Atmos. Meas. Tech. Discuss., 7, 4033–4066, 2014 www.atmos-meas-tech-discuss.net/7/4033/2014/ doi:10.5194/amtd-7-4033-2014 © Author(s) 2014. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

Potential of airborne lidar measurements for cirrus cloud studies

S. Groß¹, M. Wirth¹, A. Schäfler¹, A. Fix¹, S. Kaufmann^{1,2}, and C. Voigt^{1,2}

 ¹Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, 82234 Wessling, Germany
 ²Johannes-Gutenberg-Universität Mainz, Institut für Physik der Atmosphäre, 55122 Mainz, Germany

Received: 17 February 2014 - Accepted: 26 March 2014 - Published: 16 April 2014

Correspondence to: S. Groß (silke.gross@dlr.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.





Abstract

Aerosol and water vapour measurements were performed with the lidar system WALES of Deutsches Zentrum für Luft- und Raumfahrt (DLR) in October and November 2010 during the first mission with the new German research aircraft G55-HALO. Curtains

- ⁵ composed of lidar profiles beneath the aircraft show the vertical and horizontal distribution and variability of water vapour mixing ratio and backscatter ratio above Germany. Two missions on 3 and 4 November 2010 were selected to derive the water vapour mixing ratio inside cirrus clouds from the lidar instrument. A good agreement was found with in-situ observations performed on a second research aircraft flying below HALO.
- ECMWF analysis temperature data are used to derive relative humidity fields (RHi) inside and outside of cirrus clouds from the lidar water vapour observations. The RHi variability is dominated by small scale fluctuations in the water vapour fields while the temperature variation has a minor impact. The most frequent in-cloud RHi value from lidar observations is 98%. The RHi variance is smaller inside the cirrus than outside
- of the cloud. 2-dimensional histograms of relative humidity and backscatter ratio show significant differences for in-cloud and out-of cloud situations for two different cirrus cloud regimes. Combined with accurate temperature measurements, the lidar observations have a great potential for detailed statistical cirrus cloud and related humidity studies.

20 1 Introduction

Although clouds have an important impact on the Earth's atmosphere and climate system (Cox, 1971; Liou, 1986) their influence on the Earth's radiation budget is still hard to determine (IPCC, 2007, 2013). Especially, radiative effects of cirrus clouds are a major uncertainty for determination of the cloud feedback factor in climate response. Typically, they are assumed to have a net warming effect (Chen et al., 2000). Radiative proper-

they are assumed to have a net warming effect (Chen et al., 2000). Radiative properties of mid-latitude cirrus clouds strongly depend on their microphysical parameters,





e.g. ice crystal shape, size distribution and number concentration (Stephens, 1990; Haag and Kärcher, 2004; Fusina et al., 2007), which are influenced by ambient conditions, especially dynamics (Kärcher and Lohmann, 2003), temperature and super-saturation (Heymsfield, 1977; Khvorostyanov and Sassen, 1998b) as well as the nucleation mode, i.e. the composition of the ambient aerosol (e.g. Ström and Ohlsson, 1998; Seifert et al., 2004). Furthermore, small-scale turbulence is important for the fine structure of cirrus clouds, which affects the inhomogeneity of microphysical properties (Gu and Liou, 2000) and therewith of the cirrus' radiative effect (Liou, 1972). The inhomogeneous nature of cirrus on different spatial scales is one major issue which

- complicates modelling of their radiative properties. Model simulations usually use idealized cloud structure and microphysics, as well as radiative transfer approximations. To improve the representation of cirrus clouds in simulations and circulation models, we need a better understanding of the micro- and macro-physical properties of cirrus clouds, as well as of small-scale processes within cirrus.
- Airborne Differential Absorption Lidar (DIAL) measurements of water vapour (Ehret et al., 1993; Bösenberg, 1998; Browell et al., 1998) provide two-dimensional information of the atmospheric structure, and are thus a suitable tool to study the fine-structure of cirrus clouds, as well as their macro-physical properties. The combination of DIAL water vapour measurements with additional temperature information (e.g. from model
- analyses or dropsondes) further enables to investigate the variability of relative humidity and ice super-saturation within cirrus clouds which are crucial properties for cirrus cloud evolution (e.g. Heymsfield and Miloshevich, 1995). However, up to now, the high signal dynamics within clouds limited the use of airborne downward looking DIAL measurements for mid-latitude cirrus clouds. An optimal distance of about 2 km
- to the cirrus cloud is required to avoid an overload of detectors and data acquisition due to the immense signal dynamics in the near field resulting from the *r*-dependence of the backscatter signal. Up to now the required flight altitude to examine mid-latitude cirrus clouds up to about 13 km height was only accessible with high altitude aircraft like the Russian stratospheric aircraft Geophysica (Stefanutti et al., 1999) and the NASA





ER-2. With the new German research aircraft HALO (High Altitude and LOng range) (Krautstrunk and Giez, 2012) it is possible to reach flight altitudes of up to 15 km, and thus a sufficient distance to the cirrus cloud top in most cases.

