Response to reviewers' comments

Title: Are elevated moist layers a blind spot for hyperspectral infrared sounders? – A model study
Author(s): Marc Prange et al.
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General remarks

Dear Editor,
we thank the reviewers for their constructive comments and suggestions on improving the manuscript. In this Response we first repeat the comments of Anonymous Referee #1 and our responses from the Discussion Phase, complemented with associated changes to the manuscript, where applicable. There were no additional comments of Anonymous Referee #1 that we did not address during the Discussion Phase. Hence, we continue by repeating the comments of Anonymous Referee #3 and our responses from the Discussion Phase, complemented with some additional remarks and associated changes to the manuscript resulting from our revision. We then move to the detailed comments of Anonymous Referee #3 that we have not addressed during the Discussion Phase (https://doi.org/10.5194/amt-2021-48-RC3). We do so by citing the referee comment, followed by our response and the respective changes to the manuscript.

Anonymous Referee #1, Discussion Phase comments:

Referee comment:
"Since the performance of EML retrieval is heavily relying on the additional information from temperature profile, the temperature averaging kernel results should also be shown."

Response:
A key finding is indeed the reliance of the EML retrieval on the added temperature information. Hence, we agree that showing the temperature averaging kernels is beneficial (Figure 1). We think that it is sufficient to add them to the appendix of the paper since they do not appear as essential as the water vapor averaging kernels for the main train of thought in section 4. However, we will make sure to reference the appendix figure in that section.

Changes to manuscript:
We added the temperature averaging kernels analogous to Fig. 5 in Appendix A (L. 623).

Referee comment:
"Moreover, if temperature retrieval is not performed, instead, reanalysis or forecast temperature profiles are used, will the EML retrieval be improved more?"

“On the additional temperature information, does the retrieval need the detailed vertical structure of temperature or is a smoothed "truth" temperature profile enough?”

Response:

We try to answer these two questions simultaneously. In Fig. 4 of the manuscript, we pick a particularly large error in our a priori temperature assumption to qualitatively demonstrate its effect on the water vapor retrieval. In practice, reanalysis or forecast products are expected to be much less biased and to be a somewhat smoothed version of the true temperature profile, similar to what Anonymous Referee #1 suggests in their second question. This indeed denotes another interesting testcase, which we tried to implement with a new retrieval run, the results of which are shown in Figure 1. Here, the a priori temperature profile is set to be the true profile without the temperature inversion features and the temperature profile retrieval is omitted. The effect on the water vapor retrieval is that the retrieved EML is overly pronounced and in a slightly wrong altitude. Note that the assumed temperature a priori is highly idealized in this example. Forecasts or reanalysis temperature data would be expected to be more error prone. We set up another testcase that only deviates from the previous one by a constant 3 K bias (Figure 2). The result is that the water vapor retrieval does not converge properly (canceled after 20 steps) and errors grow much larger. To avoid having the water vapor retrieval attempt to compensate for temperature errors, it is necessary to simultaneously retrieve the temperature profile. We conclude that missed fine temperature structures deteriorate the EML retrieval but do not yield an EML blindspot, as we also try to convey in the manuscript.

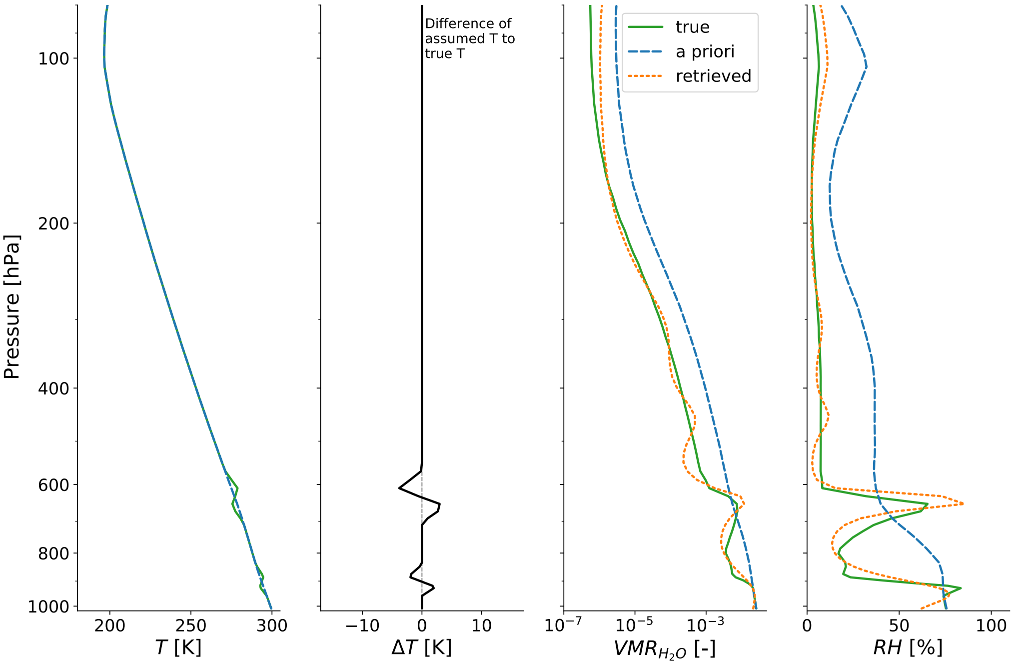

Figure 1: Profiles of EML retrieval testcase, where the temperature profile retrieval is omitted and the a priori temperature profile only misses the temperature inversion features around the EML. It is apparent that the EML is retrieved, but that the missed temperature inversions result in an overly pronounced retrieved EML and a slight increase in its altitude.

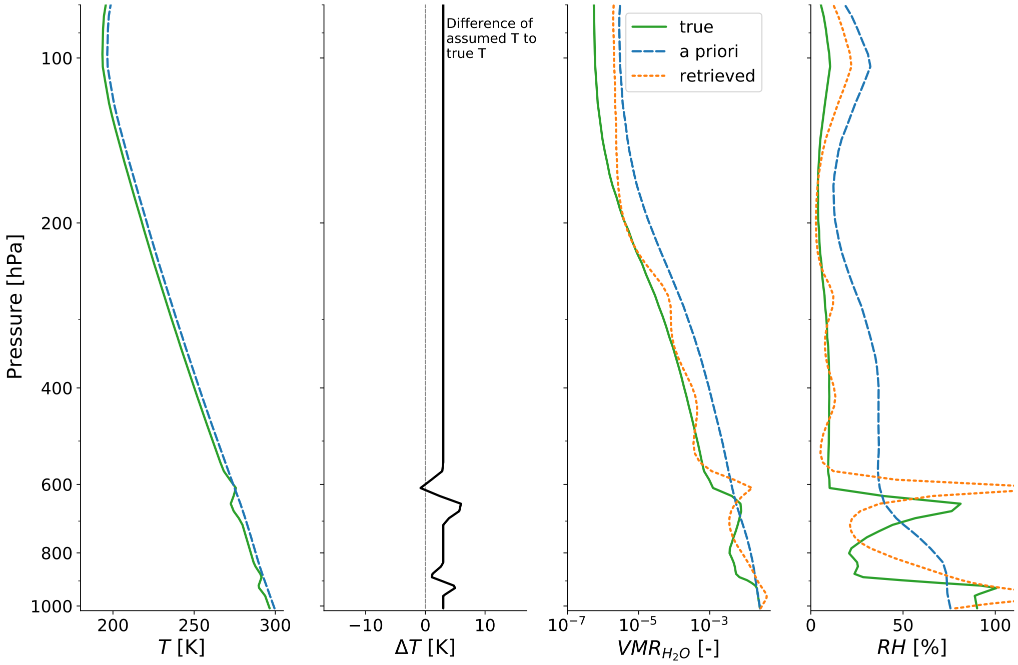

Figure 2: Same as Figure 1, but with added constant Temperature bias of 3 K between truth and a priori. The larger temperature error is compensated for by the water vapor retrieval, which does not converge after 20 iteration steps and runs into an unphysical solution (RH > 100 %).

