

**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 ( $\text{H}_2\text{O}$ ,  $\text{O}_3$ ,  $\text{HNO}_3$ ) 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

**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.
- p1L21: 2016, which --> 2016 that
- p2L3: moist-bias --> moist bias
- p2L7: changing of the --> changing the
- p2L8: play only a role in case of  $\text{HNO}_3$  --> play a role only in the case of  $\text{HNO}_3$
- 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.
- p2L10: projection --> projections
- 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.

**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.

- 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
- p2L18: can be --> include
- p2L21: knowledge on --> knowledge of
- p2L23: compartment --> layer
- p2L24: On the winter --> In the winter
- p3L6: sedimentation ... redistribute --> sedimentation ... redistributes; “eventually” is not really needed here, but if the authors want to keep it, it should come before “changes”
- 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”
- p3L13: such models are the models ICON --> such models include ICON
- 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

## Section 2: Data and diagnostics:

- p4L10: the used model setups --> the model setups used
- p4L11: overview on --> overview of
- p4L15: aircrafts --> aircraft
- p4L24: combined to --> combined into
- p5L7: is operational --> has been operational
- p6L16: delete the comma after “winter”
- p6L19: air masses suitable for --> air masses whose conditions are conducive to
- p7L1: life time --> lifetime
- p7L9: does “between ~12 to 21 hours” mean “between ~12 and 21 UTC”?
- p7L16: atmosphere --> atmospheric
- p7L20: in the --> with; T106L90MA-resolution --> T106L90MA resolution
- Fig. 3 caption: The corresponding T106 (T42) grid corresponds --> The T106 (T42) grid corresponds; reduces --> is reduced
- 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.
- p7L26: a comprehensive chemistry --> a comprehensive chemistry scheme
- 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 ...”.
- p9L9: combined to --> combined into

- p9L17: delete “that deviate”
- p9L18: e.g. --> i.e.

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

- p10L2: concerning the decades before --> relative to preceding decades
- p10L6: ended by --> ended with
- p10L9 and L11: take off --> takeoff
- p10L11-12: headed westwards (GLORIA pointing to northward directions) --> headed westward (GLORIA pointing northward)
- p10L12-13: turned to a southward direction (GLORIA pointing to westward directions) --> turned southward (GLORIA pointing westward)
- p10L13-14: back to eastward directions and ... southwards) --> back eastward and ... southward)
- 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.
  - It would be convenient to have waypoints A and B marked on these maps as well as on Fig. 1.
  - is colour-coded in contour --> is shown by colour contours; delete “together”; occlusions --> occlusions (black overlays)
- p10L21: west- --> westward-; way-point --> waypoint
- p10L24: partly dissipates on --> has partly dissipated by
- p10L24-25: pointed subsequently towards ... and into --> pointed first towards ... and then into
- p10L29: the wording “going along with” is not completely clear. Does this mean “consistent with” or “accompanied by”?
- p10L30-31: move “to date” to after “on record”
- 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.

### 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 cloud-free 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?
- 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.
- p12L15: used cloud masks --> cloud masks used
- 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
- p12L22: add a comma after “concentrations”
- Fig. 5b,c: I am a bit confused about why the tick marks on the cloud mask color bars are needed
- 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?
- p13L1: delete the comma after “GLORIA”
- p13L3: delete the comma after “fact”

- 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.
- p13L10: respective --> corresponding; EMAC-standard simulation (STD) --> EMAC standard simulation (EMAC-STD); T106L90MA-resolution --> T106L90MA resolution
- p14L1: Recalling that --> As mentioned earlier; 2.3), however the --> 2.3); however, the
- p14L2: the EMAC standard simulation (STD) --> the EMAC-STD
- p14L11: better comparable --> more comparable
- p14L19: delete comma after "model"
- p14L21: to which degree --> the degree to which
- p14L25: does "~12 h to ~20 h" mean "~12 UTC to ~20 UTC"? Also: accumulated --> cumulative
- 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.
- 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.
- p15L10-11: vicinity is found at 14 UTC and reaches --> vicinity at 14 UTC reaches
- p15L11: support that --> support the idea that
- p15L18: again, hints --> again hints
- p15L20: beside --> in addition to
- 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).
- p16L4: affects also significantly --> also significantly affects
- p16L5: the major cloud systems --> the major cloud systems observed by GLORIA
- p16L7: the ICON-ART lacks the simulation of the --> ICON-ART fails to simulate the
- p16L11: add a comma after " $q_v$ "
- 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.
- 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).
- p16L17: south-western --> southwestern; part --> flight segment
- p16L18-19: reach by ~2km up into --> reach as far as ~2km into
- p16L21: complimentary --> complementary (but "converse" is probably a better word here)
- p16L25: reach up --> reach nearly up; add a comma after "altitude"
- p16L27-29: Although I don't doubt that some nitrification at lower altitudes occurred during this winter, the morphology of the  $HNO_3$  distribution (Fig. 7c) does not seem very different from that of  $O_3$  (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  $HNO_3$  are being referred to here. The specific signatures of nitrification in this figure should be clarified.
- 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

