Project: **620**
Project title: **Vertical Propagation of Gravity Waves into the Middle Atmosphere**
Project lead: **Andreas Dörnbrack**
Report period: **2021-01-01 to 2021-08-31**

During the reporting period, computational time was primarily used for simulations of deep mountain wave propagation events observed during the SOUTHTRAC GW campaign (Rapp et al., 2021, Dörnbrack et al., 2020) and the DEEPWAVE 2014 field campaign (Fritts et al., 2016). The results presented in the last annual report in 2020 have now been finally published (Rapp et al., 2021, Mixa et al., 2021).

The ongoing simulations for the "Vertical Propagation of Gravity Waves in the Middle Atmosphere" project are closely linked to the atmospheric conditions encountered in the SOUTHTRAC-GW and DEEPWAVE field measurements. This approach allows interpretation of the measurements by examining the dominant processes of gravity wave excitation and propagation. In addition to the ongoing work that will be the subject of next year's report, this brief report focuses on a new aspect that we are currently working on: Idealized simulations of airflow over a moving tropopause low, an idea that evolved from a DEEPWAVE case study that Dörnbrack et al. (2021) recently wrote up and submitted their results to JAS.

Stratospheric gravity waves excited by the airflow across a propagating tropopause fold

The gravity wave belt around 60°S and the cold pole problem

An increasing number of gravity wave observations from satellites (e.g., Hindley et al., 2020), ground-based lidar systems (e.g., Kaifler et al., 2020), aircraft (Rapp et al., 2021 and Fritts et al., 2016), and balloons (e.g., Plougonven et al., 2013) are helping to constrain gravity wave parameterizations for global circulation models (GCMs), but also highlight their shortcomings and point to gaps in our current knowledge of gravity waves (e.g., Plougonven et al., 2020). A particularly striking phenomenon already apparent in observations by Wu and Waters (1996), but for which there is still no conclusive explanation, is a stratospheric gravity wave belt around 60°S during the austral winter. It is illustrated in Figure 1 as taken from Hindley et al. (2020), who provided a comprehensive overview of seasonally averaged multiyear gravity wave momentum fluxes (GWMFs) from satellite observations.

The orography undoubtedly leads to the gravity wave hotspot between 55°W and 80°W over the southern Andes and Antarctic Peninsula, but contributes only about 25% to the total GWMF within the latitudinal band from 35°S to 68°S, as noted by Hindley et al. (2020). If Sato et al. (2012) are followed and a downstream propagation of mountain waves excited by the Andes is considered, the observed GWMF in the east of 55°W could also be associated with this predominantly local source. However, this does not greatly affect the argument of Hindley et al. (2020) that about 75% of the zonal and meridional GWMF are observed over the Southern Ocean and usually peak around 60°S. Small, mountainous islands have been shown to contribute to this oceanic GWMF, e.g., Garfinkel and Oman (2018), but even they only result in local peaks, as shown in Figure 1b. Therefore, non-orographic origins of gravity waves are most likely the reason for the widespread belt-like structure of the GWMF. Jet streams and fronts are thought to contribute to the observed momentum flux, e.g., Hendricks et al. (2014).

