Project: **1135**
Project title: **3-d cloud-radiative effects on midlatitude cyclones and their predictability**
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Report period: **2020-11-01 to 2021-08-31**

The impact of cloud-radiative heating on midlatitude cyclones is currently not well understood, yet recent evidence suggests that it can be model dependent and important. By running global ICON-NWP simulations as well as limited-area channel simulations with ICON-NWP and by analyzing these in terms of potential vorticity error growth, we have shown that cloud-radiative heating has a noticeable impact on the cyclone dynamics and, within the idealized framework of baroclinic lifecycles, cyclone predictability. The project progress to date is summarized in the steps below.

0- Summary of used resources until August 2021

- Nodehours: 16000 out of 28000 (essentially no expired Nodehours)
- Work: 38400 Gb out of 39100 Gb allocated
- Arch: 40000 Gb out of 80000 Gb allocated

We are on very good track to use all of the requested resources. In fact, we are running a bit short regarding work and will thus apply for a larger share on work in the 2022 allocation. This is because a single channel simulation at 2.5 km resolution requires 17000 Gb of output due to the process-based analysis.

1- Model developments in ICON-NWP: Implementation of a planar channel geometry ("channel setup") and a setup that directly isolates cloud-radiative heating

We have implemented a new channel setup that so far did not exist. To this end, we have introduced a new grid that represents a limited-area Cartesian f-plane with periodic boundary conditions in the zonal direction and fixed north/south boundaries. Such a configuration was unavailable in ICON; to implement it we have built upon the planar-channel grid available for the ICON ocean component and the torus grid routines used in the ICON atmosphere component. As a result, we now have a configuration with a uniform grid (i.e., each triangle has exactly the same size), which substantially lowers the computational costs compared to a "global" channel. The initial conditions and model setup are adapted from Schäfer and Voigt (2018). Using this setup we have run baroclinic life cycle simulations at a convection-permitting resolution of 2.5 km. The domain size is 4000 km x 9000 km (~ 51 deg lon x 81 deg lat). This configuration results in a reasonable cyclone with the typical structure of a wintertime mid-latitude storm, as is shown in Fig. 1.

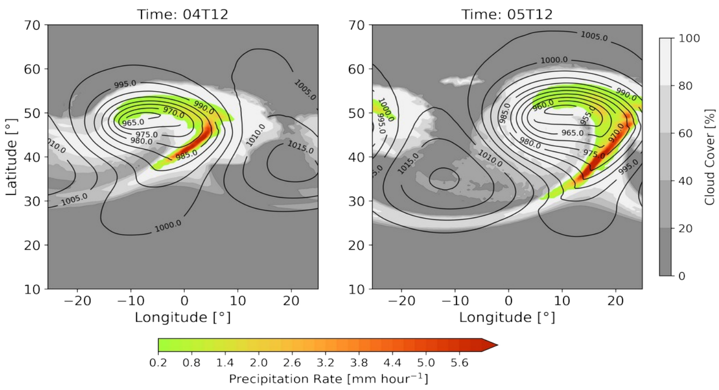


Figure 1: Baroclinic life cycle development with ICON-NWP in the channel configuration.

We have also added a new modeling technique into ICON-NWP that isolates the impact of cloud-radiative heating. This is done by only feeding cloud-radiative heating rates but not clear-sky heating rates to the dynamical core. Doing so removes the problems related to the initial adjustment to radiation described in Schäfer and Voigt (2018), and makes this setup much more suitable to study cloud-radiative heating. In particular, the cloud-radiative heating impact is more local to the cyclone, its occurrence is associated with cloud formation and ascent, and the initial environmental background is not changed because of strong clear-sky radiative cooling.

2- Model- dependent cloud-radiative impact in global ICON-NWP simulation with model releases 2.1.00 and 2.6.2.2

Building upon the results of Schäfer and Voigt (2018), who used a model version very close to ICON release 2.1.00, we repeated the global simulations with the two model releases 2.1.00 and 2.6.2.2. The former reproduces the results of Schäfer and Voigt (2018) and shows that cloud-radiative effects weaken idealized midlatitude cyclones. In contrast, and to our surprise, the latter shows a strengthening of cyclones. Further inspection of the results points to a role of radiative heating and cooling from boundary-layer clouds, which are abundant in 2.1.00 but less present in 2.6.2.2.

3- Cloud-radiative impact on mid-latitude cyclones in the channel setup with release 2.6.2.2

Our analysis of cyclone metrics, cloud fraction, and precipitation has shown an overall increase in these fields when only the interaction between clouds and radiation is considered. According to eddy kinetic energy, cloud-radiative heating increases the intensity of the cyclone, with the impact being more prominent at upper levels (Fig. 2). These results are in contrast to those presented by Schäfer and Voigt (2018) (but consistent with our results described in Sect. 2) and raise the possibility that the cloud-radiative impact might be sensitive to the cyclone structure.

