Charles University

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HABILITATION THESIS

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Uncertain projections of atmospheric dynamics and transport changes.

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Contents

Introduction

Fundamentals of global effects of increasing greenhouse gas (GHG) concentrations on the whole atmosphere are well understood. Due to the climatological decrease of temperature with height in the troposphere and GHG-induced upward shift of its characteristic emission level, the temperature in the troposphere has to increase to maintain the radiative balance [Lindzen, 2007]. On the other side, from the stratosphere to the lower thermosphere the growing GHG concentrations enhance the optical thickness and emissivity of the layers jointly resulting in radiative cooling (Goessling and Bathiany, 2016). Further above, the layers exchange energy by molecular diffusion (i.e. heat conduction) with the radiatively cooling lower layers; the energy is then radiated by CO2 and NO (the ‘heat sink’ region; Mlynczak et al., 2018), particularly in the lower thermosphere. The radiative balance assumption during the process is well justified, as the atmosphere reacts to changes in GHG concentrations very quickly, on the order of days (Mlynczak et al., 2022). As a result of basic thermodynamics, the troposphere is thermally expanding and the upper layers contracting.

However, if we go beyond the fundamentals and allow ourselves to ask more intriguing questions concerning for instance, possible nonlinear feedback from the changing atmospheric vertical structure on the radiative transfer, the answer is not clear. As yet no simple physical model capturing this has been proposed. Moreover, relaxing the global mean view and asking targeted questions on regional GHG effects that inevitably invoke circulation and dynamics of the atmosphere, numerical climate models have to be relied upon solving complex systems of partial differential equations. Since the advent of climate modeling in 1970s, the complexity of the models has been evolving over time, coupling the basic atmosphere, ocean and land models with newly added submodels of remaining parts of the earth system. Hence the name for the current generation of climate models - earth system models (ESMs, see Fig. 1.1).

However, increasing complexity does not mean improvement (as demonstrated recently for atmospheric chemistry inclusion [Morgenstern et al., 2022]). The reason is clear, besides the dynamics solver, each submodel coupled into ESM consists of a number of parameterization schemes that supplement effects of unresolved or overly complex processes based on emphirical formulas or simplified theoretical considerations. Each parameterization includes a number of free (tunable) parameters that are often exploited by the modeling centers to improve the model biases. As a results the model climatologies may look correct for wrong reasons and this is then manifested, when a new set of processes gets coupled into the model. All parts of ESM have to be retuned then. Concerning the atmospheric part of ESM, the so-called general circulation model employs parametrizations for the turbulence, convection, radiative transfer, cloud microphysics, gravity waves, etc. This thesis focuses on the orographic gravity wave (OGW) parametrization, which is a scheme that supplements the complex effects of unresolved, subgrid scale orography (SSO) to the model. This means that it concerns not only the effects of freely propagating wave modes in the free atmosphere, but also the low-level breaking, flow blocking and near-surface drag from SSO. Although the OGW parametrization being only one of many parameterization schemes employed in

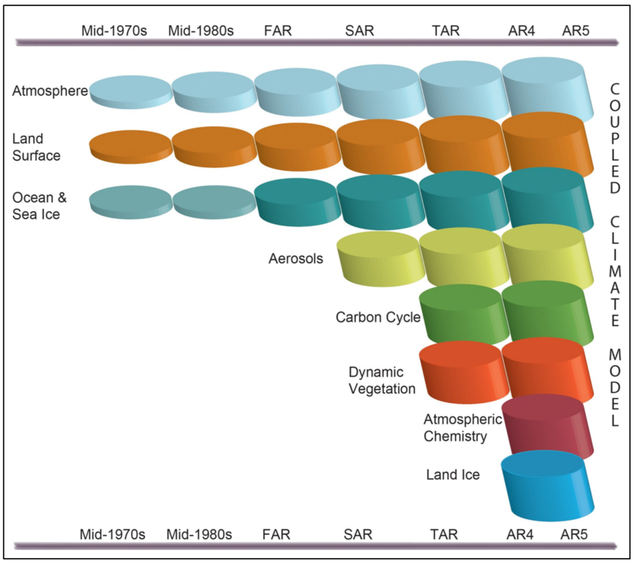

Figure 1: Evolving complexity of climate models over time with inclusion of new components adapted from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5): WG1, Chapter 1, Figure 1.13; https://www.ipcc.ch/report/ar5/wg1.

GCM, the aim of this thesis is to demonstrate that it is absolutely crucial for correct representation of the stratosphere in current ESMs and motivate the case for its future improvements.

The thesis is structured as follows. Chapter 1 gives an overview of projected changes of relevant stratospheric phenomena and discusses the reliability of these ESM projections. Chapter 2 analyses the parameterized OGWD and its complex effects in ESMs and Chapter 3 highlights the conceptual difficulties that we face when trying to derive constraints of the OGW parameterizations from observations or high-resolution numerical simulations of the atmosphere. In Conclusions, major points of the thesis are summarized and discussion is provided on how the open points identified in the thesis are being addressed by the ongoing and planned research within the GW research group at the Department of Atmospheric Physics.

