



**Evaluation of
MOZAIC Capacitive
Hygrometer**

P. Neis et al.

Evaluation of the MOZAIC Capacitive Hygrometer during the airborne field study CIRRUS-III

P. Neis^{1,3}, H. G. J. Smit¹, M. Krämer², N. Spelten², and A. Petzold¹

¹Forschungszentrum Jülich GmbH, Institut für Energie und Klimaforschung, IEK-8 Troposphäre, 52425 Jülich, Germany

²Forschungszentrum Jülich GmbH, Institut für Energie und Klimaforschung, IEK-7 Stratosphäre, 52425 Jülich, Germany

³Johannes Gutenberg Universität Mainz, Institut für Physik der Atmosphäre, 55099 Mainz, Germany

Received: 15 July 2014 – Accepted: 3 September 2014 – Published: 22 September 2014

Correspondence to: P. Neis (p.neis@fz-juelich.de)

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

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The MOZAIC Capacitive Hygrometer (MCH) is usually operated onboard of passenger aircraft in the framework of MOZAIC (Measurement of Ozone by AIRBUS In-Service Aircraft). In order to evaluate the performance of the MCH, it was operated aboard a Learjet 35A aircraft as part of the CIRRUS-III field study together with a closed-cell Lyman- α fluorescence hygrometer (FISH) and an open path tunable diode laser system (OJSTER) for water vapour measurement. After reducing the data set to MOZAIC-relevant conditions, the 1 Hz relative humidity (RH) cross correlation between MCH and reference instruments FISH (clear sky) and OJSTER (in-cirrus) yielded a remarkably good agreement of $R^2 = 0.97$ and slope $m = 0.96$ and provided the MCH uncertainty of 5 % RH. Probability distribution functions of RH deduced from MCH and reference instruments agreed well over the entire range of observations. The main limitation for the use of MCH data is related to sensor temperatures below the calibration limit of $T_{\text{sensor}} = -40^\circ\text{C}$ (corresponds to ambient temperature of $T_{\text{ambient}} = -70^\circ\text{C}$ at typical cruising speed of long-haul passenger aircraft), which causes a delay in the sensor's time response. Good performance of MCH for clear sky as well as for in-cirrus conditions demonstrated the sensor robustness also for operation inside ice clouds.

1 Introduction

Water vapour is one of the most important variables for weather prediction and climate research. Particularly, the interaction between the water vapour in the UT/LS (upper troposphere and lowermost stratosphere) and tropopause dynamics is not well understood. Thus, in the latest IPCC report (Stocker et al., 2013), it is stated that the knowledge about potential trends and climate feedback mechanisms of upper tropospheric water vapour is low because of the lack of long data records of high quality in this specific region of the global atmosphere. Neither the global radiosondes network nor satellites can provide measurements of the required spatial and temporal resolution,

AMTD

7, 9803–9838, 2014

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



while the regular in-situ measurement of upper tropospheric humidity (UTH) is still difficult.

Since 1994, the European research programme MOZAIC (Measurement of Ozone by AIRBUS In-Service Aircraft; Marenco et al., 1998) and its successor IAGOS (In-service Aircraft for a Global Observing System; Petzold et al., 2013) provide regular data for relative humidity (RH) and other meteorological quantities like temperature and pressure as well as data on atmospheric composition (e.g. ozone and CO) with high spatial and temporal resolution on a global scale. The long-term observations are obtained by in-situ measurements aboard civil passenger aircraft using the existing infrastructure of the international air transport system. However, the continuous high-quality in-situ measurements are restricted to the major global flight routes and to the cruising altitude band of 9–13 km, i.e. the observations refer to a large extent to the UT/LS region. Relative humidity data from the MOZAIC programme have been used for various climatological studies including the distribution of UTH (Kley et al., 2007; Luo et al., 2007, 2008), the distribution of RH with respect to ice (RH_{ice} , e.g., Gierens et al., 1997, 1999) and ice-supersaturation regions (e.g., Gierens et al., 2000; Spichtinger et al., 2003) in the upper troposphere. A reanalysis of the global MOZAIC RH data set for the period 2000–2009 was performed recently (Smit et al., 2014).

Atmospheric RH is measured in the MOZAIC/IAGOS approach through a compact airborne humidity sensing device using capacitive sensors (MOZAIC Capacitive Hygrometer: MCH). The sensor itself and the applied calibration techniques are described in detail by Helten et al. (1998). First validation studies from wing-by-wing flights of a MOZAIC aircraft and a research aircraft are reported by Helten et al. (1999), while Smit et al. (2008) presents an approach for a potential in-flight calibration of MCH.

In order to assess the validity of the long-term water vapour data and its limitations, Helten et al. (1999) provided an in-flight comparison of MOZAIC and POLINAT (Schlager et al., 1997; Schumann, 1997) water vapour measurements. However, this wing-by-wing flight intercomparison was difficult to analyse because the twin-engine research aircraft Falcon 20 had to follow the MOZAIC Airbus A340-300 with changing

**Evaluation of
MOZAIC Capacitive
Hygrometer**

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



time lags and distances. In 2006, there was the opportunity to participate in the aircraft campaign CIRRUS-III along with other more sophisticated instruments for measuring the water vapour volume mixing ratio (VMR). The in-flight single-platform measurements permitted a blind intercomparison of the MCH with high performance research water vapour instruments by measuring the same air masses for a longer time and under different atmospheric conditions than in the limited wing-by-wing study published by Helten et al. (1999). A similar analysis of the improved IAGOS Capacitive Hygrometer is in preparation and will be published elsewhere.

2 MOZAIC Capacitive Hygrometer

The compact airborne MCH consists of a capacitive sensor (Humicap-H, Vaisala, Finland) whose capacitance depends on the relative humidity of the dielectric layer of the condensor and a platinum resistance sensor (Pt100) for the direct measurement of the temperature at the humidity sensing surface. The basic measurement process is based on the diffusion-limited adsorption of the H₂O-molecules by the dielectric membrane of the sensor. Since diffusion is strongly temperature-dependent, the sensor response slows down at lower temperatures. Figure 1 shows how both sensors are mounted in the used air sampling housing (Model 102 BX, Rosemount Inc.; see Stickney et al., 1990). The relative humidity and temperature signals are linearized by a microprocessor controlled transmitter unit (HMP230, Vaisala).

In its original MOZAIC mounting position aboard an Airbus A340-400 the sensor housing is placed approx. 7 m downstream of the aircraft nose on the left side with a 7 cm distance from the aircraft skin to avoid possible contaminating interferences with the aircraft skin. Inside the Rosemount housing the air flow is separated into the main flow, which traverses straight through the housing and the minor flow, which follows a sharp right angle into a smaller channel where the sensors are placed. The housing is equipped with small holes in the side wall to minimise internal boundary layer effects.

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The right angle of the minor flow protects the RH and T sensors against dust, water drops, and ice particles.

Due to the strong speed reduction in the inlet part of the housing, the sampled air flow is significantly heated through adiabatic heating. Assuming 100 % conversion of kinetic energy to heat during flow deceleration, the ambient temperature T_{ambient} (Static Air Temperature SAT; see Helten et al., 1998) increases to the temperature at the sensor inside the housing, i.e. the sensor temperature T_{sensor} (Total Air Temperature TAT; see Helten et al., 1998). The relationship between ambient temperature T_{ambient} and sensor temperature T_{sensor} is a function of the aircraft speed, i.e. its Mach-number M :

$$T_{\text{sensor}} = T_{\text{ambient}} \cdot \left(1 + \left(\frac{c_p - c_v}{2c_v} \right) \cdot M^2 \right) \quad (1)$$

where c_p ($= 1005 \text{ J kg}^{-1} \text{ K}^{-1}$) and c_v ($= 717 \text{ J kg}^{-1} \text{ K}^{-1}$) are the specific heat of dry air at constant pressure and volume, respectively. The resulting difference between T_{sensor} and T_{ambient} at 10–12 km cruising altitude for different Mach-numbers is displayed in Fig. 2: for the MOZAIC-typical aircraft speed of $M = 0.81$ the adiabatic heating effect is approx. 30 K. T_{ambient} is derived from Eq. (1) with an uncertainty of less than $\pm 0.5 \text{ K}$ resulting from uncertainties in T_{sensor} ($\pm 0.25 \text{ K}$) and M (Helten et al., 1998). Because of the strong temperature increase, the detected dynamic relative humidity $\text{RH}_{\text{dynamic}}$ (RH_D ; Helten et al., 1998) is significantly lower than the static relative humidity $\text{RH}_{\text{static}}$ (RH_S ; Helten et al., 1998) of the ambient air at T_{ambient} (Helten et al., 1998):

$$\text{RH}_{\text{static}} = \text{RH}_{\text{dynamic}} \cdot \left(\frac{T_{\text{ambient}}}{T_{\text{sensor}}} \right)^{\frac{c_p}{c_p - c_v}} \frac{e_{\text{s, liquid}}(T_{\text{sensor}})}{e_{\text{s, liquid}}(T_{\text{ambient}})} \quad (2)$$

where $e_{\text{s, liquid}}$ is the water vapour saturation pressure over liquid water at T_{sensor} and T_{ambient} , respectively. The water vapour saturation pressure over liquid water $e_{\text{s, liquid}}$ follows the Goff and Gratch (1946) formulation of saturation water vapour pressure over a plane surface of pure water or ice, which was recommended by the World

