

## Answer to Comment by Michelle Santee (Referee 2)

20.12.2021

We thank the Michelle Santee very much for her time, valuable comments, and detailed corrections, which helped a lot to improve the manuscript. In the following, we provide our answers to each of the comments and corrections in sequential order. The original Referee comment is repeated in bold, and our answers and changes in the manuscript are provided in italic. Text added to the manuscript is indicated in *blue italic*.

**Review of “Challenge of modelling GLORIA observations of UT/LMS trace gas and cloud distributions at high latitudes: a case study with state-of the-art models” by Haenel et al.**

This manuscript uses GLORIA measurements taken on a PGS flight that sampled a diverse set of conditions in the UT/LMS to test the ability of two models, ICON-ART and EMAC, to simulate cloud structures and trace gas (H<sub>2</sub>O, O<sub>3</sub>, HNO<sub>3</sub>) distributions. Both models are shown to reproduce the observations quite well; discrepancies between modelled and measured cloud and composition fields are quantified and their causes investigated. The paper is well organized and well written, and the figures are generally well prepared and support the discussion. I have only a few substantive issues that I would like to see addressed before the paper is accepted for publication; most of my comments are minor wording suggestions that will take very little time to act on.

Below both major substantive issues and minor points of clarification, wording suggestions, and grammar / typo corrections are listed together for each Section in sequential order.

Respectfully,  
Michelle Santee

*We thank Michelle Santee for the accurate summary and appreciate the positive rating.*

### Abstract:

- **p1L18-19:** The wording “measurements taken in a challenging case study by the GLORIA” could be interpreted to imply that that flight was deliberately designed for this purpose, which I do not believe was the case. I think it would be better to simply say “measurements taken in a flight of the GLORIA” here and then add “challenging” in front of “multifaceted” in L23.

*Agreed and done*

- **p1L21:** 2016, which --> 2016 that

*Done*

- **p2L3:** moist-bias --> moist bias

*Done*

- **p2L7:** changing of the --> changing the

Done

- **p2L8: play only a role in case of HNO<sub>3</sub> --> play a role only in the case of HNO<sub>3</sub>**

Done

- **p2L8-9: I agree that the representativeness of these results is an important question that should be explored. However, unless I missed it, this issue is not raised anywhere in the paper other than this sentence in the abstract. It should be acknowledged elsewhere as well, at least in the Discussion and Conclusions section if not somewhere in the main text of the paper.**

*We agree that the representativeness of the results of our study should be addressed. We revisited the abstract and came to the conclusion that the corresponding statement there does not provide much helpful information. Therefore, we rephrased this part of the abstract and address the representativeness of our study now in more detail in the discussion and conclusions (Section 5):*

*“The GLORIA data were measured during a single flight on 26 February 2016 with a duration of 9 hours 40 minutes and a total distance of ~8000 km. The flight covered a multifaceted scenario of the UT/LMS at high latitudes performed prior to the final major warming (Manney and Lawrence, 2016, and Matthias et al., 2016). Therefore, the presented comparisons of the GLORIA and model data can be considered representative for the polar UT/LMS at high latitudes in late winter prior to the vortex breakdown.”*

- **p2L10: projection --> projections**

Done

- **p2L10: Although this study has certainly provided very useful information to characterize model biases, I am less convinced that it has really laid out sufficiently specific guidance to “define paths for further model improvements”. See related final comment on the Conclusions below.**

*We agree that this wording might have overrated a bit the outcome of our study. We changed the wording to “...and provide suggestions for further model improvements.” We furthermore agree that suggestions for model improvement should be summarized and discussed more clearly. We now summarize the observed model biases and provide suggestions for model improvement in the new Section 4.5 “Suggestions for model improvement” (see reply to Referee 1). Furthermore, a corresponding summary statement has been added to discussion and conclusions (Section 5).*

### Section 1: Introduction:

- **In a number of places in the presentation of background material (e.g., p2L13, p2L16, p2L21, p2L27, p2L28, p3L7), a few citations are given for very well-established concepts, but many other equally suitable papers could have been cited instead of or in addition to the ones listed. Obviously not all relevant papers can be referenced for these points, but “e.g.” should be added in these lines to avoid giving readers the impression that the selected references are the only appropriate ones.**