For the first time, measurements of the airborne aerosol and water vapour DIAL ⁵ WALES (Water vapour Lidar Experiment in Space; Wirth et al., 2009), operated onboard HALO during its first scientific mission (Techno-Mission) are presented. The HALO Techno-Mission took place in October and November 2010 and provided the opportunity to investigate cloud properties with two different aircraft. HALO, flying at a cruise altitude of ~ 14 km probed the cloud (~ 1 km below cruise altitude) with the lidar. Additionally, the DLR research aircraft Falcon was equipped with in-situ instru-

- ¹⁰ Iidar. Additionally, the DLR research aircraft Falcon was equipped with in-situ instruments to measure temperature and water vapour mixing ratio within cirrus clouds. This unique combination of these two aircraft provided the opportunity to compare the different measurement strategies, i.e. in-situ and remote sensing measurements with a focus on cirrus cloud studies. Relative humidity with respect to ice (RHi) is determined within
- the cirrus clouds based on the novel high-altitude DIAL observations combined with ECMWF model analysis temperature data.

Section 2 gives an overview over the aircraft and mission design, the WALES system, and the WARAN in-situ hygrometer on-board the Falcon used for water vapour intercomparison. Section 3 demonstrates the potential of the DIAL system for cirrus cloud

studies based on a case study with measurements inside the cirrus cloud. Section 4 provides a summary and discussion of the main findings. Section 5 gives an outlook to future cirrus cloud observations with remote sensing instruments on-board HALO.

2 Data and methods

2.1 HALO and Techno-Mission

²⁵ HALO (Fig. 1) is a modified Gulfstream G550 business jet operated by the flight department of DLR in Oberpfaffenhofen. With a range of more than 8000 km and an





endurance of up to more than 10 flight hours even large scale atmospheric features can be investigated at almost all regions around the globe. A maximum cruising altitude of more than 15 km enables measurements in the upper troposphere and lower stratosphere in high- and mid-latitude regions. With a payload of up to three tons, HALO provides enough capacity to accommodate a synergetic payload to collect a compre-

hensive atmospheric data set (Krautstrunk and Giez, 2012). Technical details can be found in Table 1.

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In the course of the first scientific HALO mission, the so-called Techno-Mission, five flights with HALO aircraft were performed from 28 October to 5 November 2010 out

- ¹⁰ of Oberpfaffenhofen, Germany. The major part of the flights took place in the Temporary Reserved Airspaces (TRA, i.e. military areas with restricted access to commercial aircraft) Allgäu in Southern Germany and Mecklenburg-Vorpommern in North-Eastern Germany (28 October to 29 October and 5 November 2010). Here we present data of the flights on 3 November (from 09:51 to 13:17 UTC) and 4 November (10:21 to
- 13:32 UTC), 2010. Lidar observations were only possible inside the TRA areas. The 4 November flight data between 10:47 and 11:54 UTC are used for the comparison of remote sensing (lidar) data and in-situ data of the beneath flying Falcon. The measurement situation was characterized by a stationary cirrus cloud covering the whole measurement area. Data from 3 November (10:15 to 11:25 UTC) are used to compare
- the RHi statistics in a different cloud regime characterized by a transient cirrus cloud drifting out of the measurement area. This gave us the opportunity to perform measurements in cloudy and in cloud free air masses. HALO was equipped with a spectrometer system operated by University of Leipzig together with an instrument for measuring the actinic flux in cooperation with Forschungszentrum Jülich (HALO-SR) (Fricke et al.,
- ²⁵ 2013), an automated high volume air sampling system (MIRAH Measurements of Stable Isotope Ratios in Atmospheric Trace Gases on HALO) of University of Wuppertal (Krebsbach et al., 2013), and an ion trap mass spectrometer of DLR (Roiger et al., 2011). Additionally, and in the focus of this paper, the DIAL system WALES (Wirth et al., 2009) was provided by DLR Institute of Atmospheric Physics (IPA). The





campaign focused on the test of the in-flight performance of new instrumentation and validation of remote sensing instruments with in situ measurements. A further aim was the development and evaluation of new sampling strategies for future campaigns, including finding an optimal flight level for remote cloud studies as well as to investigate

the possibility to use HALO as the pathfinder for a secondary aircraft with an in-situ payload for cloud studies (e.g. distance from cloud top). For inter-comparison and validation, the DLR Falcon was equipped with several in-situ instruments including the WARAN tuneable diode laser hygrometer operated by DLR (Voigt et al., 2014). Falcon flew in parallel, either wing-by-wing to compare in-situ instruments or several kilometres below HALO to compare lidar with in-situ measurements.

