Answers to Referee 1 and 2: Comparison of the fast Lyman-Alpha and LICOR hygrometers for measuring airborne turbulent fluctuations

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The authors would like to thank the anonymous referee for the thorough review with very detailed comments, which helped to improve the manuscript significantly. In the following, each comment of the referee (in italic) is answered separately. The answers are provided in normal style, and the changed text of the manuscript is given in quotation marks.

The papers addresses the question, whether the infrared gas analysers LI7200/LI7500 (and followers) – which are standard instrumentation today for the measurement of turbulent water vapor and carbon dioxide concentration fluctuations and hence for the determination of the turbulent fluxes of water vapor and carbon dioxide at fixed installations (bars, masts, towers) in the surface and lower boundary layer – are as well suited for aircraft operation and might be considered as a candidate for replacing the Ly-Alpha instruments that have been employed for airborne flux measurements over decades, but are not available on the market anymore. The authors compared the different hygrometers during two flights on two different airborne measurement platforms, the DO-128 research aircraft and the Helipod sonde. The flights have been well designed and the data analysis follows scientific standards and principles. Together with the technical-scientific relevance of the research topic this certainly justifies publication. However, I see considerable room for improving the manuscript. Some generalizations appear to be not well founded and the writing suffers from redundancy, sloppy or not very precise wording, and a rather German-language style sentence structure in several places. Detailed comments on that are given below.

The authors appreciate the positive comments about the content of the manuscript. We would like to thank the referee for the great effort, and agree that there is room for improving the language and style. This is done by taking into account the very detailed cocmments of the referees, and generally by critically proof-reading the manuscript again. In the following, we will answer each comment separately.

General Issues 1. Some statements appear too general, e.g., - P. 1, Line 20: “Measuring humidity in-situ with high accuracy is challenging”. What is high accuracy? Probably this conclusion holds for any variable?

We agree with the referee that this can be said about any variable. However, the error bar for water vapour measurements is much larger than for e.g. temperature. We changed the text to:

"For *in situ* measurements of humidity, the error bars are typically larger than for other atmospheric parameters like temperature and wind."

- P. 4, Line 11: "The Licor is the fastest and cheapest water vapor sensor commercially available" – this is too general, it is probably the cheapest fast-response sensor.

We changed the text to:// "As the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available"

- P. 4, Line 15f: Is it possible to "determine the required measurement frequency for humidity fluctuations to derive reliable latent heat fluxes"? Doesn't this depend on the environment, on the turbulent state of the atmosphere, on the height of measurements, on the aircraft flight speed?

We changed the text to:

"to determine the required measurement frequency for humidity fluctuations to derive reliable latent heat fluxes for the typical flight altitude of few 100 m and airspeed in the range of 35 to 70 $\mathrm{m\,s^{-1}}$"

- P. 11, line 2f: Here the authors state that a temporal resolution of 20 Hz is sufficient for humidity flux calculations, while on p. 10, line 27, it is said that "fluctuations in the frequency range higher than 2 Hz do not contribute significantly to the overall humidity fluxes for an air speed of 70 m s-1" – how can these two statements be brought together?

To make it clearer, we changed the concluding sentence to:

"Generally the temporal resolution of the LICOR sensors of 20 Hz is sufficient for humidity flux calculations, as the contribution of frequencies above approximately 2 Hz is negligible, so a 10 times oversampling for a sufficient amplitude retrieval is provided."

2. Some relevant information appears not at the place where it might be expected or is missing totally. E.g., information on aircraft flight speed appears when discussing the delay times between the sensors (instead of when describing the aircraft or the flight). Flight speed information for the Helipod flight is not given at all. The vertical wind component is needed for determining the turbulent fluxes, but no information is given on how these values were determined.

We included the information on the flight speed at the beginning of the section describing the flights. For the Do128: "The measurement flight with the research aircraft Do128 "D-IBUF" was conducted on 23 October 2015. The aircraft operates at a true airspeed of 70 $\mathrm{m\,s^{-1}}$. The flight was performed above different terrain of the North German Plain," For the Helipod: "During the measurement flight, the Helipod was attached to a Russian Mi8 helicopter by a 30 m rope. The flight was performed at a true airspeed of 40 $\mathrm{m\,s^{-1}}$ from the Research Station Samoylov Island in the Lena Delta, Siberia."

Determining the 3D wind speed from five-hole probe, GNSS and inertial data is quite complex, but a standard method, which is not the focus of this article. Therefore we included two additional references in the text:

"a five-hole probe and corresponding pressure transducers of Setra (static, dynamic and differential pressure), inertial navigation and global navigation satellite system (GNSS) for deriving the 3D wind vector (see description of method e.g. van den Kroonenberg et al., 2008; Bärfuss et al., 2018)"

3. As a boundary layer scientist, the reader might be interested to learn something about the absolute values of the latent heat fluxes that were determined for the flights. The more since in the discussion the authors state that "especially for small *fluxes, the relative errors might be significant". It is not completely clear, where this conclusion comes from. On the other side, significant relative errors for small fluxes might still mean small absolute errors, while even small relative errors for high flux values could mean significant absolute errors, which would have implications for budget studies. This aspect is not discussed in the paper, may be due to the limited representativeness of the data set.*

In the article, we prefer to focus on the instrumental comparison, which is the basis for retrieving latent heat fluxes. The application of the sensors for boundary layer studies, and in particular a detailed analysis of the Helipod flights in Siberia, require a complete description of the atmospheric conditions, and are beyond the scope of the article. Articles about the data set are currently under preparation.

Specific Issues

- The title of the paper appears somehow incomplete – the two types of hygrometers are differently named, one by the method, the other by the manufacturer, I suggest to modify it as follows: "Comparison of Lyman-Alpha and infrared hygrometers for measuring airborne turbulent fluctuations of water vapor"

We changed the title to "Comparison of Lyman-Alpha and LICOR infrared hygrometers for measuring airborne turbulent fluctuations of water vapor". The title suggested by the referee would include the discussion of other types of infrared hygrometers as well, which we do not provide.

- The first paragraph of the introduction consists of a series of statements which are not always in a good logical context to each other.

We re-arranged the text and tried to establish a logical order of the thoughts:

"Water vapour and clouds in the atmosphere have a large impact on the energy balance (**?**), the hydrologic cycle (e.g. **?**) and on local and global climate (**??**). Therefore, accurate knowledge about atmospheric water vapour is of high relevance for understanding climate and climate change. A general increase in atmospheric moisture measured at the surface and humidity within the troposphere has been reported (**?**). Satellite retrievals of the vertical water vapour distribution provide limited spatial resolution, e.g. 300 m in the vertical and 30 km in horizontal direction (**?**). For the quantification of atmospheric processes on local to regional scales, airborne measurements are required to fill the gap between large-scale, low resolution information from satellites and point measurements with higher vertical and temporal resolution, but limited in horizontal extent."

- P. 1, Line 14: What is "surface air moisture"? Isn't the surface layer part of the troposphere?

To clarify, we changed the sentence to:

"A general increase in atmospheric moisture measured at the surface and humidity within the troposphere has been reported"

- P. 1, Line 15: I wonder whether Klaus et al. (2012) is really a proper reference to the difficulty of measuring and modelling global water vapor distribution.

We removed the sentence with the misleading reference (However, the global distribution of moisture is difficult to measure and model accurately due to its large spatial and temporal variability (e.g. Klaus et al., 2012).). Probably it is not necessary to talk about global moisture distribution, when the scope of the article are measurements with high resolution.

- P. 1, Line 19: Point measurements are point measurements – what is the "horizontal extent" of a point?

We changed the text to:

"measurements at fixed locations with higher vertical and temporal resolution, but representative only for a small area"

- P. 1, Line 21ff: What is the relevance of the cloud chamber measurements under UTLS conditions for the present study?

We would like to emphasize that measuring atmospheric water vapour precisely is difficult, and even with the best systems under well controlled conditions in the laboratory, there are large discrepancies between different measurement systems. We changed the text to:

"The uncertainties of atmospheric water vapour measurements are high, as even for well controlled conditions in a cloud chamber, intercomparison measurements of different hygrometers probing the same air simultaneously revealed discrepancies between different measurement systems of around 10 %"

- P. 2, Line 3-4: Again, two sentences with no obvious clear context: The authors want to quantify moisture transport, but speak about latent heat flux. Why not to start: The most effective way for moisture transport from the surface to the atmosphere is turbulence. Turbulent fluxes are commonly determined with the eddy-covariance method. This method requires . . .

We changed the text to:

"The most effective way for moisture transport from the surface to the atmosphere is turbulence. Turbulent fluxes are commonly determined with the eddy-covariance method. This technique requires accurate measurements of the fluctuations of the vertical component of wind speed and humidity."

- P. 2, Line 5: What are “fast fluctuations”?

True - we removed "fast".

- P. 2, Line 7: Isn’t the high temporal resolution requested by the method, independently of whether it is used for research or not?

We changed the text to:

"Airborne sensors have to fullfil specific requirements. On the one hand, a high temporal resolution is needed in order to obtain a high spatial resolution for the moving platforms. On the other hand, long-term stability and high accuracy, if possible without the need of frequent re-calibration, are essential."

- P. 2, Line 9: Do the authors trust a sensor that has never been calibrated? I suggest to write “frequent re-calibration”.

We agree, and changed as suggested.

- P. 2, Line 9-10: Hence, there is no sensor available that meets both requirements? If this is the case you should state it.

We changed the text to:

"In practice, as no sensor is available that meets both requirements, this leads to the combination of complementary sensors for both high resolution and long-term accuracy."

- P. 2, Line 17: What is “sufficient humidity”?

As this is not quantified in the reference, we removed it from the sentence, and changed the text to:

"For temperatures exceeding 0 °C, and with the help of extensive postprocessing or modelling, the relatively slow polymer-based absorption hygrometers are sometimes used for retrieving humidity fluctuations"

- P. 2, Line 32: A comparative is missing here: 100 times weaker / stronger?

Thank you for the remark! When verifying this point, we saw that there was even a mistake in the order of magnitude of the effect. The sentence has been changed to:

"The absorption by oxygen molecules is about 1000 times weaker than by ozone molecules, and can be corrected by taking into account pressure and temperature, as the fractional density is constant."

- P. 3, Line 1: "same order" with respect to water vapor or to the previously discussed oxygen?

We changed the text to:

"same order of magnitude with respect to water vapour"

- P. 3, Line 4: What is "long-term" here? May be better write "(slow) drift". Normally with long-term one would think of weeks or months, however, for Ly-Alpha we often think of the magnitude of hours.

We changed as suggested.

- P. 3, Line 10: This sounds like the need for careful calibration is a disadvantage of the KH20 which however is essentially the same for the Ly-Alpha.

We changed the text to:

"A similar system is the Krypton hygrometer KH20 of Campbell Scientific, USA, which has a cross sensitivity to oxygen as well and therefore, like the Lyman-Alpha, has to be calibrated carefully"

- P. 3, Line 11: What about this new sensor? If it showed promising results five years ago, is it expected to become broadly introduced? Moreover, if there is this new instrument, "THE Lyman-Alpha" (as you name it throughout the manuscript) does not exist, it could be thus wise at one place to state that "the Ly-Alpha" in this paper is a synonym for "the Ly-Alpha absorption hygrometer by Buck Res.".

Very good idea! As suggested, we included in Sect. 1.2 the following sentence:

"The term "Lyman-Alpha" in this paper is used as a synonym for the Lyman-Alpha absorption hygrometer by Buck Research". Concerning the KH20: We did not find more literature about airborne applications, it seems to be mostly used for ground-based measurements. According to Foken and Falke (2010), the instrument is very sensitive to path length, and calibration is difficult even for ground-based applications. We added in the text:

"It is, however, not broadly present in airborne applications."

- P. 3, Line 19-20: This sentence does not become clear here.

We re-phrased the sentence:

"For retrieving methane and carbon dioxide with these instruments, the water vapour measurements are necessary to reference the number concentration of methane molecules to the dry mole fraction."

- P. 3, Line 22: Here the authors speak about the LICOR sensor without having introduced this. I suggest first to characterize the LICOR sensors before describing the TDLAS which is still experimental.

We changed the order of introducing the sensors. Now we first present the LICOR sensors and measurement principle, then the TDLAS.

- P. 3, Line 26: what is "fast humidity"? Please avoid this slang in a scientific paper. Humidity is a scalar property of air, it is not fast nor slow, it is just highly variable in space in time such that you need fast-response instruments to resolve this variability.

