Project: **1135**
Project title: **3-d cloud-radiative effects on midlatitude cyclones and their predictability**
Principal investigator: **Aiko Voigt**
Report period: **2022-11-01 to 2023-10-31**

Over the past decade, an increasing number of studies highlighted the importance of radiation for the midlatitude circulation. However, there has been a lack of understanding of how radiative processes within the atmosphere, especially through cloud-radiative interactions, affect the dynamics and predictability of the midlatitude circulation. During the last 3 years, our project has addressed this question. Our idealized cyclone studies showed for the first time that cloud-radiative heating and cooling (CRH) has a significant impact on cyclone intensity, with competing effects from high- and low-level clouds (Voigt et al., 2023). We have shown that the impact of CRH on the cyclone involves continuous radiatively induced changes in cloud microphysics, latent heating, and subsequent near-tropopause winds during the cyclone life cycle (Keshtgar et al., 2023a). In a follow-up study we quantified sources of uncertainty in CRH within an idealized cyclone and showed that the parameterization of ice-optical properties and cloud horizontal heterogeneity are important factors that can contribute to cyclone forecast error (Keshtgar et al., 2023b). Our work so far has focused on idealized cyclones. To put the results of idealized studies into perspective, in 2023 we started to investigate to what extent our results also hold in realistic weather situations. The progress of the project to date is summarized below.

0- Summary of used resources until October 2023

- Node hours: 6993 out of 9594 (expired Node hours: 3698)
- Work: 101000 Gb out of 180000 Gb allocated
- Arch: 64000 Gb out of 246000 Gb allocated

Initially, we planned to investigate the impact of CRH on the dynamics of one midlatitude cyclones at the convective-permitting resolution of 2.5 km (see our request for 2023). However, our recent results (Voigt et al., 2023) as well as our test hindcast simulations showed different CRH effects for different large-scale conditions. We therefore decided to investigate the impact of CRH and its uncertainty on several cyclones and for different time scales. As a result, we changed our modeling setup and used a coarser horizontal grid resolution of 10 km, as described in detail below, which resulted in less resource consumption. Raw simulation output from the idealized ICON-LEM simulations (see our 2022 report) and our 2023 hindcast simulations have not been archived yet, as we need to process the raw data on work for further analysis and for the revision of Keshtgar et al. (2023b), which has recently received minor revisions. We will archive the raw data quickly after the final publication. We also plan to use the remainder of the allocated resources for further simulations that will quantify the impact of CRH uncertainties on the midlatitude large-scale circulation.

1- Hindcast simulations during the 2016 NAWDEX field campaign with ICON-NWP

We used ICON-NWP in the limited-area setup over a large North Atlantic domain (23°-80° N and 78° W-40° E) for hindcast simulations during the 2016 NAWDEX Intensive Observing Periods (IOPs). Selected case studies are cyclone Valadiana (IOP 4), tropical-extratropical cyclone Karl (IOP 4), the so-called Stalactite cyclone (IOP 6), and the so-called Frontal-wave cyclone (IOP 7). Comparing simulations of these four cyclones allowed us to study the dependency of the CRH impact on the cyclone and the configuration of the synoptic circulation. For simplicity, we refer to the cyclones hereafter as IOPs. IOPs 4 and 7 occurred just after IOPs 3 and 6, respectively. This has the advantage that we could examine the impact of CRH and its uncertainty on the near-tropopause downstream evolution for longer 7-day simulations that include both IOPs.

We ran ICON with a horizontal resolution of R2B08 (equivalent to 10 km) and 75 vertical levels. For initial and lateral boundary conditions, we used the 3-hourly IFS analysis and forecast data. We ran ICON's NWP configuration (release version 2.6.2.2) including the operational deep and shallow convection schemes, 1-moment microphysics, and ecRad radiation. We ran two control simulations, one from 22-09 to 28-09, covering IOPs 3 and 4, and one from 30-09 to 06-10, covering IOPs 6 and 7. To verify that our setup captured the observed cyclone structures, we compared the cyclone intensity metrics between the ICON runs and the ERA5 reanalysis data, and the results showed good agreement.

2- CRH impact on the dynamics of the four studied cyclones

We performed simulations using the Clouds On-Off Climate Intercomparison Experiment (COOKIE) method (Voigt & Albern, 2019), for which clouds are made transparent to radiation. This was achieved by passing only the clear-sky radiative heating from the radiation scheme to the model dynamical core, instead of the all-sky radiative heating that includes the cloud contribution. We ran two sets of COOKIE simulations: - short 3-day simulations for each IOP, and long 7-day simulations that cover two IOPs (IOP 3 and 4, and IOP 6 and 7, respectively). The CRH impact was then diagnosed by comparing the cyclone metrics between control and COOKIE simulations.

CRH does not significantly affect the intensity of cyclones in terms of cyclone central pressure and 10 m wind speed in the short COOKIE simulation. However, the absence of CRH in the long COOKIE simulations leads to a significant weakening of IOP 4 and, to a lesser extent, IOP 7. Our idealized studies also showed that near the surface, the CRH impact on the intensity metrics is muted. However, CRH clearly increases the cyclone precipitation rate, indicating changes in the latent heating in the ascending regions of the cyclones, which affects the development of the near-tropopause flow. Figure 1 illustrates the CRH impact on the near-tropopause potential vorticity (PV) during IOPs 4 and 7. The short simulations show relatively small changes in PV, while the long simulations show substantial changes. In the latter, the absence of CRH results in weaker trough and ridge amplitudes for IOP 4. A similar pattern emerges for IOP 7, but with a smaller magnitude. Comparing the short and long simulations thus showed that the CRH impact takes about 4 days to noticeably affect near-tropopause dynamics.

