SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Support Tool for HALO Missions
Computer Project Account:	spdehalo
Start Year - End Year :	2012 - 2017
Principal Investigator(s)	Dr. Andreas Dörnbrack Dr. Marc Rautenhaus Dr. Andreas Schäfler Dr. Benedikt Ehard Sonja Gisinger
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Other Researchers (Name/Affiliation):	

Summary of project objectives

High-quality meteorological forecast and analysis products are essential for the successful planning and evaluation of airborne measurements. The novel and outstanding research possibilities offered by the German High Altitude and Long Range (HALO) research aircraft dedicated for atmospheric and geophysical research prompted the development of an innovative instrument in support of HALO missions. This special project is dedicated to access ECMWF's meteorological forecast and analysis products for developing and deploying such a mission support tool.

Summary of problems encountered

No problems encountered.

Experience with the Special Project framework

In my opinion, the special project framework provides a very effective and suitable access to the ECMWF data and computational infrastructure. Especially, the access to the real-time predictions of the IFS was key for the huge number of field campaigns we conducted during the recent years. As one can see by the large number of published papers and the extensive involvement in many international field campaigns, the availability and tailored visualization of IFS products had a remarkable impact on the scientific community.
The development of the HALO Support System profited very much from the special project and the rights to access the forecast data that are related to it. At the end, and this is really encouraging, was a close

collaboration of one of the PIs (Marc Rautenhaus) with the visualization group at the ECWMF[1]. In this way, our special project also gave something back to the ECMWF improving its capabilities to visualize meteorological data.

Summary of results

Here, we summarize selected results of the project divided into two categories. First, we touch the aircraft field campaigns which were substantially supported by the use of the HALO mission support system and highlight their scientific achievements from the recent five years starting in 2013. Second, we report briefly about the development of the HALO support system and direct the interested reader to the work that has been done by Marc Rautenhaus after his move from DLR to the Technical University Munich. The close collaboration with Andreas Schäfler in the project "Waves to Weather" supported by our special project resulted in refined visualization tools which were documented in peer-reviewed journals. Therefore, we summarize all papers which were published in the broader framework of this special project from which they were inspired and supported in some specific way.

(1) HALO aircraft missions 2013-2018

Due to long-lasting and complicated certifications of diverse instruments, HALO mission were delayed and started with a campaign called NARVAL[2] at the end of the year 2013. Subsequently, HALO was deployed regularly and our Mission Support System was used in most of the campaigns via the web site http://www.pa.op.dlr.de/missionsupport/classic/forecasts/ where standardized products of the IFS high-resolution predictions were displayed. Furthermore, the usage of the interactive planning tool was explored during aircraft missions where both HALO and/or the DLR research aircraft Falcon were deployed.

(a) In December 2013, the DLR Falcon research aircraft was deployed in the Arctic. The challenge of the Arctic mission "Investigation of the life cycle of gravity waves" (GW-LCYCLE) was to predict gravity waves (GW) excited by the flow over the Scandinavian mountain range at stratospheric and mesospheric altitudes. GW-LCYCLE is part of the German project ROMIC (Role of the Middle Atmosphere in Climate) funded by the ministry of research. In GW-LCYCLE, we investigated the excitation, propagation and dissipation of GW in the whole atmosphere to enhance the knowledge of the sources, the propagation, and the dissipation of gravity waves in the upper atmosphere. The ultimate goal of GW-LCYCLE was to deliver data sets that can be used to improve current GW parameterizations in NWP models and GCMs.

Especially; we seeked further advances in quantifying:

- wave sources and the impact of the ambient atmospheric conditions on their capability to launch propagating GWs effectively,

[1] https://www.ecmwf.int/en/elibrary/17351-gpu-based-interactive-3d-visualization-ecmwf-ensemble-forecasts
https://www.ecmwf..int/en/elibrary/17133-ensemble-and-3d-visualization-met3d-recent-research-and-software-updates
[2] http://www.mpimet.mpg.de/nc/communication/news/single-news/article/erster-messflug-forschungsflugzeug-halo-durchleuchtet-passatbewoelkung.html

- the GW propagation to the middle atmosphere in response to the ambient wind and thermal conditions,
- the response of the ambient, large-scale flow to the deposition of momentum by breaking gravity waves, and to test
- the reliability of predictions of GWs (sources, propagation, upper atmosphere) by current state-of-the-art NWP models.

During the campaign, we focussed on meteorological situations as illustrated in Fig.1;

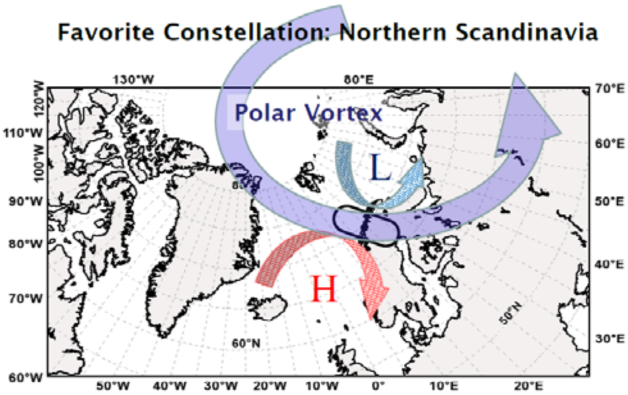

Figure 1: Flow pattern over northern Scandinavia conducive to deep gravity propagation. The large blue arrow marks the stratospheric polar vortex, the smaller ones the tropospheric low and high pressure systems leading to nearly uniform winds at all altitudes.

