Atmospheric Chemistry and Physics Discussions

Atmos. Chem. Phys. Discuss., referee comment RC1
https://doi.org/10.5194/acp-2022-420-RC1, 2022
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Comment on acp-2022-420

Anonymous Referee #1

Referee comment on "Gravity-wave-induced cross-isentropic mixing: a DEEPWAVE case study" by Hans-Christoph Lachnitt et al., Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2022-420-RC1, 2022

Title:

Gravity wave induced cross-isentropic mixing: A DEEPWAVE case study

Authors:

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Overall Remarks:

This paper presents a thorough and detailed analysis of a gravity wave induced atmospheric mixing event measured during the 2014 DEEPWAVE campaign in New Zealand. Through a combination of in-situ aircraft observations and ERA5 reanalysis data, the authors identify two distinct layers in the lower stratosphere with independent composition and isentropic characteristics. They then show how the N2O-to-potential temperature gradient weakens due to gravity wave activity, and they identify signs of turbulence and trace gas fluxes to diagnose mixing between these two layers induced by the gravity waves. This mixing mechanism is distinct from past gravity wave-induced mixing studies in that it is cross-isentropic/diabatic/irreversible and yields nonlocal consequences downstream of the orographic mixing source.

Overall, this paper presents a clear and logical sequence of results and diagnostics supporting the main arguments of the text. I recommend that this paper be accepted for publication in ACP after addressing the minor revisions detailed below in two general comments on the use of terminology/writing structure and in line-by-line specific comments. The technical nature of the paper and use of complex, codependent sentence structures can make the arguments of the paper difficult to follow and less approachable to members of the larger gravity wave community. To enhance readability and make the paper more broadly accessible to general audiences, a few simple modifications to the

writing style and sentence structure would be beneficial as detailed below. There are also several specific comments regarding how variables are discussed/plotted and the possibility of using additional data from the HIAPER aircraft, if available.

General Comments:

1. The use of overlapping terminology to describe related transport phenomena, while technically correct in all instances, makes certain aspects of this manuscript esoteric and difficult to approach for readers lacking a comprehensive background in atmospheric chemistry and tracer transport (example: phrases describing cross-isentropic/diabatic/irreversible circulation/transport/fluxes/mixing use pairs of these words somewhat interchangeably). The terminology in this manuscript also employs a number of related words with opposite meanings (example: a cross-isentropic process is not an isentropic process), which can confuse the reader when neither term is defined. When combined, these two terminology complexities make this paper less accessible for general audiences in the broader atmospheric community.

I suggest two terminology approaches to improve the readability and accessibility of the text:

a) Provide some basic definitions of terms when they are introduced to explain what they mean in the context of the other terminology used in the text (as an example, it is not explicitly stated until Page 13 that "cross-isentropic" and "diabatic" are used equivalently throughout the text because transport processes crossing lines of constant potential temperature, i.e. isentropes, are inherently diabatic). If the text states early on that cross-isentropic processes are both diabatic and irreversible, later descriptions in the text using "diabatic" and "reversible" can in many instances use the expression "cross-isentropic" since the reader will know this always refers to diabatic, irreversible processes. Though the text does define some terms like orographic gravity waves (Page 1 line 1) and passive tracers (Page 1 line 32), more definitions could be used throughout the text.

b) For multi-word dynamical behaviors, try to use consistent wording and word order to avoid confusing the reader. As an example, three sets of similar expressions are used on page 2 that alter the wording/order of two expressions meaning the same thing:

cross-isentropic mixing (line 8)

non-isentropic transport (lines 14-15)

vertical turbulent tracer flux (line 28)

turbulent vertical tracer flux (lines 29-30, word order switched)

Mountain wave induced tracer fluxes (line 29)

gravity wave induced vertical cross-isentropic tracer transport (line 31)

It may also be useful to employ acronyms for commonly used phrases to avoid having 8-word expressions for a physical concept like "gravity wave induced vertical cross-isentropic tracer transport". This will make it easier for the reader group multiword dynamical descriptions and parse out the surrounding sentence structure.

