Investigation of Cirrus cloud structure by airborne water-vapor DIAL measurements during the HALO Techno-Mission

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ABSTRACT

During the first campaign of the new German research aircraft HALO, measurements with the differential absorption lidar (DIAL) WALES from the DLR Oberpfaffenhofen were performed. Comparisons with collocated in-situ measurements on board the DLR’s Falcon20-E5, performing synchronous flights below HALO, were used to validate the DIAL measurements. Furthermore they justified the use of ECMWF analysis temperature to calculate the relative humidity from DIAL measurements of the absolute humidity, as they showed, that the main variability of the relative humidity results from the water vapour fluctuations and not from temperature fluctuation. Thus for the first time studies of the absolute and relative humidity within a fully developed cirrus cloud could be performed.

1. INTRODUCTION

Despite the large scientific awareness of the importance of cirrus clouds on the Earth’s climate system, especially their radiative effect is still only poorly understood [1]. The main question regarding the radiation balance of the Earth is, whether cirrus clouds have a cooling or a warming impact on the Earth’s atmosphere. Typically they are assumed to have a net warming effect [2], but recently it was found out, that the radiative properties of cirrus clouds highly depend on their microphysical composition [3], e.g. the ice crystal shape, the size distribution and the number concentration, which are strongly dependent on ambient vertical movement [4]. Furthermore small-scale turbulence plays an important role concerning the cirrus cloud’s structure, influencing the distribution of the microphysical properties and therewith their radiative effect. Our knowledge of the climate effect of cirrus clouds is mainly based on theoretical simulations. To better represent cirrus clouds in these simulations and in general circulation models it is crucial to improve our knowledge on small-scale processes within cirrus clouds and on their fine-structure.

We present measurements of the airborne aerosol and water vapor Differential Absorption Lidar (DIAL) system WALES of the DLR, Oberpfaffenhofen. DIAL measurements provide two-dimensional information of the atmospheric water vapor concentration and are therefore well suitable to study the fine structure of cirrus clouds. The combination of DIAL water vapor measurements and model temperature enables further to investigate relative humidity variability and ice super-saturation within cirrus clouds, crucial properties to study cirrus cloud formation.

2. METHOD

2.1. Differential Absorption Lidar WALES

Differential absorption lidar is an active remote sensing technique to measure atmospheric trace gases [5]. It is based on the different absorption of at least two different wavelengths. The so called offline wavelength is a non-absorption wavelength and serves as a reference, whereas the online wavelength is centered of a molecular water vapor absorption line.

DLR’s multi-wavelength airborne lidar system WALES (Water vapor Lidar Experiment in Space) is capable to emit simultaneously four wavelengths, three online and one offline, in the water vapor absorption band around 935 nm. Additional the system is equipped with polarization sensitive aerosol channels at 532 nm and 1064 nm, the first one with the capability of high spectral resolution lidar (HSRL) measurements. A detailed technical description can be found in [6]. An analysis of the systems accuracy can be found in [7].

2.2. HALO-Techno mission

The new German research aircraft HALO, High Altitude and LOng range, is based on a modified Gulfstream G550. It is funded by the Federal Ministry of Education and Research, the Helmholtz-Gemeinschaft and the Max-Planck-Gesellschaft and operated by the Flight Department of the DLR, Oberpfaffenhofen.

In October and November 2010 five scientific flights in the framework of the HALO-Techno mission were performed in the TRA ((Temporary Reserved Airspace) Allgäu in Southern Germany (November 3 to November 4), and Mecklenburg-Vorpommern in North-Eastern Germany (October 28 to October 29, and November 5). Four different scientific instruments (among them the WALES system) from the Forschungszentrum Jülich, Universities of Leipzig, Mainz and Wuppertal and from the DLR-Institute of Atmospheric Physics were installed. The campaign goal was twofold: technical performance and validation of remote sensing instruments, and testing of new sampling strategies, including optimal flight level for cloud studies. For this purpose, the Falcon 20-E5 partly flew below the HALO aircraft on the last three flight days to perform in-situ samples in the same air mass.
3. RESULTS – case study on 4 November 2010

Fig. 1 gives an overview over the measurement situation on 4 November 2010. It shows the lidar backscatter ratio cross-section at 532 nm of a fully developed cirrus cloud, and the Falcon flight path within the cirrus cloud.

3.1. Comparison WALES – in-situ

Since the Falcon 20-E5 flew below the HALO, the Falcon in-situ measurements can be used to validate the DIAL measurements. For this purpose we use the data of a diode laser spectrometer.

Fig. 2 shows the comparison of the DIAL and the in-situ water vapour measurements, as well as the flight distance of both aircraft. Both measurements show a very good accordance, at least when the distance is below 20 km. Even the small structures in the water vapour concentration are reproduced by the DIAL measurements.

3.2. ECMWF-Temp for relative humidity

The final goal of the DIAL measurements is to look at the relative humidity over ice (RHi). Therefore the DIAL measurements have to be combined with two-dimensional temperature information along the flight path. This information is taken from ECMWF analysis data. To proof the suitability of this temperature information for studies of RHi variability, they are compared to Falcon in-situ measurements. To avoid effects from changing flight levels, only those times are considered in which the Falcon flight altitude changed less than 100 m. The mean values of temperature, water vapour mixing ratio and relative humidity within the considered time series is listed in Tab. 1. The relative humidity differs with an absolute value of about 11 %, mainly resulting from the temperature difference of about 0.91 K within the considered time series.

