SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Atmospheric waves in the middle atmosphere measured by the ALIMA lidar onboard the research aircraft HALO
Computer Project Account:	spdekaif
Start Year - End Year :	2014 - 2016
Principal Investigator(s)	Bernd Kaifler Natalie Kaifler
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Other Researchers (Name/Affiliation):	Benedikt Ehard, DLR Andreas Dörnbrack, DLR

The following should cover the entire project duration.

Summary of project objectives
(10 lines max)

The objective of the project is to study atmospheric waves using the ALIMA instrument (short for Airborne LIDAR for the Middle Atmosphere). The lidar will measure atmospheric density, temperature and disturbances caused by atmospheric waves between 10 and 120 km using different scattering mechanisms. A prototype for the new instrument will be built and tested on ground before ALIMA is certified for operations on the research aircraft HALO. Atmospheric gravity waves are excited near ground level, e.g. by flow over mountains and propagate throughout the atmosphere up to thermospheric altitudes (> 100 km). Gravity waves interact with the background flow by convective or dynamic instabilities and are subject to selective filtering. They contribute significantly to the energy budget of the atmosphere and play a major role in the vertical coupling of the atmosphere.

Summary of problems encountered
(If you encountered any problems of a more technical nature, please describe them here.)

none

Experience with the Special Project framework
(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

positive

Summary of results
(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

During development of the novel ALIMA instrument for the DLR research aircraft HALO, two technology demonstrators were developed, build and operated since 2014. The TELMA and CORAL instruments are powerful Rayleigh lidars housed in small containers for ground-based operation during field campaigns. Semi-autonomous capabilities allow for easy maintenance, control and operation at remote sites with minimal costs and time commitment by human operators. Both Rayleigh lidar instruments perform high-resolution temperature and gravity wave soundings of the middle atmosphere up to 96 km altitude. They were so far involved in three coordinated measurement campaigns:

- TELMA during DEEPWAVE, New Zealand in winter 2014;
- CORAL during GW-LCYCLE2 at Sodankylä, Finland in winter 2015/2016 and
- CORAL at GERES station in the Bavarian Forest in summer 2016 as part of the ARISE-2 programme

Each field campaign resulted in several hundred hours of high-resolution data. As anticipated, ECMWF data was used during scientific evaluation of the measurement data, e.g. by

1. evaluation of atmospheric conditions like wind fields at the time of lidar measurements.
2. Providing atmospheric background fields (wind, temperature) for backward raytracing of gravity waves in order to identify gravity wave sources
3. assess the Doppler shift of gravity waves observed by lidar
4. validate ECMWF IFS atmospheric states with lidar point measurements of temperature at mesospheric altitudes

A list of references to scientific publications is provided below. A short summary is given here:

Gravity wave propagation during different wind regimes

The objective of the DEEPWAVE campaign was to assess conditions for so-called deep propagation of gravity waves into the stratosphere and mesosphere. Intermittent periods of enhanced stratosperic gravity wave activity were observed by lidar during times with strong tropospheric wind. In a study of mountain wave propagation into the stratosphere, ECMWF data was used to classify gravity wave forcing based on horizontal wind at the observation site as well as at an upstream location. To do this, the horizontal wind component perpendicular to the New Zealand's South Island mountain range was extracted. The rotation of the horizontal wind vector was evaluated in order to account for gravity wave filtering. The horizontal wind component was then correlated with gravity wave activity, and it could be deduced that a large portion of stratospheric gravity waves are caused by mountain waves, and that the largest-amplitude mountain waves excited by strong tropospheric forcing do not reach mesospheric altitudes either due to wave breaking or lateral refraction.

Figure from Kaifler et al, GRL, 2015:

