Response to Anonymous Referee #1 (acp-2017-334-RC1)

Our responses are written in italic.

The changes in the manuscript are transferred and marked as quotations.

We thank the reviewer for his/her positive assessment of the manuscript and the helpful comments.

The authors present an interesting case study addressing vertical transport and irreversible mixing of water vapor in the UTLS associated with a mountain wave event …

The paper is clearly of interest, as trace gas and particularly water vapor transport by mountain waves followed by irreversible mixing is little understood and represents a source of uncertainty in simulations. The presented set of observations supports a consistent picture of local upward transport by mountain waves and partial mixing, resulting in a net enhancement of water vapor in the tropopause region. The estimated radiative forcing should be taken with care, since local observations at a certain time of the year are combined with zonally and temporally averaged data. As indicated by the authors, this aspect clearly requires further studies. The paper is clear-written and well structured. The study should be published in ACP after clarification of some minor points:

P 5 line 16 and elsewhere: cloud-free conditions, water as conservative tracer: As potential condensation may influence the analysis, the absence of (thin) clouds should be assured using airborne data (e.g. particle observations or temperature). Later it is said that ice particles were detected at the leewave side. What is the detection limit for condensed water? Could significant amounts of condensed water be missed, or can this be ruled out?

We detected cirrus clouds during the campaign by measuring total water with a tunable diode laser hygrometer with a forward-facing inlet. We calculated the ice water content by subtracting the saturation mixing ratio from the total water signal and correction for particle enhancement. The resulting detection limit for the ice water content is 0.2 ppmv. The clouds in the lee of the New Zealand Alps that are mentioned in the manuscript had an ice water content of 10 to 200 ppmv and were observed on the lowest flight leg (7.7 km) of the first Falcon flight. This is in agreement with satellite measurements. No clouds were observed at higher flight altitudes of this flight and during the second Falcon flight. The possible influence of these clouds is discussed in the manuscript.

"For the flux calculations we used water vapor as conservative tracer due to the absence of supersaturation at the analysed flight altitudes. However, at the first flight leg of FF04 at 7.7 km we measured ice particles with the in-situ instrumentation with a detection limit for the ice water content of 0.2 ppmv. The cloud was detected between +150 km and +200 km distance and indicates the existence of a lee wave cirrus. This gravity wave induced cloud was also visible in the infra-red images of the MTSAT-2 satellite at 03 UTC and dissipated until 06 UTC (Bramberger et al., 2017). No further clouds were measured on the other flight legs and in particular not during those legs for which the flux calculations were performed. However, the presence of an ice cloud on a lower layer may affect the water vapor distribution at a higher flight level (8.9 km) by lowering the amplitude of the fluctuation. In Figure 3 we observe a strong negative peak in the vertical wind at +170 km distance to the summit in contrast to a small water vapor fluctuation which may be influenced by the drying of the level below. The calculated flux in this region is then also reduced. This effect does not influence the general transport direction at this flight altitude and is not relevant for the higher flight altitudes or the second Falcon flight since these lee wave clouds were not observed above 7.7 km and dissipated during the first flight."

P 5 line 28: To me it was sometimes difficult to connect the flight legs and locations/ directions with the map in Fig. 1. As Mt. Aspiring serves as reference point, coordinates should be provided in the text and it would be helpful to mark this point in the maps.

In the revised manuscript we have marked Mt. Aspiring in Fig. 1 and have provided the coordinates.

P8 sect. 4.1 and Figure 1: As the vertical domain is in the focus of this study and locations are relevant, it may be helpful to add a vertical cross section of vertical wind from the model along the cross-mountain flight path and indicate the flight legs.

We now have added a vertical cross section of the vertical wind in Fig. 1 and have marked the flight leg for which model calculations were carried out for better clarity.

P12 line 4, Figure 6: While the data suggest upward transport through the thermal tropopause, it would be interesting to include comment on the dynamical tropopause. Are thermal and dynamical tropopause approximately coincident here? Furthermore, how is the approximate thermal tropopause location determined in Figure 6 (dropsondes/model)? Could the location be biased by temperature signatures of the strong waves?

The height of the thermal tropopause on 4 July 2014 was determined by output of numerical weather prediction models (ECMWF and WRF). These findings were confirmed by analyzing the dropsonde temperature profiles. The dynamical tropopause was derived as the 2-PVU level in the WRF model data. It is approximately coincident with the thermal tropopause, i.e., it is just located a few hundred meters below. In the region of the observed mountain waves the tropopause (thermal as well as dynamical) is more structured and potentially biased by wave signatures than up- or downstream the mountains. Therefore, the given heights of the tropopause are averages over the whole flight leg distance.

