**Authors‘ Response to the Comment of Referee #1**

We thank Referee #1 for his detailed review and his suggestions for improvement.

Referee #1 identified two major problems.

1) It is unlikely that the small-scale wave structures we observe are gravity waves. They should rather be considered as instability features.

2) Our values of K and $\epsilon$ are too high and he doubts whether our approach of a rotating cylinder is the correct model for our turbulence observations.

**Passages in red have been deleted or rephrased as indicated.**

**Referring to major problem 1):**

We revised the discussion of our observed wave structures and switched to focus of our interpretation from gravity waves to instability features. The word ‘wave’ we use for convenience refers to wave-like features as seen in the images. We introduced section 4.1 with “We inserted the passage “Please note that we a using the word ‘wave’ for all wave-like structures we find in the images. The question whether these are actual gravity waves is discussed in section 5.” at the beginning of section 4.1.” to clarify this.

Referee #1 doubted that any significant portion of our observed structures with horizontal wavelengths below 5 km would be gravity waves. He gave multiple reasons why these structures would rather be instability features of gravity waves. We agree with his detailed explanations and refrain from considering wave structures with periods above the BV period gravity waves. As Referee #1 states correctly, Doppler-shifting may play a vital role and we have no systematic wind data to account for that.

We omitted the distinction between waves above and below the BV period in Figure 1. Consequently, also the sentence “The contribution of wave events with a period longer than the respective BV period is coloured in grey.” disappeared in the caption of Figure 1. We updated the wording and the statistical values in section 4.1 (results: statistics of wave parameters) Lines 165 ff. resulting from this.

*“**Instability features** are blown by the wind. GWs in general do not travel in the wind direction. But when they do two effects occur that make them **less likely to be observed** in the airglow layer. They are both related to the **dispersion relation** that shows that as the intrinsic velocity (the velocity with respect to the background wind) approaches the wave velocity the vertical wavelength decreases because the intrinsic frequency becomes small. This causes two effects.*

> *Unless the intrinsic frequency is very close to the BV frequency the vertical wavelength will be less than the horizontal wavelength. Now for the waves that are presented in this paper the **vertical wavelength will be 4.5 km or much smaller**. GWs that have wavelengths thinner than the airglow layer (8-10 km) will suffer phase cancellation and will have vastly reduced amplitudes and likely will be difficult to see (Swenson and Liu,1998).*
>
> *As the vertical wavelength decreases the waves undergoes viscous dissipation and instability formation. This is discussed somewhat in Hecht et al., 2000 as well in Hecht et al., 2018. For*

> *the former and assuming the very large viscosity implied by the current work GW,* ***lifetimes could be seconds to a few minutes*** *for the GWs in this study. Related to b is that if the features are really blown by the wind they are at a critical level and* ***probably do not survive****. I should note that waves in this study are travelling at a very low speed so it is very* ***likely that extremely common wind variations would exceed the wave speed and the critical level interaction (viscous dissipation or instability formation) would occur****. Hence, it seems very unlikely these are GWs."*

We agree with this detailed discussion of the dispersion relation.

We added 'If Figure 3b was the phase speed distribution of gravity waves, it is likely that a majority of them would encounter critical levels somewhere and would not be observable in the OH* layer.' to the discussion.

*"The characteristics of these waves if they are GWs, as currently presented, seem strange. Their phase speeds are quite low-below 20 m/s. GW climatology's typically show phase speeds of up to 50 m/s with the histogram of speeds centered closer to 40 m/s."*

We included this point in the discussion.

Line 360ff: "The quite slow phase speeds (mean value 13.3 m / s ) are one hint for this as typical gravity wave phase speeds accumulate around 40 m / s (see, e.g., Wachter et al., 2015 and Wüst et al., 2018)."

*"I was somewhat curious on how the monochromatic wavelengths were derived. They state they use a 2D FFT. Now FFTs assume the wave is present over the whole field of view and are often a little misleading with respect to monochromatic waves for airglow images because waves may be present over only a small fraction of the field. In the Hannawald reference they give a very nice image showing waves and I believe the FFT approach should be appropriate for date like that. But to date, while small scale instabilities have been identified with horizontal wavelength of a few to ~10 km there have been no reports of GWs with horizontal wavelengths of 5 km to 0.05 km. I would like to see images with their respective FFTs for images where the wavelengths are ~ 4 ,1,0.5,0.1 and 0.05 km. I am wondering if most of those images show features that resemble OH images (shown in the Hecht references) with instability features and their associated secondary instabilities and the resulting turbulences. I am really curious about GWs (or even instabilities/wave trains) with wavelengths at or much below ~500 m. These have not been reported before."*

We have not found waves with horizontal wavelengths down to 0.05 km, but this is the short-scale limit of our analysis, corresponding to twice the spatial resolution of 2*24 m = 48 m.