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capactive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Meteorological Organization (WMO, 1990) and adapted to their international temperature scale 1990 (ITS-90) by Sonntag (1994). For fast high-flying aircraft the relation $RH_{\text{static}}/RH_{\text{dynamic}}$ reaches a factor of approx. 13 (Helten et al., 1998), which leads to the fact, that the RH sensor operates in the lowest 10 % of its full dynamic range. Since the sensor is operating in the lower part of its full dynamic range, an individual calibration of each sensor is necessary, which is accomplished in the atmospheric simulation chamber at Jülich (Smit et al., 2000) before installation on the aircraft and after detachment past 500 h of flight. These calibrations are made over a sensor temperature range between -40 and $+20^{\circ}\text{C}$ against (i) Lyman- α fluorescence hygrometer (Kley and Stone, 1978) at water vapour mixing ratios below 1000 ppmv (relative accuracy $\pm 4\%$, Helten et al., 1998) and (ii) dew/frost point hygrometer (General Eastern, Type D1311R) at water vapour mixing ratios above 1000 ppmv with an accuracy of $\pm 0.5\text{ K}$. The relative humidity of a calibrated sensor (RH_C) at constant temperature T is found to be linearly related to the uncorrected output value (RH_{UC}) provided by the HMP230 transmitter unit (Helten et al., 1998)

$$RH_C(T) = a(T) + b(T) \cdot RH_{UC}(T) \quad (3)$$

Evaluation of 5 years of pre- and post-flight calibrations in MOZAIC has shown that the offset $a(T)$ is the most critical parameter in determining the uncertainty of the measurements, while the sensitivity is less critical and more stable (Smit et al., 2008).

In Sect. 3.2 the calibration procedure of the MCH is described, which was used during the CIRrus-III field study. It combines the standard procedure based on Helten et al. (1998) and the in-flight calibration described by Smit et al. (2008).

3 Experimental section

3.1 The CIRRUS-III field campaign

To extend the performance assessment of the MCH from the wing-by-wing flight intercomparison (Helten et al., 1999), the sensor was operated aboard a twin-engine business-jet aircraft of type Learjet 35A as part of the CIRRUS-III field study, which was coordinated by Forschungszentrum Jülich.

The overarching goals of CIRRUS-III were to understand the formation mechanism of cirrus clouds in different background conditions, their radiative effects and the microphysical properties of the cirrus cloud particles. In total 6 flights were conducted in the period between 23 and 29 November 2006 at mid-latitudes (45–70° N, see Fig. 3) and at flight altitudes between 7 and 12 km. These flights in the UT/LS were launched from Hohn Airforce Base in Northern Germany with the Learjet 35A operated by *enviscope GmbH*.

For the sensor intercomparison studies CIRRUS-III provided 4 flights (see Table 1). The dataset consists of approx. 13 flight hours in air masses colder than -40°C at cruise altitude, approx. 4 flight hours in cirrus clouds and 9 flight hours out of clouds. Furthermore, stratospherically influenced air masses have been sampled for 19 min with ozone VMR above 125 ppmv measured by the dual-beam UV-absorption ozone photometer JOE (Jülich Ozone Experiment) instrument (Mottaghy, 2001). Two flights had to be discarded due to inlet heating problems at the reference instrument. An overview of the individual flights is provided in Table 1.

3.2 Instrumentation

During the CIRRUS-III field campaign, sophisticated instruments were operated on board of the aircraft to characterize the air masses probed during flight patterns in frontal cirrus clouds. An important part of the instrumentation was dedicated to the measurement of gas phase and condensed phase of water. The instrumentation



stratospherically influenced air masses was about 20 ± 1 ppmv as measured by the FISH instrument. Its resulting contribution to the $\text{RH}_{\text{liquid}}$ -signal of the MCH is minimal. Compared to the pre-flight calibration an offset drift of $(4.5 \pm 1) \% \text{RH}_{\text{liquid}}$ was found. The $\text{RH}_{\text{liquid}}$ -flight data of the MCH obtained during the CIRRUS-III campaign have been corrected for this offset drift. The resulting overall uncertainty of the RH measurements by the MCH, including contributions from temperature uncertainties, is about $\pm 5 \% \text{RH}_{\text{liquid}}$ which is in good agreement with the mean uncertainty range obtained from long term MOZAIC-measurements (Smit et al., 2014).

4 Results

4.1 Case study – flight 2

The instrumentation deployed in CIRRUS-III allows an in-flight intercomparison of all water vapour instruments. Figure 4 illustrates an example of the kind of data collected during one research flight on 28 November 2006 (Flight 2). Data from the water vapour sensing instruments used for the intercomparison are shown as VMR. The ambient temperatures T_{ambient} encountered during the flight ranged from -44.1°C to -62.4°C for relevant measurement altitudes. Respective water vapour VMR covered the range from 17 ppmv at the tropopause to approx. 150 ppmv in the free troposphere and even higher values during ascent from and descent into the airport.

For the instrument intercomparison we analysed the sensors with respect to $\text{RH}_{\text{liquid}}$ since this is the parameter the MCH is calibrated against in the sensor temperature range (see Sect. 2). Further, data for water vapour VMR > 1000 ppmv were excluded in this study because the FISH instrument becomes optically thick and thus insensitive at these conditions (Zöger et al., 1999).

In Fig. 5, we compare $\text{RH}_{\text{liquid}}$ data and VMR data from MCH (red line) and gas-phase reference (blue line), i.e. OJSTER data in cloud, otherwise FISH data for a complete validation of the MCH for Flight 2. The ambient temperature T_{ambient} (green line) as

Evaluation of MOZAIC Capactive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



well as the sensor temperature T_{sensor} (black line) measured at the MCH inside the Rosemount housing are shown in the bottom panel. Largest deviations of the MCH to the reference (see e.g. $\Delta \text{RH}_{\text{liquid}}$ in the top panel) are found in clear sky air masses for cold conditions with sensor temperature $T_{\text{sensor}} < -40^\circ\text{C}$ (this corresponds to ambient temperature below approx. -60°C at $M = 0.70$). Except for these extreme conditions, the difference between the MCH and the reference is of the order of 10 % $\text{RH}_{\text{liquid}}$ or less. It has to be noted that regular operation conditions of the MCH aboard long-haul passenger aircraft like A340-300 with a cruising speed of approx. $M = 0.81$ are characterised by sensor temperature $T_{\text{sensor}} \geq -35^\circ\text{C}$ (Helten et al., 1998), whereas during the operation aboard the slower flying Learjet 35A (cruising speed $< M = 0.70$) sensor temperature T_{sensor} values $\leq -40^\circ\text{C}$ were reached since ΔT increases with M (see Fig. 2). Given the fact that during CIRRUS-III the MCH was operated at its lower limit of performance, the agreement with the research-grade reference instruments is remarkably good.

4.2 Assessment of sensor characteristics

4.2.1 Evaluation against reference

In order to prepare a data set for evaluation, data with sensor temperatures $T_{\text{sensor}} < -40^\circ\text{C}$ were excluded because of too dry measurement conditions which were below the MCH calibration limits (see Sect. 2). This fact is illustrated in Fig. 6 showing the difference in $\text{RH}_{\text{liquid}}$ between MCH and reference instruments, i.e. OJSTER data in cloud, otherwise FISH data, according to sensor temperature T_{sensor} . A first overall good agreement of the two sensors down to the calibration limit of -40°C can be stated in the range of $\pm 5\%$. Furthermore, the maximum ambient temperature T_{ambient} was set to the level of instantaneous freezing of -40°C in order to neglect effects of warmer clouds.

Finally, flight sequences of the Learjet 35A with steep ascents and descents were excluded, since these flight conditions are not comparable to conditions aboard long-haul

passenger aircraft. To obtain information about the MCH performance relevant for the MOZAIC data set, i.e. for nearly constant flight levels with moderately slow changes in temperature and humidity, the flight altitude for CIRRUS-III was smoothed over 90 s time intervals, and in case altitude changes exceeded $\Delta z > 6$ m in 5 s the respective data points were excluded from the intercomparison.

The correlation between MCH and reference $\text{RH}_{\text{liquid}}$ data from FISH (clear sky) and OJSTER (in-cirrus) is shown in Fig. 7. The bottom panel shows the 1 Hz data scatter plot for the data set reduced to MOZAIC-relevant conditions (hereafter referred to as “reduced dataset”). Linear regression analysis yields a correlation coefficient of $R^2 = 0.92$ with an offset of 0.18 ± 0.09 % $\text{RH}_{\text{liquid}}$ and a slope of 1.00 ± 0.002 . The deviations of the MCH from reference $\text{RH}_{\text{liquid}}$ data are represented in the upper panel for 1 Hz data points. Additionally, the deviations are grouped into 5 % $\text{RH}_{\text{liquid}}$ bins corresponding to the previously determined precision of the MCH of 5 % $\text{RH}_{\text{liquid}}$ (see Sect. 3.2 and Helten et al., 1999). Red lines in the box and whisker plots represent the median deviation for each bin. For the statistically relevant bins, i.e. bins with more than 100 data points, median deviations fall within ± 5 % $\text{RH}_{\text{liquid}}$ (see also Table 3).

