

# Middle Atmospheric Doppler Rayleigh Winds, Temperatures, and Gravity Waves at Kühlungsborn and ALOMAR

Robin Wing<sup>(a)</sup>, Michael Gerding<sup>(a)</sup>, Eframir Franco-Diaz<sup>(a)</sup>, Irina Strelnikova<sup>(a)</sup>, Mohamed Mossad<sup>(a)</sup>, Jens Fiedler<sup>(a)</sup>, Fede Conte<sup>(a)</sup>, Gerd Baumgarten<sup>(a)</sup>

<sup>(a)</sup> Leibniz Institute for Atmospheric Physics, Kühlungsborn, Germany

Lead Author e-mail address: [wing@iap-kborn.de](mailto:wing@iap-kborn.de)

**Abstract:** We demonstrate the capability of the Doppler Rayleigh lidars at Kühlungsborn and ALOMAR to accurately measure temperature and horizontal wind in the stratosphere and mesosphere. Comparisons are shown with radar, satellite and ECMWF. By exploiting the daylight capabilities of the ALOMAR lidar, we can produce high quality vertical and temporal gravity wave spectra in both winds and temperatures. Then using our simultaneous observations of T, u, and v, we can reconstruct quasi-monochromatic gravity wave packets and solve for all gravity wave characteristics including momentum flux.

## 1. Introduction

The scarcity of global observations of winds is a key limitation in modelling atmospheric dynamics and atmospheric reanalysis and forecasting activities. The World Meteorological Organization lists winds as the most crucial atmospheric variable for observation [1].

Despite the pressing need for measurements of horizontal wind in the middle atmosphere, there are currently only six Doppler Rayleigh lidars capable of measuring the horizontal wind in the stratosphere and mesosphere. Of these lidars, only two (Kühlungsborn and ALOMAR) are capable of simultaneous measurements of wind and temperature using the “single edge” technique and only ALOMAR is currently able to make these observations in daylight. Technical details for the ALOMAR lidar can be found in [2] and technical details for the Kühlungsborn lidar can be found in [3].

The benefit of simultaneous co-located measurements of wind and temperature by lidar is the ability to isolate and extract individual gravity wave packets from the time-altitude series. By isolating individual gravity waves, we can characterize their vertical wavelength, horizontal wavelength,

period, phase speed, and propagation direction [4]. Additionally, we can calculate higher order gravity wave parameters such as momentum flux and heat flux, which are sought after quantities by atmospheric modelers.

## 2. Winds and Temperatures

To ensure the accuracy of our wind and temperature measurements we undertake comparisons with satellites, meteor radars, and with the European Centre for Medium-Range Weather Forecasts – Integrated Forecasting System (ECMWF-IFS). In Figure 1, we can see one example from the Kühlungsborn lidar on 5 June 2023 where we have compared the nightly average lidar profile to independent measurements. In the top panel, we have compared the lidar (green) to the average SABER [5] profile (blue) in the region around the lidar (+/- 5 degrees latitude and longitude), and to the ECMWF-IFS average profile (yellow). The shaded regions represent the nightly standard deviation at each altitude of the respective profile. We see excellent agreement between the lidar and SABER at all altitudes. The ECMWF profile reports warmer temperatures above 50 km and much warmer temperatures above 75 km.

The middle panel compares the nightly average zonal winds from the lidar (blue) to the zonal winds from the SIMONE Germany meteor radar network [6] (cyan) and ECMWF-IFS (yellow). Positive winds are eastward and negative winds are westward. The dark shaded regions around each profile indicate measurement uncertainty and lighter shaded regions indicate standard deviations. We see excellent agreement between the radar and lidar above 78 km where both instruments capture the very