The thesis is based on selected papers published during my postdoctoral research career, where I acted as the main author or significantly contributed to the study. The papers are attached in the Appendices to this thesis. Chapter 1 consists from the set of three papers concerning GHG induced stratospheric contraction and its imprint in the circulation changes therein.

- Pisoft, P., Šácha, P., Polvani, L.M., Anel, J.A., de la Torre, L., Eichinger, R., Foelsche, U., Huszar, P., Jacobi, Ch., Karlicky, J., Kuchar, A., Zak, M., Miksovsky, J., and Rieder, H. E.: Stratospheric contraction caused by increasing greenhouse gases. *Environmental Research Letters*, 16(6), 064038, 2021. https://iopscience.iop.org/article/10.1088/1748-9326/abfe2b

Appendix A (p. 23)

- Eichinger, R and Šácha, P.: Overestimated acceleration of the advective Brewer–Dobson circulation due to stratospheric cooling. *Quarterly Journal of the Royal Meteorological Society*, 146, 3850–3864, 2020.

  https://doi.org/10.1002/qj.3876.

  Appendix B (p. 33)

- Šácha, P., Eichinger, R., Garny, H., Pišoft, P., Dietmüller, S., de la Torre, L., Plummer, D. A., Jöckel, P., Morgenstern, O., Zeng, G., Butchart, N., and Añel, J. A.: Extratropical age of air trends and causative factors in climate projection simulations, *Atmospheric Chemistry and Physics*, 19, 7627-7647, 2019. https://doi.org/10.5194/acp-19-7627-2019.

  Appendix C (p. 49)

Chapter 2 bases on four papers that were a continuation of the topic of my doctoral thesis and that substantially improved our understanding on the effects of OGW parameterizations in climate models.

- Hájková, D., Šácha, P. Parameterized orographic gravity wave drag and dynamical effects in CMIP6 models. *Climate Dynamics*, 2023. https://doi.org/10.1007/s00382-023-07021-0.

  Appendix D (p. 71)

- Šácha, P., Kuchar, A., Eichinger, R., Pisoft, P., Jacobi, C., and Rieder, H. E.: Diverse dynamical response to orographic gravity wave drag hotspots—a zonal mean perspective. *Geophysical Research Letters*, 48, e2021GL093305, 2021. https://doi.org/10.1029/2021GL093305.

  Appendix E (p. 98)

- Kuchar, A., Sacha, P., Eichinger, R., Jacobi, C., Pisoft, P., and Rieder, H. E.: On the intermittency of orographic gravity wave hotspots and its importance for middle atmosphere dynamics, *Weather and Climate Dynamics*, 1, 481–495, 2020. https://doi.org/10.5194/wcd-1-481-2020.

  Appendix F (p. 110)

- Šácha, P., Miksovsky, J., and Pisoft, P.: Interannual variability in the gravity wave drag – vertical coupling and possible climate links, *Earth System Dynamics*, 9, 647-661, 2018. https://doi.org/10.5194/esd-9-647-2018.

  Appendix G (p. 126)

Chapter 3 concerns two papers showing the results of a broad international collaboration effort towards deriving global constraints on the parameterized OGWD using state-of-the-science satellite measurements and high-resolution numerical atmospheric models.

- Procházková, Z., Kruse, C. G., Alexander, M. J., Hoffmann, L., Bacmeister, J. T., Holt, L., Wright, C., Sato, K., Gisinger, S., Ern, M., Geldenhuys, M., Preusse, P., and Šácha, P. (2023). Sensitivity of mountain wave drag estimates on separation methods and proposed improvements. *Journal of the Atmospheric Sciences*, https://doi.org/10.1175/JAS-D-22-0151.1.

  Appendix H (p. 142)

- Kruse, C. G., Alexander, M. J., Hoffmann, L., van Niekerk, A., Polichtchouk, I., Bacmeister, J. T., Holt, L., Plougonven, R., Šácha, P., Wright, C., Sato, K., Shibuya, R., Gisinger, S., Ern, M., Meyer, C. I., and Stein, O. (2022). Observed and Modeled Mountain Waves from the Surface to the Mesosphere near the Drake Passage, *Journal of the Atmospheric Sciences*, 79(4), 909-932.

  Appendix I (p. 163)

The selected publications present the most important contributions of the author and his collaborators to the scientific understanding of the topics concerned. Moreover, each chapter starts with a textual part that puts the selected papers in the context of the thesis. Where needed, the text is supported with yet unpublished analyses connected with the topic.

