Response to Referee #2

The authors carefully addressed the comments from the reviewers and made substantial changes to the manuscript. I appreciate that the authors spent time creating the movies. They are very helpful in interpreting the waves. What is the exposure time or temporal resolution? Section 2.1 states that it is 1 minute. However, the movie presented in the supplementary materials shows it is roughly 3 or 4 minutes from the time stamp on the movie. Did some images get skipped? This is important because it is related to the determined wave period of 6 minutes. Please confirm the time resolution.

Response:

Thank you very much for your careful comment.
Yes, you are right. We skipped some images because Lhasa station (29.7°N, 91.0°E) did not have OH airglow observation. We used OI 557 nm airglow observation (3 min time resolution) as a substitute in the video. In order to maintain a consistent rhythm in the animation, the animation time resolution was adopted at 3 min. Nevertheless, we have created a new video with high temporal resolution (1 min time resolution) (http://doi.org/10.5446/67795), please check.

What is the yellow box in Figure 2? Did you choose this area to apply the 2D FFT to get the wavenumber and phase?

Response:

Thank you very much for your careful comment.
Yes, the yellow box areas are used to obtain the wavenumber and phase spectrum using 2D FFT.

(Please check the caption of Figure 2 in revised manuscript with track)

To compare Figure 5(e) one-to-one, it is better to zoom it into the same map area as Figure (a-c).

Response:

Thank you very much for your suggestion.
We have made modifications to Figure 5e, please check.

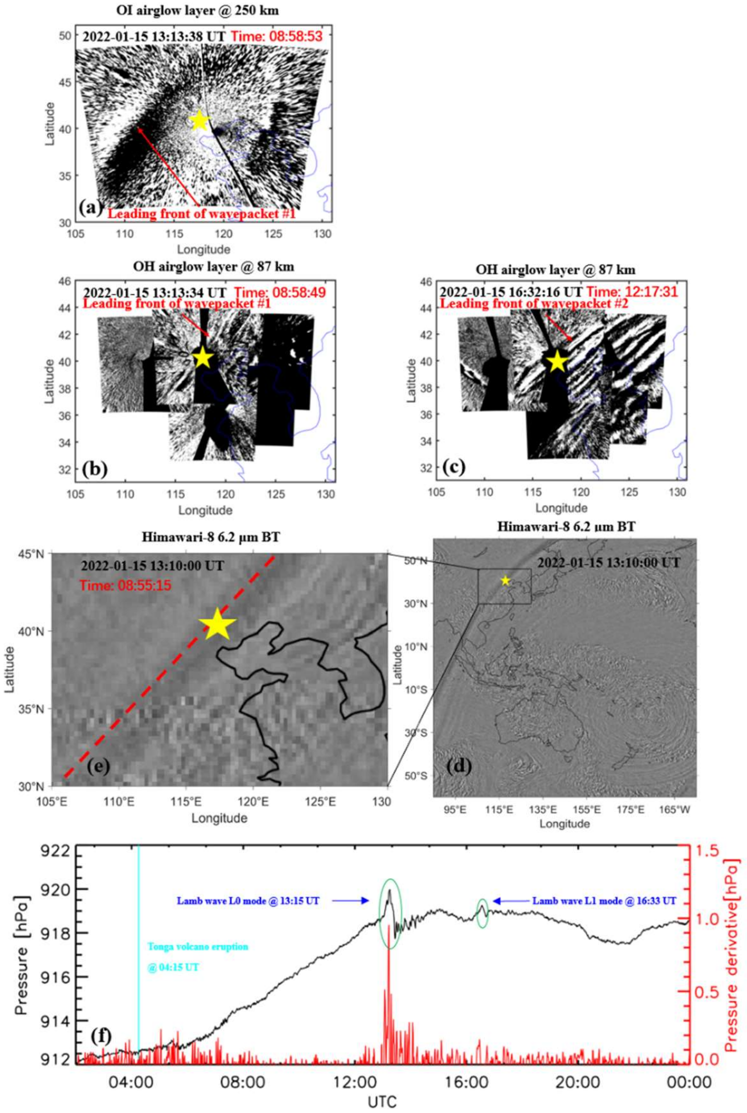

Figure 5

Checking the airglow movies and looking at the coherence and spatial coverage of the wave pattern among continuous images, I am convinced that wave packets 3 to 5 should be related to some larger-scale wave sources toward SE, the oceanic area. If further ray-tracing simulation can prove they are tracked to be related to a tsunami by independent simulation, then it is fair to say those waves are tsunami-generated.

