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Atmospheric Measurement Techniques
Discussions

Interactive comment on "Evaluation of the MOZAIC Capacitive Hygrometer during the airborne field study CIRRUS-III" *by* P. Neis et al.

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Anonymous Referee #1

We gratefully acknowledge the reviewer's thorough reading of the manuscript and her/his constructive comments and suggestions. Please find detailed answers in the

following.

This paper describes a comparison of the MOZAIC Capacitive Hygrometer (MCH) with two other "reference" water vapor instruments, FISH and OJSTER, during four aircraft flights in November 2006. The results depict good agreement between the MCH and reference instruments within a limited set of environmental parameters, including a lower limit for MCH sensor temperature and a need for general uniformity in the water vapor field being measured at low temperatures. MCH measurements of water vapor do not appear to be affected by ice particles owing to the design of the sensor inlet.

The manuscript is generally well written, succinct and appropriate for AMT. In some instances there is room for improvement in grammar, clearer explanations, removal of Figure Caption information from the main body text, and a need to present more quantitative rather than qualitative information. I feel that the number of Figures can be reduced as some repeat information presented elsewhere, some provide information deemed non-critical to the conclusions and one can be simply presented as text instead of graphically.

Major Comments:

Referee #1: The comparison results are mainly presented in units of RH(liquid), but in my opinion RH(ice) is more relevant for the vast majority of atmospheric conditions sampled by the Learjet and by MOZAIC aircraft. This would eliminate the need to identify ice saturation in terms of RH(liquid). It is also of interest for the reader to be shown the high end of RH(ice) to reveal the frequency and magnitude of ice supersaturations measured, if any. I understand that the direct MCH measurement is in units of RH(liquid), but the conversion to RH(ice) requires only temperature, which you are already using along with pressure, to interconvert between RH and volume mixing ratio.

Reply: We agree, it is also of interest to evaluate the behavior of the MCH in terms of RH(ice). For that, we added Fig.8b which shows the similar properties for RH(liquid) and RH(ice). However, we are convinced of the need to describe the MCH performance in units of the direct measurement, which are stored in the MOZAIC data base.

Referee #1: For Figure 8 and all descriptions of it - at Reference RH(liquid) > 70% the MCH signal is flat (70%) while OJSTER RH continues up to 85%. It is claimed that both MCH and OJSTER measure only water vapor, so why does this strange behavior exist? There is a good reason for this: FISH total water data (apparently with some contributions from condensed water) are included at RH>60% even though the reference data are clearly labeled "OJSTER" (i.e., water vapor only). This needs to be explained very prominently and clearly in the manuscript text and in both the Figure 8 Caption and Legend. If possible it would be beneficial to remove these FISH data from the comparison. Please see my specific comments for Figure 8 below.

Reply: Figure 8 and the description of it were misleading. We don't compare MCH against FISH total water. Instead we compare MCH against FISH gas phase and we select the respective flight sequences based on the cloud index of Krämer et al. (2009). These FISH data are now plotted in blue. When measured in cirrus cloud, we used the open path TDL OJSTER (red dots). Now the transition layer of cloud-free and in-cloud data can be clearly seen. The behavior above ∼70% RH(liquid) could be mainly explained by the increased response time of the MCH. Small scale supersaturations are smoothed out, while OJSTER can detect these with response time of ∼ 1s.

Referee #1: Figure 11 shows approximately one more hour of the same data already shown in Figure 5. Why can't the time axis in Figure 5 be expanded to 08:30-11:50 (the relevant time window of Figure 11) and Figure 11 be removed?

Reply: We agree. We removed Figure 11 and extended Figure 5.

Referee #1: For all Figures showing "Reference" data or differences between the MCH and "reference" it would be more informative to show FISH and OJSTER data in different colors. For example, the dots in Figure 6 and Figure 7 could be color-coded to show which reference instrument is being compared to each MCH measurement. Also for Figure 5 it would be interesting to see the independent time series of FISH and

OJSTER (FISH total water values will clearly show when ice particles are present).