*Agreed and done*

**p2L17-18: spread in these trends among models while perturbing ozone and other greenhouse gas abundances --> spread among modelled trends when ozone and other greenhouse gas abundances are perturbed**

*Done*

- **p2L18: can be --> include**

*Done*

- **p2L21: knowledge on --> knowledge of**

*Done*

- **p2L23: compartment --> layer**

*Done*

- **p2L24: On the winter --> In the winter**

*Done*

- **p3L6: sedimentation ... redistribute --> sedimentation ... redistributes; “eventually” is not really needed here, but if the authors want to keep it, it should come before “changes”**

*Agreed and done*

- **p3L12: I do know what is meant by “(in parts)” in this sentence; if I have understood the intent, this would be better as: “in part explicitly and in part by using” or “both explicitly and by using”**

*We have changed the sentence to “in part explicitly and in part by using”.*

- **p3L13: such models are the models ICON --> such models include ICON**

*Done*

- **p3L34: I assume that the systematic biases referred to here are in the model fields (that is, the intention is not to use the model results to validate the GLORIA data), but that should be made explicitly clear, e.g.: in the trace gas distributions --> in the modelled trace gas distributions**

*Agreed and done*

## **Section 2: Data and diagnostics:**

- **p4L10: the used model setups --> the model setups used**

*Done*

- **p4L11: overview on --> overview of**

*Done*

- **p4L15: aircrafts --> aircraft**

*Done*

- **p4L24: combined to --> combined into**

*Done*

- **p5L7: is operational --> has been operational**

*Done*

- **p6L16: delete the comma after “winter”**

• *Done*

- **p6L19: air masses suitable for --> air masses whose conditions are conducive to**

*Done*

- **p7L1: life time --> lifetime**

*Done*

- **p7L9: does “between ~12 to 21 hours” mean “between ~12 and 21 UTC”?**

We have changed the sentence to “forecasts with lead times of ~12 to 21 hours”, as we meant the lead time (i.e. the running time) of the forecast. Here, this time is identical with the time points during the flight, since the model data is interpolated in space and time to the GLORIA geolocations. For clarification, we added: “(depending on point in time during flight)”

- **p7L16: atmosphere --> atmospheric**

*Done*

- **p7L20: in the --> with; T106L90MA-resolution --> T106L90MA resolution**

*Done*

- **Fig. 3 caption: The corresponding T106 (T42) grid corresponds --> The T106 (T42) grid corresponds; reduces --> is reduced**

*Done*

- **p7L23-25: This is a very awkwardly worded and unclear sentence. If I have understood it correctly, it would be clearer to say: “To simulate realistic synoptic conditions, surface pressure and various prognostic variables (temperature, vorticity, and divergence) are “nudged” towards the ECMWF ERA-Interim reanalysis (Dee et al., 2011) above the boundary layer and below 1 hPa using a Newtonian relaxation technique.” This formulation of the sentence also introduces the term “nudged”, which is used later in the manuscript but is not currently defined.**

*Agreed, thanks. We adapted the suggested wording.*

- **p7L26: a comprehensive chemistry --> a comprehensive chemistry scheme**

*Done*

- **p7L27-30: Because of the complexity of the punctuation in these lines, some of the commas need to be replaced with semicolons (marked in red here): “... (Sander et al., 2011); the photolysis submodel JVAL (Sander et al., 2014); the submodel MSBM, mainly responsible for the simulation of PSCs (Kirner et al., 2011); the submodel CLOUD, based on the ECHAM5 cloud scheme, simulating large scale clouds (Roeckner et al., 2006); the submodel CONVECT, calculating convection and convective clouds (Tost et al., 2006b); and ...”.**

*Done*

- **p9L9: combined to --> combined into**

*Done*

**p9L17: delete “that deviate”**

*Done*

- **p9L18: e.g. --> i.e.**

- *Done*

### **Section 3: Flight overview and meteorological analysis:**

- **p10L2: concerning the decades before --> relative to preceding decades**

*Done*

- **p10L6: ended by --> ended with**

*Done*

- **p10L9 and L11: take off --> takeoff**

Done

- **p1011-12: headed westwards (GLORIA pointing to northward directions) --> headed westward (GLORIA pointing northward)**

Done

- **p10L12-13: turned to a southward direction (GLORIA pointing to westward directions) --> turned southward (GLORIA pointing westward)**

Done

- **p10L13-14: back to eastward directions and ... southwards) --> back eastward and ... southward)**

Done

- **Fig. 4 and its caption:**

- It is very difficult to make out the overlaid white contours without greatly magnifying the plot – thicker lines and larger font for the labels would make them easier to see.

