Project: **1438**

Project title: **ThE causes and consequences of exceptioNally strong stRatospherIc ArCtic polar vortices and the associated ozone Holes (ENRICH)**

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The work within the project included two parts. The first one was an ICON model experiment on gravity wave (GW) effects on the polar vortex, and the second one included the analysis of the stratospheric polar vortex (SP) with focus on extreme events, particularly extremely strong vortex (ESV) events.

1. ICON model experiment with modified GW

We utilized the ICON model version 2.6.6 with the upper-atmosphere extension (UA-ICON) as distributed by the German Weather Service (DWD). To evaluate the effect of regional forcing induced by hotspots of GWs on middle-atmosphere dynamics, specifically on the SPV, we conducted a set of 30-year-long climate sensitivity experiments using the UA-ICON model. The six ensemble simulations were run at an R2B4 ICON resolution (~160 km horizontal resolution) with 120 vertical levels extending up to 147 km.

We conducted control simulations (C) with the model in its default mode without any modifications. Additionally, we performed three sensitivity simulations with regionally intensified GW drag in the middle atmosphere. For these simulations, we modified the sub-scale orographic (SSO) drag parametrization such that only the GW drag in the middle atmosphere was intensified by a factor of 10 in three regions separately: North America (NA), East Asia (EA), and the Himalayas (HI). This scaling factor was determined experimentally through test runs to ensure that the enhanced drag remained within the bounds of natural variability, thereby maintaining realistic forcing. The stratospheric SSO drag anomaly (perturbation minus control run) for zonal wind, calculated for all ensembles, is presented in Figure 1 for these three sensitivity simulations.

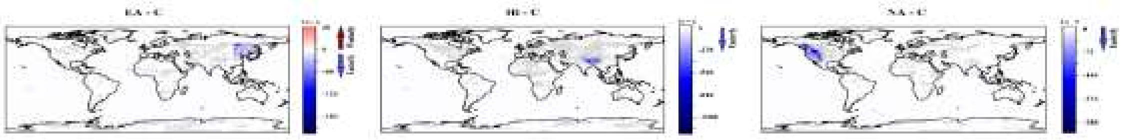

Figure 1: The SSO tendency on the zonal wind, scaled with pressure to represent the exerted forcing. The forcing is averaged over the stratosphere for all six ensemble members in three simulations. The panels display the differences between the perturbed run and the control run for East Asia (EA, left panel), Himalayas (HI, middle panel), and North America (NA, right panel). Dotted areas represent statistically significant changes between the perturbed and control runs. Note the different color scales used in each panel's color bar.

Figure 1 illustrates the stratospheric forcing exerted on the zonal wind for each simulation. We have begun analyzing these sensitivity experiments. The results indicate that the applied forcing affects the frequency of SSW and ESV events. The results were analysed using machine learning (ML) based clustering of the SPV. Optimum results are found for 10 clusters, shown in Fig. 2. Using class contribution analysis we were able to define the contribution of each cluster to mean changes through GW forcing. Robust results across ensemble members, however, may be hidden in overall variability. A publication including these results is in preparation (Mehrdad et al., 2025).

