Final Author's Response

We want to thank the authors for their detailed reviews and their recommendations for improving this paper.

In this response we will first address all major points of the referees. We try to stick to the order of the comments; except for the cases both referees had the same point.

Both referees remarked that the missing seasonal dependency of gravity wave activity below 25 min and even below 60 min might also be due to these waves having vertical wavelengths shorter than the average depth of the OH* layer and thus being not detectable with OH* spectrometers. We also took into account FoV averaging. We took detailed account of this aspect by including the following paragraph in the discussion section.

'Furthermore, GRIPS cannot measure the whole spectrum of gravity waves with equal sensitivity: this is due to horizontal averaging over the FoV and vertical averaging over the OH layer. As concerns the effect of the OH* layer, Wüst et al. (2016) show that GRIPS has reduced sensitivity for waves with short vertical wavelengths. The sensitivity is less than 70 % for vertical wavelengths below 15 km and waves with vertical wavelengths below 5 km cannot be measured at all (the authors assumed a Gaussian distribution of vertical OH* concentration). FoV averaging depends on the FoV size and the orientation of the wave fronts and leads to reduced sensitivity for horizontal wavelengths below ca. 200 km (Wüst et al., 2016). In the following, we estimate whether the period range of 6 min to 60 min is affected by both limitations. The intrinsic frequency of a gravity wave, the vertical wave number, the horizontal wave number and the Brunt-Väisälä frequency are linked via the dispersion relation (Fritts & Alexander, 2003, equation (30) for high-frequency gravity waves). As according to CIRA-86 (Committee on Space Research (COSPAR) International Reference Atmosphere; NCAS British Atmospheric Data Centre, 2006) our observed altitude range shows a zonal wind reversal we assume that the frequency observed from ground is similar to the intrinsic frequency. Using a rather small value of 0.02 s-1 for the angular Brunt-Väisälä frequency (Wüst et al., 2017b), gravity waves with periods of 6 min have a vertical wavelength below 15 km for horizontal wavelengths shorter than 8 km. The vertical wavelength of gravity waves with periods of 60 min is smaller than 15 km for horizontal wavelengths below 170 km. In these cases, the waves are strongly affected by both filtering mechanisms (vertical and horizontal) and therefore highly reduced in their amplitude. GRIPS is therefore less sensitive to variations in this period range compared to the case of medium range periods 60 - 240 min. This result does hardly change when applying equation (32) in Fritts & Alexander (2003), which describes medium-frequency waves.'*

Referee #1 asked how we ensured that the variation in the number of observations per month, that some stations exhibit, does not contribute to the seasonal patterns of gravity wave activity. For this we had a careful look at the nocturnal mean values and can confirm that e.g. winter values in the long-period range are systematically higher than the summer values so that the seasonal pattern would also occur when using only as many observations for the monthly means in winter as we observed during the summer months. The same holds for the other period ranges. This can also be seen by considering the fact that the stations with quite regular data coverage like ABA and OPN show the same seasonal behavior of gravity wave activity as the stations with a strong variation of monthly data coverage like SBO and UFS. The number of observations only contributes to the uncertainty of the monthly mean values given by $\sigma/\sqrt{N}$, considering mean values calculated from less data points to more uncertain. We also ensured ourselves that the days of month are randomly distributed in our observations and show no systematic structure.

Both referees remarked that the comparison of the stations should be expanded. We elaborated this in the second paragraph of the discussion by further comparing possible gravity wave source mechanisms:

'In general, orographic forcing may be perceived to be a major source of gravity waves at most stations. Such source regions would be the Alps for OPN, UFS, SBO and OHP, the Caucasus for ABA, the Scandinavian Mountains for ALR and the mountains in the north of Queen Maud Land for NEU.'

'Given the fact that the FoV at ABA is located above a position that lies between the Greater and the Lesser Caucasus orographic gravity wave forcing may be even larger than for the other stations. As concerns the stations at high latitudes - ALR and NEU - the polar vortex could additionally act as a strong source of gravity waves. At TAV orographic forcing is expected to play a minor role since the terrain is flatter and wind comes predominantly from the coast. The lack of orographic waves compared to the other stations could explain the deviation from the clear annual patterns as observed in Figure 5. However, the data base at TAV is rather small (Figure 1). Further observations will have to be awaited to validate the seasonal cycles.'