A more statistically based view on the data set is shown in Fig. 8, where the correlation between the sensors averaged for 5 % $\text{RH}_{\text{liquid}}$ bins is shown. The MCH agrees very well with the reference instruments over the entire range of values measured in the cloud-free atmosphere (see also Table 4). Inside cirrus clouds, i.e. $\text{RH}_{\text{liquid}} >$ approx. 60 %, the sensors deviate as expected since the reference measures total water while the MCH measures gas-phase water. Linear regression analysis provides a correlation coefficient of $R^2 = 0.97$ with an offset of 2.20 ± 2.00 % $\text{RH}_{\text{liquid}}$ and a slope of 0.96 ± 0.05 . Median values and almost all of the 25th and 75th percentiles fall within the ± 5 % $\text{RH}_{\text{liquid}}$ range around the linear regression line, which confirms the previously determined MCH uncertainty of 5 % $\text{RH}_{\text{liquid}}$.

For a better understanding of an uncertainty of 5 % $\text{RH}_{\text{liquid}}$ Fig. 9 shows water vapour VMR as a function of temperature for 5 % and 10 % $\text{RH}_{\text{liquid}}$ for pressure levels at typical passenger aircraft flight altitudes. As an example, at $T_{\text{ambient}} = 215$ K and pressure =

Evaluation of MOZAIC Capactive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



220 hPa a measured $RH_{\text{liquid}} = 5\%$ with an uncertainty of 5% RH_{liquid} corresponds to a VMR of approx. $5 \text{ ppmv} \pm 5 \text{ ppmv}$.

The proof of validity of the MCH RH_{liquid} data is shown in Fig. 10. As is shown in the bottom panel, the probability distribution function (PDF) for RH_{liquid} derived from MCH data agree very well with those derived from the reference for the entire data set. Larger deviations at higher values of RH_{liquid} , e.g. at possible cirrus cloud edges reflect the fact that the reference instrument FISH measures total water and the data are not classified as cirrus cloud by the algorithm of Krämer et al. (2009). The sensor behaviour for those conditions at the limit of the sensor operation specifications is analysed in detail in the following section.

4.2.2 Sensor characteristics at the limit of its operation range

The comparison between the MCH RH_{liquid} data and the reference RH_{liquid} data, i.e. OJSTER data in cloud, otherwise FISH data, during the CIRRUS-III field study shows a remarkably good agreement for the reduced data set. However, the performance of the MCH sensor in conditions at its limits of operation, e.g. next to the lower calibration limit of $T_{\text{sensor}} = -40^\circ\text{C}$ or during strong humidity changes has to be analysed in detail in order to assess the sensor's operation range. For this purpose, the time series of Flight 2 is revisited in Fig. 11, where the individual RH_{liquid} time series are given in the upper panel, the 60 s moving average of the difference of both RH_{liquid} time series in the middle panel, as well as the T_{sensor} time series in the bottom panel.

The following 3 phases of interest have to be analysed:

- Phase 1 is shaded in blue colour illustrates a strong humidity change while flying through a cirrus cloud. Because of slower MCH sensor response at colder sensor temperatures, the MCH RH_{liquid} values (green line) can not follow the rapid changes in RH_{liquid} as observed by the reference (blue line). However, as was shown previously in Fig. 10, there is no statistically significant effect of the delayed sensor response to strong humidity changes at low temperatures.

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capactive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



– Phase 2 is shaded in red and refers to a section of the flight when T_{sensor} reaches values below the sensor calibration limit of $T_{\text{sensor}} = -40^{\circ}\text{C}$, i.e. ambient temperatures below -70°C at commercial aircraft speed of Mach-number $M = 0.81$. The MCH shows reduced performance and increasing deviations between the MCH and the reference instruments occur.

– Phase 3 shaded in grey refers to mixed conditions with isolated rapid humidity changes, while flying through small cirrus clouds those rapid $\text{RH}_{\text{liquid}}$ changes are superimposed by strong temperature changes because of the aircraft ascent to measurement altitude and the occurrence of temperatures below the calibration limit, which both cause a reduction of the MCH time resolution.

Despite of reduced sensor response to conditions at the limit of its operation range, the MCH shows a very good overall performance during the CIRRUS-III field study. Figure 12 compares frequency of occurrence (top panel) and PDF (bottom panel) of $\text{RH}_{\text{liquid}}$ based on 5 % $\text{RH}_{\text{liquid}}$ bins of the complete MCH data set, i.e. all data points above the homogenous freezing threshold of $T_{\text{ambient}} = -40^{\circ}\text{C}$, with those of the data set reduced to MOZAIC-relevant conditions. The comparison of the observed $\text{RH}_{\text{liquid}}$ counts and PDF per 5 % bin demonstrates the equivalence of the statistical distribution of $\text{RH}_{\text{liquid}}$ of both data sets. Main quantitative deviations are observed in the transition region between clear sky ($< 25\% \text{RH}_{\text{liquid}}$) and next to cirrus clouds ($> 50\% \text{RH}_{\text{liquid}}$) during rapid changes in flight altitude at very cold conditions and therefore with a longer sensor response time at flight sequences into and out of cirrus clouds.

Figure 13 shows the PDF of water vapour VMR data as a function of T_{ambient} (panels a–c for the complete data set and panels d–f for the reduced data set, respectively) according to Kunz et al. (2008). The frequencies of occurrence are calculated in 1°C bins for the MCH data set (panels a and d), the reference data set (panels b and e) and the deviation of both PDF's (panel c and f). The water vapour VMR is binned logarithmically spaced between 0 and 8.0 with a bin size of 0.8. The colour bars are binned in 5 % spaces for a better interpretation of the contour plots.

The MCH seems to remain at dryer values for the coldest temperatures of $T_{\text{ambient}} \approx -60^{\circ}\text{C}$, which is again a result of the delayed sensor response at sensor temperatures below the calibration limit. Further, small deviations at lower temperatures are also observed. In summary data sets for both cases show a similar behaviour in the water vapour VMR distribution with only small deviations but as shown before in Fig. 12 these deviations have no statistically significant relevance.

5 Conclusions and recommendations

The CIRRUS-III (2006) aircraft campaign provided a data set for evaluating the MOZAIC Capacitive Hygrometer (MCH) in a blind intercomparison with high performance water vapour instruments based on tunable diode laser absorption spectrometry (in-cloud reference) and Lyman- α fluorescence detection (clear sky reference).

Except for conditions at its operation limit (e.g., at sensor temperatures $T_{\text{sensor}} < -40^{\circ}\text{C}$ and during rapid changes in $\text{RH}_{\text{liquid}}$), the MCH performs with a difference of 10 % $\text{RH}_{\text{liquid}}$ or less to the references, i.e. OJSTER data in cloud, otherwise FISH data.

In order to obtain a representative result for the MCH's uncertainty for its regular deployment aboard passenger aircraft, the data set was restricted to more MOZAIC relevant conditions: data with sensor temperatures below -40°C were excluded due to the calibration limit. In MOZAIC less than 1 % of RH observations are made at sensor temperatures colder than -40°C . Strong ascent and descent sequences of the aircraft were removed and the maximum ambient temperature (T_{ambient}) was set to -40°C to exclude effects of warm clouds.

The 1 Hz correlation yielded a robust linear fit with a slope of unity, with no statistically significant offset and a correlation coefficient of $R^2 = 0.92$ which was confirmed by the correlation of the binned $\text{RH}_{\text{liquid}}$ data. The $\text{RH}_{\text{liquid}}$ data grouped in 5 % $\text{RH}_{\text{liquid}}$ bins agree very well for the MCH and reference instruments over the entire cloud-free range and for most of the cirrus clouds sequences and yield MCH uncertainty of 5 % $\text{RH}_{\text{liquid}}$.

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capactive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Comparing the MCH's and references' probability distribution functions (PDF) for $\text{RH}_{\text{liquid}}$ shows no statistically significant effect of delayed sensor response because of the limitations of the MCH. Neither strong humidity changes, nor operation at the lower calibration limits causes considerable sensor failures. The main limitation for the use of MCH $\text{RH}_{\text{liquid}}$ data are related to sensor temperatures below the calibration limit of $T_{\text{sensor}} = -40^\circ\text{C}$. However, these temperatures are encountered only infrequently in the MOZAIC programme as long as the current flight tracks don't reach polar air masses with ambient temperatures below -70°C . In summary, the MCH is highly suitable for climatology analyses in the MOZAIC programme even if the sensor is not applicable to high time resolution measurements.

A value for the limit of detection is not appropriate for the MCH, but the variable to describe its performance is the here determined uncertainty of the $\text{RH}_{\text{liquid}}$ measurements. $\text{RH}_{\text{liquid}}$ measurements below 5 %, which are common in the lowermost stratosphere, have to be used carefully because these data are close to the sensor uncertainty range, which as shown before in Sect. 4.2.1, results in a relative deviation of 100 %.

Acknowledgements. The authors gratefully acknowledge Peter Spichtinger (Mainz Univ.) for fruitful discussions. The support by *enviscope* GmbH at the technical organization of the field study is also appreciated. Part of this work was funded by the German Federal Ministry for Research and Education (BMBF) in the framework of the joint programme IAGOS-D under Grant No. 01LK1223A.

