Final report for Project **1135**
Project title: **3-d cloud-radiative effects on midlatitude cyclones and their predictability**
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The dynamics and predictability of extratropical cyclones are strongly influenced by cloud diabatic processes. While the impact of latent heating is well understood, the impact of cloud radiative heating (CRH) on extratropical cyclones has received little attention. Over the last five years, our project investigated the impact CRH and its uncertainty on the dynamics of extratropical cyclones using the ICON model with various modeling approaches and methods. In total, our project resulted in three peer-reviewed publications, with one additional manuscript currently under review with minor revisions (submitted), as well as one published PhD thesis and one published Master's thesis. The novelty of our project is that for the first time, we: (i) identified the mechanisms through which CRH affects the dynamics of idealized extratropical cyclones; (ii) assessed the uncertainties in CRH due to radiation parameterization for an extratropical cyclone; (iii) investigated the impact of CRH on four different North Atlantic cyclones; and (iv) demonstrated that CRH uncertainties can in fact contribute to forecast error growth on synoptic scales.

1- How does CRH affect the dynamics of idealized extratropical cyclones?
We started by investigating the impact of CRH on idealized cyclones. We developed a new modeling technique that isolates the impact of CRH on idealized cyclones in an easy-to-interpret manner. Keshtgar et al. (2023) and Voigt et al. (2023) showed that CRH substantially affect the intensity of cyclones with the impact being more prominent at upper tropospheric levels. Voigt et al. (2023) identified a tug-of-war between low-level clouds, which weaken cyclones, and high-level clouds, which strengthen them. By diagnosing the evolution of difference potential vorticity (PV) between simulations with and without CRH, Keshtgar et al. (2023) showed that CRH affect the dynamics of an idealized cyclone and near-tropopause PV through continues modulation of latent heating within the warm conveyor belt of the cyclone which subsequently changes the divergent and rotational flows near the tropopause (Fig. 1). Results from these studies suggested that model uncertainties in CRH may also influence model predictions of cyclones.
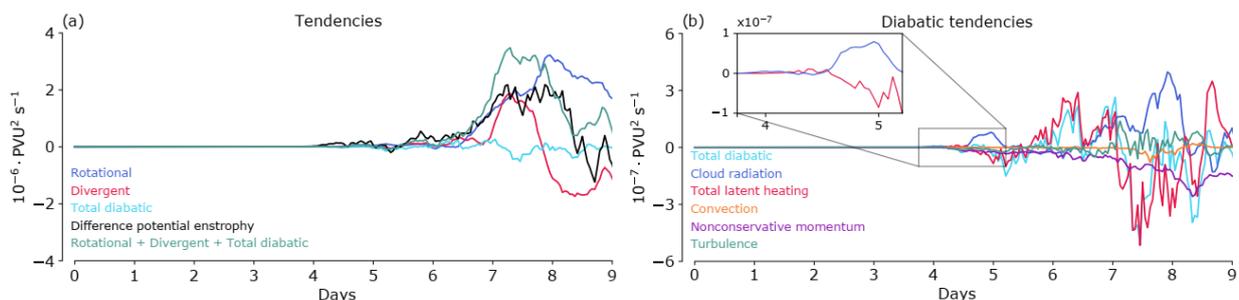

Fig. 1: Impact of CRH on near tropopause PV for an idealized cyclone (adapted from Keshtgar et al. (2023)). Panel (a) shows the evolution of the spatially-averaged difference potential enstrophy near the tropopause on the 326 K isentrope and contributions from different processes (colors). Difference potential enstrophy is defined as the squared PV difference between the simulations with and without CRH. Panel (b) decomposes the diabatic contribution into different processes. The inset in panel (b) shows that CRH initially kicks-off changes in PV (blue line), which then changes cloud latent heating (red line).

