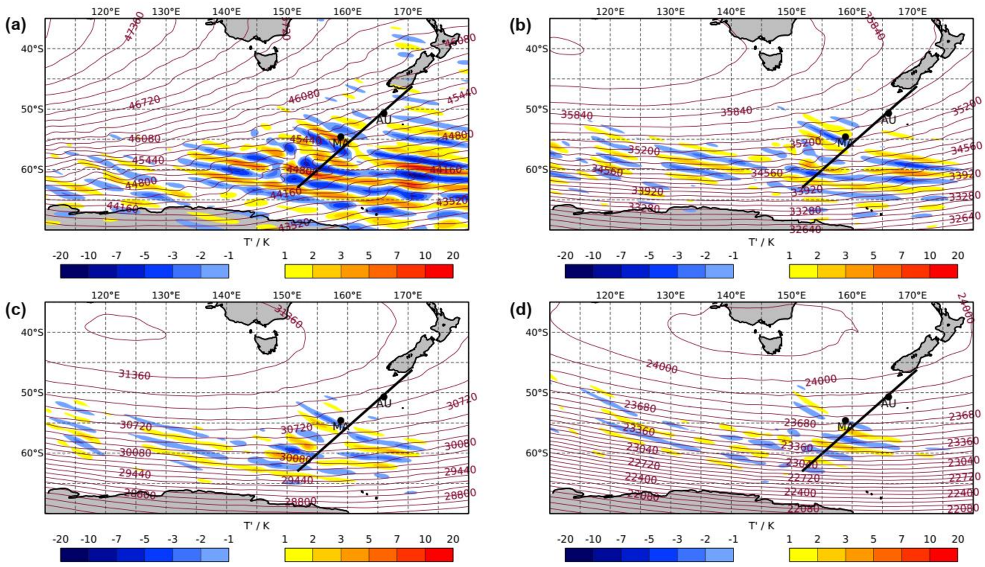

Figure 6: Temperature perturbations T'_{ERA5} (K, color-shaded) and geopotential height Z (m, burgundy solid lines) at 1 hPa (a), 5 hPa (b), 10 hPa (c), and 30 hPa (d) at 09 UTC on 18 July 2014. Data: ERA5 on a 0.28125° regular latitude/longitude grid. The black line is the flight path of the NSF/NCAR GV during the DEEPWAVE research flight RF25.