Reply on Review Process of acp-2017-472 Version 1

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First of all, we like to thank the two anonymous referees for their time expenses to comment on our manuscript acp-2017-472 published in the discussion part of the special issue of Atmospheric Chemistry and Physics "Sources, propagation, dissipation and impact of gravity waves" on 3 July 2017. In the following we first give an overview of the main changes of the manuscript, adressing both referees and the editor (Sec. 1). After that, we reply in detail on the constructive comments of Referee #1 (Sec. 2).

1 General Comments of the Authors

- Regarding the suggestion of Referee #2 to "improve the whole text" the authors decided to rewrite the whole manuscript. Therefore, the attached file including the highlighted changes looked very complex and we omitted it.
- Now, we attempt to guide the reader to the impact of our manuscript by highlighting more intensively its novel characters in the introductionary part. We expanded the literature research massively.
- As Referee #2 had concerns regarding the reliability of our data (preprocessed with the WRF Preprocessing System (WPS)) we thoroughly investigated the analysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) to find the best fitting data set and resolution of data during the last month. All calculations were redone and restricted to altitudes below 45 km to avoid the strong sponge layer in ECMWF data starting at 1 hPa, following the suggestion not just

of Referee #1 but also published findings in literature (Sec. 2.3). We avoid horizontal interpolation by keeping the data on the original latitude-longitude grid, adjusting our algorithm accordingly. The discussion on ECMWF data is shortended appreciably in favour of a brief literature review.

- We provide a step-by-step outline of the methods because Referee #2 doubts that the former explanation was sufficient (Sec. 2.1). We also add some calculations in the Appendix.
- Now, the application of the method is clearer arranged and trimmed to the analysis of three profiles from one time step (Sec.3).
- The concerns of Referee #2 regarding our pictoral schemes of hydromechanics, namely "valves and pumps" are taken care of. We erased this literal description of the analysed mechanisms from the manuscript.

We want to highlight again, that this manuscript focuses on the introduction of our novel method called "Unified Wave Diagnostics" (UWaDi). The application on the minor Sudden Stratospheric Warming on 30 January 2016 acts as a demonstrative application to show the advantage of this method. We plan to join the closer analysis of observations and models with respect to local features of GW generation and propagation. The authors highly recommend, that the introduction and the application of UWaDi should not be seperated and published in different journals as we prefer to join the special issue (SI) "Sources, propagation, dissipation and impact of gravity waves". All four issues named in the title of this SI are specifically addressed in the discussion part of our manuscript. Furthermore, we hope by belonging to this SI, that other scientists interested in this topic can find simple access to our method and cooperation.

2 Comments to the Referee #1

1. Filter and filter response
At page 7, line 10 you introduce that you use a bandpass filter. You state the filter limits in terms of wavelengths. However, most filters have a spectral response rather than a hard limit. For the further interpretation this response is important. In particular, the short horizontal wavelengths cut-off might remove part of the mountain waves and favor waves excited by spontaneous imbalance and the long vertical wavelength cut-off could remove part of the GW spectrum in the high wind case (22 January). The latter would

mean that you underestimate GWs for this case. Therefore please include a figure showing the filter response in terms of wavenumber or wavelength. In general, please explain why you need this filter at all.

The bandpass filter acts in spectral space, where we sort out waves that are not important for our analysis. Here, we use a rectangular filter with hard limits of k_{min} and k_{max}. UWaDi can be run with a gaussian shape bandpass filter, which does not have sharp limits. However, we find best results with the rectangular filter in this case.
We now choose a range of wavelengths between 100 km and 1500 km horizontally and 1 km and 15 km vertically. We find inertia GWs from spontaneous imbalance and flow over orography, as we discuss in Sec. 4 of the new manuscript. Insofar, the filter is wide enough. The bandpass filter is described a bit more in detail in Sec. 2.1, Step 4. We also performed numerous tests with the sensitivity of the results to the filter and resolution of data (grid sizes of 1°, 0.36° and 0.1°). It turned out, the characteristic wavelength mentioned in the manuscript does not depend on grid size and filter width. However, we did not dwell on these details in the manuscript, for the sake of brevity.