We changed the text to:

"The fast-response LICOR instruments LI-7500, LI-7500A and LI-7200 for measuring humidity "

- P. 3, Line 27: I wonder whether it is correct here (and in other places as well) to speak about a measurement chamber. LI7500 basically is an open-path sensor, even if the distance between the sensor head and base can be bridged with a "chamber". And the Lambert-Beer law underlying the physics of measurement considers the distance or length of the absorption path. Insofar, one might prefer "path" instead of "chamber".

We agree that "path" is the better suited expression and changed that in the manuscript.

- P. 4, Line 27f: It is not the wavelength that is absorbed but light at a wavelength of . . .

We changed this as suggested.

- P. 5, Line 11 (and also P. 6, Line 7): What makes the Humicap superior to the dew point mirror such that the latter one has not been used?

During the Do-128 flight, the dew point mirror was not operating properly. Therefore, we prefer to show only the results of the same sensor types for the Helipod as well, which are the Humicap, Lyman-Alpha and LICOR sensors.

- P. 15, Line 15: What does this mean "is calibrated regularly"? How often? How?

We changed the text to:

"The Vaisala Humicap is calibrated before and after each measurement campaign by applying saturated salt solutions and their different known equilibrium relativ humidity"

- P. 5, Line 29f: Why has the full length of the measurement path (instead of its center length) to be considered when determining the delay time?

Thank you for the hint, that is correct. We use indeed the center length for the calculation resulting in a time delay of 0.12 s, not the full length of the measurement path. In the text, this is not clear. Therefore we changed the text to:

"the time for exchanging the air of the measurement cell with an inner diameter of 25 mm and a half length of 125 mm amounts to 0.12 s."

- P. 6, Line 18: "agricultural grassland" – do you really mean "grassland", or "farmland"?

We changed the text to "agricultural farmland".

- P. 6, Line 20ff: What was the motivation to define these six small sub-legs, knowing that the "sampling-length" requirements according to Lenschow et al. are not fulfilled here?

We chose these small sub-legs with different but homogeneous surface conditions and different but constant flight altitudes to compare if there are systematic differences in the important parameters like the vibration level. We added in the text:

"These small sub-legs were chosen with different but homogeneous surface conditions and different but constant flight altitudes to compare if there are systematic differences in the parameters like the vibration level."

- P. 7, Line 1: The Ly-Alpha data were shifted, not the instrument.

We changed the text to:

" First the Lyman-Alpha data were shifted in time"

- P. 7, Line 2: Mathematically speaking the co-variance (or the correlation) is maximized.

We changed the text to:

"The synchronisation was then done by maximizing the covariance of the mixing ratio fluctuations of the Lyman-Alpha and each of the LICOR sensors"

- P. 7, Line 8, 11: On p. 5 the internal delay is given with 123 ms.

Thank you for pointing out this mistake. We verified with the manuals that the internal delay time of 130 ms is correct, as on p. 7, which is used for the calculations. We corrected the value of the internal delay given on p. 5.

- P. 7, Line 21: The "best value" can only be one value, a range "between 0.5 and 0.9" is not a very specific information.

We changed the text to:

"The best correlation between Li3 and Lyman-Alpha amounted to 0.6, thus was considerably lower (Fig. 10)"

- P. 8, line 4: Was this the mean wind at the surface or at flight level?

To clarify, we changed the text to:

"The flight on 14 August 2014 was done in conditions nearly free of clouds at the beginning with a near-surface air temperature around 17 °C and southerly wind with a speed of $5\,\mathrm{m\,s^{-1}}$ near ground. The mean wind speed at the altitude of the Helipod transects was $8\,\mathrm{m\,s^{-1}}$, and the mean wind direction at that altitude was 180 °."

- P. 8, line 14: Where is this additional time lag attributed to?

We added in the text:

"The additional time lag may be attributed to the semi-open housing geometry."

- P. 9, line 5: Why choosing a different flight section here when compared to Figure 7?

We changed that. Now Fig. 7 and Fig. 8 both show flight section D3.

- P. 9, Line 19: Why do the authors speak of "decaying turbulence" here, the -5/3 law holds for the inertial subrange of developed turbulence.

To avoid confusion, we changed the text to:

" The sloped lines represent the -5/3 drop-off expected in the inertial subrange."

- P. 10, line 12: … covariance of the vertical wind speed and the humidity values from the different sensors …

We changed as suggested.

- P. 10, line 33: … a phase shift around 0 °C … ???

We changed the text to:// "and the phase shift around 0 °"

- P. 11, line 12-19: This paragraph bridles the horse from the tail. The underestimated fluxes are a consequence of the noisy, vibration-affected humidity measurement of LI1 and LI3. I suggest to organize the paragraph along this line which was followed through the paper.

We changed the text to:

"For the Do128 application, three different LICOR sensors were subject to different vibration levels. For the Li1 and Li3 sensors, installed without particular isolation agains vibrations, the correlation with the Lyman-Alpha signal was significantly lower than for the Li2 sensor, which was installed isolated against vibrations. The different covariance spectra of the vibration-affected humidity measurements of the Li1 and Li3 sensors resulted in larger deviations of the latent heat fluxes compared to the latent heat fluxes based on the Lyman-Alpha sensor. The vibration-isolated Li2 sensor showing high correlation with the Lyman-Alpha sensor resulted in comparable latent heat fluxes. However, the spectral behaviour of the vibrations had no direct, linear impact on the humidity spectra of the Li1 and Li3 sensors, but the relationship is more complex. This is currently subject to more detailed investigations."

- At some places, the structure of sentences is very German style, e.g., P. 1 - line 20, P. 9 – line 32f, p. 10 – line 9f, p. 11 – lines 20-21.

We changed the sentences to:

"For *in situ* measurements of humidity, the error bars are typically larger than for other atmospheric parameters like temperature and wind."

"Based on the grey shaded data set of Fig. 3, Fig. 10 shows the coherence and the phase of the different LICOR sensors with the Lyman-Alpha. Overall, the Li2 provides the best coherence with the Lyman-Alpha. The coherence is virtually equal to one over a large frequency range of three decades. It only drops off for frequencies beyond 1 Hz due to the spatial separation of the two sensors. No phase difference is observed over the same frequency range."

"The response behaviour of the Vaisala Humicap is more complex. At low frequencies (<0.01 Hz) it agrees reasonably well with the Lyman-Alpha. Then the coherence decreases with increasing frequency. The phase shift disappears around 0.4 Hz, but the level of coherence remains lower."

"For the Helipod application with lower vibrations, the humidity fluxes derived from the Lyman-Alpha and LICOR sensors agreed very well after careful sensor calibration to absolute values, and correction of the time lag."

- In a few places there are unnecessary redundancies: P. 2 – Line 27 / Line 30, P. 4 – Line 24 / 25, caption of Figures 8, 9 (repeating the whole Figure legend).

We removed the redundancies for the first two parts. The sentences were changed to://

"Sensors based on atomic absorption provide the advantage of a very fast response time allowing for measurement frequencies exceeding 100 Hz, a sharp absorption line compared to the absorption bands of molecules, and a high degree of absorption. This requires only measurement cells of few mm (Buck, 1973) compared to several cm for molecular absorption."

"The working principle of the LICOR sensor series for water vapour and carbon dioxide (CO_2) is the absorption of near infrared radiation by these molecules."

However, we are not sure which figure captions the referee refers to, as Fig. 8 and 9 represent totally different parameters. When applicable, figure captions already refer to the colour schemes of previous figures. For Fig. 10 and 12, as well as Fig. 3 and 6, we prefer to repeat the figure caption, as there are the data of different sensors, displayed in different colours.

Figures

- Figure 3

- Would it be possible to indicate D1 .. D6 in the graph

As we perform the spectral analysis with the part of the data shaded in grey, we prefer not to include the flight legs D1 to D5. They were mainly used for comparison studies.

- Don't numerate the subplots without a reference, do not write "first subplot" and "main plot" etc., but "upper", "central", "lower", or label the subplots with a) … d)

We labelled the subplots as suggested.

- Unit of potential temperature should be K.

We changed to the unit K.

- The lower panel does not show the invalid data, instead it marks the "periods of invalid data"

We changed that.

- Could the part of the flight that was used for the spectral analysis (grey shading in Figure 3, marked by a different colour in Fig. 1?

The referee probably refers to the flight path in Fig. 2. We implemented this in the map.

- Figure 4:

This Figure is not really needed.

We removed Fig. 4 and removed the reference in the text.

- Figure 6:

- See also my remarks to Figure 3.

We adapted the same points as mentioned above for Fig. 6 as well.

- When looking at the vertical wind speed plot one gets the impression that the plot basically shows the movement of the Helipod for the ascent / descent flight periods. Shouldn't this component be removed in order to see the turbulence intensity?

The ascent and descent parts of the flight were done in spirals, with a reduced true air speed of $30\,\mathrm{m\,s^{-1}}$ instead of the $40\,\mathrm{m\,s^{-1}}$ required to escape the downwash effects of the helicopter, and a banking angle of $15\,^{\circ}$. Therefore we use only the straight and level flight legs for the instrumental comparison.

- Figure 7: In fact, this plot shows the time series of accelerations in z direction which illustrate the vibrations the LICOR sensors were exposed to.

True, we changed to "accelerations". We further added in the section about the Do-128: "The axis of the optical path of all sensors were oriented along the aircraft longitudinal axis."

- Figure 10: Right graph should better be named as "Co-spectra of humidity from the different sensors and vertical wind speed … "

We changed the expression for Fig. 10 and 12 as suggested.

- Figure 11: I would be a bit hesitant to present a flux derived from the Humicap humidity signal in this plot without further discussion; it might be interpreted in a way that the Humicap is still much better than the vibration-sensitive LICOR instrument.

Indeed the figure shows that in this case, the Humicap is better suited for determining latent heat fluxes than the vibration affected LICOR sensors. We added in the discussion:

"The latent heat flux determined with the Humicap amounts to 95% of the reference value determined with the Lyman-Alpha. This means that for moderate conditions (10-20°C, humidity values typical for midlatitudes), the Humicap can be used for determining airborne latent heat fluxes with an acceptable error bar. However, the response function of the Humicap is asymmetric, with a different response time for decreasing and increasing humidity, and the response time becomes significantly slower for cold conditions like in the Arctic, where the sensor is not suitable for deriving latent heat fluxes."

Some minor language issues / misprints

- P. 2, line 22: and make ... making

- P. 2, line 25: with ... allowing for

- P. 3, line 25: . . . available yet.

- P. 6, line 27: above ... over

- P. 6, line 29: humidity fluxes ... humidity fluctuations

- P. 8, line 1: urface ... surface

- P. 9, line 24: cn ... can

- P.9, line 26: sonsor ... sensor We thank the referee for careful reading and corrected the mentioned points.

The authors would like to thank the anonymous referee for the suggestions and corrections. In the following, each comment of the referee (in italic) is answered separately. The answers are provided in normal style, and the changed text of the manuscript is given in quotation marks.

GENERAL COMMENTS: This is a review of manuscript amt-2017-353, "Comparison of the fast Lyman-Alpha and LICOR hygrometers for measuring airborne turbulent fluctuations". The LICOR sensors in different forms are used at automated field stations for research networks covering large temporal and spatial scales, and are well characterized. The purpose of this manuscript is to evaluate LICOR humidity sensors in a new environment, on aircraft, compared with standard Lyman-alpha hygrometers. The results show that the LICOR sensors are well suited for airborne measurements of humidity fluctuations, provided that a vibrationless environment is given, and this turns out to be more important than close sensor spacing. This is a detailed technical assessment of LICOR sensors that should be posted online for discussion in AMTD after some major revisions are made. LICOR sensors are widely used on aircraft, so validation of their performance is needed. The manuscript is an important contribution because it analyzes the environments in which the LICOR sensors perform well compared to the "gold standard" of Lyman-alpha hygrometers. appreciate the hard work of the authors to collect the field data and carefully analyze the results.

We would like to thank the referee for acknowledging the importance of the work presented in the manuscript.

What remains for the authors to do is to rewrite the manuscript with better explanation of their reasoning and conclusions.

We included more explanations in the manuscript, which take into account the comments of the referees.

The manuscript could also benefit from better English editing.

The English style has been improved by taking into account the very detailed comments of Referee 1. Several sentences have been re-written, and the grammatical and spelling mistakes have been corrected.

SPECIFIC COMMENTS: 1 I have a concern that the authors and other research groups are using LICOR sensors in an environment that the manufacturer does not recommend.

We understand that the manufacturer does not sell the system for airborne applications, as they are aware that vibrations may hamper the data. For that reason, we consider it even more important to figure out the limitations of the sensor in terms of vibrations.