2. Many sentences start with a pronoun (this/that/they/those/these, etc.) or a broad, unspecific term (our hypothesis, our conclusions, etc.) referring to the content of a previous sentence or paragraph. Often, due to the complexity of the referenced sentences/paragraphs, it is not clear what content these expressions refer to, requiring the reader to often go back to the referenced sentence to identify which topic from the previous sentence matches the description in the next sentence. To add clarity to the text, please try to avoid this sentence structure and instead state explicitly the topic of each sentence and the content being referenced. This can be applied throughout the text, with several examples identified in the Specific Comments below.

Specific Comments line-by-line:

Page 1

1 please explain the term cross-isentropic when it is first introduced, clarifying how it refers to an irreversible diabatic process to avoid confusion when these terms are later used to describe this same phenomenon.

5 remove the comma after "shows"

8 Clarify the quantity of the referenced tracer gradient (I believe you refer to a cross-isentropic gradient of tracer concentration, but this isn't specified)

10 please define theta as potential temperature when the variable is first used

18 comma after "N2O"

22 clarify that these "irreversible diabatic" trace gas fluxes are cross-isentropic to be consistent with the terminology introduced in line 1 and used throughout.

23 Define UTLS in its first use in the text

Page 2

8,14-15,28-31 See General Comment 1 regarding consistent terminology and word order

6 Define UTLS in abstract on page 1, in which case the definition is not needed here

8 Change “They” to “Gravity Waves”. Due to complexity of general sentence structure, the manuscript will be clearer if sentences that start with a pronoun (it/this/that/these/those) referring to something from a previous sentence are changed to instead state the referenced topic from the previous sentence/paragraph explicitly.

11 Change “Both” to “Both types of instabilities” for clarity - see previous comment.

15 Comma after “barrier”

15, 17, and 18 clarify the text to make it clear that “cross-isentropic mixing” (17) and “irreversible trace gas exchange” (18) are the required diabatic processes referred to in line 15.

16 commas after “addition” and “occurrence”

25 comma after “fold”

25 remove “occurrence”

Page 3

7 Remove “steps in here to”

8 remove “will”

9 remove “non-local”, as it is already clear from the text that the location downwind of the turbulent mixing region is non-local to the turbulence.

9 change “downwind” to “downwind of”

23 change “and covered” to “that covered”

23-24 change “upper troposphere lower stratosphere” to UTLS

24 change “providing” to “and provided” - 80 km altitudes are outside of the UTLS region.

26 Was there a corresponding HIAPER flight for the Falcon flight for this case study on 12 July? Later statements in the text say the FALCON flight legs were too short to measure the longer gravity wave horizontal wavelength and that two aircraft flying at close altitudes are required to calculate the flux divergence. Many of the coordinated flights in DEEPWAVE using both aircraft had HIAPER flying higher/longer legs near to where the FALCON was flying. Was this the case on 12 July, and if so, could these statements in the text be addressed by looking at HIAPER data from corresponding legs? If there was no corresponding HIAPER flight, please clarify this in the text and also state explicitly that all observations used for this flight are from instruments on the FALCON (and not HIAPER) aircraft-this is never stated in the text.

30 change “2015).” to “2015) onboard the DLR Falcon.” See previous comment.

Page 4

1 change “CO” to “CO concentrations” to clarify what quantity this instrument measures for N2O and CO

4 Define sigma in this context-I believe it is the standard deviation in this case.

Section 2.3 - It is not always clear in your figures which data is from ECMWF and which

data is from the aircraft - please distinguish your data sources in figures containing a mixture of model data and observational data.

21 Is the “5% significance level” referenced in wavelet figure captions the same as the “95% confidence level” stated in the text? If so, please use consistent terminology or define the 5% significance level in the main body of the text.

