Final Preport for Project **1238**

Project title: **Middle atmosphere localized gravity wave forcing: Formation, impact and long-term evolution**

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Introduction

Within the project, the role of gravity waves (GW) in the formation and variability of the stratospheric polar vortex (SPV) was investigated. In particular, the project included investigations on the interaction of GW and resolved waves, effects of GW on elevated stratopause events, and effects of stratospheric aerosol intervention (SAI) on the polar vortex. The research was supported by the Deutsche Forschungsgemeinschaft (DFG) through grant # JA 836/47-1. Further analyses included the response of the polar vortex to localised GW enhancement, and the investigation of the stratospheric polar vortex morphology based on ERA5 reanalyses.

GCM experiments of GW and resolved waves interaction

We utilized the ICON version 2.6.3 with upper-atmosphere extension (UA-ICON) as distributed by the German Weather Service (DWD) with R2B4 resolution. Here, we have conducted a set of 30-year long (excluding the spin-up periods) time-slice experiments with the UA-ICON model by employing repeated annual cycles of SST, SIC, and greenhouse gases of the year 1985. This year has been chosen as both the El-Nino Southern Oscillation and the Pacific Decadal Oscillation were in their neutral phase and no major volcano eruption had occurred, hence conditions in this year can serve as a useful proxy for the multi-year mean conditions and an estimate of their internal variability. First, a control (CTL) run was carried out, where both the sub-grid scale orography (SSO) scheme and non-orographic GW scheme were used. A comparison with ERA5 (Figure 1) shows that the SPV in ICON is deeper, but more narrow. For future analyses and comparisons of different models we therefore proposed to use an SPV metric consisting of the product of vortex area and potential vorticity gradient at the vortex edge.

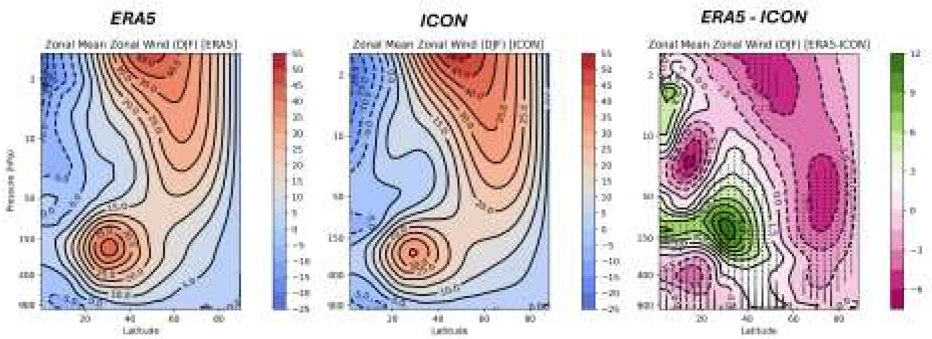

Fig.1: Comparison of zonal men zonal wind in ERA5 (left) and ICON-UA (middle). The right panel shows the differences (all in m/s). Stippled regions indicate statistically significant differences.

Second, two sensitivity tests were performed where a) the SSO scheme was disabled (noSSO) and b) the non-orographic gravity wave (GW) scheme was disabled (noGWD). All three ensembles are available at WDCC [6-8]. We have studied the interaction between the resolved waves and parameterized gravity wave drag in the UA-ICON model [1]. The stratospheric polar vortex accelerates, cools and shifts poleward in both sensitivity runs. The frequency of sudden stratospheric warmings in the CTL simulation is 5.7 events per decade and drops to 1.7 and 4 events per decade in the noSSO and noGWD, respectively. In both sensitivity runs (particularly in noGWD), an enhancement in the resolved wave amplitude was found in the high latitude stratosphere and in the mesosphere and lower thermosphere (MLT) region in all latitudes. The magnitudes of the resolved wave responses are generally larger for noGWD than noSSO. Our results confirm the compensation mechanism in the UA-ICON model, whereby the perturbed forcings in the GW parameterization drag are often cancelled or compensated by a resolved large-scale wave driving of opposite sign.