Response:

Thank you for your keen insight and unique perspective, which will be of great help to our research. We carefully checked the wave packet events, as shown in Figure S1 below. The appearance times of wave packets # 3, # 4, and # 5 are independent of each other. The time interval between the appearance of wave packets # 3 is 15:54 UT-16:14 UT, with a shorter duration of only about 20 minutes. And wave packets # 4 appeared in the northern network 4 hours later. And wave packets # 5 appear in the southern and western network. Therefore, the sources of these three groups of waves are also independent and separate. However, as we discussed in the manuscript, large tsunami waves are split into smaller scale tsunamis after passing through some islands along the southeastern coast of China. Therefore, it can also be considered that the sources of these waves come from the small-scale waves decomposed from large-scale waves.

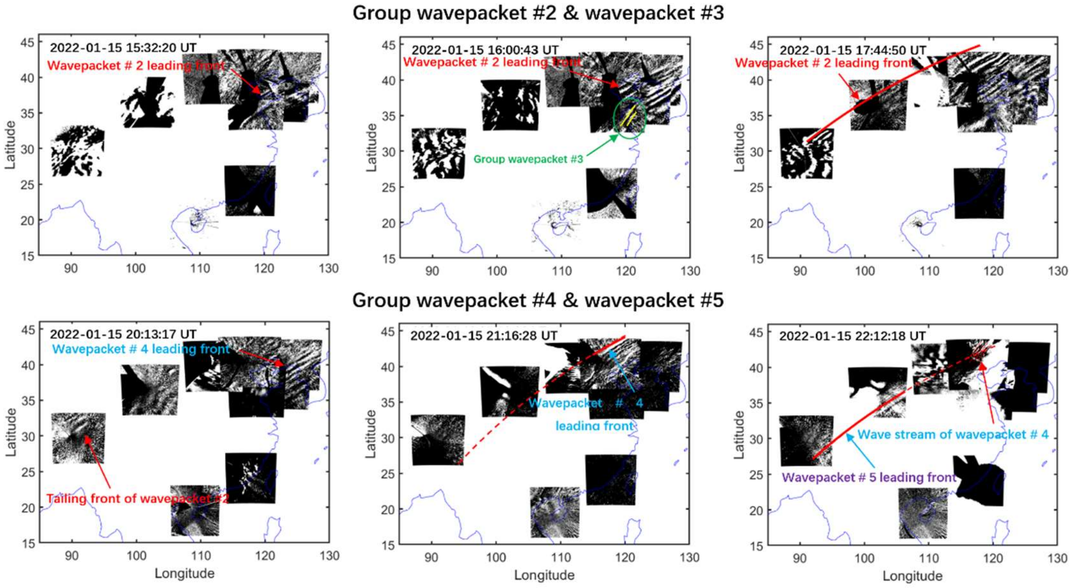

Figure S1

Back to wave packets #1 and #2 about Lamb wave mode L0 and mode L1. It seems this is still an open question about whether Lamb waves can reach the mesosphere and be detected there.

https://acp.copernicus.org/articles/24/4851/2024/acp-24-4851-2024.html
https://angeo.copernicus.org/articles/41/197/2023/angeo-41-197-2023.html

These two papers, from the same author, used Meteor radar data to analyze the wave signature in the MLT region. It seems they could not confirm that the Lamb wave reached the upper atmosphere. The following is a quote from the paper:

Based on our observations, we can almost rule out that the primary lamb wave that was caused by the volcanic eruption reached the upper atmosphere. Thus, the thermospheric/ionospheric observations are likely the result of multistep vertical coupling processes as described in Becker and Vadas (2018), Vadas and Becker (2018), and Vadas et al. (2018). However, the wind measurements indicated several other signals exhibiting a similar morphology, and the lifetimes of other peaks in the winds could not be linked to the lamb wave excited by the Hunga Tonga–Hunga Ha′apai eruption.

