Final and cumulative response to the reviewers' comments on our manuscript

"An intercomparison of stratospheric gravity wave potential energy densities from METOP GPS-radio occultation measurements and ECMWF model data"

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We greatly appreciate the reviewers' positive assessment of our work as well as their constructive comments. For the revised version, all comments have been addressed. In the following we respond to all comments point by point. For clarity, we first repeat the comments of the referees (in black), we then respond to these (in blue), and then indicate the changes made to the text where appropriate (in red).

Reviewer 1

[..] Overall, the paper shows that METOP GPS-radio occultations are a promising dataset for gravity wave analysis. The paper is very well written, and publication in AMT is recommended after addressing my minor comments.

We are grateful to the reviewer for this encouraging judgment.

My main comment is that some more discussion is needed regarding the separation of temperature altitude profiles into background and temperature fluctuations due to gravity waves. The selected method is a vertical filter with cutoff at 15 km vertical wavelength. The main idea is that all variations with wavelengths shorter than 15 km are assumed to be gravity waves. This, however, is not stated clearly enough, and the pros and cons of this approach should be briefly discussed as detailed in my specific comments.

This is an excellent point raised by both reviewers. As a consequence, we have revised the text in several places as indicated below in response to the more specific points. In addition, mainly in response to reviewer 2, we have added an additional figure (Figure 15) in the revised manuscript in which we compare latitude-altitude distributions of monthly mean zonal mean fields of E_P derived with the standard method applied in this study (i.e., using a fifth order Butterworth filter with a cutoff at 15 km wavelength in the vertical) as well as derived using a horizontal background determination method. Similarities and differences from both analysis techniques are discussed and a recommendation for future work is formulated (see also our detailed answer to comment 6 below).

Specific comments

(1) about Sect. 2.2: Please clarify that the spatial resolution mentioned in this section corresponds to the horizontal grid spacing. Atmospheric waves that are resolved by these data sets have scales that are considerably longer. According to Skamarock (2004) only scales exceeding the grid spacing by several times are resolved. Skamarock, W. C.: Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra, Mon. Wea. Rev., 132, 3019-3032, 2004.

Thanks for pointing this out. We have corrected the text accordingly.

[..] These have a horizontal grid spacing of 16 km (T_L1279) and were evaluated on 25 pressure levels between 1000 and 1 hPa which we converted to geopotential heights and interpolated them on a regular vertical grid with 1 km spacing. We note that according to Skamarock (2004) only scales exceeding the grid spacing by several times are resolved.

The horizontal grid spacing of the data set is approximately 80 km (T255).

(2) p.5, l.12, Sect. 2.3 Here, you call the reduced scatter of RO-wet temperatures a reduced "uncertainty range". Is this justified, or are RO-wet temperatures too smooth? Above 30km RO-wet temperatures show a reduced scatter with respect to ECMWF IFS. However, at these altitudes the influence of a priori data should be increasing, and it is known that at high altitudes ECMWF is known to suffer from hyper-diffusion. Could it therefore happen that temperature fluctuations are suppressed in RO-wet temperatures because of an increasing influence of relatively smooth a priori data?

The reviewer again has a good point here. In order to give a more neutral description of Figure 4 we have changed the wording “uncertainty range” to “variability range”.

(3) p.5, l.28 The idea behind using a Butterworth filter should be stated more clearly, and shortcomings mentioned. As far as I understand, variations in the vertical with scales longer than 15km are assumed to be the "background" (climatological structure plus planetary waves), while shorter scales are assumed to be fluctuations due to atmospheric gravity waves. This separation of scales will work well with a few exceptions. One exception is the tropopause region, which has been discussed in detail in the current paper. Another exception is the tropical stratosphere. While vertical wavelengths of planetary waves in the extratropics are quite long, this is different in the tropics where Kelvin waves usually have vertical wavelengths that are comparable to those of gravity waves. See also (5).

(4) p.5, l.28 Please mention that the use of the Butterworth filter in vertical direction has the advantage of being applicable in the same manner to all data sets considered, thus allowing a fair comparison.