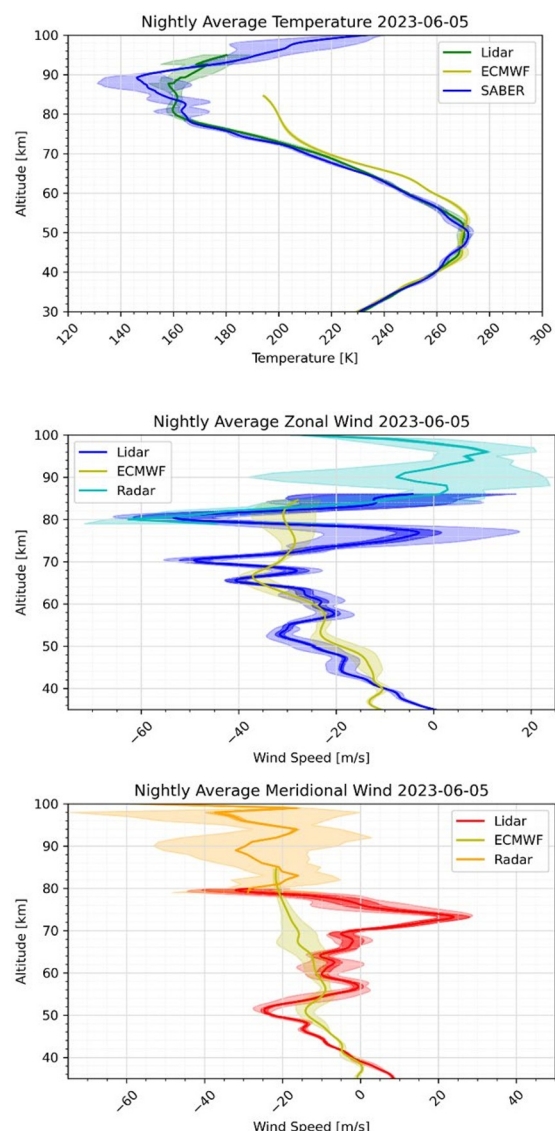


Figure 1. Example of winds and temperatures by radar and lidar at Kühlungsborn

large wave structure which is absent in ECMWF-IFS. The radar and lidar also have similar values for the standard deviations of the zonal wind indicating that

both instruments should see similar gravity wave characteristics.

The bottom panel compares the nightly average meridional winds from the lidar (red) to the meridional winds from the radar (orange) and ECMWF-IFS (yellow). Positive winds are northward and negative winds are southward. Similar conventions regarding shading apply.

### 3. Gravity Wave Spectra

Measurements of gravity wave characteristics in the middle atmosphere are irreplaceable as an observational guideline for tuning atmospheric models. Gravity wave spectra are a useful way to summarize the large amount of information present in a lidar observation into a usable format.

In Figure 2, we show an example of a 3-day continuous lidar observation from ALOMAR which starts on 17 June 2023. This plot highlights the daylight capability, which is essential for a lidar in the polar region where days are long in the summer. The top panel has three subpanels, which show the measured temperature profile with a filtered resolution of 1 km by 30 minutes. The middle subpanel shows an estimation of the background temperature and the bottom panel shows the residual fluctuations. The fluctuations are related to the gravity wave activity. The lower panel shows the spectra, which can be obtained from these lidar fluctuations. The top row (left) contains the vertical wavenumber spectrum divided into a total spectrum (black) as well as the spectra for downwards phase progression waves (blue dotted) and upwards waves (blue dashed). The grey shaded region indicates where the numerical filter contaminates the spectrum.

The top row (middle) shows perturbation amplitude as a function of height. The top row (right) shows the temporal spectrum with similar color scaling as the vertical spectrum. This temporal spectrum cannot be achieved with short, nighttime only lidar measurements. The bottom row of the lower panel shows the separation of gravity wave

phase lines, which estimate the perturbations, associated with upwards propagating gravity waves (left), stationary waves (centre) and downwards waves (right).

wave solutions for each set of perturbation profiles, we can extract wave solutions, which satisfy the gravity wave dispersion relation. By grouping wave solutions, which share common parameters (phase