Manuscript page 4, lines 9-12: The authors stated that "the manufacturer warns in the manual that the sensor should not be applied with vibrations around 150 Hz and around the harmonics". Is it possible for the authors to contact the LICOR manufacturer to get approval - or feedback from the Technical Support department - for flying a LICOR on aircraft?

Yes, we were in contact with the manufacturer, and presented the results. Some stafff members showed large interest in the investigations, however, we did not get an official statement from the company.

2 The reported experiment involved one vibration-isolated closed-path hygrometer and two non-isolated open-path hygrometers, so how do you know whether the drift and noise are due to vibration or the open-path? Are there other possible reasons for the drift (such as drift in the electronics response or internal processing?)? We operated the identical open path sensor on a platform affected by vibrations (Do128, not isolated), and on a platform with much lower level of vibrations (Helipod, carried by helicopter, without own propulsion). For the latter application, the open-path sensor performed well without any drift. This comparison allows the conclusion that the vibrations are responsible for degrading the measurements. To clarify, we added the following sentence in the conclusion section:

"Altogether, both open-path and closed-path LICOR sensors are suitable high-resolution hygrometers for airborne applications, if the vibrations are low."

3 Section 1.3, page 3, lines 14-25, describe laser hygrometers but has some gaps as listed below: 3.1) Page 3, lines 24-25 claim that "it is not possible to obtain real-time humidity data." Although the Buchholz et al. hygrometer (Buchholz et al. 2014) does not provide real-time humidity data, other laser hygrometers do this routinely (see papers such as S. B. Smith et al., JGR, 2017, R. L. Herman et al., ACP, 2017, or M. Zondlo et al.).

We added in the text:

"For large research aircraft, some specifically designed hygrometers are implemented: On the National Science Foundation Gulfstream-V aircraft, a cavity diode laser hygrometer with two absorption lines in the near-infrared is deployed with a temporal resolution of 25 Hz (Zondlo et al., 2010). On the NASA ER-2 aircraft, a specifically designed near-infrared tunable diode laser spectrometer is deployed for measuring atmospheric water vapour concentration (May, 1998), with a sampling rate of 1 Hz and 10% accuracy(Herman et al., 2017). Compared to the LICOR sensor, this tunable diode laser hygrometer can be operated much faster (up to several kHz) and with a known accuracy, providing the most precise humidity values available to date (Buchholz et al., 2013, 2014, 2016). However, this hygrometer requires extensive post processing, and at least so far it is not possible to obtain real-time humidity data. The spectroscopic sensors are experimental systems and not commercially available yet."

3.2 page 3, line 25 claims that “The spectroscopic sensors are experimental systems and not commercially available” but the Picarro and Los Gatos systems mentioned earlier are commercially available laser hygrometers that have sufficient accuracy for the science. They can also provide realtime humidity data. Yes, we agree with the referee. However, the price for a Picarro and Los Gatos sensor is much higher, and so is the weight, which makes them not so easy to use in aircraft. We changed the text to:

"As the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available, and small enough to be easily integrated into aircraft, its airborne applications will very likely increase."

3.3 page 4, lines 10-11 claims that “. . . the LICOR sensor is currently the fastest and cheapest water vapor sensor commercially available” but laser hygrometers are faster than the LICOR. We changed the text to:

"the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available"

4 I find the discussion of the time resolution of the LICOR to be disorganized and confusing (Sections 2.1 and 2.2 and 3.4). I recommend that the authors should reorganize the discussion of the time response, time delay and time synchronization to one section because these are related.

We are not very happy with this suggestion. Section 2.1 generally introduces the LICOR sensors with their properties. However, the time synchronisation stronly depends on the setup in the corresponding measurement platform with the tube lengths, and distances between hygrometers and 5-hole probe. Therefore, we would prefer to discuss the synchronisation separately for each airborne carrier platform.

4.1 What is the time resolution of the LICOR instrument? Page 5, line 2, indicates that the data is “internally processing and finally provided at a maximum frequency of 20 Hz.” Are the detector and electronics signal chain sufficiently fast to resolve changes in water vapor at 20 Hz?

Yes, the provided maximum frequency is 20 Hz. The internal data sampling and acquisition is fast enough. To avoid confusion, we changed the sentence to:

"The data sampled internally at 150 Hz frequency is processed and provided at a maximum frequency of 20 Hz."

4.2 Page 5, line 9: what is the response time of the Rosemount EL102 sensor? It is only characterized here as a “fast response time.” How fast? We changed the text to:// "Rosemount EL102 sensor with a fast response time (100 Hz)"

4.3 Page 5, lines 25-30: How can you carry out successful fast measurements with the closed-path LICOR if there is a 250-millisecond calculated delay? Have you tested the delay? What is the residence time in the sample cell?

The delay is just a temporal offset, which can be corrected. The residence time in the sample cell depends on the air flow speed, and is taken into account in Sect. 2.2.

4.4 Page 10, line 23 and Page 11, line 25: the authors state the “Generally a temporal resolution of 20 Hz is sufficient for humidity flux calculations.” It is not clearly explained how the authors came to this conclusion. Is there a reference that can be cited as evidence for this?

We included in Section 4.2 the following text:

"It can be concluded from Fig.10 and Fig.12 that the fluxes for frequencies exceeding 1 Hz are negligible for these specific flight conditions. Therefore, the sampling frequency of 20 Hz is sufficient for airborne turbulent humidity fluxes."

Furthermore, it is unclear from this manuscript whether the LICOR has an actual temporal resolution of 20 Hz (when the sampling delays and internal processing are included).

The delays are constant temporal offsets, which do not influence the capability of the sensor to provide data at 20 Hz resolution.

5) Flight figures 3 and 6 are hard to read: please consider larger font text

We enlarged the text in the figures.

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Comparison of ~~the fast~~ Lyman-Alpha and LICOR infrared hygrometers for measuring airborne turbulent fluctuations of water vapor

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Answers to referees

The authors would like to thank the anonymous referee for the thorough review with very detailed comments, which helped to improve the manuscript significantly. In the following, each comment of the referee (in italic) is answered separately. The answers are provided in normal style, and the changed text of the manuscript is given in quotation marks.

The papers addresses the question, whether the infrared gas analysers LI7200/LI7500 (and followers) – which are standard instrumentation today for the measurement of turbulent water vapor and carbon dioxide concentration fluctuations and hence for the determination of the turbulent fluxes of water vapor and carbon dioxide at fixed installations (bars, masts, towers) in the surface and lower boundary layer – are as well suited for aircraft operation and might be considered as a candidate for replacing the Ly-Alpha instruments that have been employed for airborne flux measurements over decades, but are not available on the market anymore. The authors compared the different hygrometers during two flights on two different airborne measurement platforms, the DO-128 research aircraft and the Helipod sonde. The flights have been well designed and the data analysis follows scientific standards and principles. Together with the technical-scientific relevance of the research topic this certainly justifies publication. However, I see considerable room for improving the manuscript. Some generalizations appear to be not well founded and the writing suffers from redundancy, sloppy or not very precise wording, and a rather German-language style sentence structure in several places. Detailed comments on that are given below.

The authors appreciate the positive comments about the content of the manuscript. We would like to thank the referee for the great effort, and agree that there is room for improving the language and style. This is done by taking into account the very detailed cocmments of the referees, and generally by critically proof-reading the manuscript again. In the following, we will answer each comment separately.

General Issues 1. Some statements appear too general, e.g., - P. 1, Line 20: "Measuring humidity in-situ with high accuracy is challenging". What is high accuracy? Probably this conclusion holds for any variable?

We agree with the referee that this can be said about any variable. However, the error bar for water vapour measurements is much larger than for e.g. temperature. We changed the text to:

"For *in situ* measurements of humidity, the error bars are typically larger than for other atmospheric parameters like temperature and wind."

- P. 4, Line 11: "The Licor is the fastest and cheapest water vapor sensor commercially available" – this is too general, it is probably the cheapest fast-response sensor.

We changed the text to:// "As the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available"

- P. 4, Line 15f: Is it possible to "determine the required measurement frequency for humidity fluctuations to derive reliable latent heat fluxes"? Doesn't this depend on the environment, on the turbulent state of the atmosphere, on the height of measurements, on the aircraft flight speed?

We changed the text to:

"to determine the required measurement frequency for humidity fluctuations to derive reliable latent heat fluxes for the typical flight altitude of few 100 m and airspeed in the range of 35 to 70 $\mathrm{m\,s^{-1}}$"

- P. 11, line 2f: Here the authors state that a temporal resolution of 20 Hz is sufficient for humidity flux calculations, while on p. 10, line 27, it is said that "fluctuations in the frequency range higher than 2 Hz do not contribute significantly to the overall humidity fluxes for an air speed of 70 m s-1" – how can these two statements be brought together?

To make it clearer, we changed the concluding sentence to:

"Generally the temporal resolution of the LICOR sensors of 20 Hz is sufficient for humidity flux calculations, as the contribution of frequencies above approximately 2 Hz is negligible, so a 10 times oversampling for a sufficient amplitude retrieval is provided."

2. Some relevant information appears not at the place where it might be expected or is missing totally. E.g., information on aircraft flight speed appears when discussing the delay times between the sensors (instead of when describing the aircraft or the flight). Flight speed information for the Helipod flight is not given at all. The vertical wind component is needed for determining the turbulent fluxes, but no information is given on how these values were determined.

We included the information on the flight speed at the beginning of the section describing the flights. For the Do128: "The measurement flight with the research aircraft Do128 "D-IBUF" was conducted on 23 October 2015. The aircraft operates at a true airspeed of 70 $\mathrm{m\,s^{-1}}$. The flight was performed above different terrain of the North German Plain," For the Helipod: "During the measurement flight, the Helipod was attached to a Russian Mi8 helicopter by a 30 m rope. The flight was performed at a true airspeed of 40 $\mathrm{m\,s^{-1}}$ from the Research Station Samoylov Island in the Lena Delta, Siberia."

Determining the 3D wind speed from five-hole probe, GNSS and inertial data is quite complex, but a standard method, which is not the focus of this article. Therefore we included two additional references in the text:

"a five-hole probe and corresponding pressure transducers of Setra (static, dynamic and differential pressure), inertial navigation and global navigation satellite system (GNSS) for deriving the 3D wind vector (see description of method e.g. van den Kroonenberg et al., 2008; Bärfuss et al., 2018)"

3. As a boundary layer scientist, the reader might be interested to learn something about the absolute values of the latent heat fluxes that were determined for the flights. The more since in the discussion the authors state that "especially for small fluxes, the relative errors might be significant". It is not completely clear, where this conclusion comes from. On the other side, significant relative errors for small fluxes might still mean small absolute errors, while even small relative errors for high flux values could mean significant absolute errors, which would have implications for budget studies. This aspect is not discussed in the paper, may be due to the limited representativeness of the data set.

In the article, we prefer to focus on the instrumental comparison, which is the basis for retrieving latent heat fluxes. The application of the sensors for boundary layer studies, and in particular a detailed analysis of the Helipod flights in Siberia, require a complete description of the atmospheric conditions, and are beyond the scope of the article. Articles about the data set are currently under preparation.

Specific Issues

- The title of the paper appears somehow incomplete – the two types of hygrometers are differently named, one by the method, the other by the manufacturer, I suggest to modify it as follows: "Comparison of Lyman-Alpha and infrared hygrometers for measuring airborne turbulent fluctuations of water vapor"

We changed the title to "Comparison of Lyman-Alpha and LICOR infrared hygrometers for measuring airborne turbulent fluctuations of water vapor". The title suggested by the referee would include the discussion of other types of infrared hygrometers as well, which we do not provide.

- The first paragraph of the introduction consists of a series of statements which are not always in a good logical context to each other.

We re-arranged the text and tried to establish a logical order of the thoughts:

"Water vapour and clouds in the atmosphere have a large impact on the energy balance (Ramanathan et al., 1989), the hydrologic cycle (e.g. Chahine, 1992) and on local and global climate (Trenberth et al., 2007; Zhou et al., 2011). Therefore, accurate knowledge about atmospheric water vapour is of high relevance for understanding climate and climate change. A general increase in atmospheric moisture measured at the surface and humidity within the troposphere has been reported (IPCC, 2013). Satellite retrievals of the vertical water vapour distribution provide limited spatial resolution, e.g. 300 m in the vertical and 30 km in horizontal direction (Bender et al., 2011). For the quantification of atmospheric processes on local to regional scales, airborne measurements are required to fill the gap between large-scale, low resolution information from satellites and point measurements with higher vertical and temporal resolution, but limited in horizontal extent."

- P. 1, Line 14: What is "surface air moisture"? Isn't the surface layer part of the troposphere?