2.2 Differential absorption lidar WALES

Differential absorption lidar is an active remote sensing technique for measuring atmospheric gases such as water vapour (e.g. Bösenberg, 1998; Browell et al., 1998). It is based on the absorption at different laser wavelengths with narrow spectra. The so-

- called online wavelength is centred on a molecular water vapour absorption line. For the offline wavelength a non-absorbing wavelength is used, which serves as the reference. By calculating the difference between absorptions at online and offline wavelength, a profile of the water vapour number density as function of the distance from the lidar system can be derived.
- The WALES lidar system consists of two transmitters, both based on an injectionseeded optical parametric oscillator (OPO) pumped by the second harmonic of a Qswitched, diode pumped Nd:YAG laser. Thus, WALES is capable to simultaneously emit four wavelengths, three online and one offline, in the water vapour absorption band between 935 nm and 936 nm. The three online wavelengths achieve the neces-
- $_{25}$ sary sensitivity needed for measurements over the whole range of tropospheric water vapour concentration. A complete water vapour profile of the troposphere is composed by using the information of the partly overlapping line contributions. The averaged pulse energy is 35 mJ with a repetition frequency of 2 \times 100 Hz. The vertical resolution of the



raw data is 15 m. In addition to the 935 nm channel, the receiver is equipped with polarization sensitive aerosol channels at 532 nm and 1064 nm, the first one with High Spectral Resolution capabilities using an iodine filter in the detection path (Esselborn et al., 2008). This allows for collocated measurements of humidity and optical depth,
 as well as studies of clouds and aerosol optical properties. System parameters of the WALES system are listed in Table 2. For a detailed technical description see Wirth

et al. (2009). As the main objective of the lidar measurements during the HALO Techno-Mission was high resolution measurements of cirrus clouds, only the strong absorption line of

- 935.6846 nm was used. For the second laser, the generation of laser radiation for the medium and weak absorbing line for mid- and lower tropospheric H₂O measurements was switched off. Thus, highest possible spectral purity of the HSRL (High Spectral Resolution Lidar) channel at 532 nm was achieved. The vertical resolution of the measurements is 150 m, the horizontal resolution is about 1 km (5 s averages). The statistical error of the water vapour retrievals is about 5 %. A general analysis of the systems
- cal error of the water vapour retrievals is about 5 %. A general analysis of the systems accuracy can be found in Kiemle et al. (2008).

2.3 WARAN hygrometer

The airborne in-situ hygrometer instrument WARAN consists of a commercial Tunable Diode Laser (TDL) device (WVSS-II, Spectrasensors Inc. – Voigt et al., 2014) in combination with a Rosemount inlet system. The WVSS-II is a closed cell TDL system where a diode laser is tuned continuously over the water vapour absorption line at 1.37 μm. After passing the measurement cell twice (~ 24 cm), the laser intensity is measured by a photodiode. High sensitivity is achieved by utilizing second harmonic detection as e.g. described by May and Webster (1993). The measurement range is from 30 to 40 000 ppmv covering typical atmospheric mixing ratios from ground up to the upper troposphere. The relative uncertainty increases towards lower water vapour mixing ratios from 5 % above 200 ppmv up to 20 % at 30 ppmv confirmed by a direct intercomparison with calibrated data from water vapour mass spectrometer (Kaufmann et al.,



2014). The measurement cell is passively flown through using a heated Rosemount inlet system in order to avoid particles, especially ice crystals, entering the inlet line. However, the efficiency of the particle separation is not perfect in some cases so that in-cloud measurements may partly be influenced by evaporating particles.

5 3 Results

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3.1 Overview

At the time of the observation (12:00 UTC) on 4 November 2010, the synoptic situation over Europe was characterized by a large scale ridge. Cirrus clouds at upper levels were advected towards Germany within the anticyclonic Jetstream (see increased values of relative humidity at 250 hPa in Fig. 2a). Figure 2b shows the flight track of HALO between 10:21 and 13:32 UTC in the TRA Allgäu in Southern Germany. In the following we only consider data from the 910 km long section of the flight between 10:47 and 11:54 UTC (solid line) when measurements were performed at constant flight level of about 14 km. After 11:54 UTC HALO started to descend.

