Author response to comments by Anonymous Referee #1: "Mesoscale fine structure of a tropopause fold over mountains"

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We thank Referee #1 for his/her time and valuable comments to improve the manuscript. In the following, we provide the original referee comments (italic letters), followed by our responses. Text added or modified in the revised manuscript is coloured in blue.

The paper describes detailed observations of water vapor, ozone, and temperature at a tropopause fold in the vicinity of the polar frontal jet over Italy retrieved from measurements of GLORIA on HALOE. The data are compared to in situ measurements and high resolution model results. Observed fine structures and mixing between Stratosphere and Troposphere is discussed. The paper is well written and fits the scope of this journal well.

We thank Referee #1 for this favourable statement.

Minor comments:

Page 3, line 25-26: actually already Weigel et al. (2012) (different to Ungermann et al. (2013), which is based on the same measurements) showed results of temperature and trace gas retrieval together at a topopause fold?

Here, we intended to address in situ observations only. We agree that Weigel et al. (2012) should be mentioned here. We rephrased P3/L25-26 as follows:

"…Simultaneous in situ measurements of both trace gases and temperature have not been applied up to now to characterize the mesoscale fine structure of tropopause folds. CRISTA-NF observations in July 2006 (Weigel et al., 2012) provided a first coarse perspective of a tropopause fold using this combination of parameters. Here, we present…"

Page 6 or 7, Section 2.1: it should be mentioned, that the GLORIA data are cloud filtered and how they were filtered?

We added at P6/L21: "…by Johansson et al. (2018). Prior to the retrieval, the binned spectra are cloud-filtered according to the cloud index method by Spang et al. (2004). A variable threshold value is applied, increasing linearly from 3.0 for the lowest limb-views to 1.8 at flight altitude. For the retrievals …" and provide the reference Spang et al. (2004) under "References":

Spang, R., Remedios, J. J., and Barkley, M. P.: Colour indices for the detection and differentiation of cloud types in infra-red limb emission spectra, Adv. Space Res., 33, 1041–1047, 2004.

To clarify that the binned spectra are cloud-filtered, we modified P6/L12: "… In post-flight data processing, spectra of the detector rows of each data cube are binned to reduce uncertainties. …"

Page 16, line 29ff / Fig. 7d/f: do the "green" profiles really show dry stratospheric air or is there an issue with the measurement quality? They remain surprisingly close to the a priori values and a data gap is following in Fig. 7a? For Fig. 7c/d a logarithmic x-axis would probably be better?

We confirm that there is no issue with the measurement quality. As recommended, we now adopted logarithmic x-axes for Figures 7c/d. The revised plots show that the water vapour profiles exhibit coherent fine structures different from the a priori even below 10 ppmv:

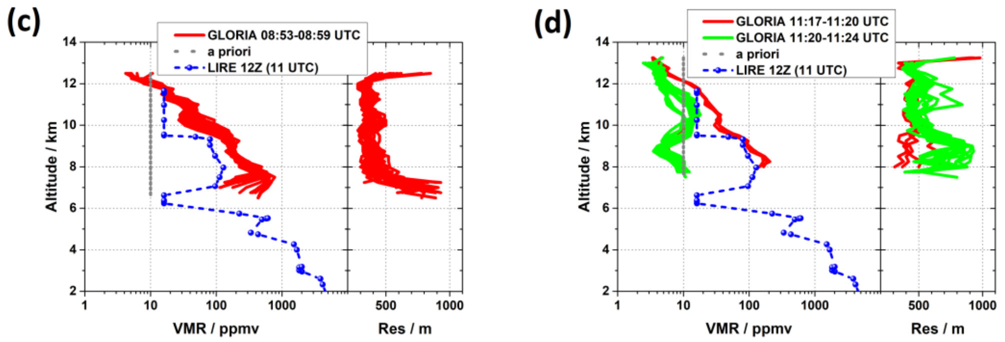
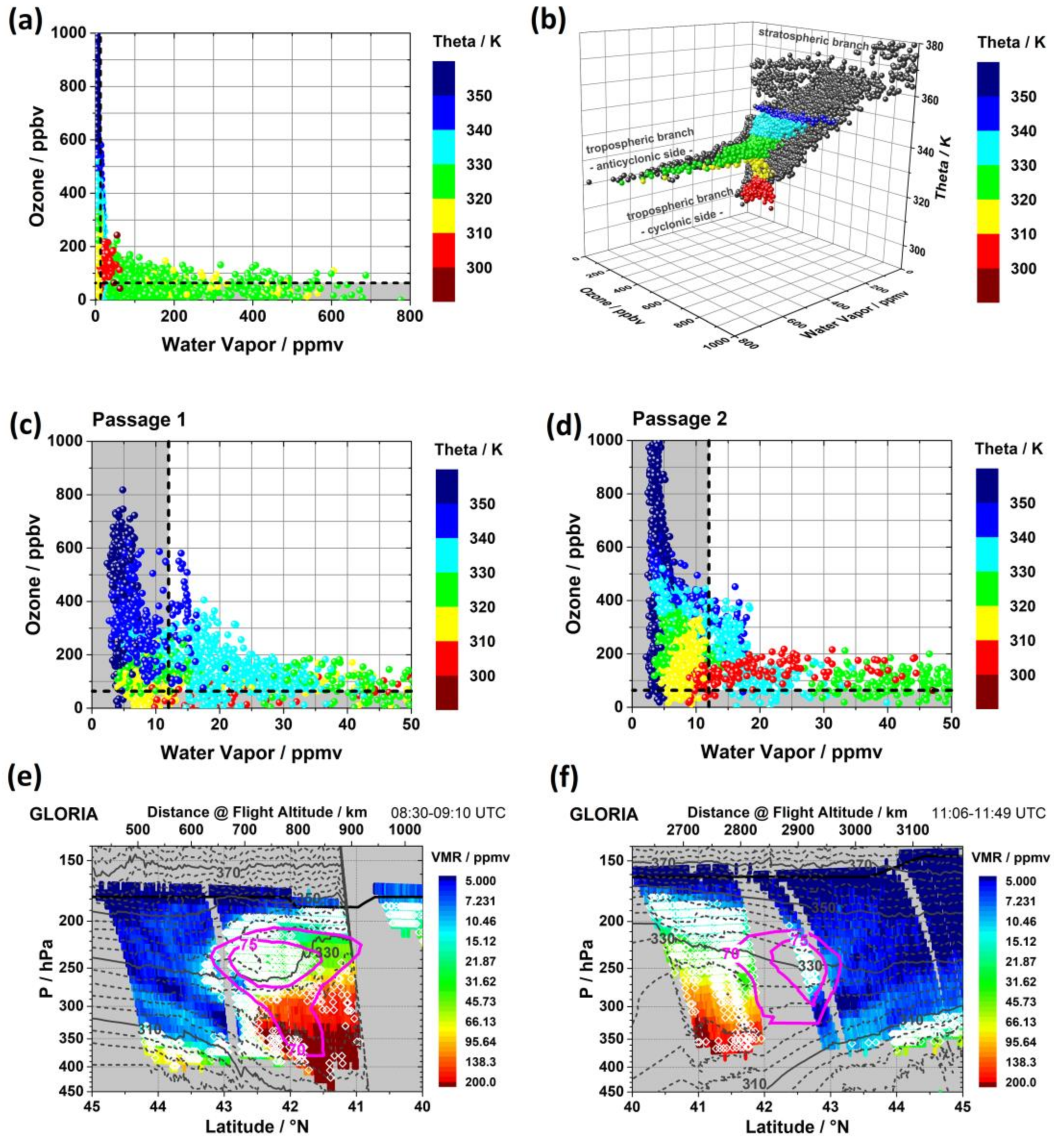


Fig. 11a: I'm not sure if the 3d figure is really helpful here? The axis are difficult to read. Is it possible to improve it or, if not switch to a 2D Figure of H_2O and O_3 versus potential temperature?

Here, our intention was to illustrate how the observed mixing zone is situated in a H_2O-O_3-Θ space. For clarification, we now changed the perspective of the 3d figure and colour-coded only the data points associated with the mixing zone. We furthermore exchanged the order of Figures 11a and b. Considering also the comments by Referee #2, we updated Figure 11:



“**Figure 11:** Tracer-tracer correlations of GLORIA’s water vapour and ozone profiles during both tropopause fold passages as function of the observed potential temperatures. All observational data along south- and northbound legs are included in the 2D and 3D illustrations in panels (a) and (b). Panels (c) and (d) display the southbound and northbound leg observations separately. Panels (e) and (f) show GLORIA water vapour (as in Fig. 9a and b), with data points characterized by ozone >65 ppbv and water vapour >12 ppmv marked by white diamonds (cf dashed black lines in panels (a), (c) and (d), colour-coded points in panel (b), and Gettelmann et al., 2011, their Sect. 4.3). Θ (K, solid and dashed grey lines, ΔΘ = 4 K) as derived from GLORIA’s temperature and IFS horizontal wind V_H (m s^{-1}, bold magenta lines) are superimposed in panels (e) and (f).”