To clarify, we changed the sentence to:

"A general increase in atmospheric moisture measured at the surface and humidity within the troposphere has been reported"

- P. 1, Line 15: I wonder whether Klaus et al. (2012) is really a proper reference to the difficulty of measuring and modelling global water vapor distribution.

We removed the sentence with the misleading reference (However, the global distribution of moisture is difficult to measure and model accurately due to its large spatial and temporal variability (e.g. Klaus et al., 2012).). Probably it is not necessary to talk about global moisture distribution, when the scope of the article are measurements with high resolution.

- P. 1, Line 19: Point measurements are point measurements – what is the "horizontal extent" of a point?

We changed the text to:

"measurements at fixed locations with higher vertical and temporal resolution, but representative only for a small area"

- P. 1, Line 21ff: What is the relevance of the cloud chamber measurements under UTLS conditions for the present study?

We would like to emphasize that measuring atmospheric water vapour precisely is difficult, and even with the best systems under well controlled conditions in the laboratory, there are large discrepancies between different measurement systems. We changed the text to:

"The uncertainties of atmospheric water vapour measurements are high, as even for well controlled conditions in a cloud chamber, intercomparison measurements of different hygrometers probing the same air simultaneously revealed discrepancies between different measurement systems of around 10 %"

- P. 2, Line 3-4: Again, two sentences with no obvious clear context: The authors want to quantify moisture transport, but speak about latent heat flux. Why not to start: The most effective way for moisture transport from the surface to the atmosphere is turbulence. Turbulent fluxes are commonly determined with the eddy-covariance method. This method requires …

We changed the text to:

"The most effective way for moisture transport from the surface to the atmosphere is turbulence. Turbulent fluxes are commonly determined with the eddy-covariance method. This technique requires accurate measurements of the fluctuations of the vertical component of wind speed and humidity."

- P. 2, Line 5: What are "fast fluctuations"?

True - we removed "fast".

- P. 2, Line 7: Isn't the high temporal resolution requested by the method, independently of whether it is used for research or not?

We changed the text to:

"Airborne sensors have to fullfil specific requirements. On the one hand, a high temporal resolution is needed in order to obtain a high spatial resolution for the moving platforms. On the other hand, long-term stability and high accuracy, if possible without the need of frequent re-calibration, are essential."

- P. 2, Line 9: Do the authors trust a sensor that has never been calibrated? I suggest to write "frequent re-calibration".

We agree, and changed as suggested.

- P. 2, Line 9-10: Hence, there is no sensor available that meets both requirements? If this is the case you should state it.

We changed the text to:

"In practice, as no sensor is available that meets both requirements, this leads to the combination of complementary sensors for both high resolution and long-term accuracy."

- P. 2, Line 17: What is "sufficient humidity"?

As this is not quantified in the reference, we removed it from the sentence, and changed the text to:

"For temperatures exceeding 0 °C, and with the help of extensive postprocessing or modelling, the relatively slow polymer-based absorption hygrometers are sometimes used for retrieving humidity fluctuations"

- P. 2, Line 32: A comparative is missing here: 100 times weaker / stronger?

Thank you for the remark! When verifying this point, we saw that there was even a mistake in the order of magnitude of the effect. The sentence has been changed to:

"The absorption by oxygen molecules is about 1000 times weaker than by ozone molecules, and can be corrected by taking into account pressure and temperature, as the fractional density is constant."

- P. 3, Line 1: "same order" with respect to water vapor or to the previously discussed oxygen?

We changed the text to:

"same order of magnitude with respect to water vapour"

- P. 3, Line 4: What is "long-term" here? May be better write "(slow) drift". Normally with long-term one would think of weeks or months, however, for Ly-Alpha we often think of the magnitude of hours.

We changed as suggested.

- P. 3, Line 10: This sounds like the need for careful calibration is a disadvantage of the KH20 which however is essentially the same for the Ly-Alpha.

We changed the text to:

"A similar system is the Krypton hygrometer KH20 of Campbell Scientific, USA, which has a cross sensitivity to oxygen as well and therefore, like the Lyman-Alpha, has to be calibrated carefully"

- P. 3, Line 11: What about this new sensor? If it showed promising results five years ago, is it expected to become broadly introduced? Moreover, if there is this new instrument, "THE Lyman-Alpha" (as you name it throughout the manuscript) does not exist, it could be thus wise at one place to state that "the Ly-Alpha" in this paper is a synonym for "the Ly-Alpha absorption hygrometer by Buck Res.".

Very good idea! As suggested, we included in Sect. 1.2 the following sentence:

"The term "Lyman-Alpha" in this paper is used as a synonym for the Lyman-Alpha absorption hygrometer by Buck Research". Concerning the KH20: We did not find more literature about airborne applications, it seems to be mostly used for ground-based measurements. According to **?**, the instrument is very sensitive to path length, and calibration is difficult even for ground-based applications. We added in the text:

"It is, however, not broadly present in airborne applications."

- P. 3, Line 19-20: This sentence does not become clear here.

We re-phrased the sentence:

"For retrieving methane and carbon dioxide with these instruments, the water vapour measurements are necessary to reference the number concentration of methane molecules to the dry mole fraction."

- P. 3, Line 22: Here the authors speak about the LICOR sensor without having introduced this. I suggest first to characterize the LICOR sensors before describing the TDLAS which is still experimental.

We changed the order of introducing the sensors. Now we first present the LICOR sensors and measurement principle, then the TDLAS.

- P. 3, Line 26: what is "fast humidity"? Please avoid this slang in a scientific paper. Humidity is a scalar property of air, it is not fast nor slow, it is just highly variable in space in time such that you need fast-response instruments to resolve this variability.

We changed the text to:

"The fast-response LICOR instruments LI-7500, LI-7500A and LI-7200 for measuring humidity "

- P. 3, Line 27: I wonder whether it is correct here (and in other places as well) to speak about a measurement chamber. LI7500 basically is an open-path sensor, even if the distance between the sensor head and base can be bridged with a "chamber". And the Lambert-Beer law underlying the physics of measurement considers the distance or length of the absorption path. Insofar, one might prefer "path" instead of "chamber".

We agree that "path" is the better suited expression and changed that in the manuscript.

- P. 4, Line 27f: It is not the wavelength that is absorbed but light at a wavelength of . . .

We changed this as suggested.

- P. 5, Line 11 (and also P. 6, Line 7): What makes the Humicap superior to the dew point mirror such that the latter one has not been used?

During the Do-128 flight, the dew point mirror was not operating properly. Therefore, we prefer to show only the results of the same sensor types for the Helipod as well, which are the Humicap, Lyman-Alpha and LICOR sensors.

- P. 15, Line 15: What does this mean "is calibrated regularly"? How often? How?

We changed the text to:

"The Vaisala Humicap is calibrated before and after each measurement campaign by applying saturated salt solutions and their different known equilibrium relativ humidity"

- P. 5, Line 29f: Why has the full length of the measurement path (instead of its center length) to be considered when determining the delay time?

Thank you for the hint, that is correct. We use indeed the center length for the calculation resulting in a time delay of 0.12 s, not the full length of the measurement path. In the text, this is not clear. Therefore we changed the text to:

"the time for exchanging the air of the measurement cell with an inner diameter of 25 mm and a half length of 125 mm amounts to 0.12 s."

- P. 6, Line 18: "agricultural grassland" – do you really mean "grassland", or "farmland"?

We changed the text to "agricultural farmland".

- P. 6, Line 20ff: What was the motivation to define these six small sub-legs, knowing that the "sampling-length" requirements according to Lenschow et al. are not fulfilled here?

We chose these small sub-legs with different but homogeneous surface conditions and different but constant flight altitudes to compare if there are systematic differences in the important parameters like the vibration level. We added in the text:

"These small sub-legs were chosen with different but homogeneous surface conditions and different but constant flight altitudes to compare if there are systematic differences in the parameters like the vibration level."

- P. 7, Line 1: The Ly-Alpha data were shifted, not the instrument.

We changed the text to:

" First the Lyman-Alpha data were shifted in time"

- P. 7, Line 2: Mathematically speaking the co-variance (or the correlation) is maximized.

We changed the text to:

"The synchronisation was then done by maximizing the covariance of the mixing ratio fluctuations of the Lyman-Alpha and each of the LICOR sensors"

- P. 7, Line 8, 11: On p. 5 the internal delay is given with 123 ms.

Thank you for pointing out this mistake. We verified with the manuals that the internal delay time of 130 ms is correct, as on p. 7, which is used for the calculations. We corrected the value of the internal delay given on p. 5.

- P. 7, Line 21: The "best value" can only be one value, a range "between 0.5 and 0.9" is not a very specific information.

We changed the text to:

"The best correlation between Li3 and Lyman-Alpha amounted to 0.6, thus was considerably lower (Fig. 10)"

- P. 8, line 4: Was this the mean wind at the surface or at flight level?

To clarify, we changed the text to:

"The flight on 14 August 2014 was done in conditions nearly free of clouds at the beginning with a near-surface air temperature around 17 °C and southerly wind with a speed of $5\,\mathrm{m\,s^{-1}}$ near ground. The mean wind speed at the altitude of the Helipod transects was $8\,\mathrm{m\,s^{-1}}$, and the mean wind direction at that altitude was 180 °."

- P. 8, line 14: Where is this additional time lag attributed to?

We added in the text:

"The additional time lag may be attributed to the semi-open housing geometry."

- P. 9, line 5: Why choosing a different flight section here when compared to Figure 7?

We changed that. Now Fig. 7 and Fig. 8 both show flight section D3.

- P. 9, Line 19: Why do the authors speak of "decaying turbulence" here, the -5/3 law holds for the inertial subrange of developed turbulence.

To avoid confusion, we changed the text to:

" The sloped lines represent the -5/3 drop-off expected in the inertial subrange."

- P. 10, line 12: … covariance of the vertical wind speed and the humidity values from the different sensors …

We changed as suggested.

- P. 10, line 33: … a phase shift around 0 °C … ???

We changed the text to:// "and the phase shift around 0 °"

- P. 11, line 12-19: This paragraph bridles the horse from the tail. The underestimated fluxes are a consequence of the noisy, vibration-affected humidity measurement of LI1 and LI3. I suggest to organize the paragraph along this line which was followed through the paper.

We changed the text to:

"For the Do128 application, three different LICOR sensors were subject to different vibration levels. For the Li1 and Li3 sensors, installed without particular isolation agains vibrations, the correlation with the Lyman-Alpha signal was significantly lower than for the Li2 sensor, which was installed isolated against vibrations. The different covariance spectra of the vibration-affected humidity measurements of the Li1 and Li3 sensors resulted in larger deviations of the latent heat fluxes compared to the latent heat fluxes based on the Lyman-Alpha sensor. The vibration-isolated Li2 sensor showing high correlation with the Lyman-Alpha sensor resulted in comparable latent heat fluxes. However, the spectral behaviour of the vibrations had no direct, linear impact on the humidity spectra of the Li1 and Li3 sensors, but the relationship is more complex. This is currently subject to more detailed investigations."

- At some places, the structure of sentences is very German style, e.g., P. 1 - line 20, P. 9 – line 32f, p. 10 – line 9f, p. 11 – lines 20-21.

We changed the sentences to:

"For *in situ* measurements of humidity, the error bars are typically larger than for other atmospheric parameters like temperature and wind."

"Based on the grey shaded data set of Fig. 3, Fig. 10 shows the coherence and the phase of the different LICOR sensors with the Lyman-Alpha. Overall, the Li2 provides the best coherence with the Lyman-Alpha. The coherence is virtually equal to one over a large frequency range of three decades. It only drops off for frequencies beyond 1 Hz due to the spatial separation of the two sensors. No phase difference is observed over the same frequency range."

"The response behaviour of the Vaisala Humicap is more complex. At low frequencies (<0.01 Hz) it agrees reasonably well with the Lyman-Alpha. Then the coherence decreases with increasing frequency. The phase shift disappears around 0.4 Hz, but the level of coherence remains lower."

"For the Helipod application with lower vibrations, the humidity fluxes derived from the Lyman-Alpha and LICOR sensors agreed very well after careful sensor calibration to absolute values, and correction of the time lag."

- In a few places there are unnecessary redundancies: P. 2 – Line 27 / Line 30, P. 4 – Line 24 / 25, caption of Figures 8, 9 (repeating the whole Figure legend).

We removed the redundancies for the first two parts. The sentences were changed to://

"Sensors based on atomic absorption provide the advantage of a very fast response time allowing for measurement frequencies exceeding 100 Hz, a sharp absorption line compared to the absorption bands of molecules, and a high degree of absorption. This requires only measurement cells of few mm (Buck, 1973) compared to several cm for molecular absorption."

