Response to reviewers' reports on the paper amt-2019-79 Advanced hodograph-based analysis technique to derive gravity waves parameters from Lidar observations

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We appreciate the reviewers' constructive comments and their positive judgment on our paper. We have taken the reviewers' suggestions into account when preparing the revised version of our manuscript.

However, we would like to make a general comment. This paper is submitted to AMT with purpose to describe a method of analysis. We demonstrate on a data set how this method works. We also demonstrate how to obtain extended set of GW parameters and summarize equations and assumptions used for estimation of different parameters. We do not claim that this data set represents a ”typical“ situation in polar winter season. Thus, in this manuscript we try to avoid making general conclusions like behavior of momentum flux or vertical wavelength as a function of altitude or any other parameter. We are currently working on another manuscript where a larger data set is analyzed by this method. We will take into account the corresponding suggestions of referees when preparing the next manuscript.

In the following we address the comments of all reviewers point by point.

To Referee 4

You produce most of your diagrams for "number of waves". However, from the dynamics point of view GW pseudo-momentum flux is most relevant. It would be very helpful if you add a second row to Figure 12 where you plot the total absolute momentum flux of the waves in a wavelength bin. (You could normalize that in a way that the total GWMF of all waves (up + down) is normalized to 1. and keep that same normalization also for up and down separately). Same for F14 and F15.

We appreciate the reviewer's suggestion and interest in seeing more geophysical results. We decided, however, to limit ourself in this paper to the technical questions of derivation of GW parameters. We also aim at doing a more in depth geophysical study based on a lager observational dataset, which in particular also covers different seasons. We will definitely address these questions in that paper.

In what follows, however we try to show to reviewer what can be inferred from this limited set of measurements.

First of all, to our understanding, the requested by the reviewer "total absolute momentum flux of the waves" is exactly the quantity which we show in our manuscript in Figs. 17 and 18 (18 and 19 in the revised version of the manuscript).

The absolute momentum flux was estimated, for example, by Ern et al. (2004); Ern et al. (2016), and can be written in form:

$$F_{Ph} = \sqrt{F_{Px}^2 + F_{Py}^2} \tag{1}$$

We show observed momentum flux in given direction ($F_{P\parallel}$). That is, we understand that the Ern et al.'s absolute momentum flux is the same as our reported momentum flux:

$$F_{Ph} = \sqrt{F_{P\parallel}^2 cos(\xi)^2 + F_{P\parallel}^2 sin(\xi)^2} = F_{P\parallel}\sqrt{cos(\xi)^2 + sin(\xi)^2} = F_{P\parallel} \tag{2}$$

To address this reviewer's question, we derived some additional dependencies and show the results here.

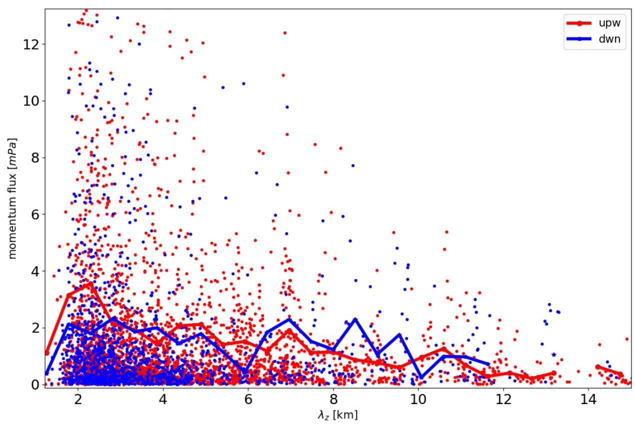

Figure 1. Absolute momentum flux. Red (blue) line and dots marks upward (downward) propagating GW.

First, in Fig. 1 we show the total absolute momentum flux of the waves as inferred from our analysis. Small dots show results derived for every successful hodograph analysis. Colored lines show an average momentum flux for up- and downwards propagating GWs separately.

Next, a momentum flux in east-west direction as a function of vertical wavelength is shown in Fig. 2. Momentum flux is positive if waves propagate towards east.

It is important to mention, that momentum flux depends not only on vertical wavelength, but also on horizontal wavelength as demonstrated in Fig. 3.