Anonymous Referee #3, Discussion Phase comments:

Referee comment:

“The fact that water vapor information from hyperpectral sounder measurements is dependent on a-priori knowledge of surface and air temperature is a well established fact.”

Response:

From Discussion phase:

While this appears to be insufficiently communicated in the paper, we are well aware of the fact that we are not introducing a new idea to the field by finding that the water vapor retrieval is reliant on the knowledge of surface and air temperature. We agree with the referee that this generally is a well established fact. However, our finding is not of such general nature, but instead applied to a very specific and to our knowledge novel use case, namely an Elevated Moist Layer (EML). In this context, we believe it is not at all obvious, how the EML retrieval is affected by temperature errors due to the strong temperature inversion features associated with the EML. In the light of the poor retrieval results of Stevens et al. (2017) for an EML case, we view our assessment of the temperature error effect for this specific case as a valuable insight, although in the end it does not appear to be the driving effect for the severely underestimated EML found by Stevens et al. (2017).

Addition for Final Author Comment:

With the notion of the referee in mind about the scientific significance of our findings

regarding the temperature dependence of the EML retrieval, we decided to slightly adjust the retrieval testcases we investigate in Sect. 4 and rewrite that section completely. We hope we are now able to more explicitly show how temperature dependent errors can deteriorate the EML retrieval. We also try to more clearly communicate awareness of how this dependence in general is well established and handled by retrievals, while the novel contribution of ours is to investigate the significance of this effect for an EML scenario and whether it could explain the EML blindspot found by Stevens et al. (2017).
Since we recently started working with the dropsonde data of the NARVAL-2 campaign that also served as reference for the EML retrieval of Stevens et al. (2017), we now decided to use the dropsonde profiles directly (complemented by a fitted mean upper tropospheric/stratospheric state above the dropsonde) for our case study in Sect. 4. In the original manuscript we attempted to reconstruct a similar atmospheric testcase. We believe this change strengthens the case study validity overall.

Changes to manuscript:
Repeated and rewrote case study in Sect. 4.

Referee comment:
"I see no reference to any of the excellent papers on IR information content from either the retrieval or data assimilation communities, whether for AIRS, CrIS or IASI. Except for Rodgers, the authors communicate no awareness of any of the operational or research algorithms successfully retrieving mid-tropospheric moisture across the globe on a daily basis. Not to mention the excellent studies on channel selection, error estimation, a-priori selection and least squares fitting."

Response:
We do cite IR retrieval literature and use their results as a premise to motivate our study. We cite Schneider and Hase (2011) and Borger et al. (2018) to raise the point that temperature induced errors are among the highest error sources for lower and mid tropospheric water vapor retrievals. We also cite Lacour et al. (2012) as the predecessor study of Stevens et al. (2017) and deploy their spectral setup to better put our results into context. However, we should have made it more clear in the text that there is a wider literature on hyperspectral IR retrieval in general and will amend that in the revised text. For example, we see the point of referencing more performance evaluation studies of operational or research algorithms that derive water vapor profiles from IASI or AIRS, such as Chazette et al. (2014) or Divarkarla et al. (2006). But we want to cite only those papers that are either directly relevant for this paper or important landmarks. If the reviewer thinks that a particular paper in these two categories is missing, then please suggest it.

Referee comment:
"Who is your target audience?"

Response:
The aim of our study is not to introduce new insights on retrieval methodology, but rather to investigate to what degree it is possible to retrieve layered moisture features in the troposphere based on established retrieval techniques with IASI. Hence, our target audience is less the retrieval and data assimilation community, but rather the community interested

in exploiting satellite data for measurement campaign or climatology purposes with particular focus on the vertical humidity structure. We currently try to convey this in our introduction by mostly referencing literature that puts EMLs into a meteorological context. However, we can see that the current length and somewhat fundamental nature of the retrieval method section may raise unintended expectations for the reader. We could see that a more concise retrieval method section would be sufficient and beneficial for the story we want to tell. Any other suggestions for communicating our target audience clearer are of course welcome.

Referee Comment:
"Except for responding to Stevens et al. 2017 (which I haven't read, but the authors stated in their motivation throughout), I am not convinced this paper has scientific merit."

Response:
With the exception of Calbet et al. (2006), which we will discuss in the revised version of the article, we are not aware of any study other than Stevens et al. (2017) that has addressed the subject of our paper, namely to what extent the retrieval from these instruments is able to faithfully characterise layered moisture structures, in particular EMLs. Typically, examples given in the retrieval literature are for rather smooth profiles, and resolution metrics are theoretical (resulting from OEM analysis), but not put to a practical test (e.g. Lerner et al., 2002). Any suggestion of studies that we might have missed that deal with this would be highly appreciated. We should more clearly communicate the scientific added value of our finding that EMLs appear possible to retrieve. Rather than focus on pointing out that our results oppose the finding of Stevens et al. (2017), we will further elaborate on the added value of being able to investigate these features in their atmospheric environment based on satellite data.

Anonymous Referee #3, general comments:

Referee comment:
The authors presented their work clearly and accurately. Their paper reads well and has a logical flow. My primary concern is with the scientific value of their work. Their findings are not new, their experimental set up is naive, their test case(s) simplistic and they fail to recognize the work by others on hyperspectral infrared sounders from the past four decades. IASI has been in orbit since 2006. Its predecessor, AIRS, was launched in 2002 and both instruments have since seen two CrIS instruments join them in low Earth orbit. At the turn of the century, these hyperspectral infrared sounders revolutionized space-based vertical atmospheric observations. Now, we have nearly two decades of real measurements publicly available as a scientific community and well documented retrieval products from multiple different algorithms with which to study weather and climate phenomena. The existing record of retrieval products and the algorithms they are based on is by no means perfect or complete, but I fail to see how the work presented in this paper contributes to this body of knowledge.

Response:
The referee questions the scientific value of our study with respect to the established hyperspectral infrared (IR) retrieval literature. However, the main goal of our study is not to

establish a new retrieval method, in fact we view our retrieval setup merely as a tool to assess the findings of Stevens et al. (2017) and Elevated Moist Layer (EML) retrievability in general. We provide new insights within this scientific context, namely whether temperature induced errors in the water vapor retrieval are capable of masking EMLs. In addition, we view our study as a first systematic attempt of characterizing moist layer retrievability for hyperspectral IR instruments by introduction and application of a new evaluation method in Sect. 3 and 6. We realize that the way we presented the introduction and retrieval section have led to this misunderstanding and amended this as follows:
To frame our study more clearly, we adjusted the Introduction to clarify the purpose of our own synthetic OEM retrieval, namely to investigate a possible physical explanation for the EML blindspot and to conduct a first systematic analysis of moist layer retrievability. We also shortened the technical OEM retrieval description in Sect. 2, to avoid centering the reader's attention on these established details. Finally, we acknowledge that citing more retrieval literature that previously considered moist layer cases is something our manuscript benefits from. We thank the referee for pointing out relevant studies in that context. In our revised manuscript we added Sect. 1.1 to discuss these and some additional studies we found to be relevant. With this section, we aim to put the findings of Stevens et al. (2017) into context of current retrieval literature and to clarify the entry point of our own study, making the frame of our study more clear from the beginning. We also added more retrieval literature references throughout the manuscript to emphasize the novelty of our findings.