1. Stratospheric contraction and its imprint on circulation changes.

Terrestrial atmosphere is changing. Ongoing atmospheric composition changes affect surface climate [Hegerl et al., 1996] and alter atmospheric structure [Pisoft et al., 2021], dynamics, and transport [Shepherd and McLandress, 2011b], which in turn affect the atmospheric composition. In the middle atmosphere [Andrews et al., 1987], the composition, including distribution and trends of radiatively important gases like ozone and water vapor, is influenced by the Brewer-Dobson circulation (BDC) [Butchart, 2014], an interhemispheric meridional overturning circulation. Hence, realistic representation of structure, strength, and variability of BDC is a crucial goal for climate modelers [Abalos et al., 2021]. Analytically, the BDC is commonly defined as consisting of a diffusive and advective part described by the residual mean circulation [Eichinger et al., 2019]. Climate model simulations consistently show that the advective BDC part accelerates due to greenhouse gas (GHG) induced climate change and this acceleration dominates the middle atmospheric changes in climate model projections throughout the 21st century [Butchart et al., 2010]. However, recent BDC trends in climate models could not yet been fully matched with those of observations [Abalos et al., 2021], a topic that is to date still under active discussion.

Another robust impact of the GHG concentration changes is the changing structure of the atmosphere across layers. The troposphere is thermally expanding [Santer et al., 2003], stratosphere is cooling and contracting [Pisoft et al., 2021] and this is then reflected in the mesosphere and above as a downward shift of pressure levels [Lübken et al., 2013], which can be characterized by the hypsometric equation with a good precision. Assuming that the stratosphere is dry, its global mean thickness $\overline{H}$ can be deduced from a global mean stratospheric temperature $\overline{T}$ and the tropopause $\overline{p_{tp}(t)}$ and stratopause pressure $\overline{p_{sp}(t)}$ at each time instant as:

$$\overline{H(t)} = \frac{R\overline{T(t)}}{g} ln(\frac{\overline{p_{tp}(t)}}{\overline{p_{sp}(t)}}), \tag{1.1}$$

where R is the specific gas constant for dry air and g stands for the gravitational acceleration. As can be seen in Fig. 1.1, stratospheric thickness reconstructed according to this formula overestimates the modeled, directly diagnosed global mean stratospheric thickness (possibly due to implicitly neglected variations of g with height and latitude or due to the omission of the Eötvös effect). However, it captures accurately the time-evolution of the global mean stratospheric thickness (i.e. the rate of the stratospheric contraction). 1.1 can be also used for partitioning the drivers of stratospheric contraction trend - differentiating the equation one gets separate estimates of the roles of the global mean stratospheric temperature and tropopause and stratopause pressures for the contraction.

The stratospheric contraction in combination with the tropospheric expansion in particular, have been shown to interfere with diagnosed BDC trends [Shepherd and McLandress, 2011a, Šácha et al., 2019, Eichinger and Šácha, 2020]. In

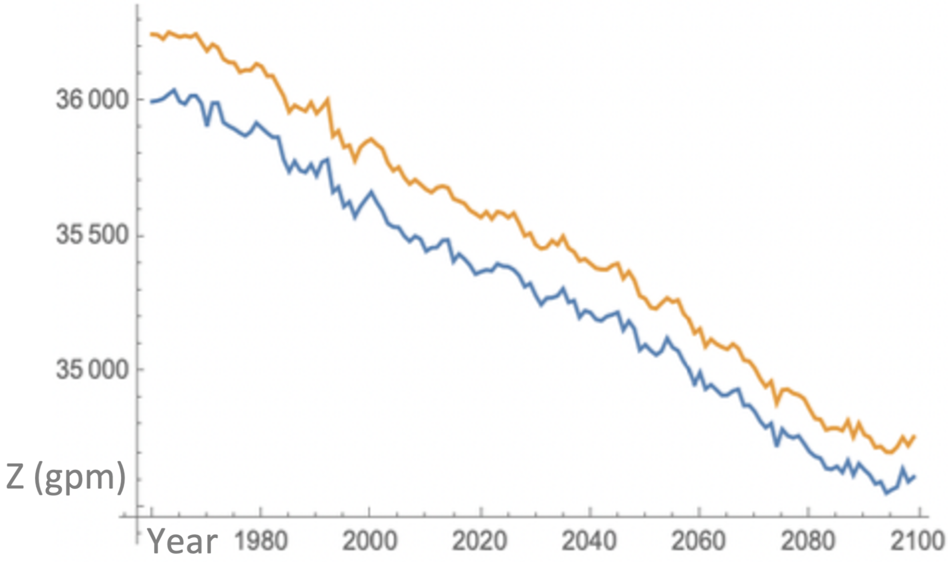

Figure 1.1: Time evolution of a directly diagnosed global mean stratospheric thickness (in geopotential meters) from a selected ESM projection in blue and its reconstruction using the hypsometric equation (orange curve).

Oberländer-Hayn et al. [2016], the authors argued that there is no detectable increase in the net tropical upwelling, when heuristically accounting for the tropopause rise, prompting the question whether the advective BDC is increasing or moving upwards. Complicating the attribution of the BDC change even further, the horizontal structure of the troposphere and stratosphere is changing as well, again affecting the BDC trends [Stiller et al., 2017]. The schematic illustrating the overlaying kinematic effects of a set of co-occurring different long-term atmospheric structure and circulation changes is given in Fig. 1.2. Attributing the causative factors of the BDC trends is of an utmost importance. Knowledge of the roles of individual factors can help to understand and reconcile the disagreement between observations and models regarding the past BDC trends and enhance confidence in future climate projections.