2. Discuss the advantages and disadvantages of the technique
All techniques to analyze waves need to make a trade off between spectral and spatial resolution. The Hilbert transform is an innovative and elegant concept for high spatial resolution. Since one of the major objects of the paper is to introduce the new technique you should have a paragraph highlighting the properties of the new method. If I understand this correctly, the advantages are:

- *The tool is mathematically well defined*
- *It is applicable to data of any dimension 1D to 4D*
- *Beside some spectral filter it does not make a preselection of the wavelengths, i.e. it is superior to e.g. Fourier transform, which works on a fixed grid and distributes spectral power from any other wavelengths to that grid, which needs to preset the analysis volume and thus either smears out waves with small wavelengths or becomes unreliable at large wavelengths*
- *With FFT behind, it is fast*
  The prize you have to pay:

- *You can determine only one wave vector per location, i.e. you attribute all the wave energy to a single wave. This does not allow to separate, for instance, the superposition of an upward and a downward propagating wave close to a reflection layer. (maybe that could be the reason for some peaks of wave action below the tropopause)*

- *With FFT behind some filter issues should apply*

According to this comment, we extended the method part in the introductary part as well as the method section itself (Sec. 2 to 2.2) where we discuss the above listed issues.

3. Introduce the idea
You could make better use of the introductory paragraph of section 2 and motivate the main idea of introducing the Hilbert transform. Perhaps something like: In this section we develop and validate an algorithm to extract wave parameters from equidistant three-dimensional data. For local diagnosis of waves, e.g. inertia gravity waves, phase-independent estimates of wave amplitudes as well as estimates of the wave vector are essential. For this we employ the Hilbert transform. The Hilbert transform shifts any sinusoidal wave structure by a quarter phase, i.e. turning a sine into a cosine. By constructing a new complex number consisting of the original field as real part and its Hilbert transform as the imaginary part, the absolute value is always the amplitude (square-root sum of sine and cosine), independent of the phase, the wavelength of the oscillation and without any explicit fitting of a wave. In addition the phase and, from the phase gradient, the wavenumber are determined. A tool called "Unified Wave Diagnosis" (UWaDi) is developed, which ..

Exceptionally minor changes, we have made use of this suggestion at the beginning of Sec. 2.

4. Graphics
Please use axis scaling which comprise all data. Quite frequently in your figures the curves run out of the selected value range. That is quite unnecessarily hampering the interpretation since often a small extension should suffice.

Because of the different data that we use now, we adapted the scaling of the axis and all corresponding figures are comparable.

5. Selection of individual profiles
The selection of individual profiles is somewhat arbitrary. With oblique wave propagation and finite vertical group velocity there may be other mechanisms contributing to the vertical structure than you would expect from a single column model. That should be noted in the text. In addition, profiles just in the vicinity seem to be quite different though similar filter arguments would apply. I think it would be more meaningful to select a longitude range of similar filter conditions and show the average profile for that range. Most of your conclusions would still hold and these are the valid ones. For the discussion of these profiles use the actual values (and not as sometimes now average values). For the critical wind filtering discussion you may assume upward propagation and then you should have a horizontal propagation direction and see whether a critical layer is approached.

We inserted the restriction of a vertical-only columnar propagation analysis in the introduction. Further, we checked if spatial averaging over a longitude range of similar wind filtering conditions affect our vertical profile approach. This was not the case so we want to keep our approach of local profiles to point out that we are able to find reliable wave quantities on every grid point without the necessity of spatial averaging. In detail, instead of the local profiles at 7.56° E, 151.92° E and 240.12° E we spatially averaged over 340-30° E, 125-180° E and 190-270° E and found no change in the overall results compared to our local analysis.