It is true that assuming stationarity the 2D-FFT rather finds wave structures that extend over the entire image. We have added a sample image of the smallest structure we found with a horizontal wavelength of ca. 1.9 km with its 2d spectrum (new Figure 1) and it does extend over at least half of the image.

In fact, we observed and reported a small "wave-like" instability feature with a horizontal wavelength of 550 m several years ago (see Sedlak et al., 2016). However, we doubt that such a small wave packet of limited spatial extension would appear in the 2D-FFT. A 2-dimensional wavelet analysis could account for such non-stationary features in future work.

**Referring to major problem 2):**

Considering the referee’s extensive argumentation, we agree that assuming a rotating cylindrical model, as we did, exhibits several weaknesses. Demanding a perfect rotating cylinder is a very strong assumption that may apply to some of the turbulent vortices, but definitely not to all of them. As Referee #1 states correctly, there are several non-cylindrical vortices besides the rotation cylinder in our example in Figure 3 and there is no particular need for a rotating model. Furthermore, we agree that using climatological values of N for our quite short-time and localized episodes is relatively coarse.

We decided to follow his advice and adapted the method of Hecht et al. (2021) following Chau et al. (2020). We refrained from determining K from a rotating cylinder model. Instead, we read the feature size L and the residual velocity $v_{res}$ from the image series and directly calculated $\varepsilon$ by using the equation $\varepsilon = C\frac{v_{res}^3}{L}$ with $C \approx 1$ (Hecht et al., 2021). As Referee #1 assumed correctly, this was not always easy for all our examples. Staying with the episodes where the derivation of $\varepsilon$ was possible with this method, our data basis reduced from 45 to 25 episodes. This changed the results of our correlation analysis with gravity wave activity: We now hardly see any significant correlation with the activity of gravity waves between 6 and 480 min.

Although the values are now a bit lower (the rotating cylinder model certainly served as an upper boundary value since it assumed maximum mixing; Referee #2 stated this quite correctly) some of them still exceed the limit of 1 W/kg with the maximum being 9 W/kg. We provide a careful discussion of the deviations from previous studies.

As the derivation of $\varepsilon$ is quite difficult and due to the variety of turbulent episodes we furthermore decided to show more of our turbulent observations. Besides our former video supplement from 4 November 2018, we now present three more video sequences.

**Changes made in the manuscript:**

**Abstract**

Lines 14, 38, 49, 55, 72, 77, 108, 186, 264, 269, 272, 279, and 312: We put commas before and behind “e.g.”.

Line 16f: Added “instability features from breaking secondary waves”

Line 17: Replaced “originating from breaking primary waves” by “that were created” and dropped “(westward)” and “(summer)”.

Line 20f: We changed “Furthermore, observations of turbulent vortices allowed the estimation of eddy diffusion coefficients in the UMLT from image sequences in 45 cases. Values range around $10^3 - 10^4\ \mathrm{m^2 s^{-1}}$ and mostly agree with literature. Turbulently dissipated energy is derived taking into account values of the Brunt-Väisälä frequency based on TIMED-SABER (Thermosphere Ionosphere Mesosphere Energetics Dynamics, Sounding of the Atmosphere using Broadband Emission Radiometry) measurements as presented by Wüst et al. (2020). Energy dissipation rates range between $0.63\,\mathrm{W\,kg^{-1}}$ and $14.21\,\mathrm{W\,kg^{-1}}$ leading to an approximated maximum heating of

0.2 - 6.3 K per turbulence event. These are in the same range as the daily chemical heating rates reported by Marsh (2011), which apparently stresses the importance of dynamical energy conversion in the UMLT."

to

"We present multiple observations of turbulence episodes captured by our high-resolution airglow imager and estimated the energy dissipation rate in the UMLT from image sequences in 25 cases. Values range around $0.08 \text{ and } 9.03 \ \mathrm{W\,kg^{-1}}$ and are higher than those in recent literature. The values found here would lead to an approximated localized maximum heating of 0.03 - 3.02 K per turbulence event. These are in the same range as the daily chemical heating rates for the entire atmosphere reported by Marsh (2011), which apparently stresses the importance of dynamical energy conversion in the UMLT."