P12 line 6, Figure 6b: exact localization of maxima : : : not possible: It is clear that it is difficult to have observations at many different levels in a short time window and here the best possible is done. However, could the pattern in Figure 6b change significantly if more/other levels would be available?

We added a short note on this discussion topic. The first Falcon flight shows the same pattern of vertical divergence for the lower altitudes. A significant change should not appear by using other levels, but maxima could possibly shift in altitude. In another field campaign conducted two years after DEEPWAVE, a lidar for water vapor measurements pointed upward and made it possible to derive a profile of the vertical water vapor flux. However, the operating lidar instruments on board the Falcon and the GV were not measuring water vapor during DEEPWAVE.

"For the first Falcon flight we find a similar pattern and values for the flux divergence between 7.7 and 10.8 km (Table 3). The use of other levels could change the pattern slightly but the general trend appears to be robust. Vertically resolved data (e.g. by lidar measurements) would be required to derive the vertical curtain of the flux divergence but were not performed during this campaign."

P13 line 25: Turbulence is identified in the dropsonde data between 329 and 334 K and suggests mixing. Figure 7b shows that the situation is changing within hours. Is it robust to apply this potential temperature range from a single dropsonde profile to the H2O-O3 correlation from a full flight covering several hours?

We clarify this remark. The potential temperature range of 329 to 334 K for turbulence is derived from a total of 9 dropsonde launches during the GV flight. These dropsondes were launched over 5 hours so we assume a similar range for the first Falcon flight. The altitude range of the turbulence occurence changed due to a change in the tropopause height.

“The layers of suggested turbulence, found in all nine dropsondes launched above the middle and eastern part of the mountains, generally have a thickness of approximately 200 m and are correlated with a potential temperature range of 329 to 334 K.”

“The dropsondes, covering a time range of 5 hours before, during and after the second Falcon flight FF05, always show turbulence in the same potential temperature range with slight changes in the altitude due to the descent of the thermal tropopause. Thus, we also assume the presence of turbulence layers for similar potential temperatures during the first Falcon flight FF04.”

P13 line 21: A local _ 1 W/m2 radiative forcing is estimated locally above New Zealand in July. However, Figure 6 in Riese et al. (2012) refers to annually and zonally averaged values. How could this affect this estimate?

We have tried to moderate our statement by emphasizing the difference between our own study and the study of Riese et al. (2012). We attempted to relate the results of Riese et al. (2012) to our measurement region and then derived a lower limit for the radiative effect. Since we compare our case for mixing by mountain waves with annually and zonally averaged values a large uncertainty exist. Water vapor shows a seasonality in the mid latitude region of the Southern Hemisphere (e.g. Hegglin et al., 2013[1]*) with lower mixing ratios in July than in January. The use of absolute values for the difference in the water vapor mixing ratio induced by mixing would lead to a biased estimation of the radiative forcing. However, we based our estimation on the percentage difference which slightly reduces the uncertainty for a comparison of annually averaged mixing ratios with a case on a specific day.*

“Under the assumption that the simulated difference in the distribution of water vapor as a result of enhanced mixing may also be representative for our case of mixing induced by mountain waves, we estimate a radiative forcing larger than 1 W m^{-2} locally above New Zealand during and after the mountain wave event. Riese et al. (2012) do not give a physical reason for the changes in the mixing strength, so our case may present a physical process (among other processes) contributing to the change in the water vapor distribution in the UTLS. While we used the calculations by Riese et al. (2012) at the measurement location, their study has a coarser vertical and horizontal resolution and is averaged over one year. We here neglect the seasonality in the water vapor mixing ratio that is present in the southern hemisphere at this latitude range. Thus, our estimate has a large uncertainty. Nevertheless, it emphasizes the relevance of mountain waves on the water vapor distribution and the radiation budget of the UTLS.”

Technical:

Thank you for the following remarks; they are now corrected in the manuscript.

P3 line 3: correlations

P6 Eqns 1 and 2: define x and t

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[1] Hegglin, M. I., Tegtmeier, S., Anderson, J., Froidevaux, L., Fuller, R., Funke, B., Jones, A., Lingenfelser, G., Lumpe, J., Pendlebury, D., Remsberg, E., Rozanov, A., Toohey, M., Urban, J., von Clarmann, T., Walker, K. A., Wang, R., and Weigel, K.: SPARC Data Initiative: Comparison of water vapor climatologies from international satellite limb sounders, J. Geophys. Res. Atmos., 118(20), 11,824-811,846, doi:10.1002/jgrd.50752, 2013.

P9 line 18: check number/unit: -176 m ppmv

P9 line 28: strong negative peak

Figure 5: numbers at right y-axes of panels on the right side would be helpful