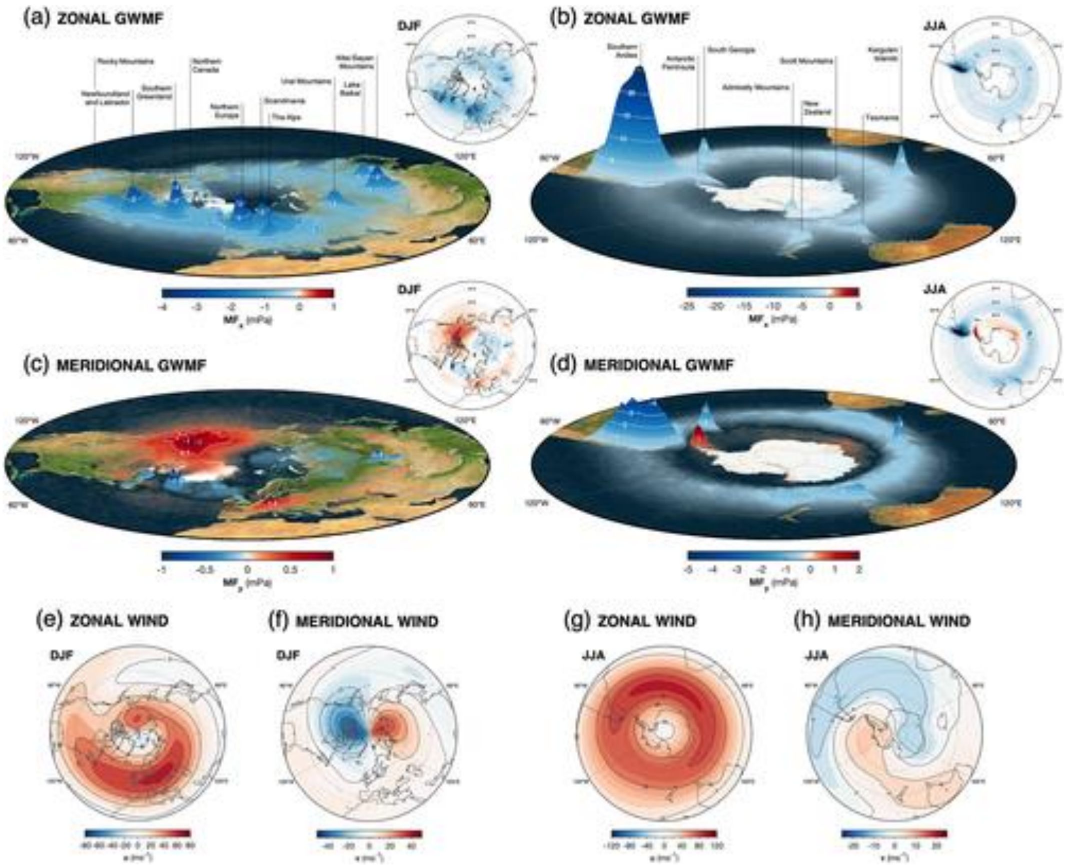

Figure 1: Stereographic maps of average wintertime zonal (a, b) and meridional (c, d) GWMF near 40 km altitude derived from AIRS observations for the period 2002–2019. Winter is defined as December–February (June–August) for the Northern (Southern) Hemisphere. GWMF values that are close to zero have been made transparent to reveal the surface features below, and landmarks that lie beneath regions of increased GWMF have been labeled. Inset in the top right of each panel is a stereographic map of the same data but centered on the north and south poles. These inset panels share a color scale with the corresponding 3-D contours. Panels (e)–(h) show average wintertime zonal and meridional winds at 3 hPa for the period 2002–2019 from ERA5 reanalysis. Taken from Hindley et al. (2020).

In an overarching sense, the gravity wave belt around 60°S has been of critical importance since McLandress et al. (2012) demonstrated its connection to the long-standing cold pole problem in almost all modern GCMs. During the Southern Hemisphere winter, the polar vortex develops with the stratospheric polar night jet (PNJ) surrounding it at about 60°S. GCMs often overestimate the strength of the PNJ, ultimately resulting in low stratospheric temperatures over the pole compared to observations (Butchart et al., 2011, Geller et al., 2013). McLandress et al. (2012) and Garcia et al. (2017) demonstrated that the absence of gravity wave drag in the parameterization can explain this significant bias in zonal winds around 60°S. A broader knowledge of the key processes leading to the observed gravity wave belt during the austral winter could greatly improve these gravity wave parameterizations and ultimately improve long-term climate predictions through more realistic and robust GCMs.

Excitation of gravity waves above a propagating tropopause depression

As indicated earlier, non-orographic gravity wave sources have already been studied from various viewpoints, but are not yet able to fully explain the consistent, widespread occurrence of gravity waves around 60°S. In particular, a specific process for how these waves are excited and how they propagate into the PNJ is still missing. Based on unique airborne lidar observations and analysis of high-resolution ERA5 data, Dörnbrack et al. (2021) propose a new mechanism that has the potential to fill this gap. The results of their study demonstrate that stratospheric gravity waves (such as those detected on dedicated research flight RF25 during DEEPWAVE) can be excited by eastward Rossby wave trains along the midlatitude waveguide. Figure 2 shows a snapshot at different stratospheric pressure surfaces of what these gravity waves look like in the form of temperature perturbations.