Done

- It would be convenient to have waypoints A and B marked on these maps as well as on Fig. 1.

Done

- is colour-coded in contour --> is shown by colour contours; delete “together”; occlusions --> occlusions (black overlays)

Done, (we furthermore added “(black and dark grey overlays)”, since further fronts and another occlusion above the Atlantic are shown in panel (d) in dark grey)

- **p10L21: west- --> westward-; way-point --> waypoint**

Done

- **p10L24: partly dissipates on --> has partly dissipated by**

Done

- **p10L24-25: pointed subsequently towards ... and into --> pointed first towards ... and then into**

Done

- **p10L29: the wording “going along with” is not completely clear. Does this mean “consistent with” or “accompanied by”?**

We meant “accompanied by”. We corrected the wording accordingly

- **p10L30-31: move “to date” to after “on record”**

Done

- **p11L6: Why is the word “subsequently” used here? The air masses observed during the flight contained these features – they were not observed subsequent to the flight.**

Agreed. We deleted the word “subsequently”.

#### Section 4: Observed and modelled cloud and trace gas distributions:

- **p12L4-5: It is stated here that CI values “approaching four and higher” are indicative of cloudfree conditions. Since the color scale in Fig. 5a saturates at CI=3.0, does that imply that on this flight GLORIA never encountered air masses that can be considered cloud-free?**

Thanks for pointing out this inconsistency. The threshold value of 4 applies to spaceborne limb-sounding observations, while different threshold values were found to be suitable for airborne limb sounding. We added the following explanation:

*“In the case of airborne limb observations, CI values of 2 to 4 have been found to be suitable to separate between cloud-affected and cloud-free conditions in previous studies (Johansson et al., 2018 and references therein). In the case presented here, a cloud index of ~2.5 represents the threshold between cloud-affected and cloud-free conditions.”*

- **p12L9:** It seems a bit odd to characterize air masses affected by clouds as having an “enhanced” CI since it is actually low values of CI that indicate the presence of clouds.

*Agreed, we changed the wording to “reduced”.*

- **p12L15:** used cloud masks --> cloud masks used

*Done*

- **p12L18:** threshold of the cloud mask for the ICON-ART- and EMAC-model at --> threshold for the ICON-ART and EMAC model cloud masks at

*Done*

- **p12L22:** add a comma after “concentrations”

*Done*

- **Fig. 5b,c:** I am a bit confused about why the tick marks on the cloud mask color bars are needed

*Agreed. We removed the tick marks*

- **p12L33:** Discrepancies between measured and modelled clouds at lower altitudes for the system around 20 UTC are attributed to GLORIA data being affected by optically dense cloud layers above, but couldn't this explanation be applied to the mismatch for other clouds as well, such as the one between 12 and 13 UTC?

*Yes, agreed. We now mention in the text that the same effect might explain the differences between the observed and modelled cloud systems between 12 and 13 UTC at lower altitudes.*

- **p13L1:** delete the comma after “GLORIA”

*Done*

- **p13L3:** delete the comma after “fact”

*Done*

- **p13L8:** I'm not sure what “appear more sharply in the ICON-ART simulation” means, as the cloud systems in question barely register at all in the model cloud mask.