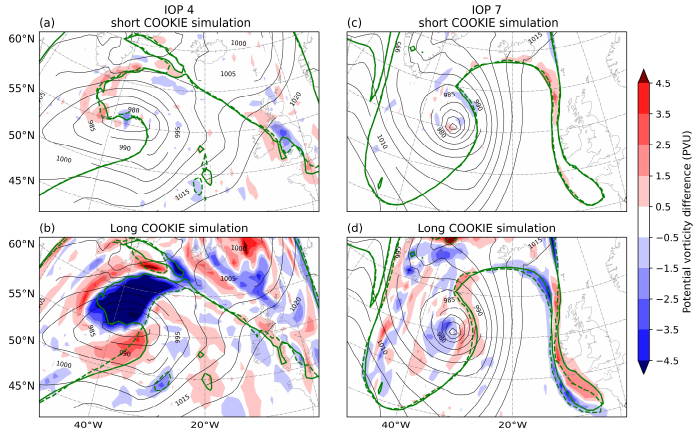

Figure 1: Potential vorticity difference at the 320 K isentrope around the time of maximum cyclone intensity between simulations with and without CRH for (a, b) IOP 4 and for (c, d) IOP 7. The top and bottom panels show the result for the short and long COOKIE simulations, respectively. Black contours show the mean sea level pressure for cyclones with CRH runs. Green solid and dashed contours represent the position of the dynamic tropopause (2 PVU) for simulations with and without CRH, respectively.

3- Understanding the mechanism underlying the cloud-radiative impact

To understand how CRH affects the near-tropopause dynamics and why its impact depends on time and the synoptic situation, we applied the PV error growth framework (Baumgart et al., 2018). As in our idealized cyclone studies, for each IOP the direct diabatic modification of PV near the tropopause due to the presence of CRH precedes further changes by the upper-tropospheric divergent flow as a result of latent heating modulation by CRH. Subsequently, differences in PV are amplified and dominated by the rotational flow. To evaluate the growth of the differences, we examined the evolution of the different contributors to the potential enstrophy calculated between the control and long COOKIE simulations (Figure 2). The differences are much larger during IOPs 4 and 7, as the differences are amplified by the existing differences in the tropopause already caused by CRH during the earlier IOPs 3 and 6. However, in contrast to the general mechanism of error growth amplification (Baumgart et al., 2018), which is always dominated by changes in the rotational flow, we see times of sudden increases or decreases in the divergent flow tendencies. These times coincide with the time of maximum upward motions in the warm conveyor belts of IOPs 4 and 7 (annotations in Figure 2), during which CRH changes the amount of latent heating and subsequently the divergent flow. Interestingly, we found that changes in the divergent flow amplify the error during IOP4 but reduce the error during IOP7. This suggests that CRH uncertainty might have a stronger effect on the near-tropopause dynamics during IOP 4 than IOP 7.

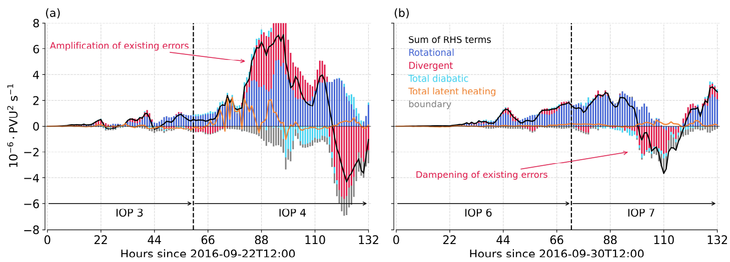

Figure 2: Evolution of the spatially averaged different contributors to potential enstrophy between simulations with and without CRH at the 320 K isentrope level during (a) IOPs 3 and 4 and (b) IOPs 6 and 7. The vertical dashed line separates the time of the first and second IOPs in both panels.

4- Impact of CRH uncertainty on the evolution of near-tropopause dynamics

We ran additional simulations to check whether CRH uncertainties impact the near-tropopause dynamics and whether PV differences increase to larger values for a specific large-scale synoptic configuration, such as during IOP 4. For the first set of simulations, we replaced the default ice-optical parameterization of Fu with Baran and for the second set we used the old operational RRTM radiation scheme instead of ecRad. Although CRH uncertainties are quite small in magnitude, we showed that they can influence the near-tropopause dynamics. The pattern of the different tendencies is quite similar to Figure 2 and differences grow to larger values during IOP 4 than IOP 7. In our idealized studies we showed that longwave cloud top cooling is much stronger with RRTM than ecRad and this leads to stronger latent heating variation in the warm conveyor belt of the cyclone. This is consistent with our realistic cyclone studies, illustrating the benefit of combining idealized and realistic simulations. We are currently writing these results up for publication. Our plan for the coming year is to study these results more in detail, especially focusing more on the impact of CRH uncertainties on the dynamics of the warm conveyor belts (see our request document for 2024).

References:

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