**Introduction**

Line 40: We changed "ground" to "troposphere"

Lines 54ff: We changed

"They cause turbulent mixing of the medium, which is described by the eddy diffusion coefficient $K$. $K$ can be calculated from the eddy radius $r_e$ and the circumferential velocity $v_e$ by

$$K = \frac{2}{3\pi} r_e v_e \qquad (1)$$

(see e.g. Prölss, 2001. The derivation is outlined in detail in appendix A.). According to Weinstock (1978), knowing $K$ and the BV frequency $N$, an estimate for the energy dissipation rate ϵ - the rate at which turbulent kinetic energy is dissipated into heat at the short-scale end of the energy cascade of the inertial subrange (Li et al., 2016) - can be calculated using

$$K \approx 0.81 \cdot \left(\frac{\epsilon}{N^2}\right). \qquad (2)$$"

to

"They cause turbulent mixing of the medium, resulting in the dissipation of turbulent energy at an energy dissipation rate $\epsilon$. According to the theory of stratified turbulence, $\epsilon$ depends on the characteristic length scale $L$ and velocity scale $U$ of the turbulent features. The energy dissipation rate is then given by

$$\epsilon = C_\epsilon \frac{U^3}{L} \qquad (1)$$

(see, e.g., Chau et al, 2020; who apply this equation to radar observations of KHIs). $C_\epsilon$ is a constant which is found to be equal to 1 (Gargett, 1999)."

Lines 70ff: We changed

"This is why turbulence investigations in the UMLT are challenging and there are only few values of $K$ available at UMLT heights. Lübken et al. (1997) use rocket measurements to retrieve $K$ and $\epsilon$ in the height range 65 - 120 km. Liu (2009) presents a method for the estimation of $K$ from gravity wave momentum fluxes derived from lidar data. Baumgarten & Fritts (2014) use imaging techniques of mesospheric noctilucent clouds to investigate the formation of KHIs and the onset of turbulence."

to

“This is why turbulence investigations in the UMLT are challenging and there are only few values of $\epsilon$ available at UMLT heights. Lübken et al. (1997) use rocket measurements to retrieve $\epsilon$ in the height range 65 - 120 km. Baumgarten & Fritts (2014) use imaging techniques of mesospheric noctilucent clouds to investigate the formation of KHIs and the onset of turbulence.”.

Line 76: We changed “These include…” to “Remote sensing techniques include…”

Line 83: We changed “Proceedings” to “Improvements”

## **Data Basis**

Line 138: We inserted “…from the input images…”during the 2d-FFT”.

Line 156: We inserted “An exemplary event and the respective 2-dimensional spectrum are shown in Figure 1. We often observe episodes of turbulence in our image series that exhibit the typical dynamics of vortex formation and quasi-chaotic behavior.”

Line 164: Replaced “45” by “25” and “vortex” by “turbulence”

Lines 166ff: Omitted “For both, gravity wave statistics (section 4.1) and the calculation of the energy dissipation rate (section 4.2) the BV frequency is required, which is adapted from the climatology presented by Wüst et al. (2020). It is based on TIMED-SABER (Thermosphere Ionosphere Mesosphere Energetics Dynamics, Sounding of the Atmosphere using Broadband Emission Radiometry) temperature data and takes into account the seasonal variability of the angular BV frequency. The climatology of the grid point (45 ° N, 10 ° E) is used, which is closest to our FOV. Depending on the day of the year (DoY) the BV frequency is given by

$$N = 2.20 \cdot 10^{-2}\mathrm{s}^{-2} + 0.19 \cdot 10^{-2}\mathrm{s}^{-2} \sin\left(\frac{2\pi}{324.51\mathrm{d}} \cdot DoY - 2.02\right) + 0.05 \cdot 10^{-2}\mathrm{s}^{-2} \sin\left(\frac{2\pi}{180.00\mathrm{d}} \cdot DoY + 1.61\right). \quad (3)$$

We use an uncertainty of ±5 % as according to Wüst et al. (2020) 91 % of their data lie within this range around the harmonic approximation. The BV period is then referred to as $\tau_{BV} = \frac{2\pi}{N}$.”

## **Results**

We inserted the passage “Please note that we a using the word ‘wave’ for all wave-like structures we find in the images. The question whether these are actual gravity waves is discussed in section 5.” at the beginning of section 4.1.

