ACP-2022-505 – Vertical structure of the lower-stratospheric bias in the ERA5 reanalysis and its relation to mixing processes

By Krüger et al. (2022)

Reply to the Editor

I agree with the referees that this is in excellent study. While waiting for the second referees comment I also had a look at the manuscript and have a bunch of rather technical comments which I would like the authors to consider when they do the revision. We thank the editor for the positive feedback and the careful revision of our manuscript. We answered each comment below using a blue font.

Generally comment:

I would suggest to write throughout the manuscript "moist bias" instead of just "bias" and "jet stream" instead of just "jet". We followed the editor's recommendation wherever applicable.

Specific comments:

P1, L10: What kind of errors/uncertainties does this cause? Regarding e.g weather, does it affect predictions for cloud formation and/or precipitation? Can you give an example? We do not want to detail the impact on climate and weather predictions in the abstract, but the reader can find all relevant information in the introduction and discussion sections. Future studies may focus on implications of the bias and ways to improve the analyses. These points are partly raised in the discussion.

P1, L13: Mention here also how many campaigns were preformed. Corrected. We included the number of campaigns.

P1, L14: The number of 31000 humidity profiles is impressive, However, could you also provide the time resolution of the data?

We think that this is too much detail for the abstract, but of course the reader can find this information about temporal and spatial resolution of the data in Sec. 2.1.

P1, L21: Add here "(O3)" after ozone and "(H2O)" after water vapour to introduce the abbreviations that are used then in the next line. Thank you for pointing to this inconsistency. Instead of using the abbreviations we consistently rely on "water vapor" and "ozone" throughout the manuscript.

P1, L26: I would add after positive impact "i.e. more accurate" since I think that will be the outcome positive impact of a lower moist bias on the forecasts. We clarified this sentence and replaced the "*positive impact on weather and climate forecasts*" by *"lead to more accurate weather and climate forecasts"*.

P1, L20: See my comment on P1, L13. That is why I suggest to mention above already that several campaigns have been performed. Otherwise writing here "During one campaign" is rather confusing. We included the number of campaigns as documented above and therefore think "during one campaign" should be clear now.

P2, L29ff: This paragraph is rather confusing. I would suggest to revise it. Start with describing the general vertical distribution of H2O (high in in the troposphere, low in the stratosphere) and then discuss the gradient and the exchange between troposphere and stratosphere. The vertical distribution of H2O is not only dynamically driven, also the chemical sources and sinks of H2O play a role.

We cannot completely understand where the confusion comes from. The first sentence highlights the general relevance of water vapor. We removed the second sentence (impact on the T-profile), which is repeated later and might be confusing. Then we actually start with the distribution and its UTLS

impact, which is at the centre of this study. Afterwards, we close the paragraph with relevance of the vertical structure for weather and climate.

We agree that the dynamical processes are only part of the complete story. Therefore, we revised a sentence in the second paragraph, which now reads as follows: *"In the extratropical UTLS, the distribution of water vapor is driven by transport and mixing processes related to baroclinic waves and associated synoptic and meso-scale weather systems, which are interacting with chemical processes (e.g., Gettelmann et al., 2011; Schäfler et al., 2022)."*

P2, L56: co-loacted cold bias. Where exactly is this bias located? Also in the stratosphere? Or in the atmospheric layer below (troposphere) or above (mesosphere)? Updated. In order to be more specific, we added "*at the same altitudes*" to the sentence.

P3, L65: "for" is not correct here. Do you mean "from" different radiosonde types (thus two types of radiosondes show the opposing vertical structure) or do you mean "by comparing to two different radiosonde types"? In the updated version, we now use *"from"* instead of *"for"*.

P3, L65ff: I would suggest to rephrase the sentence and to start with what Woiwode et al. compare with and then what the result is. Corrected as suggested.

P3, L71ff: This sentence/paragraph is also rather confusing and should be improved. Numerical diffusion is something that affects Euler models, especially if a rather course grid is used, thus naming in this sentence the "semi-Lagrangian" is a bit confusing. Further, two my knowledge not the ECMWF model itself is Lagrangian, its rather one of the schemes used in the model that is semi-Lagrangian. You actually name it, it is the advection scheme. So it should read rather "the semi-Lagrangian advection scheme used in the ECMWF model". Corrected as suggested.

