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

The impact of cloud-radiative heating (CRH) on the dynamics and predictability of extratropical cyclones remains poorly understood. However, recently we have shown that cloud radiative effects can considerably impact idealized extratropical cyclones (Keshtgar et al., 2022; Butz., 2022). We have shown that the cloud radiative impact can be understood from the modulation of latent heating by CRH and well-studied impacts of latent heating on extratropical dynamics. However, CRH is uncertain in models due to inherent problems of approximations applied in the radiation schemes, the poor representation of clouds, and limitations in the parameterization of cloud ice optical properties. These uncertainties in CRH have the potential to influence the dynamics of cyclones and error growth in cyclone forecasts (Keshtgar et al., 2022). Therefore, we have quantified uncertainties in CRH in different parts of an idealized extratropical cyclone using ICON-LEM simulations and offline radiative transfer calculations. Furthermore, we have shown how these uncertainties could be relevant to the dynamics of cyclones. The project's progress to date is summarized below.

0- Summary of used resources until October 2022

- Node hours: 15000 out of 206360 (Expired Node hours: 139934)
- Work: 78000 Gb out of 95000 Gb allocated
- Arch: 18000 Gb out of 290000 Gb allocated

In the first quarter of 2022 (Jan-Mar), Levante was not ready for productivity simulations with ICON, and the resources expired. In addition, there was a large chunk of resources that were requested for two sets of ICON-LEM simulations with the 3d-radiation scheme "TenStream". Although we successfully coupled the TenStream solver to ICON-LEM and used it for the first time on Levante, it turned out that using it interactively in ICON-LEM is too computationally expensive and that further code optimizations would be necessary, which is outside of our area of expertise and project aims. Parallel to this effort, our offline radiative transfer calculations with the MYSTIC solver showed that 3d-radiative effects are small for the simulated cyclone. Thus, in the interest of time and to focus more on relevant aspects of CRH uncertainties, we decided to drop the simulations with the interactive TenStream solver and instead target our efforts at offline radiative transfer simulations. Although the latter simulations took much time to prepare and post-process, they did require substantially fewer computational resources, leading to a seemingly large chunk of expired resources. We plan to use the remaining resources for this year to i) run LEM simulations with ecRad's 3-d radiation scheme "SPARTACUS" and ii) additional sensitivity tests with ICON-NWP to assess the relative magnitude of CRH uncertainties on the large-scale evolution and circulation of the idealized cyclone.

1- Model developments in ICON-LEM: using a planar grid with time-dependent lateral boundary conditions and LEM simulations

We used a planar grid for the ICON-LEM simulations. In contrast to the planar channel grid used in our NWP simulations (see the report of 2021), this grid does not apply a periodic boundary in the zonal direction and does not use fixed north/south boundaries. Instead, it utilizes time-dependent lateral boundary conditions provided by a previously performed ICON-NWP simulation. In addition, we have added in ICON-LEM our modeling technique to isolate the impact of CRH by removing the impact of clear-sky radiative heating (see the report of 2021).

Figure 1 shows the position of the LEM domains within the cyclone simulated with ICON-NWP at a convection-permitting resolution of 2.5 km. The initial and lateral boundary conditions are derived for each LEM domain from the NWP simulation. The LEM domain sizes are 471 km x 667 km (equivalent to a 6x6 degrees plane at 45°N) with a horizontal resolution of 300 m and 150 vertical model levels. Each domain targets different cloud types within the extratropical cyclone (Figure 1 b). We ran LEM simulations for 12 hours using explicit convection, two-moment microphysics, 3-d Smagorinsky diffusion for turbulence, and the ecRad homogenous radiation solver.

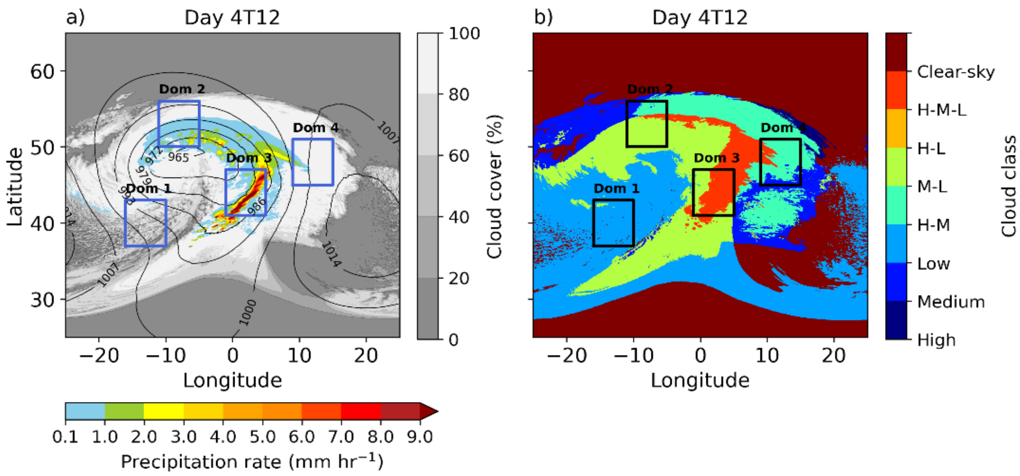

Figure 1: (a) Distribution of cloud cover and precipitation rate at day 4.5 of the baroclinic life cycle simulation with ICON-NWP. Panel (b) represents different cloud types classified into seven categories according to their vertical extension. Rectangles in both panels show the position of LEM domains analyzed in Figs. 2 and 3.