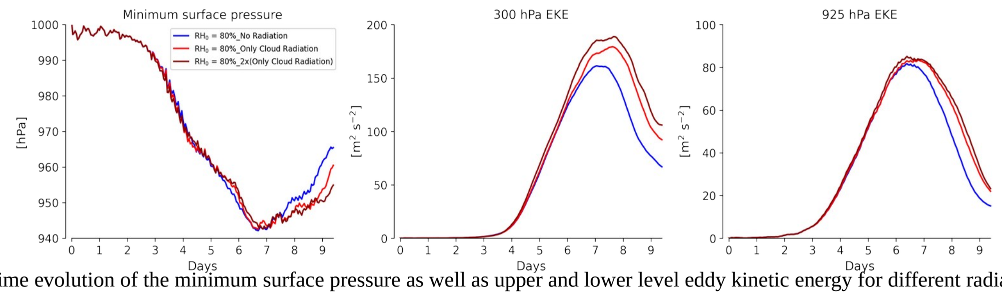
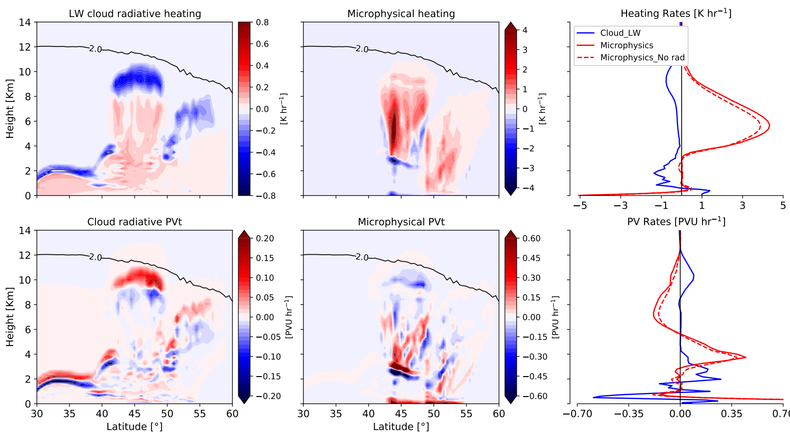


Figure 2: Time evolution of the minimum surface pressure as well as upper and lower level eddy kinetic energy for different radiative setups.

Our analysis of the Lorenz energy cycle is consistent with the found increase in cyclone intensity. Eddy available potential energy also was found to increase due to the increased baroclinic conversion from the zonal mean flow energy and diabatic generation of eddy available potential energy (not shown).

From a potential vorticity (PV) perspective, differential patterns of cloud-radiative heating are associated with the production and destruction of PV anomalies in the atmospheric column, resulting in different dynamical responses (Fig. 3). Cloud radiation also destabilizes the cloud environment; this results in enhanced latent heat release and a stronger PV anomaly-dipole (Fig. 3). Cloud radiation further destabilizes the boundary layer, resulting in more turbulent and effective friction, which might explain the weak cloud impact on lower level EKE and cyclone core pressure.

Figure 3: Cross-section through the warm conveyer belt at day 5 depicting heating rates and associated PV tendency for longwave cloud-radiative heating and cloud microphysical processes. Vertical profiles show time and spatially integrated values from day 5 to 8.



4- Potential vorticity error growth

Potential vorticity tendency error growth provides a quantitative view of the direct and indirect impact of cloud radiation on the cyclone dynamics. Comparing simulations with no radiation and only cloud radiation, we quantified the relative importance of different processes to PV error growth near the tropopause using the PV error growth framework developed by Baumgart et al (2019) (Fig. 4). This has revealed distinct stages of the error growth, which is dominated locally by cloud radiation in the beginning and quickly errors associated with microphysical processes dominate as radiation interacts with clouds. Differences in the upper-level divergent wind then project these diabatic errors on the larger-scale circulation, followed later by near-tropospheric dynamics.

Although cloud-radiative heating has a comparatively small contribution to PV error growth, its impact on the predictability of the cyclone remains interesting and important. Accounting for errors associated with the representation of radiative processes in the atmosphere and their interaction with clouds make their contribution to cyclone predictability even more important.

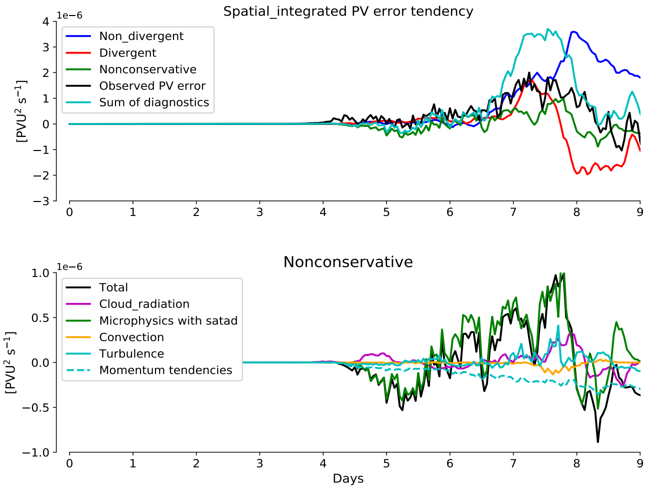


Figure 4: Partitioning of the mean error tendency of PV enstrophy into the contributions from individual processes (top). Partitioning of the mean nonconservative tendency into contributions from individual parameterization schemes (bottom) at the 325 K isentrope.

References:

Schäfer, S. A. and A. Voigt (2018): Radiation weakens idealized midlatitude cyclones. Geophys. Res. Lett., 45, 2833-2841, doi: 10.1002/2017GL076726.

Baumgart et.al (2019): Quantitative View on the Processes Governing the Upscale Error Growth up to the Planetary Scale Using a Stochastic Convection Scheme, Monthly Weather Review, 147(5), 1713-1731.