Project: **1438**

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

Principal investigator: **Christoph Jacobi**

Report period: 2025-07-01 to 2026-06-30

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, the second one included the analysis of the stratospheric polar vortex (SP) with focus on extreme events, particularly extremely strong vortex (ESV) events, and the development of a machine learning (ML) model to predict stratospheric ozone. A third part included the application and extension of a ML tool to analyse northern hemisphere circulation patterns based on ERA5 and CMIP6 model predictions.

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 used a set of 30-year-long climate sensitivity experiments using the UA-ICON model that has been performed during the first phase. The six ensemble simulations were run at an R2B4 ICON resolution (~160 km horizontal resolution) with 120 vertical levels extending up to 147 km. The experiments have been described in papers that now has been published (Mehrdad et al., 2025, 2026). Analysis of the model results with respect to ESV and SSW occurrence is currently ongoing.

2. Polar vortex analysis with respect to extreme events and ML based ozone prediction

The work in this part included two components (1) Analysis of the SPV morphology using ERA5 and ICON data, (2) 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. In addition (3), we extended and applied a ML tool (Mehrdad et al., 2024) to analyse northern hemisphere circulation patterns based on ERA5 and CMIP6 model predictions.

The main results are the following:

In (1) we examined 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. 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. These analyses have mainly been performed in the first phase, while in the second phase the related publications have been completed (Kumar et al., 2025a,b). Analysis of CMIP6 data with respect to ESV and SSW occurrence and their changes is currently ongoing.

In (2), a novel approach to ozone prediction based on the morphological and dynamical properties of the SPV was constructed and has now been published (Kumar et al., 2025c). A scatter plot of predicted vs. observed ozone to show the performance of the model is presented in Figure 1.

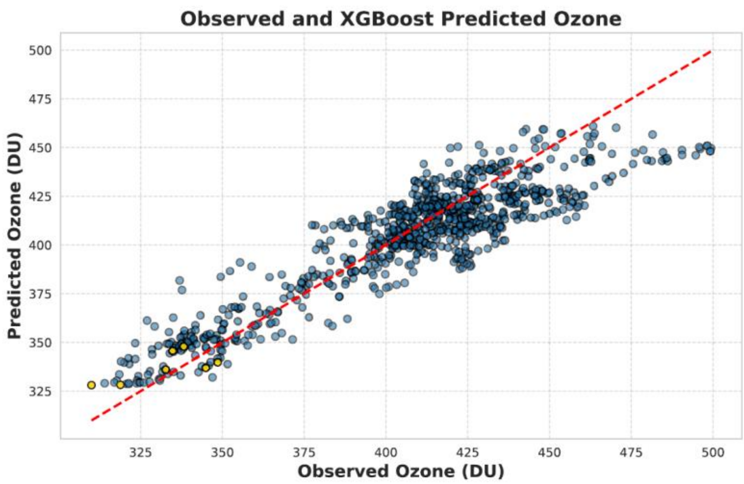

Figure 1: Observed and XGBoost predicted ozone with 0.91 correlation coefficient. The yellow filled symbols represent the dates when the ozone hole was recorded (2020-03-12, 2020-03-13, 2020-03-17, 2020-03-18, 2020-03-19, 2020-04-01, 2020-04-02).

In a further work package (3), we adapted and applied an existing ML tool (Mehrdad et al., 2024) to analyse CMIP6 model results guided by circulation patterns analysed from ERA5. This included the training of an autoencoder using ERA5, and finetuning with CMIP6, while analysing the obtained ERA5 circulation patterns based on the CMIP data. First results have been obtained from historical CMIP6 data and presented (Bizdaz et al., 2026). Application to future scenarios is ongoing. Figure 2 shows 6 pressure anomaly patterns obtained from k-means clustering for extended winter based on ERA5 and CMIP6, with good correspondence. Circulation patterns reasonably reproduced by the ML approach. The observed Northern Hemisphere circulation patterns are well captured by CMIP6 models.