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

References

- Bange, J., Esposito, M., Lenschow, D. H., Brown, P. R. A., Dreiling, V., Giez, A., Mahrt, L., Malinowski, S. P., Rodi, A. R., Shaw, R. A., Siebert, H., Smit, H., and Zöger, M.: Measurement of Aircraft State and Thermodynamic and Dynamic Variables, in: Airborne Measurements for Environmental Research: Methods and Instruments, edited by: Wendisch, M. and Brenguier, J.-L., Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, doi:10.1002/9783527653218.ch2, 2013. 9823
- 5 Gierens, K., Schumann, U., Smit, H., Helten, M., and Zangl, G.: Determination of humidity and temperature fluctuations based on MOZAIC data and parametrisation of persistent contrail coverage for general circulation models, Ann. Geophys., 15, 1057–1066, doi:10.1007/s00585-997-1057-3, 1997. 9805
- 10 Gierens, K., Schumann, U., Helten, M., Smit, H., and Marenco, A.: A distribution law for relative humidity in the upper troposphere and lower stratosphere derived from three years of MOZAIC measurements, Ann. Geophys., 17, 1218–1226, doi:10.1007/s00585-999-1218-7, 1999. 9805
- 15 Gierens, K., Schumann, U., Helten, M., Smit, H., and Wang, P.: Ice-supersaturated regions and subvisible cirrus in the northern midlatitude upper troposphere, J. Geophys. Res.-Atmos., 105, 22743–22753, doi:10.1029/2000JD900341, 2000. 9805
- 20 Goff, J. A. and Gratch, S.: Low-pressure properties of water from -160 to 212 F, Trans. Amer. Soc. Heat. Vent. Eng., 51, 125–164, 1946. 9807
- Helten, M., Smit, H., Strater, W., Kley, D., Nedelec, P., Zoger, M., and Busen, R.: Calibration and performance of automatic compact instrumentation for the measurement of relative humidity from passenger aircraft, J. Geophys. Res.-Atmos., 103, 25643–25652, doi:10.1029/98JD00536, International Workshop on Biogenic Hydrocarbons in the Atmospheric Boundary Layer, Univ. Virginia, Charlottesville, VA, August 1997, 1998. 9805, 9807, 25 9808, 9812, 9823, 9826, 9827
- Helten, M., Smit, H., Kley, D., Ovarlez, J., Schlager, H., Baumann, R., Schumann, U., Nedelec, P., and Marenco, A.: In-flight comparison of MOZAIC and POLINAT water vapor measurements, J. Geophys. Res.-Atmos., 104, 26087–26096, doi:10.1029/1999JD900315, 30 1999. 9805, 9806, 9809, 9813

AMTD

7, 9803–9838, 2014

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Kley, D. and Stone, E.: Measurement of water-vapor in stratosphere by photo-dissociation with ly-alpha-(1216 Å) light, *Rev. Sci. Instrum.*, 49, 691–697, doi:10.1063/1.1135596, 1978. 9808
- Kley, D., Smit, H. G. J., Nawrath, S., Luo, Z., Nedelec, P., and Johnson, R. H.: Tropical Atlantic convection as revealed by ozone and relative humidity measurements, *J. Geophys. Res.-Atmos.*, 112, D23109, doi:10.1029/2007JD008599, 2007. 9805
- Krämer, M., Schiller, C., Afchine, A., Bauer, R., Gensch, I., Mangold, A., Schlicht, S., Spelten, N., Sitnikov, N., Borrmann, S., de Reus, M., and Spichtinger, P.: Ice supersaturations and cirrus cloud crystal numbers, *Atmos. Chem. Phys.*, 9, 3505–3522, doi:10.5194/acp-9-3505-2009, 2009. 9810, 9814
- Kunz, A., Schiller, C., Rohrer, F., Smit, H. G. J., Nedelec, P., and Spelten, N.: Statistical analysis of water vapour and ozone in the UT/LS observed during SPURT and MOZAIC, *Atmos. Chem. Phys.*, 8, 6603–6615, doi:10.5194/acp-8-6603-2008, 2008. 9815
- Luo, Z., Kley, D., Johnson, R. H., and Smit, H.: Ten years of measurements of tropical upper-tropospheric water vapor by MOZAIC. Part I: Climatology, variability, transport, and relation to deep convection, *J. Climate*, 20, 418–435, doi:10.1175/JCLI3997.1, 2007. 9805
- Luo, Z., Kley, D., Johnson, R. H., and Smit, H.: Ten years of measurements of tropical upper-tropospheric water vapor by MOZAIC. Part II: Assessing the ECMWF humidity analysis, *J. Climate*, 21, 1449–1466, doi:10.1175/2007JCLI1887.1, 2008. 9805
- Marenco, A., Thouret, V., Nedelec, P., Smit, H., Helten, M., Kley, D., Karcher, F., Simon, P., Law, K., Pyle, J., Poschmann, G., Von Wrede, R., Hume, C., and Cook, T.: Measurement of ozone and water vapor by Airbus in-service aircraft: the MOZAIC airborne program, an overview, *J. Geophys. Res.-Atmos.*, 103, 25631–25642, doi:10.1029/98JD00977, International Workshop on Biogenic Hydrocarbons in the Atmospheric Boundary Layer, Univ. Virginia, Charlottesville, VA, August 1997, 1998. 9805
- May, R. and Webster, C.: Data-processing and calibration for tunable diode-laser harmonic absorption spectrometers, *J. Quant. Spectrosc. Ra.*, 49, 335–347, doi:10.1016/0022-4073(93)90098-3, 1993. 9810, 9823
- Mottaghy, D.: Ozonmessungen in der unteren Stratosphäre, Master's thesis, Rheinisch-Westfälische Technische Hochschule Aachen, in cooperation with the Institute for Chemistry and Dynamics of the Geosphere, ICG-1: Stratosphere, 2001. 9809
- Petzold, A., Volz-Thomas, A., Thouret, V., Cammas, J.-P., and Brenninkmeijer, C.: IAGOS – In-service Aircraft for a Global Observing System, in: 3rd International Conference on Transport, Atmosphere and Climate, edited by: Sausen, R., Unterstrasser, S., and Blum, A.,

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Forschungsbericht 2012-17, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany, 69–76, 2013. 9805

Schlager, H., Konopka, P., Schulte, P., Schumann, U., Ziereis, H., Arnold, F., Klemm, M., Hagen, D., Whitefield, P., and Ovarlez, J.: In situ observations of air traffic emission signatures in the North Atlantic flight corridor, *J. Geophys. Res.-Atmos.*, 102, 10739–10750, doi:10.1029/96JD03748, 1997. 9805

Schumann, U.: Pollution from aircraft emissions in the North Atlantic flight corridor (POLINAT), vol. Air Pollut. Res. Rep. 58, Rep. EUR 16978 EN, Europ. Commission, Luxembourg, 1997. 9805

Smit, H., Sträter, W., Helten, M., and Kley, D.: Environmental Simulation Facility to Calibrate Airborne Ozone and Humidity Sensors, Tech. rep., Report No. 3796, Berichte des Forschungszentrums Jülich, 2000. 9808

Smit, H. G. J., Volz-Thomas, A., Helten, M., Paetz, W., and Kley, D.: An in-flight calibration method for near-real-time humidity measurements with the airborne MOZAIC sensor, *J. Atmos. Ocean. Tech.*, 25, 656–666, doi:10.1175/2007JTECHA975.1, 2008. 9805, 9808, 9810

Smit, H. G. J., Rohs, S., Neis, P., Boulanger, D., Krämer, M., Wahner, A., and Petzold, A.: Technical Note: Reanalysis of upper troposphere humidity data from the MOZAIC programme for the period 1994 to 2009, *Atmos. Chem. Phys. Discuss.*, 14, 18905–18942, doi:10.5194/acpd-14-18905-2014, 2014. 9805, 9811

Sonntag, D.: Advancements in the field of hygrometry, *Meteorol. Z.*, 3, 51–66, 1994. 9808

Spichtinger, P., Gierens, K., Leiterer, U., and Dier, H.: Ice supersaturation in the tropopause region over Lindenberg, Germany, *Meteorol. Z.*, 12, 143–156, doi:10.1127/0941-2948/2003/0012-0143, 2003. 9805

Stickney, T. M., Shedlov, M., and Thompson, D. I.: Rosemount total temperature sensors, Tech. rep., Tech. Rep. 5755, Revision B, Aerosp. Div. Rosemount Inc., 1990. 9806

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M.: Climate change 2013: the Physical Science Basis, Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5), Cambridge Univ. Press, New York, 2013. 9804

WMO: World Meteorological Organization: measurement of atmospheric humidity, Tech. rep., in: Guide to Meteorological Instruments and Methods of Observation, 5th Edn., WMO Rep. 8, 5.1–5.19, Geneva, 1990. 9808

Zöger, M., Afchine, A., Eicke, N., Gerhards, M., Klein, E., McKenna, D., Morschel, U., Schmidt, U., Tan, V., Tuitjer, F., Woyke, T., and Schiller, C.: Fast in situ stratospheric hygrometers: a new family of balloon-borne and airborne Lyman alpha photofragment fluorescence hygrometers, J. Geophys. Res.-Atmos., 104, 1807–1816, doi:10.1029/1998JD100025, 1999. 9810, 9811, 9823

5

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Evaluation of
MOZAIC Capacitive
Hygrometer**

P. Neis et al.

Table 1. CIRRUS-III flight overview at cruise altitude. Air masses are divided into “troposphere” and “stratosphere” with the ozone VMR threshold of 125 ppmv.