Reply: We don't see the need of splitting all reference data into groups of FISH and OJSTER, because we treat them as a combined reference set. However, we identified cases, when it is useful to separate both data sets. For that, the color code of Fig 4 was changed. OJSTER data (now in grey) is also only available near the cirrus cloud. Additionally, we decided to separate the temperature dependence for both reference instruments, so that the drift towards too dry measurements below -40°C can be seen for both instruments.

Referee #1: I don't see a compelling reason to include Figure 9. This information can be easily described in the body of the paper and does not need to be shown graphically. I don't find Figures 10 or 12 to be very convincing of good agreement between MCH and the reference instruments. Figure 13 is much more convincing and, in my opinion, eliminates the need for Figures 10 and 12. The fact that the MCH and reference instrument have similar PDFs with respect to 5% RH(liquid) bins doesn't attest to the point-to-point agreement between them like the correlation analysis does (Figures 7 and 8). The PDFs are just the distributions of thousands of RH measurements - if the MCH is low biased by during a flight and high biased during another we can't assume the PDF will clearly reveal this. Figure 13 does a much more complete job of describing measurement biases at specific ambient temperatures than do Figures 10 and 12.

Reply: Figure 9 describes graphically the transition from the temperature-dependent RH(liquid) to the absolute measurement of volume mixing ratio. There have been a lot of inquiries about the absolute detection limit in the past we want to answer with this figure. We agree Figure 12 isn't necessary for the evaluation and removed it from the text. Figure 10, however, shows the statistically significant agreement of the MCH measurements with the reference measurements. The MCH was chosen for long term trend analysis and with that for statistically analysis of the UT/LS relative humidity.

Specific Comments: (P=page, L=line)

P9804, L12: What is the "entire range of observations"? This statement provides no information to the reader. (refer to "quantitative vs qualitative" comment above).

Reply: We replaced the sentence with more quantitative information: “Probability distribution functions of RH deduced from MCH and reference instruments agreed well between 10 and 70% RH in the ambient temperature field of approx. -70 to -40°C.”

L26: Limb sounders like Aura MLS are providing water vapor measurements at spatial and temporal resolutions adequate for many type of studies. It would help here to be more specific about the types of investigations that require higher resolution measurements unavailable from satellite sensors.

Reply: The main difference is the fact, that the MOZAIC program measures in-situ and with a significant higher resolution in space and time than satellites usually do. Particularly at cruise altitude (Z=9-12 km) in the UTH near the tropopause MOZAIC-RH/T measurements resolve the atmospheric dynamics of water vapor much better than satellites do. Therefore the vertical resolution is much higher than the Aura MLS resolution of the order of approx. 1 km.

P9805, L1-2: Why is the "regular in-situ measurements of UTH still difficult" ?

Reply: It is still difficult when it comes to global coverage. The MOZAIC program aims to measure simultaneously and continuously all representative regions for a global coverage. The low water vapour concentrations in the UTH requires still advanced hygrometer instruments which usually only can be flown on research aircraft and need quasi permanent operator support. MCH (capacitive humidity sensor) is an exception because it measures relative humidity with similar signal values at both high and low temperatures. The global radiosonde network measuring RH and T but with rather limited to poor performance above altitudes above Z=8 km.

L22, L28: The term "wing-by-wing" (should be "wing-to-wing") is used several times in the manuscript. To pilots this term literally means flying two aircraft beside one another

such that the wingtips are nearly touching. If that is what you mean every time you use this term please ignore this comment. However, if you mean something different please change the terminology.

Reply: We changed the term to “formation flight” which describes the approach in a better way.

P9806, L2: What exactly is a "sophisticated" instrument? This term is used several time in the manuscript. Does it mean "more complicated" . . . "more mature" . . . "measurement validated"?

Reply: It means a high precision research-grade instrument. It is replaced accordingly in the manuscript.

L18: "linearized" sounds like some sort of black magic. What exactly does this mean? Raw capacitance signals are processed into RH values?

Reply: Data conversion from capacitance signals to RH values is performed off-line in a separate data quality assurance and analysis step. Here we simply describe that the raw sensor signals are fed into a microprocessor-controlled transmitter unit (HMP230, Vaisala) which passes the signals to the data acquisition system. The sentence is rephrased accordingly.