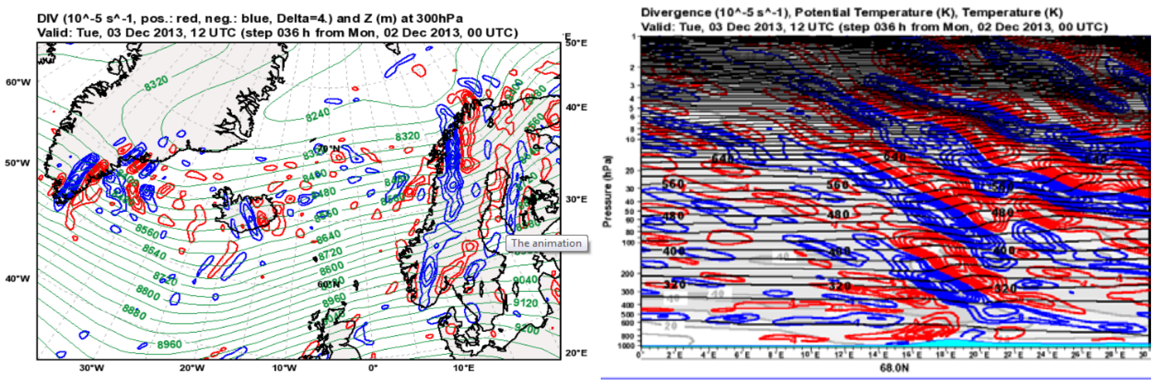

Figure 2: Horizontal divergence at 300 hPa (flight level of the Falcon research aircraft) and a vertical section along the flight track reaching up to 1 hPa altitude. The pictures show the resolved deep vertical propagation of gravity waves excited by the flow across the Scandinavian Alps in the IFS.

The research flights were planned according to ECMWF forecasts which cover an altitude range from the Earth surface up to 1 hPa, see Fig. 2. In addition to the high-resolution deterministic forecasts of the ECMWF's IFS, mesoscale forecasts with the WRF model and driven by the IFS output were performed operationally during the campaign and afterwards as hindcasts to validate the observations (Wagner et al., 2017). Figure 3 shows an exemplary comparison of the flight level wind measurements with the mesoscale forecasts.

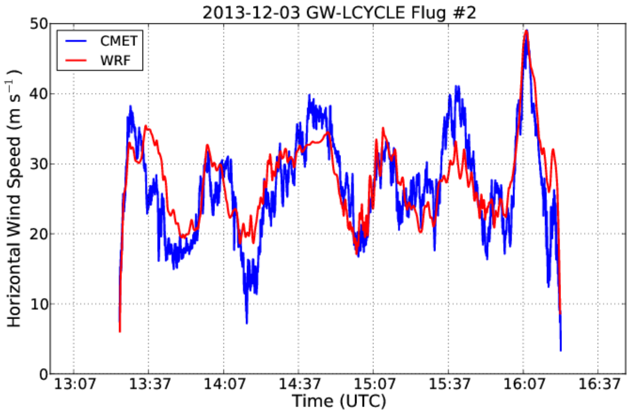

Figure 3: Horizontal wind at flight level as measured from the aircraft (blue line) and the numerical results obtained by mesoscale numerical simulations using the WRF model along a flight track crossing the Scandinavian Alps (Wagner et al., 2017).

(b) In the year 2014, two HALO research missions were supported by providing standardized forecasts on the web-site and by personnel providing met briefings at the campaign sites. The first HALO aircraft mission - called NARVAL[3] - took place in January 2014 and observed postfrontal mesoscale precipitation over the North Atlantic For this mission, the Mission Support System was used via the web site http://www.pa.op.dlr.de/missionsupport/classic/forecasts/ where standardized products of the IFS high-resolution prediction were displayed. Additionally, extensive use of the interactive Mission Support System was made to design optimal flight routes over the northern Atlantic. During the subsequent ML-CIRRUS[4] campaign, a team of scientists from the DLR, ETH Zürich, the University of Mainz, and the Technical University of Munich provided detailed cirrus and contrail forecast for a period of more than three weeks in March 2014 (Voigt et al., 2017)..

(c) The DLR Institute of Atmospheric Physics participated in the Deep Propagating Gravity Wave Experiment (DEEPWAVE) organized by various US American institutes (NCAR, Yale University, GATS, NRL, University of Utah, …) with airborne observations, radiosonde launches, and ground-based lidar observations of the stratospheric and mesospheric temperature, respectively. Furthermore, detailed ECMWF IFS forecasts were provided to guide the aircraft operations of the DLR Falcon and the NSF/NCAR Gulfstream V over New Zealand and the Southern Ocean. In a overview paper, the DEEPWAVE experiment is summarized as follows (Fritts et al., 2016):

"The DEEPWAVE experiment was designed to quantify gravity wave (GW) dynamics and effects from orographic and other sources to regions of dissipation at high altitudes. The core DEEPWAVE field phase took place from May through July 2014 using a comprehensive suite of airborne and ground-based instruments providing measurements from Earth's surface to ~100 km. Austral winter was chosen to observe deep GW propagation to high altitudes. DEEPWAVE was based on South Island, New Zealand to provide access to the New Zealand and Tasmania "hotspots" of GW activity and additional GW sources over the Southern Ocean and Tasman Sea. To observe GWs up to ~100 km, DEEPWAVE utilized three new instruments built specifically for the NSF/NCAR Gulfstream V (GV): a Rayleigh lidar, a