It appears that gravity wave phase lines from an unknown source at about 50°S migrate south-eastward into the core of the PNJ, as indicated by the denser contour lines of geopotential heights. This pattern is very similar to the well-known trailing mountain wave patterns observed in the stratospheric airflow leeward of the New Zealand Southern Alps (Ehard et al. 2017, Jiang et al., 2019), the Andes (e.g., Gupta et al. 2021), and the European Alps (Dörnbrack, 2021). Nevertheless, the source of stratospheric gravity waves here remains obscure.

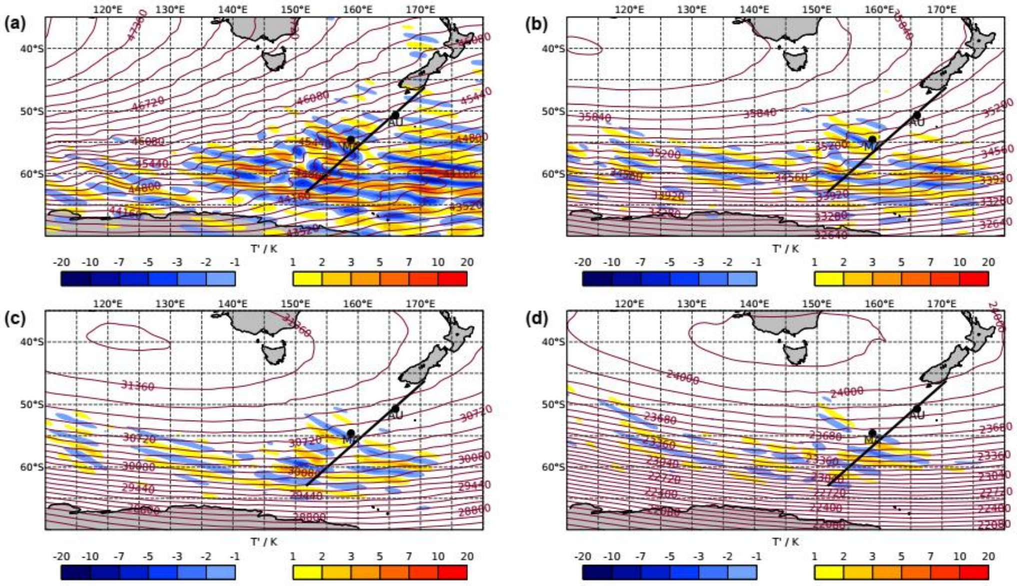

Figure 2: Temperature perturbations T'_{ERA5} (K, color-shaded) and geopotential height Z (m, burgundy solid lines) at 1 hPa (a), 5 hPa (b), 10 hPa (c), and 30 hPa (d) at 09 UTC on 18 July 2014. Data: ERA5 on a 0.28125° regular latitude/longitude grid. The black line marks the flight track of the research flight RF25 from DEEPWAVE. From Dörnbrack et al. (2021).

The basic kinematic process, as proposed by Dörnbrack et al. (2021), is the relative stratospheric air flow over a migrating tropopause depression associated with the upper-level front of the Rossby wave. In the ERA5 data, we found quasi-stationary gravity waves over the tropopause depression at various times, propagating eastward at the phase velocity of the Rossby wave (see Figure 3). During the Rossby wave life cycle, there are periods of quasi-linear phase progression that can persistently excite such gravity waves. Under favourable wind conditions, these gravity waves propagate vertically into the stratosphere. Depending on the ambient flow and the latitudinal position of the PNJ, these stratospheric gravity waves can be refracted into the PNJ (see Figure 2). Knowledge of the combination of both processes - excitation and propagation - could aid in explaining the observed and modelled widespread occurrence of stratospheric gravity waves over the Southern Ocean far from large topographic barriers. Furthermore, the identified mechanism could also contribute to the observed increased stratospheric wave energy in the southern hemispheric gravity wave belt. In this way, our results are consistent with those of Hendricks et al. (2014), who showed a correlation of the baroclinic Eady growth rate at 525 hPa with stratospheric wave energy in the gravity wave belt. In this way, we identified at least one kinematic process possibly leading to large amplitude stratospheric gravity waves.