Effect of GW on elevated stratopause events

In addition, we have studied the climatology of the stratopause height and temperature in the UA-ICON model and have examined them by comparing to a 11-year Microwave Limb Sounder (MLS) climatology. In addition, the elevated stratopause (ES) events occurrence, their main characteristics, and driving mechanisms in the UA-ICON model are examined in the above-mentioned sensitivity runs [2]. Our modelling results suggest that the contributions of both GWs and resolved waves are important in explaining the enhanced residual circulation following ES events compared to the SSW-only events but their contributions vary through the lifetime of ES events. We emphasize the role of the resolved wave drag in the ES formation: when the non-orographic GW drag is absent, the anomalously enhanced resolved wave forcing in the mesosphere gives rise to the formation of the elevated stratopause at about 85 km.

SPV and GW effects in aerosol intervention experiments

We also studied the teleconnection between the quasi-biennial oscillation and the Arctic stratospheric polar vortex, or the Holton–Tan (HT) relationship, which, according to simulations, weakens in a warmer climate or one with stratospheric aerosol intervention and compared them with the present-day climate [3] using large datasets such as NCAR's GLENS simulations. The weakening of the HT relationship under the RCP8.5 scenario is likely due to the weaker QBO wind amplitudes at the equator. In general, the changes in the HT relationship cannot be explained by changes to the critical line. The changes in the residual circulation (particularly due to the gravity wave contributions) are important in explaining the changes in the HT relationship.

The allocated resources are also used to study the impact of climate change and stratospheric aerosol injection on the polar vortex morphology using GLENS and ARISE simulations [4]. Since there simulations describe different scenarios, the results differ, but some features are similar. So In the high-latitude SPV region of the NH under SAI (compared to CTL) in both GLENS and ARISE simulations, a weak and insignificant temperature response was found. However, in the SPV region of the SH, especially at the upper stratosphere, the zonal mean temperature responses under SAI are large and significant. The SPV often forms earlier under SAI than under CTL at all altitudes in both hemispheres and for both GLENS and ARISE simulations. Since the ARISE's or GLENS' changes in the EPV inside the SPV are relatively small or uniform, respectively, they do not cause a significant shift in the centre of the vortex.

Polar vortex response to locally enhanced GW activity

Additional ensemble runs have been performed using the UA-ICON model including stratospheric SSO GW hotspots with enhanced GW activity. This experiment has additionally been supported by DFG through project TRR 172 and grant KA 5835/3-1 and DKRZ resources have also been used through project bb1438.

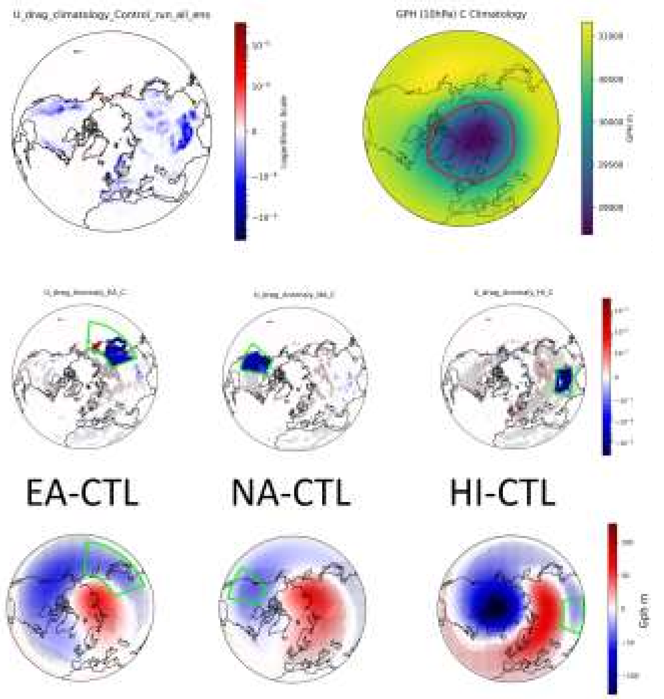

Fig. 2: Upper row: November- March mean zonal GW drag at 10 hPa (left) and height climatology and SPV boundary (right). Middle row: Zonal GW drag anomalies for the three experiments. Lower row: 10 hPa geopotential height anomalies for three experiments with localized GW enhancement.