P3, L79: highest altitude → give an approximate altitude. Instead of *"highest altitude"*, we use *"> 2 km above the tropopause"* in accordance with Bland et al. (2021)

P3, L82: The reference of Hegglin et al. (2009) is not correct here. In that study ACE data has been used which is a solar occultation instrument and not a microwave sounder. I think the Hegglin reference you meant here is the paper where the H2O climatologies are compared (Hegglin et al., 2013, JGR). Also here additionally some of the WAVAS-II comparison papers should be cited (e.g. Lossow et al., (2017, 2018), Khosrawi et al. (2018), Read et al. (2022), see WAVAS special issue https://acp.copernicus.org/articles/special_issue830.html although I am not sure if one of the studies explicitly mentions the problem with the vertical resolution of the microwave sounders. We are grateful for pointing to the incorrect reference and for suggesting Khosrawi et al. (2018), which we were not aware of. The references were updated.

P4, L101: Not clear what you mean here with air mass classes. Through removing the term "*air mass class*", we tried to clarify the sentence in the outline, which now reads as follows: *"The relationship between the vertical structure of the moist bias and the distribution of tropospheric, stratospheric and mixed air is presented in Sect. 3."*

P4, L113: Rephrase. Not the wavelengths itself consist of online channels. Rather the observations at these wavelengths are separated into the/by the channels". Corrected as suggested.

P4, L116: The wavelength ranges have been optimized? We now use "*are selected*" instead of "*have been optimized*".

P4, L116: Also here rephrase the sentences. Generally, the whole paragraph should be revised. We considered the two previous comments to make this paragraph clearer. Apart from this, we kept this paragraph, as it was not clear to us what needs to be changed to further improve comprehensibility.

P5, L155: This sentence is also rather confusing. Better to write "parts of the HALO flight tracks of all research flights where DIAL observations where obtained." Corrected as suggested. We furthermore

revised the whole paragraph (starting P5, L137 in the preprint version) to give it a clearer structure. This paragraph now reads as follows:

"In this study, we use DIAL observations from six campaigns from 2013–2021 that provide almost 33000 water vapour profiles obtained during 41 research flights. The profiles were sampled along the flight track and extend from the surface up to about 14 km altitude corresponding to the maximum flight level of the HALO aircraft (Krautstrunk and Giez, 2012). As the focus of this study is the midlatitude UTLS, we only consider flights that provide a significant amount of data across the tropopause. The majority (25) of these flights took place in the northern hemispheric fall season during the North Atlantic Waveguide Downstream impact EXperiment (NAWDEX; Schäfler et al., 2018) and the Wave-driven ISentropic Exchange campaign (WISE; Kunkel et al., 2019). As part of the campaigns ElUcidating the RolE of Cloud-Circulation Coupling in ClimAte (EUREC^{4}A; Stevens et al., 2021), the Next-generation Aircraft Remote sensing for VALidation studies (NARVAL; Klepp et al., 2014) and NARVAL2 (Stevens et al., 2019) measurements were taken during eight flights in winter season. In addition, the Cirrus in High-Latitudes (CIRRUS-HL) mission provides observations in summer. Figure 1 depicts the parts of HALO research flights where DIAL observations were obtained. Most flights were carried out over the North Atlantic between 48 °N and 66 °N, the North Sea and central to western Europe. Additionally, the subtropics (> 35 °N) and the Arctic were covered by individual flights as well.

During the WISE campaign, WALES was operated in a different setup to measure both water vapour and ozone, concurrently. For this purpose, two of the 935 nm NIR water vapour channels were replaced by two ultraviolet (UV) channels covering the 300–305 nm ozone absorption line (Fix et al., 2019). The use of two instead of four channels per trace gas leads to a reduced vertical coverage which was optimized so that the selected NIR wavelengths cover the tropopause region. Increased statistical noise required averaging over a period of 24 s (~6 km horizontally) while the effective vertical resolution remains approximately 300 m (Fix et al., 2019)."

P8, L186: T639? Is there something missing? Usually the T gives the horizontal resolution and the L the number of levels. We understand this comment as one can find different terminologies in literature. However, we follow table 2 in Hersbach et al. (2020) where "TL639" to used for the spatial resolution of ERA5.

P8, L192: You mean you do here the conversion from sigma coordinates to pressure coordinates? We don't want to go into more detail here as the procedure is documented in the given ECMWF reference. In summary, pressure on model levels needs to be calculated using specific coefficients and surface pressure. By using pressure and temperature the altitude is derived.

P9, L210: "respectively" not correct here, either it should read "...and the lapse rate, respectively" or if you mean the vertical temperature gradient is equal to the lapse rate then it should read "The vertical temperature gradient, i.e. the lapse rate". Corrected.

P9, L211: provide the unit in the text (and based on the ACP style it should read k m-1). Thanks for pointing to this inconsistency. We now use the ACP style for the units.

