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Report on the doctoral thesis submitted by RNDr. Petr Šácha

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Dear Prof. Dr. Kratochvíl,

Gravity waves are a long- and well-studied feature in Geophysical Fluid Dynamics. Internal gravity waves (IGWs) occur naturally in the Earth's atmosphere and are of immanent importance for the large-scale circulation and climate variability. These waves propagate both horizontally and vertically, occur at relatively fast temporal and small spatial scales and manifest the various ways in which waves interact with the mean state. One crucial aspect is their role in the upward transport of angular momentum thereby significantly influencing the dynamic structure of the atmosphere. The particular importance of gravity waves for middle atmosphere dynamics is recognized since the mid of the last century and active research during recent decades has fostered our understanding of the importance of IGWs. A significant influence of IGWs has been documented on e.g., the formation of the Quasi-Biennial Oscillation, the acceleration of the Brewer-Dobson Circulation and transport in the middle atmosphere. A detailed process-level understanding of IGW-related processes is needed to properly model middle and upper atmospheric dynamics. Given their horizontal scales IGWs cannot be resolved in current generation circulation and climate models and thus have to be parameterized. The advent of new, highly resolved, observational data sets along with increasing computational capabilities (allowing for higher resolved model runs) aide the improvement of these parametrizations. Given the importance of stratospheric chemistry and dynamics for the troposphere and surface climate an improved representation of stratospheric dynamics could significantly improve our long- and short-range forecast skills. Having stressed why the study area of the thesis is of immanent importance in atmospheric and climate research I am turning to the thesis review.

Petr Šácha has delivered a comprehensive doctoral thesis titled '*New Perspective on the Role of Gravity Waves in the Stratospheric Dynamics and Variability*'. The thesis is clearly written, well-structured and thoroughly organized. In the introduction the candidate highlights the importance for IGWs in atmospheric and climate research and motivates clearly the importance of the presented thesis research.

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In the first chapter the candidate presents a comprehensive review of middle atmospheric flow, wave theory and wave-mean flow interactions. The physical principles and fundamental equations are clearly described. Chapter 1 provides a comprehensive review that covers all central aspects of wave-mean flow interaction. Petr Šácha focuses the second chapter of his thesis on the observation of gravity waves. While traditional observations including soundings and lidar or radar measurements are available for several decades, the last two decades brought the advent of a sophisticated remote sensing technique, GPS radio occultation (GPS-RO). Atmospheric waves have been studied utilizing GPS-RO data since the early 2000s. IGWs have been commonly retrieved from temperature profiles, which involves problems in clearly separating the tropospheric and stratospheric parts of the profile. The candidate introduces a novel concept for the analysis of IGWs in GPS-RO data using density profiles. As atmospheric density is a first-order quantity in RO data it is not affected by additional retrieval assumptions. Furthermore atmospheric density with height can be inferred directly via statistical physics. Petr Šácha describes in detail the methodological approach to obtain density perturbation profiles, including the separation of background density profiles. He demonstrates the application of the novel method for data from the Constellation of Observing Systems for Meteorology, Ionosphere and Climate (COSMIC). The advantage of the use of density profiles instead of temperature profiles for IGW analysis is clearly illustrated and discussed. Chapter 2 provides important information to the scientific community regarding a cautious use of GPS-RO temperature profiles in dynamic analyses due to deviations from the assumption of hydrostatic balance.

In the third chapter a previously unknown hotspot of lower stratospheric IGW activity is highlighted. IGW activity in the lower stratosphere is investigated for a region bounded by a tilted ellipse with end points near 30°N 120°E and 60°N 180°E, referred to as the northeastern Pacific-eastern Asia coastal region (EA/NP). Monthly means of temperature, geopotential height, ozone mixing ratio and zonal wind in the domain of interest are analyzed in two reanalyses, MERRA and JRA-55. Annual cycle amplitudes in these quantities are analyzed using standard continuous wavelet transformation, while the spatial variation of the annual cycle amplitude is analyzed using pseudo-2D wavelet transformation. IGW activity in the study domain is derived from L2 level FORMOSAT-3/COSMIC RO data. Between October and November enhanced IGW potential energy values are identified over the EA/NP. A careful investigation of potential IGW sources is conducted, identifying that the prevailing surface winds and their direction change provide optimal conditions for wave propagation. Further convective activity connected to Doppler shifting of vertically propagating waves, in-situ wave generation in the UT-LS and the Kuroshio current are found to enhance wave activity in the study region.

The analyses presented in the third chapter is complemented by results from chapter 4, illustrating mechanistic model sensitivity simulations that explain potential effects of the IGW hotspot in the EA/NP region on the large scale circulation and stratospheric transport. Simulations discussed in chapter 4 are performed with the Middle and Upper Atmosphere Model (MUAM) with boundary conditions from the ERA-Interim reanalysis. Zonal mean temperatures in MUAM are nudged to ERA-Interim up to 30 km altitude as MUAM does not account for topography and several important radiative processes. IGWs are parameterized in the model and initialized at 10 km altitude with phase speeds ranging from 5 to 30 m/s. The IGW parameterization scheme has been updated by the candidate for the source function to reflect the mean January field of potential energy of disturbances from FORMOSAT-3/COSMIC RO density profiles. A comprehensive set of sensitivity simulations is performed in which an artificially changed gravity wave drag is imposed on the model, after spin-up, through modulation of the IGW parametrization output. This modulation, although necessary to create a forced response, represents also a caveat as the artificial GWD enhancement introduces an artificial momentum sink in the model. This intrinsic caveat is acknowledged and thoroughly discussed by the candidate. The results of chapter 4 highlight the importance of the spatial distribution of IGW activity for the strength and structure of the zonal mean residual circulation and polar vortex stability. The results of the sensitivity studies contain also several interesting findings for other areas of study in the middle atmosphere, such as stratospheric sudden warmings and blocking.

In summary the thesis by Petr Šácha indicates that IGWs, although being a small scale phenomenon, have stronger influence on stratospheric dynamics than previously thought. Especially aspects regarding the spatial distribution of IGW activity and the newly identified IGW 'hotspot' in the EA/NP region deserve notion. The results also implicate that inaccurate gravity wave drag distributions may introduce additional uncertainty in state-of-the-art climate model simulations. The thesis presents several interesting ideas for future research and the results and hypothesis presented will foster the ongoing debate in the scientific community and trigger additional research efforts in the immediate and neighboring fields. The candidate has clearly demonstrated the ability to perform independent, creative work and advance the understanding in our exciting research field. I recommend the thesis committee to accept the doctoral thesis in present form for oral defense and wish the candidate all the best for his career in the years ahead.

Sincerely,

Dr. Harald E. Rieder
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