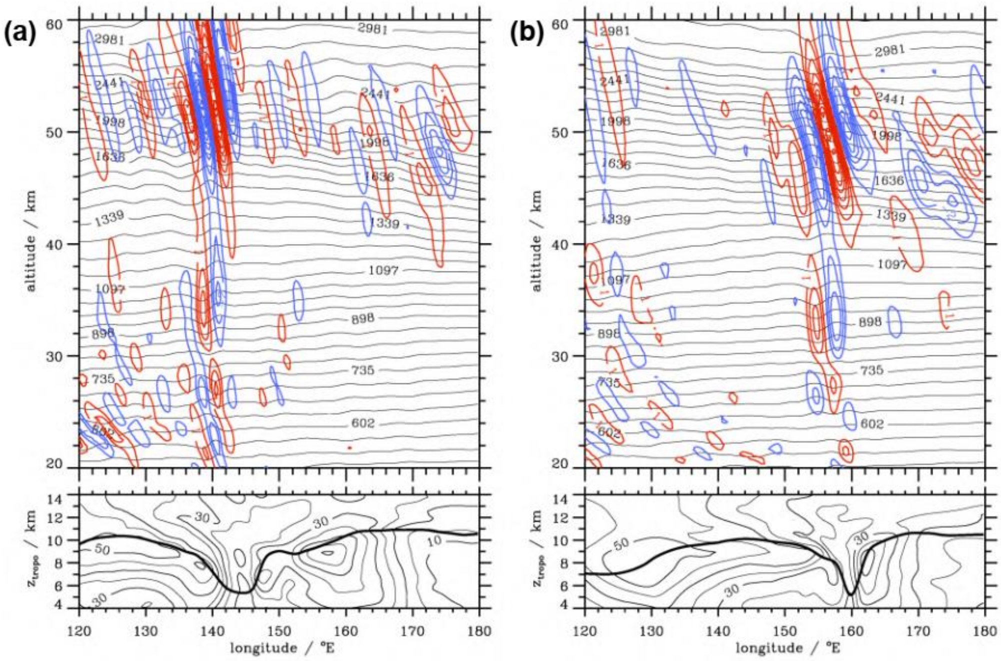

Figure 3: Temperature perturbations T'_{ERA5} (K, red and blue contour lines) and potential temperature (K, black lines in logarithmic scaling) along 55°S on 17 July 2014 15 UTC (a) and 18 July 2014 09 UTC (b). The bottom panels depict the height of the dynamical tropopause (thick black lines, meridional 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. From Dörnbrack et al. (2021).

EULAG Simulations to quantify the gravity wave characteristics above a propagating tropopause depression

The goal of the ongoing research is to investigate the key processes associated with gravity waves excited b the airflow over tropopause depressions through idealized numerical simulations. Specifically, we will answer the following research questions:

(a) How sensitive is the excitation and propagation of gravity waves over tropopause depressions to the shape of the depression (depth, width, asymmetry)?

(b) What wave regimes are present over propagating tropopause depressions and what horizontal and vertical wavelengths and amplitudes do we find for varying profiles of the stratospheric winds?

(c) What is the contribution of horizontal wind shear $\partial U/\partial y$ in the stratosphere to meridional propagation of gravity waves into the PNJ?

To answer these questions, a series of idealized numerical simulations will be conducted during the next months, the hierarchy of these simulations is listed in Figure 4.