Changes to manuscript:

1. We clarify our motivation for introducing an OEM retrieval setup in the Introduction (L. 56):
   "In Sect. 2, we introduce our own basic Optimal Estimation (OEM) retrieval setup that we extensively use later on to investigate a physical cause for missing the EML structure and to attempt a first quantitative and comprehensive analysis of moist layer retrievability".
2. We condensed the technical description of our retrieval algorithm to the most important information and simply cite Rodgers (2000) for more technical details (L. 179):
   "Besides the state vector depicted in Eq. 1, our OEM setup includes profiles of other atmospheric absorption species, namely N2, N_2O, CH_4, O_2, CO_2 and O_3 as fixed forward model parameters. To account for nonlinearity, an iterative Levenberg-Marquardt (LM) solver (Levenberg, 1944; Marquardt, 1963) is used, which as input, besides the (synthetic) spectrum needs a priori and measurement covariance matrices, an a priori state vector and Jacobians, calculated for each iteration step by a forward model. We follow the notation introduced by Rodgers (2000), who provides an elaborate description of the procedure."
3. We added a significant number of retrieval studies as references and try to put our results more in context in order to communicate our study's contribution to the existing retrieval literature more clearly.
   a. Addition of Sect. 1.1 about moist layers in previous retrieval studies. Includes discussion of Smith et al. (2012), Weisz et al. (2013), Smith and Weisz (2018), Zhou et al. (2009), Calbet et al. (2006) and Chazette et al. (2014). We introduce the purpose of this section in L. 55:
      "We start out by providing additional scientific context to the findings of

    Stevens et al. (2017) by briefly reviewing the results of other hyperspectral IR retrieval studies that investigated EML-like cases in Sect. 1.1."

  b. We highlight awareness that a temperature error dependence of the humidity retrieval is an established fact, while we contribute new results on how this applies to an EML scenario (L. 324):
    "While other previous retrieval studies deliberately try to account for this issue by deploying either a simultaneous retrieval approach (Smith et al., 2012; Weisz et al., 2013; Irion et al., 2018) or a sequential retrieval approach (Smith and Barnet, 2019, 2020; Susskind et al., 2014) we want to highlight the importance of doing so, specifically in an EML scenario."
  c. We put the retrieval results of our case study (Sect. 4) in context of other OEM based moist layer case studies (L. 358):
    "We conclude that while the EML investigated by Stevens et al. (2017) does not appear to pose a general blind spot for hyperspectral IR satellite observations, we are able to find a retrieval configuration that reproduces a similar result as theirs. The deciding property of that configuration is the lack of independent temperature information, which in an EML scenario can yield radiatively compensating errors in temperature and water vapor. With retrieval setup 1 on the other hand, we present a retrieval setup that is able to capture both temperature and humidity profiles well, including the EML, which is in line with other OEM based moist layer case studies (Zhou et al., 2009; Calbet et al., 2006)."
  d. We put our averaging kernel analysis for an EML scenario into context of similar analyses of other studies (L. 369)
    "Several previous studies showed IASI averaging kernels for mean atmospheric states (Lerner, 2002; Schneider and Hase,2011; Smith and Weisz, 2018). Here we want to highlight the dependence of vertical resolution on the atmospheric state by contrasting the averaging kernels of a tropical mean atmosphere to the reference EML case discussed in the previous subsection. Smith and Barnet (2020) also considered the dependence of ***A*** *on the atmospheric state, which they find can be quite severe. In contrast to their more general study, we want to focus on comparing the variability of* ***A*** *with respect to a well characterised mean and EML state."*
    L. 385:
    "The averaging kernels of the mean tropical ocean atmosphere in Fig. 5(a) expectably show a very smooth behaviour with height and the deduced vertical resolution is similar to that of Smith and Weisz (2018), e.g. it is on the order of 1.5 km throughout the free troposphere between around 200 to 800 hPa."

4. To address the notion that our experimental setup appears naive and our test cases appear simplistic, we added the following sentences at the beginning of Sect. 2 (L. 130):
   "Note that we do not aim our retrieval to be particularly performant or as versatile as operational retrieval schemes. Instead, we use the retrieval as a tool to assess basic moist layer retrievability on a low level of complexity."

Referee comment:
Hyperspectral infrared sounders have hundreds of channels that allow one to apply sophisticated channel selection methods (e.g., Gambacorta and Barnet, 2011; Coopmann et al., 2020; Rabier et al., 2002; Fourrié and Rabier, 2004; Fourrié and Thépaut, 2003; Engelen and Bauer, 2014; Collard, 2007; Ventress and Dudhia, 2014; Martinet et al., 2014; Chang et al., 2020) to stabilize and maximize information content for a target variable. As reader and reviewer, I think Section 2.1 can be strengthened with a short description of the main principles of the method they employed, followed by a justification for their total of 1845 channels. That is a lot of channels. Why did the authors not thin it down, given the large degree of redundant information in these channels?

Response:
We agree with the referee that we should communicate our decisions for channel selection clearer. Our channel selection method is not sophisticated since our retrieval is not required to be particularly performant. For water vapor information, we use the spectral range of Schneider and Hase (2011) because they showed promising error metrics with regard to the water vapor profile retrieval and because it is simple. The channels used include all IASI channels in the spectral range between 1190 to 1400 cm^{-1}. In the revised manuscript we add temperature information from all IASI channels in the longwave CO_2 band (15 µm) between 645 to 800 cm^{-1}. We do not want a thinning of channels with sophisticated methods because our aim is to explore the limitations of hyperspectral IR sounders to resolve the vertical moisture structures. Hence, the significance of our results is strengthened when we do not conduct a thinning of channels.

Changes to manuscript:
We added a paragraph to Section 2.1 (L. 162):
"As a final note on the channel selection, the aim with our retrieval is not to make it computationally efficient, but to use it as a tool to explore the limitations in resolving vertical moisture features with IASI. Hence, we do not deploy sophisticated channel selection methods, although we are aware of the rich literature in this context (Fourrié and Thépaut, 2003; Fourrié and Rabier, 2004; Collard, 2007; Martinet et al., 2013; Chang et al., 2020, among others)."

Referee comment:
"An interesting aspect of this study is the author's choice of using temperature channels from the shortwave IASI band. This is an unusual choice because, historically, radiative transfer models generated large biases for the shortwave channels due to non-LTE effects (Yin, 2016; DeSouza-Machado et al., 2007) that cause diurnal differences. This is mostly addressed in modern-era radiative transfer models (e.g., SARTA and RTTOV) so this effect is minimized so that data assimilation and retrieval teams are looking at the shortwave temperature channels anew. Do the authors see diurnal differences in their results? It will be interesting if the authors can repeat their study but with temperature channels from the longwave IASI band as comparison."