[3] https:/halo-db.pa.op.dlr.de/mission/6
[4] http://www.pa.op.dlr.de/ML-CIRRUS/

sodium resonance lidar, and an advanced mesosphere temperature mapper. These measurements were supplemented by in-situ probes, dropsondes, and a microwave temperature profiler on the GV and by in-situ probes and a Doppler lidar aboard the German DLR Falcon. Extensive ground-based instrumentation and radiosondes were deployed on South Island, Tasmania, and Southern Ocean islands. Deep orographic GWs were a primary target, but multiple flights also observed deep GWs arising from deep convection, jet streams, and frontal systems. Highlights include the following: 1) strong orographic GW forcing accompanying strong cross-mountain flows, 2) strong high-altitude responses even when orographic forcing was weak, 3) large-scale GWs at high altitudes arising from jet stream sources, and 4) significant flight-level energy fluxes and often very large momentum fluxes at high altitudes."

The results of DEEPWAVE have been published continuously since 2015. Alone the mentioned BAMS overview article by Fritts has been cited more than 45 times since its publication in 2016 (31 July 2018). Here, we provide just a list of contributions from our institute with contributions from scientists participating in the special project: Kaifler et al. (2015, 2017), Ehard et al. (2016, 2017, 2018), Gisinger et al. (2017), Matthias et al. (2017), Dörnbrack et al. (2017), Fritts et al., (2018), Bossert et al. (2015), Bramberger et al. (2017), Portele et al. (2018), Heller et al. (2017), see list of references.

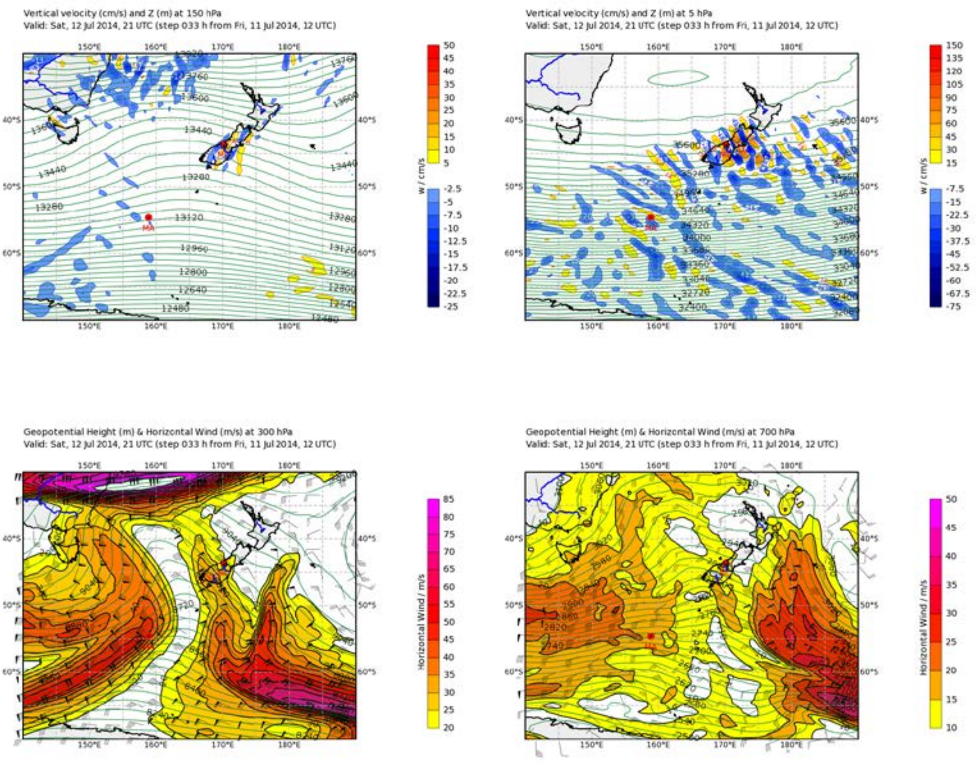

Figure 4: Forecasts charts showing the horizontal wind at 700 hPa and 300 hPa (lower panels) and the vertical velocity at 150 hPa and 5 hPa (upper panels) valid for 13 July 2014 21 UTC. The green contour lines are the geopotential heights.

Altogether, the ECMWF IFS forecasts were extremely useful in guiding the aircraft operations during DEEPWAVE. Especially, the occurrence of upper stratospheric gravity waves over the Southern Island of New Zealand and over the Southern Oceans with varying phase orientations made the forecasts challenging. Figure 4 shows an example where the phase lines in the lower stratosphere (150 hPa) are oriented parallel to the mountain ridge whereas at higher levels (5 hPa) the wave fronts are oriented perpendicular to the ridges.

Figure 5 illustrates that the predicted deep wave propagation was a consistent feature of the three subsequent forecasts runs of the IFS.