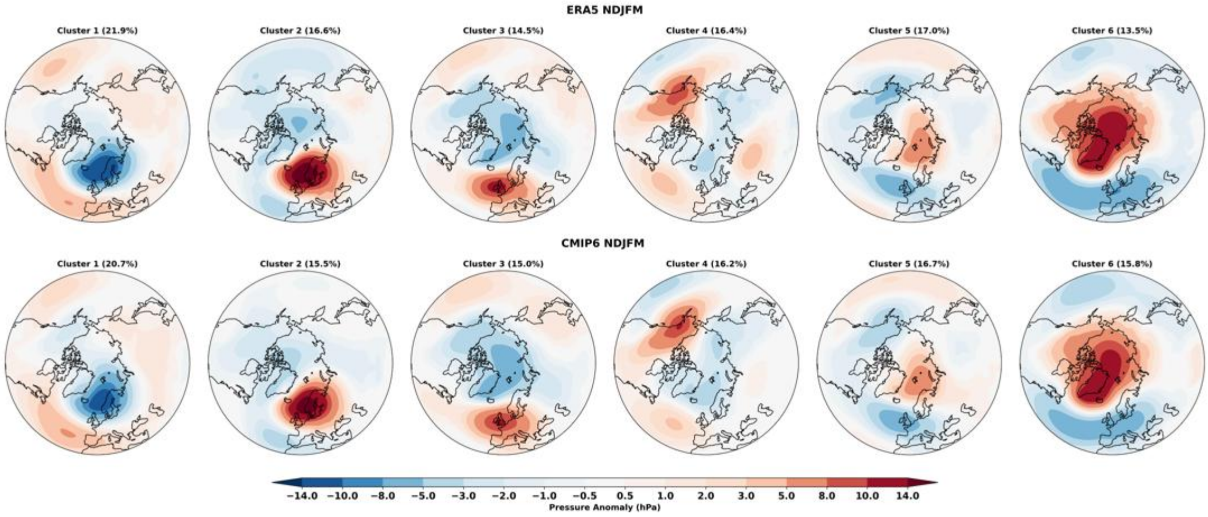

Figure 2: Extended winter (November – March, NDJFM) circulation patterns analysed from ERA5 (upper row) and CMIP6 (lower row).

References

1. Bizdaz, A., C. Jacobi, and D. Handorf, 2026: Assessing the ability of CMIP6 models to capture northern hemisphere circulation patterns: A data-driven analysis, Arctic System Science Conference 2026, 23.-27.3.2026, Potsdam.
2. Mehrdad, S., D. Handorf, I. Höschel, K. Karami, J. Quaas, S. Dipu, and C. Jacobi, 2024: Arctic Climate Response to European Radiative Forcing: A Deep Learning Approach, Weather Clim. Dynam., 5, 1223–1268, https://doi.org/10.5194/wcd-5-1223-2024.
3. Mehrdad, S., S. Marjani, D. Handorf, and C. Jacobi, 2025: Non-zonal gravity wave forcing of the Northern Hemisphere winter circulation and effects on middle atmosphere dynamics, Weather Clim. Dynam., 6, 1491–1514, https://doi.org/10.5194/wcd-6-1491-2025.
4. Mehrdad, S., S. Marjani, D. Handorf, and C. Jacobi, 2026: Northern Hemisphere stratospheric polar vortex morphology under localized gravity wave forcing: a shape-based Classification, Atmos. Chem. Phys, 26, 3391–3415, https://doi.org/10.5194/acp-26-3391-2026.
5. Kumar, A., K. Karami, and C. Jacobi, 2025a: A 45-year climatological study of Arctic stratospheric polar vortex dynamics and morphology using ERA5 Data (1979-2023), Clim. Dyn., 63, 403, https://doi.org/10.1007/s00382-025-07889-0.
6. Kumar, A., K. Karami, C. Jacobi, and S. Mehrdad, 2025b: Exploring the impact of orographic and non-orographic gravity waves on Arctic stratospheric polar vortex dynamics and springtime ozone loss, J. Atmos. Sol.-Terr. Phys., 273, 106538, https://doi.org/10.1016/j.jastp.2025.106538.
7. Kumar, A., J. Mandal, S. Mehrdad, and C. Jacobi, 2025c: A novel approach to predict the arctic stratospheric ozone from stratospheric polar vortex dynamics using explainable machine learning, Sci. Rep., 15, 36473, https://doi.org/10.1038/s41598-025-24379-9.