2- Quantifying cloud radiative heating uncertainties in different parts of the extratropical cyclone

To account for factors contributing to CRH uncertainty, we ran offline radiative transfer calculations with the LibRadTran software package (Emde et al., 2016) using output from the LEM simulations. Also, to account for the problem of poor representation of clouds in the NWP model, we reduced the information content of LEM clouds by horizontally coarse graining the cloud optical properties in each vertical layer to a resolution comparable to the NWP horizontal resolution (2.5 km). The resolution factor in Figure 2 thus is a measure of the impact of cloud horizontal heterogeneity.

Figure 2 shows that, on average and for a given meteorological condition, the resolution is the largest source of CRH uncertainty (Figure 2, blue bars). This uncertainty is much higher for the shallow stratocumulus clouds southwest of the cyclone center than the more uniform and extensive clouds in the cyclone's warm conveyor belt and fronts (cf. Figure 2 panel a with panels b, c, and d). The 3-d cloud-radiative effects are small for all four domains (black bars) and are much smaller than uncertainties caused by differences in the radiation solvers and the assumed ice optical properties.

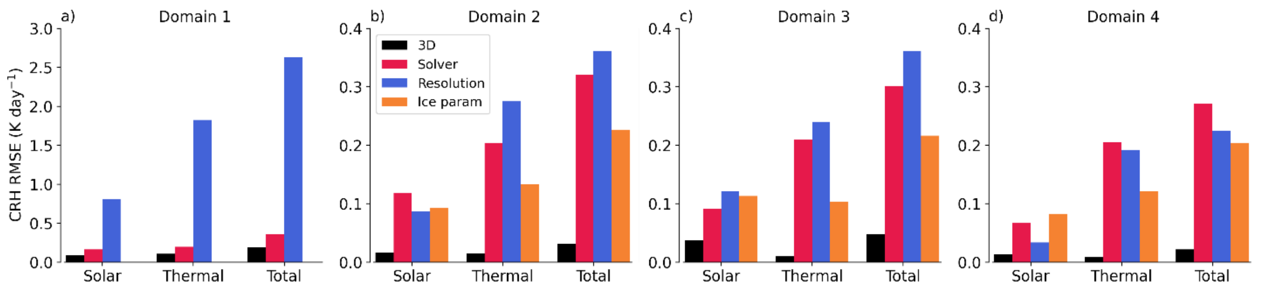

Figure 2: Cloud radiative heating uncertainties diagnosed as root mean square error (RMSE) due to 3-d radiative effects (black), radiation solvers (red), resolution (blue), and ice optical parametrization (orange) averaged over the 4 LEM domains.

Our results also showed that adding a cloud vertical overlap parametrization leads to considerable uncertainty in CRH (not shown). The magnitude of CRH uncertainty due to the resolution in the cyclone's warm conveyor belt and fronts is more or less in the same range as the uncertainty due to changes in ice optical properties. This suggests that in order to reduce CRH uncertainty in NWP models, improving the ice optical parametrization is more important than increasing horizontal resolution or using a comprehensive radiative transfer solver.

3- Impact of ice optical parametrization on cloud radiative heating and precipitation rate

Although the CRH uncertainty due to ice optical properties seems small in the domain average (Figure 2), local differences might be large enough to change the cloud microphysical heating and affect the cyclone.

To test this idea, we first analyzed the sensitivity of CRH to different ice optical parametrizations in the offline radiation calculations using the ice optical parametrizations of Fu (Fu., 1996; Fu et al., 1998) and Baum (Baum et al., 2014). Then, we ran further LEM simulations over the cyclone's warm conveyor belt using the ice optical parametrization available in ICON (Echam6, Fu, and Baran (Baran et al., 2016)).

Figure 3 shows that in comparison to the more realistic cloud ice optical parametrization of the Baum scheme, the Fu parametrization (also used in ICON'S implementation of the ecRad scheme) overestimates longwave cloud top radiative cooling and warming from below (implying a stronger radiative destabilization of the cloud). The same finding holds for shortwave cloud top radiative warming and cooling from below (implying a stronger cloud stabilization). This means that the shortwave and longwave cloud radiative uncertainties for Fu parametrization partially compensate for each other.