Finally, the total absolute momentum flux of the waves in a 100 km wavelength bin is shown in Fig. 4.

Nonetheless, as mentioned above, we believe that including such figures in the manuscript, will defocus the paper from methodological to scientific emphasis, which contradicts our current goal.

The vertical wavelengths you observe are rather small. Starting from the very first work on saturated spectra (Smith, Fritts VanZandt, 1987) we have indication that the wavelength of the maximum in the distribution shifts to longer

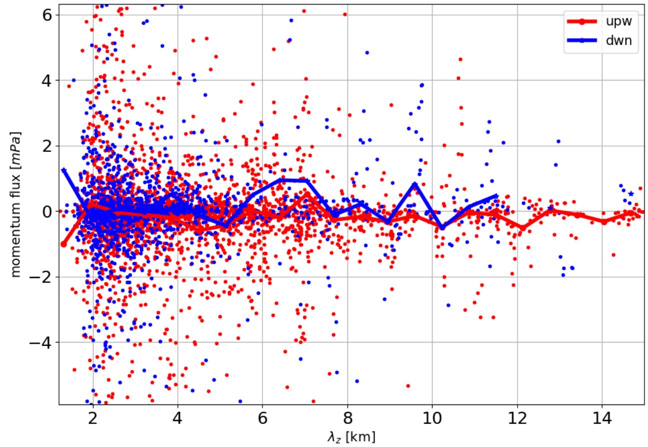

Figure 2. Momentum flux in East-West direction

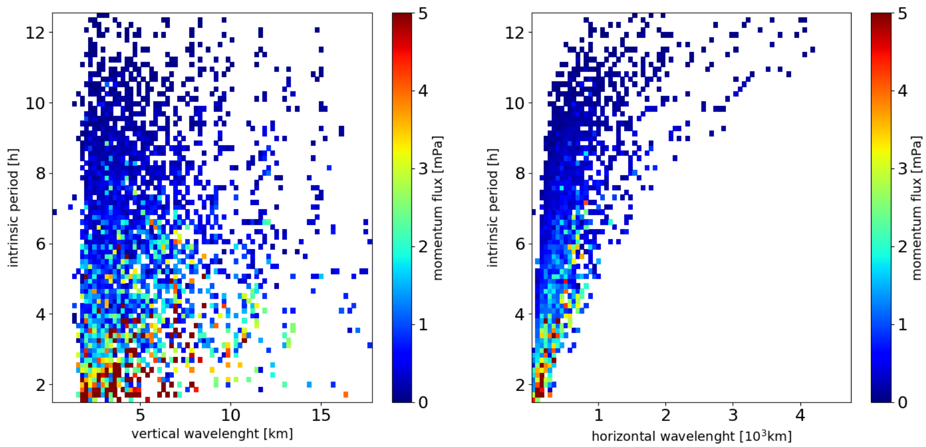

Figure 3. Momentum flux

wavelengths at higher altitudes. Follow-up work by e.g. Gardener et.al. and the general concept of the Warner & McIntyre scheme infer a power law for this. You can put in several observations by e.g. radio sondes, rockets ... to calibrate this. Then you would expect something like 2 km in the lower stratosphere, 10-15 km in the mesopause region and accordingly ~ 5 km around the stratopause. The satellite data certainly have a long-bias, but they confirm the increase of typical wavelengths with altitude. Compared to this you have 2 km which one would expect for the low stratosphere in a data set which goes up to the mesopause. One reason may be that you give your histograms for number

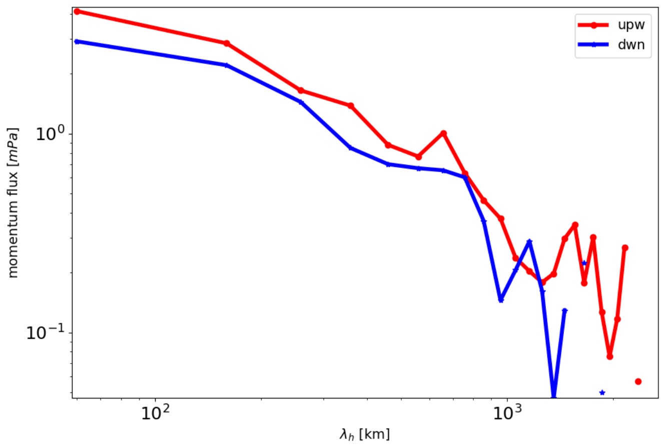

Figure 4. Momentum flux averaged in 100 km bins

of waves only. Still it would be good to see some vertical profile of aveerage vertical wavelengths, normal average as well as GWMF weighted, up + down separately, so for profiles in total.