*Agreed. We changed the sentence to “...are barely reproduced in the ICON-ART simulation”*

- **p13L10:** respective --> corresponding; EMAC-standard simulation (STD) --> EMAC standard simulation (EMAC-STD); T106L90MA-resolution --> T106L90MA resolution

*Done*

- **p14L1:** Recalling that --> As mentioned earlier; 2.3), however the --> 2.3); however, the

*Done*

- **p14L2:** the EMAC standard simulation (STD) --> the EMAC-STD

*Done*

- **p14L11:** better comparable --> more comparable

*Done*

- **p14L19: delete comma after “model”**

Done

- **p14L21: to which degree --> the degree to which**

Done

- **p14L25: does “~12 h to ~20 h” mean “~12 UTC to ~20 UTC”?**

*In this case we mean the lead time (i.e. running time) of the forecast, which is however identical here with times of the GLORIA geolocations. For clarification, we added “forecast lead time” prior to “between”.*

**Also: accumulated --> cumulative**

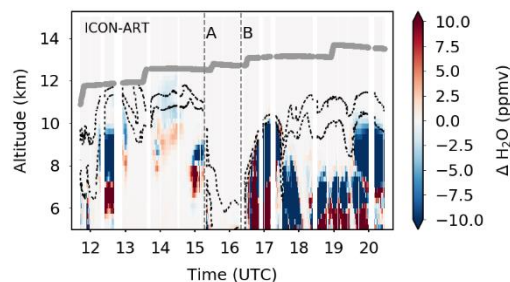
Done

- **p15L4-5: It is stated that “all of the observed cloud systems coincide qualitatively with a corresponding precipitation pattern at the respective geolocations in the ICON-ART-data”, but the  $\Delta H_2O$  diagnostic does not pick up the cloud system observed by GLORIA prior to 12 UTC.**

*We agree that there are only very weak indications in the  $\Delta H_2O$  diagnostic prior to 12 UTC (i.e. at ~11:45 and 11:55). We added: “However, as in the case of the ICON-ART cloud mask prior to 12 UTC, only weak indications of cloud systems are found here.”*

- **p15L8: Although I see weak negative residuals just below the tropopause, even with the figure greatly magnified it is difficult to discern non-negligible residuals above the tropopause.**

*Agreed. We changed the range of the colour scale to -10 ... 10 ppmv to make it easier to identify these patterns:*



**Figure 6.** Modelled short-term changes in specific humidity due to cloud processes. Residuals between *nested* ICON-ART domain of specific humidity and corresponding  $H_2O$  tracer without cloud microphysics. Black dashed lines: ICON-ART 2 PVU and 4 PVU isolines (lower and higher lines, respectively) as indicators for the dynamical tropopause. Grey lines: HALO flight altitude.

- **p15L10-11: vicinity is found at 14 UTC and reaches --> vicinity at 14 UTC reaches**

Done

- **p15L11: support that --> support the idea that**

Done

- **p15L18: again, hints --> again hints**

Done

- **p15L20: beside --> in addition to**

Done

- **p16L3-4:** The use of the term “precipitation” is ambiguous here – I believe that the authors mean “cirrus cloud ice particle sedimentation”, but that should be clarified. I also think that it would be appropriate to add discussion putting these results about “precipitation” affecting the humidity of the LMS into the context of previous studies that have examined the impact of convection and cirrus cloud processes on moistening / dehydrating the LMS (especially in light of my previous comment that I had trouble identifying these weak signatures in Fig. 6).  
*Agreed, we meant “cirrus clouds ice particle sedimentation” and corrected the text accordingly. We rephrased p14/L19ff as following:*  
*“Another proxy for the characterisation of detectable cloud systems in the model is looking at the cirrus cloud ice particle sedimentation events, which include the processes of nucleation, sedimentation and subsequent evaporation of cirrus cloud ice particles. As a consequence, local irreversible dehydration is found when ice particle growth removed water from the gas phase, and hydration is found at lower altitudes where the particles sublimate.”*  
*To provide context to previous studies, we added the following statement after p16L4:*  
*“Cirrus clouds under cold conditions in the LMS have been found by many observations (e.g. Lelieveld et al., 1999; Kärcher and Solomon, 1999; Spang et al., 2015) and are likely to affect LMS humidity by ice particle sedimentation (e.g. Kärcher, 2005). Furthermore, as discussed in the literature, convective hydration is known to affect the LMS and can drive air masses to saturation (Schoeberl et al., 2018; Zou et al., 2021).”*
- **p16L4:** affects also significantly --> also significantly affects  
*Done*
- **p16L5:** the major cloud systems --> the major cloud systems observed by GLORIA  
*Done*
- **p16L7:** the ICON-ART lacks the simulation of the --> ICON-ART fails to simulate the  
*Done*
- **p16L11:** add a comma after “q<sub>v</sub>”  
*Done*
- **p16L12:** It should be reiterated when Fig. 7 is introduced that the presence of optically thick clouds precludes trace gas retrievals, as comparison of the patterns in Figs. 5 and 7 shows.  
*Agreed. We added: “When compared with the cloud index plot (Fig. 5a), gaps in the retrieved trace gas distributions are explained by the fact that the presence of dense clouds precludes trace gas retrievals in the affected regions. Cloud filtering is applied here prior to the trace gas retrieval.”*
- **p16L13-14:** The tropopause is located near 10 km in all panels of Fig. 7, not just 7a. In addition, use either “around” or “~”, not both (see also L16).  
*Done*
- **p16L17:** south-western --> southwestern; part --> flight segment  
*Done*
- **p16L18-19:** reach by ~2km up into --> reach as far as ~2km into  
*Done*
- **p16L21:** complimentary --> complementary (but “converse” is probably a better word here)