<table>
<thead>
<tr>
<th>Variable</th>
<th>In-situ</th>
<th>ECMWF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature/K</td>
<td>220.002</td>
<td>219.085</td>
</tr>
<tr>
<td>H2Omix ppm</td>
<td>99.631</td>
<td>100.083</td>
</tr>
<tr>
<td>RHi/%</td>
<td>91.802</td>
<td>103.326</td>
</tr>
</tbody>
</table>

The relative variability (stdv/mean) of the individual variables is listed in Tab. 2. It shows that the main variability of the relative humidity over ice comes from the variability of the water vapour mixing ratio. In contrast, the difference in the temperature variability of model analysis and in-situ measurements is negligible.

<table>
<thead>
<tr>
<th>Variable</th>
<th>In-situ</th>
<th>ECMWF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.000671395</td>
<td>0.000343987</td>
</tr>
<tr>
<td>H2Omix</td>
<td>0.126121</td>
<td>0.0313324</td>
</tr>
<tr>
<td>RHi</td>
<td>0.124184</td>
<td>0.0284574</td>
</tr>
</tbody>
</table>
The comparison of ECMWF model analysis temperature and in-situ measurements shows, that it is justified to use model derived temperature information for the calculation of RHi, at least in stable high pressure systems, as we found during the the HALO-Techno mission.

3.3. Relative Humidity over ice inside a fully developed Cirrus Cloud

To derive RHi from WALES’ measurements and ECMWF analysis, the model data were interpolated in space and time to match with the DIAL water vapour field. The ECMWF temperature field was bias corrected. For the calculation of the RHi, the Goff Gratch formula was used to determine the saturation pressure over ice. The cross section of absolute humidity (in combination with the model temperature field) and relative humidity over ice inside the cirrus cloud is shown in Fig. 3. The RHi field is used to investigate the RHi variability and ice supers-saturation inside the cirrus cloud. The relative variability of RHi within the whole cirrus cloud is about 1.14. A histogram of the observed relative humidity over ice within the fully developed cirrus cloud is shown in Fig. 4. The bin size of the histogram is 2 %.

Figure 3. Water vapour volume mixing ratio as measured with WALES on HALO and contour lines of ECMWF temperature on November 4, 2010 (upper panel), and relative humidity over ice from combined WALES and ECMWF data.

Figure 4. Frequency distribution of the relative humidity over ice inside the fully developed cirrus cloud.
The threshold for the decision cloud/no cloud was set to an empirical value of the backscatter ratio at 532 nm of 2. The frequency distribution of RHi over the whole cirrus cloud shows a nearly Gaussian distribution with a maximum at 98 % RHi. About 30 % of all measurement points inside the cirrus cloud show RHi values higher than 100 %, only 2 % of all measurement points show RHi values higher than 120 %. However, an absolute error of about ±10 %, resulting from uncertainties in the used temperature, has to be taken into account.

To determine a possible height dependence of RHi within the cirrus cloud, the cloud was divided in height levels of 500 m (see Fig. 5).

In the middle part of the cloud, no significant difference in the frequency distribution of RHi can be seen, only in the uppermost layer small differences are visible. The uppermost layer shows a maximum at 91 % RHi and a shift to lower RHi values.

![Figure 5](image.png)

**Figure 5.** Frequency distribution of the relative humidity over ice dependent on the height level inside the fully developed cirrus cloud.

The relative RHi variability and the most frequently RHi value of the considered height levels is shown in Tab. 3.

<table>
<thead>
<tr>
<th>Height Level</th>
<th>Rel. Var</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 km</td>
<td>0.99</td>
<td>98%</td>
</tr>
<tr>
<td>10.5 km</td>
<td>0.51</td>
<td>95%</td>
</tr>
<tr>
<td>11 km</td>
<td>0.43</td>
<td>98%</td>
</tr>
<tr>
<td>11.5 km</td>
<td>0.67</td>
<td>93%</td>
</tr>
<tr>
<td>12 km</td>
<td>3.52</td>
<td>91%</td>
</tr>
</tbody>
</table>

**4. SUMMARY and OUTLOOK**

DIAL measurements performed during the first mission of the new German research aircraft HALO are presented. In-situ measurements were used to compare the DIAL measurements and to validate the use of ECMWF model data to covert the measured absolute humidity in relative humidity over ice. For the first time, time and height resolved information of the absolute and relative humidity in a fully developed cirrus cloud could be derived. The extended vertical range of the HALO aircraft made it possible to keep a minimum distance of about 2 km to the cloud tops to avoid overload in the capability of detectors and data acquisition.

Since the Techno mission had more technical goals, the potential of the measurements to deal with unanswered questions of cirrus cloud formation are limited. Future HALO missions, like ML-Cirrus, will address the problem of cirrus cloud formation.

**5. ACKNOWLEDGEMENT**

This work has been funded by HALO-SPP No. 1294/2. We thank the DLR flight department for the supply of the in situ data from HALO and Falcon 20-E5, and Stefan Kaufmann from our institute for providing the water vapour in-situ data of diode laser spectrometer. Further we like to thank Andreas Schäfler from our institute for running the ECMWF model system and producing hourly interpolations between the standard 6 h analysis outputs.

**6. REFERENCES**