Page 11 line 14. Referee #1 asked why we do not observe any substantial equinoctial minima for gravity wave activity in the period range 6-60 min. As a possible explanation we included

'The reason why gravity wave activity below 60 min shows no substantial minima during the equinoxes may be that these are gravity waves with a high horizontal phase speed or which are mainly generated above the stratosphere. Both cases would leave them unaffected by the seasonal cycle of stratospheric winds.'

in the discussion section on page 10. Another explication could again be short vertical wavelengths, see above.

Both referees suggested providing a physical scale to the results by linking gravity wave activity to actual temperature amplitudes. We actually tried this by applying the wavelet analysis to synthetic waves of equal amplitudes throughout the spectrum of periods, just as Referee #2 proposed. However, as we state on page 7 line 1, peaks in the wavelet spectrum exhibit a slight but period-dependent blur in the period domain. This would add further uncertainty to derived temperature amplitudes and it would be difficult to compare these temperature values to those derived by other methods. To retain consistency we decided to forego the calculation of temperature amplitudes and focus on the relative behavior of gravity wave activity.

Referee #2 liked the discussion and commentary section around secondary wave generation in and above the stratosphere to be expanded. In this part of the discussion we replaced 'altitudes above the stratospheric wind fields' by 'higher altitudes'. We put more focus on secondary gravity waves and included the proposed literature.

'However, Becker & Vadas (2020) remark that especially secondary gravity waves are important in the UMLT as they yield the strongest amplitudes and vertical mixing effects of the OH layer during winter. They are created due to intermittent body forcing or nonlinearities induced by breaking primary gravity waves (see e.g. Vadas & Fritts, 2002; Vadas et al., 2003; Franke & Robinson, 1999).*

Recent observations show that secondary gravity waves are often generated in the stratosphere and propagate upward into the UMLT (Chen et al., 2013, 2016; Yamashita et al., 2009; Zhao et al., 2017) where they would be observable, e.g. with OH spectrometers.'*

'It is possible that secondary gravity waves also play a major role during summer. The aforementioned observations and also modeling performed by Becker & Vadas (2018) suggest that breaking orographic gravity waves in the stratosphere cause secondary waves with phase speed in the direction of the background wind, which are able to propagate to greater heights. Following this assumption, the wind fields in the stratosphere may block most of the upward propagating waves above the tropopause during summer, however the subsequent wave breaking could excite secondary waves with westward oriented phase speeds that may ascend into the UMLT. Unfortunately, with the here-presented measurements alone we can determine neither the zonal orientation nor whether periodic signatures are due to primary or secondary waves. As explained in Becker & Vadas (2018) and Vadas & Becker (2018), secondary gravity waves can either have larger scales than the primary wave, when being created by intermittent body forcing, or smaller scales when they are the product of nonlinearities accompanying primary wave breaking. According to Vadas et al. (2018), the large scale type of secondary gravity waves exhibits quite broad spectra with horizontal wavelengths between 500 and thousands of kilometres and horizontal phase speeds between 50 and 250 m/s. This corresponds to the larger part of the period range addressed in this work (periods > 33 min). Due to the large horizontal phase speeds these wave can propagate long vertical distances (Vadas & Becker, 2018) and are likely to reach the OH layer after being excited in the stratosphere. Becker & Vadas (2018) note that small scale secondary waves do not tend to propagate large distances in the vertical due to their low phase speeds. Thus, it is unlikely that we observe the small-scale type of secondary gravity waves unless they are excited directly below the OH* layer.'*

Referee #2 asked why GWs in the period range 60-240 min should be produced above the stratospheric wind fields and lead to the summer maximum, but not the periods below or above that range. He also asked if there could be other sources that could cause the summertime wave activity and encouraged to include more references on observations and modeling.