Agreed, we have changed the word to “converse”

- **p16L25: reach up --> reach nearly up; add a comma after “altitude”**

*A closer inspection of the Fig 7b shows that the filaments in ozone reach even higher up to the flight altitude. We therefore inserted “even” instead of “nearly” and modified the end of the sentence to “, therefore deeper into the LMS than the filaments seen in the water vapour distribution.” We added the comma, as suggested.*

- **p16L27-29: Although I don’t doubt that some nitrification at lower altitudes occurred during this winter, the morphology of the HNO<sub>3</sub> distribution (Fig. 7c) does not seem very different from that of O<sub>3</sub> (Fig. 7b) to me, and abundances of both would be expected to be higher in the LMS than in the UT. Thus I am not certain what local maxima in HNO<sub>3</sub> are being referred to here. The specific signatures of nitrification in this figure should be clarified.**

*Thanks for pointing out this shortcoming. We agree that the local maximum can hardly be seen with the applied range of the colour bar and the discussion is unclear. We extended the colour bar to 8 ppbv to resolve the maximum more clearly. Furthermore, there was a mistake in the time interval. Our intention is to discuss the local HNO<sub>3</sub> maximum below flight altitude between 15 UTC and ~17 UTC seen in the updated plot, which is not found in the O<sub>3</sub> distribution.*

*Furthermore, Ziereis et al. (2021) discuss in their recent publication that during this flight both nitrified air masses, but also denitrified air masses that had descended from above were probed. We corrected the sentence with regard to the time interval of the local maximum. Furthermore, with reference to Ziereis et al. (2021), we now discuss that both, nitrified air masses (prior to ~15 UTC and after ~17 UTC) and denitrified air masses (between ~15 and 17 UTC) were probed at flight altitude. We discuss furthermore that the local maximum seen in the GLORIA data below flight altitude between 15 and 17 UTC is interpreted as subsided nitrified air masses which are located below denitrified air masses at flight altitude in this section of the flight.*

*This interpretation is furthermore consistent with the results of the EMAC sensitivity run, which shows nitrification below flight altitude between 15 and 17 UTC (Fig. 10c, now Fig. 12c).*

- **p17L8: is the comparison (“higher”) with respect to ICON-ART or GLORIA? Assuming the latter: reach here higher up by 1-2 km --> reach altitudes higher than those observed by 1-2 km**

*Yes, we meant with respect to GLORIA. We modified the sentence accordingly*

- **p17L12: “schematically” is not quite the right word here – maybe “broadly” or “generally”?**

*Agreed, we have changed the wording to “broadly”*

- **p18L3: fine-structures --> fine structures**

*Done*

- **p18L19: complimentary --> complementary**

*Done*

- **p18L31: Thereby --> However**

*Done*

- **p18L32: which is by a factor of ~5 lower than that the ICON-ART R2B7 nest --> which is lower than that of the ICON-ART R2B7 nest by about a factor of 5**