"The working principle of the LICOR sensor series for water vapour and carbon dioxide (CO_2) is the absorption of near infrared radiation by these molecules."

However, we are not sure which figure captions the referee refers to, as Fig. 8 and 9 represent totally different parameters. When applicable, figure captions already refer to the colour schemes of previous figures. For Fig. 10 and 12, as well as Fig. 3 and 6, we prefer to repeat the figure caption, as there are the data of different sensors, displayed in different colours.

Figures

- Figure 3

- Would it be possible to indicate D1 .. D6 in the graph

As we perform the spectral analysis with the part of the data shaded in grey, we prefer not to include the flight legs D1 to D5. They were mainly used for comparison studies.

- Don't numerate the subplots without a reference, do not write "first subplot" and "main plot" etc., but "upper", "central", "lower", or label the subplots with a) … d)

We labelled the subplots as suggested.

- Unit of potential temperature should be K.

We changed to the unit K.

- The lower panel does not show the invalid data, instead it marks the "periods of invalid data"

We changed that.

- Could the part of the flight that was used for the spectral analysis (grey shading in Figure 3, marked by a different colour in Fig. 1?

The referee probably refers to the flight path in Fig. 2. We implemented this in the map.

- Figure 4:

This Figure is not really needed.

We removed Fig. 4 and removed the reference in the text.

- Figure 6:

- See also my remarks to Figure 3.

We adapted the same points as mentioned above for Fig. 6 as well.

- When looking at the vertical wind speed plot one gets the impression that the plot basically shows the movement of the Helipod for the ascent / descent flight periods. Shouldn't this component be removed in order to see the turbulence intensity?

The ascent and descent parts of the flight were done in spirals, with a reduced true air speed of $30\,\mathrm{m\,s^{-1}}$ instead of the $40\,\mathrm{m\,s^{-1}}$ required to escape the downwash effects of the helicopter, and a banking angle of $15\,^{\circ}$. Therefore we use only the straight and level flight legs for the instrumental comparison.

- Figure 7: In fact, this plot shows the time series of accelerations in z direction which illustrate the vibrations the LICOR sensors were exposed to.

True, we changed to "accelerations". We further added in the section about the Do-128: "The axis of the optical path of all sensors were oriented along the aircraft longitudinal axis."

- Figure 10: Right graph should better be named as "Co-spectra of humidity from the different sensors and vertical wind speed . . . "

We changed the expression for Fig. 10 and 12 as suggested.

- Figure 11: I would be a bit hesitant to present a flux derived from the Humicap humidity signal in this plot without further discussion; it might be interpreted in a way that the Humicap is still much better than the vibration-sensitive LICOR instrument.

Indeed the figure shows that in this case, the Humicap is better suited for determining latent heat fluxes than the vibration affected LICOR sensors. We added in the discussion:

"The latent heat flux determined with the Humicap amounts to 95% of the reference value determined with the Lyman-Alpha. This means that for moderate conditions (10-20°C, humidity values typical for midlatitudes), the Humicap can be used for determining airborne latent heat fluxes with an acceptable error bar. However, the response function of the Humicap is asymmetric, with a different response time for decreasing and increasing humidity, and the response time becomes significantly slower for cold conditions like in the Arctic, where the sensor is not suitable for deriving latent heat fluxes."

Some minor language issues / misprints

- P. 2, line 22: and make ... making

- P. 2, line 25: with ... allowing for

- P. 3, line 25: . . . available yet.

- P. 6, line 27: above ... over

- P. 6, line 29: humidity fluxes ... humidity fluctuations

- P. 8, line 1: urface ... surface

- P. 9, line 24: cn ... can

- P.9, line 26: sonsor ... sensor We thank the referee for careful reading and corrected the mentioned points.

The authors would like to thank the anonymous referee for the suggestions and corrections. In the following, each comment of the referee (in italic) is answered separately. The answers are provided in normal style, and the changed text of the manuscript is given in quotation marks.

GENERAL COMMENTS: This is a review of manuscript amt-2017-353, "Comparison of the fast Lyman-Alpha and LICOR hygrometers for measuring airborne turbulent fluctuations". The LICOR sensors in different forms are used at automated field stations for research networks covering large temporal and spatial scales, and are well characterized. The purpose of this manuscript is to evaluate LICOR humidity sensors in a new environment, on aircraft, compared with standard Lyman-alpha hygrometers. The results show that the LICOR sensors are well suited for airborne measurements of humidity fluctuations, provided that a vibrationless environment is given, and this turns out to be more important than close sensor spacing. This is a detailed technical assessment of LICOR sensors that should be posted online for discussion in AMTD after some major revisions are made. LICOR sensors are widely used on aircraft, so validation of their performance is needed. The manuscript is an important contribution because it analyzes the environments in which the LICOR sensors perform well compared to the *“gold standard” of Lyman-alpha hygrometers. appreciate the hard work of the authors to collect the field data and carefully analyze the results.*

We would like to thank the referee for acknowledging the importance of the work presented in the manuscript.

What remains for the authors to do is to rewrite the manuscript with better explanation of their reasoning and conclusions.

We included more explanations in the manuscript, which take into account the comments of the referees.

The manuscript could also benefit from better English editing.

The English style has been improved by taking into account the very detailed comments of Referee 1. Several sentences have been re-written, and the grammatical and spelling mistakes have been corrected.

SPECIFIC COMMENTS: 1 I have a concern that the authors and other research groups are using LICOR sensors in an environment that the manufacturer does not recommend.

We understand that the manufacturer does not sell the system for airborne applications, as they are aware that vibrations may hamper the data. For that reason, we consider it even more important to figure out the limitations of the sensor in terms of vibrations.

Manuscript page 4, lines 9-12: The authors stated that “the manufacturer warns in the manual that the sensor should not be applied with vibrations around 150 Hz and around the harmonics". Is it possible for the authors to contact the LICOR manufacturer to get approval - or feedback from the Technical Support department - for flying a LICOR on aircraft?

Yes, we were in contact with the manufacturer, and presented the results. Some stafff members showed large interest in the investigations, however, we did not get an official statement from the company.

2 The reported experiment involved one vibration-isolated closed-path hygrometer and two non-isolated open-path hygrometers, so how do you know whether the drift and noise are due to vibration or the open-path? Are there other possible reasons for the drift (such as drift in the electronics response or internal processing?)? We operated the identical open path sensor on a platform affected by vibrations (Do128, not isolated), and on a platform with much lower level of vibrations (Helipod, carried by helicopter, without own propulsion). For the latter application, the open-path sensor performed well without any drift. This comparison allows the conclusion that the vibrations are responsible for degrading the measurements. To clarify, we added the following sentence in the conclusion section:

"Altogether, both open-path and closed-path LICOR sensors are suitable high-resolution hygrometers for airborne applications, if the vibrations are low."

3 Section 1.3, page 3, lines 14-25, describe laser hygrometers but has some gaps as listed below: 3.1) Page 3, lines 24-25 claim that “it is not possible to obtain real-time humidity data.” Although the Buchholz et al. hygrometer (Buchholz et al. 2014) does not provide real-time humidity data, other laser hygrometers do this routinely (see papers such as S. B. Smith et al., JGR, 2017, R. L. Herman et al., ACP, 2017, or M. Zondlo et al.).

We added in the text:

"For large research aircraft, some specifically designed hygrometers are implemented: On the National Science Foundation Gulfstream-V aircraft, a cavity diode laser hygrometer with two absorption lines in the near-infrared is deployed with a temporal resolution of 25 Hz (Zondlo et al., 2010). On the NASA ER-2 aircraft, a specifically designed near-infrared tunable diode laser spectrometer is deployed for measuring atmospheric water vapour concentration (May, 1998), with a sampling rate of 1 Hz and 10% accuracy(Herman et al., 2017). Compared to the LICOR sensor, this tunable diode laser hygrometer can be operated much faster (up to several kHz) and with a known accuracy, providing the most precise humidity values available to date (Buchholz et al., 2013, 2014, 2016). However, this hygrometer requires extensive post processing, and at least so far it is not possible to obtain real-time humidity data. The spectroscopic sensors are experimental systems and not commercially available yet."

3.2 page 3, line 25 claims that "The spectroscopic sensors are experimental systems and not commercially available" but the Picarro and Los Gatos systems mentioned earlier are commercially available laser hygrometers that have sufficient accuracy for the science. They can also provide realtime humidity data. Yes, we agree with the referee. However, the price for a Picarro and Los Gatos sensor is much higher, and so is the weight, which makes them not so easy to use in aircraft. We changed the text to:

"As the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available, and small enough to be easily integrated into aircraft, its airborne applications will very likely increase."

3.3 page 4, lines 10-11 claims that "… the LICOR sensor is currently the fastest and cheapest water vapor sensor commercially available" but laser hygrometers are faster than the LICOR. We changed the text to:

"the LICOR sensor is currently the cheapest fast-response water vapour sensor commercially available"

4 I find the discussion of the time resolution of the LICOR to be disorganized and confusing (Sections 2.1 and 2.2 and 3.4). I recommend that the authors should reorganize the discussion of the time response, time delay and time synchronization to one section because these are related.

We are not very happy with this suggestion. Section 2.1 generally introduces the LICOR sensors with their properties. However, the time synchronisation stronly depends on the setup in the corresponding measurement platform with the tube lengths, and distances between hygrometers and 5-hole probe. Therefore, we would prefer to discuss the synchronisation separately for each airborne carrier platform.

4.1 What is the time resolution of the LICOR instrument? Page 5, line 2, indicates that the data is "internally processing and finally provided at a maximum frequency of 20 Hz." Are the detector and electronics signal chain sufficiently fast to resolve changes in water vapor at 20 Hz?

Yes, the provided maximum frequency is 20 Hz. The internal data sampling and acquisition is fast enough. To avoid confusion, we changed the sentence to:

"The data sampled internally at 150 Hz frequency is processed and provided at a maximum frequency of 20 Hz."

4.2 Page 5, line 9: what is the response time of the Rosemount EL102 sensor? It is only characterized here as a "fast response time." How fast? We changed the text to:// "Rosemount EL102 sensor with a fast response time (100 Hz)"

4.3 Page 5, lines 25-30: How can you carry out successful fast measurements with the closed-path LICOR if there is a 250-millisecond calculated delay? Have you tested the delay? What is the residence time in the sample cell?

The delay is just a temporal offset, which can be corrected. The residence time in the sample cell depends on the air flow speed, and is taken into account in Sect. 2.2.

4.4 Page 10, line 23 and Page 11, line 25: the authors state the "Generally a temporal resolution of 20 Hz is sufficient for humidity flux calculations." It is not clearly explained how the authors came to this conclusion. Is there a reference that can be cited as evidence for this?

We included in Section 4.2 the following text:

"It can be concluded from Fig.10 and Fig.12 that the fluxes for frequencies exceeding 1 Hz are negligible for these specific flight conditions. Therefore, the sampling frequency of 20 Hz is sufficient for airborne turbulent humidity fluxes."

Furthermore, it is unclear from this manuscript whether the LICOR has an actual temporal resolution of 20 Hz (when the sampling delays and internal processing are included).

The delays are constant temporal offsets, which do not influence the capability of the sensor to provide data at 20 Hz resolution.

5) Flight figures 3 and 6 are hard to read: please consider larger font text

We enlarged the text in the figures.

Changes to the manuscript

The fundamental changes to the manuscript include:

- Change in almost all figures, as requested by the referees
- Smaller changes concerning logics of sentences
- Checking of grammar and spelling.

In details, the changes are marked in the following version of the text:

Abstract. The ~~properties of~~ measurement data of several fast hygrometers, the Lyman-Alpha and different LICOR humidity sensors, are analysed in direct intercomparison flights on different airborne platforms. One vibration isolated closed-path and two non-isolated open path LICOR sensors were installed on ~~the twin engine turbo-prop aircraft Dornier 128~~ a Dornier 128 twin engine turbo-prop aircraft. The closed-path sensor provided absolute values and fluctuations of the water vapour mixing ratio in good agreement with the Lyman-Alpha. The signals of the two open-path sensors showed considerable high frequency noise, and the absolute value of the mixing ratio was observed to drift with time in this vibrational environment.

On the helicopter-towed ~~sonde~~ sensor system Helipod with very low vibration level the open-path LICOR sensor agreed very well with the Lyman-Alpha over the entire frequency range up to 3 Hz.

The results show that the LICOR sensors are well suited for airborne measurements of humidity fluctuations, provided that a vibrationsless environment is given, and this turns out to be more important than close sensor spacing.

