Reply to the Reviewer 2

Manuscript #: angeo-2021-48

Title: A case study of a ducted gravity wave event over northern Germany using simultaneous airglow imaging and wind-field observations

Overview

This paper is about multi-wavelength airglow observations of a gravity wave event above northern Germany. The peculiar finding is a strong wave signature visible in the $O(^1S)$ (97 km altitude) and O_2 (94 km altitude) bands, a fainter signature in the Na band (91 km altitude), and no wave signature in the OH band (86 km altitude). Auxiliary data used in the study are wind measurements by a meteor radar network and temperature profiles acquired by the SABER instrument on the TIMED satellite. To my knowledge, this is the first report on such a wave event with co-located local measurements of horizontal wind. Information on horizontal wind is of particular importance for the estimation of intrinsic wave parameters. Using the available measurements, the authors derive a vertical wavenumber profile from the gravity wave dispersion relation and conclude that a thermal duct is responsible for the non-detection of wave signatures in the OH band.

The paper is well written and presents some novel results. I recommend it for publication in Annales Geophysicae subject to the authors addressing the comments below. My main concern is the lack of a plausible explanation for the non-detection of wave signatures in the OH band (see major comment below). Without an explanation, the paper is merely a compilation of observations. Although the uniqueness of the presented observations may justify their publication (I leave this to the editor), a proper description, discussion and evaluation of potential mechanisms responsible for the diminishing modulation in OH airglow brightness will greatly increase the scientific value of this paper.

Reply: We thank the reviewer for the appreciation and critical comments that will improve the content of the manuscript significantly. The responses to the reviewer's comments are provided below in the same sequence.

Major comment

I am surprised that the authors did not use Fig. 6 to estimate the vertical wavelength. From the slopes of the dashed lines I get values ranging between 8 and 12 km. On the other hand, m^2 = 0.5 (taken from Fig. 7e) leads to lambda_z = 8.8 km. This value is consistent with the previous estimate and thus increases confidence in the derived vertical wavelengths. Also, from Fig. 7e I estimate the width of the duct h=5.5 km. According to lambda_z = 2h/n (see e.g., Dong et al. 2021; reference id given below) we can conclude that the wave propagating within the duct is likely of 0^{th} order (n=1) assuming that the vertical wavelength inside the duct is approximately the same as above the duct. Indeed, based on Fig. 7e, m^2 values at 88 km (center of the duct) and at 95 km (above the duct) are similar. However, the 0^{th} mode is a symmetric mode and, because the center of the duct (~88 km) is approximately aligned with the center of the OH layer (~86 km), the ducted wave should result in detectable

modulations in airglow brightness. Some pieces of the explanation of the non-detection of wave signatures in OH airglow are clearly missing here. On the other hand, the authors provide no explanation either. In my opinion the sentence "The coincidental appearance of the duct layer caused the wave amplitudes to diminish" (l.327) is unsupported speculation. Before making such a statement, the authors should at least discuss conditions which *can* result in cancellation of wave signatures in OH airglow due to the viewing geometry or otherwise.

Reply: We thank the reviewer for the suggestion to estimate the vertical wavelength from Figure 6 and will include this aspect in the revised manuscript.

The waves were visible in the OH airglow images during the course of the event, but were faint compared to $O(^1S)$ and O_2 emissions. Dong et al. 2021 discussed the various wave modes that can exist in a ducting region. The vertical wavelength of the ducted wave (λ_z) and the duct width (h) are related via the relationship of $\lambda_z = 2h/n$ (n = 1, 2, 3, … denotes 0th, 1st, 2nd wave mode). Using Figure 7e, we calculated the duct thickness to be 6 km and the vertical average wavelength in the OH emission layer to be 11.5 km. Hence from the above relation, we can conclude that the 0th wave mode (n = 1) can exist in the duct.

We suggest that the ducting layer (85-91 km) observed in the present case (Figure 7c & e) was weak and so inhibited free propagation within that particular altitude region. Only part of the energy of the wave could penetrate through the bottom of the duct layer and the other part of the energy will be reflected back downward. Being localized, the part of the wave continued to propagate upwards into the O_2 and $O(^1S)$ emission layer at higher altitudes (represented schematically in Figure 8). Since only a part of the wave energy could enter in the duct region (85-91 km), the wave structure was observed to be faint in the OH airglow images.

We agree that the sentence "The coincidental appearance of the duct layer caused the wave amplitudes to diminish" is somewhat confusing and we will modify it in the revised manuscript.