22 To be consistent with your use of American English spellings of words such as “color” rather than “colour”, use “analyze” in place of “analyse”

Page 5

Figure 1 is not utilized in the text and may be unnecessary. The flightpath is shown already in Figure 2, and arrows could be added to indicate flight direction in that figure. The text discussion of the tropopause height also does not refer to Figure 1 - it only references the red line in Figure 2b on Page 6, and the discussion of the “approaching upper level trough” references Gisinger et al (2017) rather than Figure 1. Please provide more direct references that utilize Figure 1 to justify its inclusion in the text.

Page 6

Figure 2 In panel b, consider adding gray shading of the flight sections that are later used for detailed analysis to make it easier to see which part of the ECMWF modeled wave response is sampled in the regions of interest in Figure 3.

Figure 2 Caption: change “horizontal” to “ECMWF horizontal” to clarify the data source

Figure 2 Caption: change both instances of “denotes” to “denote” - the subject (“lines”) is plural in both cases.

8 There is no panel (e) in Figure 2 - please clarify this reference.

13 change “South Island” to “the South Island”

13 change “horizontal” to “ECMWF horizontal” to explicitly state the data source.

Page 7

Figure 3 Caption: Does analyzed PV come from ECMWF? If so, please state this explicitly in the caption.

Figure 3 Caption: change “potential vorticity” to “potential vorticity (PV)” to link with figure labels.

Figure 3 Caption: Clarify what quantity of N2O and CO is plotted. The units in the plot seem to indicate that these are concentrations, yet the text refers to the N2O line as the mixing ratio (line 10), making the quantity that is plotted in the figure ambiguous. See General Comments above regarding the use of consistent terminology.

Page 8

2 θ should be defined as potential temperature much earlier in the text, not here.

Figure 4: label the upper leg and lower leg panels on the right side of the plots

Figure 4 Caption: State in the caption that the data plotted from the upper leg and lower leg corresponds to the shaded regions of Figure 3.

Figure 4 Caption: From the text (Page 7 Line 17) and the tropopause height in Figure 2, the upper leg is “just above the tropopause”, whereas the lower leg is farther from the tropopause and shouldn’t be labeled as “just below the tropopause”. If anything, the clarifying statement in the figure caption should indicate that the upper leg is just above the tropopause, as in the text. See General Comments above regarding the use of consistent wording.

Page 9

3 remove “,which has a lifetime of 110 years in the lower stratosphere,” - this lifetime information is restated later in the text where it is relevant to the discussion, but it is not important to state this information a second time in this location.

7 Consider replacing “such a breakdown of scales” with “such turbulence” to unambiguously refer to the “occurrence of turbulence” mentioned in the previous sentence. See General Comments above regarding the use of consistent wording.

7 Maybe state more clearly in the text that you identify a kinematic flux of N2O by collocated, phase-shifted fluctuations of theta and w indicating a nonzero w’theta’that has corresponding fluctuations in N2O concentrations.

11-13 Change word order to “The vertical turbulent kinetic energy was larger in the lower leg ($\overline{w'^2} = 0.70$ m^2 s^{-2}) than in the upper leg ($\overline{w'^2} = 0.53$ m^2 s^{-2}), where the overline denotes the average over the whole 200 km flight leg.” This will make the sentence less confusing.

14 Does “this energy” refer to the energy in the lower leg or the energy in the upper leg? Please state explicitly which leg is referenced here. See General Comments above regarding unclear use of pronouns referring to previous sentences.

Page 10

5 Was there a corresponding HIAPER flight with longer legs that could identify the longer gravity wave horizontal wavelengths? Clarify earlier in the text whether both aircraft were flying, and if there is corresponding HIAPER data, perhaps it is worth checking to see if the longer wavelength can be identified.

10 Reference Table 1 values in the text where you mention the zonal momentum fluxes

15 I believe that the vertical derivative is taken by comparing values from the two flight legs at different altitudes, right? Or is the estimate from ECMWF? Perhaps clarify how this value is estimated - it is confusing to say you take a vertical derivative from flight legs that only sample horizontally unless more information is provided.