	Simulation	Description
2D	001: Fundamental flow regimes over orography	- Non-hydrostatic wave regime - Hydrostatic wave regime - Inertia-gravity wave regime
	002: Mtn / TD shape comparison	- Witch of Agnesi - $(1+cos(\phi))$ shape - $(1+cos(\phi))^4$ shape
	003: Transient lower boundary test	- Mtn rises or moves in x-direction - No background wind - Test smooth start up / end of motion
	004: Transient TD like Prusa et al. (2003)	- Oscillating TD in zonal direction - Constant stratospheric background wind - Constant stratospheric stability
	005: Propagating TD with vertical shear	- PNJ at $\approx$ 40km - TD moves with phase velocity of Rossby wave - Design idealized wind profile - Use wind profile from ECMWF - **Sensitivity analysis** wrt. shape of depression (h_0, a and asymmetry)
	006: Propagating TD with meridional wind	- Run 2D005 with Coriolis force
3D	007: Propagating TD with vertical shear	- Run 2D005/006 in 3D - TD oriented N-S - Compare elongated and local depression (elliptic shape)
	008: Tilted TD with vertical shear	- Run 3D007 with tilted TD (oriented NW-SE)
	009: Barocl. (or barotropic) PNJ above TD	- Include horizontal shear - 2D Gaussian distribution (for barocl. jet) - θ_{env} from thermal wind relation (for barocl. jet) - PNJ directly above tropopause depression
	010: Barocl. (or barotropic) PNJ shifted south	- Simulation 3D009 with PNJ shifted south
	011: Full simulation including troposphere	- Initialisation based on Bush et al. (1994) - Extension of barocl. instability with PNJ

Figure 4: Planned numerical simulations with EULAG to investigate the characteristics of gravity waves above propagating tropopause depressions (here abbreviated by TD). Table as presented by Michael Binder for his master thesis project.

Figure 5 shows first, preliminary results of the ongoing numerical simulations. Shown are 2D stratospheric gravity waves over an eastward propagating tropopause low. These encouraging results demonstrate the suitability of the numerical approach.