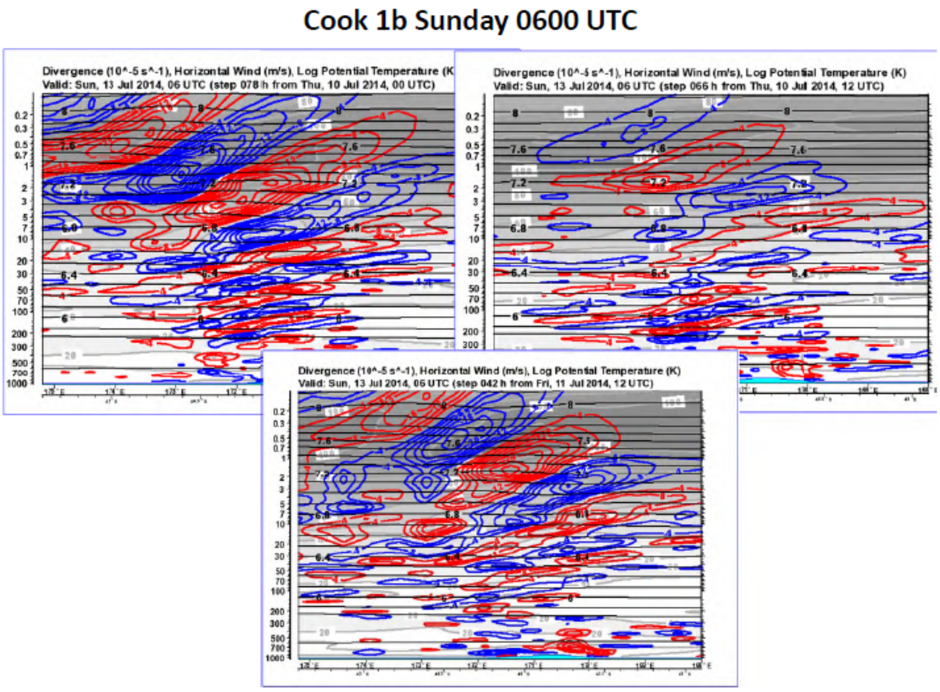

Figure 5: Horizontal divergence (red/blue contour lines), potential temperature (black lines), and horizontal wind (grey shadings) along the planned flight track "Cook 1b" for three subsequent forecast runs valid on 13 July 2014 at 06 UTC.

A short flight with the NSF/NCAR GV was designed to investigate deep gravity-wave packets predicted to occur at flight time (06-09 UTC on 13 July 2014) over the South Island of New Zealand during a period of progressive weakening in surface orographic forcing during the day. Surface forcing over the South Island earlier in the day generated orographic gravity waves at lower altitudes that were sampled by two daytime DLR Falcon flights. The GV research flight RF22 took place after this daytime phase of stronger orographic forcing had abated, and was designed to observe high altitude waves still evident in the forecasts, that pose interesting scientific questions. Are these deep gravity waves the final signatures of the orographic gravity waves forced earlier in the day that take ~12-24 hours to propagate their energy to higher altitudes of the atmosphere? Or are these waves generated instead from an entirely different source? On the latter hypothesis, possible non-orographic sources include spontaneous emission from the strong stratopause jet over Christchurch, and/or jet instabilities in the troposphere possibly associated with an approaching cold front. Another possibility is that these deep waves in the forecasts are spurious and artefacts of the model.

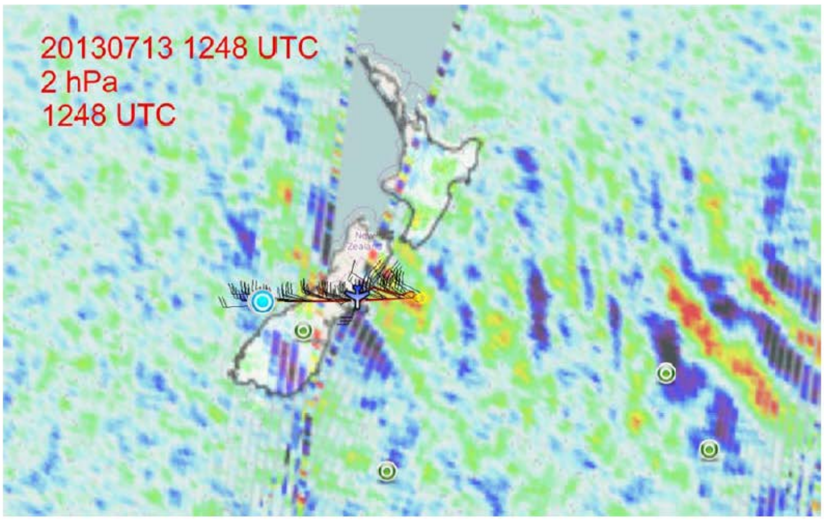

Figure 16: AIRS 2 hPa imagery at 1248 UTC on 13 July 2014, with flight track overlayed. This corresponds to about 3 hours after landing.

Figure 6: Upper stratospheric temperature fluctuations over New Zealand and the Southern Ocean as measured by AIRS about 3 h after a research flight with the NSF/NCAR GV (courtesy S. E. Eckermann, NRL Washington, DC).

Figure 6 answers at least the question that the predicted waves were real and no numerical artefacts of the IFS as the Atmospheric Infrared Sounder, AIRS, aboard NASA's Aqua satellite observed them shortly after the research flight. Currently, a publication is in preparation documenting the effort to use AIRS data for nowcasting and near-real time validation of gravity wave forecasts in the middle atmosphere for research flight campaigns.