Line 165 ff: We dropped “For each wave event the individual BV period is calculated based on Eq. (3) and the DoY. Ca. 63 % of the observed wave events have a period longer than the respective BV period and will be referred to as gravity wave events in the following. Their statistical contribution is highlighted in grey in **Fehler! Verweisquelle konnte nicht gefunden werden.**.”

Line 168 f: We dropped “The median value of gravity wave periods is found at 517 s (8.6 min).”.

Line 169: 17.6 m/s changed to 139.8 m/s; 7.9 m/s changed to 13.3 m/s

Line 170: 3.3 m/s changed to 10.3 m/s. 50.7 % (49.3 %) changed to 52.7 % (47.3 %). Dropped the word “gravity”.

Line 171: Dropped the word “gravity”.

Line 172: 5.4 m/s (5.3 m/s) changed to 9.4 m/s (8.2 m/s). 3.0 m/s (3.1 m/s) changed to 8.9 m/s (7.4 m/s).

Line 173: 53.8 % changed to 56.0 %. 46.2 % changed to 44.0 %.

Line 174: 47.9 % changed to 49.5 %.

Line 175: 52.1 % changed to 50.5 %. 44.4 % (53.5 %) changed to 42.0 % (55.7 %).

Line 176: 4.7 m/s (5.3 m/s) changed to 7.5 m/s (9.4 m/s).

Line 177: 3.0 m/s (3.2 m/s) changed to 7.1 m/s (8.7 m/s).

Lines 192 ff: We added: “To give an impression of the turbulent dynamics we observe, we present four of our turbulence episodes as video supplement. On 16 November 2017, 02:16 UTC, the turbulent breakdown of parts of an extended wave field can be observed (video 1). On 6 December 2017, 00:26 UTC, several fronts seem to be building up and form rotating vortices (video 2). This can be observed even clearer on 14 October 2018, 17:08 UTC, where the residual movement of turbulent features can be well recognized above the general background movement (video 3). On 4 November 2018, 19:18 UTC, breaking wave fronts seem to form rotating structures of nearly cylindrical shape, while these are accompanied by other turbulently moving eddies (video 4).

We estimate the turbulent energy dissipation rate $\epsilon$ using equation (1). However, in contrast to Chau et al. (2020) who used radar measurements, we only have horizontal information from our airglow imager. Hecht et al. (2021) demonstrate an approach how to apply equation (1) to purely horizontal airglow imager data, which we adapt to our observations in the following. The characteristic length scale $L$ can be read from the images by measuring the size of the turbulent features. The velocity scale is given by the residual velocity $v_{res}$ of these features. In our observations, they are part of larger instability features, which we assume to be advected by the background wind. We determine $v_{res}$ by reading the actual velocity of the turbulent features and subtracting the background movement $v_{bg}$ in the resulting direction. This is exemplarily shown in Figure 4. The two patches highlighted therein are both moving to the upper right direction but are approaching each other. This helps distinguishing background and residual movement.”

and dropped:

“The eddy parameters needed for the calculation of the eddy diffusion coefficient (Eq. 1) are determined manually from the image series of the 45 observations of turbulence. It has to be kept in mind that we are deriving properties of a three-dimensional movement from two-dimensional data.

We assume the vortices to rotate in a perfect circular shape. The lateral expansion creates the impression of a rotating cylinder. Coherently moving structures give indication of the horizontal velocity vector. Unless the rotational axis is aligned perpendicular to the image plane, the three-dimensional vortex rotation manifests as more than one coherent structure that is moving against or overtaking each other (see e.g. Sedlak et al., 2016; Figure 6 therein). During data inspection we noticed that the orientation of the rotational axis can be aligned in any direction. It tends to be parallel to the image plane when it evolves directly from the crests of a breaking wave. However, we could also observe eddies rotating around an axis aligned almost perpendicular to the image plane. An example of a rotating vortex within a FAIM 3 snapshot on 4 November 2018 at 19:36:41 UTC is displayed in Figure 3a. The rotational axis and the direction of rotation are marked therein and on an actual cylinder (Figure 3b) for clarification. Since it is very difficult to identify a vortex structure in a single picture we have attached a video sequence of this episode (Video 1). The vortex radius and velocity are read from the images. Besides measuring the vortex rotation, it has also to be taken care of the overall image: if additional to the eddy movement all structures in the FOV are moving into a common direction, this background motion has to be subtracted. In the example shown above the vortex is advected toward the left corner. The distance between camera and observed vortex is much larger than the expansion of the vortex along the rotation axis so that falsifications arising from different perspectives of the vortices can be neglected. This principle is illustrated in Figure 4. As the vortices are three-dimensional the alignment of the rotational axis should not affect the value of the vortex parameters in the images: it does not matter if the axis is aligned perpendicular, parallel or in any other angle to the image plane, the vortex size will be accessible from the two-dimensional projection of the image assuming circular eddy movement. The same holds for the circumferential velocity since both the radius and the circulation time remain unchanged. However, perfectly circular eddy rotation does not necessarily occur in nature. Deviations from circularity can lead to both over- and underestimation of vortex sizes depending on the vortex orientation. Since isotropy is one of the characteristic properties of turbulent movements one may presume that from a statistical point of view both cases occur equally so that no systematic error is made.”

