Editor's comments on revised Gravity wave induced cross-isentropic mixing: A DEEPWAVE case study

We thank the editor for the clarifications and suggestions to improve the paper. We hope that we adequately addressed the key points.

Comment Page 1 Line 18: downwind of the Alps

Comment Page 1 Line 19: and N_2O, are

Reply to comments: We changed it as suggested.

Changes in manuscript: The Θ-N_2O-relation downwind of the Alps modified by the gravity wave activity provides clear evidence that trace gas fluxes, which were deduced from wavelet co-spectra of vertical wind and N_2O, are at least in part cross-isentropic.

Comment Page 1 Line 23: downstream of the mountain

Comment Page 1 Line 24: prior to the measurements

Reply to comments: We changed it as suggested.

Changes in manuscript: Despite only weak turbulence during the stratospheric leg, the cross-isentropic gradient and the related composition change on isentropic surfaces from upstream to downstream of the mountain unambiguously conserves the effect of turbulent mixing by gravity wave activity on the trace gas distribution prior to the measurements.

Comment Page 2 Line 5: I think this sentence would read better as 'Orographic gravity waves affect the large-scale stratospheric circulation and play an important role in determining the thermal and dynamical structure of the atmosphere'

Reply to comment: We changed as suggested.

Changes in manuscript: Orographic gravity waves affect the large-scale stratospheric circulation and play an important role ~~for~~ in determining the thermal and dynamical structure of the atmosphere ~~and affect the large scale stratospheric circulation~~

Comment Page 2 Line 10: I don't think the sentence 'Gravity waves ... 2010)' is needed – the paragraph reads better without it.

Reply to comment: We removed the sentence.

Changes in manuscript: ~~Gravity waves propagate across the UTLS where static stability increases at the tropopause~~

Comment Page 2 Line 13: Both types of instability

Comment Page 2 Line 14: occurs, potentially leading to mixing...

Reply to comments: Changed as suggested.

Changes in manuscript: Both types of ~~instabilities~~ instability may lead to the occurrence of turbulence, particularly when wave breaking occurs ~~with potential subsequent,~~ potentially leading to mixing of trace species

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Comment Page 2 Line 17: radiation-driven

Reply to comment: We added the hyphen.

Changes in manuscript: To overcome this dynamical barrier diabatic processes are required, which can be associated with radiation-driven processes or phase transitions of water.

Comment Page 2 Line 18-25. also next comment line 25-26: This part of the text needs redrafting. Do you mean that wave breaking causes diabatic heating (or cooling) separate to its role in promoting turbulence? If so, please explain what process you are referring to. Otherwise the sentence beginning 'Wave breaking' could be omitted and the following sentence changed to 'In addition, turbulence produced by wave breaking and wind shear above the tropopause ....' While I like the term 'cross-isentropic mixing', all mixing driven by turbulence (whether cross-isentropic or not) is irreversible. I'm not sure what point you're trying to make here so won't offer an alternative wording.

Reply to comment: As indicated by one of the reviewers we wanted to include a link to the scale breakdown initiated by [planetary] wave breaking and subsequent stirring as opposed to the small scale gravity wave induced turbulence, which is followed in the next sentence.
Regarding the terminology we fully agree, that turbulence is irreversible. We want to clarify in this section, that an irreversible exchange across the tropopause can occur via turbulence, and second to emphasize the entropy changing (and thus potential temperature changing) nature of this. The later is directly linked to the observations later, though a redundant statement. However, we think it helps for the later discussions throughout the paper.
Irreversibility is associated with entropy change and thus change of potential temperature, which is also the case for a diabatic process. The opposite however is indeed not true and diabatic is not necessarily irreversible. We sharpened this further.

Changes in manuscript: Wave breaking of planetary waves and stirring may cause ~~diabatic transport and~~ a scale breakdown in the tracer structure with subsequent mixing of tracers by molecular diffusion (e.g. Balluch and Haynes, 1997).
In addition, turbulence ~~occurrence, associated with~~ produced by wave breaking and wind shear above the tropopause (Shapiro, 1980; Söder et al., 2021; Kaluza et al., 2021, 2022; Lilly et al., 1974) provides such another efficient diabatic process. It leads to cross-isentropic mixing and thus irreversible trace gas exchange at the tropopause. We will use the term 'cross-isentropic' to emphasize the irreversible (entropy changing i.e. potential temperature changing and therefore diabatic) nature of this process. Further the term 'cross-isentropic' allows to distinguish from 'quasi-isentropic mixing'. The latter is driven by synoptic and planetary waves leading to stirring and mixing best approximated along isentropes.
~~Diabatic~~ Irreversible (entropy changing) processes lead to a~~n irreversible~~ redistribution of tracers which must be therefore cross-isentropic providing a tracer flux crossing isentropes.

