Answers to Referee 1: 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 $100\,\mathrm{m}$ 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 $20\,\mathrm{Hz}$ is sufficient for humidity flux calculations, as the contribution of frequencies above approximately $2\,\mathrm{Hz}$ 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 $30\,\mathrm{m}$ 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

5   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.

10   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

15   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 $180\,°$."

- 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."

20   *- 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:

25   " 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 $0\,°$"

30   *- 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

35   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 (**?**) 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.

5   *- 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.

10   *- 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.

15   *- 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.

20   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

25   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."

30   *- 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.

35   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 asym-

5   metric, 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

10 *- 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

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

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