- Figure 3a presents the lidar backscatter ratio cross-section at 532 nm, the ECMWF cloud water content, and the flight altitude of the Falcon within the cirrus cloud. The backscatter ratio indicates the cirrus cloud with a base altitude at about 10 km and the cirrus cloud top at about 13 km. The backscatter ratio within the cirrus cloud shows a wide range of values from about 4 up to more than 50. The comparison of the backscatter ratio and the ECMWF cloud ice water content ensures that model data and observation of cloud beight and location are in good agreement. a crucial require-
- and observation of cloud height and location are in good agreement, a crucial requirement to combine model data and lidar measurements. The Falcon flight track reaches the cloud at constant height level at about 11 km at 11:25 UTC and both aircraft flew in short horizontal distance until 11:54 UTC. Therefore Falcon in-situ measurements dur-
- ing that period can be used for validation of the lidar measurements and comparisons of model data within the cloud. Figure 3b shows the lidar derived upper level (9–13 km)





optical depth (OD) at 532 nm, which is a measure of the attenuation of light on its way through the atmosphere. The OD in the upper level ranges between about 0.1 and 1.5 with a very variable structure.

Figure 4a shows water vapour in-situ measurements from the WARAN on-board the
Falcon and remote sensing observations at the same altitude and location by the DIAL WALES. In Fig. 4b the horizontal distance between HALO and Falcon is plotted. The blue line (Fig. 4a and b) indicates the time when the Falcon reached a constant flight altitude of about 10.8 km. Both measurements agree well when the distance between both measurements is less than 10 km (after ~ 11:20 UTC). The mixing ratio during the
selected time period is about 100 ppmv. Even small scale features can be resolved well by the WALES-DIAL measurement.

3.2 Relative importance of temperature and humidity for the determination of RHi

Additionally to the water vapour measurements the calculation of RHi requires collo-

cated temperature information. As there was no remote measurement of the temperature field beneath HALO 3-dimensional temperature fields provided by ECMWF model are interpolated in space and time to match with the position of the WALES measurement (Schäfler et al., 2010).

To estimate the accuracy of the ECMWF model temperature inside cirrus clouds and its applicability for RHi studies we compare the ECMWF temperature data with in-situ temperature measurements of the Falcon flying in the cirrus cloud beneath HALO. For this purpose, a flight path in which the Falcon flight level of about 10.8 km varied by less than 100 m (11:25–11:54 UTC) was chosen, to avoid uncertainties resulting from sharp vertical temperature gradients at changing flight altitudes.

Figure 5 presents the comparison of the Falcon in-situ measurements and the ECMWF temperature (Fig. 5a), water vapour mixing ratio (Fig. 5b) and derived relative humidity (Fig. 5c). The ECMWF temperature is almost constantly colder than the in-situ measurements with mean values of ~ 219.1 K from ECMWF model analysis





and ~ 220.0 K from Falcon in-situ measurements. The mean temperature difference between Falcon measurement and ECMWF in the considered height level is about -0.9 K. The mean value of the water vapour mixing ratio (Fig. 5b) agrees well in the considered time series with mean values of $\sim 100 \, \text{ppmv}$ from model analysis and $\sim 99 \, \text{ppmv}$ from

- WARAN in-situ measurements, whereas the calculated relative humidity (Fig. 5c) dif-5 fers by about 11% (~ 103% using ECMWF data and ~ 91% using in-situ observations of temperature and water vapour) due to a bias in temperature data (Table 3). Additionally, RHi is calculated with WARAN water vapour measurements and ECMWF model temperatures, showing higher RHi values (Fig. 5c) which is due to the lower modelled temperatures. Figure 5 further shows that the local variability of the relative humidity is 10
- mainly caused by fluctuations in the water vapour mixing ratio. The smaller temperature fluctuations have a minor influence on RHi within the observed cirrus cloud.

This is also visible regarding the relative variability, which is the ratio of the standard deviation and the mean, of the temperature, the water vapour mixing ratio, and the RHi data within the considered time period. The relative variability of both temperature data sets is similar. In contrast, the distributions of mixing ratio and RHi differ significantly

between model analysis and in-situ measurements. The relative variability of mixing ratio and RHi are considerably larger than for the temperature, and differ by factor of around 4 with ECMWF showing less variation than in-situ data. The relative variability of the individual variables is listed in Table 3.