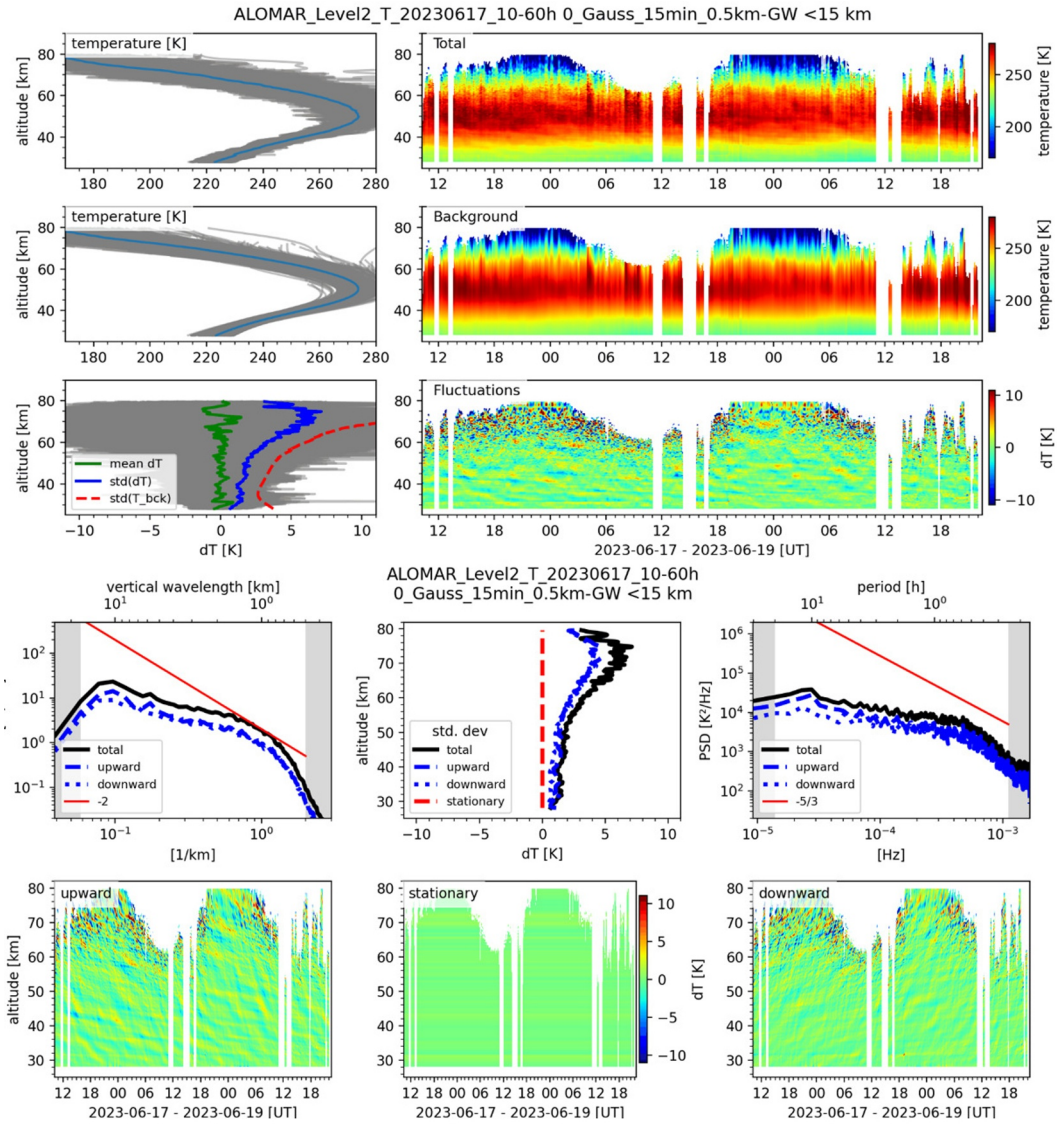


Figure 2. Example of a 3-day gravity wave spectra measured by the lidar at ALOMAR

#### 4. Gravity Wave Packets

Gravity wave phase line analysis by lidar can be biased in the presence of a non-zero background wind. Using the ALO-GW method (algorithm for decomposition of T, u, v profiles into quasi-monochromatic Gravity Waves) [4] we can decompose our lidar measurements of temperature, zonal and meridional wind into perturbation profile  $T' u', v'$ . Then by fitting common

velocity, vertical wavelength, and horizontal wavelength) together, we can reconstruct quasi-monochromatic gravity waves. Two examples of waves reconstructed from this technique are shown in Figure 3. In the top panel, we see an example of an upwards propagating wave measured at ALOMAR on 12 July 2023. This wave was propagating north with a phase velocity of 82 m/s, vertical wavelength of 28 km, horizontal wavelength of 997 km, an amplitude of  $\sim 2$  K, and had a momentum flux of 0.97 mPa. The wave was present for the entire

observation above 35 km. The polar plot shows the direction of wave propagation (S<sub>W</sub>) relative to wind direction (S) over the course of the night. The example in the lower panel is from the same night at ALOMAR. It shows a gravity wave in the stratosphere. This wave has different parameters: phase velocity of 56 m/s, vertical wavelength of 14 km, horizontal wavelength of 1381 km, an amplitude of ~2 K, and had a momentum flux of 1.00 mPa. This wave entered the lidar field of view at 11:00 UTC and on the polar plot you can see that this wave started travelling northwest (135 degrees) and over two hours changed to travelling north (90 degrees). This was in response to changing background wind conditions from West-southwest to West-northwest.

