1 Response to Referee No.1

We sincerely thank the reviewer for devoting time and effort into reading the manuscript and suggesting ways in which it could be improved. The reviewer comments are listed below in italic and the changes added to the manuscript corresponding to each are given in blue, while red indicated parts that have been removed.

1.1 Overall comment

The manuscript describes an interesting methodology to derive GW perturbations by using a scale-separation Python-based toolbox. The methods and assumptions are mostly clearly outlined with some missing details. I recommend publication after addressing the following comments.

1.2 Specific comments

1. *In Section 4.2 (Figure 4) and Appendix: In describing the comparisons between the temperature background estimated by GLOFI and actual temperature perturbations – "almost identical", virtually identical" and the model spectrum is "very well" reproduced, "stronger deviations" is not quantitative. Please provide for e.g. differences and/or standard deviation etc.*

   The following modifications have been made to the paragraph to quantify the comparisons (Moreover, a new section was added to the appendix to furthur explain PW spectra differences:):

   Overall, the model spectrum is very well reproduced in terms of dominating wave modes and their amplitudes: the 99th percentile of absolute amplitude deviation is smaller than 0.3 K globally. There are, however, also some more spread out deviations between the reference and the satellite observations. ... Nevertheless, the amplitudes of the spurious wave modes are comparatively low at below 0.1 K and, therefore, do not lead to problems in the scale separation. Higher absolute deviations from the reference are found for wave modes with higher amplitudes, especially for the mean, i.e., ZWN 0, f=0.0 / day, where absolute deviations of up to 5 K are found. In general, however, the relative deviation to the reference amplitudes is below 2% for components with amplitudes higher than 1 K.

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   Appendix D: PW fitting deviations

   Figure D1 shows the deviations of the fitted PW amplitudes and phases in Fig. 5a, b, d, and e to the reference directly estimated from the model grid shown in Fig. 5c and f. In general, the deviations are very minimal even where the PW amplitude is very strong in the northern upper stratosphere. The phases are well recovered as well wherever the amplitude is high enough to give enough signal for the fitting (here around 0.3 K seems to be sufficient for the algorithm).

   The application of the Savitzky-Golay smoothing filter (11° in latitude, 5 km in altitude) leads to smoothed deviations overall. However, it also deteriorates the performance of the algorithm around the tropopause. This can mostly be attributed to the vertical smoothing. Therefore, if your main interest is the upper troposphere/lower stratosphere, the Savitzky-Golay filter should limit to the meridional direction.

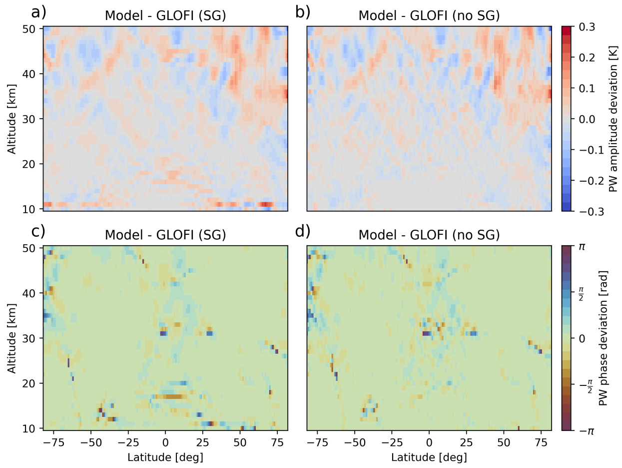

Figure D1: Difference in PW amplitude (upper row) and PW phase (lower row) between the reference estimated from the model and the GLOFI algorithm. Left and right columns show the corresponding deviations with and without the Savitzky-Golay filter applied.

2. Section 2:

   (a) *It might be useful to the reader to summarize the spatial technique in Strube et al (2020).*

   A short explanation of the aforementioned technique was added below it:

   This is done by performing zonal FFT at each altitude and latitude of individual snapshots in time to get the spectra. Each spectrum is smoothed using a third order Savitzky–Golay filter in latitude (width 7.5°) and afterwards inverted to obtain the large-scale background of the temperature field. Subtracting this background from the reanalysis data temperature field gives us the GW perturbations.

   (b) *The text and figures in Figure 2 are too small. Please make this more readable.*

   A modified version (shown below) of the figure was added to the manuscript:

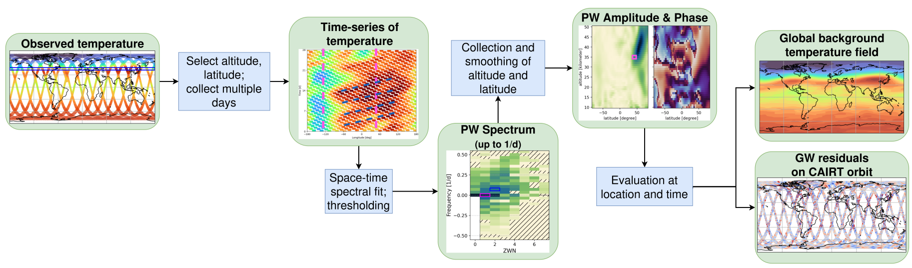

Figure 2: Illustrated flowchart of the global wave fit algorithm.

   (c) *Please clarify if 'GW residuals', 'GW perturbations', 'residual GW perturbations' (Sec 3) all mean the same thing*

   The terms are clarified in the modified sentence in the 'Algorithm description' section:

   The product of the methodology is a physically meaningful large-scale background that can be subtracted from the measurements to obtain temperature residuals that can be attributed almost entirely to perturbations due to GWs, i.e., 'GW perturbations' or 'GW residuals', which can then be used for further analysis.