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The influence of temperature variability on the variability of relative humidity over ice is further estimated along the Falcon flight section (see Fig. 5) by comparing RHi values calculated with the mixing ratio from WARAN and different temperatures. The relative variability of relative humidity calculated with the Falcon temperature measure-

ments is 0.12, with the uncorrected temperature from ECMWF analysis is 0.13, and 25 with a constant temperature value (i.e. the mean of the Falcon measurements) is 0.12. Values differ only by about 10% meaning that the major part of local RHi fluctuations is caused by local variations in the water vapour mixing ratio. Temperature variations give only a minor local contribution.





It is worthwhile mentioning that the ECMWF model predicts the cloud where it is detected by lidar. However, additional uncertainties in the absolute values of RHi resulting from differences in model temperature and actual temperature have to be taken into account.

5 3.3 Relative humidity over ice within cirrus cloud

To derive RHi using WALES water vapour measurements, ECMWF temperature data were interpolated in space and time to match with the measured field. Figure 5 showed differences between observed and modelled temperatures at the flight altitude of the Falcon. To verify the applicability of the model temperature in this altitude range, we compare the vertical profile of different measurements; radiosonde data from the 12:00 UTC ascends over Munich and Stuttgart, ECMWF temperature analysis data at 12:00 UTC, and HALO and Falcon profiles derived from the total air temperature sensors of both aircraft during descent to Oberpfaffenhofen airport (11:57 to 13:32 UTC for HALO and 12:13 to 13:29 UTC for the Falcon) which is closest in time (Fig. 6).

- As can readily be seen from Fig. 6a, the temperature profiles of the two radiosonde temperature profiles of Munich and Stuttgart agree well (with minor deviations between 12 and 13 km, i.e. the tropopause region) which indicates little horizontal variability of the temperature field. This is also confirmed by horizontal sections of ECMWF temperature at 10 km altitude (not shown). This is important as the location of the aircraft
- ²⁰ measurements lies in between both stations. Another important result of this comparison is that the tropopause region between 12 and 13 km altitude is captured well in the model data, confirming that model data are appropriate to use in this altitude range. Also, the temperature profiles from the two aircraft show very comparable results up to the maximum ceiling altitude of the Falcon which is not surprising since both aircraft use the same type of total air temperature sensors (Stickney et al., 1994).

However, differences between the model temperature profile and the temperature profile measured on-board the aircraft descents can be seen (Fig. 6b). Between 9 and 11 km altitude, model and HALO temperature differ nearly height-independent by





about 0.8 K ($T_{HALO} - T_{ECMWF}$), whereas in the upper cloud region (11–13 km altitude) the difference is height dependent and varies between -1.4 K (uppermost level) and about 1.5 K (about 12.2 km). The mean difference in this height range is about 0.6 K. In the entire altitude range (9–13 km) the mean difference is about 0.8 K. The sources

- of the differences between model and HALO temperature are not entirely clear, although up to altitudes where both radiosondes agree very well (~ 12 km) the deviation is still within the combined error that is given in the literature (~ 0.3 K for radiosondes at daytime (Nash et al., 2010) and ~ 0.5 K for the aircraft temperature sensors (Giez, personal communication 2014; Stickney et al., 1994)). Possible reasons may be uncer-
- tainties in the temperature measurements of the aircraft due to insufficient correction for flight performance parameters (Giez, personal communication 2014), due to radiation or clouds effects (Nash et al., 2010), or due to resolution artefacts. Comparing radiosonde temperature measurements to model and airborne temperature data we see that model and radiosondes occasionally show good agreements while airborne
- and radiosonde temperature measurements show similar differences than model and airborne data. To create the analysis fields, preferably the most realistic representation of the state of the atmosphere, ECMWF assimilates multitude of different observation types, e.g. from surface stations, satellites and also radiosondes. This can explain the smaller deviations between modelled temperatures and the radiosonde profiles and again and aircraft data.

Although the uncertainties of the temperature measurements lead to a relative uncertainty of about 10–15% in the retrieved RHi in the considered temperature range, we conclude that the ECMWF model temperature field is suited for this kind of study.

In our case we used the available observed temperature profile of HALO to offset the ECMWF temperature field with a vertically constant temperature bias (of 0.8 K) in the altitude range between 10 and 13 km. For the calculation of RHi (from WALES and ECMWF data), the Goff Gratch formula (Goff and Gratch, 1946) was used to determine the saturation pressure over ice. The cross section of water vapour mixing ratio (in combination with the model temperature field) and relative humidity over ice





inside the cirrus cloud is shown in Fig. 7. The ECMWF model temperature shows low horizontal variability (Fig. 7a). Considering the water vapour DIAL measurements the high intensity of the backscattered signal at about 12.5 km causes data gaps. Beneath 12.5 km the water vapour mixing ratio increases from $\sim 25 \times 10^{-6}$ to $\sim 150 \times 10^{-6}$ at the

⁵ cloud base. Below 10 km altitude no data is available due to the low backscatter in the cloud free air and due to the light extinction within the cloud. In contrast to the water vapour profiles, the RHi field (Fig. 7b) depicts vertical uniformly distributed values.