6. Remove inconclusive parts
You compare to radiosonde data and find that they are different. However, there are many reasons why this could be the case and a detailed discussion is beyond the scope of the paper. Similar, there is no reason why wave action should be Gaussian shaped in the altitude profile, so a comparison of peak altitudes is not physically plausible. Please remove these discussions.

We removed this parts from the manuscript. Furthermore, we added results from other publications which are more comparable to ours (e.g. Krisch et al. (2017)).

Specific comments:
P1L1 Why "maintain"? What do you want to say?

Except from a few spectral decomposition methods, the analysis of GWs is based on local methods, and at first reveals local wave phenomena. The calculation of zonal means then is a decision for generating a climatological mean state, but not a question

The abstract was rewritten. We distinguish our methods from other methods now clearer in the Introduction and the method part (Sec. 2-2.2): We want to have phase-independent local wave quantities.

P1L13 1000km (at the equator zonal wave 40) is more commonly called synoptic scale

We removed this.

P1L23 Complicated sentence

Changed

P1L24 "forbidden" is always a matter of the phase speed of the waves. Perhaps: as well as zones where wind reversals inhibit the propagation of GWs.

Changed

P1L25 "Models and simulations" That are not two equal terms to be linked by "and"; you need the model to perform a simulation.

It is removed.

P2L14 At altitudes below the sponge. Above about 40km GWs are very strongly damped and not realistic at all

We restrict our analysis to an altitude up to 45 km now. A discussion on the impact of the stratospheric sponge layer is given in Sec. 2.3 and Sec. 4.

P2L15 Even though the tropical portion of parameterised convective GWs is still too small Not clear what you want to say: ECMWF has a parametrization for convection. This likely results in a misrepresentation of the resolved subtropical/tropical gravity *waves. ECMWF does not use a specific parametrization for convective waves, only a non-orographic GW parametrization.*

This missunderstanding was removed.

P2L34 Other methods are 3D S-transform (Wright et al., ACP, in press), localized sinusoidal fits (Lehmann et al., AMT, 2012, Preusse et al., ACP, 2014) and 3D wavelets. These are more closely related to your own method and should hence be quoted here. These would be the methods you could delineate your own tool against in a separate paragraph.

We followed this suggestion in Sec. 2.2 and included a careful comparison for a test case. It revealed clearly the differences between the methods. We are very grateful to the Reviewer #1 for this particular suggestion.

P4L1 discrete Fourier transform

Changed

P4L4 ... a user-defined ... since you pronounce like "you" and not like "us", i.e. the word as pronounced starts with a consonant

Changed

P4L21 As I understand it, d is not the vector of spatial coordinates x,y,z as in the lines before (e.g. a[x,y,z]). Instead it corresponds to the spatial index of e.g. a wavenumber k_x for the x direction, i.e. the sums above are the sums over the three spatial dimensions. Correct? Please use different notations for different things.

Yes, you are correct. It is changed.

P4L24 The noise threshold is essential for understanding the results. How is that calculated? Globally? Locally? Please include the definition.

Now, the definition of the quality checks can be found in Sec. 2.1, Step 9.

P4L25 Why is this necessary after you have applied a band-pass filter already above?

The necessity of the low-pass filtering is now explained in more detail in Sec. 2.1, Step 8. Furthermore we provide a short explanation in Appendix A on that topic.

P5L4 A one- ...

The typo has been changed.

What happens for two waves of similar size in the same volume?

We now discuss the impact of a two-wave mixture in Appendix A.

P5L14 sufficiently monochromatic

This exact formulatin was rewritten in the new manuscript. We refer on the method sensitivity on spectral properties of the data mainly in the discussion part of the new manuscript. It is an important aspect, so we come back to it in several parts of the manuscript. In the step-by-step outline we mention that all variance is considered independent on the spectral properties. Problems may arise with the calculation of the wave number for wide spectra because for that the amplitude-weighted mean is taken. Special care is taken of this issue in the two-wave mixture calculation in the Appendix. In the Conclusion we give references regarding this issue.