"Line 97: I'm intrigued by the authors' choice of using shortwave CO2 channels for retrieving temperature information. This is an unconventional choice as most operational retrieval and data assimilation algorithms employ longwave CO2 channels for temperature information.

Can the authors justify their choice and discuss the benefits of using these shortwave CO2 channels?”

Response:
The referee raises a good point that we did not sufficiently address up to now. The original motivation with using the shortwave CO_2 band was that there appears to be less interference from water vapor absorption than in the longwave CO_2 band, indicating more independent temperature information content. This can visually be seen in Fig. 1 of the manuscript. However, given the model frame of our study we admit that we did not sufficiently account for applicability of our results to real observations, where daytime dependent non-LTE effects are a severe issue in the shortwave bands, although progress is being made in that area (Matricardi et al., 2018). Hence, we decided to repeat our analysis based on the longwave CO_2 band, using the spectral range between 645 to 800 cm^{-1}. While this adaptation does not change any major conclusion of our study, it results in some non-negligible quantitative changes. Of the total of 1599 testcases we conduct the retrieval for, a converged solution was originally found in 1438 cases based on the shortwave CO_2 band. Now a converged solution is only found in 1288 cases for the longwave CO_2 band. Additionally, the derived moisture anomaly characterization metrics in general show a better performance of the retrieval based on the longwave than on the shortwave CO_2 band (Table 1). We attribute this behavior to the decreased noise level (relative to signal) in the longwave band (0.1 K, compared to 0.2 K in the shortwave band, Clerbaux et al., 2009), which increases the temperature information that can be obtained from it, counteracting our initial inference that more temperature information would be available from the shortwave band. To demonstrate the severity of this effect, we compare the temperature averaging kernels based on these two CO_2 bands in Figure 3. It is apparent that the kernels are greater in amplitude and smoother with height when using the longwave CO_2 band, explaining the better performance regarding retrieved moisture anomaly characteristics (Table 1).

Table 1: Comparison of mean moisture anomaly characterization metrics as fraction of Retrieved/Truth between conducting our analysis based on the shortwave (2150 to 2400 cm^{-1}) or the longwave (650 to 800 cm^{-1}) CO_2 band. All fractions are found to be closer to unity when using the longwave CO_2 band.

Moisture anomaly metric	**Shortwave CO_2 band Retrieved / Truth**	**Longwave CO_2 band Retrieved / Truth**
Thickness	137 %	117 %
Strength	83 %	85 %
Number of anomalies	72 %	80 %
Number of anomalies beneath 5 km	30 %	52 %

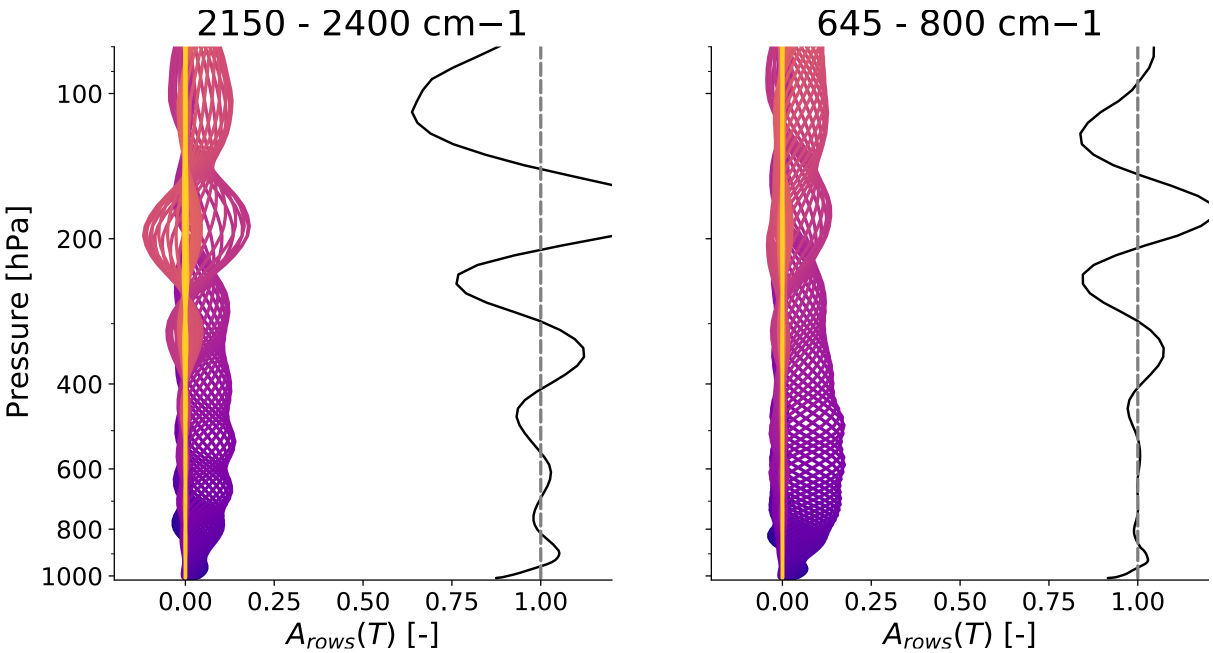

Figure 3: Temperature averaging kernels based on a tropical mean atmosphere, when only the spectral band denoted in the panels' respective title is used. For the lefthand panel a noise covariance of 0.2 K is assumed, while for the righthand panel a noise covariance of 0.1 K is assumed (Clerbaux et al., 2009).

We decide not to cover these findings in detail in our manuscript to avoid making it lengthier than it already is. However, for the purpose of tracking changes in the manuscript, we wanted to elaborate a bit more here.

Changes to the manuscript:

1. The change to the longwave CO_2 band implied remaking Figures 4 to 10.
2. We changed the associated paragraph in Sect. 2.1 and added some additional discussion (L. 146):
   "To reduce this error, we add independent temperature information to the retrieval from the spectral range between 645 to 800 cm^{-1}, which is part of the CO_2 absorption band centred around 15 µm (666.67 cm^{-1}). The blue shading in Fig. 1 indicates where water vapor independent information can be extracted from the spectrum, which is desirable to maximize temperature information content. Interestingly, Fig. 1 visually shows that the shortwave CO_2 band is associated with less water vapor interference in its flank between around 2200 to 2300 cm^{-1} than the longwave CO_2 band. […] However, due to known daytime dependent non-LTE associated biases and a worse signal to noise ratio in the shortwave channels of IASI (Razavi et al., 2009; Matricardi et al., 2018; Clerbaux et al., 2009), we stick with the longwave CO_2 channels."

We noticed a typo in the original manuscript about the assumed radiometric noise of that we add to our forward simulated synthetic spectra (L. 197 in revised manuscript, L. 150 in original manuscript):

"To better represent the instrument Gaussian noise with a standard deviation of 0.2 K for wavenumbers below 1750 cm^{-1} and 0.3 K above 1750 cm^{-1} is added to the forward simulated spectra (Clerbaux et al., 2009)."