1 Introduction

Water vapour and clouds in the atmosphere have a large impact on the energy balance (Ramanathan et al., 1989), the hydrologic cycle (e.g. Chahine, 1992) and ~~therefore~~ on local and global climate (Trenberth et al., 2007; Zhou et al., 2011). Therefore, accurate knowledge of atmospheric water vapour concentration and transport is of high relevance for understanding climate and climate change. A general increase in ~~surface air~~ atmospheric moisture measured at the surface and humidity within the troposphere has been reported (IPCC, 2013). ~~The global distribution of moisture is difficult to measure and model accurately due to its large spatial and temporal variability (e.g. Klaus et al., 2012)~~ Satellite retrievals of the vertical water vapour distribution provide limited spatial resolution, e.g. 300 m in the vertical and 30 km in horizontal direction (Bender et al., 2011). For the quantification of atmospheric processes on local to regional scales, airborne measurements are required to fill the gap between large-scale, low resolution information from satellites and ~~point~~ measurements at fixed locations ~~with~~ providing higher vertical and temporal resolution, ~~but limited in horizontal extent~~ which are representative of a small area only. ~~Also measuring humidity *in situ* with high accuracy is challenging. In the troposphere, the water vapour concentration in ppm varies over two orders of magnitude (e.g. Schneider et al., 2010). Even for well controlled conditions in a cloud chamber, intercomparison measurements of different hygrometers probing the same air simultaneously revealed discrepancies between different measurement systems of around 10 %. For cold and dry conditions, as encountered in the upper troposphere and lower stratosphere, the instruments had a variation around the reference value of 20 % (Fahey et al., 2014).~~

~~For quantifying~~ The most effective way for moisture transport from the surface ~~into~~ to the atmosphere ~~a commonly deployed method~~ is turbulence. Turbulent fluxes are commonly determined with the eddy-covariance ~~technique~~ method. ~~The turbulent fluxes of latent heat are calculated under the assumption that vertical transport takes place via turbulent eddies. For calculating the latent heat flux,~~ This technique requires accurate measurements of the ~~fast~~ fluctuations of the vertical component of wind speed and humidity ~~are necessary~~.

For *in situ* measurements of humidity, the error bars are typically larger than for other atmospheric parameters like temperature and wind. In the troposphere, the water vapour concentration in ppm varies over two orders of magnitude (e.g. Schneider et al., 2010). The uncertainties of atmospheric water vapour measurements are high, as even for well controlled conditions in a cloud chamber, intercomparison measurements of different hygrometers probing the same air simultaneously revealed discrepancies between different measurement systems of around 10 %. For cold and dry conditions, as encountered in the upper troposphere and lower stratosphere, the instruments had a variation around the reference value of 20 % (Fahey et al., 2014).

Airborne sensors ~~for meteorological research~~ have to fullfil specific requirements. On the one hand, a high temporal resolution is needed in order to obtain a high spatial resolution for the moving platforms. On the other hand, long-term stability and high accuracy, if possible without the need of frequent re-calibration, are essential. In practice, as no sensor is available that meets both requirements, this leads to the combination of complementary sensors for both high resolution and long-term accuracy. In the following, the measurement principles of the different humidity sensors used in this study are shortly summarized.

1.1 Material absorption

Capacitive sensors are based on taking up humidity in a porous or hygroscopic material, changing the dielectric properties. An example ~~are~~ is the Vaisala Humicap sensor~~s~~, which ~~are~~ is used as the standard for radiosondes. However, the response times for increasing and decreasing humidity may differ significantly due to the different diffusion coefficient into the material and out of the material, and the temporal resolution is limited. For temperatures exceeding 0 °C, ~~sufficient humidity,~~ and with the help of extensive postprocessing or modelling, the relatively slow polymer-based absorption hygrometers are sometimes used for retrieving humidity fluctuations (Wildmann et al., 2014).

The typical calibration procedure consists of applying saturated salt solutions with different known relative humidities, and recording the sensor output, thus creating a calibration curve. The sensor is sensitive to contamination by e.g. sea salt, which may alter the sensor properties significantly, making a regular cleaning and re-calibration necessary.

1.2 Atomic absorption

Sensors based on atomic absorption provide the advantage of a very fast response time allowing for measurement frequencies exceeding 100 Hz, a sharp absorption line compared to the absorption bands of molecules, and a high degree of absorption~~,~~ ~~which~~ . This requires measurement cells of only few ~~mm~~ millimeters (Buck 1976) compared to several cm for molecular absorption. The sensor is based on the emission of ultraviolet (UV) radiation at a wavelength of 121.56 nm (transition of an electron from the first excited state n=2 to the ground state n=1 in the hydrogen atom, called Lyman-Alpha emission line). ~~The required length of the measurement chamber is only a few mm (Buck 1973).~~ As the Lyman-Alpha wavelength is strongly absorbed by water vapour, the signal in the ion chamber detector is weakened accordingly. The relation is given by the attenuation law of Lambert-Beer. The absorption of the Lyman-Alpha line has cross sensitivities with oxygen and ozone molecules. ~~The about 100 times absorption by oxygen atoms~~ The absorption by oxygen molecules is about 1000 times weaker than by ozone molecules, and can be corrected by taking into account pressure and temperature, as the fractional density is constant. The correction of the absorption by ozone molecules (same order of magnitude with respect to water vapour) is only necessary in the stratosphere (Buck, 1976).

Calibration is done by applying air of known humidities and recording the detector signal as a calibration curve. The aging of the lamp, or degradation of the magnesium fluoride windows, lead to a reduced signal strength with time, which is interpreted as higher absorption, thus higher water content. This ~~long-term~~ (slow) drift makes a regular calibration of either the sensor or the retrieved data necessary.

The term "Lyman-Alpha" in this paper is used as a synonym for the Lyman-Alpha absorption hygrometer by Buck Research (Buck, 1973, 1976). It ~~The Lyman-Alpha sensor~~ has been operated as the standard fast humidity sensor in many research aircraft for several decades (Busen and Buck, 1995; Corsmeier et al., 2001; Drüe and Heinemann, 2007; Twohy et al., 1997). However, with the end of the life time of the radiation sources (glow discharge lamps) and difficulties in replacing them, a variety of other fast humidity sensors is now available. A similar system is the Krypton hygrometer KH20 of Campbell Scientific, USA, which has a cross sensitivity to oxygen as well and therefore , like the Lyman-Alpha, has to be calibrated carefully (Foken and Falke, 2012). It is, however, not broadly present in airborne applications. For the research aircraft of NCAR, a new Lyman-Alpha sensor was built, which showed promising first results (Beaton and Spowart, 2012).

1.3 Molecular absorption

Hygrometers based on molecular absorption can be sub-divided into systems based on a laser light source and the simpler and cheaper technique of using a broadband light source combined with interference filters. However, laser sources and fibre optics are now easily available as well due to advances and application in telecommunications. The disadvantage of molecular absorption is line broadening with pressure, resulting from the impact of other molecules. These measurement systems include the Picarro greenhouse gas analyser (Crosson, 2008) and the Los Gatos Fast Greenhouse Gas analyser, which measure the three most important greenhouse gases water vapour, carbon dioxide and methane simultaneously. ~~Further, the information of the amount of water vapour is needed for correction due to cross sensitivity.~~ For retrieving methane and carbon dioxide with these instruments, the water vapour measurements are necessary to reference the number concentration of methane molecules to the dry mole fraction.

~~On the DLR HALO (High Altitude Long-Range Aircraft), an innovative spectroscopic sensor developed by the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig is deployed (Buchholz et al., 2014). Compared to the LICOR sensor, this tunable diode laser hygrometer can be operated much faster (up to several kHz) and with a known accuracy, providing the most precise humidity values available to date (Buchholz et al., 2013, Buchholz et al., 2014, Buchholz et al., 2016). However, this hygrometer requires extensive post processing, and at least so far it is not possible to obtain real-time humidity data. The spectroscopic sensors are experimental systems and not commercially available.~~

The fast-response LICOR ~~sensors~~ instruments LI-7500, LI-7500A and LI-7200 for measuring ~~fast~~ humidity are based on the absorption of near infrared radiation. They have a longer measurement ~~chamber~~ path of 12.5 cm compared to the few mm of the Lyman-Alpha. The LICOR sensors in different forms are used at automated field stations for research networks covering large temporal and spatial scales, and they are therefore well characterised concerning the transfer function of different components (Metzger et al., 2016). The closed-path sensors requiring a gas sampling system can be affected by high-frequency attenuation, so inlets and tubes have to be dimensioned reasonably (Aubinet et al., 2016; Metzger et al., 2016).

Like for the Lyman-Alpha, the attenuation of the signal obeys the law of Lambert-Beer relating absorptance to the number density of the absorbing gas, taking into account pressure, and requires correction terms due to cross-sensitivities. The calibration procedure consists of applying air of well-defined humidity for two points, and adapting the calibration coefficients accordingly. Zero signal is created by dry, carbon dioxide free gas. The second point can be applied e.g. with the LICOR dew point generator.

The LICOR humidity sensors have been used for airborne applications additionally to the Lyman-Alpha or to replace the Lyman-Alpha for many years (Beringer et al., 2011; Pillai et al., 2011; Hiller et al., 2014). The sensors have been implemented in various configurations, some facing with the sensor head forward, e.g. on the helicopter borne ~~sondes~~ sensor system Helipod, and the Airborne Cloud Turbulence Observation System ACTOS (Siebert et al., 2013), some with the sensor head oriented vertical (French Piper Aztec research aircraft), some with an open housing (Siebert et al., 2013), some with a metal grid (Helipod), some with additional purging with synthetic air to keep the detector free of water vapour (Schmitgen et al., 2004).

The manufacturer warns in the manual that the sensor should not be applied ~~with~~ at vibrations around 150 Hz and around the harmonics (Licor, 2014). However, the impact on measurements is not specified or even quantified. As the LICOR sensor is currently the ~~fastest and cheapest~~ cheapest fast-response water vapour sensor commercially available, and small enough to be easily integrated into aircraft, its airborne applications will very likely increase.

For large research aircraft, some specifically designed hygrometers are implemented: On the National Science Foundation Gulfstream-V aircraft, a cavity diode laser hygrometer with two absorption lines in the near-infrared is deployed with a temporal resolution of 25 Hz (Zondlo et al., 2010). On the NASA ER-2 aircraft, a specifically designed near-infrared tunable diode laser spectrometer is deployed for measuring atmospheric water vapour concentration (May et al., 1998), with a sampling rate of 1 Hz and 10% accuracy (Herman et al., 2017). On the DLR HALO (High Altitude Long-Range Aircraft), another spectroscopic sensor developed by the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig is deployed (Buchholz et al., 2014). Compared to the LICOR sensor, this tunable diode laser hygrometer can be operated much faster (up to several kHz) and with a known accuracy, providing the most precise humidity values available to date (Buchholz et al., 2013, Buchholz et al., 2014, Buchholz et al., 2016). However, this hygrometer requires extensive post processing, and at least so far it is not possible to obtain real-time humidity data. The spectroscopic sensors are experimental systems and not commercially available yet.

~~Therefore~~ The aims of this article are (1) to show limitations and provide information for successful handling for the airborne use of LICOR humidity sensors, (2) to quantitatively compare fluxes of latent heat obtained with the former "standard" Lyman-Alpha and with the LICOR sensors for airborne applications, and (3) to determine the required measurement frequency for humidity fluctuations to derive reliable latent heat fluxes for the typical flight altitude of few 100 m and airspeed in the range of 35 to 70 $\mathrm{m\,s^{-1}}$.

2 Experimental setup

This section provides the background of the sensors used in the study, including a short overview of the LICOR sensor working principle, and a description of the airborne platforms and their sensor setup. For the flights, both a Lyman-Alpha and at least one LICOR sensor were operated in parallel, and the latent heat fluxes derived from the different humidity sensors and the same wind vector measurements are compared directly.

