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 review #1

This paper evaluates the lower-stratospheric moist bias in a NWP reanalysis. A moist bias is a common problem in NWP and climate models in both the analysis and forecasts, as documented by others, but the novelty of this paper lies in the use of a large dataset of lidar data from aircraft observational campaigns covering several seasons and different years, and characterising well the vertical profile of the error in the latest reanalysis from ECMWF (ERA5). This is very relevant as the lower-stratospheric moist bias leads to a significant temperature error through radiative cooling, which has potential impact on the atmospheric circulation. Importantly, the paper largely confirms the results of other studies on the ECMWF (re)analysis that use other data sources, showing a significant bias in the lowermost stratosphere (LS) but additionally it quantifyies the reducing bias in the upper part of the LS, and uses ozone and water vapour to show the largest error is in the mixed tropospheric-stratospheric air layer suggesting the source of the problem is too much mixing of water vapour across the tropopause.

It is a very well written paper and excellent analysis of the DIAL data and evaluation of the ERA5 moist bias. I just have a few points to investigate and a few minor suggestions for text edits that need to be considered before publication.

We would like to thank the reviewer for the positive evaluation of our manuscript and for the valuable and constructive comments that helped us to improve the manuscript. Below, we answer each comment using a blue font.

SPECIFIC COMMENTS

1. Observational errors

Although the precision of the high quality observational data is discussed in Section 2.1 and various studies referenced, a quantitative description of the measurement uncertainty in this paper is missing, either in percentage terms or absolute specific humidities, as well as a discussion of any possible sources of bias in the observations. Although this information may be adequately described in other papers, it is important to review the estimated observational error here to be confident about the evaluation.

We follow the reviewer's suggestion and aimed to improve the discussion of data quality and possible implications for our results. As discussed in the manuscript one has to distinguish statistical (precision) and systematic errors (accuracy) that may affect the data quality. The statistical error is not expected to cause a bias in the observed humidity. We improved the discussion of error sources and quantified the estimated (total) error in the UTLS. The paragraph within Sec. 2.1 was changed to:

"In the DIAL data retrieval, the statistical error of the observed volume is different for each flight and depends on the water vapour distribution and the background light. To remove high noise, typically occurring in dry air lying underneath moist air, e.g., in the vicinity of stratospheric intrusions (Trickl et al., 2016), we filtered 5 % of the noisiest data for each individual flight. This threshold turned out to be useful, however, reduced the data availability in the lower-to-mid troposphere. Furthermore, Rayleigh-Doppler beam broadening, laser spectral impurity and uncertainties in spectral databases are sources for systematic errors, which are compensated for in the retrieval algorithm. The total systematic error was found to be in the order of 5 % (Kiemle et al., 2008). The high reliability of WALES was

demonstrated in various intercomparisons, e.g., with Lyman-alpha in situ hygrometers (Kiemle et al., 2008), comparable airborne and ground-based DIAL instruments (Bhawar et al., 2011) and radiosondes with a frost point hygrometer (Trickl et al., 2016).”

In summary, the expected error of the DIAL water vapor profiles is about an order of magnitude smaller than the diagnosed lower-stratospheric moist bias. We agree with the reviewer that possible implications of observational errors were not discussed and therefore we added to Sect. 4:

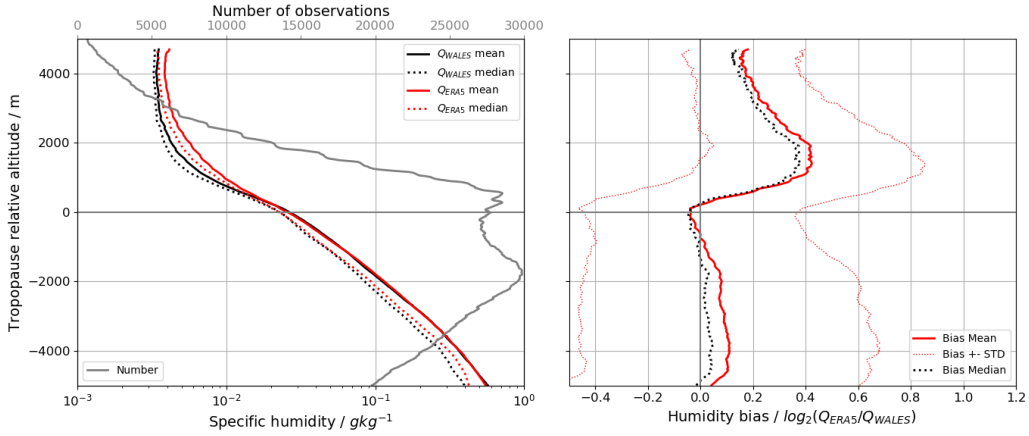
“Furthermore, the magnitude of the LS moist bias exceeds the expected error of the DIAL humidity observations by approx. one order of magnitude which underlines the significance of our results.”

2. Moist bias in the troposphere - Figure 5 and elsewhere

Could the small positive bias in the troposphere be due (or partly due) to a systematic shift between the observed and ERA5 tropopause? Bland et al. (2022) shows the height of the thermal tropopause in the operational ECMWF analyses is on average 200m higher than in the radiosonde observations and this might also apply to the ERA5 reanalyses? In tropopause relative coordinates (using the ERA5 derived tropopause), this would then lead to an apparent moist bias given the significant vertical gradient in the troposphere. Is it negligible? Can you quantify this? Is there possibility of a bias in the DIAL data? These need to be discounted to be sure that the error is in the re-analysis.

We thank the reviewer for this valuable comment that we picked up in the discussion of our results. In contrast to Bland et al. we do not have collocated temperature profiles available and, thus cannot evaluate a systematic tropopause altitude bias for our data set.

To evaluate the impact of such a 200-m shift we reproduced Fig. 5 by lowering the ERA5 tropopause altitude by 200 m (see below). Indeed, the tropospheric bias is significantly reduced with the median being close to zero. The vertical structure of the lower-stratospheric bias remains comparable and although the magnitude is reduced, our results remain valid.



We mentioned the differences between observed and simulate tTP already in the preprint version (LL212-213) However, as we were not precise enough, we deleted this sentence and instead, we added a paragraph to the discussion in Sect. 4: *“Please note that Bland et al. (2021) show that tTP altitudes are on average about 200 m higher when derived from ECMWF IFS profiles compared to radiosondes which may impact tropopause-relative moisture distributions and in turn the bias. As no temperature observations are available, this study relies only on ERA5 tTP altitudes. Assuming a systematic shift by 200 m would reduce the tropospheric bias, however, the LS moist bias, although slightly weakened would persist.”*

3. Section 3.2.2 "Synoptic and seasonal variability".

Figure 9 shows the synoptic variability of the vertical profile (by binning the whole dataset by tropopause altitude) and I was expecting to see a similar figure for the vertical profile binned by season. Instead Figure 8 shows the vertical profile separated by observational campaign, and then seasonal biases then has to be inferred from the specific months of each campaign. As two of the campaigns have only a small amount of data, we are also asked to disregard these profiles. Would it not be better to include a figure (or replace Fig 8) for the whole dataset binned by season to more robustly and clearly make the point about the seasonal variation of the bias? [I note that there is a sentence in lines 509-510 that refers to the similarity of two campaigns in Fig 8]

We agree and removed the NARVAL2 and EUREC4A profiles from Fig. 8. Although a plot for different seasons would be interesting, we do not think it would add much information due to the limited amount of flights. As WISE and NAWDEX represent autumn data sets and Cirrus-HL and NARVAL represent summer and winter, respectively, we think that the updated version of Fig. 8 is suitable to discuss the seasonality. Please note, that we refrain from a detailed discussion of seasonal differences of the bias due to the limited data set, which can only give some evidence for such an effect (see discussion in Sect. 4).

TECHNICAL CORRECTIONS

Abstract, lines 24 and 26-27 say essentially the same thing. We removed the sentence in line 24.