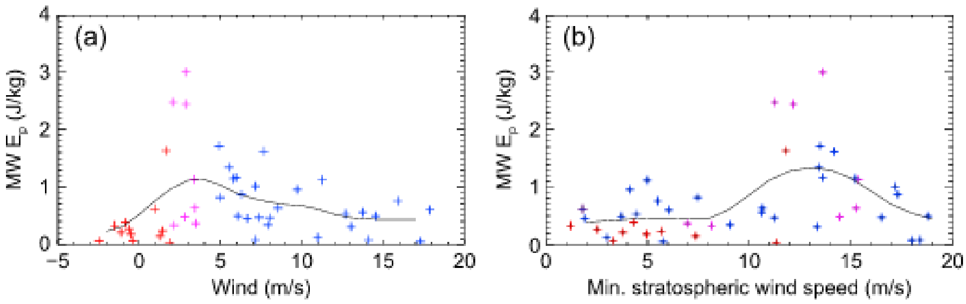

Figure 5. E_p of quasi-stationary GW (MW) from 3 h averages (at least 30 min of observational data) in the height range 60–76 km versus (left) wind speed perpendicular to the Southern Alps at 1 km altitude and (right) minimum wind speed perpendicular to the Southern Alps in the height range 15–40 km. The solid line shows the values smoothed with an 8 m/s Hann window. Colors indicate three different wind speeds (1 km level): <2 m/s (red), 2–4 m/s (magenta), and >4 m/s (blue).

Backward raytracing of gravity waves

In the case study of an extreme mountain wave event observed during the DEEPWAVE campaign in New Zealand in August 2014, ECMWF analysis were extensively used to assess the synoptic situation and track the vertical and horizontal propagation of gravity waves in the middle atmosphere. Geographic maps, latitude-height sections and Hovmöller diagrams of geopotential height, horizontal wind speed, height of the dynamical tropopause and horizontal divergence were used for this purpose. Temperature and wind fields from ECMWF were fed into a ray tracing model in order to track the propagation of gravity waves. It was found that the propagation of the mountain wave is determined by two effects: wave breaking due to instabilities in weak wind layers in the lower stratosphere, and subsequent refraction into the polar night jet due to strong meridional shear of the zonal wind.

Figure from Ehard et al., JGR, 2017:

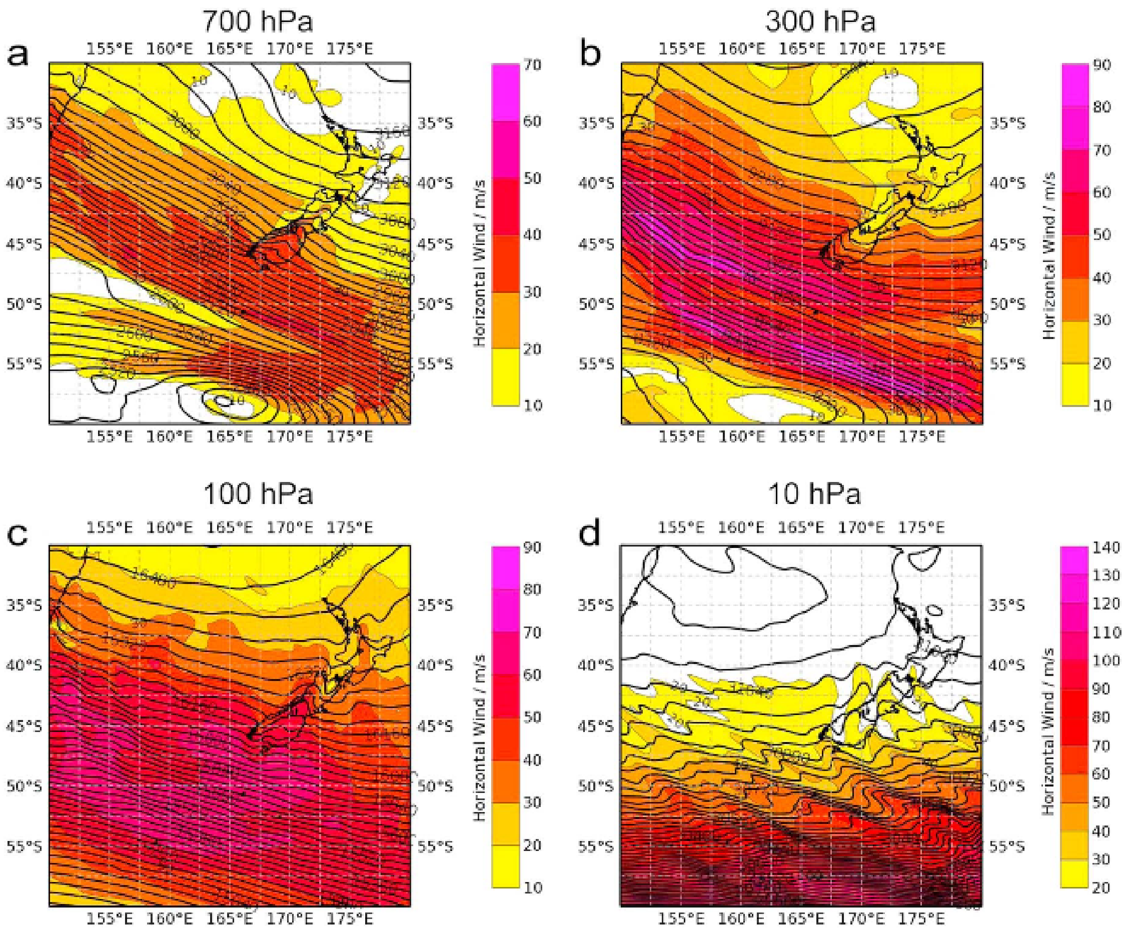

Figure 1. Geopotential height (m, solid lines) and horizontal wind speed (m s^{-1}, color coded) at (a) 700, (b) 300, (c) 100, and (d) 10 hPa on 31 July 2014 at 1200 UTC. Data are taken from the ECMWF IFS T1279/L137.

Evaluating the Doppler shift of gravity waves

During atmospheric soundings above New Zealand and Finland, close to or outside the polar vortex, a rare type of gravity waves that appear to propagate downward was detected. A close inspection of several cases was carried out in order to describe and characterize these waves. ECMWF horizontal wind data below 60 km was essential to assess the question whether these waves are indeed downward-propagating or are so strongly Doppler shifted such that they only appear to do so in the special measurement geometry of a ground-based point measurement. ECMWF data was also used to compare background conditions at the two sites and assess the proximity to the polar vortex during different times.

Figure from Kaifler et al., JASTP, 2017:

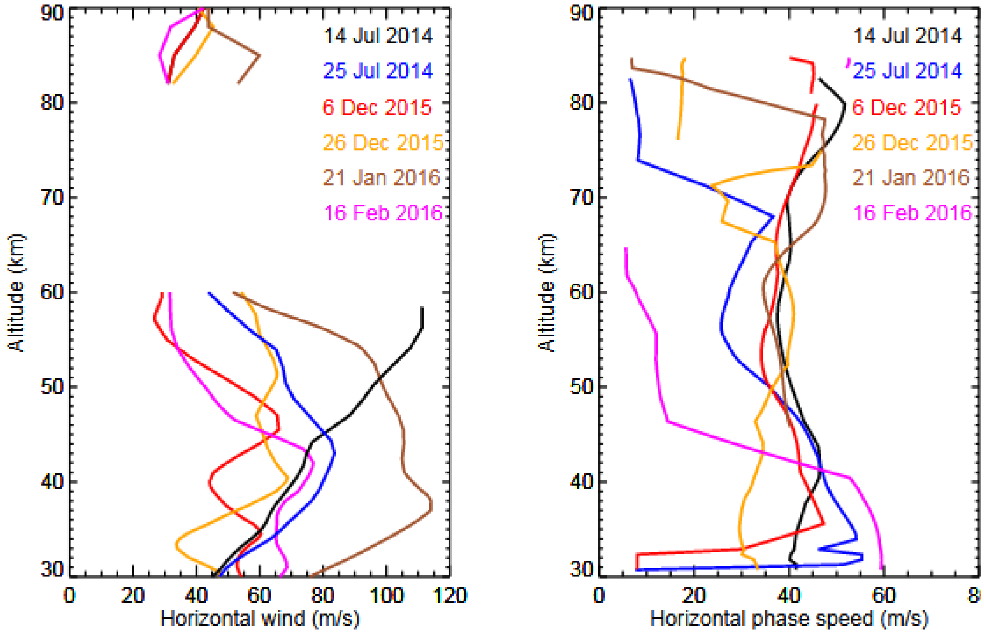

Figure 12: (a) Co-located horizontal wind data $\bar{u}_h$ from meteor radar measurements (above 82 km) and ECMWF (below 60 km). (b) Intrinsic horizontal phase velocity $|\hat{c}_h|$ of waves with upward phase progression.

Comparison of ECMWF high resolution analysis to lidar temperatures

Several sets of atmospheric states computed by the ECMWF IFS with changing horizontal resolution and modelled science were compared to high-resolution temperature data obtained by the CORAL lidar above Sodankylä, Finland in December 2015. A remarkable agreement of atmospheric temperatures was found below 45 km altitude. The temporal evolution of gravity wave activity below 45 km is very well represented. Within the IFS sponge layer above 45 km and towards the model top, a polar mesospheric cold bias occurs. Its strength depends on both the resolution upgrade and model changes changes. Sensitivity studies with several test-runs were performed in order to characterize the deviation from the point measurements and assist improvements of the mean state of ECMWF datasets in the mesosphere.

