1 Response Referee No. 2

We thank the reviewer for the positive review of our article. The comments and suggestions were very helpful in improving the presentation of our work and refining the science.

The responses to specific comments are given below. The original reviewer comments are given in italic and any text given in blue has been added to the manuscript in response to the comment.

1.1 Overall comment

This paper constitutes a proof of concept for the ESA Earth Explorer 11 candidate CAIRT in terms of ability to provide valuable global information on gravity wave characteristics, including dissipation, throughout the middle atmosphere. Two high resolutions models are sampled to generate synthetical observations, mimicking the observational design of an the instrument on board (an limb imaging Michelson interferometer). The results show the great potential of the instrument.

The manuscript is clearly written, I only have a few minor comments, as listed below.

1.2 Specific comments

1. *- Line 23-25. Although there exists a wave-induced flux of momentum, strictly speaking waves in fluids do not have momentum (McIntyre 1981). So (gravity) waves do not gain or release momentum. Perhaps it would be more precise to say that gravity waves transport (or redistribute?) momentum/energy within different layers of the atmosphere.*

   McIntyre ME. On the 'wave momentum' myth. Journal of Fluid Mechanics. 1981;106:331-347. doi:10.1017/S0022112081001626 .

   Agree, this was misleading. The sentence was changed to:

   From their excitation processes like flow over orography, convection, jet instabilities, and other effects [Fritts and Alexander, 2003], they carry momentum to higher layers of the atmosphere by wave propagation.

2. *- Lines 29-30. Radiative cooling is a very important driver of the vortex recovery after SSWs. Are GWs really the main driving force?*

   Indeed this is not true as it was written and thus the sentence has been changed accordingly. GWs contribute to the recovery of the stratospheric vortex and the downward propagation of the elevated stratopause. The updated text reads:

   "They are likely a major driving force in the recovery phase of the stratospheric vortex and the downward propagation of an elevated stratopause [Ern et al., 2016, Thurairajah and Cullens, 2022, Harvey et al., 2022, 2023]."

3. *- Line 45. This sentence is not well written, needs to be rephrased.*

   The sentence has been rephrased to:

   "Satellite missions are best suited for the long-term observation of large-scale momentum transport needed for understanding global-scale processes."

4. *- Lines 60-65. To my knowledge, the first successful implementation of a GW drag parameterization in a climate model (actually a NWP model) was reported by Palmer et al. (1986), not by Lindzen (1981). Lindzen's study was indeed one of the first to show that a parametrization based on linear saturation theory (convective instability) of a monochromatic wave could provide a dynamical forcing in the mesosphere able to explain the warm mesopause in winter and the cold in summer, but no GCM was used.*

   Palmer, T.N., Shutts, G.J. and Swinbank, R. (1986), Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parametrization. Q.J.R. Meteorol. Soc., 112: 1001-1039. https://doi.org/10.1002/qj.49711247406

   Yes, you are absolutely correct. The sentence was rephrased to:

   "However, the general idea of GWs accelerating large-scale winds, developed by Lindzen [1981] and first implemented in a GCM by Palmer et al. [1986], has proven to be essential for global wind-systems also in other parts of the atmosphere."

5. *- Line 187. At what altitude does the sponge layer start?*

   The sponge layer starts above 0.78 hPa. This information is included in the revised text:

"The simulations have 137 vertical levels including a sponge layer of reduced strength compared to the standard IFS setup in order to limit the damping of GWs in the upper levels. The sponge layer starts above 0.78 hPa (about 50 km)."

6. *- Lines 360, 363. Vertical gradient of the GWMF → vertical derivative (or divergence of the momentum vertical flux).*

   Changed as suggested.

7. *- Line 368. They should cancel out also in the time mean, which may be more relevant if the process we are dealing with is wave propagation imprint on the EP flux divergence.*

   Indeed, uniformly distributed fluctuations would also cancel out in the time mean, while consistently unidirectional propagation would become visible. Since CAIRT has a long revisit time (compared to model time resolution), a time mean would only be possible for persistent GW activity in the monthly mean. This is of course something that would be very interesting to look at.

   By taking the zonal mean, we try to keep the observation period short, i.e., daily, while getting rid of propagation fluctuations in the zonal direction. Of course, consistent meridional GW propagation could still lead to spurious drag as discussed in the text.

   Surely they also cancel out in a time mean, however, we can not perform such an time averaging with CAIRT - only possible for longer term propagation studies, e.g., on a monthly mean basis.