(d) In the year 2015, no aircraft missions were actively supported by our institute applying the HALO mission support system. Instead, we concentrated on the publication of previous mission results, the further development and publication of Marc Rautenhaus MET.3D visualization of ensemble forecasts (see Section 2), and the preparation of the upcoming missions in 2016. These missions POLSTRACC/SALSA/GW-LCYCLE 2[5] and NAWDEX[6] are international field campaigns combining the two research aircraft HALO and the DLR Falcon together with ground-based and airborne instrumentations of a variety of partners. For both missions, so-called dry runs were conducted at our institute to test, modify, and customize the forecasts tools together with their application under quasi real conditions one normally encounters in a field campaign. In cooperation with the Ludwig-Maximilians Universität in Munich, tutorials were offered how to use the interactive MSS and MET.3D most effectively.

(e) In the year 2016, two large aircraft missions with different science foci were conducted and supported by the special project scientists. POLSTRACC/SALSA/GW-LCYCLE 2 and NAWDEX were international field campaigns combining the two research aircraft HALO and the DLR Falcon together with ground-based and airborne instrumentations provided by a variety of partners. For both missions, the customized forecasts tools were used for flight planning.

[5] https://www.polstracc.kit.edu/polstracc/index.php/POLSTRACC
[6] http://www.pa.op.dlr.de/nawdex

An overview of the NAWDEX campaign can be found in the BAMS paper by Andreas Schäfler (Schäfler et al., 2018).

In addition to the extensive use of the interactive Mission Support System for designing optimal flight routes over the northern Atlantic in NAWDEX a new forecast component was deployed: the Graphical Turbulence Guidance System (GTG) developed by Bob Sharman, NCAR (Sharman, R. D., C. Tebaldi, G. Wiener, and J. Wolff, 2006: An integrated approach to mid- and upper-level turbulence forecasting. *Wea. Forecasting*, **21**, 268–287, doi:10.1175/WAF924.1.).

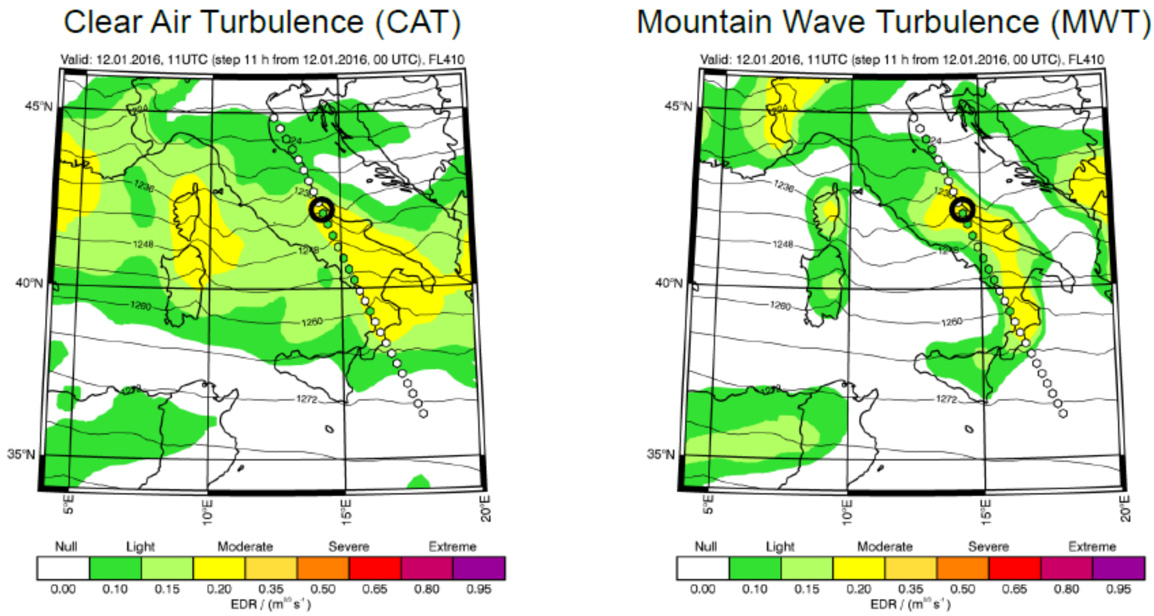

Figure 7: Regions of predicted clear-air turbulence and mountain wave turbulence at FL 410 over Italy on 12 January 2016. Predictions by the GTG forced my ECMWF IFS high resolution forecasts. The dotted lines mark the aircraft flight track, the enhanced bold circle the location of observed turbulence encounter.

The GTG was installed on ECMWF's Linux cluster Ecgate and it was run in n operational mode during both field campaigns. The visualisation of forecast products for clear-air turbulence (CAT) and mountain wave turbulence (MWT) helped to identify scientifically interesting regions for studying instability processes in the free atmosphere and to analyse unexpected encounters with CAT. Figure 7 shows an example of predicted mountain wave and clear-air turbulence along the flight track of HALO during the transfer flight from Oberpfaffenhofen to Kiruna (via Malta) on 12 January 2016. Over the Apennine Mountains, HALO encountered light turbulence due to breaking mountain waves. Additionally, the large amplitude mountain waves led to local cooling of the stratospheric air and HALO entered a hazardous flight situation. This case is thoroughly documented by Bramberger et al. (2018).