Flight No.	Date	Take-off/ Landing (UTC)	Temperature Range	H ₂ O VMR Range	In/out of Cirrus	Stratosphere/ Troposphere
1	24 Nov	10:47/14:53	−62.6–52.8 °C	24–107 ppmv	95/96 min	2/190 min
2	28 Nov	08:22/12:07	−62.4–44.1 °C	17–138 ppmv	4/160 min	11/153 min
3	28 Nov	13:31/17:25	−60.0–42.4 °C	27–360 ppmv	56/124 min	5/175 min
4	29 Nov	09:16/13:51	−61.2–45.8 °C	16–216 ppmv	62/158 min	2/218 min
Sum			−62.6–42.4 °C	16–360 ppmv	217/537 min	19/735 min

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Table 2. Instruments and parameters used during CIRRUS-III field campaign (FISH: Fast in situ Stratospheric Hygrometer; OJSTER: Open path Jülich Stratospheric TdI ExpeRiment; MCH: MOZAIC Capacitive Hygrometer; LT: lower troposphere; UT: upper troposphere; LS: lower stratosphere).

Instrument	Detection Quantity	Remarks	Time Resolution	Uncertainty	Source
FISH	VMR [ppmv]	Lyman- α -hygrometer	1 s	7 % \pm 0.3 ppmv (precision 1 %)	Zöger et al. (1999)
OJSTER	VMR [ppmv]	Open path TDL	1 s	10–15 %	May and Webster (1993)
MCH	RH _{liquid} [%]	Capacitive sensor	LT: 1 s MT: 10 s LS: 1 min	\pm (4–7) % @ 10–13 km below 10 km \pm (4–6) %	Helten et al. (1998)

For further information see Bange et al. (2013).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Table 3. Medians, 25th/75th percentiles and counts of $\Delta RH_{\text{liquid}}$ (MCH-reference). Data were classified into 5 % RH_{liquid} bins relating to the reference, i.e. OJSTER data in cloud, otherwise FISH data.

	0–5 %	5–10 %	10–15 %	15–20 %	20–25 %	25–30 %	30–35 %	35–40 %	40–45 %
$\Delta RH_{\text{liquid}} [\%]$	–	$3.0^{+0.2}_{-0.4}$	$1.0^{+1.6}_{-1.1}$	$0.4^{+2.2}_{-2.9}$	$-1.8^{+2.4}_{-2.7}$	$-2.3^{+5.5}_{-2.8}$	$-0.1^{+5.2}_{-4.4}$	$3.7^{+3.4}_{-7.3}$	$3.9^{+4.2}_{-2.9}$
counts [#]	–	13	1276	4037	2335	1471	1606	776	569
	45–50 %	50–55 %	55–60 %	60–65 %	65–70 %	70–75 %	75–80 %	80–85 %	85–90 %
$\Delta RH_{\text{liquid}} [\%]$	$5.4^{+3.5}_{-3.1}$	$4.2^{+2.6}_{-2.9}$	$1.7^{+3.8}_{-4.2}$	$0.4^{+3.7}_{-2.8}$	$-0.8^{+2.7}_{-3.3}$	$-3.3^{+2.9}_{-2.8}$	$-7.7^{+3.8}_{-4.0}$	$-12.3^{+3.8}_{-7.1}$	$-8.9^{+0.8}_{-0.8}$
counts [#]	813	2015	2910	2567	1109	512	148	24	3

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Table 4. Medians, 25th/75th percentiles of RH_{liquid} of MCH and reference, respectively. Data were classified into 5 % RH_{liquid} bins relating to the reference, i.e. FISH (clear sky) and OJSTER (in-cirrus).

	0–5 %	5–10 %	10–15 %	15–20 %	20–25 %	25–30 %	30–35 %	35–40 %	40–45 %
$RH_{\text{liquid}}[\%]$									
MCH	–	12.2 ^{+0.4} _{–0.7}	14.7 ^{+1.1} _{–1.4}	17.5 ^{+2.2} _{–2.2}	20.4 ^{+1.9} _{–2.5}	24.8 ^{+6.9} _{–3.5}	31.9 ^{+6.2} _{–3.7}	41.6 ^{+2.9} _{–8.9}	46.4 ^{+4.9} _{–3.9}
reference	–	9.6 ^{+0.4} _{–1.2}	13.9 ^{+0.6} _{–1.4}	17.2 ^{+1.3} _{–1.0}	22.0 ^{+1.5} _{–1.2}	26.9 ^{+1.5} _{–1.1}	32.5 ^{+1.2} _{–1.2}	37.0 ^{+1.4} _{–1.1}	42.5 ^{+1.2} _{–1.2}
	45–50 %	50–55 %	55–60 %	60–65 %	65–70 %	70–75 %	75–80 %	80–85 %	85–90 %
$RH_{\text{liquid}}[\%]$									
MCH	53.6 ^{+2.9} _{–3.5}	56.9 ^{+3.0} _{–2.6}	58.8 ^{+4.1} _{–3.8}	62.7 ^{+3.8} _{–2.3}	67.0 ^{+2.1} _{–3.8}	68.7 ^{+2.1} _{–2.7}	69.3 ^{+3.1} _{–4.4}	69.1 ^{+2.8} _{–7.2}	77.1 ^{+0.1} _{–0.6}
reference	47.8 ^{+1.1} _{–1.2}	53.0 ^{+1.0} _{–1.2}	57.4 ^{+1.2} _{–1.2}	62.4 ^{+1.2} _{–1.2}	67.1 ^{+1.2} _{–1.1}	71.9 ^{+1.2} _{–1.0}	76.9 ^{+1.6} _{–1.2}	81.0 ^{+1.1} _{–0.7}	85.4 ^{+1.5} _{–0.3}

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



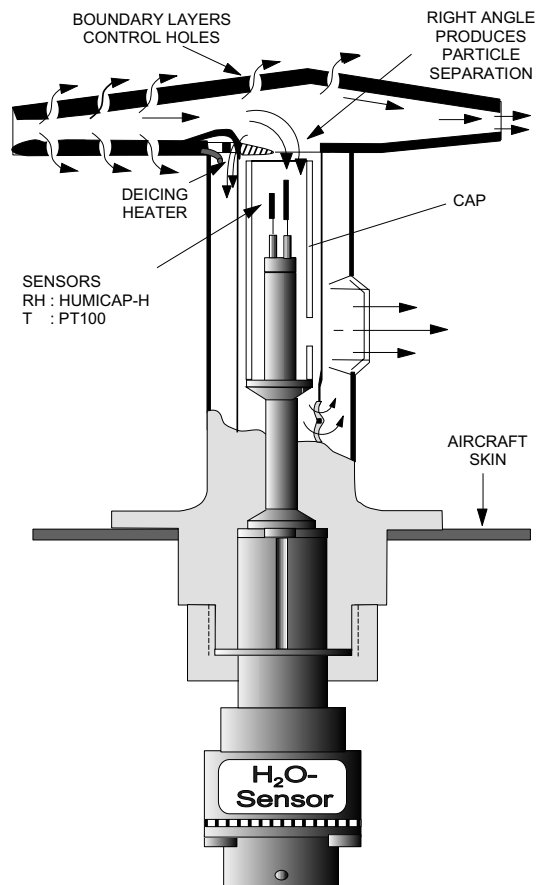


Figure 1. Cross section of the airborne capacitive sensing element. Right angle protects against particles and control holes in the side wall neglect internal boundary layer effects (Helten et al., 1998).

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



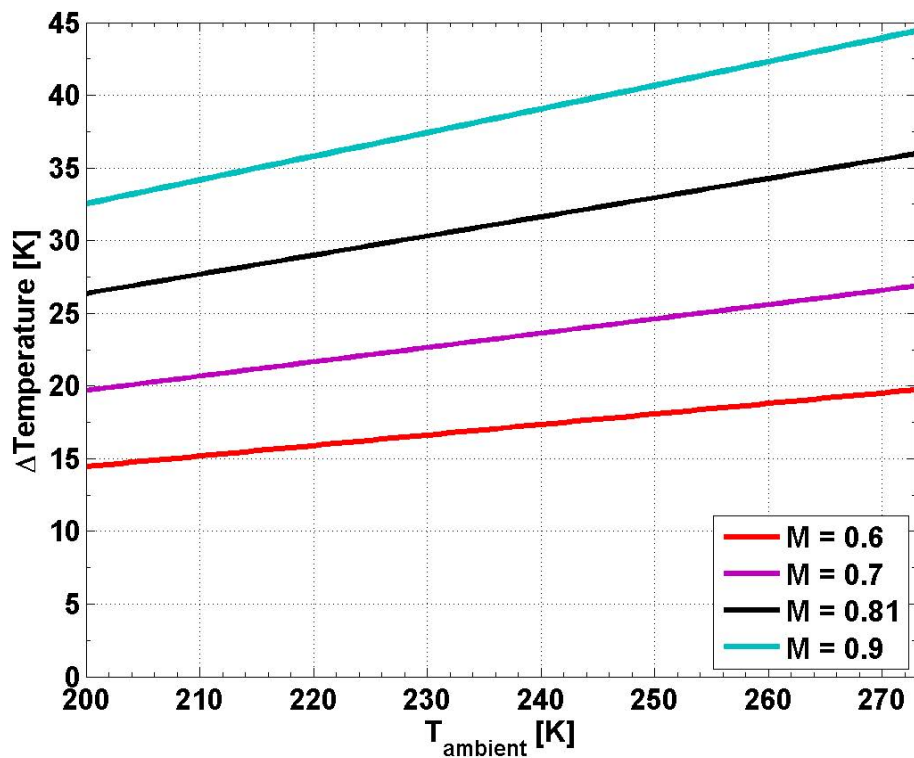


Figure 2. Sampled air flow is heated through adiabatic heating effects when entering the inlet. $\Delta\text{Temperature}$ describes the increase relative to the ambient temperature T_{ambient} (Static Air Temperature SAT; see Helten et al., 1998) for several aircraft speeds, i.e. the Mach-number M , by assuming 100 % conversion of kinetic energy to heat during flow deceleration.