The author of the thesis contributed to the research of the above mentioned topics by conceptualizing the detailed multi-model study of stratospheric contraction (Appendix A) that received a significant scientific community and media attention. Even before this paper, the author sounded a strong warning for the middle atmospheric community by highlighting that the improper utilization of the traditional methodology for diagnosing transport that relies on the constant scale-height in the atmosphere, contaminates the analyses of middle atmospheric transport trends with an additional uncertainty (Appendix B). This uncertainty stems from the implicit neglection of co-occurring structural changes in the atmosphere and can be eliminated by small changes in the formalism. As a chronologically first paper of this series (Appendix C), the author led a study that realized based on the meridional distribution of Age-of-Air (proxy for BDC strength) changes that majority of this change can be explained by vertical shifts of the Age-of-Air isolines. As a side result of this paper, the role of parameterized GWD for BDC changes has been questioned, which provides further motivation for Chapter 2.

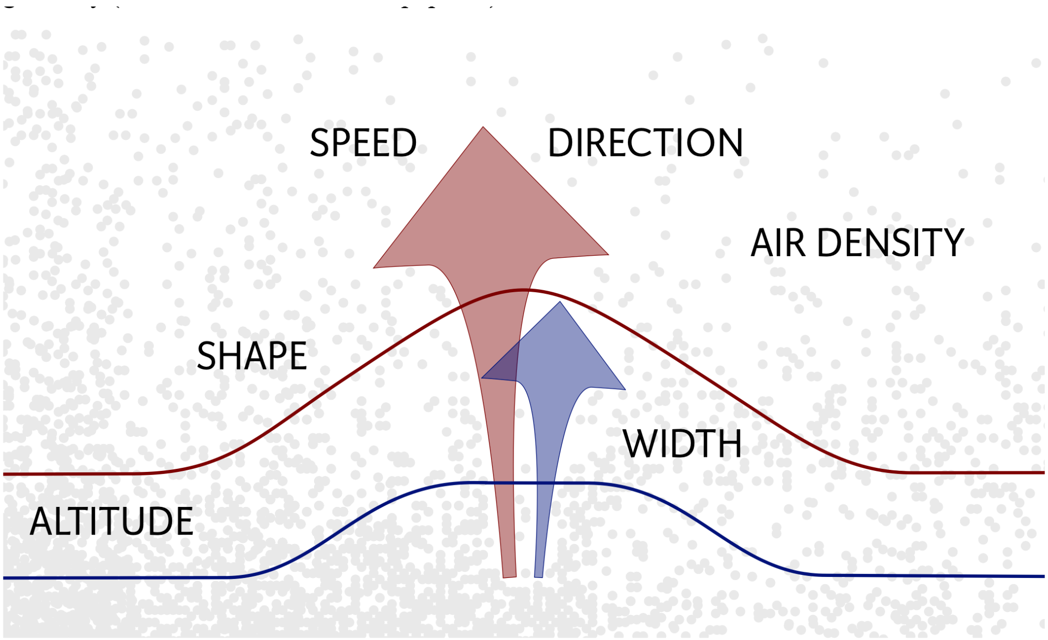

Figure 1.2: Schematic illustration of the contributions to the change of a net upwelling across a material line between the time instants A (grey lines) and B (black lines). The net change consists of contributions from changes of the speed of the circulation (size of the arrow), the width of the upwelling region, the vertical shift of the material line, changes in the shape of the material line controlling the contribution of meridional and vertical transport (inclination of the arrow) and of changing density of air that is connected with the spatially variable temperature trends (stippled background). The graphics is a courtesy of Petr Pišoft and Roland Eichinger.