For the calculations, however, we used values of 0.1 K for wavenumbers below 1750 cm^{-1} and 0.2 K above 1750 cm^{-1} (same for the measurement error covariance

assumption), which is in line with Clerbaux et al. (2009).
We changed this sentence to the following, also accounting for the fact that we do not use shortwave channels anymore:
"Gaussian noise with a standard deviation of 0.1 K is added to the forward simulated spectra to represent the radiometric noise of IASI within the spectral range used in this study (Clerbaux et al., 2009)."

Referee comment:
"Can the authors include a paragraph in their Summary section stating their thoughts on the value of their results to future algorithm upgrades or new instruments, like IASI-NG? Here are examples of how National Weather Service forecasters in the USA use NUCAPS retrievals (NOAA-Unique Combined Atmospheric Processing System) (Esmaili et al., 2020; Berndt et al., 2020), and the value they find in mid-tropospheric moisture retrievals. I wonder if the authors have observed EMLs in any one of the operational, publicly available retrieval products from NUCAPS (CrIS and IASI), CLIMCAPS (AIRS and CrIS), AIRS V7 or the EUMETSAT IASI Level 2 products? Do these products fail to sufficiently capture the EMLs in question?"

Response:
We added a section at the end of our summary to give an outlook along the lines of the referee's recommendation. We have not had a comprehensive look at operational products' capabilities to resolve EMLs yet, although we looked at some individual cases of the EUMETSAT IASI L2 product, with mixed impressions. Fig. 4 shows the two examples we have considered up to now: The top panels show a dropsonde sounding and the L2 profiles for a particularly well collocated case (within 15 km, 10 minutes apart) during the EUREC^{4}A campaign. There is no hint of the EML in the L2 retrieval. However, the EML in the other case (Fig. 2, bottom panels), which is the one discussed by Stevens et al. (2017) and used as reference in our manuscript, shows that the EML is resolved reasonably well by the L2 retrieval. We want to highlight that these plots are quite preliminary and very recent, hence not included in the manuscript. We plan to investigate these and more cases more deliberately in the upcoming months. Our idea is to keep an analysis of operational products separate from the more conceptual, model based work presented in the current manuscript. Instead, we want to focus on an analysis of operational products in a more dedicated study with more testcases.

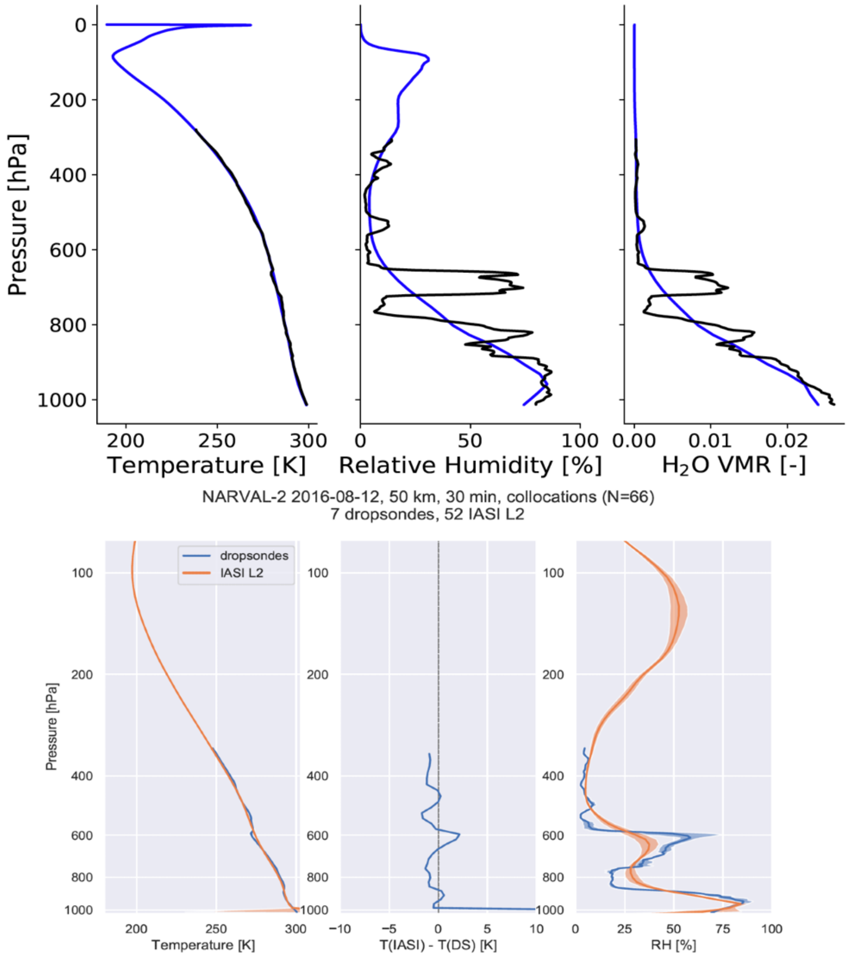

Figure 4: Profiles of temperature and humidity for collocated dropsondes with the IASI L2 product by EUMETSAT. Top panel shows case from the EUREC4A field campaign, where the blue line denotes the retrieval product and the black line the dropsonde profiles. Bottom panel shows collocations from the NARVAL-2 campaign that was also discussed by Stevens et al. (2017) and is extensively used as reference in our manuscript.

Changes to manuscript:

We added the following paragraph to the summary section (L. 604):

“In summary, the retrieval result of the EML case study shows that hyperspectral IR satellite instruments are in principle capable of resolving a sufficiently strong EML in an otherwise simply structured atmospheric profile. The statistical evaluation of retrieved moisture anomaly characteristics shows that the retrieval is able to represent moisture anomlies of various thickness, height and strength. Significant shortcomings are found in the lower to mid troposphere where about half of the moisture anomalies are missed by the retrieval and with regard to capturing particularly strong vertical gradients, causing limitations to resolve extreme cooling rates. It would be interesting to apply a similar analysis to operational retrieval products, such as the IASI L2 product (EUMETSAT, 2017), the NUCAPS product (NOAA Unique Combined Atmospheric Processing System, Berndt et al. 2020) or the CLIMCAPS product (Community Long-term Infrared Microwave Combined AtmosphericProduct System, Smith and Barnet 2020). The benefit of our new method for analysing moisture anomalies is that it allows for a direct statistical evaluation of the different product’s capabilities to resolve EMLs and vertical humidity structures in general by being easy to apply to large datasets. As a next step we plan to apply our retrieval and evaluation techniques introduced in this work to real IASI observations, with focus on EML-

like cases that we identify based on dropsonde observations from the NARVAL and EUREC^{4}A (Stevens et al., 2021) measurement campaigns. This may also serve as a good first testbed of data to assess operational products' capabilities to resolve the vertical moisture structures of interest."

Anonymous Referee #3, specific comments:

Referee Comment:
"Line 57: Can the authors give examples of what they mean by "instrument issues"? Clouds would be another factor."

Response:
Our statement on "instrument issues" was of rather general nature and we acknowledge that without specific examples, it is not useful. The major reason to conduct our study in a model framework is to reduce complexity in error sources, e.g. due to clouds, collocation uncertainty and forward modelling errors. By excluding these sources of error we hope to better be able to assess the more inherent limitations in resolving vertical moisture structures.

Changes to manuscript:
We rewrote large parts of the Introduction and introduce the synthetic nature of our retrieval with this new sentence (L. 58):
"This study is based on forward modelled (synthetic) observations to reduce the complexity of error sources (e.g. by collocation uncertainty, clouds, forward modelling errors) and to rather assess inherent limitations in resolving vertical moisture structures with hyperspectral IR observations."