*Done*

- **p19L2: delete “respective”**

Done

- **p19L3-4: It would be appropriate to acknowledge some of the previous studies that have also found substantial troposphere-to-stratosphere exchange associated with tropopause fold events; folded airmass structures reach --> airmasses in tropopause fold structures reach**

*We added references regarding tropopause folding and air mass exchange. We adapted the wording suggested by the Referee with a slight modification (i.e., “variations in the dynamical tropopause”), since a less developed tropopause fold is found here when compared with the study by Shapiro (1980). We rephrased as follows:*

*“The combination of ozone and water vapour data clearly shows that air masses characterised by tropospheric moisture levels reach deeply into the LMS and are connected to variations in the dynamical tropopause. Tropopause folds and steps in the tropopause are regions where isentropic levels cross the tropopause and jet streams. They are known bidirectional exchange regions between the tropopause and stratosphere (e.g. Shapiro, 1980; Keyser and Shapiro, 1986) and to contribute to transport and mixing of tropospheric air into the LMS such as diagnosed e.g. by Werner et al. (2010), Krause et al. (2018), and Jing et al. (2018) (note however that a net exchange from the LMS to the troposphere dominates).”*

*Following the suggestion by Referee 1, we added a detailed analysis of the evolution of the filaments and tropopause folds at the days before the flight (see Reply to Referee 1).*

- **p19L6: shows highly --> shows a highly**

Done

- **p19L7: I think that “broadly captures” or something like that would be better wording than “resolves in principle”**

Done

- **p19L10: In case of --> In the case of**

Done

- **p19L14: by both --> from both**

Done

- **p20L5-8: I think that the flow would be improved by moving the introduction of Fig. 10 in these lines to after the end of the discussion of Fig. 9 on the following page. Also: on it) --> on them)**

*Agreed and done*

- **p20L11: bias, which is known for the --> bias that is known to affect the**

Done

- **Fig. 9 caption: EMAC and ICON-ART output --> ICON-ART and EMAC output**

Done

- **p21L5: found and increases --> found that increases**

Done

- **p21L8: fine-structures --> fine structures**

Done

- **Fig. 10: It might be helpful to add an overlay outlining the zero contour, especially in Fig. 10b, since it is hard to tell where the EMAC ozone residuals change sign.**

Done

- **p21L12: that ozone --> that the ozone**  
*Done*
- **p21L14: B, ozone is significantly --> B is ozone significantly**  
*Done*
- **p21L17: scheme by --> scheme used by**  
*Done*
- **p21L18-19: above the troposphere and strongly --> above the tropopause that strongly; amounts --> amounts to**  
*Done*
- **p21L21: while comparing --> in a comparison of**  
*Done*
- **p21L23: due --> due to; (de-) nitrification --> denitrification/nitrification**  
*Done*
- **p21L23-24: It is confusing to focus only on the evaporation of PSC particles here, as that leads to HNO<sub>3</sub> enhancement (renitrification). If I understand correctly, the modelled HNO<sub>3</sub> depletion associated with the subsided air mass encountered in the middle of the flight is being attributed to sequestration in existing PSC particles or permanent denitrification through their subsequent sedimentation. That should be clarified.**  
*We agree that this sentence is confusing. As discussed by Ziereis et al. (2021), denitrified air masses are seen in the middle of the flight (as discussed by the authors, PSC particles were not detected any more in situ at flight altitude during this phase of the winter). At higher altitudes, sequestration in existing PSC particles might still have played a role here, if temperatures were cold enough. We corrected the sentence accordingly.*
- **Fig. 11 caption: T106 vs T42 resolution --> T106 minus T42 resolution**  
*Done*
- **p22L1-5: I am not convinced of the value of including the T106 vs T42 sensitivity test shown in Fig. 11a-c, as the benefit of using the higher resolution in EMAC has already been demonstrated in the Khosrawi et al. papers mentioned here. Why was it necessary to repeat this comparison?**  
*We agree that the conclusion is the same as provided by Khosrawi et al. However, we think that our results are still useful, since the study by Khosrawi et al. focused mainly on the stratosphere, while our study has a more detailed focus at the upper UT/LMS region. Furthermore, our study provides another dataset to support this interpretation. We changed the wording to: “A similar behaviour of EMAC was found in the stratosphere by Khosrawi et al. (2017), who stated ...”*
- **p22L2: “enhances” can have a positive connotation, hence: enhances --> exacerbates**  
*Done*
- **p22L4: stating --> who stated; MLS --> Microwave Limb Sounder**  
*Done*
- **p22L6: The findings about scavenging processes only being important for HNO<sub>3</sub> are presented here and later in Section 5 in a manner that suggests that they were unexpected. Did the**