19 Clarify in the text that you are referring back to wind components that are plotted back in Figure 3 and/or Figure 4.

Page 11

Figure 6: The use of similar colors for different variables makes it more difficult to explain and distinguish which variables are plotted. It would be more effective to use different colors (instead of 3 shades of gray/black) and add a legend to the plot identifying each plotted variable color.

Figure 6 Caption: It is unclear which datapoints are "colored data points" since all datapoints are colored. Does this sentence refer to all the datapoints in the figure or a specific subset?

Page 12

4-5 replace "The orographic waves at the lower leg" with "N2O concentrations in the lower leg (black) to clarify that you're referring to the N2O concentration in the plot

5 replace "N2O-levels" with "concentration levels"

9 what do you mean by "branches"? Perhaps clarify you are referring to the two separate regions on the plot which appear to have a constant N2O:CO ratio with distinct linear fits.

11 "N2O mixing ratios": Perhaps you should identify and show fits of these mixing ratios in the plot, as people from outside the field may not understand that you refer to regions of near-constant ratios between concentrations of N2O and CO as "mixing ratios" when the term is not defined or plotted explicitly. You could also clarify that "N2O mixing ratio" is the ratio between N2O and CO, otherwise it is unclear why you don't refer to it is the "CO mixing ratio" or the "N2O:CO mixing ratio".

11 your "detailed analysis" is not shown - please provide more information on how these two temperature ranges were identified and what their physical significance (if any) is.

13 What is a "compact relation"?

14 Please explain how the "compact relations" are given above.

17 comma after "context"

20 change inbetween to “between”, here and elsewhere in the text

21 Figure 7 does not show vertical winds, only potential temperature - please omit “vertical wind and” or refer to a previous figure that contains the vertical winds.

28 change “vertically closely stacked levels” to “closely stacked vertical levels”

29 change “can not” to “cannot”

29 Clarify earlier in the text whether there was one or two aircraft flying on 12 July.

30 change “km potential” to “km, the potential”

31 change “levels” to “flight levels”

Page 13

Figure 7 Caption: fix the broken figure reference “Fig. ??”

1 It should be stated much earlier in the text that cross-isentropic fluxes are diabatic.

1 and onward: the text refers to species gradients as d(X)/d(theta), yet the plotted gradient in Figure 11 appears to be inverted as d(theta)/d(X). Because the text indicates that the tracer slope changes as a function of theta (instead of saying the theta slope changes as a function of the tracer), it would be much clearer to plot d(X)/d(theta) rather than d(theta)/d(X).

7 Perhaps use the wording “cross-isentropic” somewhere in this description to refer back to the title and previously used terminology. See General Comments above regarding the use of consistent wording.

8 perhaps say “above the tropopause” instead of “at the tropopause” since your measurements are not directly at the tropopause. Figure 8 only shows a diagram of this relationship above the tropopause, so using the same terminology in the text will make it clearer.

9 Your “hypothesis” is difficult to parse from the text due to complex sentence structure - please modify lines 5-7 to more clearly indicate your prediction refers only to the cause of the observed changes to d(X)/d(theta) (gravity wave induced turbulent mixing). Otherwise your hypothesis could be misidentified as just saying that d(X)/d(theta) changes, which we know already from the data, vs your actual hypothesis of why d(X)/d(theta) changes.

9-10 Change “at the tropopause” to “just above the tropopause” since the data you present in Figure 7 is “just above the tropopause” according to the figure caption.

Page 14

Figure 8: Since our discussion in the text refers to d(X)/d(theta), perhaps it would be better to have your diagram in Figure 8 be a diagram of d(X)/d(theta) vs. theta or altitude instead of making the reader infer changes to d(X)/d(theta) from a theta vs N2O plot. You could then compare this diagram with Figure 11 instead of with Figure 9.