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023GL103809

However, this paper supports the L1 Lamb wave signature in the meteor radar, aka mesosphere.

Response:

Thank you very much for providing a new theoretical perspective, which is very meaningful for improving our work.

Yes, you are right, Stober et al. (2018, 2024) found through meteor radar wind field observations that the anomalous peak signal cannot be solely determined to be caused by the Lamb wave generated on the Tonga volcanic eruption. In other words, it is debatable whether the Lamb wave can directly propagate to the upper atmosphere as the only way.

Therefore, reaching the upper atmosphere through secondary waves or high-order of multistep vertical coupling process is also a possible way

As for lamb wave L1 mode, as discussed in the manuscript, the lamb wave L1 mode can be regarded as internal gravity waves.

(Please check lines 263-291; 473-478 in revised manuscript with track)

It is well known that the airglow imaging system is more likely to capture high-frequency waves, especially if you use the time-difference method. The meteor radar would average out those high-frequency waves.

So the key question here: Do we believe the airglow imagers captured higher frequency waves are lamb waves?

Response:

Thank you very much for your comment.

As mentioned above. Our OH airglow observation has a time resolution of 1 minute. Therefore, our airglow observation has the ability to observe high-frequency waves. If high-frequency lamb waves can reach the upper atmosphere, the airglow imagers are able to capture this high-frequency fluctuation.

Of course, we cannot rule out that the high-frequency fluctuations observed by our OH airglow imager instrument are caused by the dissipation of the leading waves or secondary lamb waves generated by the primary lamb waves in the lower atmosphere.

You have estimated the following wave parameters: 300 m/s phase speed, 6-min period, 100 km wavelength.

The 300 m/s wave speed seems to be good in the acoustic range. The 6-minute period is also good and might explain why they are not captured by the meteor radar. My main concern is on the 100-km wavelength. If we carefully check Liu et al. 2023, the WACCM-X simulation indeed presented continuous wave trains above 31 km and a solitary wave pattern below. However, the wavelength does not vary much between solitary waves and wave trains. For wave packet #1 presented in this study, the wavelength estimated from the Himawari-8 satellite brightness temperature should be much larger than 100 km, as well as the OI airglow at about 250 km altitude. What kind of background condition between the stratosphere and mesosphere (30-80 km) would lead to waves of several hundred km wavelengths “breaking” into a much smaller scale?

Response:

Thank you very much for providing a unique perspective. We believe that wave trains may come from two mechanisms, one of which is the energy leakage of the solitary waves. Solitary waves dissipate energy by generating wave trains; Large scale main wave breaking in the stratosphere generates small-scale secondary waves that propagated to the upper atmosphere.

We observed wave trains following the leading wave front with a horizontal wavelength of ~ 120 km from Himawari-8 satellite brightness temperature observation (the area pointed by the yellow arrows in Figure S2). We also observed waves with a horizontal wavelength of ~ 400 km from Himawari-8 satellite brightness temperature observation (the area pointed by the red arrows in Figure S2).

Besides, as you mentioned, the wave features are mostly captured by stations near 40N and 120E. So, it is difficult to capture large-scale waves like satellite observations (much larger than 100 km).