Line 115-116: Wording with the use of "respectively" not quite clear to say the different trace gas concentrations represent different altitude levels. Changed to: *"The online channels are sensitive to different trace gas concentrations and in turn to different altitude levels."*

Line 193: "method used on a horizontally" -> "method used a horizontally" Changed.

Line 210: Again, unusual use of the word "respectively". In this case you could use "(i.e. the lapse rate)" Done.

Line 237: You could just state this is a logarithmic formulation with base 2, just to be clear. Done.

Line 238: Something odd here with the typesetting for the equation number. Changed.

Table 2: As there is negative humidity bias in various later figures, you could add a few negative numbers in the table as well? We included one example that shows an underestimation of humidity and in turn a negative bias.

Figure 4 caption: Presumably all the derived tropopause, pot temp and wind speed is also from ERA5? State in the caption. We revised the caption of Figure 4.

Line 312: "compared the observations" -> compared to the observations" Corrected.

Line 380: "Tracer-trace" -> "tracer-tracer" Corrected.

Lines 383, 385 and Figure 11 caption: Figure 11 looks like the VMR H2O limit is 6.5ppm as the caption states, but this is inconsistent with the text on p19. Thank you for pointing to this inconsistency. Corrected to 6.5 ppm.

Could you also say why this particular value is chosen? We revised this paragraph and tried to be more precise. The selection of this values is always a bit arbitrary as e.g. discussed in Schäfler et al. (2021) and different approaches have been used. However as slight changes of the thresholds have only minor impact on the distributions in geometrical space and the percentage values in Fig. 13, we

did not go into further detail. The interested reader may find more details in the given references. We revised the entire paragraph (preprint version: pp. 19-20, LL379-389) which now reads as:

"Following the approach by Schäfler et al. (2021), the collocated water vapour and ozone observations for four WISE flights are illustrated in tracer–tracer (T–T) phase space in Fig. 11 and three classes of observations are identified based on the characteristic distributions (e.g., Pan et al., 2004). First, tropospheric observations are characterized by low VMR_{O3} (typically < 100 ppb) and a large spread of VMR_{H2O}. Second, high VMR_{O3} at low VMR_{H2O} (< 6.5 ppm or < $4x10^{-3}$ g kg^{-1}) are assigned to lower stratospheric air. Additionally, a class with intermediate chemical characteristics (VMR_{H2O} > 6.5 ppm and VMR_{O3} > 100 ppb) is attributed to mixed air masses that experienced mixing between the troposphere and stratosphere."

Lines 416-417: Although the average vertical profile from the WISE flights (Fig 13b) is similar to the full dataset (Fig 5b) in the stratosphere, the tropospheric profile looks a bit different, i.e. fairly constant in the full dataset (0.2-0.25), but decreasing with increasing altitude in the WISE data (0.4-0.1). Please reword.

We agree that this sentence on the UT bias could be more precise and adjusted the wording based on the suggestion. The sentence reads as follows:

"The average vertical profile of the moist bias for the WISE flights (Fig. 13a) is similar to the full dataset (Fig. 5b) at the tTP and in the LS, i.e., a local minimum is found at the tTP (0.1; 7 %) and a pronounced maximum of 0.62 (54 %) peaking at about 1 km above the tTP. The tropospheric part of the profile, however, is almost constant in the full dataset (0.2–0.25) but decreasing with increasing altitude in the WISE data (0.4–0.1)."

Line 473: "This supported" -> "This is supported" Corrected.

Line 493 and Line 94: Research question 1 has slightly different wording here compared to the Introduction, but should be the same. Perhaps a more succinct sentence to consider is: "1. Can the mutli-campaign DIAL data set robustly quantify the LS moisture bias in ERA5". We agree and took the revised wording from the introduction.

Line 498: "The flights that were performed in different times of the year can reproduce seasonal differences in the observed humidity distributions". They rather "show" or "highlight" the seasonal differences than "reproduce" them. Changed to *"indicate"*

Line 501: "What is of the vertical" -> "What is the vertical". Corrected

Line 502: "moist bias is also contained in" Suggest, "moist bias is present in" Corrected.

Line 523: "In future" -> "In the future" Corrected