The experiment consists of a Control and run and three Experiment runs with lower stratosphere GW enhancement in the in the Himalayan (HI), North American (NA), and East Asian (EA) region (Figure 2). Each run consists of a six member ensemble. First results show that all additional GW forcings lead to higher geopotential heights over Eurasia. The response in the single ensemble members, however, is relatively different. The aim of the study is to define clusters of vortex response and analyze their contribution to the observed response across all ensemble members

Stratospheric polar vortex morphology based on ERA5 reanalyses

Properties of the Arctic polar vortex such as onset and breakup dates, strength, shape and position have been analyzed based on ERA5 data of 45 winters, with a focus on extreme events, both SSW and extremely strong events [5]. This analysis has additionally been supported by DFG through grant KA 5835/3-1 and DKRZ resources have also been used through project bb1438. We find that, consistent with literature, the SPV center moves equatorward with time. To define the vortex strength, the SPV metric consisting of the product of vortex area and potential vorticity gradient at the vortex edge has been used. Generally, vortex position and strength are correlated (Figure 3). Special attention was given to three prominent extremely strong vortex (ESV) events, including the record breaking 2019 ESV. Considering the implications of climate change, it is hypothesized that both SSWs and ESVs could potentially occur in a single NH winter. For instance, an SSW might take place in December, while an ESV, potentially linked to ozone loss, could emerge during late winter/spring.

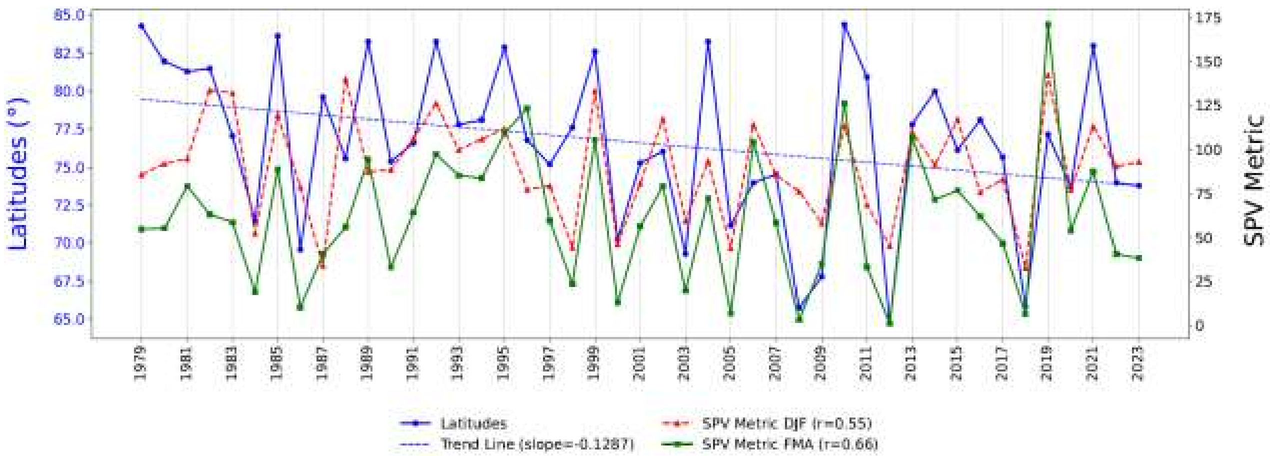

Fig. 3: Annual latitudinal variation of the height averaged SPV center (blue) and SPV metric for DJF and FMA. Correlation coefficient between SPV latitude and SPV metric at respective heights are given in the legend.

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Datasets

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