P7 Please state precisely which data you are using. Though both Cy41r1 and Cy41r2 use T1279 the effective resolution is different and for Jan 2016 both versions were generated.

A precise description can be found in Sec. 2.3 now.

P7L4 restricted -> reduced

Not relevant any more.

P7L6 222km / cos(lat) for zonal direction; makes a factor of 2 at 60N and introduces *an anisotropy in the cutting frequency*

After a couple of tests with grids of 1°, 0.36° and 0.1°, now, we use data with a resolution of about 40 km horizontal grid distance (0.36°). With our lower bandpass limit of 100 km we make sure that we find waves that are resolved in the data. In order to acknowledge the latitude-dependence of the longitudinaldistance, we first take the meridional sectoin for which, from the lat-lon grid, we calculate the distance in this direction and apply the filter, FFT, etc. Because we operate separately with the three dimensions and respective filtering, we take this anisotropy into account.

P7L10 These limits are coarse. ECMWF resolves in both relevant model cycles mountain waves with wavelengths shorter than 200km, i.e. you have performed here a preselection in physics.

The lower limit is reduced to 100 km horizontally.

P7L23 ... but not interacting with the mean flow Is that true? A wave refracted horizontally would conserve its wave action, but change direction and thus transfer momentum to the mean flow.

We rewrote this part. The wave action is a conserved quantity describing waves in an inhomogeneous background wind field. It does not change for upward propagating waves, as long as they do not interact with the mean flow.

P7L26 in a mid- and low-frequency approximation:

Inserted

Say -> From

Changed.

P7L30 Please use always intrinsic and ground-based, respectively.

With first appearance of intrinsic and apparent we added the terms (flow-relative) and (ground-based) to clear this up.

P8L1 omit: "one has to accept that"

Yes. Done.

P8L3 for the following analysis primarily wave action is used.

Changed

P8L7 The period 21 January to 21 February 2016 exhibits interesting wind features and is chosen for further analysis.

Not relevant any more.

P8L8 zonal mean?

Not relevant any more.

A change in wave action is supposed to be caused by a variation in the intrinsic frequency hinting at a steepening of GWs You mean relative to energy? Steepening = longer vertical wavelengths

The steepening of waves regarding the vertical wave lengths is explained more in detail, now, in Sec.4.

Your analysis in F3 is 2D (in the horizontal plane)? Please highlight this.

Former Fig.3 has been removed.

P9L1 but not well above the filter!

Yes, this does not happen in this new analysis with different data. The largest wavelength, found in the mountain-wave case ① is well inside the vertical filter of 1 km to 15 km.

P9LL1 What is the use of average values. In particular of e.g. average intrinsic phase speeds.

This discussion was removed.

P9L9 Here you do a cross-comparison with four differences: location, time, generic data and analysis method. This is very difficult to interpret. Better keep at least time and space the same.

Mentioned above, this discussion was replaced by a comparison to observations made during a comparable synoptic situation.

Figure 4: Please show also plots for wave action from UWADI

This can be seen in Fig. 2, now.

P9L24 Where is there any evidence for orographic waves in the figure?

This was removed.

In the stratosphere you can use the rule of thumb: 3km vertical wavelength correspond to 10m/s intrinsic phase speed. With a vertical cut-off of 15km that would mean that at 50m/s background wind speed most slow waves (such as mountain waves) are still in, and at 75m/s background wind speed a considerable part is removed.
Yes, we also did similar thumbs for any of our profiles to be sure we do not cut the GWs. Actually, the wind was not as large in the considered cases so we do not run into trouble.

How is a vertical wavenumber zero compatible with a long-wavelength filter edge of 15km?

Sorry, this was a bit loose writing. The algorithm does not return a Zero wave number. Now, we find the smallest wavelength (highest vertical wave number) in the stratospheric jet case ② with 2 km. This is well in the limites of our filter (1 km to 15 km).