2. Parameterized orographic gravity wave drag effects in climate models.

Atmospheric waves affect transport of momentum, energy, and mass and thereby atmospheric composition, which makes them one of the most important coupling mechanisms between atmospheric layers [Fritts and Alexander, 2003]. Apart from the equatorial region, where numerous wave types play important roles, Rossby waves (RWs) and internal gravity waves (GWs) dominate the processes in the atmosphere and especially in the middle atmosphere (from the upper troposphere across the stratosphere and mesosphere up to the mesopause; [Andrews et al., 1987]. While RWs are large-scale phenomena well resolved in the models, GWs occur on a broad range of scales (from synoptic to well below mesoscale) and remain to a large extent unresolved (in ESMs) or are only partially resolved (i.e., lie in a grey zone in numerical weather prediction models (NWPMs)). A hierarchy of numerical models (spanning from conceptional models to NWPMs and ESMs) has played an increasingly important role in atmospheric research during the last decades, providing information on the state of the atmosphere and climate system and its changes. Model simulations and projections have not only fueled scientific discovery but also provided timely information for policy makers and broadened the societal dialogue on climate change. Although CCMs are evolving in complexity, they still rely on a diverse set of parameterizations for processes which cannot be explicitly resolved. In current generation ESMs, most of the GW spectrum is smaller than the model resolution, hence the GW effects are unresolved and must be parameterized [Achatz et al., 2023a]. Commonly, two parameterization schemes are employed in current models to distinguish between orographic and non-orographic GWs (OGWs and nOGWs). Various GW parameterization schemes of both types have been developed to date. Regardless of the scheme applied, the GW parameterizations comprise various degrees of simplifications and rely on various tunable parameters poorly constrained by observations [Plougonven et al., 2020]. More to this, in most global models the only GW effect explicitly parameterized is the dissipative deposition of momentum due to the GW breaking resulting in a GW drag (GWD). OGW parameterizations that supplement the transfer of momentum from the sub-grid scale orography have originally been applied to separate the stratospheric polar night jet from the tropospheric subtropical jet by reducing its overall magnitude and increasing the easterly wind shear in the upper troposphere [Kim et al., 2003]. The nOGW schemes improved simulations of the upper levels of the middle atmosphere and drove more realistic quasi-biennial and mesospheric semiannual oscillations (QBO and SAO, [Richter et al., 2019]). Since the advent of the so-called wave driving paradigm [Holton et al., 1995b] the dynamical effect of parameterized GWs has been increasingly evaluated as a contribution to the driving of the advective Brewer-Dobson circulation (BDC), the interhemispheric meridional overturning circulation in the middle atmosphere [Sato and Hirano, 2019]. Another GW impact that receives considerable attention is connected to sudden stratospheric warming (SSW) events [Šácha et al., 2016]. Recent research of the author of the thesis has substantially propelled our understanding of complexity of the parameterized OGWD effects in the models. Šácha et al. [2018] highlighted that the OGW parameterizations act as a quick propagator of the near surface variability to the stratosphere, thereby playing a significant role in the stratosphere-troposphere coupling in CCMs. Moreover, Eichinger et al. [2020] documented that parameterized OGWD has an indirect, though pronounced, effect on atmospheric transport and composition in CCMs. Expanding on this work Sacha et al. [2021] illustrated the close dynamical coupling of the parameterized OGWD with leading RW modes on short time-scales. All the OGWD effects described in the research articles above are not constrained by the theory or observations and the OGW parameterizations included in models were originally not implemented or tuned for such purpose.

On the other hand, several GW processes that are deduced from theory or numerical studies are not parameterized in the models. For example, it is widely understood that GWs can influence atmospheric composition and transport directly via turbulent mixing during their breaking and via so-called non-dissipative effects connected with GW propagation and fluctuating trajectories inside the GWs [Bühler, 2014]. This way GWs can modify also cloudiness [Podglajen et al., 2018], boundary layer [Roy et al., 2021] and precipitation [Cohen and Boos, 2017]. Our current understanding of the GW effects and the correspondence with their parameterized effects in ESMs is illustrated in Fig. 2.1. The uncertainties connected with the GW parameterizations may prove as increasingly problematic, given that the accurate calculation of the advective transport of chemical species is of fundamental importance for the overall performance of ESMs, especially in connection with interactive chemistry.

From the climate modeling perspective, the sensitive interaction between GWD and the large-scale circulation has been considered among the most un-

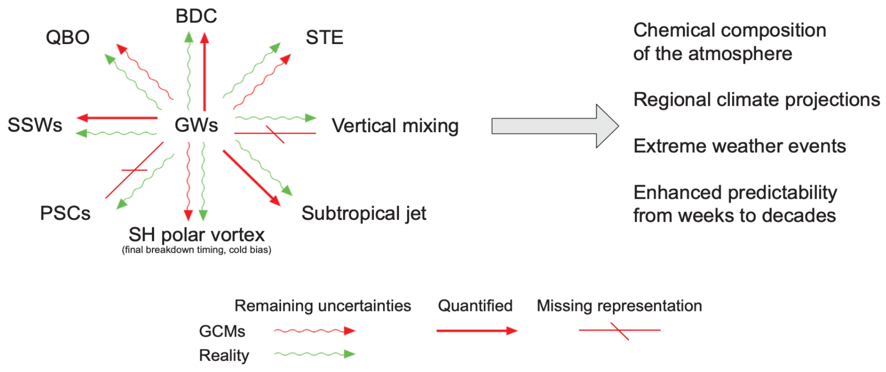

Figure 2.1: Schematic of climate GW impacts based on theoretical or observational evidence (green) and model-based evidence (red). BDC is an acronym for the Brewer-Dobson circulation, STE for the stratosphere-troposphere exchange and coupling, PSCs stand for polar stratospheric clouds, SSWs for sudden stratospheric warmings and QBO for the quasi-biennial oscillation. The representation of societally highly relevant phenomena (the right-hand side of the scheme) is expected to be improved due to more realistic representation of the GW effects in models.