In context of the modified Figure 11, we updated the discussion from P21/L9 to P22/L9: “… Maximum water vapour values appear at the intermediate range of 310 K < Θ < 330 K, marking high tropospheric mixing ratios sampled south of the tropopause fold (compare Fig. 11b with high mixing ratios and isentropes south of the tropopause fold in Figs. 11e and 11f). Low H_2O-values in Figures 11a to 11d around Θ = 310 K and 320 K correspond to the stratospheric water vapour mixing ratios within the lower compartment of the tropopause fold, while the slightly enhanced H_2O-values below Θ = 310 K mark the upper troposphere at the north of the tropopause fold (cf Fig. 11b, 11e and 11f).

Classically, the tracer relationship is used to define the provenance of the sampled air masses. Gettelman et al. (2011) used H_2O mixing ratios of less than about 12 ppmv as threshold for stratospheric air and ozone values of less than about 65 ppbv as threshold for tropospheric air. The respective thresholds are added in Figs. 11a, c and d. This means, data points which are close to both tracer axes of the diagrams in Figs. 11a to 11d indicate an atmospheric state with no mixing and belonging either to the stratosphere or the troposphere, e.g. Plumb (2007) and Gettelman et al. (2011). Data outside these regions are called mixed regions of the ExTL. Typical aircraft observations of stratosphere-troposphere mixing along vertically stacked flight legs appear in such diagrams as so-called mixing lines connecting both reservoirs; see Fig. 11 in Gettelman et al. (2011). Here, the zoom into the GLORIA observations along the individual legs reveals a wide-spread mixing area without individual mixing lines. These observations indicate active stratosphere-troposphere exchange in the vicinity of the tropopause fold. Especially between 330 K and 350 K, we find enhanced water vapour values, which are accompanied by notably enhanced ozone volume mixing ratios above 200 ppbv (Fig. 11b, c and d). On the other hand, slightly enhanced ozone values up to 200 ppbv, which are accompanied by enhanced H_2O well above 20 ppmv are found particularly below 330 K. The change of the shape of mixing region with potential temperature is visualised in Figure 11b by colour-coding only data points falling into the 2D mixing area.

To illustrate the locations of the mixing regions, data points indicative for the ExTL mixing region (water vapour > 12 ppmv and ozone > 65 ppmv) are flagged in the vertical cross section displayed in Figures 11e and 11f. Particularly, the data points with Θ-values between 330 K and 350 K, sticking out most of all in the correlations (data points with ozone up to 400 ppbv and more at water vapour well above 12 ppmv), show compact distributions above the PFJ core which are tilted towards the fold. This suggests that the secondary circulation around the core of the PFJ (cf. Fig. 10c and 10d) entrains moist air from the troposphere at the anticyclonic side and mixes it into the stratosphere. Vice versa, the flagged data points characterized by lower Θ values below the PFJ core in Fig. 11e indicate mixing of stratospheric air masses into the troposphere due to advection and filamentation, probably intensified by the PFJ secondary circulation. Here, and also in the ExTL mixing region south of the tropopause fold, only weaker enhancements of ozone up to ~200 ppbv are found for the data points attributed to the mixing zone. In Fig. 11f, the dense mixing region in the lower compartment of the fold is missing probably due to the data gap between 42°N and 43°N. Figure 11b reveals how the mixing region changes, like on a spiral stair, from a predominantly tropospheric correlation (low ozone, strongly variable water vapour) below 330 K to a predominantly stratospheric correlation (low water vapour, strongly variable ozone). Thereby, the 330 K isentrope roughly separates the regions of stratosphere-to-troposphere and troposphere-to-stratosphere exchange.

The ExTL mixing zone during the first passage of the tropopause fold is notably disturbed by the mountain wave (cf. Fig. 11e). …"

Probably beyond the scope of this study, but it would be interesting, if the retrieval of additional trace gases is possible and how their distribution looks like?

Retrievals of more tracers are possible from the GLORIA observations (see Johansson et al., 2018 and supplement https://doi.org/10.5194/amt-11-4737-2018-supplement; further species are accessible). Here, we use H_2O and O_3, since these species show strong gradients in the considered vertical range and are well accessible with GLORIA in terms of vertical resolution and uncertainties.