Show the filter response for the respective axes.

We experimented with overplotting the filter response over these already rather detailed plots. Unfortunately, we did not arrive at a satisfactory solution without causing confusion. So, we rather left it out.

Fig 6 Please use the same vertical axis for panels a and b

We do provide different profiles with similar axis in the new manuscript.

P11L13 "This finding contributes to our understanding to the density decrease with height which is not considered for the kinematic wave energy." Perhaps instead: The vertical profile results mainly from two competing effects: at increasing altitude density decreases. As the kinematic wave energy does not include density, we expect exponential energy growth for conservative wave propagation and hence a strong increase in regions of weak dissipation. Above 40km the mesospheric sponge of the ECMWF model sets in and cause strong, arteficial dissipation, which results in the decrease of wave energy at larger altitudes. In addition, ...

This was rewritten.

P11L15 Wave action should decrease above source altitude and there is no reason to assume it to be Gaussian. Please remove the sentence

With this little calculation we wanted to show that the energy maximum is always above the corresponding action maximum. Therefore, the Gaussian shape was taken as an arbitrary example for a function with maximum. However, as this calculation achieved more questions than clarity, we removed it.

P13L5 afterwards -> above

Not relevant any more.

P13L6 the slow westward

This was rewritten.

P13L9 This is mid frequency approximation. If you use further approximations, note in the text

This was added.

P13LL7 You use a single profile at one fixed time for your argumentation, but wave propagation may be oblique, requires time and the tropopause may cause partial reflection (what happens in the latter case?). Are your conclusions valid the same way for the profile at 40W? It would make much more sense to me to integerate over a small region.

We discussed the issue of local profiles vs. spatial averaging already above. Because we want to show the advantages of local estimates, we do not average over regions. For a rough interpretation of profiles, the columnar (vertical-only) thinking was helpful. We are aware of the more complicated horizontal and vertical propagation issues and mention this in the text.

P13L21 GWs are forbidden -> GW propagation is strongly inhibited. Unless $N^2 < 0$ *you always have some GWs which may exist*

This was rewritten.

P13L28 A longitudinal profile at 20° An altitude profile at 20° west ... Where do I see the wavelike structure in the figure?

This Figure was removed.

P13L32 wave guide A wave guide means keeping the wave between two reflection layers as you would have it e.g. at the tropopause or mesopause for short horizontal wavelength waves. Open-walve region?

We decided to remove the terms of hydromechanics in favour of a more distinguished style of writing.

P17L4 Split this up: The tool is applicable to ... Here we apply the tool on divergence *fields and limit towards long wavelengths thus isolating GWs. The procedure leads to re<liable results for synthetic test cases. As a first application we run it on operational analysis data of ECMWF for a stratospheric warming case.*

This was rewritten.

In future, the lack ... For comparing the phases you do not even need to have the Hilbert transform 4D. The most serious limitation is that you need ECMWF data at sufficient dense sampling which you could get from forecast data. For a first step you could assume upward propagation of the wave energy.

Yes, you are right. In some cases one may fix the direction of wave numbers with a-priori assumptions. E.g. this is done in Wright et al. (2017). For the vertical wave number upward propagation can be fixed. However, any method working on spatially can solve this sign problem in general. We note this in the new manuscript.

17LL14 You use a pump=source and valve picture. 1.) You should have an introducing sentence that this is a picture for a more complicated process. 2.) That's based on Ron Smith's ideas? Is there any peer-reviewed article to quote? 3.) While the valve summarizes the properties of a wind profile, source is already such a general expression. Is it necessary to introduce a new word? In particular since source could work already in such a hydraulic picture.

This terms are removed. See above (Sec. 1).

References

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Airs/aqua measurements over the southern andes and drake passage. *Atmospheric Chemistry and Physics*, 17(13):8553.