8. *- Line 371. What is the meaning of "potential drag"?*

   The sentence has been extended for a clarification:

   "Regions where GWs propagate into are characterized by negative "potential drag" derived from absolute values of GWMF [Ern et al., 2011], i.e., GWMF increasing with altitude in a strict columnar consideration - something which should not occur according to classical theory."

9. *- Line 576-577. It would seem that those numbers have been calculated using the mid-frequency approximation of the wave dispersion relation. Please specify.*

   This has been changed for clarification and now reads as follows:

   "In mid-frequency approximation and in the stratosphere, where $N \approx 0.02\,\mathrm{s}^{-1}$, 3 km vertical wavelength corresponds to about $10\,\mathrm{ms}^{-1}$ (intrinsic) phase speed."

10. *- Line 695. Many scientific articles that present results on observations of gravity waves, both from a global perspective or based on case studies, use the argument that GW parameterizations are poorly constrained by observations, and hence the need for those kind of studies. The argument is valid, but it is not straightforward how to use the information provided by observations to improve the calibration of the parameterizations. Perhaps the main reason for this is that the tunable parameters have to do with GW characteristics (e.g. momentum flux, phase speed spectrum, etc.) at the source level. But the propagation and dissipation of the waves are not easily tunable.*

    One of the strengths of CAIRT in this respect is to be able to provide information on the dissipation of waves (phase speeds, drag, range of altitudes, etc.). This would be extremely valuable to assess the output of current parameterizations, study and refine their performance, and evaluate whether their level of complexity (WKB solutions, columnar approach, etc.) is good enough to emulate the observations.

    Thank you for this comment and I think you might be right that typical parametrizatons follow sort of a "fire and forget" approach where most of the tuning happens by modulating the source spectra. And indeed CAIRT could provide further insights into the dissipation or even the importance of non-linear processes.

    A note on this has been added in the conclusions:

    "... Further, GW parametrizations will be in future use for long-term runs and require tuning to observations. And since CAIRT observes a wide range of altitudes, the GW dissipation and propagation are observed and could be used for more advanced parametrizations of these processes. The validity of the existing parametrizations could be investigated giving an estimation of the importance of non-linear effects. ..."

References

M. Ern, P. Preusse, J. C. Gille, C. L. Hepplewhite, M. G. Mlynczak, J. M. Russell III, and M. Riese. Implications for atmospheric dynamics derived from global observations of gravity wave momentum flux in stratosphere and mesosphere. *J. Geophys. Res.*, 116, 2011. doi: 10.1029/2011JD015821.

M. Ern, Q. T. Trinh, M. Kaufmann, I. Krisch, P. Preusse, J. Ungermann, Y. Zhu, J. C. Gille, M. G. Mlynczak, J. M. Russell, III, M. J. Schwartz, and M. Riese. Satellite observations of middle atmosphere gravity wave absolute momentum flux and of its vertical gradient during recent stratospheric warmings. *Atmos. Chem. Phys.*, 16(15):9983–10019, AUG 9 2016. ISSN 1680-7316. doi: 10.5194/acp-16-9983-2016.

D. Fritts and M. Alexander. Gravity wave dynamics and effects in the middle atmosphere. *Rev. Geophys.*, 41 (1), APR 16 2003. ISSN 8755-1209. doi: 10.1029/2001RG000106.

V. L. Harvey, N. Pedatella, E. Becker, and C. Randall. Evaluation of polar winter mesopause wind in WACCMX+DART. *J. Geophys. Res. Atmos.*, 127(15):e2022JD037063, 2022. doi: 10.1029/2022JD037063. URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JD037063`.

V. L. Harvey, C. E. Randall, L. P. Goncharenko, E. Becker, J. M. Forbes, J. Carstens, S. Xu, J. A. France, S. r. Zhang, and S. M. Bailey. CIPS observations of gravity wave activity at the edge of the polar vortices and coupling to the ionosphere. *J. Geophys. Res. Atmos.*, 128(12), JUN 27 2023. ISSN 2169-897X. doi: 10.1029/2023JD038827.

R. S. Lindzen. Turbulence and stress due to gravity wave and tidal breakdown. *J. Geophys. Res.*, 86:9707–9714, 1981.

T. N. Palmer, G. J. Shutts, and R. Swinbank. Alleviation of a systematic weterly bias in general circulation and numerical weather prediction models trough an orographic gravity wave drag parameterization. *Quart. J. Roy. Meteorol. Soc.*, 112:1001–1093, 1986.

B. Thurairajah and C. Y. Cullens. On the downward progression of stratospheric temperature anomalies using long-term SABER observations. *J. Geophys. Res. Atmos.*, 127(11), JUN 16 2022. ISSN 2169-897X. doi: 10.1029/2022JD036487.