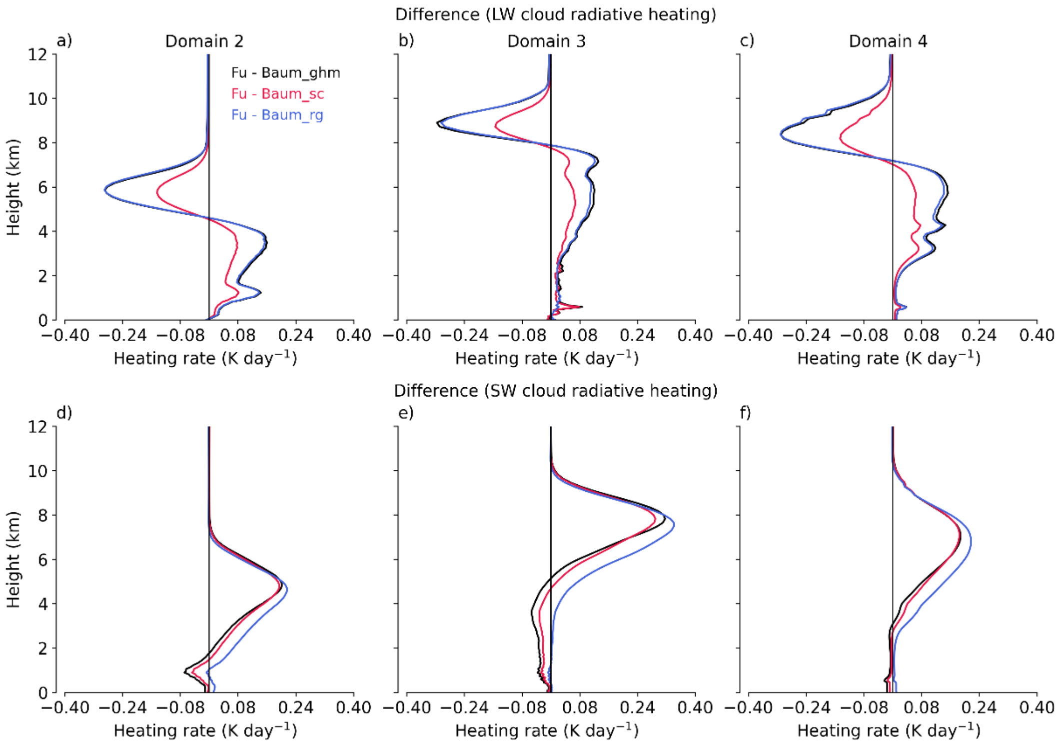

Figure 3: Differences in vertical profiles of longwave cloud radiative heating between simulations with the ice optical parametrization of Fu and Baum using different ice habits for domains 2, 3, and 4. The bottom row is for shortwave cloud radiative heating.

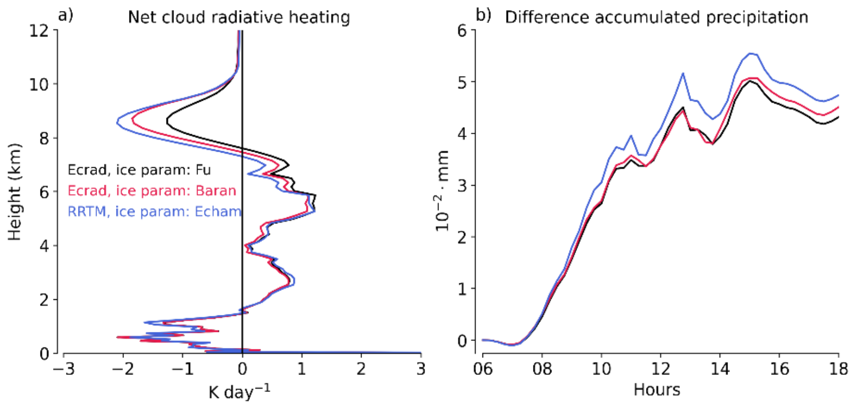

Figure 4: (a) Domain and time mean of net cloud radiative heating over the cyclone's warm conveyor belt using ice parametrization of Echam6, Baran, and Fu. (b) Time evolution of accumulated precipitation differences with respect to the simulation without CRH.

In ICON-LEM simulations, the cloud radiative destabilization effect is smaller with Fu parametrization compared to the better ice optical parametrization of Baran (Figure 4 a). On the other hand, the Echam6 cloud optical parametrization overestimates cloud top cooling, which leads to stronger changes in cloud microphysical heating. This is shown by the evolution of precipitation differences between simulations with different ice optical properties and the simulation without CRH. The biggest difference in precipitation is for the simulation with ice optical parametrization of Echam6, followed by the simulations with Baran and Fu ice optical parametrizations, respectively.

We are currently writing these results up for publication. Our plan for the coming year is to study these impacts by simulating a case study of a North Atlantic cyclone observed during the NAWDEX field campaign (see our request document for 2023).

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