2- How large are the CRH uncertainties and what are their implications for the dynamics of cyclones?
Building on our previous findings, we quantified the uncertainties in CRH due to various factors in an idealized extratropical cyclone using large-eddy-model simulations and offline radiation transfer calculations. We demonstrated that cloud horizontal heterogeneity and ice optical parameterization have a greater impact on the mean CRH uncertainty at larger spatial scales, making them more relevant to the large-scale dynamics of the cyclone (Keshtgar et al., 2024). Conversely, 3D cloud-radiative effects are

generally much smaller, particularly for stratiform clouds within the warm conveyor belt of the cyclone. In particular, our work highlighted the potential for improving the simulation of CRH by better representing ice optical properties.

3- How does CRH affect the dynamics of North Atlantic cyclones?

To bridge the gap between idealized studies and practical application, we investigated the impact of CRH on the dynamics of four North Atlantic cyclones observed during the North Atlantic Wave and Downstream impact EXperiment (NAWDEX) field campaign by performing hindcast simulations. Our study demonstrated that CRH also affects the intensity of North Atlantic cyclones and PV near the tropopause, and that the magnitude of the impact can vary over time and depends on the large-scale flow configuration (Keshtgar, 2024; Keshtgar et al., 2026 (under review)). Our PV tendency budget analysis confirmed that, consistent with idealized studies, CRH affects the dynamics of North Atlantic cyclones mainly through changes in latent heating and vertical motion, which subsequently affect the large-scale flow near the tropopause.

4- Do uncertainties in CRH have a measurable impact on near-tropopause dynamics?

To highlight the importance of CRH uncertainties for the dynamics of extratropical cyclones and forecast error growth on synoptic scales, we ran hindcast simulation during different IOPs of NAWDEX using different ice optical parameterizations and radiation solvers. Our work showed that uncertainties in CRH affect the dynamics of cyclones and PV near the tropopause through the same mechanism identified for the impact of the presence of CRH (see Fig. 2; Keshtgar et al., 2026 (under review)). The greater the uncertainty in CRH, the greater the impact on cyclones and PV near the tropopause. Our work, therefore, highlighted the importance of improving the representation of CRH in numerical weather prediction models.
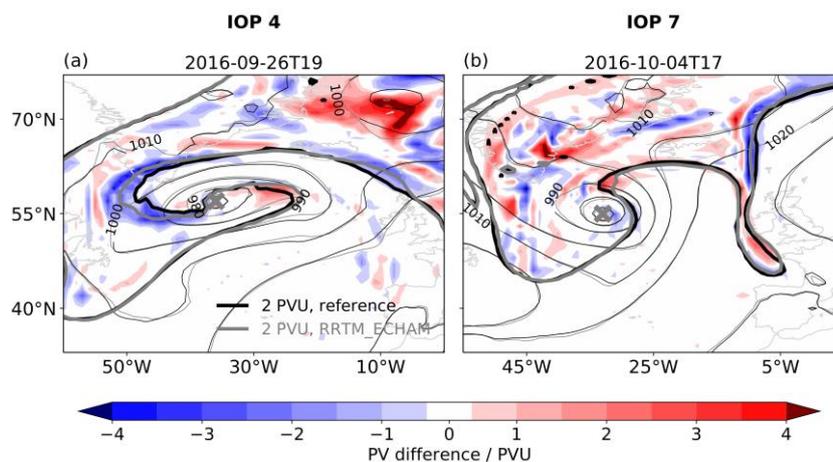

Fig. 2: Impact of CRH uncertainty on PV near the tropopause at the time of cyclone peak intensity during IOPs 4 and 7 of NAWDEX. *PV differences are calculated between the simulations run with the RRTM radiation scheme (RRTM_ECHAM) and with the ecRad (reference) radiation scheme. Black indicates the reference simulation, while grey indicates the RRTM_ECHAM simulation. The thin contours show mean sea level pressure (every 10 hPa), the thick contours show the dynamical tropopause as given by the 2 PVU contours, and the crosses show cyclone positions.*

References and project's publications

Butz, K. (2022): The radiative impact of clouds on idealized extratropical cyclones, *Master's thesis, University of Vienna*. https://doi.org/10.25365/thesis.71895

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