The threshold for the decision whether a data point is inside the cirrus or not was set to an empirical value of 4 for the backscatter ratio (BSR) at 532 nm. A BSR threshold

of 2 did not show significant differences. A histogram of the observed relative humidity over ice within the fully developed cirrus cloud (BSC > 4) is shown in Fig. 8. The frequency distribution of RHi over the whole cirrus cloud shows a nearly Gaussian distribution with a maximum at approximately ice saturation. About 30 % of all data points inside the cirrus cloud show RHi values above ice saturation, only 2 % of all data points are higher than 120 %.

To determine a possible altitude dependence of RHi within the cirrus cloud, the cloud was divided in vertical layers with a depth of 500 m (see Fig. 9). Between 10 and 12 km no significant difference in the frequency distribution of RHi can be seen relative to the complete spectrum (Fig. 9). Only in the upper layers small differences are visible. The uppermost layer shows a shift to lower RHi values compared to the layers below with a maximum at 91 % RHi.

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To obtain information about the cirrus cloud life cycle we perform a correlation analysis using the 2-dimensional RHi and backscatter ratio fields. For this analysis the backscatter and relative humidity data were interpolated to the same time-height reso-

²⁵ lution. For studying the RHi conditions in- and outside the cirrus cloud in different cloud regimes, the presented persistent cirrus cloud observed on 4 November (discussed above) is compared with a transient/intermittent cirrus cloud drifting out of the observation area followed by cloud free air on 3 November 2010. In this case we had the opportunity to study cloudy and cloud free areas. Figure 11 shows the joint distribution





of backscatter ratio and relative humidity over ice for both cirrus regimes. In the persistent cirrus cloud on 4 November 2010 (Fig. 10a) only very few RHi values exceed 120%; even outside the cirrus at low backscatter ratios. In contrast, in the transient cirrus case (Fig. 10b) high RHi values up to 150% are found outside the cirrus cloud. In both cases, the corresponding RHi value of the maximum backscatter ratio is about 100%.

4 Summary and discussion

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We used combined airborne water vapour lidar measurements and ECMWF temperature data to analyse RHi within a cirrus cloud observed on 4 November 2010. For this analysis it is important that the model is able to reproduce the general cloud situation as otherwise uncertainties may occur mainly due to temperature differences. For the examined case, on 4 November 2010, we therefore verified that the model is able to reproduce the cloud situation in terms of location and vertical extent of the cirrus cloud. This ensures comparability of observed and modelled cloud properties.

- ¹⁵ Considering RHi within the cirrus cloud, we experimentally found that about 30 % of all data points showed supersaturation; but only 2 % of all data points showed higher values than 120 %. This is in good agreement with former findings of about 30 % ice supersaturation within mid-latitude cirrus clouds over the Southern Great Plains from combined Raman lidar measurements (Comstock et al., 2004) and from in-situ mea-
- ²⁰ surements in the vicinity of Ireland (Ovarlez et al., 2002) during INCA (INter hemispheric difference in Cirrus properties from Anthropogenic emissions), respectively. The small differences in the observed fraction of supersaturated data points may be explained by an absolute error of about 10–15% in the RHi data, resulting mainly from uncertainties in the used temperature, as well as from differences of the evolution stage of the examined cirrus cloud regimes. Considering the INCA dataset, Ovarlez
- et al. (2002) found that two types of distributions can be fitted to the observations; a Gaussian distribution for warm cirrus clouds (T > -40 °C), and a Rayleigh distribution





to cirrus clouds colder than -40 °C. The dependence of the RHi distribution on the temperature is interpreted as an effect of the length of time a cirrus cloud needs from formation to a mature equilibrium state (Spichtinger et al., 2004). Thus, the tail towards higher RHi values might be a signature of clouds that have not yet reached values close to equilibrium. The RHi distribution within the cirrus cloud of 4 November 2010 showes a pearly Gaussian distribution at a temperature range of about 45° C to 65° C. We

a nearly Gaussian distribution at a temperature range of about -45 °C to -65 °C. We therefore conclude that the observed cloud is fully developed potentially with a tendency to dissolve.