1 Change “This is schematically shown” to “A schematic of our hypothesized changes to d(X)/d(theta) is shown”. See General Comment above regarding unspecific use of pronouns at the beginning of sentences.

9 The use of the word “steeper” is confusing in this case - due to the orientation of the axes in Figure 8, the downstream slope looks “steeper” to the eye than the upstream slope because the plot is oriented to show the dependent variable (theta) on the y axis rather than the x axis. To avoid confusion, it would be clearer to say the gradient d(X)/d(theta) is larger upstream. As suggested above, this would be easier to see visually if the diagram in Figure 8 shows d(X)/d(theta) vs theta or altitude rather than theta vs N2O.

10 Though it follows from the text, it may be good to state explicitly that the vertical gradient decreases due to mixing, rather than just stating that the gradient is higher upstream than downstream.

Page 15

Figure 9: maybe zoom in on the region from 320 K - 340 K to make it easier to see the changing N2O vs theta relationship.

4 change “corresponding to the hypothesis described above” to “consistent with our hypothesis that d(X)/d(theta) will be reduced in regions impacted by gravity wave induced mixing”. See General Comments above regarding the use of consistent wording.

5 As stated above, please clarify what is meant by a “compact relationship”

Page 16

7-8 remove “as given in detail further below”

9 after “different scales”, add “using the formula”

15 Perhaps it would be valuable to explain why the slope d(N2O)/d(theta) decreases due to mixing, as up to this point the only “explanation” is that the slope will change, not how it will change or why.

Page 17

4 Why are wavelengths of 33 km and 4 km selected for Figure 10? Why not show averaging periods corresponding to the spectral peaks in Figure 5 that match the dominant orographic gravity wave frequencies you identified?

Figure 11: use a clearer label for the y axis than “Slope” (i.e., d(theta)/d(N2O))

Figure 11: As discussed earlier, why not plot d(X)/d(theta) instead of d(theta)/d(X)? This would make it easier to see that the magnitude of d(X)/d(theta) is larger upstream like you discussed on pages 13-14.

Figure 11: Because your analysis is focused on spatial scales, please convert the x-axis

label to spatial scales (i.e. km) to facilitate more intuitive comparisons with orographic wave scales identified in the text and in Figure 5. This will also make it easier to understand how these scales correspond to the wavelet coherence plotted in Figure 12 where scales are converted to km.

Page 18

7-9 It is confusing to identify the slope behavior at "larger wavelengths" and then refer to these dynamics as "at small scales" in the next sentence, as the greatest downstream slope modulation from the upstream slope occurs for the largest averaging times in the figure (i.e., the largest spatial scales). Please use consistent terminology, as referring to the same scale range as both "larger" and "small" from one sentence to the next is needlessly confusing.

Figure 12 Caption: please clarify what variable is plotted by the arrows and what it means for N2O and theta to be phase shifted by 180 degrees

Figure 12 Caption: Is the 5% significance level the same as the 95% confidence level discussed earlier in the text? If so, please use the same terminology throughout. See General Comments above regarding the use of consistent wording.

Last paragraph (lines not numbered):

-Please clarify that this discussion corresponds to Figure 12.

-Scales referenced in the text should be converted to km to be easier to identify in Figure 12 where you have converted the temporal scale sampling to km scales.

-Please clarify what the "phase relation" is, how it is plotted in Figure 12, and what it means to have a phase relation that is constant at 180 degrees.

Page 19

1 Because the phase relation is not explained, it is unclear what it means or how it relates to previous conclusions in the text. In addition, it is unclear which conclusion you are referring to by saying "the conclusion from the previous upwind slope analysis" - please state this conclusion explicitly and explain how it is confirmed by this analysis.

3-14 Perhaps these lines of text can all be part of the same paragraph rather than having 3 paragraphs discussing the same thing in groups of 1-2 sentences.