Minor comments

l. 50: It would be helpful if you could define "large-scale waves"

Reply: In this context, we meant "large-scale waves" as those with several tens of kilometers horizontal wavelength. It will be included in the revised manuscript.

l. 55: "Instabilities present in the atmosphere do not support free propagation of GWs." This sentence is not clear to me. The assertion implies that instabilities are a property of the (background) atmosphere. However, the question whether an instability arises also very much depends on the properties of a particular wave propagating through the atmosphere. For instance, depending on the wind profile, an eastward propagating wave may propagate freely whereas a westward propagating wave is filtered due to a critical level.

Reply: We agree with the reviewer that this sentence is somewhat confusing. We will remove it.

l. 56: This may be a discussion about terminology, but it is my understanding that wave breaking is a process during which a wave breaks down and energy is transferred to smaller

eddies. I wouldn't call these eddies waves because the word 'waves' implies some form of coherent structure. The generation of secondary waves is a separate process.

Reply: We will modify the sentence in the revised manuscript.

l. 65: Please explain "inhomogeneities in the background medium". Do you mean variations in density?

Reply: The inhomogeneities in the temperature and wind field are responsible for the static/convective and dynamic instabilities, respectively, in the atmosphere which affect the wave propagation. We will include this statement in the revised manuscript.

l. 75: "according to whether m^2 arises". I believe you meant "imaginary m^2"?

Reply: We will modify the sentence in the revised manuscript.

l. 124: What is the horizontal averaging of the SABER measurements?

Reply: SABER views the Earth's limb in a direction of 90 degrees to the velocity vector of the spacecraft. The instantaneous field of view of the instrument is 2 km. The limb view offers high inherent vertical resolution due to the exponential decrease of pressure with altitude. Most of the radiance observed by SABER at a given tangent height originates within ±110 km of the tangent point. From this perspective, the 'horizontal' resolution of the measurements along the line-of-sight limb view is approximately 200 km.

l. 142: What window sizes did you use?

Reply: For our present case, the window size of SG-filter is taken as 400 pixels for OH, 350 pixels for 589.3 nm, 300 pixels for 866.0 nm, 300 pixels for 557.7 nm filter.

On the other hand, the Gaussian filter has standard deviation (σ) of 20 pixels for OH, 20 pixels for 589.3 nm, 15 pixels for 866.0 nm, 15 pixels for 557.7 nm filter. Here, 1 pixel on the airglow images is nearly equal to 1.16 km. We will include this information in the revised manuscript.

Equation 1: What are the values used for H and k_x?

Reply: The values of H = 5.4 km and $k_x = 2\pi/ \lambda_x$ = 0.084 km^{-1} (λ_x = 75 km). We will include this information in the revised manuscript.

l. 185: What are the time offsets between acquisitions with different filters?

Reply: The image time gap of different filters:

OH: 27 Seconds $\Rightarrow$ 866.0 nm: 134 Seconds $\Rightarrow$ 557.7 nm: 260 Seconds $\Rightarrow$ 589.3 nm: 263 Seconds.

This is the cycle of the filter wheel operation. We will include this information in the revised manuscript.

l. 185: "mean phase velocities". Are these observed phase velocities?

Reply: Yes, these are observed phase velocities. We will mention that in the revised manuscript.

l. 216: "there will not be any significant differences in the temperature". Well, I agree that significant differences between the SABER measurement and the temperature one hour later are not very likely, but the possibility can't be ruled out.