3. *There are 3 Appendices that are not referenced anywhere in the main text (except for the mention of Figure C1)*

A few paragraphs were added which point to the appendices not referenced in the manuscript (i.e., all except B):

App. A presents some of the methods used in previous studies to extract these global wave modes which, along with the mean atmospheric state and seasonal trends, constitute the 'background'.

Another, more technically detailed flowchart is shown in Fig.C1 in App. C.

The deviations of the GLOFI processing to the model reference is further detailed in App. D.

4. *Section 4.4/Figure 8. No discussion/summary of the differences is provided.*

   The following was added to better explain the differences:

   A comparison of these GW perturbations to the satellite-sampled GW perturbations of the model allows the estimation of the algorithm performance for realistic observations as shown in Fig 8. Fig 8 shows an example of such a comparison. The differences between the sampled reference (Fig. 8a) and GLOFI-recovered GW perturbations (Fig. 8b) is shown in Fig. 8c. The differences have a zero mean with a standard deviation of 0.02 K. The regions of higher deviations, where differences go to a maximum of 0.29 K, coincide with latitudes at which the GLOFI estimated background deviate strongest from the reference, as shown in Fig. 6c. As discussed, these show up due to to aliasing from higher frequency planetary modes.

5. *Line 25: '... hard to resolve in atmospheric models" – please clarify that GWs can indeed be resolved in high-resolution models (e.g. Becket et al., 2022) Becker, E., Vadas, S. L., Bossert, K., Harvey, V. L., Zülicke, C., & Hoffmann, L. (2022). A High-resolution whole-atmosphere model with resolved gravity waves and specified large-scale dynamics in the troposphere and stratosphere. Journal of Geophysical Research: Atmospheres, 127, e2021JD035018. https://doi.org/10.1029/2021JD035018*

   That sentence was corrected to:

   Their short horizontal and vertical scales, however, make them hard to resolve in atmospheric models, although not impossible for specific high resolution model setups (e.g., Becker et al., 2022).

6. *Line 155: Please provide reference for the Savitzky-Golay (SG) filter*

   The filter was cited in the 'Data' section:

   Each spectrum is smoothed using a third order Savitzky–Golay filter (Savitzky and Golay, 1964)

1.3 Typos etc.

1. *Provide abbreviations appropriately:*

   (a) *Line 67: what does DW1 stand for?*

   It stands for Diurnal Westward-propagating zonal wavenumber 1 tide. This was added next to the abbreviation DW1 as follows:

   The effect is most striking for the DW1 (Diurnal Westward-propagating zonal wavenumber 1 tide)

   (b) *Line 88: what does PW stand for (Planetary Waves is mentioned several times previously)*

   PW does stand for Planetary Waves in this study. The abbreviation was added during its first occurrence in introduction:

Some of the global wave modes, the quasi-stationary planetary waves (PWs),

2. *Line 84: "This gives. . . ." – correct to, for e.g. This 'manuscript/paper/study' gives . . . .*
   Clarified the sentence by changing it to:

   This study gives a detailed algorithmic description...

3. *Line 204: Typo in 40°W*

   The typo was fixed and the line was modified to:

   ...this is visible around 40°∘W,..

2 Response to Referee No.2

We sincerely thank the reviewer for devoting time and effort into reading the manuscript and suggesting ways in which it could be improved. The reviewer comments are listed below in italic and our responses corresponding to each are given in blue.

2.1 Overall comment

This paper tackles an important issue: how to efficiently and accurately recover temperature fluctuations due to gravity waves that are masked by large scale planetary and tidal wave values in satellite data. It is particularly important to understand the strengths/limitations of new satellite instruments. The methodology/algorithm for using 2D spectral decomposition to remove the large-scale components due to planetary waves and tides is well described and tested using simulated data. The recovery of gravity wave fluctuations is convincing. However, like any technique there will be instrumental limitations that constraint the range of gravity wave scales that can be observed, as summarized in Appendix A for a range of techniques. It would help the reader to understand these limitations if there was a diagram similar to Fig 8 in Alexander et al QJRMS 136: 1103–1124 (2010) that describes observational constraints. More information is required on what GW scales can be recovered with these proposed new satellite measurements.

Since the background removal method sets a limit only on the wavenumber and frequency of the large-scale waves that can be removed, the GW spectra that can be recovered mostly depends on the instrument design. So the aforementioned diagram is applicable here as well, without much changes. In the case of CAIRT, with its planned 1 km vertical, 50 km along-track, and 25 km across-track resolution, Rhode et al. (2024) resolved GWs with horizontal wavelengths above 100 km and vertical wavelengths above 2.8 km. To address these points, the following sentences have been added to Appendix B:

It should also be noted that the GW visibility limits depend on the instrument design as well. An overview of the general regions of the GW spectra that is observed by different measurement techniques is given in Fig. 8 of Alexander et al. (2010) and Fig. 9 of Preusse et al. (2008). For the observable spectrum of the CAIRT instrument used in this study, refer to Rhode et al. (2024).

2.2 Specific comments

There are some minor issues:

1. *Appendix A is not mentioned in the body of the text. Probably should be referenced in about line 31.*

   A paragraph was added to the 'Introduction' section of the manuscript to point to Appendix A which was not referenced in the main body:

App. A presents some of the methods used in previous studies to extract these global wave modes which, along with the mean atmospheric state and seasonal trends, constitute the 'background'.

2. *L 69: What does it mean that a tide is a 'true resonant mode and propagating wave'?*

   The sentence was meant to convey that tides are forced by solar heating and have specific frequencies. For better clarity, it was rephrased to:

   Note that the tide is a true propagating wave mode driven by the sun that has a specific zonal wavenumber and frequency. Accordingly, at different altitudes, latitudes, or local times...

3. *L230 'date' not 'data'*

   The typo was fixed and the line was modified to:

   ...at the central date...

References

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