We appreciate this reviewer's constructive comment and totally agree to properly address this question in our next paper (see also our general comment and reply to reviewer's comment 1). Here, again we show what can be inferred so far from this first, limited (in sense of data coverage) observational set.

To address this reviewer's question we split the data shown in the leftmost histogram in Fig. 12 of our manuscript in several altitude bins. The result is shown here in Fig. 5. One can see, that distribution gets broader with increasing altitude which is consistent with the increase of the wavelength pointed out by the reviewer. Several following reasons, however, prohibit from drawing strong conclusions. First, upper and lower boundaries of our observational domain cannot include long-wavelength-waves due to limitation of the analysis techniques (we require that the wave packet is almost completely present in the observations, vertical wavelengths longer than 15 km are partly attributed to the background and, therefore, are not considered). Second, this statistics ultimately includes all kind of GWs including secondary, tertiary, whatsoever appears in the atmosphere, whereas reviewer's argument might only refer to the waves propagating from the ground (or troposphere).

Phase speed is approx proportional to vertical wavelength. The observational filter for airglow is totally different (lz>10km), so no wonder that phase speeds are much higher. There is a wealth of literature on phase speeds from different sources (convection, spontaneous imbalance, ...). Maybe it is more worthwhile to compare to that. The phase speed diagram kind of seems to exclude convection as dominant source here. Still there is the general issue about the short vertical wavelengths.

Again, we appreciate the the reviewer's valuable suggestion which we plan to address in our next work with more detailed geophysical analysis. The sources of GWs with different characteristics is for sure of a great scientific interest. For this partic-