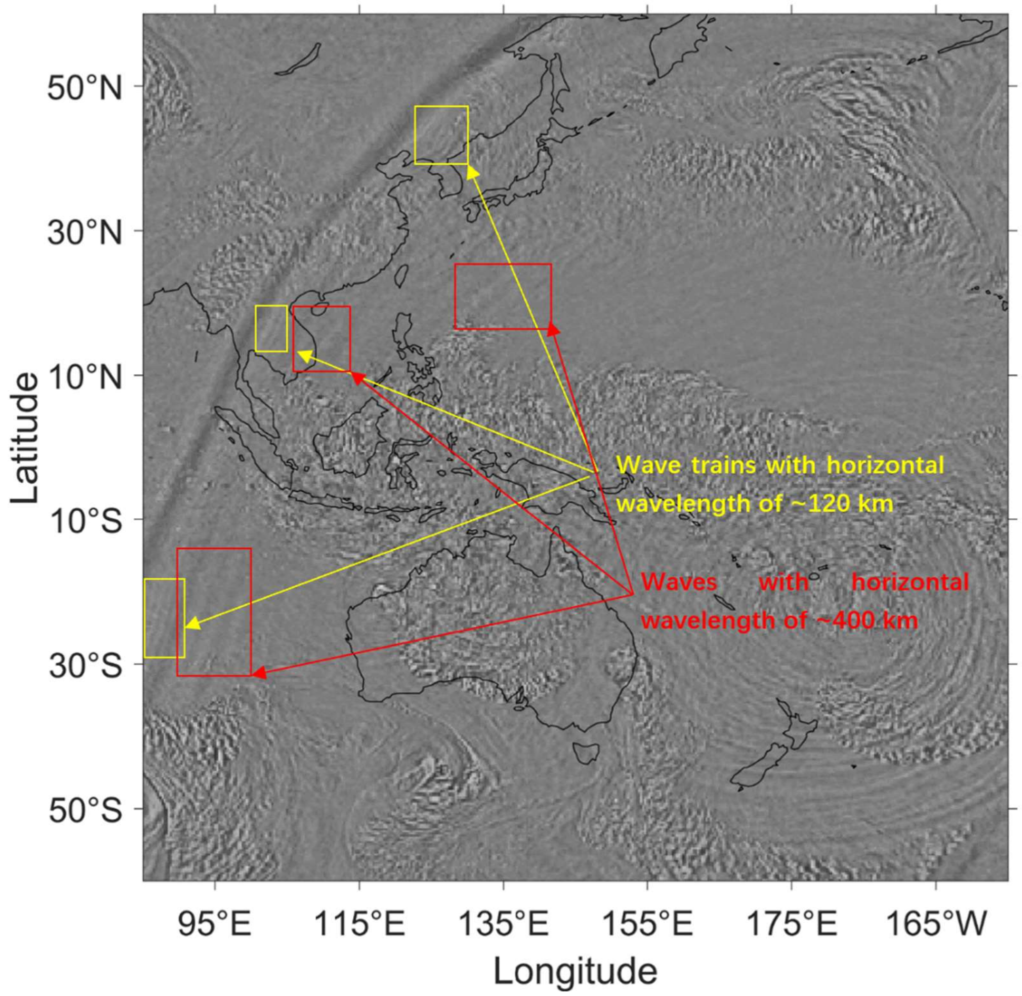

Figure S2

From Figure 10, the winds between 40-80 km are mostly eastward and southward, so the Lamb waves propagate against the background winds. Could the wind explain something about the wavelength?

Response:

Thank you very much for your careful comment.

According to the theory of wind field filtering for atmospheric waves, waves propagating downstream may experience wind field filtering effects and dissipate into the background atmosphere, while atmospheric waves propagating upstream are easier to propagate, with increased vertical wavelengths and easier to be observed by airglow imager instruments, and have a smaller impact on horizontal wavelengths.

Wave #2 (Lamb L1) comes together with the gravity waves; it looks very much like gravity waves, except for the slight phase front orientation differences.

Response:

Thank you very much for your careful comment.

As discussed in the manuscript, the lamb wave L1 mode can be regarded as internal gravity waves.

(Please check lines 275-277, 473-478 in revised manuscript with track)

Also, it is disappointing that the wave #1 and #2 features are mostly captured by stations near 40N and 120E, making them appear like localized features. The wave signatures are very vague in the two coastal stations, so it is hard to tell the actual scale of the waves.

Response:

Yes, optical observations are easily affected by weather conditions. Nevertheless, clear waves (Figure S3) can still be seen in the observation gaps of observation stations with poor weather conditions.