The comparison of the vertical RHi structure shows a shift to lower values in the uppermost cirrus cloud layer compared to the lower and middle part of the cloud. This is in contrast to former model studies (Khvorostyanov and Sassen, 1998a, b) indicating the region of highest ice supersaturation in the middle part of the cloud layer, the so-called ice crystal growth region, and lower ice supersaturation in the upper and lower layers with lowest ice supersaturation in the lowest layer. From ground-based

- Raman lidar measurements in combination with model temperature data (Comstock et al., 2004) a relatively similar frequency distribution in the upper 75% of the cloud with a high fraction of ice supersaturation was found, while in the lowermost 25% of the cloud 84% of the data points were below ice supersaturation. These findings are in good agreement with model simulations of Heymsfield and Miloshevich (1995), which
- showed enhanced ice supersaturation in the uppermost cloud layer and a sublimation region near the cloud base. It has to be kept in mind that we consider only a single case study in our analysis and, as mentioned above, the comparability of this case study with former findings is limited by the evolution state of the observed cloud as well as by ambient conditions. Similar to earlier findings of a positive skewness in cold
- ²⁵ clouds (Ovarlez et al., 2002), Spichtinger et al. (2004) found asymmetric RHi distributions in the upper (and colder) cloud layers based on the MOZAIC (Measurement of Ozone by Airbus In-service aircraft project) dataset. They interpret their findings with the influence of vertical motion on the duration of the transition to equilibrium (Gierens, 2003) and therewith on the distribution of (super-)saturation within the cloud. As we





assume the observed cloud of 4 November 2010 to be in equilibrium with a tendency to dissolve, this may explain the differences in the observed vertical RHi structure.

By comparing the relative humidity inside and outside the cirrus cloud for the fully developed stage on 4 November 2010 we found a limit of RHi values of about 120% inside as well as outside the cloud. This supports the assumption that the cloud is rather stable, maybe with a tendency to evaporate at that stage. High RHi values of

approximately 140–150 % RHi are needed for homogeneous ice nucleation (DeMott et al., 1998; Koop et al., 2000; Haag et al., 2003; Kärcher 2012). Thus the high RHi values of up to 150 % following the transient cirrus cloud on 3 November 2010 suggest that homogeneous ice nucleation may play a role in cirrus cloud formation in this situation. The relative humidity corresponding to the maximum backscatter ratio was ~ 100 % in both cases. We interpret that in the centre of the cirrus, where particle density causes high backscatter ratios, the water uptake by and evaporation of ice crystals is in equilibrium. As expected, in both cases the RHi range is much wider outside the cirrus than within.

The presented novel analysis technique enables to classify the evolution stage in the life cycle of the cirrus cloud as it provides information of the RHi distribution shape within the cirrus cloud, the vertical structure of the RHi, and the joint distribution of in-cloud and out of cloud RHi values. As these parameters are (amongst others) dependent on the life cycle of the cloud, the novel analysis technique can give indications whether the cloud is in a formation or dissipation stage. However, additional observations of different cloud regimes and environmental conditions are required for a thor-

5 Conclusion

ough analysis.

WALES measurements during the HALO Techno-Mission show the great potential of observing water vapour with a DIAL on board the high altitude aircraft HALO for cirrus cloud studies. The extended vertical range of the HALO aircraft makes it possible to





keep a required distance of about 1.5 km to the cloud top to avoid overload of the detectors and data acquisition and maintain sufficient sensitivity at the same time. Comparisons with in-situ measurements of humidity on the research aircraft Falcon flying inside the cirrus cloud confirmed the high accuracy of the WALES system. The presented study shows the advantages of lidar cross-sections to provide additional in-

⁵ presented study shows the advantages of lidar cross-sections to provide additional information about the vertical structure of the humidity field compared to in-situ measurements. The profile data allow performing simultaneous statistical analysis in different cloud layers.

Since the Techno-Mission was focused mainly on the technical performance of aircraft and instruments, it is beyond the scope of this study to address all details of cirrus cloud formation to its full extent. The flights were limited with respect to the operation area and to local meteorological conditions. For the future, additionally data is required during the entire life cycle of a cirrus cloud. Future HALO missions, especially the ML-Cirrus mission, are focusing on this topic and will benefit from the findings and techniques presented in this article. The measurement of temperature profiles with a microwave temperature profiler, as planned for the ML-Cirrus mission, will allow elaborating the presented methods.

Acknowledgements. This work has been funded by the Deutsche Forschungsgemeinschaft (DFG) in the SPP (No. 1294/2) "Atmosphären- und Erdsystemforschung mit dem Forschungs ²⁰ flugzeug HALO (High Altitude and Long Range Research Aircraft)" under contract Nr. KI1567/1-1 and Nr. VO1504/2-1. S. Kaufmann was funded by the Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V. (HGF) under contract VH-NG-309 within the Helmholtz-Hochschul Young investigators group AEROTROP. The authors like to thank the staff members of the DLR Falcon and the HALO aircraft from DLR Flight Experiments for preparing and performing the measurement flights and providing Falcon in-situ temperature measurements and analysis.

