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

5 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.

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

To Referee 3

1) GW Polarization

The authors present gravity-wave polarization relations, relating zonal and meridional wind fluctuations (Eqn 2), and temperature and zonal wind perturbations (Eqn 3). In equation 3, the authors claim to use the follow Hu et al. (2002)

15 **($Hetal02$) and Geller and Gong (2010) ($G\&G10$). In $Hetal02$ the authors have a $(1/2H)$ term added to the $(I'm)$ term. In $G\&G10$ the authors suggest that their derivation of a polarization relationship relating relative temperature perturbations to pressure perturbations is based on the assumption that the relative temperature fluctuations are identical to the relative potential temperature fluctuations. Do the authors know how these relationships compare to the formulation based on the ideal gas law that relates relative pressure, density, and temperature perturbations directly? If the**

20 **authors find insignificant differences, particularly for the inertia-gravity waves in this study, then they could explicitly state that.**

Eq. 3 from Hu et al. (2002) is:

$$\widehat{T} = H[im + 1/(2H)]\frac{\widehat{\omega}^2 - f^2}{\widehat{\omega}k_h R} \cdot \widehat{u} \tag{1}$$

where $H = kT_0/mg = RT_0/g$ is scale height. Thus, Eq. 1 can be rewritten:

$$\frac{\widehat{T}}{T_0} = [im + 1/(2H)]\frac{\widehat{\omega}^2 - f^2}{g\widehat{\omega}k_h} \cdot \widehat{u} \tag{2}$$

if therm $1/(2H)$ is neglected, we derive equation used also in Geller and Gong (2010):

$$\widehat{T} = \frac{imT_0}{g}\frac{\widehat{\omega}^2 - f^2}{\widehat{\omega}k_h} \cdot \widehat{u} \tag{3}$$

Indeed, we use an assumption that $\theta'/\overline{\theta} = T'/\overline{T}$. Actually, it is better to use Eq. 7.36 from Holton (2004): $\theta'/\overline{\theta} = \rho'/\rho_0$.

If gravity wave advects air parcels adiabatically, it has a small displacement amplitude ($\Delta z/H \ll 1$) and produces a negligible pressure perturbation within displaced parcels (Fritts and Rastogi, 1985; Eckermann et al., 1998), than we can use equation:

$$\frac{\widehat{T}}{\overline{T}} = \frac{\widehat{\theta}}{\overline{\theta}} = -\frac{\widehat{\rho}}{\overline{\rho}} \tag{4}$$

on the other hand, vertical displacement is related to temperature fluctuation as:

$$\Delta z^2 = \left(\frac{g}{N^2}\frac{\Delta T}{T_0}\right)^2 \tag{5}$$

As can be seen from Fig. 10 of our manuscript, amplitude of the obtained temperature fluctuations is less than $10\,\mathrm{K}$. If we use $T_0 = 253.5\,K$, $N^2 = 3.825 \cdot 10^4\ s^{-2}$, $g = 9.7\ m/s^2$, we obtain vertical displacement equal to 1 km, that is less than H.

2) Intrinsic and Observed Frequencies

The authors have complete wind measurements that allows them determine both the observed and intrinsic frequencies of the waves. Can the authors add the observed frequency of the waves to the list of results for the three waves in Table 1. In general, can the authors comment on the relationship between the observed and intrinsic frequencies for the waves they have characterized.

To address this reviewer's comment we extended the Table 1 by adding the observed wave period. The observed period is estimated from the equation:

$$\widehat{\omega}_{intr} = \widehat{\omega}_{obs} - \overline{k} \cdot \overline{u}. \tag{6}$$

It is worth noting here, that another way to derive the observed period from such observations is to apply e.g., Fourier transform to the measured time series. Before that, one has to define the time period during which the wave is present in the observations. This, in turn, can be done (and usually is done so) "manually", by estimating the wave presence by eye. Also, our algorithm in its current status does not allow to estimate the duration of a wave event. We note that it will be difficult (or rather impossible) to find all three waves summarized in Table 1 by this technique.

More specifically, the wave 1 (Table 1), which propagates downward in the same direction as the background wind reveal a period of 38 min. With 15 min temporal resolution such high frequency fluctuations are smeared out in the data.

Wave 2 propagates against wind with phase speed of 22.2 m/s. The wind component along wave propagation is 24 m/s, i.e. is larger than phase speed of this GW. As a result, such wave will reveal 80 h period with upward propagating phase lines. This will appear in the data as horizontal lines not reminiscent of GW.

Wave 3 also propagates upward against the background wind, but its phase speed is higher than the wind speed in the direction of propagation. As a result, the observed period is $19\ h$. Similar to the wave 2, this will be hardly resembling the GW and, therefore, rather not detectable.

Our analysis technique based on hodograph, in turn, allows to detect such long period waves by utilizing the Eq. 6. Left panel of Fig. 10 demonstrates that the most of the detected waves reveal large periods. Periods of downward propagating GW is more difficult to estimate even from such reconstructed time series because they are essentially not continuous.

We extended discussion of these issues in the revised version of manuscript to properly address this reviewer's comment.

3) Identifying Waves

The study reports 4507 quasi-monochromatic waves. However, if I understand it right the study has found 4507 snapshots of some number of waves based on hodograph analysis of 240 profiles. The authors discuss that the individual waves persist in their presentation of temperature fluctuations and intrinsic periods in Figures 10 and 11. Can the author quantify the life-time of the waves in the data set? There have been discussions in the literature about how many gravity waves are present and the intermittency of gravity waves. This study has the opportunity to address the life-time of gravity waves, particularly relating it to the spatial and temporal scales of the waves, that would address a variety of questions about wave dynamics and evolution.

The reviewer is absolutely correct that we found 4507 snapshots of some number of waves based on hodograph analysis of 240 profiles. We also agree that the scientific questions pointed out by the reviewer in this comment are of a high interest and importance.

However, as we already mentioned in our response to the previous comment, at the current stage of development our analysis technique is not capable of detecting life-time of gravity waves in observational data set. We are working on this and anticipate some progress in the nearest future. At the moment we can only make some statistics and analyze the relations between different GW-parameters and e.g., amplitude of wave as a function of background wind.

Fig. 10 and 11 from the manuscript represent our first attempt to analyze temporal development of the detected wave packets. Thus, for instance, on Fig. 11, one can recognize regions of near the same color which resulted from many adjacent profiles that reveal very close intrinsic frequencies. This can be picked up by the naked eyer. We can assume that such regions depict propagation of the same wave packets. However, a more in depth analysis must be performed (that probably should utilize some additional criteria) to developed a more robust algorithm to pick out wave packets automatically.

At the moment we decided to characterize GW based on so far well established combinations of wave parameters. Thus we can select waves, for example, that propagate in a given direction (up or down) and horizontal wavelength in some fixed range of values and reconstruct pictures like Fig. 10 and 11 for speculative analysis.

To address this reviewer's comment we added a short discussion of this issue in our manuscript.

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