The results of the POLSTRACC/SALSA/GW-LCYCLE 2 campaigns are documented in two special issues "Sources, propagation, dissipation and impact of gravity waves"[7] and "The Polar Stratosphere in a Changing

[7] https://www.atmos-chem-phys.net/special_issue899.html

Climate”[8] in the EGU journals *Atmospheric Chemistry and Physics* and *Atmospheric Measurement Techniques*. Currently, there are altogether 20 papers submitted and published in the open access journals.

Here, we want to highlight three short papers that might be of relevance for the ECMWF scientists. In a short, recently submitted contribution to the “picture of the month” of Monthly Weather Review, we documented an interesting case observed at the end of December 2015 (Dörnbrack et al., 2017). The presented picture of the month is a kind of collage, a superposition of space-borne lidar observations and high-resolution temperature fields of the ECMWF IFS.

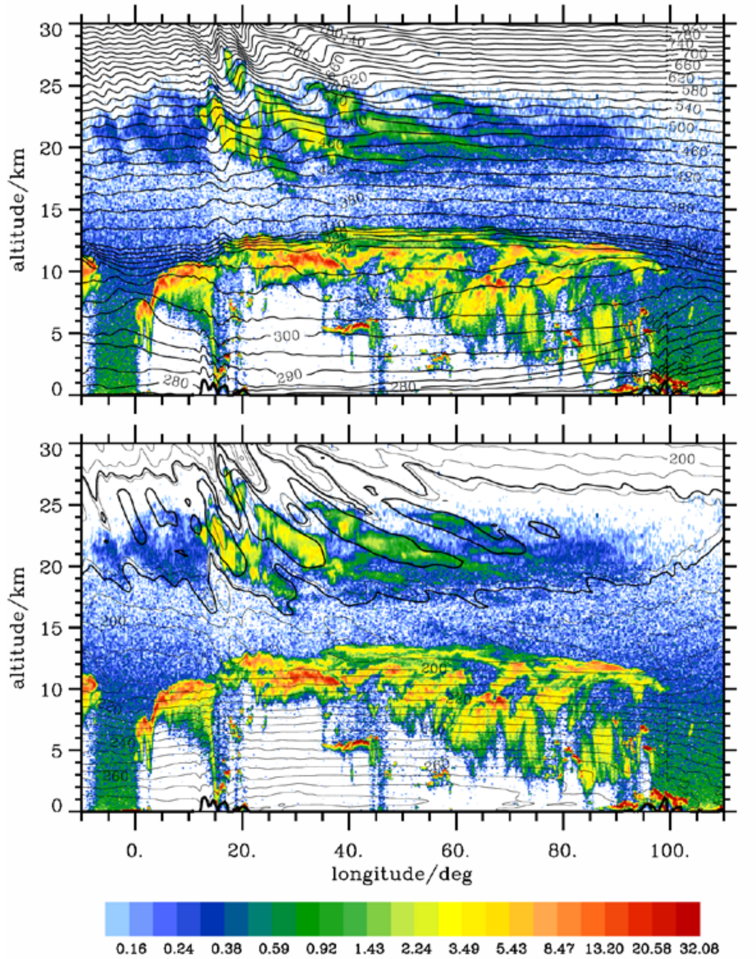

Figure 8: Composite of 532 nm total attenuated backscatter (10^{-3} km^{-1} sr^{-1}, color shaded) and ECMWF potential temperature (top, K, solid black lines) and absolute temperature (bottom, K, thin black lines every 5 K and thick black lines at 185 K and 191 K) valid on 30 December 2015 at 04 UTC (+ 4 h lead time from the 00 UTC high res IFS forecast of cycle 41r2.

Figure 8 displays complex tropospheric and stratospheric clouds over Svalbard at 30 December 2015. On this day, the unusual north-eastward propagation of warm and humid subtropical air masses as far north as 80°N lifted the tropopause by more than 3 km in 24 h and cooled the stratosphere on a large scale. A widespread formation of thick cirrus clouds near the tropopause and of synoptic-scale polar stratospheric clouds occurred as the temperature dropped below the thresholds for the existence of ice cloud particles. Additionally, mountain waves were excited by the strong flow at the western edge of the ridge across

[8] https://www.atmos-chem-phys.net/special_issue913.html

Svalbard, leading to the formation of mesoscale PSCs. Two different IFS cycles using horizontal resolutions of 16 km and 8 km globally reproduce the large-scale and mesoscale flow features well whereby the higher resolution IFS cycle produces larger mountain wave amplitudes.

In the same spirit, Ehard et al. (2018) compared ECMWF high resolution analyses to lidar temperature measurements in the middle atmosphere. In this paper, middle atmospheric lidar temperature observations conducted during the GW-LCYCLE 2 campaign in December 2015 above Finland are compared to two sets of simulations by IFS. One of the simulations is the operational cycle 41r1 with a horizontal resolution of 16 km and the other is the e-Suite 69 (later cycle 41r2) with a 9 km horizontal resolution. A remarkable agreement between both ECMWF IFS simulations and the lidar temperature observations is found below 45 km altitude (Figure 9). Above 45 km altitude, within the sponge layer of the ECMWF IFS, both simulations depict lower temperatures than the observations, with the high-resolved ECMWF IFS version showing the largest cold bias. Test runs of the ECMWF IFS were analysed and compared to the lidar observations to investigate the effect of the high-resolution horizontal grid.