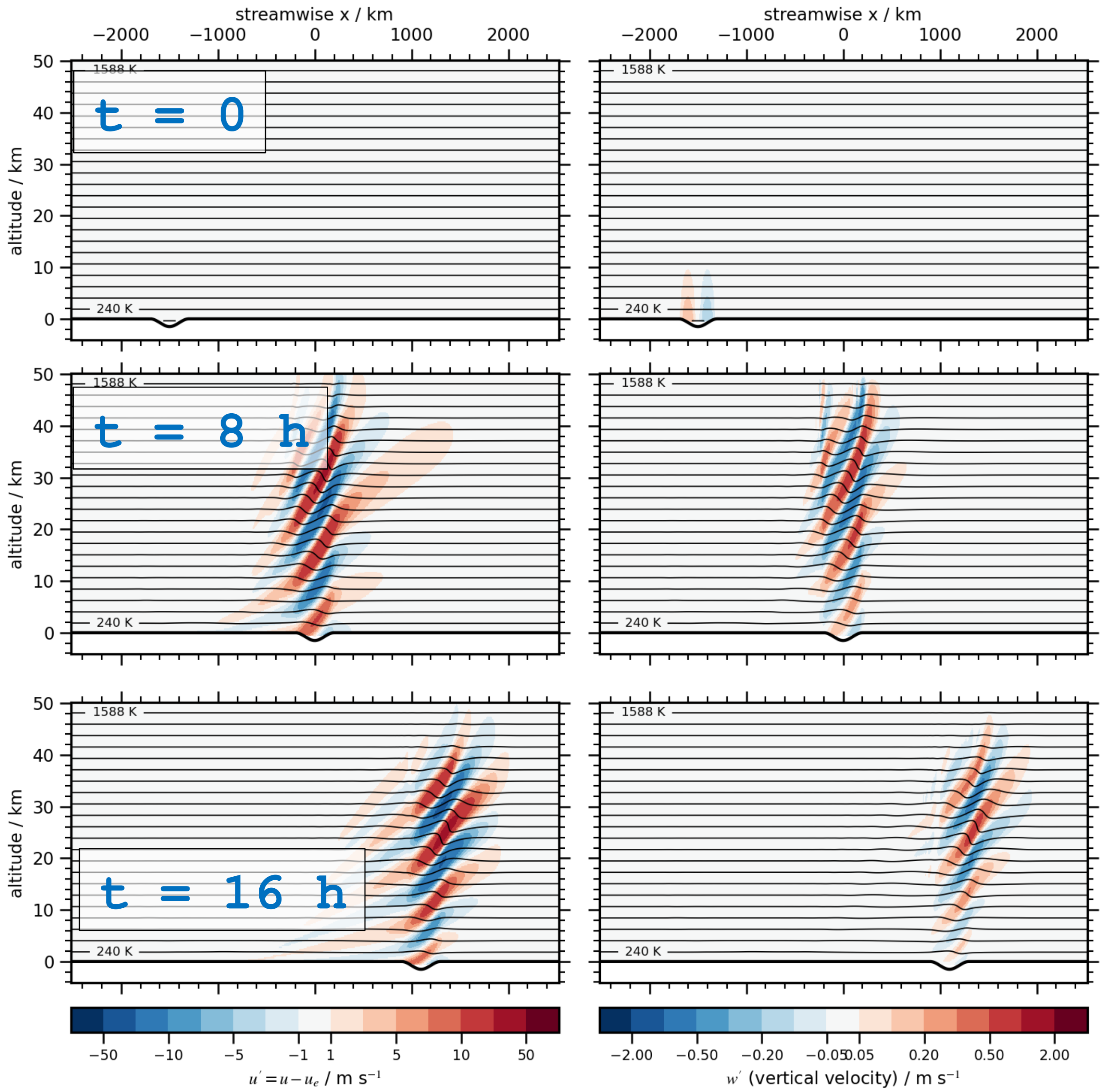

Figure 5: Preliminary results of idealized 2D numerical simulations of a uniform airflow across an eastward propagating tropopause depression modelled as time-dependent and frictionless lower boundary, like a membrane. Shown are the perturbations of the zonal velocity component (left column) and the vertical wind (right column) at three different times. Thin black lines are isentropic surfaces.

References (bold names are members of the project and the stars in front of the names mark this year's publications in the framework of the project))

Butchart, N., Charlton-Perez, A. J., Cionni, I., Hardiman, S. C., Haynes, P. H., Krüger, K., Kushner, P. J., Newman, P. A., Osprey, S. M., Perlwitz, J., Sigmond, M., Wang, L., Akiyoshi, H., Austin, J., Bekki, S., Baumgaertner, A., Braesicke, P., Brühl, C., Chipperfield, M., . . . Yamashita, Y. (2011). Multimodel climate and variability of the stratosphere. *Journal of Geophysical Research*, ***116***(D5), D05102. https://doi.org/10.1029/2010JD014995

*__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

*__Dörnbrack, A__., 2021: Stratospheric mountain waves trailing across Northern Europe, *J. Atmos. Sci.*, (published online ahead of print 2021) https://journals.ametsoc.org/view/journals/atsc/aop/JAS-D-20-0312.1/JAS-D-20-0312.1.xml

*__Dörnbrack, A__., S. D. Eckermann, B. P. Williams, and J. Haggerty, 2021: Stratospheric gravity waves excited by propagating Rossby wave trains. *Journal of the Atmospheric Sci*ences, under revision.

Ehard, B., et al. (2017), Horizontal propagation of large-amplitude mountain waves into the polar night jet, *J. Geophys. Res. Atmos.*, **122**, 1423– 1436, doi:10.1002/2016JD025621.

Fritts, D.C., R.B. Smith, M.J. Taylor, J.D. Doyle, S.D. Eckermann, **A. Dörnbrack**, M. Rapp, B.P. Williams, P. Pautet, K. Bossert, N.R. Criddle, C.A. Reynolds, P.A. Reinecke, M. Uddstrom, M.J. Revell, R. Turner, B. Kaifler, J.S. Wagner, T. Mixa, C.G. Kruse, A.D. Nugent, C.D. Watson, **S. Gisinger**, S.M. Smith, R.S. Lieberman, B. Laughman, J.J. Moore, W.O. Brown, J.A. Haggerty, A. Rockwell, G.J. Stossmeister, S.F. Williams, G. Hernandez, D.J. Murphy, A.R. Klekociuk, I.M. Reid, and J. Ma, 2016: The Deep Propagating Gravity Wave Experiment (DEEPWAVE): An Airborne and Ground-Based Exploration of Gravity Wave Propagation and Effects from Their Sources throughout the Lower and Middle Atmosphere. *Bull. Amer. Meteor. Soc.*, **97**, 425–453.