certain aspects of climate modelling [Shepherd, 2014]. However, for the OGW parameterization, Sigmond and Shepherd [2014] argued that this uncertainty does not fully affect the robustness and confidence of future climate projections due to the existence of a "compensation mechanism" between resolved and unresolved drag in the models [Cohen et al., 2013, 2014]. Using a GW resolving model, van Niekerk et al. [2018] raised questions how realistic the coupling between GWD and resolved dynamics is, given that the compensation between resolved and unresolved drag prevents agreement in orographic impacts between low resolution and high-resolution model versions. Adding to this argument from the ESM perspective, the author of this thesis demonstrated that the parameterized OGWD - resolved dynamics interaction is dominated by the efficient interaction with planetary- scale RW modes [Sacha et al., 2021]. This supports the hypothesis that the interaction dominating the model dynamics in the middle atmosphere may to a large extent be artificial, because theoretically, the GW interaction with the background atmosphere is assumed to be strongest at meso- to synoptic scales [Achatz et al., 2017]. In his recent paper, the author of the thesis together with his student clearly documented that the parameterized OGWD with all of its tuning controls the stratospheric dynamics in state-of-the-science ESMs and is responsible for inter-model differences therein [Hájková and Šácha, 2023].

Below, the most important findings of the thesis author contributing to the scientific understanding of the dynamics of ESMs and the role of parameterized OGWD therein are listed together with links to relevant papers in the Appendices.

- Parameterized OGWD in ESMs is tuning and type of the scheme dependent and the resulting differences in OGWD are from a large part responsible for the intermodel differences in stratospheric dynamics (Appendix D).
- Parameterized OGWD affects the model dynamics mainly indirectly, by modifying the wind field in the so-called valve layer in the extratropical upper troposphere-lower stratosphere and hence also the resolved wave propagation from the troposphere upwards (Appendices D and E).
- The interaction between resolved waves and parameterized OGWD occurrs on a time-scale of a few days and planetary Rossby waves are mainly affected (Appendix E)
- The parameterized OGWD is maximal in the lower stratosphere, organized horizontally into so-called hotspots with intermittent episodes of extreme magnitudes, which makes it a highly non-trivial forcing to analyze (Appendix F).
- The dynamical effect of the parameterized OGWD is sensitive to the hotspot distribution in the stratosphere, while the hotspot distribution mainly reflects lower tropospheric conditions and is highly variable also on interannual timescales (Appendices G and E).

3. Deriving constraints on orographic gravity wave drag parameterization schemes.

The uncertainty and artificiality of the leading dynamical effects of parameterized GWD in ESMs documented in 3 presents an urgent motivation for a further research of GWs and understanding of their influence in the atmosphere, which would pave the way for improving the physical and mathematical basis of GW parameterization schemes. GW parameterizations will have to be employed in state-of-the-science ESMs but also global NWPMs in years to come, with significant and broad implications for our ability to forecast short- and medium-term weather conditions on the one hand (important for example for disaster-relief planning and crop-planting) and the accurate prediction of weather pattern and circulation changes at the scale of decades or longer at the other (information which is needed to plan for the major societal changes expected later this century). Properly understanding and simulating GWs is vital to advancing state-of-the-art modelling over the coming decade and beyond, underlining the critical importance of this research topic.

At present, despite intensive international research efforts (numerous major national and international research projects and activities are currently focused on GW research, funded by both public and business sector) the constraints on global GW characteristics, sources and effects remain very loose. In the last decades, however, as reviewed recently by Achatz et al. [2023b], the field of GW observations has seen significant progress, mainly in connection with rapidly evolving possibilities of satellite measurements and analysis techniques. Also, high-resolution atmospheric model simulations capable of resolving large part of the GW spectrum began to emerge, displaying an unprecedented degree of realism both in regional [Kruse et al., 2022] and global models [Polichtchouk et al., 2023]. Unlike direct observations that are sparse in space and time and suffer from the observational filter bounds on the observable GW spectrum, the GW permitting simulations allow studying the full spatio-temporal variability of the GW field (on the scales above their effective resolutions). That said, caution is needed when interpreting the model results, because simulated GW fields show great sensitivity on the model formulation and configuration, which reinforces the importance of observations for validating the high-resolution models (see Fig. 1 in Kruse et al. [2022] for a schematic on cross-validation strategies between models and observations for the GW research).

In Appendix H, a land-mark paper summarizing the activities of the international team on New Quantitative Constraints on Orographic Gravity Wave Stress at the International Space Science Institute, Bern (ISSI) is appended, where a group of international experts (including the thesis author), for the first time, performed a dedicated comparison between a set of the state-of-the-art high-resolution models with satellite observations. To select a few key points from this study, the team demonstrated that all the analyzed models reproduce observed middle-atmosphere gravity waves with remarkable skill. But still, all models un-