We added

'Similar results have been reported by Manson & Meek (1993) on the basis of radar measurements: a strong semi-annual variation of wave periods 10 - 100 min with solsticial maxima has been found around 87 km height, as well as dominant winter maxima and secondary summer maxima for wave periods 2 - 6 h. A semi-annual cycle is even observed with OH airglow imagers for short periods 5 - 30 min (Nakamura et al., 1999).'

'The assumption that this mechanism leads to a strong winter maximum for longer periods is supported by Tsuda et al. (1994), who observed the winter maximum in the period range 2 -21 h and state that gravity waves in this period range are mainly generated near the ground.'

and in the case of the summer maximum

'Tsuda et al. (1994) also observe a strong summer maximum and attribute this to short-period waves in the range 5 min - 2 h, which are predominantly excited at the height of the jet stream.' in the discussion section. The same mechanism could apply for the shorter range 6 – 60 min, however it might be due to short vertical wavelengths that our measurements are less sensitive to this part of

the spectrum (see above), which is why the summer maximum for short periods is quite weak. We have inserted 'even' before 'the UMLT region itself'.

Concerning other mechanisms for the summer maximum, we included *'During summer, Senft & Gardner (1991) observed enhanced wave energy at periods shorter than 3 h in the mesopause, which they attribute to increased importance of tropospheric convection as a source mechanism.'* in the discussion section.

We also referred to recent modelling results by including *'Recent studies based on the CMAT (Coupled Middle Atmosphere and Thermosphere) general circulation model show that the wind filtering concept as described above leads to realistic results (Medvedev & Klaassen, 2000; England et al., 2006). However, Medvedev & Klaassen (2000) remark that during summer fast gravity waves, which are able to penetrate into the mesopause, deposit wave drag of the same order of magnitude as the total eastward drag during winter due to their large amplitudes.'.*

Referring to the minor comments of Referee #1:

Page 6 line 7: The referee is right, it should rather be 'sampling rate' instead of 'resolution'. We changed this.

Page 6 line 27: We added *'This effect is strongest for short time series and weakens for longer time series. In the worst case – a time series of 240 min length – the peak intensity of a 480 min signal is 34 % of the peak intensity of a 6 min signal having the same amplitude. We attribute this to be an artefact due to boundary effects, which occurs as long as the time series is not much longer than the periods analysed.'*

Page 8 line 33: Unfortunately the period range Offermann et al. (2009) addressed is hard to estimate since they do not mention it explicitly and estimate wave activity by calculating the standard deviation of temperature profiles. They rather focused on separating different wave types like planetary waves, tides and gravity waves from squared temperature standard deviations instead of resolving the exact gravity wave periods. It also has to be mentioned that Offermann et al. (2009) use vertical temperature profiles of TIMED-SABER measurements.

Page 9 line 3: The meteor radar Hoffmann et al. (2010) used addressed the altitude range 80 – 100 km. We added "at an altitude of 80 - 100 km above".

Referring to the further specific comments of Referee #2:

Page 1 line 28: 'temporal course' changed to 'evolution'.

Page 2 line 10: 'region of' changed to 'region for'

Page 2 line 15: We changed *'please note that the term 'gravity wave activity' does not have the same meaning in all these publications – it refers either to variations of wind or temperature caused by gravity waves'* to *'please note that 'gravity wave activity' can be calculated from variations of either wind or temperature and that different measurement techniques may be sensitive to different ranges of wave parameters'*.

Page 4 line 5: *'Due to solar radiation measurements are only possible during the night-time'* changed to *'Measurements are only possible during the night-time since the OH* emission would not be detectable above the solar background.'*

Page 4 Heading. 'Data Basis' changed to 'Data Bases'

Page 4 line 7: omitted 'its'

Page 4 line 19: omitted 'Apart from that'

Page 4 line 21: omitted 'the'

Page 4 line 28. The temperature uncertainty is determined by Gaussian error propagation in the course of temperature retrieval as described in Schmidt et al. (2013). We added '(calculated by Gaussian error propagation)' after 'uncertainty'.

