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Reply on RC1

Sumanta Sarkhel et al.

Author comment on "A case study of a ducted gravity wave event over northern Germany using simultaneous airglow imaging and wind-field observations" by Sumanta Sarkhel et al., Ann. Geophys. Discuss., <https://doi.org/10.5194/angeo-2021-48-AC1>, 2021

Reply to the Reviewer 1

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

The work combines Airglow imager and Meteor radar observations from Germany and uses SABER measurements to bring out/discuss a special gravity wave event that leaves its footprint in oxygen green line, O₂ emissions but not in OH emission. The authors propose the formation of a leaky duct to explain the observations. While this is a realistic possibility, other factors need to be ruled out to strengthen the argument. The observation of this wave activity in Na emission is also enigmatic and require more attention. The observations reported merit publication but the authors need to critically address a few issues described below.

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.

On dataset and techniques: Does this imager consist of 512 × 512 pixels ANDOR back-illuminated CCD camera or 1k × 1k camera as mentioned by Vargas et al. (2021)? For completeness, provide details on the bandwidth of the interference filters. Is there a possibility of contamination of OH broadband emission from other mesospheric lines? How do the authors rule that this contamination is not

responsible for the lack of wave signatures in the OH band? What are the integration times used for these observations?

Reply: Yes, it is the same $1k \times 1k$ CCD camera mentioned in Vargas et al. (2021). On the night of 25 April 2017, the images were binned 2×2 (in real time) in order to achieve better signal-to-noise ratio. The bandwidth of the 589.3 nm, 866.0 nm, and 557.7 nm filters is 2.0 nm whereas, the OH filter is a broadband (695–1050 nm). Hence, there is no contamination of OH broadband emission from other mesospheric lines (557.7 and 589.3 nm).

The nearest lines of OH ($X^2\Pi$) are at P1(6) and R(7,3) (854.9 and 877.1 nm respectively) that are quite far-off from O_2 emission line (866.0 nm) (Chamberlain, 1961). In addition, the wave signatures in the OH (when detected) and O_2 images differed in both morphology and phase. Hence, we are confident that no significant broadband OH occurred within the 866.0 nm filter bandwidth. The integration times for the 589.3 nm, 866.0 nm, and 557.7 nm images were 120s and 15s for the OH filter. We will include this information in the revised manuscript.

Figures 2-5: Why does the central dark spot appear in all the images? Detector issue? How does the 2D FFT filtering remove this feature?

Reply: The central dark spot appearing in every all-sky airglow image is due to the van Rhijn effect; a combination of the finite width of the emission layer and the variation of the line of sight through the layer with increasing zenith distance. There was no issue with the CCD detector. We will mention this in the revised manuscript.

We have used 2D FFT filtering techniques adopted from Mondal et al. (2019). In this filtering technique, the Gaussian filter window behaves as a low-pass filter and therefore chosen to remove high frequency noises. In the spatial domain, the filtered image is the convolution of an unfiltered image and the Gaussian filter. However, in the power spectral domain, we can simply multiply the 2D FFT power spectra of the unfiltered image with the 2D power spectra of Gaussian filter window by positioning it at the peak-power position of the 2D FFT spectra of the image and then perform the inverse 2D FFT. The airglow image contains range of spatial scale sizes instead of monochromatic of gravity waves. Hence choosing the proper window size of Gaussian filter, we can select the desired scale sizes of gravity waves and the filtered images get enhanced with those features. In this process, the central dark spot is automatically removed.

Science issues: Figures 2-5: The wind fields are widely different even within the "ducted" layer. Why? This is contrary to the argument (used later for Figure 7a) that the profile does not show any drastic change within the ducted layer.

Reply: We wanted to convey that the thermal gradient dominates in the m^2 profile whereas the wind shear doesn't play any significant role. We will remove the sentence "The wind profile does not show any drastic change within the duct layer (Figure 7a)." in order to avoid any confusion.

Figure 6: Why is the downward phase progression not seen in the Na airglow intensity? The authors have mentioned 91 km as the emission height of this emission and 85-91 km as the altitude extent of the thermal duct. The intensity variation at this wavelength also seems to be different at larger horizontal distance.

Reply: The upper half of the Na airglow emission is situated above the ducted layer which is the free upward propagating region of waves. However, the bottom half of layer lies in the ducted region (as sketched in Figure 8) wherein the wave is confined to propagate horizontally and not in the upward direction. Therefore, the difference in the vertical phase progression in the Na airglow intensity is caused by the combined effect of wave structure within and beyond the ducted layer as the airglow imager captured vertically integrated Na airglow emission intensity. Whereas, the $O(^1S)$ and O_2 airglow emission layers are beyond the ducted layer and hence clearly shows the downward phase progression.

Yes, we agree with the reviewer that the intensity variation at this wavelength also seems to be different at larger horizontal distances. However, we are unable find out the cause based on the present dataset. We will mention this in the revised manuscript.

I feel that the sub-units of Figure 7 are wrongly described in the text. For example, 7c and 7e (instead of 7d and 7e) show variations in m^2 . Same for Figures 7b and 7c.

Reply: We thank the reviewer for pointing out these typos. We will correct it in the revised manuscript.

Is m^2 negative at 85 km? How important is the negative m^2 ? If it is less but positive (at 85 km), how efficient is the ducting? This is an important issue as the authors propose a leaky duct here. If there is leakage each time the wave is reflected from the edges of the duct, how does the Na intensity variation show similar intensity variation but different phase progression (at least at shorter horizontal distances) in Figure 6? Will the original and reflected waves inside the duct not interfere? How is the spatial coherence maintained? This is also an important issue given the different wind fields at the airglow emission altitudes. The authors need to discuss these issues.

Reply: The m^2 profile at SABER 2 reveals that a duct region exists in the altitude range of 85-91 km where positive m^2 is vertically sandwiched between a negative m^2 value (at 91 km) and a less positive value (at 85 km). The m^2 profile indicates that the existence of a weak evanescent region at 85 km (as m^2 is not negative). Therefore, the duct layer observed in the present case is a "leaky duct" from the bottom side. Hence, some of the energy of the wave could penetrate through the bottom of the duct layer and other part of the energy will be reflected back downward. The penetrated wave got trapped inside the duct layer and could only travel horizontally.

As we have already discussed above that the upper half of the Na airglow emission is situated above the ducted layer which is the free upward propagating region waves. However, the bottom half of layer is lies in the ducted region wherein the wave is trapped and don't any propagate in the upward direction. Therefore, the difference in the vertical phase progression in the Na airglow intensity is caused by the combined effect of wave structure within and beyond the ducted layer as the airglow imager captured vertically integrated Na airglow emission intensity.

The penetrated wave only entered the leaky duct layer from the bottom side. The reflected wave from the edge of the bottom of the duct layer propagated downward below and didn't enter the duct layer. Therefore, there won't be any interference between the original and the reflected waves inside the duct layer.

The winds are analyzed as an average along the propagation path of the wave fronts. The spatial wind retrievals imply a large spatial coherence of about 60 km (the correlation length is set to include the next grid cell) and a temporal correlation of about 30 minutes. Thus, a certain degree of coherence is an essential part of the wind analysis for this case. Furthermore, due to the thermal wind balance, changes in the vertical temperature profile led to corresponding changes of the winds at the different altitudes. The spatial variability of the wind field is also indicated by the bending of the wave fronts found in Figure 2 and 3, whereas the wind fields remain stable at the altitude of the OH emission line presented in Figure 5. However, due to the missing spatial information of temperature observations, it is not possible to understand how this spatial variability affects also the leakage of the duct.

We will discuss this in the revised manuscript.