L19: It would be good to know at what rate the MCH reports RH values. Actually, it would be good to know this for all the instruments. If instruments report at different rates how is this handled in the comparison of their data?

Reply: The time resolution for all instruments is 1 Hz, while the respective response times differ. The FISH and OJSTER respond in 1 HZ, whereas the MCH response time is temperature dependent and increases with decreasing temperature from about 1 s at 0°C up to approx. 1 min at upper troposphere temperatures. “Time Resolution” in Table 2 was replaced with “Response Time”.

L26: What exactly are "internal boundary layer effects" ? Are you addressing memory effects of the housing walls (i.e., that may take some time to dry out after sampling a wet air mass?)

Reply: The internal boundary layer air is sucked off through the small holes in the inlet section of the housing, minimizing internal boundary layer effects. This protects the core of the sampled air flow from thermal or humidity influences as might originate from contact of the outer parts of the sampled flow with the walls of the housing.

P9808, L5-8: It would be informative to know how much the MCH calibration changes after 500 flight hours. How many real-time days elapse during 500 flight hours?

Reply: For details of routine calibration see Smit et al. (2014). Here in Table 2 the differences of slope and offset between pre- and post-flight are reported in statistical way. On the average their impact on the RH measurements is about $\pm$ 5%. Four to 6 weeks of flight operation corresponds to about 500 flight hours.

L18-20: this is a perfect place to add quantitative information about offset and sensitivity drift.

Reply: For details of routine calibration see Smit et al. (2014). Here in Table 2 the differences of slope and offset between pre- and post-flight are reported in statistical way. We have revised the paragraph accordingly with: “Evaluation of 9 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 with a shift of about -5 % RH, while the sensitivity (slope b(T)) is less critical and only changes by about -2 % (Smit et al. (2014)).

P9809, L19-21: Which reference instrument(s) experienced inlet heating problems?

Reply: The FISH instrument had heating problems.

L26: The "condensed phase of water" was not measured by a dedicated instrument. Instead, condensed phase water is inferred as the difference between total water and water vapor measurements by FISH and OJSTER, respectively. How does FISH evap-

orate liquid water and sublimated ice to measure total water? Is the contribution of the condensed phase to total water "enhanced" or proportional to the pure vapor signal?

Reply: We agree and replaced the paragraph with “An important part of the instrumentation was dedicated to the measurement of gas phase and total water. The instrumentation included a MCH and an open path tunable diode laser system OJSTER to measure gas phase water vapor VMR. Simultaneously, total water VMR (= gas phase plus ice water) was measured by the reference measurement instrument FISH.” The FISH instrument gathers ice particles with the front facing inlet, which are evaporated by forced heating. The contribution of the condensed phase to total water is enhanced. However this enhancement has been corrected afterwards.

P9810, L7: What is the threshold for the ratio of RH(ice) that indicates a cirrus cloud?

Reply: The ratio is 1.05. For details see Krämer et al. (2009).

L8: How is it guaranteed that OJSTER measures only water vapor and is not affected by ice particles entering its inlet?

Reply: There is no inlet involved, because OJSTER is an open path TDL.

L11-13: As written, it sounds like the MBW was also flown on the Learjet. I think it is used in the laboratory to calibrate FISH.

Reply: This was misleading and was the sentence was replaced with “During the laboratory calibration water vapor mixing ratio was determined using a commercial dew point hygrometer (MBW DP30).”

L21: How "significantly" can the offset change and how "almost stable" is the sensitivity? Please be more quantitative.

Reply: As mentioned above: For details of routine calibration see Smit et al. (2014). Here in Table 2 the differences of slope and offset between pre- and post-flight are reported in statistical way. We have revised the paragraph accordingly with: “the offset a(T) can change significantly by about 5 % RH while the slope b(T) is changing less than 2 % on the relative scale (see Eq.3 and Smit et al. (2014)).”

P9811, L3-5: How do you know the drift in offset is linear with time between pre- and post-flight calibration? Aren’t there really dry and cold periods of flights where the predominant MCH signal is offset, not gain? Can these be plotted against time to show that the offset drift is linear with time?