2.1 LICOR sensors

The working principle of the LICOR sensor series for water vapour and carbon dioxide (CO_2) is the absorption of near infrared radiation by ~~H_2O and CO_2~~ these molecules. The radiation source is a small lamp with broadband emissions in the near infrared

(NIR) spectral range. The radiation is focussed on a filter wheel with bandpass filters of different wavelengths, rotating at a speed of 150 Hz. The light at a wavelength of 2590 nm is absorbed by water vapour but not by carbon dioxide, the light at a wavelength of 4260 nm by CO_2, but not by water vapour, and the light at a wavelength of 3950 nm serves as a reference, where neither CO_2 nor water vapour have absorption bands. The narrow band-pass filtered radiation then passes the measurement cell of 12.5 cm length, where the ambient air either passes passively (open path sensor, LI-7500, and the newer LI-7500A) or is pumped through (closed path sensor, LI7200), and partly absorbs radiation depending on the number density of the absorbing water molecules, as well as for the CO_2 concentration. The detector on the other side of the measurement cell is a thermopile, additionally cooled by Peltier elements. The system is described in more detail in Licor (2014). The data ~~obtained originally~~ sampled internally at 150 Hz frequency is ~~internally~~ processed and ~~finally~~ provided at a maximum frequency of 20 Hz. The delay time for internal processing is specified for the LI-7500 as ~~185 ms~~ 0.185 s, and for both the LI-7500A and LI-7200 as ~~123 ms~~ 0.130 s.

2.2 Do128 instrumentation

The standard meteorological equipment of the research aircraft Do128 "D-IBUF" of the Institute of Flight Guidance, TU Braunschweig, consists of a five-hole probe and corresponding Setra pressure transducers (static, dynamic and differential pressure), inertial navigation and global navigation satellite system (GNSS) for deriving the 3D wind vector see description of methods by e.g. Kroonenberg et al., 2008, Bärfuss et al., 2018, a slow, but highly accurate Rosemount DB102 temperature sensor, and a fast response (100 Hz) Rosemount EL102 sensor ~~with a fast response time~~. The temperature sensors are mounted in a sophisticated Rosemount inlet to directly obtain the static air temperature, and can additionally be heated for flights ~~through~~ in icing conditions. The humidity channel includes a dew point mirror TP 3-S of Meteolabor (not used for this study), a capacitive humidity sensor (Vaisala HMP233 Humicap) and a Lyman-Alpha optical sensor L-6 / HMS-2 of Buck Research. Further, a surface temperature sensor KT15 is included. Temperature and humidity sensors, as well as the five-hole probe are integrated into the nose boom. More details on the instrumentation can be found in Hankers (1989); Bange et al. (2002); Corsmeier et al. (2001, 2002). The Vaisala Humicap is calibrated ~~regularly~~ before and after each measurement campaign by applying saturated salt solutions and their different known equilibrium relativ humidity, and the combined signal of the slow Humicap and the fast Lyman-Alpha has been shown to agree well with other independent measurements of humidity (Sodemann et al., 2017).

For the humidity intercomparison flight, three different LICOR systems were available (open path LI-7500 with serial number 75H-0775, open path LI-7500A with serial number 75H-2287, and closed-path LI-7200 with serial number 72H-0584). The two open path sensors were covered by a ~~sheet~~ metal grid ~~with holes~~ to enforce turbulent mixing and avoid gradients of concentration in the measurement cell. The three LICOR sensors were installed in addition to the standard equipment at the following locations: on the nose boom (LI-7500A, in the following called Li1), in the cabin directly under the roof (LI-7200, called Li2), with an inlet sampling the air near the LI-7500 (called Li3) on the roof (see Fig. **??**). ~~All sensors were oriented along the aircraft.~~ The axis of the optical path of all sensors were oriented along the aircraft longitudinal axis. No purging of the sensors with nitrogen or dried air was applied.

The stainless steel inlet to the Li2 sensor had a length l_1 of 350 mm, an inner diameter of 9.6 mm, resulting in an area of A_1=7.24·10^{-5}m^2. ~~The pump~~ A volume flow controller provided a flow of Q=15 l min^{-1}=2.5·10^{-4} m^3 s^{-1}. For the tube, the airspeed is therefore v_1=$\frac{Q}{A_1}$=3.45 m s^{-1}. This results in a time delay $\Delta t_1 = \frac{l_1}{v_1} =$ 0.1 s. Similar calculations are applied for the nylon tube of length l_2 = 400 mm and inner diameter of 8 mm, guiding the air from the inlet to the sensor, which results in an additional time delay of 0.03 s. Additionally, the time for exchanging the air of the measurement cell with an inner diameter of 25 mm and a half length of 125 mm amounts to 0.12 s. Altogether, there is a delay time of 0.25 s caused by the sampling system for the Li2.

For the humidity intercomparison flight, vibration sensors of type M3555B04/03/02 and M356B18 of the company PCB Piezotronics Inc., US, were integrated along the x-axis (perpendicular to ~~in~~ flight direction ~~along the aircraft and the sensors~~) and z-axis (upward directed) of the LICOR sensors. For the Li2, another vibration sensor in y direction (~~perpendicular to~~ in flight direction along the aircraft and the sensors) was available.

2.3 Helipod instrumentation

The data of a measurement flight with the "Helipod", a meteorological ~~sonde~~ sensor system towed by rope to a helicopter (e.g., Bange and Roth, 1999; Bange et al., 2002; Martin and Bange, 2014), is analysed here. The Helipod is equipped with different meteorological sensors: Humidity measurements are performed with a Lyman-Alpha sensor L6 of Buck Research, US, a capacitive Vaisala Humicap HMP110, a dew point mirror 1011B of General Eastern, US (not used for this study), and the LI-7500 (same sensor as used for the Do128 flight, there called ~~there~~ Li3). Temperature is measured with a Pt100 by Rosemount, and a fine wire by Dantec. A five-hole probe with the same differential pressure sensors as in the Do128 is integrated (D289 for differential pressure, D270 for static pressure, Setra, US), as well as a GPS system with eight receivers for a full 3D attitude alignment (GNATTI System of Geo++ GmbH, Germany) and IMU (LCR 88, LITEF, Germany). A Heimann KT19 sensor (Heimann, Germany) records the surface temperature. Altitude information is provided by GPS, barometric pressure, and a radar altimeter ERT180 (Thomson-CFS, France).

3 Flights and atmospheric conditions

3.1 Do128 flight on 23 October 2015

The measurement flight with the research aircraft Do128 "D-IBUF" was conducted on 23 October 2015. The aircraft operates at a true airspeed of 70 m s^{-1}. The flight was performed above different terrain of the North German Plain, including areas dominated by forest, by agricultural ~~grass~~farmland, and above open water North of the East Frisian Islands (Fig. ??). ~~For the analysis, the flight was sub-divided into six straight legs D1-D6 of 10 km length above terrain that was chosen as homogeneous as possible: D1 above forest at an altitude of 430 m above mean sea level, D2 above agricultural land at an altitude of 430 m, D3~~

~~above agricultural land at 220 m altitude, D4 and D5 above open water at 100 m altitude, and D6 above forests at 270 m altitude (Fig. **??**). Apart from these short legs, a longer~~ The part of the flight that was used for the sensor comparison is displayed in white on the flight track (Fig. **??**) and grey shaded in Fig. **??**, which fullfills the requirements of Lenschow et al. (1994) for the sampling length for several sub-legs above homogeneous terrain.

The flight took place under varying cloud conditions, mostly overcast with a cloud bottom at an altitude of around 1000 m. Above land, a neutrally stratified boundary layer was observed up to an altitude of around 1000 m, with a strong increase of potential temperature of 6 K in 1000 to 1200 m ~~Fig. xx~~. However, above the North Sea, the atmosphere was stably stratified. Therefore, significant latent heat fluxes were only observed over land.

3.2 Synchronisation of the Do128 humidity sensors

Before calculating the humidity fluctuations, the four fast humidity sensors (Lyman-Alpha, Li1, Li2, Li3) onboard the Do128 located at different places were synchronised. As mentioned in Sect. 2.2, the Lyman-Alpha and the Li1 are located at the nose boom, the Li3 at the cabin roof, and the inlet of the Li2 is close to the Li3 on the cabin roof. First the Lyman-Alpha ~~was~~ data were shifted in time against the vertical wind speed by maximizing the turbulent latent heat flux. The synchronisation was then done by ~~retrieving the maximum correlation of~~ maximizing the covariance of the mixing ratio fluctuations of the Lyman-Alpha and each of the LICOR sensors for varying temporal offsets. The time step providing the highest correlation was used as the delay time between the sensors. The time signal of the Lyman-Alpha was used as reference. The part of the flight used for the synchronisation (shaded in grey in Fig.**??**) contains large variability in the signals (changes of altitude, and high fluctuations), facilitating to derive a high correlation of the signals. The time shift between the Lyman-Alpha and the Li1 sensor in the nose boom was 0.15 s. As stated in the LI7500A manual, an internal delay of 0.13 s is caused by data processing. The remaining small difference of 0.02 s may be explained by the sampling geometry, as the Li1 is covered by a sheet metal as explained in Sect. 2. The time shift between the Lyman-Alpha and the Li3 sensor at the cabin roof was 0.3 s. Therefore, the delay time between the two open path sensors Li1 and Li3 amounted to 0.15 s. This can be well explained by the different internal delay times of 0.13 s for the Li1 and 0.185 s for the Li3, amounting to 0.05 s, plus additionally the distance $\delta\, s$ of 7 m between the two sensors (Li1 installed at the nose boom, Li3 at the cabin roof) and the true airspeed v_{tas} of 70 m s^{-1}:

$$\Delta t = \frac{\Delta s}{v_{tas}} = \frac{7\,m}{70\,m\,s^{-1}} = 0.1\,s \tag{1}$$

The time shift between the Lyman-Alpha and the Li2 in the cabin was 0.45 s. Subtracting the values for the time shift caused by the distance (0.1 s) and the internal delay (0.13 s), this results in a time difference of 0.22 s. This delay can be explained by the tube length and flow speed for guiding the air to the measurement cell in the cabin, as calculated in Sect. 2.

For further calculations, the best fitting time shift correction was applied to all three LICOR sensors. The correlation between the LICOR signals and the Lyman-Alpha ~~amounted to values exceeding~~ was better than 0.95 for the Li2 and Lyman-Alpha, and exceeding 0.8 for the Li1 and Lyman-Alpha for the part of the flight considered here. The best correlation between Li3 and Lyman-Alpha amounted to ~~values between 0.5 and 0.9~~ 0.6, thus was considerably lower (Fig.**??**).

The calculations of the best fitting time delay were verified by maximizing the coherence spectra of the Licor sensors and the

Lyman-Alpha as a reference, and at the same time minimizing the phase between the two signals. This resulted in the same delay times as determined by the method of maximizing the correlation.

3.3 Helipod flight on 14 August 2014

The overall aim of the Helipod measurements was to study greenhouse gas emissions on a scale of up to 100 km to investigate the spatial variability, and to analyse how representative the continuous emission measurements on local scales are on a climatically relevant sub-regional scale. During the measurement flight, the Helipod was attached ~~by a 30 m rope~~ to a Russian Mi8 helicopter by a 30 m rope. The flight was performed at a true airspeed of 40 m s^{-1} from the Research Station Samoylov Island in the Lena Delta, Siberia.

The Helipod flight analysed here took place on 14 August 2014, when seasonal thawing of the active layer on top of the permafrost was still in progress. The roundtrip flight pattern ~~consisted of a vertical profile up to 1500 m altitude, then a straight, horizontal flight leg of around~~ followed a 100 km horizontal leg at ~~low altitude (around 100 m) towards North-West~~ 100 m altitude in north-western direction with vertical profiles up to 1500 m altitude at both ends of the leg ~~There, another vertical profile was performed, and the flight back followed the same track.~~. The atmosphere was neutrally stratified in the lowermost 150 m, then slighly stable up to 1000 m (increase in potential temperature smaller than 1 K from the surface up to that altitude), and the ABL top was evident by an increase of potential temperature at 1000 m altitude ~~not shown~~.

The flight on 14 August 2014 was done in conditions nearly free of clouds at the beginning with a near-surface air temperature around 17 °C and southerly wind with a speed of 5 m s^{-1} near ground. The mean wind speed at the altitude of the Helipod transects was 8 m s^{-1}, and the mean wind direction at that altitude was 180 °. For this instrumental intercomparison, the first long flight transect from Samoylov Station to Arga-Muora is analysed (Fig. **??**). On the way back, short rain showers were encountered. The time series of the height, vertical wind speed, mixing ratio, potential temperature and valid data is shown in Fig.**??**.

3.4 Synchronisation of the Helipod humidity sensors

As the LI-7500 system was calibrated directly before the measurement campaign, and therefore provides reliable absolute values, the Lyman-Alpha values of the mixing ratio were calibrated against the LICOR data using a linear regression method. Before calculating turbulent fluxes of latent heat, the time shift between the LICOR and the Lyman-Alpha was corrected by calculating the maximum coherence with minimum phase shift of the two signals. The best correlation was found for a total time shift of 0.315 s. This includes the time delay caused by internal processing of ~~186 ms~~ 0.186 s, plus an additional time shift of around ~~130 ms~~ 0.13 s. The additional time lag may be attributed to the semi-open housing geometry. This value was confirmed by calculating the best correlation between the time series. The time lag was the same for straight and level flight sections throughout three campaigns in Siberia in April, June and August 2014.