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

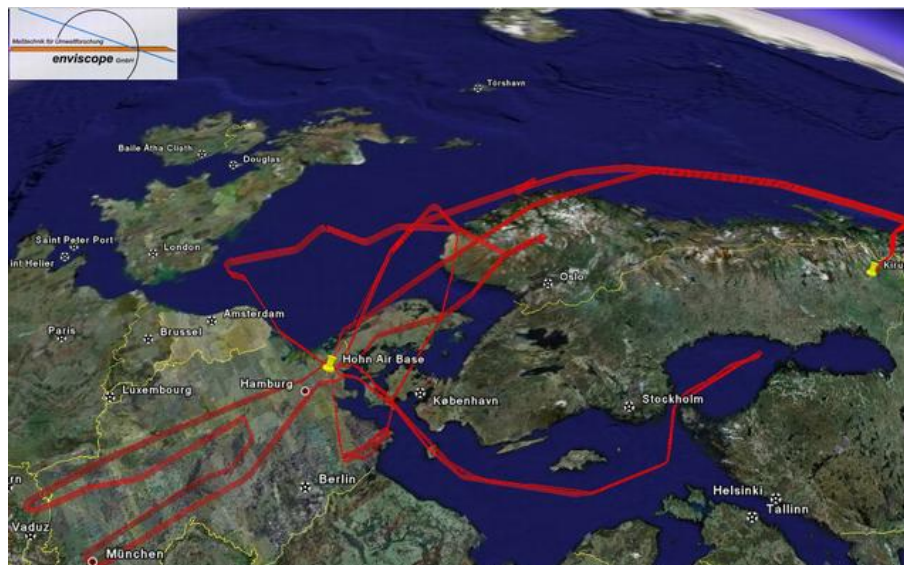


Figure 3. CIRrus-III flight track overview (Map Data © 2008 Google, Sanborn).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

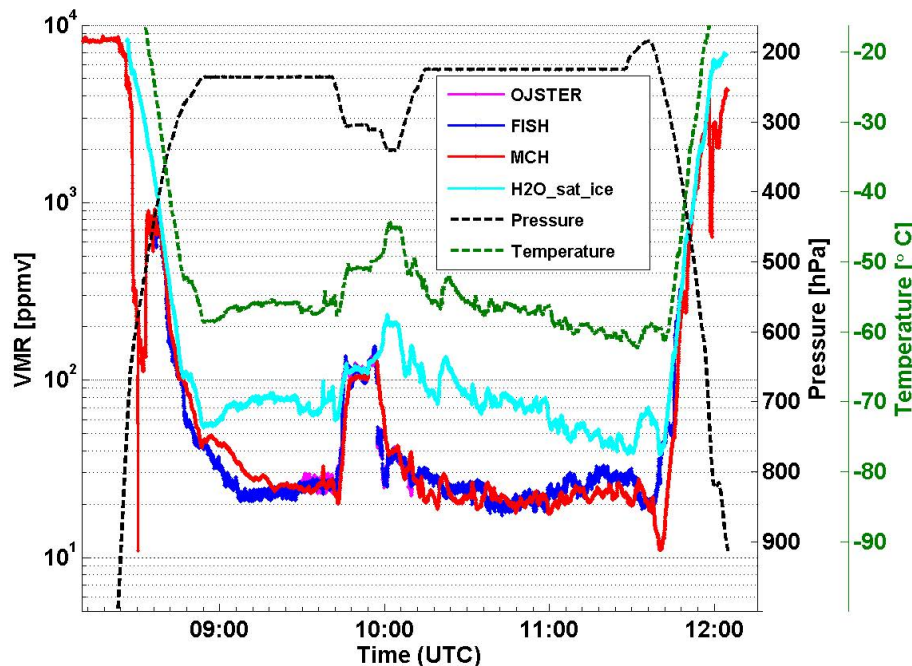


Figure 4. Time series of water vapour volume mixing ratios (VMR) from MCH (red), FISH (blue) and OJSTER (pink) during CIRRUS-III flight on 28 November 2006. Ice saturation is shown in cyan, while pressure (black) and ambient air temperature (green) are plotted with dashed lines.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

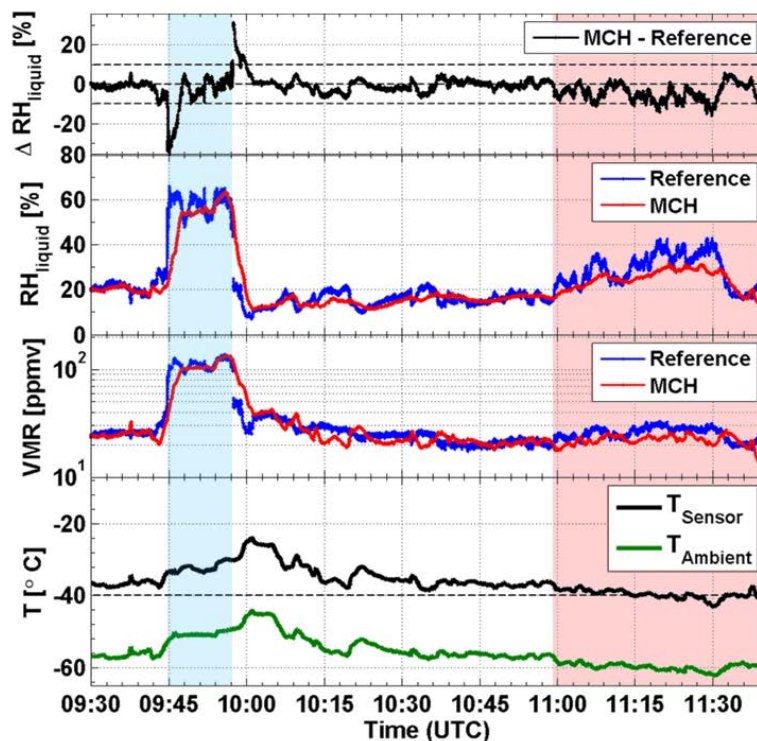


Figure 5. Top-down: $\Delta RH_{\text{liquid}}$ (MCH-reference), RH_{liquid} and VMR measured by the MCH (red) and the reference (blue), i.e. FISH (clear sky) and OJSTER (in-cirrus), as a function of flight time during flight 2 on 28 November 2006. Sensor temperature T_{sensor} (black) as well as ambient temperature T_{ambient} (green) are shown in the bottom panel of the figure. The blue-shaded area represents air masses with high humidity and possible cirrus cloud. Air masses with sensor temperatures at and below the calibration limit are shaded in red.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

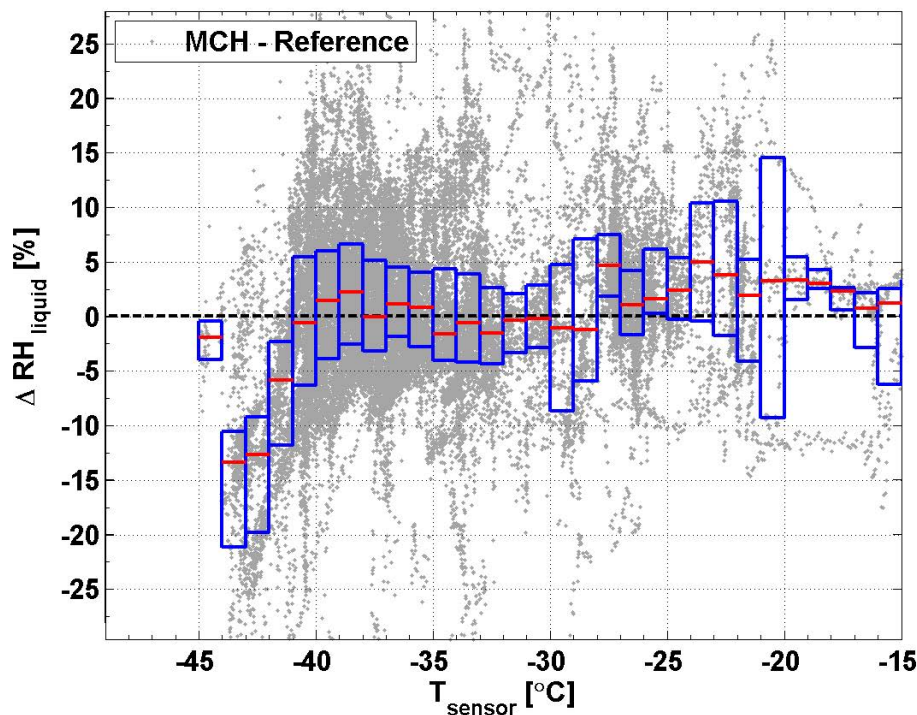


Figure 6. Differences in relative humidity RH_{liquid} of MCH and reference, i.e. FISH (clear sky) and OJSTER (in-cirrus), are scattered against the sensor temperature T_{sensor} . A drift towards too dry MCH measurements below the calibration limit of -40°C is clearly seen. The median values (red lines in the box) of the 1°C -binned data as well as the 25th and 75th percentiles are within the calibration limits.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