Reply: Long term experience showed the change, not drift, in the offset. We changed “drift” to “change”. In Smit et al. (2008) it is shown in detail that during dry periods after subtraction of the stratospheric water vapour contribution the remaining MCH-signal corresponds to the offset and not gain.

L22: "signal saturated" is more accessible to the reader than "optically thick"

Reply: We replaced it with “optically opaque”

L24-2: This is Figure Caption information (e.g., "green line", "black line", "shown in the bottom panel"). Instead, describe what is revealed by the Figure and what can be concluded from it - rather than what is shown in the Figure ("sensor temperature = black line"). This occurs several times in the manuscript so please try to change all instances because the reader doesn’t want to read the Figure Caption in the text and then read it again in the Figure Caption.

Reply: We agree and have revised these paragraphs accordingly.

P9812, L13: "the agreement with the research-grade reference instruments" - is the MCH not a research-grade instrument?

Reply: Because of the restrictions in the dynamic area of measuring relative humidity and the resolution, the MCH is not a research-grade instrument in the lower humidity region.

L23-25: you may want to further describe the "effects of warmer clouds" since this may

not be obvious to all readers. I assume you are referring to liquid water problems with inlets, housings and sensors (i.e., "memory effects"). Is this what you mean here?

Reply: Yes, it is. We added “to exclude the perturbation of measurements by erroneously sampled liquid water droplets”.

P9813,L21-22 and Figure 8: Why does MCH RH(liquid) top out at 70% while OJSTER continues up to 85%? In the text (L21-22) you state that the "reference measures total water while the MCH measures water vapor". But at RH(liquid)> 60% in this Figure you indicate that these data are only from OJSTER that measures only vapor (P9810, L8). Also see my comment for P9814, L6-9 below.

Reply: Like we already mentioned above, the behavior above ∼70% RH(liquid) could be mainly explained by the increased response time of the MCH. Small-scale supersaturations are smoothed out, while OJSTER can detect these with response time of ∼ 1s.

L22-24: Do the linear regression results include the data > 70% RH(liquid) that are clearly not linear between MCH and the Reference?

Reply: All data contribute to the linear regression weighted with the number of occurrence.

P9814, L3: What exactly is "proof of validity"? Again, I don’t think the PDFs in Figures 10 or 12 prove much at all.

Reply: These figures should illustrate that in terms of statistics the MCH and the reference instrument measure nearly the same quantities. We softened the wording and rephrased the sentenced to “The consistency of the data. . .”.

L6-9: Here I think I’ve found the source of confusion with Figure 8. This information cannot remain buried in the final paragraph of the Evaluation section! If FISH total water data contribute to RH>60% bins in Figure 8 this needs to stated more prominently (and earlier) in the text and in the Figure Caption and Legend. Currently the Figure Legend shows that the Reference RH>60% data are only from OJSTER. Can you omit FISH data when they are possibly influenced by ice particles? Is there another method for doing this other than the "cirrus cloud algorithm" mentioned?

Reply: You're right this information has to be stated earlier in the text. For that, we colored separately the associated data points in the scatterplots and in Figure 8 we introduce the "transition area" were both reference instruments are involved. We can omit FISH data when they are possibly influenced by ice particles with the cloud index of Krämer et al. (2009).

L21: "phases of interest" is awkward, "intervals" or "periods" of interest is better.

Reply: We changed "phases of interest" to "sequences of interest".

L25-27: The data in Figure 11 disagree with this claim of "no statistically significant effect". Between times 08:40 and 09:20 the MCH is biased high by 5-20 %RH. There may be some evidence of MCH lag at the RH "peaks", but mostly the MCH is biased high during the RH "valleys". To me this represents a "statistically significant effect".

Reply: Since this sentence of non-statistically significant effect is wrong and misleading, we deleted it.

P9815, L4: "reduced performance" is not specific - what part of the measurement quality is reduced at low sensor temperatures?

Reply: In our understanding "reduced performance" means an increased response time for the MCH. We rephrased this accordingly.

L6-10: This sentence is far too long and does not provide an adequate explanation of the MCH high bias from 08:40 to 09:20.