Lines 232ff: We changed

“As stated in section 3 we found 45 episodes of turbulence that allowed the derivation of the vortex radius and circumferential velocity. The resulting eddy diffusion coefficients $K$ are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. We assume a general read-out error of $\pm3$ pixels, which corresponds to a distance of $\pm72$ m. The circumferential velocity is determined by reading the distance a patch on the rotating cylinder surface covers within an episode of at least ten images, which corresponds to a time span of 28 s. Thus, the circumferential velocity is estimated with an error of $\pm2.6$ m s$^{-1}$. The arising uncertainties of $K$ are calculated following the rules of error propagation.

The values of $K$ range from $0.12$ to $1.94 \cdot 10^4\ \mathrm{m^2 s^{-1}}$. The mean value is $0.76 \cdot 10^4\ \mathrm{m^2 s^{-1}}$”

to

“As stated in section 3 we found 25 episodes of turbulence that allowed the derivation of $L$ and$v_{res}$. Using equation (1), the energy dissipation rate is then calculated by $\epsilon = \frac{v_{res}^3}{L}$.The resulting values are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. We assume a general read-out error of $\pm3$ pixels, which corresponds to a distance of $\pm72$ m. Velocities are determined by reading the distance a feature covers within an episode of at least ten images, which corresponds to a time span of 28 s. Thus, velocities are estimated with an error of $\pm2.6$ m s$^{-1}$. The arising uncertainties of $\epsilon$ are calculated following the rules of error propagation.

The values of $\epsilon$range from 0.08 to $9.03$ W kg$^{-1}$. The median value is $1.45$ W kg”

Lines 240ff: We dropped

“(standard deviation of $0.53 \cdot 10^4\ \mathrm{m^2 s^{-1}}$) and we retrieve a median of $0.59 \cdot 10^4\ \mathrm{m^2 s^{-1}}$. It is difficult to exactly quantify the error of manual parameter determination from the images. However, in this work we rather focus on the order of magnitude of $K$. When calculating $K$ two distance values are read from the images (one for the vortex size and one for the determination of the circumferential speed). Considering Eq. (1), a mistake of factor 10 is made for $K$ if these distances are misread by a factor of at least $\sqrt{10}$. The shortest (and therefore most difficult to determine) diameter in our analysed examples was 768 m. For an error of one order of magnitude of $K$ this distance must be misread as either shorter than 243 m or longer than 2428 m, i.e. a distance of 32 pixels must be wrongly interpreted as shorter than 9 pixels or longer than 101 pixels. This lies far beyond the read-out uncertainty of $\pm 3$ pixels we introduced above and can be assumed to be much worse than any read-out error one would normally make.

The energy dissipation rate $\epsilon$ can be estimated from the eddy diffusion coefficient $K$ according to Eq. (2) using the BV frequency as described by Eq. (3).

As can be seen in **Fehler! Verweisquelle konnte nicht gefunden werden.** the energy dissipation rate of the observed turbulence events is in the range $0.63 - 14.21\,\mathrm{W\,kg^{-1}}$.”

Line 254: We updated “146 s” to “241 s” and “2.4” to “4.0”.

Line 258: We updated “220” to “30” and “6346” to “3015”.

Line 262: We updated “0.2-6.3 K” to “0.03-3.02 K” and dropped “64 % (21 out of 33) of these values are larger than one Kelvin.”

Line 268: We inserted a missing “°”

Lines 277ff: We changed “We find a slight but significant anticorrelation for gravity wave periods in the range 122 - 207 min. For these periods the mean value of the correlation coefficient is -0.46. The highest coefficient of anticorrelation is -0.52 at a period of 178 min. ”

to

“We find almost no significant correlation for any gravity wave period.”