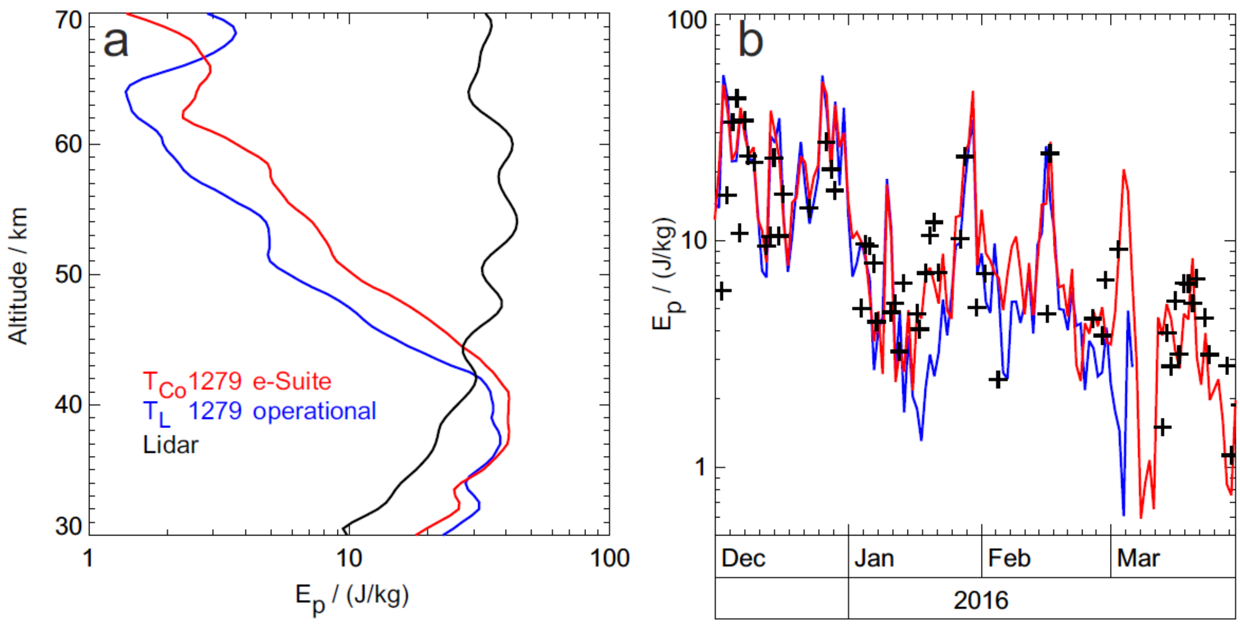

Figure 9: Figure 3 taken from Ehard et al. (2018) documenting both the astonishing agreement between the ECMWF IFS predictions in layers below 45 km altitude and the enormous differences in gravity wave potential energy above that altitude.

The last paper to be mentioned is a climatological study of the cold Arctic stratospheric winter 2015/2016 using the operational IFS analyses and ERA-Interim data (Matthias et al., 2016). The Arctic polar vortex in the early winter 2015/16 was the strongest and coldest of the last 68 years. Using global reanalysis, satellite observations, and mesospheric radar wind measurements over northern Scandinavia we investigated the characteristics of the early stage polar vortex and related them to previous winters. We found a correlation between the planetary wave (PW) activity and the strength and temperature of the northern polar vortex in the stratosphere and mesosphere. In Nov/Dec 2015, a reduced PW generation in the troposphere and a stronger PW filtering in the troposphere and stratosphere, caused by stronger middle latitudes zonal winds, resulted in a stronger polar vortex. This effect was strengthened by the more equatorward shift of PWs due to the strong zonal wind at polar latitudes resulting in a southward shift of the Eliassen-Palm flux divergence and hence inducing a decreased deceleration of the polar vortex by PWs.

(2) Met.3D - Visualization of Ensemble Weather Predictions

Marc Rautenhaus defended his PhD thesis on the visualization of ECMWF ensemble weather predictions at the Technical University of Munich in September 2015. Two publications from this work appeared (Rautenhaus et al.. 2016 a, b) and his MET.3D tool was extensively been used during the NAWDEX field campaign which was embedded in the Transregional Collaborative Research Center “Waves to Weather” at the LMU Munich[9].

List of publications/reports from the project with complete references

Members of the Special Project are highlighted in bold in the following list.