Referee Comment:
"Line 72: Instead of simply stating "poses an inverse problem", I suggest preemptively qualifying this statement as "poses an under-constrained inverse problem"."

Response:
We agree with the referee that qualifying this statement here already as an under-constrained inverse problem is beneficial and made the suggested change.

Changes to manuscript:
L. 125:
"Extracting atmospheric state variables such as the temperature or concentrations of atmospheric constituents from passive satellite observations generally poses an under-constrained inverse problem."

Referee Comment:
"Line 80: There are many examples in the literature of research and operational retrieval algorithms that employ OEM for hyperspectral IR sounders, namely AIRS, CrIS and IASI. To strengthen this statement and communicate awareness of these other systems, I recommend that the authors add citations to these other OEM algorithms."

Response:
We agree with the referee that the addition of references to other retrieval algorithms helps in justifying the introduction of our own retrieval setup. We tried to implement this by highlighting the added discussion of retrieval studies in Sect. 1.1, which specifically motivates the introduction of our own OEM based retrieval and by pointing out the different scopes of operational algorithms compared to our own algorithm.

Changes to manuscript:
L. 127:
"The OEM approach showed the most promising results for resolving non-trivial moisture structures in the studies discussed in Sect. 1.1, but was also used for the missed EML case of Stevens et al. (2017). This motivates the introduction of our own OEM retrieval setup to more systematically assess possibilities and limitations in resolving EMLs. Note that we do not aim our retrieval to be particularly performant or as versatile as operational retrieval schemes (EUMETSAT, 2017; Smith and Barnet, 2020; Berndt et al., 2020)."

Referee Comment:
"Line 88: For those unfamiliar with the channel selection method of Schneider and Hase (2011), I recommend that the authors add a sentence or two explaining the basic premise. There are numerous approaches to selecting hyperspectral IR channels and I think a clarification and justification of the authors' choice will strengthen this work."

"Lines 99-102: I return again to the question about the channel selection method employed. Does the Boukachaba et al. (2015) method use the same principles as Schneider and Hase (2011)? A total of 1845 channels. How many of these channels are used for water vapor information? What are the exact spectral ranges where these channels come from? How many DOF does this set of channels have for water vapor versus surface and air temperature? I'm wondering how much spectral redundancy the authors are factoring into their method and why."

Response:
We tried to clarify our approach to channel selection earlier in the response and added a few sentences to Sect. 2.1 of the manuscript to communicate our approach clearer to the reader. We use all channels in the spectral range between 1190 – 1400 cm^{-1} to obtain water vapor information, a total of 840 channels, following Schneider and Hase (2011). Additionally, we add 5 channels for dedicated surface temperature information, following Boukachaba et al. (2015). The work of Boukachaba et al. (2015) is independent of that of Schneider and Hase (2011) and aims to retrieve land surface temperatures for which they simply choose the 5 IASI channels that we adopted with our setup. We also add the spectral range from 645 to 800 cm^{-1} to obtain additional temperature information, adding another 619 channels. This adds up to total number of 1464 channels that yield 12.91 DOFs in H_2O VMR, 23.54 DOFs in temperature and 0.99 DOFs in surface temperature.
We are aware that we are factoring in a lot of spectral redundancy, which we are now communicating to the reader in an added paragraph. We are not aiming for a particular performant retrieval with this study.

Changes to manuscript:

1. We now explicitly state that we use *all* spectral channels in the declared spectral range (L. 138):
   "We use all IASI channels in the range between 1190 to 1400 cm^{-1}, following the work of Schneider and Hase (2011), who demonstrated the suitability of this spectral range for retrieving profiles of water vapor and its secondary isotopologues."
2. We added information on the DOFs of the retrieval quantities based on our setup (L. 152):
   "The total DOF for water vapor in the used channel set is approximately 12.9, for temperature 23.5 and for surface temperature 0.99."
3. We added a paragraph on why we are not applying more sophisticated channel selection techniques (L. 162):
   "As a final note on the channel selection, the aim with our retrieval is not to make it computationally efficient, but to use it as a tool to explore the limitations in resolving vertical moisture features with IASI. Hence, we do not deploy sophisticated channel selection methods, although we are aware of the rich literature in this context (Fourrié and Thépaut, 2003; Fourrié and Rabier, 2004; Collard, 2007; Martinet et al., 2013; Chang et al., 2020, among others)."

Referee Comment:
"Line 90: The spectral signal of water vapor is sensitive to temperature, yes, but also mid-tropospheric methane, surface emissivity and temperature and nitrous oxide (to a lesser degree)."

Response:
We acknowledge that besides a sensitivity to temperature, the water vapor signal is sensitive to the other parameters stated by the referee, which we did not explicitly mention. We include these now to present our awareness and argue that temperature induced errors are more significant than other sources of error, based on previous studies of Schneider and Hase (2011) and Borger et al. (2018). Besides, we decided to add nitrous oxide and methane as absorption species with fixed concentrations to our forward simulations, which we had previously left out for simplicity. When redoing our calculations anyway, this was an easy to make addition.

Changes to manuscript:

1. L. 141:
   "The spectral signal of water vapor depends not only on the atmospheric water vapor itself but also on the temperature, surface emissivity and temperature, methane and nitrous oxide. Schneider and Hase (2011) and Borger et al. (2018) concurrently found that temperature induced errors can yield up to 15 % relative error for the lower to mid tropospheric H_2O retrieval, which is significant compared to other sources of error, such as interfering species."
2. Figure 1:
   We updated Figure 1 to include methane and nitrous oxide.

Referee Comment:
"Lines 95-96: Can the authors substantiate this statement with a citation?"

Response:
The sentence referred to by the referee (L. 94 – 96) does include citations to two studies. Hence, we don't see the need for any change here.

Changes to manuscript:
None

Referee Comment:
"Figure 1: I'm wondering if I read this figure correctly. Does each IASI channel in the range 1250 – 2000 cm-1 have 1 x degree of freedom (DOF)? This appears too high. Can the authors explain how they defined their variables for the Rodgers (2000) DOF equation?"

Response:
We can see that we introduce the contents of Fig. 1 insufficiently in the text, leaving the reader too much room for questioning what we are attempting to show. However, the referee is right in their assumption that in fact the channels between 1250 – 2000 cm^{-1} yield DOFs very close to unity. We calculate them using the equation of Rodgers (2000), e.g. by calculating the trace of the channel specific averaging kernel matrix. We calculate the channel specific H_2O averaging kernel matrix by feeding in the relative Jacobian Vector of the respective channel, the logarithmic H_2O VMR covariance matrix and the noise covariance matrix, which is just a 1x1 matrix for one channel. The relative Jacobian refers to the fact that we use a fixed relative change of H_2O VMR with height instead of a fixed absolute change to calculate the change in Brightness Temperature. The relative approach is directly compatible with the logarithmic H_2O VMR covariances we are feeding into the averaging kernel calculation. The Jacobian matrix is obtained with ARTS based on a mean tropical ocean atmosphere. We want to highlight that while each channel may yield a DOF close to unity, there is significant redundancy between the channels. In Figure 5 we show the same basic plot as in the manuscript, but we show the DOFs gained from each channel, when the DOFs from the channel at 1450 cm^{-1} (randomly chosen as an example) is used as the baseline, e.g. we calculate the DOFs of the 1450 cm^{-1} by itself and subtract that number from the DOFs obtained when using any of the other channels paired with the 1450 cm^{-1} channel. We find that channels near the 1450 cm^{-1} channel yield significantly decreased additional information and channels on the other flank of the 6 µm H_2O band that are similarly sensitive do, too. This behavior gives us confidence that our calculations are plausible.

