Project: **1135**
Project title: **3-d cloud-radiative effects on midlatitude cyclones and their predictability**
Principal investigator: **Aiko Voigt**
Report period: **2023-11-01 to 2024-10-31**

Over the past four years, our project has demonstrated the importance of cloud-radiative heating (CRH) and its uncertainty for the dynamics of extratropical cyclones, with implications for predictability. We combined different modeling approaches and methods to gain a comprehensive understanding of the CRH impact, from idealized baroclinic life cycle (Keshtgar et al., 2023; Voigt et al., 2023) to large eddy model (Keshtgar et al., 2024) and hindcast simulations (Keshtgar, 2024). In 2024, our focus was on the impact of CRH and its uncertainties on the dynamics of North Atlantic cyclones. We have also performed different simulations to better understand the interaction between CRH and cloud microphysics, which we have argued to be the most important aspect of the CRH impact on cyclones. The progress of the project to date is summarized below.

0- Summary of used resources until October 2024

- Node hours: 4352 out of 5106 (expired Node hours: 1766)
- Work: 78000 Gb out of 89000 Gb allocated
- Arch: 14000 Gb out of 41000 Gb allocated

Part of the allocated resources for 2024 were utilized to repeat our hindcast simulations to address a minor inconsistency identified between the simulations (see our 2023 report). Progress on our 2024 proposal experienced some delays as the PhD candidate carrying out the project focused on completing his thesis, which successfully was defended this summer (Keshtgar, 2024). Thus, we will continue with our 2024 proposal in 2025, with some adjustments (see our request for 2025). The raw simulation output from our 2024 simulations have not been fully archived, as we need to process the raw data on the workspace for further analysis and for the submission of our new preprint.

1- Cloud-radiative impact on the dynamics of North Atlantic cyclones

We used the ICON model in a limited area mode to perform hindcast simulations during the 2016 NAWDEX field campaign (see our 2023 report for details of the model setup). To investigate the impact of CRH on North Atlantic cyclones, we compared simulations with and without CRH. Our results showed that CRH significantly affects latent heating, vertical motion, and precipitation rate associated with cyclones. We showed that the same as for the idealized cyclones, CRH affects potential vorticity (PV) near the tropopause by modulating the latent heating within the warm conveyor belts (WCBs) and subsequent changes in the upper-level large-scale winds. We further showed that uncertainties in the CRH associated with the ice optical parameterization also affect PV near the tropopause. Results from this study have been published in the PhD thesis of Behrooz Keshtgar (Keshtgar 2024). We have also prepared a manuscript based on these results, which will be submitted soon.

2- Cloud-radiative impact on the warm conveyor belt of the Frontal-wave cyclone

Our studies have shown that the impact of CRH mainly works by modulating cloud microphysical heating within the WCB of cyclones. To better understand the interplay between CRH and cloud microphysics, we investigated the impact of CRH on the WCB of a cyclone using large eddy model simulations (see our 2024 proposal).

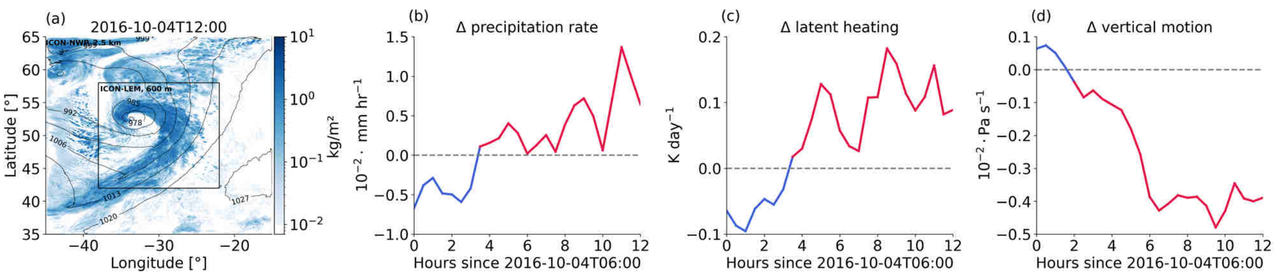

Figure 1: *A snapshot of column-integrated cloud water from the ICON-NWP and ICON-LEM (inner domain) simulations at 12 UTC on 4 October 2016. Panel (b) shows the evolution of domain-mean difference precipitation rate. Panels (c) and (d) show domain- and mass-weighted vertical mean difference of latent heating, and vertical motion, respectively. Differences are calculated between simulations with and without CRH.*

