Review of thesis

submitted at Faculty of Mathematics and Physics, Charles University

❑ Review by supervisor ☒ Review by opponent

❑ Bachelor thesis ☒ Master thesis

Author: Dominika Hájková
Thesis title: Towards improved orographic gravity wave parameterization in chemistry-climate models
Study program: Atmospheric Physics, Meteorology and Climatology
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Name of the supervisor/opponent: Andreas Dörnbrack
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Scientific level of the thesis:
❑ excellent ❑ very good ☒ average ❑ below average ❑ insufficient

Factual errors:
☒ almost none ❑ acceptable number ❑ numerous but non-critical ❑ serious

Results:
❑ original ☒ original & adopted ❑ nontrivial compilation ❑ cited ❑ plagiarized

Extent of the thesis:
❑ large ☒ standard ❑ sufficient ❑ insufficient

Graphical, language & formal level of the thesis:
❑ excellent ❑ very good ☒ average ❑ below average ❑ insufficient

Print errors:
☒ almost none ❑ acceptable number ❑ numerous

Overall level of the thesis:
❑ excellent ❑ very good ☒average ❑ below average ❑ insufficient

Evaluation and comments by supervisor/opponent:

The overarching topic of this thesis is the interaction of orographic gravity waves with the large-scale atmospheric flow, a topic usually classified as wave-mean flow interaction. After a rather short Introduction, the equations of linear orographic gravity waves in a Boussinesq fluid without rotation are derived and discussed. The second chapter “GWs in models” deals primarily with the effect unresolved gravity waves have in general circulation models (GCMs) with coarse spatial resolutions, i.e. essentially climate models or chemistry-climate models as used for the Coupled Model Intercomparison Project (CMIP). This chapter presents the first own results of the master thesis, which were published recently by Hájková and Šácha (2024). The third chapter deals with 2D numerical simulations over idealized hills. After assessing the quality of the numerical results based on the published results from a model intercomparison, the third chapter focusses on the off-line computation of the parameterized wave drag. This part of the thesis offers detailed insight into the various “tuning” parameters often changed to minimize biases in GCMs. A short Conclusion finalizes the thesis. In addition, a bibliography, list of figures, tables and abbreviations as well as four appendices with further results from the second and third chapter of results are included.

Overall, the thesis is written in an easy-to-comprehend language and the results are presented in a rather personal, descriptive, often only qualitative style. The Introduction is contented with providing essential keywords to familiarize the reader with the topic and the context of the work. A more substantial reference to existing, published knowledge (e.g., the overview paper by Teixeira, 2014: https://www.frontiersin.org/articles/10.3389/fphy.2014.00043) would be desirable here. However, no literature references are given. The first chapter is essentially providing the known foundations of linear wave theory for a 2D Boussinesq fluid without rotation. This chapter is fine apart from a few glitches (e.g., minus missing in Eq. 1.15 and 1.44; the formulation after Eq. 1.44 is misleading as the right-hand side is the divergence of the vertical flux of horizontal momentum not the momentum flux itself). After reading the whole thesis, I asked myself why the author have not introduced orographic gravity waves for rotating as well as for non-Boussinesq flows as well. This would make the transition to the second and third chapter easier, more consistent and coherent.

The second chapter jumps directly into the representation of gravity waves in GCMs and uses the output of CMIP6 models to correlate the orographic gravity wave drag with the divergence of the Eliassen-Palm flux and the refractive index RI. These results are original and were recently published. The result section 2.2.2, however, is sometimes hard to follow as references to the figures discussed are missing (e.g., to Fig. 2.3b, to Fig. 2.6) and the discussion is rather descriptive. The (I guess dimensionless) refractive index RI is not defined, I suppose also that Eq. 2.14 is not correct (1/a missing in first term, ¼ missing in last term). Furthermore, a reference to the recent paper by Weinberger et al. (2011) and a solid discussion of the refractive index would be desirable. I fully agree with the author that a mere correlation of the above-mentioned variables does not indicate causality. So, more work is needed here. In addition, sentences like this: “All effects described in this section are possibly strongly artificial — found only in models and do not necessary reflect real processes in the atmosphere.“ are irritating and require discussion. Useful further references on the subject of wave-mean flow interaction might be the both papers by Gupta et al. (2021, 2024).

The chapter 3.1 continues Chapter 1 by deriving linear solutions for the uniform and stratified flow across two idealized mountains. Here, the Boussinesq approximation must be skipped to allow for an exponentially decreasing density. This part could have been shifted to Chapter 1 in order to provide a coherent ordering of the content. A coherent description of the setup for the numerical simulations (domain size, time step, grid increments, boundary conditions, parametrizations of internal friction, etc.) is also missing in chapter 3.1. At some points later, some information is provided but for the reader it is sometimes hard to find them and a systematic description would be desirable. Section 3.2 qualitatively compares the numerical simulation results with the derived analytic solution and another linear wave model called ICAR. The presentation of the results went further on by comparing (again qualitatively) the nonlinear results with simulations from the model intercomparison published by Doyle et al. (2011). My strongest criticism of the thesis relates to the simulation time of 24 hours. In my humble experience, 2D numerical simulations should be terminated when the flow becomes strongly nonlinear and 3D processes dominate the dynamics due to localized wave breaking. Furthermore, the use of only open boundary conditions could be easily modified by using an additional sponge at the inflow and, especially, outflow side to prevent reflection of waves or vorticities. Therefore, the results averaged over the whole domain and the entire simulation time may change when only averaged over a limited domain centered at the mountain peak location and over a time period when nonlinearities are still weak.

The modified analysis for a limited domain and time would also impact the comparison with the off-line parametrizations presented in Section 3.3. Remember that the presented parameterizations are derived for small amplitudes of the perturbation quantities, i.e. for flow regimes without overturning waves. Maybe, you should compare the amount of momentum that is deposited to the mean flow just after the breaking event. All other dynamics that goes on afterwards is strongly 3D and cannot be captured by 2D numerical simulations. Nevertheless, I was impressed by the detailed analysis of the impact of the different tuning parameters. This part of the thesis has a good potential to become an original contribution to the existing literature. However, I recommend closely observing what other colleagues are doing in this regard, e.g. Kwon and Park (2024).

In summary, I appreciate Dominika's efforts to familiarize herself with the complicated topic of gravity waves in the atmosphere. Through her detailed analysis of the CMIP6 model outputs and the orographic gravity wave drag parameterizations, she will be able to continue her work at a high scientific level.

References

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Gupta, A., Birner, T., Dörnbrack, A., & Polichtchouk, I. (2021). Importance of gravity wave forcing for springtime southern polar vortex breakdown as revealed by ERA5. Geophysical Research Letters, 48, e2021GL092762. https://doi.org/10.1029/2021GL092762

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Weinberger, I., C. I. Garfinkel, I. P. White, and T. Birner, 2021: The Efficiency of Upward Wave Propagation near the Tropopause: Importance of the Form of the Refractive Index. *J. Atmos. Sci.*, **78**, 2605–2617, https://doi.org/10.1175/JAS-D-20-0267.1.

Eventual questions and topics for discussion:

See report above.

I do
☒ recommend
❑ not recommend
to accept the thesis as bachelor/master one.

Suggested classification:
❑ excellent ❑ very good ☒ good ❑ insufficient

Place, date & signature:

Oberpfaffenhofen, 31 May 2024

Andreas Dörnbrack