Comment Page 2 Line 25 and 26: Just because a process is diabatic doesn't mean it's irreversible. Radiative heating and cooling for example is in principle reversible, as is condensation and subsequent evaporation of a cloud. You need to be much clearer about the difference between diabatic and irreversible processes.

Reply to comment: See comment and changes above.

Comment Page 3 Line 11: omit 'occurrence'

Reply to comment: We removed it.

Changes in manuscript: Direct observations of gravity wave induced cross-isentropic tracer mixing are sparse, since this requires high resolution measurements of passive tracers (i.e. tracers without chemical or microphysical sources or sinks) exactly in the region of turbulence ~~occurrence~~ associated with these waves.

Comment Page 3 Line 18: omit 'diabatic'

Reply to comment: We omitted it.

Changes in manuscript: This study provides evidence on the basis of observed passive tracers that the breaking of mountain waves can lead to ~~diabatic~~ tracer redistribution in the tropopause region by cross-isentropic mixing.

Comment Page 4 Line 5: During 12 July, which...... paper, no HIAPER.....

Reply to comment: We changed it accordingly.

Changes in manuscript: During the 12~~.~~ July, which is the day of the analysis in this paper no HIAPER flight was performed.

Comment Page 4 Line 9: Herriott cell

Reply to comment: Correct, we changed it.

Changes in manuscript: The instrument consists of a ~~Harriott~~ Herriott cell with a path length of 36 m.

Comment Page 5 Line 17: on 12 July

Reply to comment: We changed it accordingly.

Changes in manuscript: In this study we focus on research flight FF09 of the Falcon aircraft on the 12~~.~~ July 2014 starting at 17:15 UTC to 20:15 UTC

Comment Fig 1 caption: 'The solid red line in b) denotes the -2 pvu isoline' , also say that the solid black line is the flight track.

Reply to comment: True, we changed it.

Changes in manuscript: The solid red line denotes the -2 pvu isoline~~, the~~ and the solid black line denotes the flight track. The black dashed lines denote contours of the horizontal wind velocity (10, 15, 20, 25 m s^{-1} in (a) and 10, 20, 30 m s^{-1} in (b)) and the gray dashed lines in (b) denote contours of potential temperature.

Comment Page 6 Line 7: upwind of the region

Reply to comment: Accordingly changed.

Changes in manuscript: The flat dynamical tropopause structure is mirrored by the ozone distribution from ERA5 data (not shown), which shows a rather homogeneous distribution at Θ = 330 K (approximately flight altitude) and notably also upwind of the region of our measurements.

Comment Page 7 Line 1: Particularly in the regions of strong variability of the vertical wind, Θ, N_2O........

Reply to comment: Changed as suggested.

Changes in manuscript: Particularly~~,~~ in the regions of strong variability of the vertical wind ~~also~~, Θ, N_2O and CO show enhanced variability and strong fluctuations during the stratospheric part of the flight.

Comment Page 8 Line 1: downwind of

Reply to comment: We added it.

Changes in manuscript: However, its variability does increase downwind of the mountains similar to w and Θ, indicating the occurrence of turbulence.

Comment Page 13 Line 15: downwind of the mountain is indicative of

Reply to comment: We changed it as suggested.

Changes in manuscript: Therefore, a change of tracer gradient (i.e. $\partial N_2O/\partial\Theta$) as a function of Θ downwind of the mountain is indicative ~~for~~ of irreversible cross-isentropic tracer exchange which might have occurred above the mountain ridge.

Comment Page 13 Line 20: downstream of

Reply to comment: We added it.

Changes in manuscript: We therefore investigated if tracer gradients with respect to potential temperature Θ were changed due to the occurrence of gravity wave induced turbulence leading to cross-isentropic mixing by comparing local tracer profiles upstream and downstream of the mountains ($\partial\chi/\partial\Theta|_{up} \neq \partial\chi/\partial\Theta|_{down}$).

Comment Page 13 Line 22: either ‘led’ or ‘leads’ but not ‘lead’

Reply to comment: Correct. We changed it.

Changes in manuscript: In particular, the gradient change of the conservative tracer N_2O at the tropopause is perfectly suited to test our hypothesis that gravity wave-induced turbulence ~~lead~~ led to cross-isentropic mixing.