**Discussion:**

Line 280: We replaced “The directions of propagation are quite uniformly distributed over all quadrants as can be seen in Figure 2” by “As can be seen in Figure 3, the wave structures we observed exhibit multiple directions.”

Line 288: We replaced “(positive zonal phase speed) and in westward direction during summer. Although this tendency is quite weak,” by “whereas zonal directions are quite balanced during summer. Although the eastward tendency during winter is quite weak,”.

Line 290: We added “tropospheric and”.

Lines 292ff: We replaced “The reversed stratospheric winds during summer would consequently allow some more eastward travelling gravity waves to propagate upward (see e.g. Hoffmann et al., 2010; Hannawald et al., 2019). Since the highest observed phase speed of waves with periods longer than the BV period is only 17.6 m s-1, it can be assumed that in the majority we do not observe gravity waves that are originating from low altitudes and are fast enough not to be blocked by the stratospheric wind fields.”

by

“During summer the stratospheric winds reverse to westward direction, so that eastward oriented gravity waves are filtered in the tropopause and westward oriented gravity waves are filtered in the stratosphere (see, e.g., Hoffmann et al., 2010; Hannawald et al., 2019).”.

We inserted

“As we have no accompanying wind measurements in the height of our observations it is difficult to decide by means of the period whether the wave structures presented in section 4.1 are small-scale gravity waves or instability features. Ca. 63 % of the observed wave events have an observed period above the BV period (here we used the climatology presented by Wüst et al., 2020), however these could also be Doppler-shifted instability features instead of gravity waves. While the distinction between largely extended wave-fields (bands) and small localized wave structures that are related to instability (ripples) is often made at a horizontal wavelength of 10 - 20 km (Taylor et al., 1997; Nakamura et al., 1999), Li et al. (2017) remark that even structures with horizontal wavelengths of 5 - 10 km may sometimes be gravity waves rather than instability features.”

after this passage.

Line 302 ff: We changed “Considering the directional distribution, it is possible that the major part of our waves may” to “If this would be true for our small-scale wave structures, they might rather”.

Line 321 f: We changed “southward in 62 % of cases.” to “southward in 71 % of cases.”.

We inserted

“However, regarding the small horizontal wavelengths below 4.5 km, it is more likely that the major part of the observations presented in section 4.1 are related to instability features. The quite slow phase speeds (mean value 13.3 m / ) are one hint for this as typical gravity wave phase speeds accumulate around 40 m / s (see, e.g., Wachter et al., 2015 and Wüst et al., 2018). If Figure 3b was the phase speed distribution of gravity waves, it is likely that a majority of them would encounter critical levels somewhere and would not be observable in the OH* layer.”

after this passage.

Line 371 ff: We replaced “Li et al. (2017) report that ripples are hard to distinguish from small-scale gravity waves. Height-resolved measurements of the horizontal wind would be needed to determine the local wind shear and make a profound statement about atmospheric instability. Nevertheless,”

by

“Considering the fact that the directional peculiarities of our observed wave events fit well with the expected behavior of secondary gravity waves, as discussed above, support the scenario of the wave structures being ripples from dynamic instabilities of secondary gravity waves, that originate from the stratospheric and mesospheric jet.”.

We added

“Nevertheless, height-resolved measurements of the horizontal wind would be needed to determine the local wind shear and make a profound statement about atmospheric instability. It has to be kept in mind that a 2d-FFT was used. Thus, periodic structured are assumed to be stationary, i.e., they extend over the entire image. Faint structures that appear only in small parts of the image (as does for example the 550m wave packet in Sedlak et al., 2016; Fig. 2) would be underrepresented by this analysis.”

at the end of the discussion section of the wave statistics.