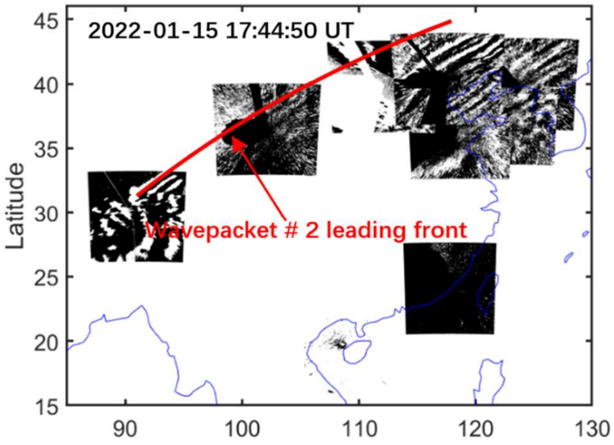

Figure S3

In summary, I am still unconvinced that waves #1/#2 are Lamb waves, but I could not provide clear arguments for why they are not. If this paper were purely about gravity waves #3-#5, it would be solid and comprehensive. I do not want to stop the manuscript from being published, but I would recommend the authors down-tune the conclusive remarks about wave #1/#2 since they are still debatable.

Response:

Thank you very much for your comments and suggestions. It is of great significance to comprehensively improve this manuscript. Your meticulous research spirit will also be of great benefit to our future research. The question of whether lambs can propagate directly to the upper atmosphere is an open question and cannot provide a unique conclusion. We have conducted in-depth and extensive discussions on possible propagation mechanisms to make the manuscript more comprehensive and error free.

(Please check lines 263-291; 473-478 in revised manuscript with track)

The following references has been added to the manuscript.

Stober, G., Vadas, S. L., Becker, E., Liu, A., Kozlovsky, A., Janches, D., Qiao, Z., Krochin, W., Shi, G., Yi, W., Zeng, J., Brown, P., Vida, D., Hindley, N., Jacobi, C., Murphy, D., Buriti, R., Andrioli, V., Batista, P., Marino, J., Palo, S., Thorsen, D., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Baumgarten, K., Kero, J., Belova, E., Mitchell, N., Moffat-Griffin, T., and Li, N.: Gravity waves generated by the Hunga Tonga–Hunga Ha′apai volcanic eruption and their global propagation in the mesosphere/lower thermosphere observed by meteor radars and modeled with the High-Altitude general Mechanistic Circulation Model, Atmos. Chem. Phys., 24, 4851–4873, https://doi.org/10.5194/acp-24-4851-2024, 2024.

Stober, G., Liu, A., Kozlovsky, A., Qiao, Z., Krochin, W., Shi, G., Kero, J., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Baumgarten, K., Belova, E., and Mitchell, N.: Identifying gravity waves launched by the Hunga Tonga–Hunga Ha′apai volcanic eruption in mesosphere/lower-thermosphere winds derived from CONDOR and the Nordic Meteor Radar Cluster, Ann. Geophys., 41, 197–208, https://doi.org/10.5194/angeo-41-197-2023, 2023.

Vadas, S. L., Becker, E., Figueiredo, C., Bossert, K., Harding, B. J., and Gasque, L. C.: Primary and secondary gravity waves and large-scale wind changes generated by the Tonga volcanic eruption on 15 January 2022: Modeling and comparison with ICON-MIGHTI winds, Journal of Geophysical Research: Space Physics, 128, https://doi. org/10.1029/2022JA031138, 2023.

Vadas, S. L., and Becker, E.: Numerical modeling of the excitation, propagation, and dissipation of primary and secondary gravity waves during wintertime at McMurdo Station in the Antarctic, Journal of Geophysical Research: Atmospheres, 123, 9326–9369. https://doi.org/10.1029/2017JD027974, 2018.

Vadas, S. L., Zhao, J., Chu, X., and Becker, E.: The excitation of secondary gravity waves from local body forces: Theory and observation, Journal of Geophysical Research: Atmospheres, 123, 9296–9325, https://doi.org/10.1029/ 2017 JD027970, 2018.

Becker, E., and Vadas, S. L.: Secondary gravity waves in the winter mesosphere: Results from a high-resolution global circulation model, Journal of Geophysical Reseach: Atmospheres, 123, 2605–2627, https://doi.org/ 10.1002/2017JD027460, 2018.