Comment Page 13 Line 28: the following analysis (omit ‘below’)

Reply to comment: We omitted it.

Changes in manuscript: We will apply this convention with Θ in the numerator and N_2O in the denominator throughout the following analyses ~~below~~.

Comment Page 13 Line 30: ‘referring to specific measurements’ (omit ‘further below’)

Reply to comment: We removed it.

Changes in manuscript: The term Θ-N_2O-relation refers to general aspects of their relation, the term Θ'/N_2O'-ratio (associated with a slope) will be used when referring to the specific measurements ~~further below~~.

Comment Fig 7: Gray arrows mentioned in caption but not visible on diagram

Reply to comment: In the last update we removed the gray arrows. We changed the caption.

Changes in manuscript: Schematic evolution of potential temperature Θ versus N_2O in the presence of cross-isentropic mixing ~~(indicated by the gray arrows)~~ at the tropopause (e.g. by orographic wave-induced turbulence).

Comment Page 16 Line 9: omit ‘on display’

Reply to comment: We removed it.

Changes in manuscript: The Figure shows the same subset of data using averaging periods ~~on display~~ of 150 s (Fig. 9(a)) and 20 s (Fig. 9(b)) corresponding to a horizontal scale of 33 km and 4 km, respectively.

Comment Page 17 Line 1: -0.6 K/ppbv (you have it as +!) (also l.8)

Reply to comment: True. We changed it in both places.

Changes in manuscript: With a value of about -0.6 K/ppbv the ratio is almost constant over all averaging periods.

Comment Page 19 Line 16: Reference is made here to ‘the last region’ and in the next section to ‘the second region’. Which parts of the plot are you referring to in each case?

Reply to comment: Correct. We changed it accordingly.

Changes in manuscript: The first region is between 170.0°E and 170.6°E, the second ~~at~~ between 170.8°E and 171.0°E. The ~~last~~ first region shows mainly positive trace-gas fluxes with values up to 0.50 ppbv m s^{-1} at wavelengths ranging from 8-16 km corresponding to the vertical wind energy maximum around $\lambda_x = 10$ km

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Comment Page 20 Line 11: 'frequencies smaller than 721 m' – clearly this is nonsense even if you do put 0.3 Hz in brackets. More importantly, the E~k^{-3} spectrum of geostrophic (2-D) turbulence is usually found at much larger scales than here (several hundred km e.g. Nastrom and Gage 1985) so although your results are consistent with k^{-3} for wavelengths 1-10 km it doesn't follow that this is due to 2-D turbulence. I don't agree either that the slopes of both w and Θ 'turn to -5/3' at high frequency – the Θ spectrum in particular could be argued to have the same slope throughout.

Reply to comment: We apologize for the incorrect assignments. We also agree, that a slope of -3 is indicative for geostrophic turbulence at large scales. We therefore changed the text accordingly. Regarding the slopes also see reply and changes to the next comment.

Changes in manuscript: The power spectral density (PSD) for ~~the~~ Θ~~,~~ and the vertical wind component w in Fig. 13 show~~s~~ a slope of -3 for ~~frequencies smaller~~ wavelengths longer than 721 m (< 0.3 Hz), ~~which is indicative for geostrophic turbulence (Zhang et al., 2015)~~ in agreement with the observations during airborne measurements during START08 (Zhang et al., 2015) for wavelengths < 10 km. For ~~higher frequencies (i.e. shorter wavelengths)~~ shorter wavelengths (i.e. higher frequencies) the increase of the power spectral density at 433 m (0.5 Hz) would be consistent with a potential source of turbulent energy above the mountains.

Comment Page 21 Line 6: you're saying here that the N_2O spectrum has the same slope (-5/3) throughout, which isn't what the diagram shows. You need to be very careful with your argument here. Both N_2O and Θ are passive tracers on the time and length scales of turbulence, so their spectra should look the same. The fact that their slopes are so different suggests either an instrumental issue, probably with N2O, or some sampling issue. I certainly don't see a 'transition from geostrophic to isotropic turbulence' (p21 l.8).