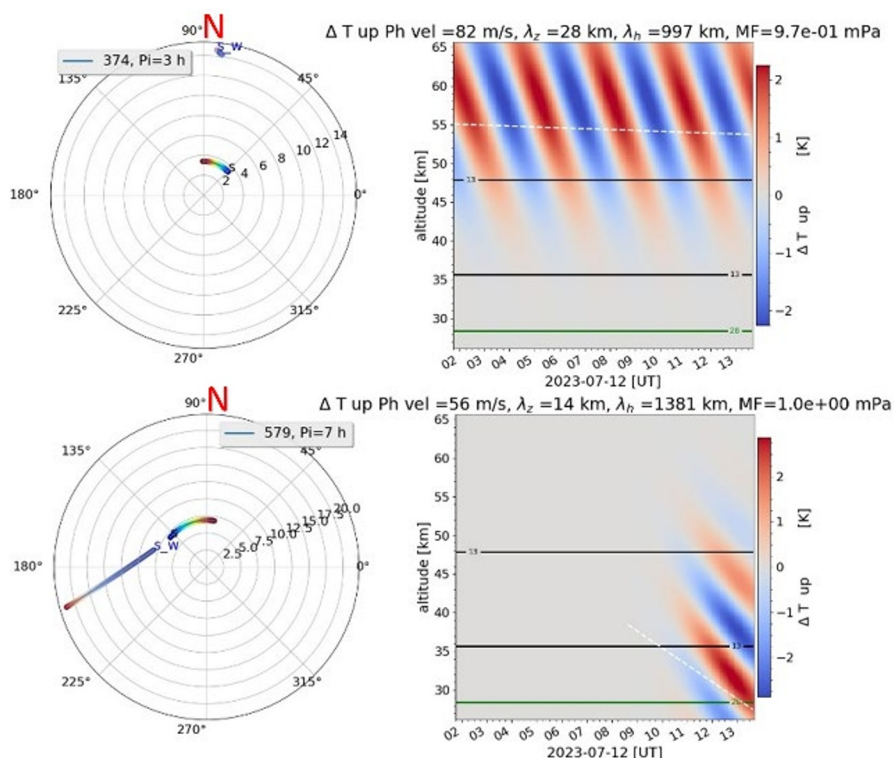


Figure 3. Example of reconstructed quasi-monochromatic gravity wave packets using temperature and wind measurements from ALOMAR.

## 5. References

- [1] WMO. (2018) Rolling Review of Requirements and Statements of Guidance. Available at: <http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html>. and OSCAR database [https://www.wmo-sat.info/oscar/variables/view/wind\\_horizontal](https://www.wmo-sat.info/oscar/variables/view/wind_horizontal)
- [2] Baumgarten, Gerd. "Doppler Rayleigh/Mie/Raman lidar for wind and temperature measurements in the middle atmosphere up to 80 km." Atmospheric Measurement Techniques 3.6 (2010): 1509-1518.F.
- [3] Gerding, Michael, et al. "The Doppler wind, temperature, and aerosol RMR lidar system at Kühlungsborn/Germany–Part 1: technical specifications and capabilities." EGU sphere 2023 (2023): 1-29.
- [4] Strelnikova, Irina, et al. "Seasonal cycle of gravity wave potential energy densities from lidar and satellite observations at 54 and 69 N." Journal of the Atmospheric Sciences 78.4 (2021): 1359-1386.

[5] Mlynyczak, Martin G., and James M. Russell. "An overview of the SABER experiment for the TIMED mission." Optical remote sensing of the atmosphere (1995): MA2.

[6] Chau, Jorge Luis, et al. "Novel specular meteor radar systems using coherent MIMO techniques to study the mesosphere and lower thermosphere." Atmospheric Measurement Techniques 12.4 (2019): 2113-2127.