authors have any expectation that scavenging processes would affect the O<sub>3</sub> or H<sub>2</sub>O distributions? More background and context motivating this sensitivity test is needed.

*We agree that these aspects should be addressed and added the following statement:*

*“Scavenging processes by cirrus cloud ice particles are capable of removing trace gases from the gas phase. Sedimentation of the ice particles is capable of removing the trapped gases from affected altitudes. While previous studies focused mainly on scavenging on liquid cloud droplets (Tost et al., 2010; Wang et al., 2010; Pierce et al., 2015; Kaiser et al., 2019), Tost et al. (2010), however, found HNO<sub>3</sub> values in the Northern hemisphere upper troposphere to be low due to uptake on ice particles and subsequent sedimentation. Thereby, relative changes were found to be large due to low absolute values there. In addition, the vertical redistribution of HNO<sub>3</sub> could induce secondary effects on other trace gases via chemical processes. In particular, altering HNO<sub>3</sub> could lead to changes in the budget of reactive nitrogen oxides (NO<sub>x</sub>), which, in turn, could impact ozone (e.g. Kelly et al., 1991; Krämer et al., 2008; Schiller et al., 2008). Here, our goal is to test whether the effect of scavenging over ice on the trace gas composition is significant in the LMS in the EMAC simulation.”*

- **p22L7: ppbv in --> ppbv than in**

*Done*

- **p22L8: Reminding --> Recalling**

*Done*

- **p22L10: delete “, however,”; most parts of a region --> most of the region**

*Done*

- **p22L11: delete “respective”; delete comma after “means”**

*Done*

- **Fig. B1 and caption:**

- **It seems odd to me to create an Appendix just to duplicate one figure from the main text with an additional row. It would make more sense and be easier for readers to simply add the panels showing the residuals to Fig. 7 and then refer back to that figure in this section. Some discussion of the residuals could be added where Fig. 7 is first presented as well.**

*Agreed. We added the residuals to Fig. 7 and discuss them already in this section.*

- **respective residuals between GLORIA and EMAC --> corresponding residuals (GLORIA minus EMAC)**

*Done*

- **p22L12: delete comma after “region”**

*Done*

- **p22L13: These findings about the impact of scavenging by high-altitude cirrus on HNO<sub>3</sub> in the UT/LMS should be placed in the context of other studies that have examined this issue.**

*See comment to p22/L6. We furthermore added a statement that our results are consistent with the results by Tost et al. (2010), who found a similar effect in the upper troposphere.*

## Section 5: Discussion and Conclusions:

- **p23L2: What does “ACM” mean? Also: during --> taken during**  
*We have now spelled out “ACM” to “atmospheric chemistry model”*
- **p23L13: delete “used”**  
*Done*
- **p23L15: by generated cloud masks from --> by cloud masks generated from**  
*Done*
- **p23L17: between the models are reproduced to --> between the two models are attributed to**  
*Done*
- **p23L18: It is not clear what “limitation of the comparison” means here.**  
*Our goal was to express that the comparison of the measured quantity cloud index with cloud masks generated from the models is limited. We modified the sentence accordingly.*
- **p23L19: respective --> corresponding; used for --> used as**  
*Done*
- **p24L6: life time --> lifetime**  
*Done*
- **p24L7: with comparing --> by comparing**  
*Done*
- **p24L9: 2019) and suggests --> 2019), which suggests**  
*Done*
- **p24L13: a change in --> a reduction in**  
*Done*
- **p24L16: show practically --> has practically**  
*Done*
- **p24L20: Again, “schematically” is not quite the right word here. Maybe “in a broad sense”?**  
*Agreed, we have changed the wording to “broadly”*
- **p24L21: simulations --> simulation**  
*Done*
- **p24L23-24: “continuous” is not an appropriate word here – aircraft measurements are not continuous.**  
*Agreed, we have meant “continuing”, done*  
**Also: to continuously test --> to continue to test; delete comma after “required”**  
*Done*
- **p24L22-25: The authors “speculate” that the biases and sensitivities found in this study might help provide better forecasts and long-term projections. But it is not clear to me that they have provided “actionable” information that will really inform model development / refinement in a concrete way. It might help to add another sentence or two about how they think these results could be used to guide model improvement efforts.**  
*Agreed, see comment to p2L10.*