Reply to comment: We thank for this comment, which we took for a piecewise analysis of the slopes: Focusing on Θ and N_2O we derive for the frequency interval 0.015 Hz - 0.3 Hz -2.8 (N_2O) and -3.2 (Θ). For the high frequencies (> 0.9 Hz) we get -1.3 (N_2O) and -1.8 (Θ). For vertical wind we used only the frequencies > 1.9 Hz due to the local maximum around 0.6 Hz and derive a slope of -1.9. For clarity Fig. 1 shows the PSD for N_2O, Θ and vertical wind separately.
We have no indications for technical problems with the N_2O measurement system nor clear indication, that we are approaching the white noise limitation of the measurement at highest frequencies. Different slopes between the passive tracers N_2O, O_3 and the potential temperature are described in Bacmeister (1996). A similar behavior (with a flattening slope at high frequencies) was reported by Zhang et al. (2015) for pressure. It is interesting to note that in their measurements the spectral behavior did not follow potential temperature and that the flattening slope of static pressure was reported for a flight segment, where the vertical wind showed a source of turbulence (their section M2), which is similar to our observation. Nonetheless, since we can't fully exclude an artifact, we changed the relevant text passage and also removed the mentioning of a transition of geostrophic to isotropic turbulence.

Changes in manuscript: ~~The slope of the PSD of both w and Θ turns towards -5/3 for frequencies exceeding 108 m (2 Hz)~~ For wavelengths below 108 m (> 2 Hz), the slope of the PSD of both w and Θ approach -5/3, which can be related to isotropic turbulence. Fig. 13 also shows the PSD of N_2O ~~which show a slope of -5/3 for frequencies smaller than 721 m (0.3 Hz) and a -5/3 slope for higher frequencies.~~. It has a slope of -3 for longer wavelengths (smaller frequencies) and a flattening slope for wavelengths smaller than 721 m (> 0.3 Hz). ~~The transition of geostrophic to isotropic turbulence~~ A change of the turbulent behavior as indicated by the transition of PSD-slopes occurs in the wavelength range between 271 m to 721 m (corresponding to 0.8 Hz to 0.3 Hz), where the PSD of the vertical wind indicates a source of turbulent energy. Notably the PSD of N_2O indicates towards a turbulent behavior for ~~high frequencies~~ small wavelengths and thus the occurrence of turbulent fluxes corresponding to the analysis in the previous section.

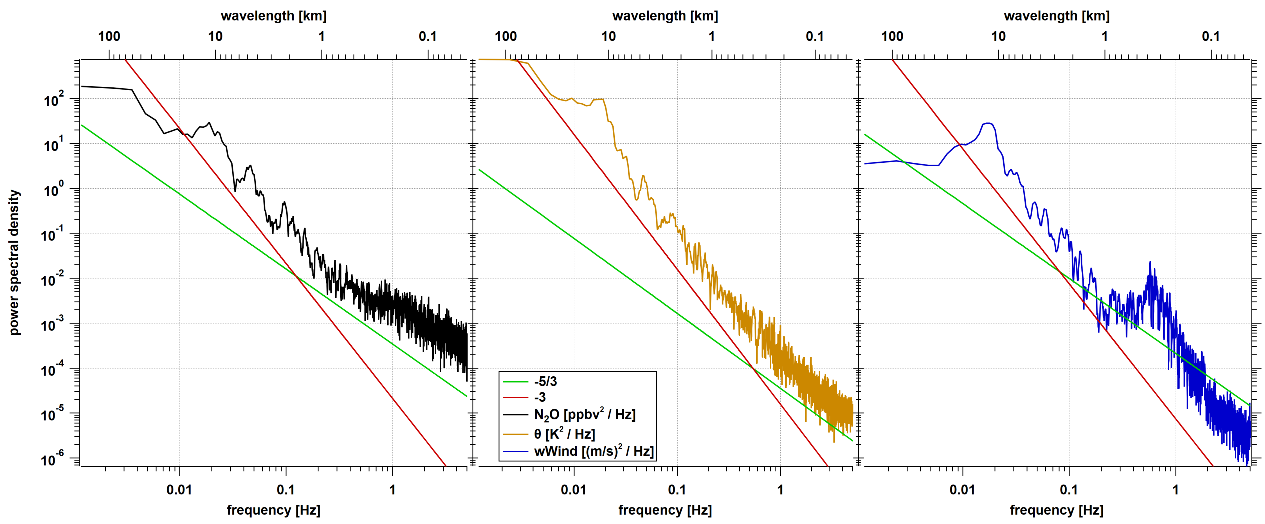

Figure 1. Power spectral density for N_2O (left; black), potential temperature (middle; orange) and vertical wind (right; blue) for the flight segment above the mountains. The power spectral density has been smoothed by a boxcar average of 5 seconds. The green and red reference lines have slopes of -5/3 and -3.