Reply: We agree with your remark. After reordering the sequences, we rephrased the sentence accordingly. "Sequence 1 takes place between 08:40 and 09:10 UTC where the MCH shows still a good response at higher sensor temperatures of about

-20°C and agrees within 5-10% with the reference. However, at decreasing sensor temperature, the response time of the MCH increases significantly. This results into a delay causing higher humidity values and higher differences in the comparison with the reference. Because of the Van der Waals forces it is easier and for that faster to adsorb new water molecules than to desorb them from the dielectric membrane of the sensor. For that, the response to positive humidity gradient is faster than to negative gradient, which can be seen in the behaviour of the RH(liquid) differences in time. "

L11: Please use "Despite" or "In spite of"

Reply: Done.

L15: The cut-off in Figure 13 appears to be T(ambient) >-42, not >-40

Reply: The cut-off is at around T(ambient) >-42 but this is because of the missing sequences of the ascents and descents. So the warmest temperature values are at approx. -42°C.

Table 1: "divided" not "devided". Why is 125 ppmv ozone the magic divider between the troposphere and stratosphere?

Reply: We corrected the first remark. The 125 ppmv ozone threshold is a commonly accepted value, e.g. see Thouret et al. (2006).

Table 2: I prefer "Measurement Technique" over "Remarks" and "Reference" instead of "Source".

Reply: Thanks, we changed this.

Table 3: add "These values are plotted in Figure 7a."

Reply: We removed this panel from Figure 7.

Table 4: the same argument for omission of Figures 10 and 12 applies to this table. Do these values really demonstrate agreement between the MCH and reference any

better than Figures 7, 8 and 13 (and the values for Figure 7a in Table 3)?

Reply: We agree and removed this table.

Figure 1: "neglect" (meaning ignore) is not used correctly here - how about "minimize" or "eliminate" instead? Also, the "H2O-Sensor" label at the bottom of the Figure is confusing because the sensor location is right next to the external housing, not inside the aircraft.

Reply: Thanks for your recommendations. We have revised Figure 1 accordingly and we believe that there aren't any misleading statements anymore.

Figure 4: The OJSTER data are not really visible here. Since mixing ratios > 1000 ppmv are least important in this study please change the VMR scale to a maximum of 1000 ppmv to (hopefully) better show the OJSTER data.

Reply: We tried, to get the OJSTER data more visible here by changing the color to grey and by zooming in a little bit. But as you see OJSTER data is only available around the cirrus sequence and the benefit of changing the VMR scale to a maximum of 1000 ppmv would lead to loss of clarity of the complete flight overview.

Figure 5: I suggest putting the panels showing absolute measurements (ppmv and RH) at the top and the deltaRH panel beneath the RH panel. Please color FISH and OJSTER differently (see Major Comment above). Mention that the deltaRH values are in absolute %RH values, not relative (%) values because the nomenclature deltaRH (%) can be easily misinterpreted.

Reply: We agree with your comment and changed the RH units to "% RH" in all Figures and Tables. Your suggestion for the order of the panels was also picked up and now the order is from top to bottom: VMR, RH, deltaRH, Temperature.

Figure 7: What are the "outer values" shown by whiskers? 5th and 95th percentiles? Something different? Please color the FISH and OJSTER data differently (same for Figure 4).

Reply: In all our revised Figures with boxes or whiskers, we show besides the median the 25th and 75th percentiles.

Figure 13: The cut-offs for "reduced data" in this graph appear to be -62 < T(ambient) < -42 , not -40 and -60 as stated in the text. Please mention in the caption that the differences are MCH-Reference. Why is the y-axis label "SAT" instead of T(ambient) as it is called throughout the paper? The dry bias of MCH extends down to about -52, not just "for the coldest T(ambient) of -60C" as stated in the text (P9816, L1-2).

Reply: As mentioned before, the cut-off is at around T(ambient) >-42 but this is because of the missing sequences of the ascents and descents. So the most warm temperature values are at approx. -42°C. The cut-offs at -60°C are in the reduced data panels (bottom line) like they are stated in the text at -60°C. Thanks for your note about the wrong y-axis label. We changed it to T(ambient). Additionally we added the information that the delta PDFs are the result of the difference of the responsible MCH and Reference PDF values.

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