Garcia, R. R., Smith, A. K., Kinnison, D. E., Cámara, Á. d. l., & Murphy, D. J., 2017: Modification of the Gravity Wave Parameterization in the Whole Atmosphere Community Climate Model: Motivation and Results, *Journal of the Atmospheric Sciences*, **74**(1), 275-291. https://doi.org/10.1175/JAS-D-16-0104.1

Garfinkel, C. I., & Oman, L. D., 2018: Effect of Gravity Waves From Small Islands in the Southern Ocean on the Southern Hemisphere Atmospheric Circulation. *Journal of Geophysical Research: Atmospheres*, **123**(3), 1552–1561. https://doi.org/10.1002/2017JD027576

Geller, M. A., Alexander, M. J., Love, P. T., Bacmeister, J., Ern, M., Hertzog, A., Manzini, E., Preusse, P., Sato, K., Scaife, A. A., & Zhou, T., 2013: A Comparison between Gravity Wave Momentum Fluxes in Observations and Climate Models. *Journal of Climate*, **26**(17), 6383–6405. https://doi.org/10.1175/JCLI-D-12-00545.1

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

Hendricks, E. A., Doyle, J. D., Eckermann, S. D., Jiang, Q., & Reinecke, P. A., 2014: What Is the Source of the Stratospheric Gravity Wave Belt in Austral Winter? *Journal of the Atmospheric Sciences*, **71**, 1583-1592. https://doi.org/10.1175/JAS-D-13-0332.1

Hindley, N. P., Wright, C. J., Hoffmann, L., Moffat-Griffin, T., & Mitchell, N. J., 2020: An 18-year climatology of directional stratospheric gravity wave momentum flux from 3-D satellite observations. *Geophysical Research Letters*, **47**, e2020GL089557. https://doi.org/10.1029/2020GL089557

Jiang, Q., Doyle, J. D., Eckermann, S. D., & Williams, B. P. (2019). Stratospheric Trailing Gravity Waves from New Zealand, *Journal of the Atmospheric Sciences*, **76**, 1565-1586. https://doi.org/10.1175/JAS-D-18-0290.1

Kaifler, N., B. Kaifler, **A. Dörnbrack**, M. Rapp, J. L. Hormaechea, and A. de la Torre, 2020: Lidar observations of large-amplitude mountain waves in the stratosphere above Tierra del Fuego, Argentina. *Sci Rep* **10,** 14529 (2020). https://doi.org/10.1038/s41598-020-71443-7

McLandress, C., Shepherd, T. G., Polavarapu, S., & Beagley, S. R., 2012: Is Missing Orographic Gravity Wave Drag near 60°S the Cause of the Stratospheric Zonal Wind Biases in Chemistry–Climate Models?, *Journal of the Atmospheric Sciences*, **69**, 802-818. https://doi.org/10.1175/JAS-D-11-0159.1

***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://doi.org/10.1175/JAS-D-20-0230.1

Plougonven, R., Hertzog, A., & Guez, L., 2013: Gravity waves over Antarctica and the Southern Ocean: Consistent momentum fluxes in mesoscale simulations and stratospheric balloon observations. *Quarterly Journal of the Royal Meteorological Society*, *139*(670), 101–118. https://doi.org/10.1002/qj.1965

Plougonven, R., la Cámara, A., Hertzog, A., & Lott, F., 2020: How does knowledge of atmospheric gravity waves guide their parameterizations? *Quarterly Journal of the Royal Meteorological Society*, *146*(728), 1529–1543.https://doi.org/10.1002/qj.3732

*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://doi.org/10.1175/BAMS-D-20-0034.1

Sato, K., Tateno, S., Watanabe, S., & Kawatani, Y., 2012: Gravity Wave Characteristics in the Southern Hemisphere Revealed by a High-Resolution Middle Atmosphere General Circulation Model. *Journal of the Atmospheric Sciences*, **69**, 1378–1396. https://doi.org/10.1175/JAS-D-11-0101.1

Wu, D. L., & Waters, J. W., 1996: Satellite observations of atmospheric variances: A possible indication of gravity waves. *Geophysical Research Letters*, **23**(24), 3631–3634. https://doi.org/10.1029/96GL02907