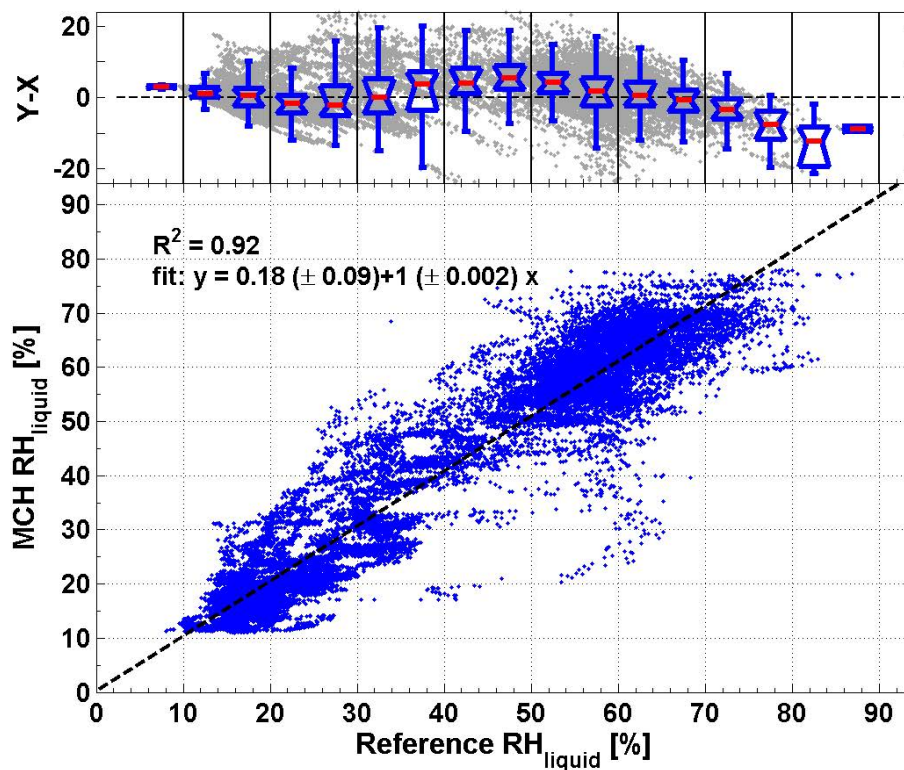


Figure 7. Bottom: Comparison cross plot between reference, i.e. FISH (clear sky) and OJSTER (in-cirrus), and MCH RH_{liquid} displayed as scatter plot with robust fitting curve (dashed line). Top: The related comparison cross plot between the reference and the difference of MCH (y) and reference (x) values is shown again as scatter plot. The additional box-and-whisker-plot represents the median, 25th/75th and outer values for the RH_{liquid} differences per 5 % RH_{liquid} bin.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

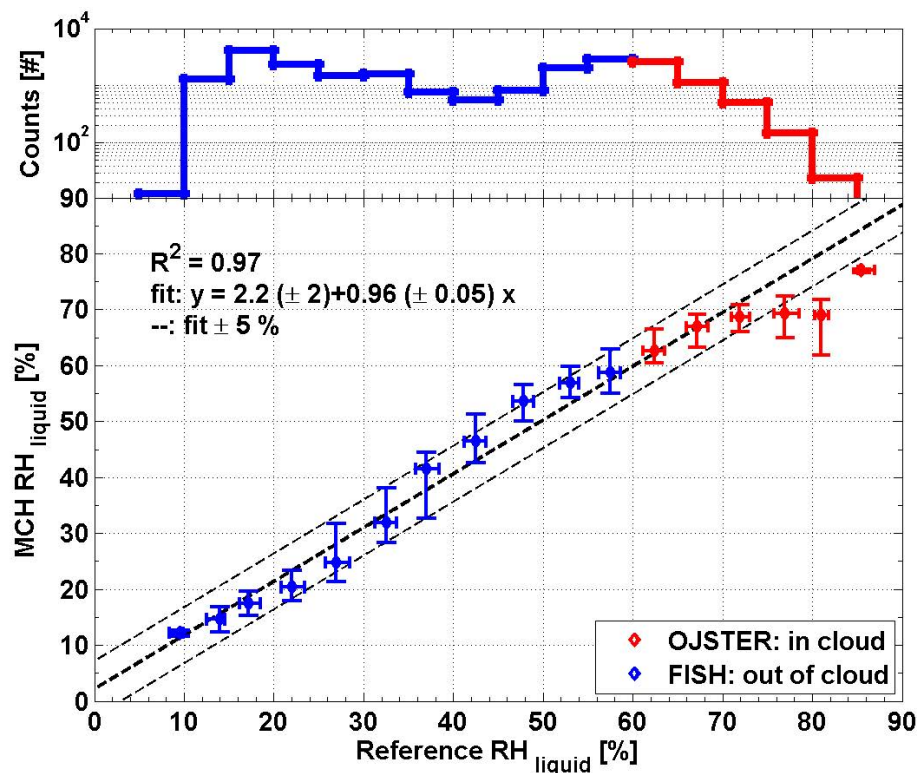


Figure 8. Correlation of RH_{liquid} data from MCH and FISH/OJSTER during CIRRUS-III; the straight line indicates the linear regression line while the dashed lines illustrate the sensor uncertainty range $\pm 5\% RH_{liquid}$. The top panel shows the number of data points per $5\% RH_{liquid}$ bin.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

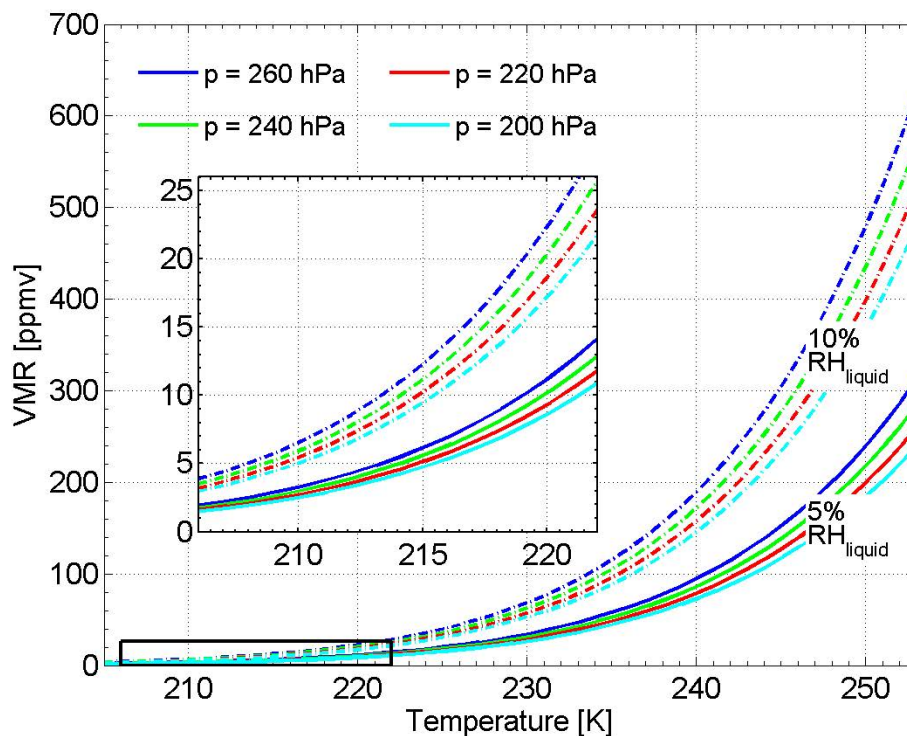


Figure 9. Water vapour volume mixing ratios (VMR) as a function of ambient temperature for 5% (solid lines) and 10% $\text{RH}_{\text{liquid}}$ (dashed lines), respectively. The different pressure levels represent typical passenger aircraft flight altitudes. The inner box shows a zoom of the lower temperature and VMR values.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

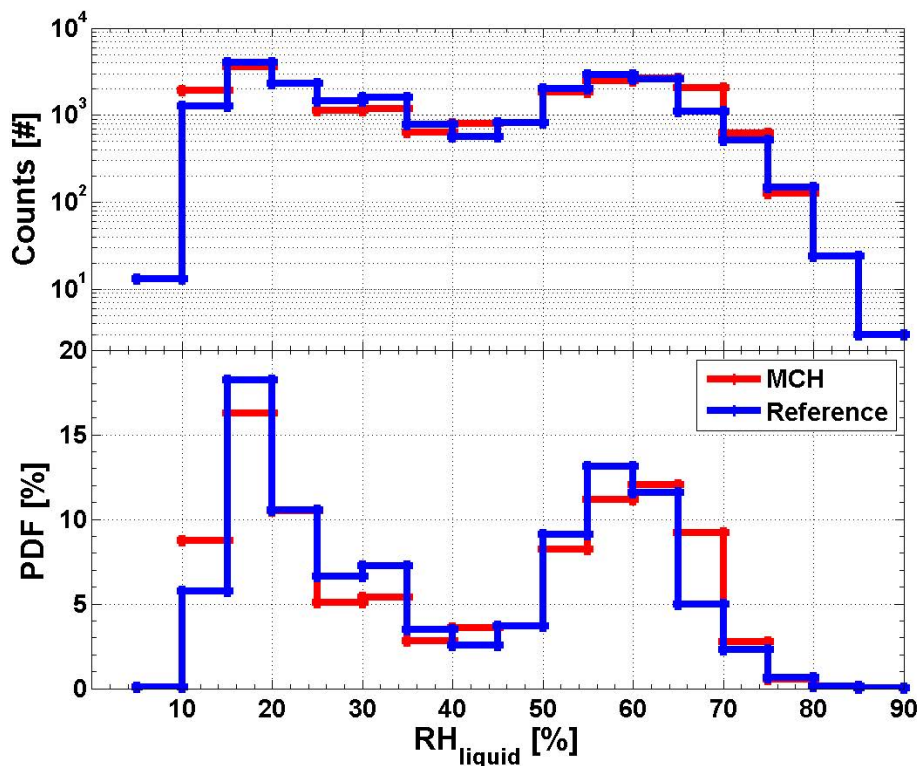


Figure 10. Number of data points (top) and frequency of occurrence (bottom) for observations of RH_{liquid} during CIRRUS III; blue and red lines refer to data from reference, i.e. FISH (clear sky) and OJSTER (in-cirrus), and MCH, respectively. The number of counts of both data sets agree in almost all 5 % RH_{liquid} bins. The exponential decline at higher values is in accordance to the result of Spichtinger et al. A bimodal distribution can be seen clearly in the probability density function (PDF) view of the data sets, where there is a clear sky section at lower values and a cirrus section at higher values, respectively. The differences in the PDF distribution can be mainly explained by the longer response time of the MCH into and out of the clouds.