## Appendix A:

- **p25L8: EMAC-model (panels g-i) between -10 --> EMAC (panels g-i) model at various times between -10**

*Done*

- **p25L9: add comma after “geolocations”**

*Done*

- **p26L2: and it is --> and is**

*Done*

- **p26L3: the measured cloud system by --> the cloud system measured by**

*Done*

- **p26L5: is dissolving --> dissolves; “supposably” is not an English word, and I cannot even guess what the authors may have meant so I am unable to offer an alternative (“supposedly” is a word but does not make sense in this context)**

*Agreed, we have changed the wording to “presumably”*

- **p26L6-7: The cloud system not only appears in the model a few hours earlier than observed but it also covers a much shallower altitude domain. Is that because of the problem with “false” GLORIA cloud detections below optically dense cloud layers discussed in Section 4.1? On the other hand, EMAC also shows the cloud to have a much larger vertical extent than ICON-ART.**

*In principle, the explanation with regard to optically thick cloud tops might partly explain the discrepancy here, too. However, since some structures are seen in the GLORIA cloud index at lower altitudes here, this cloud, at least in parts, are not completely optically thick. Furthermore, it should be remembered that the comparison of the model cross sections several hours before the measurements is limited, since the atmospheric scenario changes. We added these aspects in the discussion.*

- **p26L6-7: data, however --> data; however,**

*Done*

- **p26L10: It is stated that the cloud “breaks apart into two pieces” at T=-6 h, but to me it seems that even at T=-10 h (Fig. A1g) there were already two connected but distinct features.**

*Agreed. We modified the discussion accordingly.*

- **p26L10-11: is also dissolving --> dissolves; is also subsiding and decreasing --> subsides and decreases**

*Done*

- **p26L14: Figure --> Figures**

*Done*

- **p27L1: add a comma after “flight”**

*Done*

- **p27L7: delete comma after “cases”**

*Done*

- **p27L10: in accordance to --> in accordance with**

*Done*

### Recurring minor wording issues:

- **p10L19, p17L2, p21L12:** it is not clear what is meant by “late” polar vortex in these lines. If I understand correctly, then “late-stage”, “late-winter”, or “aged” would be better than “late”.  
*Agreed, changed the wording to “late-stage”*
- **p10L24, p11L5, p17L3:** backward leg --> return leg  
*Done*
- **p12L18, p14L1, p14L6, p14L8, p14L16, p15L16, p22L12, p25L8, p26L8, p27L5, p27L7, p27L9:** EMAC-simulation --> EMAC simulation; EMAC-cross section --> EMAC cross section; EMACmodel --> EMAC model; EMAC-data --> EMAC data (i.e., delete hyphens)  
*Done*
- **p12L18, p14L14, p15L5, p15L6, p15L13, p15L17, p15L23, p25L8, p26L2, p26L14, p27L3:** ICON-ART- --> ICON-ART (i.e., delete hyphens after “ART”)  
*Done*
- **p14L12, p14L14, p14L15, p14L16:** GLORIA- --> GLORIA (i.e., delete hyphens)  
*Done*
- **p14L27, p15L15, p15L22:** at the day --> on the day  
*Done*
- **p16L15, p17L1, p17L7:** behind --> after  
*Done*
- **p17L6, p18L3, p19L11:** less details --> fewer details  
*Done*
- **p18L4, p18L12, p18L13, p21L21:** delete the comma after “al.”  
*Done*
- **p18L10, p18L21, p19L8, p21L20:** hardly --> barely, or, not well  
*Done*

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