Figure from Ehard et al., QJRMS, 2017:

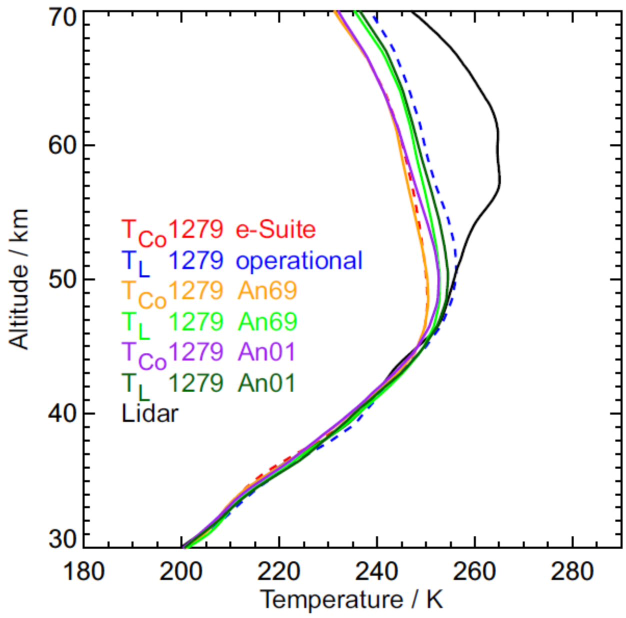

Figure 4. Mean temperature profiles above Sodankylä from 10 to 17 December 2015. Black line: CORAL measurements; red/blue dashed line: 4 lead days forecasts from 41r2 e-suite/operational 41r1 HRES; Colored solid lines: test-runs with 4 lead days. Only IFS profiles with simultaneous lidar measurements are used.

List of publications/reports from the project with complete references

- Ehard, Benedikt (2017): Horizontal and vertical propagation of mountain waves from New Zealand into the polar night jet. Dissertation, LMU München: Fakultät für Physik
- Ehard, Benedikt and Malardel, Sylvie and Dörnbrack, Andreas and Kaifler, Bernd and Wedi, Nils. Comparing ECMWF high resolution analyses to lidar temperature measurements in the middle atmosphere. Submitted to Q. J. R. Meteorol. Soc.
- Kaifler, Natalie and Kaifler, Bernd and Ehard, Benedikt and Gisinger, Sonja and Dörnbrack, Andreas and Rapp, Markus and Kivi, Rigel and Kozlovsky, Alexander and Lester, Mark and Liley, Ben (2017). Observational indications of downward-propagating gravity waves in middle atmosphere lidar data. Journal of Atmospheric and Solar-Terrestrial Phycis. DOI: 10.1016/j.jastp.2017.03.003 (in press).
- Ehard, Benedikt und Kaifler, Bernd und Dörnbrack, Andreas und Preusse, P. und Eckermann, Stephen D. und Bramberger, Martina und Gisinger, Sonja und Kaifler, Natalie und Liley, Ben und Wagner, Johannes und Rapp, Markus (2017) Horizontal propagation of large-amplitude mountain waves into the polar night jet. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES, Seiten 1-14. DOI: 10.1002/2016JD025621 ISSN 2169-897X
- Kaifler, Bernd und Kaifler, Natalie und Ehard, Benedikt und Dörnbrack, Andreas und Rapp, Markus und Fritts, David C. (2015) Influences of source conditions on mountain wave penetration into the stratosphere and mesosphere. Geophysical Research Letters, Seiten 1-7. AGU Publications. DOI: 10.1002/2015GL066465 ISSN 0094-8276
- Kaifler, Bernd und Lübken, F.-J. und Höffner, J. und Morris, R. J. und Viehl, T. P. (2015) Lidar observations of gravity wave activity in the middle atmosphere above Davis (69°S, 78°E), Antarctica. Journal of Geophysical Research: Atmospheres, 120 (10), Seiten 4506-4521. DOI: 10.1002/2014JD022879 ISBN 2169-8996 ISSN 0148-0227

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Research in middle atmospheric dynamics with special emphasis on gravity waves will continue at our institute. CORAL will soon be brought to southern Argentina as part of the ARISE2-programme. Additionally, two airborne instruments (balloon and research aircraft) are in development and are expected to conduct measurements of the middle atmosphere during the next three years.