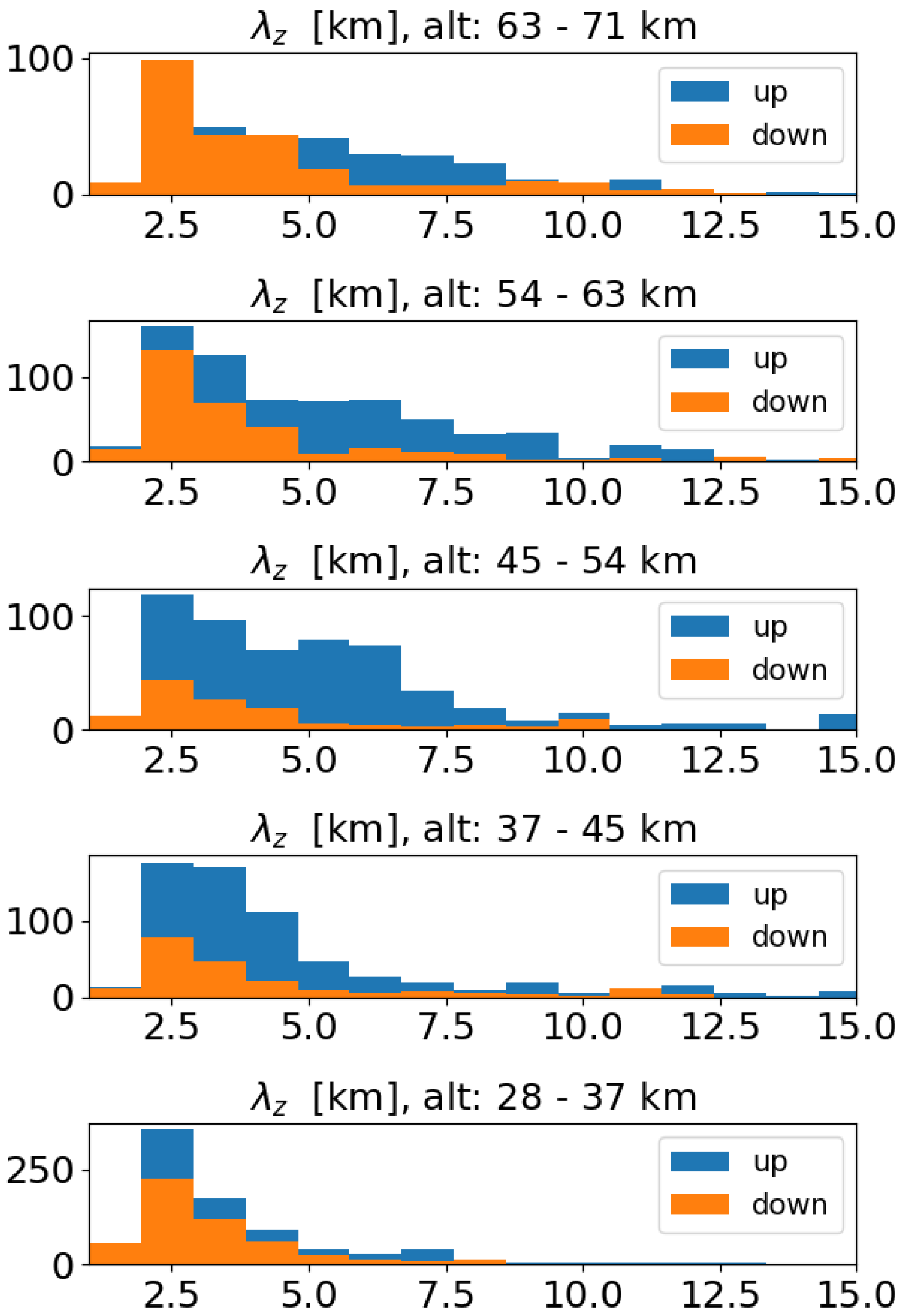

Figure 5. Histograms of observed vertical wavelengths. Different altitude ranges are shown in different plots.

ular purpose we additionally involve analysis of different simulation data which, we believe must shad some more light on this question, than simply speculate based on limited observational base.

Minor comments and technical suggestions:

P2L20 Did the Shigaraki radar not provide some winds? If so: provide high-resolution wind

All MST radars are not capable of measuring in the altitude range ∼30 to ∼60 km because of the absence of suitable scatters. As we can judge from the description in the WebSite

($http://www.rish.kyoto-u.ac.jp/organization_e/collaborative_research/mur/$),

Shigaraki MU Observatory also provides lidar observations in the altitude range 30 to 60 km.

P7L17 So you don't do that? Why not?

Zink and Vincent (2001) and Murphy et al. (2014) used sum of scalograms of both wind components. We used product of scalograms of all three components, i.e., u, v, and T.

A product of spectra works similar to Cross Wavelet Spectrum (Torrence and Compo, 1998) with difference that it allows to compare three spectra simultaneously. It will only reveal an enhanced power where all spectra under analysis show high power. As an example, if some wave with large enough amplitude is only presented in one component, but absolutely absent in all other components, the sum of scalograms will show signature of this wave. Our purpose is to detect regions where all three components (u, v, T) reveal wave oscillation. The product, in turn, will show low power. E.g., for u=0, v=0, T=1 product gives 0, whereas sum is equal to 1.

F13 I like that figure, but it would be great if you could add two more panels: Vertical wavelengths and GWMF.

Here we have to refer to our major comment. In particular, we do not see any dependence of vertical wavelength on altitude in this dataset. Also, to our understanding, the requested GWMF is shown in Fig. 17 (Fig. 18 in the revised version of manuscript).

P14L1 And this is really puzzling! You have most of the waves and the momentum flux propagating against the wind and the wind velocity increases at higher altitudes, so no critical level filtering. Vertical wavelengths then should increase which leads to lower amplitudes at same GWMF, so no saturation expected either. Reflection? It would be good to know at least which parameter changes most (wavelengths, amplitudes ...) as to produce this result. Or do you have an edge effect in your retrieval or your method?

We recall, that the chosen data set does not represent a typical picture at observational site. Moreover, we found, that during the period of observations presented in this work strong polar vortex was observed right above the ALOMAR observatory. Also, two upper panels in Fig. 3 of the manuscript reveal zonal wind higher than 100 m/s between 40 and 50 km. This suggests, that most likely the majority of detected waves was generated in stratosphere.

All other minor comments and suggestions were implemented as suggested.

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