Lines 384ff:

We changed

“There are still very few measurements of turbulent eddy diffusion coefficients in the UMLT. Lübken (1997) reports $K$ to be around $10^1 - 10^2\ \mathrm{m^2 s^{-1}}$ at a height of 87 km at high latitudes. Hodges (1969) states that the eddy diffusion coefficient caused by gravity waves is typically around $10^3\ \mathrm{m^2 s^{-1}}$. According to the CIRA (Committee on Space Research (COSPAR) International Reference Atmosphere) climatology of 1986 (NASA National Space Science Data Center, 2007) global values range between magnitudes of $10^2$ and $10^3\ \mathrm{m^2 s^{-1}}$. LIDAR measurements above New Mexico, USA deliver values that vary strongly around a magnitude of $10^2\ \mathrm{m^2 s^{-1}}$ (Liu, 2009). Smith (2012) notes that the WACCM (Whole Atmosphere Community Climate Model) climatology exhibits rather small values with magnitude $10^1\ \mathrm{m^2 s^{-1}}$ and that the huge discrepancies of $K$ estimates cannot be fully explained yet. The here-presented values of $K$ exhibit a magnitude of $10^3 - 10^4\ \mathrm{m^2 s^{-1}}$, which partly agrees with recent results, although some of our values are higher.”

to

“Measuring the eddy diffusion coefficient in the UMLT is still challenging and there are only few studies yet. Rocket measurements of Lübken (1997) deliver energy dissipation rates between ca. 0.01 and 0.1W $\mathrm{kg^{-1}}$ between 85 and 90 km height at high latitudes. Chau et al. (2020) find an energy dissipation rate of 1.125 W $\mathrm{kg^{-1}}$ for their KHI event observed in the summer mesopause and state that this a rather high value compared to the findings of Lübken et al. (2002). Hocking (1999) provides a rescaled overview of earlier values of the energy dissipation rate and these have a maximum magnitude of 0.1 W $\mathrm{kg^{-1}}$. Hecht et al. (2021) derive a value of 0.97 W $\mathrm{kg^{-1}}$ from airglow images of a KHI event. Ranging from 0.08 up to 9.03 W $\mathrm{kg^{-1}}$ the values of energy dissipation rate derived here are higher than reported by other studies. However, the median value of 1.45 W $\mathrm{kg^{-1}}$ is not too far away from the values of Chau et al. (2020) and Hecht et al. (2021).”.

Lines 402f: We added “– except for the studies of Hecht et al. (2021), whose value is quite similar to the median value of our data –„

Lines 405ff: We dropped “Nevertheless, the agreement of the above-mentioned authors on eddy parameters in the UMLT is quite good, considering the fact that energy dissipation rate in the upper troposphere and lower stratosphere varies by a factor of more than five orders of magnitude (Li et al., 2016).”.

Line 408: Changed “vortex” to “turbulence”

Line 409: Changed “Circumferential speed and vortex radius” to “The length scale and velocity scale of turbulent features”

Line 410: “and we” changed to “. We”

Lines 412f: Inserted “However, using equation (1) velocity dominates the length scale due to its power of 3, so that $\epsilon$ strongly depends on a parameter, which is quite difficult to extract from the images.”

Line 414: Dropped “eddy diffusion coefficient and”

Line 415: Replaced “eddy diffusion coefficients” by “energy dissipation rate” and replaced “significant anticorrelation” by “no significant correlation”

Lines 416: Changed “122-207 min” to “6-480 min”

Lines 416ff: Changed

“One may assume that turbulent vortices we observe could be predominantly attributed to breaking gravity waves in this period range. If this was the case, stronger wave breaking would manifest as higher eddy diffusion coefficients and result in a lower activity of gravity waves with periods 122 - 207 min in the UMLT. However, especially observations of period-resolved gravity wave activity at altitudes below would be needed to confirm this assumption.

Assuming that the turbulently dissipated energy is entirely converted into heat we find temperature changes of 0.2 - 6.3 K that occur within time spans of 2.4 – 15.4 min. Marsh (2011) report chemical heating rates in the atmosphere to be around 3 – 4 K per day. Given that our analysed episodes are typical representatives of turbulent wave breaking, dynamical heating by gravity wave dissipation would deliver the same effect within few minutes as does chemical heating during an entire day. ”

to

“Turbulence thus cannot be related to distinct periods of the gravity wave spectrum with the here-presented data. Note that the spectrometer GRIPS is sensitive to much larger spatial scales than FAIM. A larger data basis of turbulence parameters and especially observations of period-resolved gravity wave activity at altitudes below will be needed to answer the question if all parts of the gravity wave spectrum drive turbulence generation in the UMLT equally.

Assuming that the turbulently dissipated energy is entirely converted into heat we find temperature changes of 0.03 - 3.02 K that occur within time spans of 4.0 – 15.4 min. Marsh (2011) report chemical heating rates in the atmosphere to be around 3 – 4 K per day. Given that our analysed episodes are typical representatives of turbulent wave breaking, dynamical heating by gravity wave dissipation would deliver the same effect within few minutes at very localized areas in the UMLT as does chemical heating during an entire day for the whole atmosphere."