Changes to manuscript:
L. 148:
"The shading in Fig. 1 indicates the H_2O degrees of freedom (DOFs) calculated as the trace of the averaging kernel matrix when only each respective channel is used (Rodgers, 2000). It is apparent that water vapor absorption is significant throughout most of the thermal IR spectrum, yielding DOF values close to unity. Blue shading indicates where water vapor

independent information can be extracted from the spectrum, which is desirable to maximize temperature information content. Note that channels are highly redundant, so DOFs of individual channels do not add up. The total DOF for water vapor in the used channel set is approximately 12.9, for temperature 23.5 and for surface temperature 0.99."

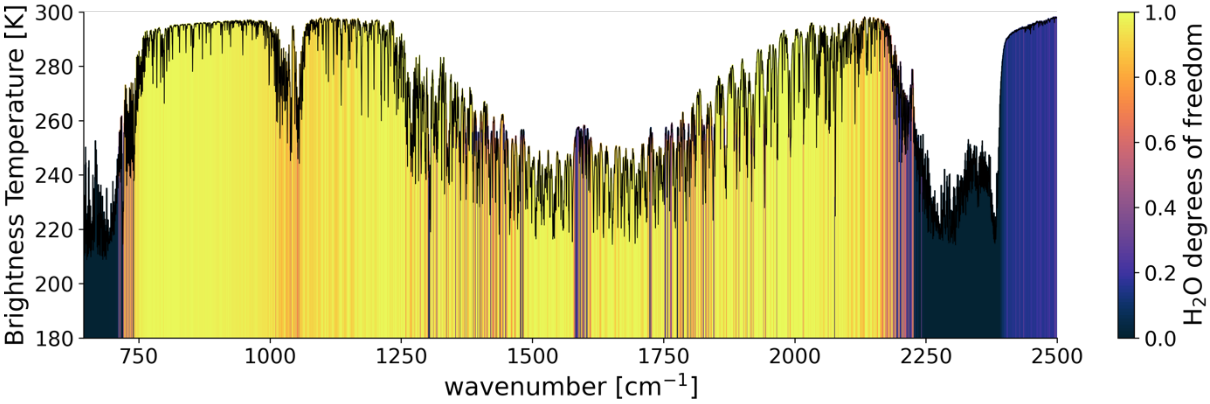

Figure 5: Same as Fig. 1 in the manuscript, but DOFs now refer to the added DOFs of each channel, in addition to the DOFs obtained when only the channel at 1450 cm^{-1} is used. We calculate this by calculating the DOFs based on pairing each respective channel with the 1450 cm^{-1} channel and subtracting the DOFs of the 1450 cm^{-1} by itself.

Referee Comment:

"Line 141: This is the first time I read of ARTS. For IASI radiative transfer calculations, I'm much more familiar with RTTOV. From reading this section, I conclude that the authors used ARTS for its "internal OEM module" (Line 155), and not for its more accurate shortwave radiative transfer calculations. Is this correct? And are the authors confident that ARTS calculate non-LTE effects for IASI shortwave IR channels correctly? What vertical grid does ARTS employ?"

Response:

The referee is correct in concluding that a major reason for using ARTS instead of RTTOV is its internal OEM module. Although ARTS has some capability to handel non-LTE, this was not used the present study, which is why in the revised version we swapped to the longwave CO_2 band as thoroughly discussed earlier in this response. ARTS internally employs a pressure grid as its vertical coordinate.

Changes to manuscript:

None

Referee Comment:

"Line 207: "making the term EML more graspable"… What does this mean?"

Response:

We agree that this is an unclear expression. We try to articulate here that an aim with our new framework is for it to be an intuitive quantitative description of what we consider an EML.

Changes to manuscript:

L. 252:

"This section introduces a quantitative framework to identify and characterise EMLs. This framework on the one hand aims to provide an intuitive quantitative description of moisture

anomaly features through a number of scalar moisture anomaly characterisation metrics and on the other hand allows for a more targeted evaluation of retrieval results in Sect. 4 and 6."

Referee Comment:
"Line 209: "EMLs can be described as layers of anomalously large humidity…". This is a very awkward statement that I struggle to understand."

"Line 210: "one unconsciously also envisions"? I suggest rewriting this paragraph. It is difficult to follow."

Response:
We agree with the referee and decided to cut the paragraph out completely as it did not contain any important information but was simply used to setup the more important paragraph afterwards. After rereading, it does not appear necessary to have such a paragraph.

Changes to manuscript:
Deleted paragraph in question (L. 255).

Referee Comment:
"Paragraph starting on line 215: I fully agree with the authors statement and appreciate their clear explanation here."

Response:
We appreciate the positive feedback of the referee about the clarity of our explanation.

Changes to manuscript:
None

Referee Comment:
"Line 234: As made clear from the beginning, the study the authors present here is in response to the findings by Stevens et al. (2017). I see the value in using the same atmospheric test case and this makes me wonder if Stevens et al. (2017) also used ARTS? The results the authors present here draws a different conclusion, but how much of that is due to differences in experimental set up, e.g., choice of radiative transfer model, channel subsets, simultaneous retrieval of air and surface temperature, etc. I'm curious to know how the water vapor averaging kernels compare between your study and that of Stevens et al. (2017). Did the authors achieve a similar signal-to-noise?"

Response:
The referee rightfully inferred that our work is closely tied to the findings of Stevens et al. (2017), who did not use ARTS but, as we understand it, a model called "Atmosphit" that was used by Lacour et al. (2012), a predecessor study of Stevens et al. (2017). In the revised version of Sect. 4 in our manuscript we try to more clearly communicate, that while we use the same testcase as Stevens et al. (2017), we do not aim to reproduce their exact setup.

Instead, we use our own setup to explore whether temperature induced errors are capable of preventing the EML from being resolved as observed by Stevens et al. (2017). Unfortunately, there are no averaging kernels available from the study of Stevens et al. (2017) or Lacour et al. (2012). We are also not aware of their signal-to-noise, either.

Changes to manuscript:
We added the following paragraph to Sect. 4 to point out our caution regarding direct comparability of the results of Stevens et al. (2017) to our study (L. 313):
"As a note on comparability of our results to Stevens et al. (2017), we want to be cautious. There are several differences in the exact way the retrieval is setup, e.g. in the assumed a priori states and covariances, the iteration scheme (Gauss-Newton vs.LM) and also the radiative transfer model (Atmosphit vs. ARTS). Besides, our study is conducted in a synthetic framework, since we aim to assess the retrieval of EMLs more fundamentally than the discussed case studies did up to now. With this in mind, we tried to seek out a retrieval feature of the study of Stevens et al. (2017) that is capable of masking the EML in our setup. This feature is the used spectral region that is closely tied to the temperature information content as we want to show in the following."

Referee Comment:
"Line 271: This statement starting with "Note that…" should be introduced and explained early on in the text to avoid creating the confusion that I now find myself in as reader and reviewer."