We performed a simulation with the ICON-NWP model at a convection-permitting resolution of 2.5 km to simulate the Frontal-wave cyclone (IOP 7 of NAWDEX). The output of this simulation provided the initial and hourly lateral boundary conditions for the LEM simulations. We ran ICON-LEM simulations at a 600 m resolution over the WCB of the cyclone during its growth phase (Fig. 1a, inner domain). To assess the impact of CRH, we compared simulation with and without CRH. Figure 1 shows a systematic impact of CRH on the WCB of the cyclone, with weakened and enhanced mean precipitation rate coinciding with weakened and enhanced latent heating and vertical motion (Fig. 1b, c and d). Our preliminary results indicate that even on shorter time scales of hours and prescribed large-scale flow, CRH can significantly affect the dynamics of the WCB. We are going to extend our analysis from these simulations and plan to repeat the ICON-NWP and LEM simulations next year to further assess the impact of CRH and microphysical uncertainties on the dynamics of the WCB (see our 2025 proposal).

3- Cloud-radiative impact on an idealized deep convective cloud

Motivated by our findings on the impact of CRH on the WCB of a cyclone, we also investigated the impact of CRH on an idealized deep convective cloud, which can represent the embedded convection within the WCBs. The simulations were based on the Weisman and Klemp (1982) test setup. Following Keshtgar et al. (2023), we ran two simulations, one without radiation and one with only the contribution of CRH. The results show that CRH significantly increases the convection and precipitation rate by enhancing latent heating and vertical motion (not shown). In addition, we derived the microphysical process rates from the two-moment microphysics we used in the simulations to gain a process-based understanding of the CRH impact on cloud microphysics.

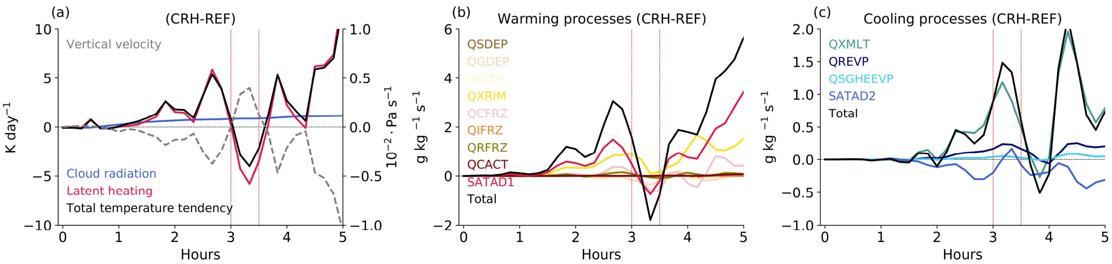

Figure 2: *Evolution of (a) mass-weighted difference temperature tendencies, vertical motion, (b-c) microphysical process rates. Processes leading to warming and cooling are shown in panels (b) and (c), respectively. Processes are shown for vapor deposition on ice (QIDEP), snow (QSDEP), graupel and hail (QGDEP), riming (QXRIM), freezing of rain (QRFRZ), melting of ice hydrometeors (QXMLT), evaporation of melting ice hydrometeors (QSGHEVAP), evaporation of rain (QREVAP), first and second saturation adjustments (SATAD1 and 2), homogeneous freezing of cloud droplets (QCFRZ), homogeneous and heterogeneous ice nucleation (QIFRZ), and CCN activation (QCACT).*

Figure 2 shows a systematic change in atmospheric temperature tendency, vertical motion and microphysical process rates by CRH. CRH enhances heating from warm microphysical processes, most notably from condensation and riming. The enhanced temperature tendency promotes vertical motion and feedback on microphysical process rates. Interestingly, the negative temperature tendency between hours 3 and 3:30 corresponds to the enhanced melting of frozen hydrometeors and therefore strong cooling and weakened vertical motion. Our results show that assessing the evolution of microphysical process rates is useful in explaining the impact of CRH on the dynamics of WCBs which we are going to explore further in 2025.

References:

Keshtgar, B., Voigt, A., Hoose, C., Riemer, M., & Mayer, B. (2023). Cloud-radiative impact on the dynamics and predictability of an idealized extratropical cyclone. *Weather and Climate Dynamics*, *4*(1), 115–132. https://doi.org/10.5194/wcd-4-115-2023

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