- p17L12: “schematically” is not quite the right word here – maybe “broadly” or “generally”?
- p18L3: fine-structures --> fine structures
- p18L19: complimentary --> complementary
- p18L31: Thereby --> However
- 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
- p19L2: delete “respective”
- 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 air mass structures reach --> air masses in tropopause fold structures reach
- p19L6: shows highly --> shows a highly
- p19L7: I think that “broadly captures” or something like that would be better wording than “resolves in principle”
- p19L10: In case of --> In the case of
- p19L14: by both --> from both
- 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)
- p20L11: bias, which is known for the --> bias that is known to affect the
- Fig. 9 caption: EMAC and ICON-ART output --> ICON-ART and EMAC output
- p21L5: found and increases --> found that increases
- p21L8: fine-structures --> fine structures
- 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.
- p21L12: that ozone --> that the ozone
- p21L14: B, ozone is significantly --> B is ozone significantly
- p21L17: scheme by --> scheme used by
- p21L18-19: above the troposphere and strongly --> above the tropopause that strongly; amounts --> amounts to
- p21L21: while comparing --> in a comparison of
- p21L23: due --> due to; (de-) nitrification --> denitrification/nitrification
- 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.
- Fig. 11 caption: T106 vs T42 resolution --> T106 minus T42 resolution
- 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?
- p22L2: “enhances” can have a positive connotation, hence: enhances --> exacerbates
- p22L4: stating --> who stated; MLS --> Microwave Limb Sounder
- 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.

- p22L7: ppbv in --> ppbv than in
- p22L8: Reminding --> Recalling
- p22L10: delete “, however,”; most parts of a region --> most of the region
- p22L11: delete “respective”; delete comma after “means”
- 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.
  - respective residuals between GLORIA and EMAC --> corresponding residuals (GLORIA minus EMAC)
- p22L12: delete comma after “region”
- 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.

#### Section 5: Discussion and Conclusions:

- p23L2: What does “ACM” mean? Also: during --> taken during
- p23L13: delete “used”
- p23L15: by generated cloud masks from --> by cloud masks generated from
- p23L17: between the models are reproduced to --> between the two models are attributed to
- p23L18: It is not clear what “limitation of the comparison” means here.
- p23L19: respective --> corresponding; used for --> used as
- p24L6: life time --> lifetime
- p24L7: with comparing --> by comparing
- p24L9: 2019) and suggests --> 2019), which suggests
- p24L13: a change in --> a reduction in
- p24L16: show practically --> has practically
- p24L20: Again, “schematically” is not quite the right word here. Maybe “in a broad sense”?
- p24L21: simulations --> simulation
- p24L23-24: “continuous” is not an appropriate word here – aircraft measurements are not continuous. Also: to continuously test --> to continue to test; delete comma after “required”
- 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.

#### Appendix A:

- p25L8: EMAC-model (panels g-i) between –10 --> EMAC (panels g-i) model at various times between –10
- p25L9: add comma after “geolocations”
- p26L2: and it is --> and is

- p26L3: the measured cloud system by --> the cloud system measured by
- 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)
- 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.
- p26L6-7: data, however --> data; however,
- 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.
- p26L10-11: is also dissolving --> dissolves; is also subsiding and decreasing --> subsides and decreases
- p26L14: Figure --> Figures
- p27L1: add a comma after “flight”
- p27L7: delete comma after “cases”
- p27L10: in accordance to --> in accordance with

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”.
- p10L24, p11L5, p17L3: backward leg --> return leg
- p12L18, p14L1, p14L6, p14L8, p14L16, p15L16, p22L12, p25L8, p26L8, p27L5, p27L7, p27L9: EMAC-simulation --> EMAC simulation; EMAC-cross section --> EMAC cross section; EMAC-model --> EMAC model; EMAC-data --> EMAC data (i.e., delete hyphens)
- p12L18, p14L14, p15L5, p15L6, p15L13, p15L17, p15L23, p25L8, p26L2, p26L14, p27L3: ICON-ART- --> ICON-ART (i.e., delete hyphens after “ART”)
- p14L12, p14L14, p14L15, p14L16: GLORIA- --> GLORIA (i.e., delete hyphens)
- p14L27, p15L15, p15L22: at the day --> on the day
- p16L15, p17L1, p17L7: behind --> after
- p17L6, p18L3, p19L11: less details --> fewer details
- p18L4, p18L12, p18L13, p21L21: delete the comma after “al.”
- p18L10, p18L21, p19L8, p21L20: hardly --> barely, or, not well