Page 4 line 30: 'succeeding' changed to 'successive'

Page 5 line 4: 'the' added

Page 5 line 5: 'Also Alpine stations (SBO, UFS) show a minimum of observations during summer. However, in these cases this effect is mainly due to bad weather.' changed to 'Also the Alpine stations (SBO, UFS) show minimal observations during summer, principally due to bad weather'

Page 6 line 5: 'method' added

Page 6 line 6: 'delivers' changed to 'provides'

Page 6 line 16: 'In the further course of' changed to 'Later in'

Page 6 line 19: 'short-periodic' changed to 'short-period'

Page 6 line 27+. Linking intensities to temperature amplitudes: see above.

Page 7 line 3. We agree that 'nocturnal mean of the significant wavelet intensity' is misleading and implies a single value. We changed 'nocturnal mean' to 'nocturnal means'.

Page 7 Figure 2. 'Long term courses of' omitted in caption. 'Arb. unit' changed to 'rel. unit' at the colorbar. '60 min' and '200 min' markers enlarged. We have changed the 2d plots to a discrete 'block-by-block' design without interpolation between the months.

Page 7 line 4: 'average' changed to 'overall'

Page 7 line 5-6: It is true that the display of very short periods is disadvantaged in this visualization. However, choosing a log plot would assign huge space to short periods < 60 min and in turn little space to medium and long periods. We decided that is would be better to properly display the period ranges with strong semi-annual and annual cycles than those with weak seasonal dependencies. Another reason is that we followed the referee's suggestion to plot the 2d spectra without interpolation and a log plot with this specification would not allow to plot the values in regular blocks next to each other. About short vertical wavelengths in the OH* layer: see above.

Page 7 line 9. Dashed line at 200min for ABA added.

Page 7 line 11. ‘using the data of OPN’ changed to ‘using OPN data’

Figure 3. Besides the lower and upper boundaries at 6 min and 480 min we have highlighted the periods 25 min, 60 min, 200 min and 240 min that are mentioned in the text. We omitted the original ‘240 min’ marker. It seemed a bit confusing as it implied a linear period scale in height dimension of the image. However, the color-coded graphs for each period are separated by linear offsets in the mean wavelet intensity. Longer periods are displayed above shorter periods, but not necessarily equidistantly. Successive graphs above 25 min are less dense than e.g. above 240 min.

Page 7 Figure 3: ‘arb. unit’ changed to ‘rel. unit’ (as suggested for Figure 2). We changed the first sentence to ‘Monthly mean values of nocturnal means of significant wavelet intensity, averaged over all years’, hoping this formulation will be less confusing.

Page 7 line 12+. We withdrew the focus on the identification of local peaks and tried to emphasize the general behavior. As Referee #2 stated correctly, also local minima may be interesting as they are indicating periods of enhanced consistency. We changed ‘It is interesting to note the occurrence of local peaks’ to ‘Furthermore, local maxima and minima are visible’ and dropped ‘A local peak of enhanced variability can be found at a period around 45 min for six out of eight stations (ABA, ALR, NEU, OHP, SBO, TAV). Another peak, or at least a strongly increased slope, is visible around a period of 105 min for four out of eight stations (ABA, SBO, TAV, UFS). Other local peaks can be found at periods of about 80 min (NEU, UFS, TAV; shoulder at ALR and SBO) and about 160 min (SBO and TAV).’.

> Figure 4: As we are no longer referring to distinct periods we have removed the period markers again and omitted ‘The positions of local maxima around the periods 45min, 80min, 105min and 160min are marked by dashed grey lines.’ in the caption. We changed ‘arb. unit’ to ‘rel. unit’ in the y axis label.

Page 8 line 6/Figure 5. We replaced the 60-480 min range by a 240-480 min range. The caption of Fig 5 has been adapted. We changed the y axis label from ‘arb. unit’ to ‘rel. unit’.

> Further changes in this context: replaced ’60-480’ by ‘240-480’ on page 8 lines 6, 12 and 13; page 10 line 16.

Page 8 line 10. ‘course’ changed to ‘variation’.

Page 8 line 10+: see Page 8 line 6/Figure 5.