1. Woiwode, W., **A. Dörnbrack**, M. Bramberger, F. Friedl-Vallon, F. Haenel, M. Höpfner, S. Johansson, E. Kretschmer, I. Krisch, T. Latzko, H. Oelhaf, J. Orphal, P. Preusse, B.-M. Sinnhuber, and J. Ungermann, 2018: Mesoscale fine structure of a tropopause fold over mountains, submitted to *Atmos. Chem. Phys. Discuss*, 22 June 2018; https://doi.org/10.5194/acp-2018-625, under review, 2018.
2. Rapp, M., **A. Dörnbrack**, and P. Preusse, 2018: Large mid-latitude stratospheric temperature variability caused by inertial instability. *Geoph. Res. Lett*., under review.
3. Sandu, I., A. van Niekerk, T. G. Shepherd, S. Vosper, A. Zadra, J. Bacmeister, A. Beljaars, A. Brown, **A. Dörnbrack**, N. McFarlane, F. Pithan, and G. Svensson, 2018: Orography and its impacts on the atmospheric circulation, *npj Climate and Atmospheric Science*, under review.
4. **Dörnbrack, A., S. Gisinger**, N. Kaifler, T. Portele, M. Bramberger, M. Rapp, M. Gerding, J. Söder, N. Žagar, and D. Jelić, 2018: Gravity Waves excited during a Minor Sudden Stratospheric Warming, submitted to *Atmos. Chem. Phys. Discuss*, 2 March 2018, under review.
5. Fritts, D. C., S. B. Vosper, B. P. Williams, K. Bossert, M. J. Taylor, P.-D. Pautet, S. D. Eckermann, C. G. Kruse, R. B. Smith, A. Dörnbrack, M. Rapp, T. Mixa, I. M. Reid, and D. J. Murphy, 2018: Large-Amplitude Mountain Waves Accompanying Weak Cross-Mountain Flow During DEEPWAVE Research Flight RF22 on 13 July 2014. *J. Geophys. Res*., accepted.
6. Bramberger, M., **A. Dörnbrack**, S. Gemsa, K. Raynor, and R. D. Sharman, 2018: Vertically Propagating Mountain Waves - A Hazard for High Flying Aircraft? *J. Appl. Met.Clim*. accepted.
7. **Schäfler, A**., G. C. Craig, H. Wernli, P. Arbogast, J. D. Doyle, R. McTaggart-Cowan, J. Methven, G. Rivière, F. Ament, M. Boettcher, M. Bramberger, Q. Cazenave, R. Cotton, S. Crewell, J. Delanoë, **A. Dörnbrack**, A.Ehrlich, F. Ewald, A. Fix, C. M. Grams, S. L. Gray, H. Grob, S. Groß, M. Hagen, B. Harvey, L. Hirsch, M. Jacob, T. Kölling, H. Konow, C. Lemmerz, O. Lux, L. Magnusson, B. Mayer, M. Mech, R. Moore, J. Pelon, J. Quinting, S. Rahm, M. Rapp, **M. Rautenhaus**, O. Reitebuch, C. A. Reynolds, H. Sodemann, T. Spengler, G. Vaughan, M. Wendisch, M. Wirth, B. Witschas, K. Wolf, and T. Zinner, 2018: The North Atlantic Waveguide and Downstream Impact Experiment, *Bull. Amer. Meteor. Soc*., https://doi.org/10.1175/BAMS-D-17-0003.1 , accepted.
8. Chu, X., J. Zhao, X. Lu, V. L. Harvey, R. M Jones, C. Chen, W. Fong, Z. Yu, B. R. Roberts, and **A. Dörnbrack**, 2018: Lidar observations of stratospheric gravity waves from 2011 to 2015 at McMurdo (77.84° S, 166.69° E), Antarctica: Part II. Potential energy densities, lognormal distributions, and seasonal variations. *J. Geophys. Res*., accepted.
9. Voigt, C., **A. Dörnbrack**, M. Wirth, S. M. Groß, M. C. Pitts, L. R. Poole, R. Baumann, B. Ehard, B.-M. Sinnhuber,, W. Woiwode, and H. Oelhaf, 2018: Widespread polar stratospheric ice clouds in the 2015/2016 Arctic winter – Implications for ice nucleation, submitted to *Atmos. Chem. Phys. Discuss*, doi:10.5194/acp-2017-1044, 6. under review.

[9] http://www.w2w.meteo.physik.uni-muenchen.de

10. Ehard, B., S. Malardel, **A. Dörnbrack**, B. Kaifler, N. Kaifler, and N. Wedi, 2018: Comparing ECMWF high resolution analyses to lidar temperature measurements in the middle atmosphere. submitted to *Q. J. R. Met. Soc*. 16.4.2017; accepted.
11. Rapp, M., **Dörnbrack, A**., and Kaifler, B., 2018: An intercomparison of stratospheric gravity wave potential energy densities from METOP GPS radio occultation measurements and ECMWF model data, *Atmos. Meas. Tech*., **11**, 1031-1048, https://doi.org/10.5194/amt-11-1031-2018.
12. Portele, T.C., **A. Dörnbrack**, J.S. Wagner, **S. Gisinger, B. Ehard**, P. Pautet, and M. Rapp, 2018: Mountain-Wave Propagation under Transient Tropospheric Forcing: A DEEPWAVE Case Study. *Mon. Wea. Rev.*, **146**, 1861–1888, https://doi.org/10.1175/MWR-D-17-0080.1
13. Krisch, I., Preusse, P., Ungermann, J., **Dörnbrack, A.**, Eckermann, S. D., Ern, M., Friedl-Vallon, F., Kaufmann, M., Oelhaf, H., Rapp, M., Strube, C., and Riese, M., 2017: First tomographic observations of gravity waves by the infrared limb imager GLORIA, *Atmos. Chem. Phys*., **17**, 14937-14953, https://doi.org/10.5194/acp-17-14937-2017, 2017.
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15. Heller, R., Voigt, C., Beaton, S., **Dörnbrack, A.,** Giez, A., Kaufmann, S., Mallaun, C., Schlager, H., Wagner, J., Young, K., and Rapp, M., 2017: Mountain waves modulate the water vapor distribution in the UTLS, *Atmos. Chem. Phys*., **17**, 14853-14869, https://doi.org/10.5194/acp-17-14853-2017.
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