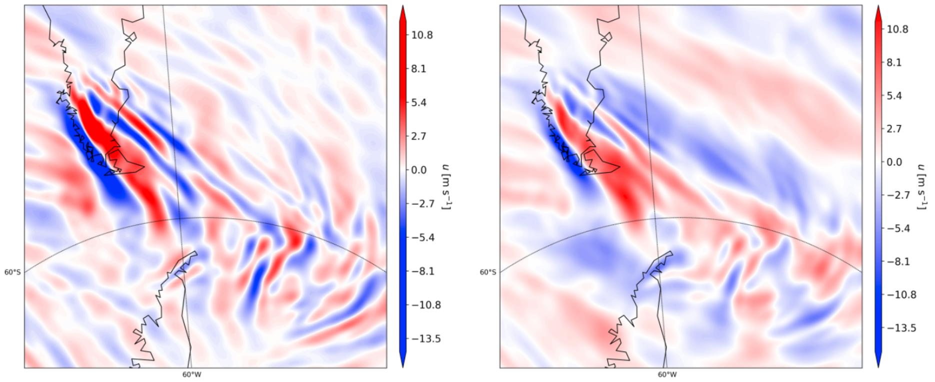

Figure 3.1: Examples of the GW induced zonal wind perturbation field in the stratosphere around the Drake Passage extracted using zonal filtering (left) and spherical smoothing (right) of the spherical harmonics field from one time instant of the latest reanalysis dataset.

derrepresent observed wave amplitudes, even after accounting for model effective resolution and instrument noise, suggesting that even at few kilometer horizontal resolutions, small-scale mountain waves are underresolved and/or overdiffused. Also, the paper contributes to understanding of the outstanding issue of atmospheric and climate modeling - the GWD gap around 60°S in the stratosphere of the models, by highlighting the role of lateral propagation of gravity waves towards the polar night jet in the Drake Passage region.

An uncertain factor omitted in the Kruse et al. [2022] paper, which complicates the GW research based on complex datasets like GW permitting simulations or observations even further, is the lack of optimal and standardized methodology for diagnosing GWs and separating the GW field from other co-occurring processes. As illustrated in Fig. 3.1, even two related methods from the same family of statistical GW detection methods produce GW fields with pronounced differences in distribution and magnitude of the perturbations. This issue has been adreessed in a paper given in Appendix G. Under the supervision of the author of the thesis, his PhD student coordinated a study seeking to define an optimal method for GW separation that is combining the best of efficient statistical methods with the physics - information on GWs contained in the horizontal kinetic energy spectrum of the flow. In this study, the authors highlighted the sensitivity of resulting GW momentum fluxes and induced drag to the methodology, and proposed two modified versions of a classical statistical gravity wave detection method enhanced by the spectral information that improved the accuracy of GW activity estimates, especially when oblique GW propagation plays a role and a full divergence of the complete Reynolds stress tensor has to be taken into account.

4. Conclusion

In the frame of this thesis, selected papers with major contributions from the thesis author have been grouped into the three interconnected chapters with a concise message that our understanding of the atmospheric system is far from complete and that our ability to numerically simulate the evolution of the climate system is fairly limited. Of course that such message is in a stark contrast with the perception the public and a wider scientific community may have from discussions and recommendations at the policy-maker's level. The overarching goal of the thesis is to underline the need for continuing basic research of the atmosphere, across spatial and temporal scales combining state-of-the-art observational and numerical modeling capabilities with advances in mathematics and physical theories. It must be noted that the list of issues and open questions in meteorology and climate modeling is much broader than given here, with some issues of even greater importance (e.g. the physics of cloud formation). However, this overarching goal is demonstrated here without loss of generality using the topics, where the thesis author has a proven track record of expertise.

In the first chapter, the radiatively induced structural changes in the middle atmosphere has been described. This type of changes, where external forcings of the atmosphere are in play are important, because they offer the possibility of unequivocal attribution of causality. Therefore it is important to detect imprints of these changes in long-term trends of the in-situ processes, causes to which may otherwise be misleadingly attributed to other internally generated processes. A particular example is the wave-driving paradigm of BDC [Holton et al., 1995a], which keeps to be used by many authors using flawed reasoning for attributing the acceleration of BDC to long-term trends in the wave forcing, including parameterized OGWD. This was our motivation for highlighting the structural changes in the middle atmosphere in the first chapter, where it is argued that the structural changes of the middle atmosphere affect the BDC trends therein. Regarding this point, the thesis author has another paper in a final review round, which has not been included in the thesis due to copyright and similarity report concerns.