The service charges for this open access publication have been covered by a Research Centre of the

30 Helmholtz Association.



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Potential of airborne lidar measurements for cirrus cloud studies

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Table 1. Technical features of Gulfstream G550 HALO aircraft adopted from Krautstrunk and Giez (2012).

Engine	Rolls Royce BR710	
Aircraft Performance Maximum range Maximum cruise altitude Take-off distance Maximum speed	12 500 km 15 540 m 1801 m 0.885 Mach	
Weights Maximum take-off weight Maximum payload	41 277 kg 3 t	
Exterior Length Height Wingspan	29.4 m 7.9 m 28.5 m	
Interior Cabin length Cabin height Cabin width Cabin volume	15.3 m 1.88 m 2.24 m 47.3 m ³	



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Table 2. System parameters of WALES.

Transmitter type	Nd:YAG laser pumped OPO
Pulse energy (mJ)	40
Pulse rate (Hz)	200
Wavelength (nm)	532, 935, 1064
Strong absorbing line (nm)	935.6846
Medium absorbing line (nm)	935.6083
Weak absorbing line (nm)	935.5612
Telescope diameter (cm)	48
Vertical resolution (m)	150
Horizontal resolution (km)	1 (5 s)

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Table 3. Mean values and relative variability (averaged between 11:25 and 11:54 UTC) along Falcon flight path on 4 Nov 2010. For the ECMWF relative humidity uncorrected model temperature data are used. In-situ relative humidity is determined from WARAN water vapour measurements and in-situ temperature measurements onboard the Falcon.

	Mean		Variability	
Temperature/K H ₂ O mix/ppmv RHi/%	ECMWF 219 100 103	In-situ 220 99 91	ECMWF 0.0003 0.03 0.03	In-situ 0.0006 0.12 0.12





Fig. 1. HALO (High Altitude and LOng range) aircraft. Photo adopted from http://www.halo.dlr. de/.







Fig. 2. (a) ECMWF analysis of geopotential height (in dm, black contour lines) and relative humidity (%, grey shading) at 250 hPa valid on 12:00 UTC 4 November 2010. **(b)** Flight track of HALO between 10:46 and 13:32 UTC (dashed line). The thick black line in **(b)** indicated the section shown in Fig. 3. Grey area in **(b)** shows the TRA Allgäu. Black rectangle in **(a)** indicates the section shown in **(b)**.





Fig. 3. (a) Backscatter ratio at 532 nm (colour shading) between 10:47 and 11:54 UTC on 4 November 2010. White areas are caused by signal overload. The thick black solid line indicates the altitude of the DLR Falcon; the black contour lines show the ECMWF cloud ice water content of $0.5-4.5 \text{ mgkg}^{-1}$. (b) Optical depth (OD) at 532 nm of the cirrus cloud derived from WALES measurements.



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Fig. 4. (a) Water vapour mixing ratio as retrieved by the WARAN instrument flown on the Falcon (red line) and the WALES instrument (black line) at the same altitude. (b) Horizontal distance between the two aircraft as a function of time.



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Fig. 5. Comparison of in-situ temperature, water vapour and RHi measurements on 4 November 2010 from WARAN onboard the Falcon (blue lines) with data from ECMWF model analysis (red lines). (a) Static air temperature, (b) water vapour mixing ratio and (c) relative humidity over ice along the flight track. The red line shows RHi calculated from ECMWF temperature and water vapour data, the thick blue line shows RHi calculated from WARAN water vapour mixing ratio and Falcon in-situ temperature measurements, and the thin blue line shows RHi calculated from WARAN water vapour mixing ratio measurements and ECMWF model temperature.













Fig. 7. (a) Water vapour volume mixing ratio as measured with WALES on HALO and contour lines of ECMWF temperature. **(b)** Relative humidity over ice from combined WALES and ECMWF data. In the white areas no trustworthy measurements are available due to signal overload and strong variability.





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Fig. 9. Frequency distribution of the relative humidity over ice at different vertical layers inside the cirrus cloud shown in Figs. 3 and 7.





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Fig. 10. Histogram of the joint occurrence of the relative humidity over ice (RHi) and the extinction corrected backscatter ratio (BSR) at 532 nm (a) for a fully developed cirrus cloud on 4 November 2010 and (b) for a transient cirrus cloud on 3 November 2010.