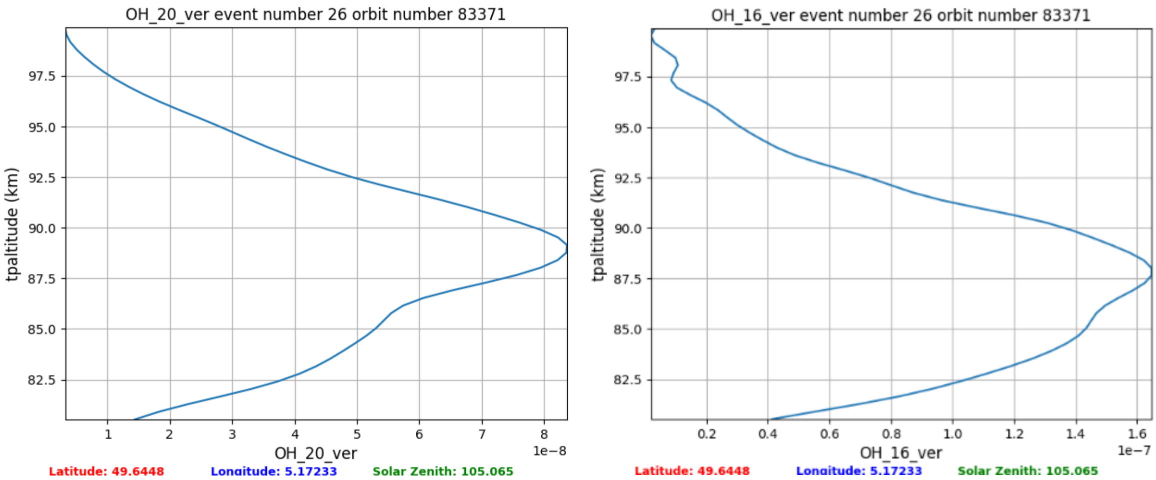
Reply: Yes, it may be possible that the temperature changes after 1 hour. The change in the temperature within this short time scale is mainly due to wave perturbations, e.g., atmospheric tides. However, one hour is still a short enough time scale to assume that the change in the background temperature is very small and, thus, is not going to affect the analyses. We will include this information in the revised manuscript.

l. 255: "In fact, clear signatures of wave activities were observed on other nights in OH airglow images over northern Germany." What about before and after the event you described in this paper? Was there any coherent structure observable in all four airglow bands?

Reply: No, we didn't observe any other wave activities before and after the event. We will include this information in the revised manuscript.

l. 264: "The SABER measurements indicated that the centroid height of OH airglow emission occurred near 87 km." Can you also provide estimates of the thickness of the OH layer (and potentially shape)? Because the vertical wavelength of the gravity wave is likely comparable to the thickness of the OH layer, even small changes in the thickness may have a large impact on the observability of the wave in OH airglow.

Reply: The figure given below represents the OH volume emission rate (VER) profiles (both at 1.6 and 2.0 µm emissions) at SABER 2 measurement location.



From the above VER profiles, we can determine the thickness of the OH emission layer as 10.2 km. From Figure 7e, the average vertical wavelength of the wave structure is calculated to be 11.5 km ($m^2 = 0.3 \times 10^{-6}$ m^2). Thus, it is clear that the vertical wavelength of the wave structure is longer than the OH emission layer thickness. In addition, we have analyzed SABER OH emission profiles for ±2 nights from nearby locations which is tabulated as follows:

Date	**Time (UTC)**	**Latitude (°N)**	**Longitude (°E)**	**Thickness of OH layer (km)**
2017-04-23	20:06:11	51.3812	6.12034	8.99
2017-04-24	20:19:49	50.5787	6.6311	10.05
2017-04-25	20:33:06	49.6448	5.17233	10.2
2017-04-26	20:47:06	47.385	6.60191	10.7
2017-04-27	21:00:33	45.5016	5.02261	10.2

It is to be noted that the OH emission layer thickness is similar. Hence, we believe that the small changes in the thickness will not have any significant impact on the observability of the wave in OH airglow. We will include this information in the revised manuscript.

l. 273: "We believe that the perturbation wave amplitude will finally decide whether the structure observed in the OH airglow image is faint or not." Please explain. Are you arguing that the strength of the OH airglow emission ("faint or not") solely depends on the amplitude of the gravity wave?

Reply: We will delete the line in order to avoid confusion.

l. 294: conductive

Reply: We wrote "… conducive background condition…" in the manuscript (submitted version). We meant "favorable background condition".

l 302: "It is well-known that the MIL tends to be quite stable within a few hours' time scale." Well, it depends on how you define "a few hours' time scale". For instance, tides can have a huge impact on the MLT *within a period of few hours*. Depending on the phase of the tide, mountain waves may propagate well into to the OH airglow layer or experience critical levels below.

Reply: The MIL tends to be quite stable at least for 3-4 hours (e.g., Meriwether and Gerrard, 2004; Dao et al., 1995). We will modify the statement in the revised manuscript.

The tidally driven MIL tends to occur above 85 km in the MLT region. This MIL originates from large-amplitude tidal waves propagating into the mesosphere and their subsequent nonlinear interactions with gravity waves and tends to be quite stable.

l. 309: delete "that" -> indicates the existence

Reply: It will be deleted in the revised manuscript.

l. 311: delete first "of" -> some energy

Reply: We will modify in the revised manuscript.

l. 341: Please check the grammar of this and the following sentences.

Reply: We will modify the sentence in the revised manuscript.