**Summary**

Lines 429ff: We changed

"We present an analysis of small-scale wave dynamics from OH* imager data acquired between 26 October 2017 and 6 June 2019 at Otlica Observatory, Slovenia. Measurements have been performed with the imager FAIM 3, which has a spatial resolution of ca. 24 m pixel$^{-1}$ and a temporal resolution of 2.8 s.

Wave structures in the images are systematically identified by applying a 2d-FFT to nocturnal image sequences during clear sky episodes. All wave events meeting our persistency criteria were used to derive a statistical analysis of wave structures with horizontal wavelengths between 48 m and 4.5 km. 63 % of the wave events have a period longer than the BV period and may be tentatively considered as gravity waves. We find an isotropic distribution of directions of propagation, which indicates that wave structures may be mostly created above the stratospheric wind fields. However, a weak seasonal dependency is found: zonal directions of wave propagation are slightly more eastward during winter and westward during summer. We speculate these to be generated by breaking gravity waves in the course of wind filtering, receiving their zonal direction through advection by the background wind. We find a stronger tendency of southward propagation during summer, which may point to a vital role of gravity wave filtering and excitation of secondary waves by the meridional mesospheric circulation. It is possible that secondary waves and instability features represent the majority of our observed waves.

Furthermore, we estimated turbulence parameters from 45 episodes of vortex observations. The derived values of eddy diffusion coefficients are in the range around $10^3 - 10^4\ \mathrm{m^2 s^{-1}}$ and agree mostly with earlier results from rocket and lidar measurements and simulations. Considering the respective values of the BV frequency as calculated by Wüst et al. (2020) we retrieve energy dissipation rates between $0.63\,\mathrm{W\,kg^{-1}}$ and $14.21\,\mathrm{W\,kg^{-1}}$, that cause estimated heatings by 0.2 - 6.3 K per turbulence event. These have the same order of magnitude"

to

"We present an analysis of small-scale dynamics of instability features and turbulence from OH* imager data acquired between 26 October 2017 and 6 June 2019 at Otlica Observatory, Slovenia. Measurements have been performed with the imager FAIM 3, which has a spatial resolution of ca. 24 m pixel$^{-1}$ and a temporal resolution of 2.8 s.

Wave-like structures in the images are systematically identified by applying a 2d-FFT to nocturnal image sequences during clear sky episodes. All events meeting our persistency criteria were used to derive a statistical analysis of wave-like structures with horizontal wavelengths between 48 m and 4.5 km. The small horizontal scales are a strong hint that these are likely instability features of breaking gravity waves like ripples. We generally find variable directions of propagation, which indicates that these wave-like structures may be mostly created above the stratospheric wind fields. However, a weak seasonal dependency is found: zonal directions of propagation are slightly more eastward during winter and westward during summer. We speculate these to be instability features generated by breaking secondary gravity waves, receiving their zonal direction through advection by the background wind. We find a stronger tendency of southward propagation during summer, which may point to a vital role of gravity wave filtering and excitation of secondary waves and their subsequent instability features by the meridional mesospheric circulation.

Furthermore, we observed and presented OH* imager observations of turbulence with high spatio-temporal resolution. We estimated turbulence parameters from 25 episodes of eddy observations. Following the approach of Hecht et al. (2021) we derived the energy dissipation rates for our observed events by reading the turbulent length and velocity scale from the image series. Our values range between $0.08$ and $9.03\ \mathrm{W\,kg^{-1}}$ and are higher than earlier rocket measurements. The values presented here would cause localized heatings of 0.03 - 3.02 K per turbulence event. The largest of these reach the same order of magnitude"

## Appendix

We dropped Appendix A.

## Figures

Figure 1 is now a sample event with its 2D-FFT spectrum.

Figure 2 (former Figure 1): Histograms of wave parameters without separation by the BV period

Figure 3 is now former Figure 2

Figure 4 (former Figure 3): New snapshot showing how to read the new wave parameters from the images.

Former Figure 4: dropped

Figure 5: Plot of temporal course and histogram of $\epsilon$ (no K values anymore)

Figure 6: Updated histogram of temperature changes

Figure 7: Updated plot of correlation analysis

Figure 8 (concept of rotating cylinder): dropped

## Tables

We updated Table 1 by dropping those lines referring to events which we could not analyse anymore with the new method. We dropped the columns "DoY", "K" and "Angular BV Frequency".