P13, Figure 5: Could you add a panel showing the bias in percent? In Sect. 2.3.2 we pointed out that the selection of an adequate statistical metric is crucial for a reliable quantification of humidity errors in the UTLS. Hence, we decided to use the logarithmic formulation of the bias which is symmetrically centered around zero and not distorted after averaging (which is not the case for calculating the ratio Q_{ERA5} / Q_{DIAL}. (see Kunz et al., 2014). Since we are aware that this log bias is more difficult to interpret, we provide the corresponding percentage value for each given value of the log bias. In addition, table 2 should help the reader.

P14, L303: Can you also add the mean bias in percent? We believe that we already had included % values in the preprint version: "*The bias increases to a maximum of +0.63 (55 %) at 1.3 km altitude above the tTP*"

P23, L439, L440 and 455: "Highest altitude" → Give here an approximate altitude. We added altitudes.

Last but not least, the original referee 2 who unfortunately could not submit a report, but thinks your study is excellent, asked why you did not use any in-situ data that was obtained during the campaigns?

We thank for providing this question. Our study focusses on the humidity profile data set from the WALES lidar, which extends previous work using comparable in situ data (Kunz et al., 2014; Kaufmann et al., 2018; Bland et al., 2021). We demonstrate that our unique data set with its large number of vertical profiles allows us to better characterize the bias in the vertical and the collocated water vapor/ozone observations indicate a possible origin. We do not think that in situ data with a limited amount of profiles would add more information for this purpose. Certainly, in situ data may be useful to pinpoint processes that are responsible for the bias in future studies.

Technical corrections:

P1, L14: data set → observations Corrected.

P1, L15: add "of moisture" so that it reads "vertical gradients of moisture" Corrected.

P1, L22: small → smaller (?), since you use "higher" before it should read here rather "smaller". Otherwise you could write "high" and "small". Corrected.

P2, L32: a layer → the layer Corrected.

P3, L92: from WALES? Please add. It was not clear to us how to add "from". WALES is the DIAL's name so that we think the sentence should be okay.

P4, L124: a DIAL → the DIAL Corrected.

P5, L126: Not clear. Leakage of what? In this sentence, we wanted to point to the main differences of the averaging kernels between active and passive remote sensing techniques. We tried to improve the comprehensibility of this paragraph, which now reads as follows:

"It should be stressed, that the averaging kernel of the WALES DIAL is exactly zero outside of about $\sqrt{2}$ *times the effective resolution. This is in sharp contrast to most passive remote sensing techniques where the side modes of the kernels can lead to erroneous dry or wet layers in the retrieved humidity profile."*

P5, L140: coverage → resolution We kept coverage which we think is correct at this place. The reduced number of online wavelengths reduces the data coverage, as these wavelengths are selected to be sensitive to different water vapor concentrations and in turn to different altitude ranges. The 4-wavelength DIAL allows to measure water vapor profiles from the LS to the ground while the 2-wavelength setup (with additional ozone capability) covers only the UTLS.

P5, L144: delete "instrumented" and add "aircraft" after HALO Corrected.

P5, L157: Beyond this → However (or Additionally) Corrected.

P5, L157: are → were Corrected.

P8, L185: in 2016 → since 2016 (?) We kept "in" as the model cycles (model versions) change over time. Please see https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

P8, L187: with → of the Corrected.

P8, L189: one 1 hour intervals → with a time resolution of 1 h Corrected.

P9, L229: a typical location → the typical location Corrected.

P10, L242: Rephrase sentence so that it reads "gives some example values for the bias for certain moisture observations"? Updated. Selected?

P11, Table 2 caption: Add "Some" so that it reads "Some example values" and add "according" or "respective" before "computed". Updated.

P11, L251: introduced → provided Corrected.

P11, L260: lower → smaller (?) We agree that smaller is more appropriate here.

P11, L263: add comma after model and Eq(3). Corrected.

P12, Figure 4 caption: Write "On the panels are the…….superimposed". We revised the caption in a slightly different way: *"Vertical cross sections of (a) the DIAL specific humidity (colour shading, g kg^{-1}), (b) ERA5 specific humidity (colour shading, g kg^{-1}) as well as (c) the corresponding humidity bias (colour shading) on the 1st October 2017. (a) – (c) are superimposed by ERA5 fields of the potential temperature (grey contours, $\Delta\theta$ = 3K) and the isopleths of the wind speed (magenta contours, in m s^{-1}), and the thermal (thick black dots) and the dynamical tropopause (2 PVU, black isoline)."*

P14, L312: add "the" or "a" before bias. Corrected.

P14, L312: compared → compared to Corrected.

P15, L326: replace "=" by "i.e." Corrected.

P19, L372: illustrated → shown Corrected.

P23, L461: delete "the" before Dyroff et al. Corrected.