(5) p.6 l.10-14 Epot close to the equator will be high-biased due to Kelvin waves Kelvin waves in the tropics can have quite short vertical wavelengths, comparable to those of gravity waves. Kelvin waves can have considerable temperature variances of a few K^2 on zonal average, and corresponding zonal average values of Epot could easily reach values of around 5 J/kg, which is non-negligible. This is particularly important because Fig.6 represents a case of tropical easterlies. Under these conditions the amplitudes of Kelvin waves will be amplified. A climatology Kelvin waves in the tropical stratosphere is given, for example, in Ern et al. (2008) Ern, M., Preusse, P., Krebsbach, M., Mlynczak, M. G., and Russell III, J. M.: Equatorial wave analysis from SABER and ECMWF temperatures, Atmos. Chem. Phys., 8, 845- 869, 2008.

Reply to 3, 4, and 5: We agree that it is critical to better explain the idea behind using a Butterworth filter. Also the limitations of this approach in the tropics must be more clearly mentioned and it needs to be pointed out more directly that the most important advantage of this approach is that all four data sets (including the ground based lidar data) can be analyzed with identical analysis routines. The text has been changed as follows:

For this study, we follow the approach of Ehard et al. (2015), i.e., we apply a fifth-order Butterworth filter with a cutoff wavelength of 15 km to vertical temperature profiles from the RO-measurements, from ERA Interim, from the IFS, as well as from ground based lidar -measurements. Applying this filter to altitude profiles implies that scales longer than 15 km are assumed to be the "background" (climatological structure plus planetary waves), denoted $T_0(z)$, while shorter scales are assumed to be fluctuations due to atmospheric gravity waves. This separation is expected to work well except for the tropical stratosphere where Kelvin waves are known to occur with vertical wavelengths well below 15 km (e.g., Ern et al., 2008; Randell and Wu, 2005). Hence, E_P must be expected to be biased high in the tropics.
Nevertheless we stick to this approach since it has the advantage that all data sets analyzed in this study can be treated with identical analysis routines thus allowing us to directly and quantitatively compare E_P-values from four independent data sets.

(6) p.9, about the Epot correction: Do you think that monthly average temperatures are sufficient for deriving a correction, as proposed? Or may there be changes in the background on shorter time scales that would require averaging over shorter time intervals? Of course, this may be beyond the scope of the current paper, but should be carefully considered before making this correction operational. See also p.11, l.16+17

We agree with both reviewers that this correction indeed warrants a more in-depth discussion. In the new Figure 15 we show a monthly mean zonal mean distribution of E_P that was derived using a horizontal background determination method. In the same figure we further show monthly mean zonal mean fields of vertical kinetic energies, i.e., $VE=0.5*w^2$, due to gravity waves (see e.g., Geller and

Gong, 2010). Note that the mean vertical velocity is zero so that non-zero VE-structures are mainly due to gravity waves. This comparison clearly shows that E_P-values derived with the horizontal background derivation agree much better in terms of their morphology to vertical kinetic energy values than E_P-values determined from vertical profiles (compare Figures 14 and 15). Figure 15 further shows that the correction method improves the qualitative comparison between E_P and VE but that it cannot eliminate all features that are apparently not due to gravity waves. Closer inspection of the data sets reveals that this is partly because some of the non-gravity wave structures (mainly the TTIL) are not zonally homogeneous such that correcting for them using zonal mean fields cannot eliminate the corresponding signatures completely.

In the context of Figure 15, the following text has been added:

We finally attempt to determine the quality of the corrected Ep -values in Figure 14 by comparing them to Ep -values using a horizontal background determination method. Horizontal estimation of T_0 was previously found to be superior to a vertical background determination by Khaykin (2016) and Schmidt et al. (2016). While the sampling statistics of the METOP RO-data on a daily basis (i.e., only 1100 profiles distributed over the whole globe) is too poor to allow us to apply a horizontal background determination to them we may easily perform a corresponding analysis of the high resolution IFS-data. For this purpose, the spectral model output of the IFS for December 2015 has been reconstructed at T42, i.e., at a horizontal grid spacing of 500 km. These fields have then been used as background temperatures $T_0(z,\lambda,\phi)$, where λ is latitude and ϕ is longitude, in order to compute monthly mean zonal mean distributions of Ep . Such monthly mean zonal mean Ep -distributions for December 2015 are presented in Figure 15. In the same figure we also show corresponding fields of the vertical kinetic energy, $VE = 0.5*w^2$ (Geller and Gong, 2010). Note that VE is a good indicator for gravity waves in the stratosphere since vertical velocities due to other air motions are significantly smaller. While VE-values are significantly smaller than Ep -values (by about a factor of 1000 in the IFS-model) it is still instructive to compare the spatial morphology of the corresponding fields. This comparison clearly reveals that the proposed correction of Ep -distributions derived using a vertical background determination (see Figure 14 and related text) improves the comparison between Ep and VE but that it cannot eliminate all features that are apparently not due to gravity waves. Closer inspection of the data sets reveals that this is partly because some of the non-gravity wave structures (mainly the TTIL) are not zonally homogeneous such that correcting for them using zonal mean fields cannot eliminate the non-gravity wave structures completely. We hence conclude that this correction may be recommended for application to data sets that can only be analyzed using a vertical background determination method such as for the METOP data with relatively scarce sampling statistics. However, even after this correction, regions within +/- 30° latitude around the equator need to be considered with care due to additional potential contamination of Ep by Kelvin waves or other planetary scale features. In any case, if the sampling statistics allows, our analysis clearly shows that in general a horizontal background determination is advantageous in that it better avoids contributions to E_P that are not caused by gravity waves.

Likewise, statements in abstract and conclusions were added.

Abstract: This correction may be recommended for application to data sets that can only be analyzed using a vertical background determination method such as the METOP data with relatively scarce sampling statistics. However, if the sampling statistics allows, our analysis also shows that in general a horizontal background determination is advantageous in that it better avoids contributions to E_P that are not caused by gravity waves.

Conclusions: In addition, this technique to derive and correct E_P based on vertical profiles was compared to an alternative method applying a horizontal background temperature determination method to IFS-data. We find that the above introduced correction may be recommended for application to data sets that can only be analyzed using a vertical background determination method such as the METOP data with relatively scarce sampling statistics. However, if the sampling statistics allows, our analysis also shows that in general a horizontal background determination is advantageous in that it better avoids contributions to E_P that are not caused by gravity waves like the TTIL and potentially also Kelvin waves and other planetary scale features with short vertical wavelengths (i.e., less than 15 km).

(7) p.11, l.22 Please include the information that Kelvin waves could produce a high bias of Epot in the tropics.

Done.

TECHNICAL COMMENTS:
p.2, l.7 GW are a major means to couple the -> GW are an important mechanism that couples the

Changed as suggested.

p.2, l.30 please correct: ECMWF = "European Centre for Medium-Range Weather Forecasts"

Thanks. Changed as suggested.

Fig.1a Is the red dot at 90N an artifact, or is this a real accumulation of ROs?

It is indeed an artifact and has been removed.

p.3, l.18 The expression in parentheses is confusing; suggestion a corresponding gridding (i.e., 36 x 36 5deg latitude x 10deg longitude bins) -> a corresponding gridding of 36 x 36 grid points (i.e., 5deg latitude x 10deg longitude bins)

Thanks. Changed as suggested.

p.4, l.8 Please check whether it is correct that T1279 corresponds to a horizontal resolution of 8km.To my knowledge, the ECMWF grid uses 2560 points at the equator, corresponding to 15km grid spacing. The numbers of T255/80km that given for ERA-Interim should however be correct.

The reviewer is correct. We have corrected the grid spacing to 16 km.

p.4, l.12 from -> starting from

We corrected the typo.

p.7, l.23 wavelengths if the phase fronts are perpendicular to the line of sight, -> wavelengths than is the case if the phase fronts are perpendicular to the line of sight,

Thanks. Changed as suggested.

p.8, l.33 cleat -> clear

Corrected.

p.13, l.33 stratopsphere -> stratosphere

Corrected.

p.13, l.34: Ern et al., 2016 -> Ern et al., 2017

Corrected.

p.14, l.12: LOVE -> Love ??

Corrected.

p.14, l.15 Hei, H., T., T. T., and Hirooka: -> Hei, H., Tsuda, T., and Hirooka, T.:

Corrected. Thanks for the careful reading!