3 please express “time scales < 40 s” in units of km to make them identifiable in Figure 12

5 Please explain what feature in Figure 12 indicates a “defined phase transition” and how it is distinct from the rest of the plot (phase transitions are not described in terms of phase shift, which is the only explanation given for the meaning of the arrows in Figure 12)

7 change “matches roughly” to “roughly matches”

8 change “co-vary. The” to “co-vary: the” - you seem to be explaining what it means to co-vary in the next sentence, which is easier to understand if the sentences are combined.

8 Is the “calculated slope” from Figure 11? If so, please state this as the text here is talking about Figure 12.

10 What is this “new slope relation”? How is it visible in Figure 12? If you are referring back to Figure 11, please say so and quantify this “new slope relation” with a value from the appropriate plot.

12-14 Please provide more detailed explanations in the text from lines 3-11, as I do not follow how this conclusion is supported by the analysis of Figure 12.

Figure 13 Caption: change “colors denotes” to “colors denote”

Page 20

1 is the “cross wavelet transformation” the part of Page 4 line 25 inside {} ? This is the first usage of the term “cross wavelet transformation” as it is not mentioned in section 2.4. See General Comments regarding consistent use of terminology.

13 It is not explained why having a temporal resolution of 10 s precludes the analysis of ozone fluxes - please clarify.

Section 4.3: Figure 14 and its associated discussion would be easier to understand in the context of the spatial scales plotted in Figures 12 and 13 if Figure 14 was discussed in terms of horizontal scales rather than in terms of temporal frequencies. These scales are included in Figure 14 - please modify the discussion here to include the wavelengths in Figure 14 instead of only referring to the frequencies in Hz.

26 Remove the comma after “both”

27 change “smaller 0.3 Hz” to “smaller than 0.3 Hz”

29 remove the comma after “range”

29 Please explicitly state the frequency range you are talking about

Page 21

1 and 8: Starting these two paragraphs with “Further support for our hypothesis and our results come from the analysis of …” is unclear in both cases - Please state which aspect of your hypothesis is supported by the data in these introductory sentences.

5 “v” should also be a subscript in EDR $_{u,v}$

6 change “when also” to “where”

6 change “was enhanced” to “was also enhanced”

9 change “GTG (Graphical Turbulence Guidance)” to “Graphical Turbulence Guidance (GTG)”

13 change “upper flight” to “upper flight leg”

Page 23

4 change “activity the” to “activity at the”

4 change “and propagating” to “that propagates”

5 change “this observations” to “these observations”

7 remove “occurrence”

10 change “gravity wave occurrence” to “gravity waves”

17 change “θ also strong” to “θ, strong”

17 change “were observed” to “were also observed”

20 change “gradient above” to “gradient was observed above”

21 comma after “inert”

22 change “ridge showing reversible” to “ridge with reversible”

23 Again, please clarify what is meant by the “compact slope”

25 “The behaviour” - what behavior? Please be specific. (also note the spelling of behavior without a "u" if you prefer to use American English spelling practices)

28-29 change “occurring potentially previously” to “that may have occurred”

30 “The tracer conserves the effect” - what tracer, and what effect? Please be specific.

30-31 Again, please define what a “compact relation” is.

30-32 “At…Mahalo et al., 2011)” - divide this sentence into two sentences. You could do this in line 31 by changing “mountains modulating” to “mountains. The modified compact N2O-theta relation also modulates”

32 change “similar as” to “similar to the mechanism”

Page 24

2 change “to 0.5” to “to be 0.5”

4 remove comma after “fact”

5 remove comma after “shows”

7-8 combine this sentence with the previous paragraph

7 remove comma after “shows”

9-16 Use caution introducing new citations in the conclusions - some of these explanations and citations may be better suited to the introduction. The conclusions of your paper should focus specifically on your results.

10 replace “tropopause region and lower stratosphere” with “UTLS”

11 change “and high degree” to “and a high degree”

12 comma before “regions”

12 remove “occurrence”

13 change “this” to “gravity wave induced turbulence”

15-16 The organization and meaning of the last sentence is unclear.