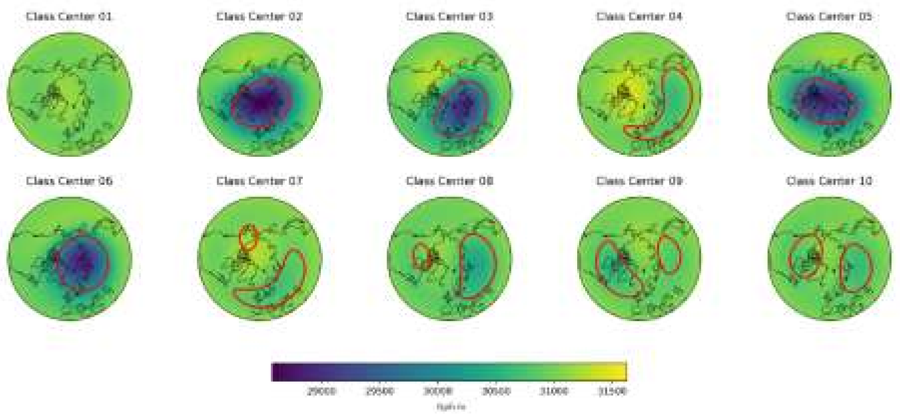

Figure 2: Class centers of 10 classes based on number of objects (vortices): C1: > 2 objects (unstable vortex), C2-C6: 1 object, C7-C10: 2 objects.

2. Polar vortex analysis with respect to extreme events

The work in this part included three components (1) Analysis of the SPV morphology using ERA5 data, (2) Comparison of the SPV morphology in existing ICON model data with switched of GW (3) Prediction of the stratospheric ozone content based on dynamical properties using ML, with focus on extremely strong events (ESVs). ESVs were recorded in the winters of 1996/97, 2010/11, and 2019/20. The main results are the following:

In (1) we explored the interannual variability and differences in SPV dynamics and morphology across three various levels (530 K, 600 K, 850 K). This includes examining extreme SPV events such as SSWs and ESVs, their intensity, frequency, and the climatic variables influencing their formation. We also address the shifting trend of the vortex center towards the Eurasian continent and the earlier formation of the vortex in the upper stratosphere (Kumar et al., 2025a).

In (2), ICON model results showed that removing of SSO GWs leads to a strong increase in frequency of ESVs, while missing non-orographic GWs resulted in no ESVs in the model. The former clearly shows the SSO GW forcing of the SPV, while the latter indicates the compensation effect owing to which missing GW drag may be compensated by resolved wave drag (Kumar et al., 2025b).

In (3) a novel approach to ozone prediction based on the morphological and dynamical properties of the SPV was constructed (Kumar et al., 2025c). We developed an algorithm using an explainable ML model, achieving an R^2 score of 80% and a correlation of 0.91 with observations. The training data set included two ESVs. Three ML models have been considered to develop the optimal algorithm for predicting ozone, namely XGBoost, Decision Tree, and Multilayer Perceptron. The algorithm using XGBoost accurately predicts the daily and seasonal patterns of ozone variations. It successfully captures the pattern of the lowest recorded ozone levels in the winter of 2019/20, though it overestimates ozone values by approximately 20 Dobson units. The observed and predicted ozone values are shown in Fig. 3. Note that mean ozone averaged over the polar cap > 63°N are shown, while ozone holes had a smaller area and not necessarily show up clearly in these data.

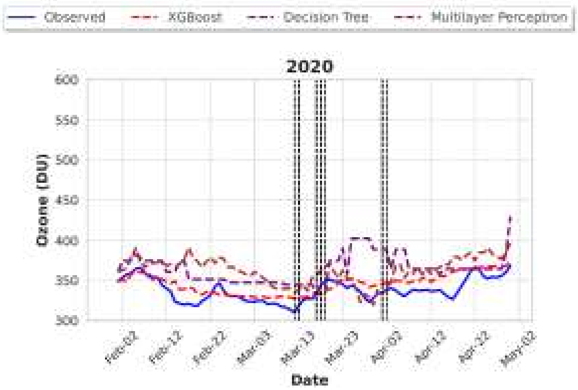

Figure 3: Time series of Observed and XGBoost, Decision Tree and Multilayer Perceptron predicted ozone during February-April in 2020. The black dotted vertical line represents dates when an ozone hole was recorded in 2020 (from Kumar et al., 2025c).

References :

Mehrdad, S., S. Marjani, D. Handorf, J. Quaas, C. Jacobi, 2025: Non-zonal forcing of the Northern Hemisphere winter circulation and effects on middle atmosphere dynamics. In preparation.

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