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

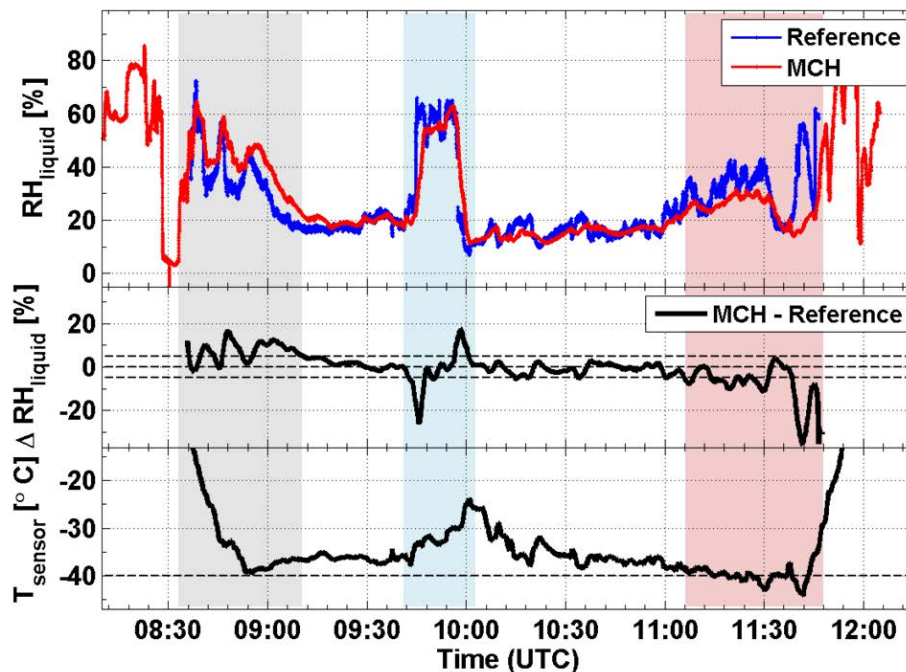


Figure 11. Upper panel shows the RH_{liquid} data from MCH (red) and reference (blue), i.e. FISH (clear sky) and OJSTER (in-cirrus), during CIRRUS-III flight on 28 November 2006. The 60 s moving average of the difference of both RH_{liquid} time series is given in the middle panel. Further, the sensor temperature T_{sensor} time series reaches the lower calibration limit of -40°C several times in the lower panel. The shaded areas represent different limitations for the sensor. Blue: strong humidity change (cirrus cloud), Red: sensor temperature below calibration limit, grey: combination of flying through a small cirrus with steep ascent and very cold sensor temperature, respectively

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

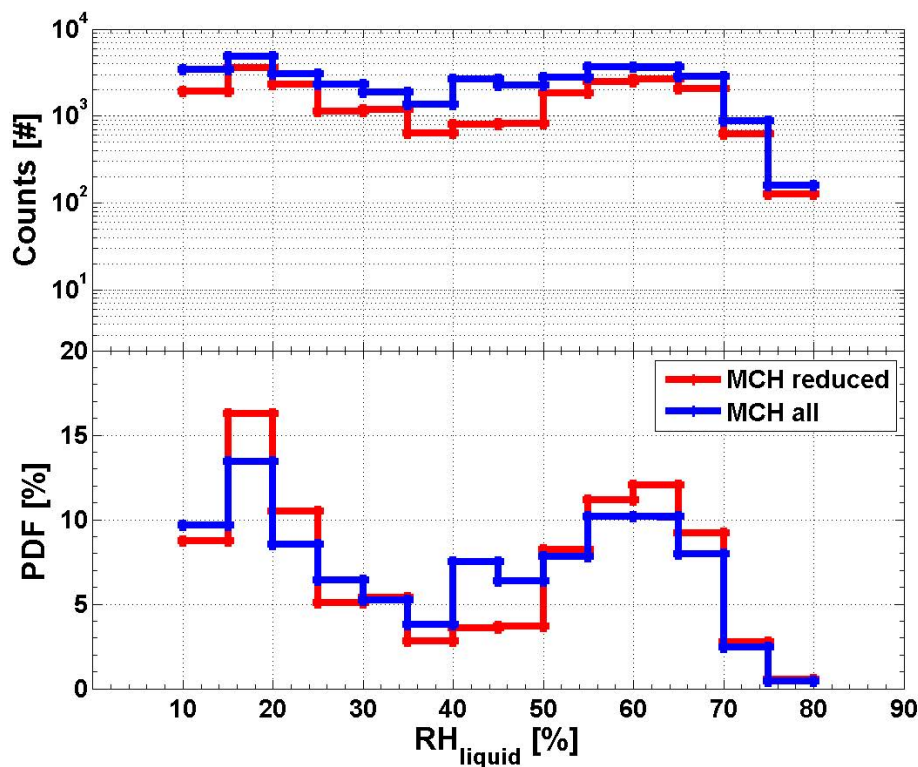


Figure 12. Counts (top) and frequency of occurrence (bottom) for observations of RH_{liquid} during CIRRUS III; blue and red lines refer to data from the complete and reduced MCH data, respectively.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Evaluation of MOZAIC Capacitive Hygrometer

P. Neis et al.

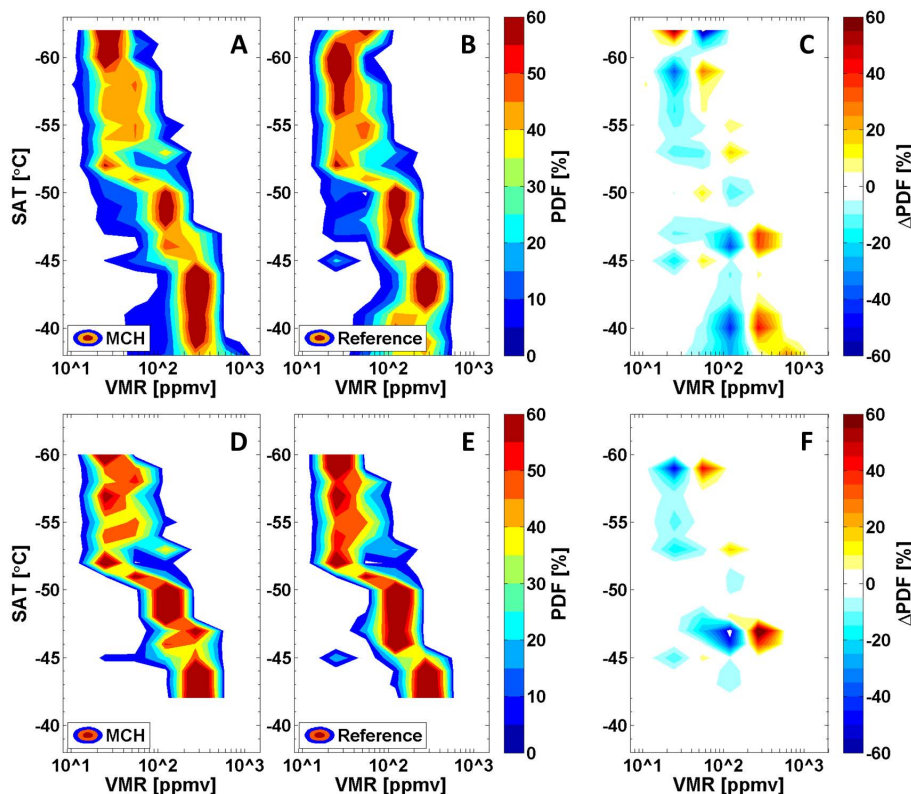


Figure 13. Probability density function (PDF) of the complete (a–c) and reduced (d–f) MCH (a, d) and reference (b, e), i.e. FISH (clear sky) and OJSTER (in-cirrus), water vapour volume mixing ratio (VMR) data related to the ambient temperature T_{ambient} , respectively. Water vapour volume mixing ratio is binned in the logarithmical space between 0 and 8.8 with a bin size of 0.8, the temperature in 1°C bins. Panels (c) and (f) show the difference of the complete and reduced data PDFs.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)