Response:
We understand the referee's confusion and added a sentence about this to the Introduction.

Changes to manuscript:
L. 65:
"We want to note that we do not aim to reproduce the results of Stevens et al. (2017), but discuss a possible physical reason for their found EML blindspot."

Referee Comment:
"Line 281: ". It shows that the EML strength s_anom of retrieval setup 1 is about half the value of the true state". What does this mean?"

Response:
We understand that the moisture anomaly strength is the least trivial of the quantities and revised this section by adding more thorough explanations of how the results can be interpreted. We want to highlight, though, that by putting the s_{anom} values in relation to each other, they should appear more intuitive than by themselves. For example, underestimating s_{anom} by a factor of 2 with the retrieval indicates that only half of the mean anomalous H_2O VMR is captured by the retrieval. We hope that we convey this more clearly in our revised manuscript.

Changes to manuscript:
We discuss the resulting s_{anom} values in a dedicated paragraph (L. 352):
"*While the EML strength s_{anom} may appear as the least trivial moisture anomaly characteristic, being without units due to its definition based on VMR H_2O, it becomes more intuitive when values are put into relation to each other. The true EML strength of $2.8 \cdot 10^{-3}$, which reflects the mean anomalous VMR H_2O within the EML, is about about 30 % greater than the EML strength derived from retrieval setup 1 and about 2.5 times greater than the EML strength derived from retrieval setup 3.This reflects the notion that while retrieval setup 1 is able to resolve the EML well, retrieval setup 3 yields a strongly smoothed EML that is significantly less pronounced than its true counterpart.*"

Referee Comment:
"Table 2: I assume the authors converted profiles in pressure units to distance units using the geopotential height calculation? It will be helpful if the caption explain what "Strength" means. Of the four quantities reported here, "Strength" is the most obscure and abstract, being without units."

Response:
We use the pressure and altitude grids that are part of the ECMWF IFS profile database (Eresmaa et al., 2012). For the case study in Sect. 4, we interpolated the dropsonde profiles to a pressure grid that is part of the ECMWF IFS profile database. We added a sentence to the caption of Table 2, reminding that explanations to the metrics are given in Table 1. In the revised version of Sect. 4 we now more deliberately split the discussion of Table 2 from the rest and try to put more context to the results shown in Table 2.

Changes to manuscript:
L. 309: We add information on our vertical grid.
"As a technical note, we extrapolate the dropsonde profiles (launched at about 350 hPa) into the upper troposphere and above by fitting a tropical mean atmospheric state (Anderson et al., 1986).We fit these profiles onto a 137 level vertical pressure grid of the ECMWF IFS model atmospheres that also come with an associated altitude grid (Eresmaa and McNally, 2014)."
L. 339 – 357: Revised discussion of Table 2.

Referee Comment:
"Lines 287-299: I appreciate the authors' clear, direct response to Stevens et al. (2017), refuting their notion that hyperspectral IR measurements lack mid-tropospheric water vapor information. I agree with the authors' main conclusions here, but as stated earlier, it is well established that the retrieval of water vapor information depends on knowledge about temperature. I suggest that the authors acknowledge this with relevant citations. E.g., as far as retrieval systems go, there is the simultaneous approach (Smith et al., 2012; Weisz et al., 2013; Irion et al., 2018) and sequential approach (Smith and Barnet, 2020, 2019; Susskind et al., 2014, 2003; Maddy et al., 2009) to account for temperature uncertainty in water vapor retrievals."

Response:
We agree with the referee that we should make a clearer distinction between what is

established knowledge and where the novelty in our work lies, in particular with respect to temperature induced errors.

Changes to manuscript:

1. We added a sentence to the beginning of Sect. 4 (L. 296):
   "*While in general it is well known that the humidity retrieval depends on the quality of the assumed or retrieved temperature profile, we arguethat for EMLs this effect is of particular relevance.*
2. We added the references suggested by the referee to Sect. 4 (L. 324):
   "*While other previous retrieval studies deliberately try to account for this issue by deploying either a simultaneous retrieval approach (Smith et al., 2012; Weisz et al., 2013; Irion et al., 2018) or a sequential retrieval approach (Smith and Barnet, 2019, 2020; Susskind et al., 2014), we want to highlight the importance of doing so, specifically in an EML scenario."*

Referee Comment:

"Line 316: "Values close to 1 indicate a good sensitivity of the retrieval." This sentence is misleading since it appears to refer to the black line in Fig. 5(a) and (c). The correct statement should be: Averaging kernel values close to 1 indicate strong sensitivity of the retrieval to the true state. But because the inversion of hyperspectral IR measurements into water vapor profiles is, by definition, an under constrained, ill-posed solution, averaging kernels never approach 1 (see Smith and Barnet, 2020 and references therein)."

Response:

We agree with the formulation of the referee about individual averaging kernels. While we do not see a direct contradiction to our statement about the measurement response (black line), we assume the referee is implies that our wording overvalues a measurement response close to 1. We hope that by slightly weakening our statement it remains valid without being misleading. While a measurement response close to unity (black line) indicates that the retrieval is generally able to detect and respond to a disturbance in a given height, an averaging kernel near unity would imply a near perfect ability of the retrieval to resolve the disturbance. Hence, we would argue that both measures, the kernels themselves and the measurement response, offer insight to the capabilities of the observing system. We chose our formulation along the lines of Rodgers (2000), who we now also reference in this context.

Changes to manuscript:

L. 381-384:

1. We replace the word "capture" by "detect and respond to" to avoid misleading the reader to think the measurement response is a very strong quality measure of the retrieval.
2. In the same spirit, we also changed the last sentence of the paragraph to:
   "Values close to unity indicate that the retrieval is sensitive to disturbances in the true profile (Rodgers, 2000)."

Referee Comment:
"While accurate, this discussion lacks depth without citations and only a single example of "an exemplary" EML case. I wonder how the water vapor averaging kernels for EML's change under different temperature conditions, such as day versus night. Can the authors include a sentence on the sensitivity of averaging kernels to different EML cases?"

Response:
We added references to Sect. 4.2 to better put our results into context of other studies that presented hyperspectral IR averaging kernels. We thank the referee for pointing out some relevant studies in that context. While interesting, adding more discussion on averaging kernels for varying EML cases appears to us to go beyond the scope of our intended discussion, with the manuscript already being on the lengthy side. We are looking forward to conduct a similar analysis for more cases and based on real observations in the future, as we point out in our Summary.

Changes to manuscript:
L. 369:
"Several previous studies showed IASI averaging kernels for mean atmospheric states (Lerner, 2002; Schneider and Hase,2011; Smith and Weisz, 2018). Here we want to highlight the dependence of vertical resolution on the atmospheric state by contrasting the averaging kernels of a tropical mean atmosphere to the reference EML case discussed in the previous subsection. Smith and Barnet (2020) also considered the dependence of ***A*** *on the atmospheric state, which they find can be quite severe. In contrast to their more general study, we want to focus on comparing the variability of* ***A*** *with respect to a well characterised mean and EML state."*
L. 385:
"The averaging kernels of the mean tropical ocean atmosphere in Fig. 5(a) expectably show a very smooth behaviour with height and the deduced vertical resolution is similar to that of Smith and Weisz (2018), e.g. it is on the order of 1.5 km throughout the free troposphere between around 200 to 800 hPa."

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