In this paper under review, we aim to disentangle the question of underlying BDC driving, by providing a methodology allowing quantification of the roles of different factors behind the BDC changes. By identifying the problem as the change of the mass transport across a time-variable material line, a complete set of mechanisms contributing to the net tropical upwelling changes is derived within the manuscript and their roles are quantified precisely. Net tropical upwelling is studied in the manuscript, because it is advantageous to define a single scalar number as a proxy for BDC strength. The kinematic nature of the problem means that the quantification can be different for each material line (tropopause, individual pressure levels), where the transport is diagnosed. Thus, generally, for one material line the BDC can for example be accelerating and shifting upwards, while for another one downwards and decelerating at the same time. The identified complete set of mechanisms contributing to the upwelling changes includes the increasing residual mean vertical mass flux, the vertical shift of a material line, the widening of the upwelling region and for the first time, the role of the change of geometry of the material line (changing curvature/slope). The latter can also allow for contributions from the meridional component of the residual mean mass flux. The mass fluxes themselves can be divided into two parts - accelerating/decelarating circulation part and density changes. This is the complete set of mechanisms and the accuracy of the method is proven in the paper to be excellent. In the second chapter, a comprehensive review of parameterized OGWD and its effects in ESMs has been given. The papers included in the chapter significantly contributed to our understanding of the properties of this decelerating force and of the sensitivity of stratospheric dynamics in ESMs to subtle nuances of this particular parameterized process. Also thanks to our research there is a renewed concern in the community about the accuracy of current OGW parameterization schemes that were in recent decades slightly left behind the trending focus on non-orographic GW parameterizations. Many current international initiatives aim at proposing whole new or improved OGW parameterization schemes, either based on new physics included, machine learning methods or tighter observational constraints. Also, the author of the thesis is contributing actively to this topic. In Fig. 4.1, the motivation is illustrated for adding a stochastic factor to the grid scale winds that are the input for the OGW parameterization. This modification proposed by the author has been applied in cooperation with colleagues from the German Aerospace Center to one particular ESM and the initial test simulation indicated direct improvement of some of the model biases in the stratosphere, even before tuning the model and the modified parameterization scheme. The manuscript presenting this OGW parameterization modification and describing the initial results is currently under development.

As an interesting aspect, the dynamical importance and uniqueness of spatio-temporal intermittency of parameterized OGWD compared to other forcings in

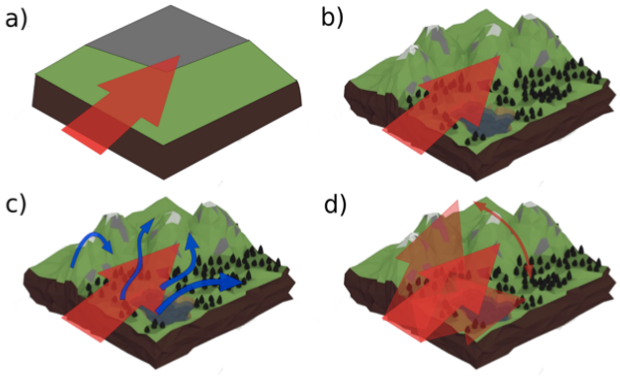

Figure 4.1: Schematic motivating the stochastic wind modification in the OGW parameterization scheme (credit for the graphics - Roland Eichinger). Panel a) shows grid-scale orography and winds (red arrow). Panel b) shows the real orography (grid-scale orography and subgrid scale orography variations). Panel c) shows assumed distribution of subgrid scale variations of winds due to the subgrid scale orography. Panel d) illustrates the slight oscillation of the direction of the grid scale wind entering the OGW parameterization as an effect of stochastic modification that should at least partly account for the wind distribution depicted in c).

the stratosphere underlined in the second chapter, served as one of the motivations for the proposal of a new selected ESA mission (CAIRT) that among other goals should validate whether the localized GWD hotspots exist also in the real atmosphere (IUGG2023 talk and personal communication with Dr. Peter Preusse). In the third chapter, two papers rooted in broad international collaboration demonstrate the incredible detail and amount of information on scales dominated by GWs that can be derived by state-of-the art methodologies (highly developed, but still a source of uncertainty) from satellites and high-resolution experimental simulations. However, it is not straightforward to use such information for constraining GW parameters in the parameterizations and even less for constraining their effects on the atmospheric dynamics up to the climate timescales. To understand the GW influence on selected atmospheric phenomena, the author of the thesis leads a five-year project funded by the Czech Science Agency - Unravelling climate impacts of atmospheric internal gravity waves. This project helped to establish a GW research group at the Department of Atmospheric Physics, Faculty of Mathematics and Physics, Charles University. The research group works on various aspects of atmospheric dynamics and transport related to GWs in the atmosphere and their representation in models. Using a synergy of theory, observations, existing data mining and experiments with a a hierarchy of numerical models (spanning from idealized to GW resolving and ESMs) the goal is to revisit and advance our understanding of the climate impacts of GWs and improve their current parameterizations. Properly understanding and simulating GWs is vital to advancing state-of-the-art modelling over the coming decade and beyond. Although, it is foreseen that global models in the near future will fully resolve almost all processes of the GW life-cycle (the turbulent cascade connected with the GW dissipation will hold out longest), GW parameterizations will remain important for paleoclimate and distant future climate projections and also near future climate modeling and seasonal predictions by model ensembles will keep using codes where a significant part of the GW spectrum will have to be parameterized [**?**]. Given the pronounced effects that GWs have in climate but also weather prediction models, GW research will remain an important part of atmospheric sciences, with significant and broad implications for our ability to forecast short- and medium- term weather, important for example for disaster-relief planning and crop-planting, and for the accurate prediction of weather pattern changes at the scale of decades or longer, information which is needed to plan for the major societal changes expected later this century.

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Appendix B

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Appendix C

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Appendix D

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Appendix E

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Appendix F

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Appendix H

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Appendix I

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