Comment Page 21 Line 13: cube root, also ‘the we used’ at the end of the line

Reply to comment: We changed it accordingly.

Changes in manuscript: Further support for our hypothesis that mountain wave induced turbulence perturbed the N_2O profile comes from the analysis of the ~~cubic~~ cube root of the eddy dissipation rate EDR = $\epsilon^{1/3}$ from the measured 3D-winds. For this analysis ~~the~~ we used the method by

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Comment Page 22 Line 1: First of all, it is difficult to distinguish the lines in the EDR panel of fig 14 – could they be coloured? But either way, two of the components are enhanced at the end of the line whereas the third is not. The text says the opposite – that only one component was enhanced. Text and figure must be consistent.

Reply to comment: We changed the colors of the figure (Fig. 2) and clarified the text.

Changes in manuscript: However, the values of $EDR_{u,v}$ for the horizontal wind components are enhanced over the mountains ~~are similar to those of the end of the leg, where EDR_w was also enhanced in the lee of the mountains~~. In the lee of the mountains the EDR of all wind components is enhanced.

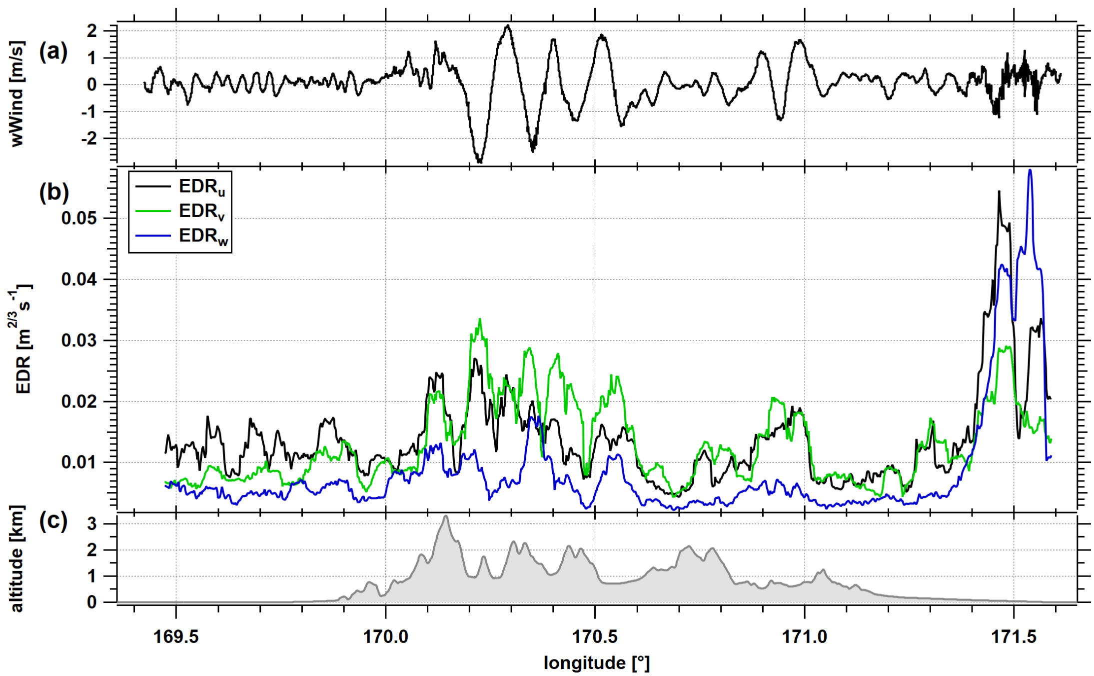

Figure 2. Time series of (a) vertical wind, (b) EDR for the measured wind components for the upper flight leg indicating weak, but non-vanishing turbulence during the time of flight above the Southern Alps (orography shown in (c)).

References

Bacmeister, J. T.: Stratospheric horizontal wavenumber spectra of winds, potential temperature, and atmospheric tracers observed by high-altitude aircraft, Journal of Geophysical Research Atmospheres, 101, 9441–9470, https://doi.org/10.1029/95JD03835, 1996.

Zhang, F., Wei, J., Zhang, M., Bowman, K. P., Pan, L. L., Atlas, E., and Wofsy, S. C.: Aircraft measurements of gravity waves in the upper troposphere and lower stratosphere during the START08 field experiment, Atmospheric Chemistry and Physics, 15, 7667–7684, https://doi.org/10.5194/acp-15-7667-2015, 2015.