Page 8 line 16. ‘undisturbed’ changed to ‘contiguous’ (both occurrences)

Page 8 line 16+. It is true that it is not surprising that our results agree with Wüst et al. (2016, 2017a), considering our similar data sets and methods. We integrate our wavelet results over the broad period ranges and compare it to the GWPED in order to validate our method. Being sure that we get the same results, we then make use of the great advantage of the wavelet analysis and calculate gravity wave activity for resolved periods. We try to emphasize this by adding the sentence ‘The agreement with the findings of Wüst et al. (2016, 2017a) is an important verification of our wavelet approach being well suited for the estimation of gravity wave activity.’ at page 8 line 24.

Page 8 line 18. On average, 67 % of the nights of which potential energy density can be calculated following the method of Wüst et al. are of sufficient quality to allow the application of the heredescribed wavelet method. Thus 33 % of the data analyzed by Wüst et al. are unavailable for the wavelet method. This indeed highlights the limitation of our method. We expanded the sentence to 'Our data base is smaller by 33 %.'.

Page 8 line 19: 'us' changed to 'this work'. 'data basis' changed to 'data base' in line 19 and line 20

Page 8 line 24: 'long-periodic' changed to 'long-period'

Page 9 line 12: 'a' added

Page 9 line 26: 'Minimum' changed to 'The minima in'

Page 9 line 27: 'episodes' changed to 'times'

Page 10 paragraph 1 (following page 7 line 12+): We changed 'peaks were identified' to 'maxima and minima are visible'. We dropped 'most prominently around 45 min, 80 min, 105 min, and 160 min, which occur for more than one station'. We changed 'The peaks' to 'These'. We changed 'These might be periods' to 'The maxima might indicate periods' and extended this sentence by *', while the minima in opposite would represent periods for which gravity wave activity remains consistent throughout the year. Most minima are found at different periods for different locations. One may tentatively speculate that these can be traced back to persistent sources of gravity waves, which are not subject to seasonal variations and are individual characteristics of the respective geographical locations.'*.

Page 10 paragraph 2: Moved behind paragraph 1 of the discussion section. Referee #2 suggested to expand the comparison between the stations, discussing also the similarities and uniqueness of each site. We took care of this as described above. We have added the 240-480 min range to Figure 5. Specifically, Referee #2 asked, why we attribute the high intensity at ABA to orographic forcing, while also other stations are near mountainous regions. We speculate that orographic forcing at ABA may be particularly high due to the Greater Caucasus being situated north of the FoV and the Lesser Caucasus being located south of the FoV. The changes in the manuscript are described above. Referee #2 asked why there is a dip in long-period GW intensity at TAV in September. Unfortunately we have no explanation for this. We included *'At this moment we cannot explain the unusual low value in September, which appears at none of the other stations.'.* Concerning the maximum during June-July in the 6-60 min period range, we changed 'summer maximum in some cases' to 'maximum in June or July (also NEU)'.

Page 10 line 10: 'agrees with' changed to 'supports'

Page 10 line 11: 'prominently' changed to 'importantly stratospheric'

Page 11 line 3: 'have been' changed to 'were'

Page 11 line 8. We expanded this sentence by *',which implies enhanced excitation of orographic gravity waves'*.

Page 11 line 14: We have expanded the sentence by 'except for a weak maximum in June / July'.

Page 11 line 9: 'turns out to be' changed to 'is observed to be'

Page 11 line 14: We expanded the sentence by 'except for a weak maximum in June / July'.

Page 11 line 19: As the discussion section has been expanded we replaced ‘It can explain the observed annual and semiannual modes of gravity wave activity in the UMLT under the following assumptions: gravity waves with periods between 60 and 240 min (240 min and 480 min) are generated at altitudes of or above (below) the stratospheric jet.’ by *‘Assuming gravity waves originating from the ground, this would explain the winter maximum of wave activity in the UMLT. The maximum in summer leading to a semi-annual variation of gravity waves with periods between 60 and 240 min might be due to wave generation above the stratospheric jet. Secondary gravity waves could contribute to both solsticial maxima. In the case of ALR and NEU the polar vortex could also act as a source of gravity waves.’*.

Page 11 line 25: ‘proxy’ changed to ‘values’