4 Results

4.1 Vibrations during the Do128 flight

The time series of the mixing ratio (Fig. **??**) shows the general behaviour of the Li2 sensor, the slow Humicap and the fast Lyman-Alpha sensor. The time periods affected by radio communication were excluded for further analyses, as they occasionally induce artificial spikes on the Lyman-Alpha sensor. The data used for calculating the spectra are shaded in grey. They were chosen to exclude the flights at higher altitude, where the signal of the Lyman-Alpha differs significantly from the other sensors. Under these different pressure conditions, a different sensitivity range would be necessary, which was not adapted during the flight. For the data of the Li1 and Li3, different effects can be observed:

- The signals of the open path sensors Li1 and Li3 contain a higher level of noise compared to the closed path Li2 system and the signal of the Lyman-Alpha.
- Changes in altitude affect the signals of Li1 and Li3, and the absolute values of the mixing ratio do not follow the behaviour of the Li2 and the Humicap. This might be caused by changing vibration environments due to different power settings.
- There is a general slow drift in the signal of the open path sensors Li1 and Li3, which does not follow the trend of the closed path Li2 sensor, the signal of Lyman-Alpha, and Humicap.

Differences are apparent in the time series of the vibrations (Fig. **??**): The amplitude of acceleration in z direction is around $50\,\mathrm{m\,s^{-2}}$ for the Li3, around $40\,\mathrm{m\,s^{-2}}$ for the Li1 and around $3\,\mathrm{m\,s^{-2}}$ for the Li2 sensor. The example shows ~~flight section D1, but is comparable for all sections.~~ a small flight section of 3 min, but is representative for sections of this length at constant altitude.

The acceleration spectra for all three sensors in ~~x~~ y and z direction (along sensor and aircraft axis, and vertical direction) as well as ~~y~~ x direction (perpendicular to sensor and flight direction) for the Li2 sensor are shown in Fig. **??** for ~~flight section D3~~ a short flight section of 3 min. Strong and sharp vibration peaks at distinguished frequencies were recorded at the locations of all sensors, as well as differences in the broadband features.

Generally, the acceleration ~~values~~ for high frequencies (exceeding 200 Hz) ~~are~~ is several orders of magnitude lower for the Li2 sensor compared to the Li1 and Li3 sensors. This feature gets more pronounced for frequencies exceeding 1000 Hz. The strength of vibrations contained within individual peaks is more pronounced for the Li1 and Li3 sensor compared to the Li2 sensor. In Fig.**??**, the critical frequencies of 150 Hz and higher harmonics, as specified by the manufacturer, are indicated by vertical black lines. Especially around 450 Hz it can be seen that the vibration level of the Li3 is more than an order of magnitude higher than the vibration level of the Li1. This feature is observed during all flight legs analysed here, persistent throughout each flight leg. The high level of vibrations at the critical frequencies and potential impact on the internal signal processing could be an explanation for the different humidity spectra shown in the following.

4.2 Powerspectra of humidity fluctuations

The above mentioned properties of the sensors are reflected in the spectra of the mixing ratio, shown in Fig. **??** for each humidity signal. The sloped lines represent the -5/3 drop-off expected in the inertial subrange. Between 0.003 and 0.3 Hz all sensors ~~quite nicely~~ follow the Kolmogorov prediction (Kolmogorov, 1941) very well, and those of the Lyman-Alpha and Li2 continue for a further decade, while Li1 and Li3 level off indicating a substantial level of white noise superimposed on the humidity signal. The Humicap spectrum gradually decreases slightly faster.

Overall, the Lyman-Alpha spectrum most closely behaves as expected from the theory, and ~~that for~~ the Li2 ~~sensor~~ spectrum is very similar but drops off marginally faster beyond 1 Hz. This behaviour can be attributed to somewhat increased dampening due to longer inlet tubes in comparison to those for the Lyman-Alpha.

At low frequencies the Vaisala Humicap and even more the Li3 sensor show higher variances. It will be shown in the next subsection that this variance is differently correlated with the vertical wind velocity, which has implications for the flux calculation.

4.3 Cospectral analysis

As the Lyman-Alpha humidity sensor has been used widely in turbulence studies over decades, it is taken as a reference to compare the behaviour of the other sensors. Cospectra between each of these other sensors and the Lyman-Alpha are calculated. ~~Fig.**??** (left column) shows the coherence and the phase for the flight sections marked grey in Fig.**??**.~~ Based on the grey shaded data set of Fig.**??**, Fig.**??** shows the coherence and the phase of the different LICOR sensors with the Lyman-Alpha. ~~The overall best coherence with Lyman-Alpha shows the Li2~~ Li2 provides the best coherence with Lyman-Alpha, ~~it is~~ virtually equal to one over a large frequency range of three decades ~~and~~. It only drops off for frequencies beyond 1 Hz ~~as a result of~~ due to the spatial separation of the two sensors. No phase difference is observed over the same frequency range. In the phase spectrum the coherence is coded in the thickness of the dots as a phase can only be interpreted if a significant coherence between the signals is present. The marginally positive phase between Li2 and Lyman-Alpha is a result of the advancement of the Li2 signal over 0.315 s ~~of the Li2 signal~~. This constant shift can only approximate the more complex difference in the high-frequency response behaviour between Li2 and Lyman-Alpha due to spacing and tubing. A smaller advancement, however, leads to reduced coherence and a trailing phase shift of Li2 for frequencies below 1 Hz. The other two LICOR sensors (Li1 and Li3) have far less coherence with the Lyman-Alpha. At low frequencies this reflects the drift of both vibration affected sensors, and at high frequencies the noise fades more coherence that might exist. Note that for all three LICOR sensors the coherence inversely correlates with the amount of vibration the sensors are exposed to. ~~More complex is~~ The response behaviour of the Vaisala Humicap is more complex. At low frequencies (<0.01 Hz) it agrees reasonably well with the Lyman-Alpha ~~then starts to trail it with increasing frequencies, but at e.g. 0.4 Hz it responds to some degree in phase with the Lyman-Alpha, but at a reduced level of coherence.~~. Then the coherence decreases with increasing frequency. The phase shift disappears around 0.4 Hz, but the level of coherence remains lower. To assess the sensor behaviour on the moisture flux calculation, Figure **??** (right) shows the covariance of the vertical wind speed and the different humidity sensors after correction of the time lag.

The spectral estimates are multiplied by the frequency, thus the area below the curves is proportional to the humidity flux. Flux estimates based on Li2 and Lyman-Alpha reasonably agree, but those calculated by the vibration affected LICOR sensors are too low, most pronounced for Li3. The Humicap shows an interesting behaviour: overestimation on a scale of minutes (0.02 Hz) and underestimation for higher frequencies, both of which compensate to a certain degree. This behaviour seems to be a specific property of the Vaisala Humicap sensor. The latent heat flux determined with the Humicap amounts to 95% of the reference value determined with the Lyman-Alpha. Thus, for moderate conditions (10-20°C, humidity values typical for midlatitudes), the Humicap can be used for determining airborne latent heat fluxes with an acceptable error bar. However, the response function of the Humicap is asymmetric, with a different response time for decreasing and increasing humidity, and the response time becomes significantly slower for cold conditions like in the Arctic, where the sensor is not suitable for deriving latent heat fluxes.

Finally the total moisture flux as calculated by the five different moisture signals was compared. In Fig.**??** the integrated covariance spectra (ogives, see e.g. Sievers et al., 2015) are shown, normalised by the integral of the cospectrum of w and the Lyman-Alpha humidity. With the closed-path Li2, 98.1% of the Lyman-Alpha value is reached, the small high frequency loss is due to different sensor spacing and tubing. The vibration affected open-path LICOR sensors reach 47% and 83% of the Lyman-Alpha value.

It can be concluded from Fig.**??** and Fig.**??** that the fluxes for frequencies exceeding 1 Hz are negligible for these specific flight conditions. Therefore, the sampling frequency of 20 Hz is sufficient for airborne turbulent humidity fluxes.

The scale of eddies corresponding to the frequency of 1 Hz and the airspeed of 70 $\mathrm{m\,s^{-1}}$ is around 70 m. Contributions from eddies smaller than the size of few 10 m are negligible. This information is visible in the cospectra and in the ogive functions.

The results emphasise on which scales turbulent transport of humidity takes place: Fluctuations in the frequency range higher than 2 Hz do not contribute significantly to the overall humidity fluxes for these conditions, an air speed of 70 $\mathrm{m\,s^{-1}}$, altitude of 100 m and the specific surface properties. This is different to flux measurements near ground, where high resolution sampling and close sensor spacing are essential (Caughey and Palmer, 1979; Kaimal and Finnigan, 1994; Bange et al., 2002).

4.4 Spectral analysis of mixing ratio for the Helipod flight

Fig.**??** (left) shows the spectra of coherence and phase of the LI7500 signal (time corrected and not time corrected) against the Lyman-Alpha. For a frequency up to 3 Hz, the coherence for the time corrected signal is higher than 0.8, and the phase shift around 0 °~~C~~, thus the agreement of the two signals is high. The plot on the right represents the humidity flux for both sensors, i.e. the covariance spectra of the humidity and the vertical wind speed component. The areas under the curves are proportional to the humidity fluxes. The Lyman-Alpha and LICOR signals agree perfectly in the frequency range up to 2 Hz. For higher frequencies, the humidity flux is negligible anyway. The effect of the time correction for the humidity fluxes can be seen for frequencies exceeding 0.2 Hz: There are differences in the area under the lines representing the time corrected and uncorrected values. The overall effect is in the range of few percent. As the LI7500 used on the Helipod flew on the Do128 as well (Li3), the excellent agreement with the Lyman-Alpha here demonstrates that the vibrations of the Do128 are the main reason for poor performance there.

5 Recommendations for airborne applications

For calculating turbulent fluxes, the best temporal correlation of the sensors has to be determined first. The time shifts that were determined are not negligible and have to be taken into account. This is a standard procedure in the flux community (Moore, 1986). Time delays for the LICOR sensors are partly caused by internal processing, partly by different locations of the sensors and tube lengths.

For the Do128 application, ~~the humidity fluxes determined by the~~ three different LICOR sensors ~~did not always match satisfactorily the humidity fluxes determined with the Lyman-Alpha sensor~~ were subject to different vibration levels. ~~For the Li2 sensor, which was installed isolated against vibrations, the latent heat fluxes were comparable to the Lyman-Alpha. However, for the Li1 and Li3 sensors, installed without particular isolation agains vibrations, the correlation with the Lyman-Alpha signal was significantly lower, and the covariance spectra were different, resulting in larger deviations of the latent heat fluxes. As an explanation, the different levels of vibrations for the LICOR sensors at the specific location within the aircraft was shown.~~ For the Li1 and Li3 sensors, installed without particular isolation agains vibrations, the correlation with the Lyman-Alpha signal was significantly lower than for the Li2 sensor, which was installed isolated against vibrations. The different covariance spectra of the vibration-affected humidity measurements of the Li1 and Li3 sensors resulted in larger deviations of the latent heat fluxes compared to the latent heat fluxes based on the Lyman-Alpha sensor. The vibration-isolated Li2 sensor showing high correlation with the Lyman-Alpha sensor resulted in comparable latent heat fluxes. However, the spectral behaviour of the vibrations had no direct, linear impact on the humidity spectra of the Li1 and Li3 sensors, but the relationship is more complex. This is currently subject to more detailed investigations.

For the Helipod application with lower vibrations, ~~after careful sensor calibration to absolute values and correction of the time lag,~~ the humidity fluxes derived from the Lyman-Alpha and the open-path LICOR sensor (Li3) agreed very well after careful sensor calibration to absolute values, and correction of the time lag. Altogether, both open-path and closed-path LICOR sensors are suitable high-resolution hygrometers for airborne applications, if the vibrations are low.

In summary, some precautions have to be taken for employing a LICOR sensor for airborne turbulent humidity flux measurements. Especially the level of vibrations and its impact on the measurements should be evaluated critically, and the spectra of the measurements should be checked for plausibility. Especially for small fluxes, the relative error might be significant. Generally ~~a~~ the temporal resolution of the LICOR sensors of 20 Hz is sufficient for humidity flux calculations, as the contribution of ~~the higher frequency parts of the spectrum is negligible~~ frequencies above approximately 2 Hz is negligible, so a 10 times oversampling for a sufficient amplitude retrieval is provided.

Competing interests. The authors declare that they have no conflict of interest.

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