Evaluating Microphysics Options with the MUSC M-PACE Case Study

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Summary

The three physics packages - HARMONIE-AROME, AROME-MF, and ALARO all come with numerous options for microphysics parameterisations and tuning variables. It can be difficult to assess each option's impact based on full 3D model runs, due to confounding factors and feedback, along with a high computational cost. We have set up a test case in the single-column model framework, MUSC, based on the atmospheric profile from the M-PACE case representing a mixed-phase cloud. Two different experiments were performed for each physics package. The results divide into two main groups, AL1M, ARI3, and ARLI with low liquid and high ice fraction, and HARE, HAIT, and AL2M with high liquid and low ice fraction.

Introduction

Clouds are important for the climate and hydrological cycle and are difficult to forecast correctly. This is due to their complexity, where both large-scale and microscale processes play crucial roles. In numerical weather prediction, the microphysics scheme is responsible for the representation of the in-cloud microscale processes, such as condensation, droplet growth, ice nucleation, deposition, and collision-collection between hydrometeors.

In Autumn 2004 the Mixed-Phase Arctic Cloud Experiment (M-PACE) field campaign was carried out around Barrow, Alaska (Figure 1). They collected observations of cloud microphysics, dynamics, thermodynamics, radiation, and the evolution of Arctic mixed-phase clouds (Verlinde et al. 2007). There was a single-layer stratocumulus cloud over the sea water (no ice) with the temperature profile below 0°C in the troposphere and an inversion at around 850 hPa (Klein et al. 2009). Observations include 24h accumulated precipitation, total water content (TWC), and estimates of liquid water content (LWC), ice water content (IWC).

We used the single column unified model (MUSC) (Gleeson et al. 2020). This is a quick and simple tool for testing different physics settings in a controlled environment. The initial MUSC profiles can be seen in Figure 2. We interpolated the profile to 180 vertical levels, and conducted experiments with a time-step of 30s.

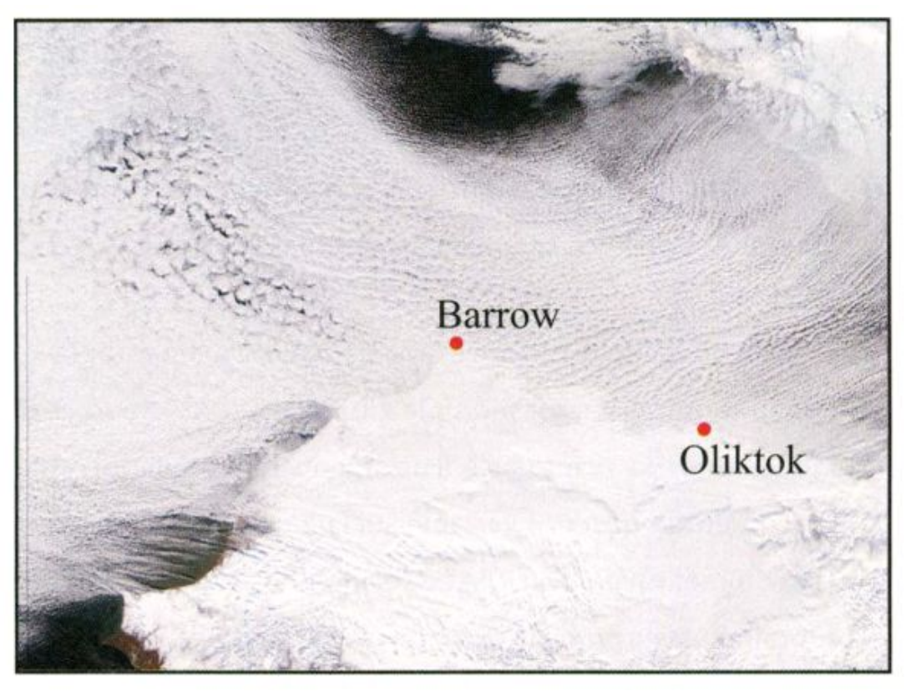


Figure 1: Satellite image from Oct 9 2004 from Verlinde et al. 2007

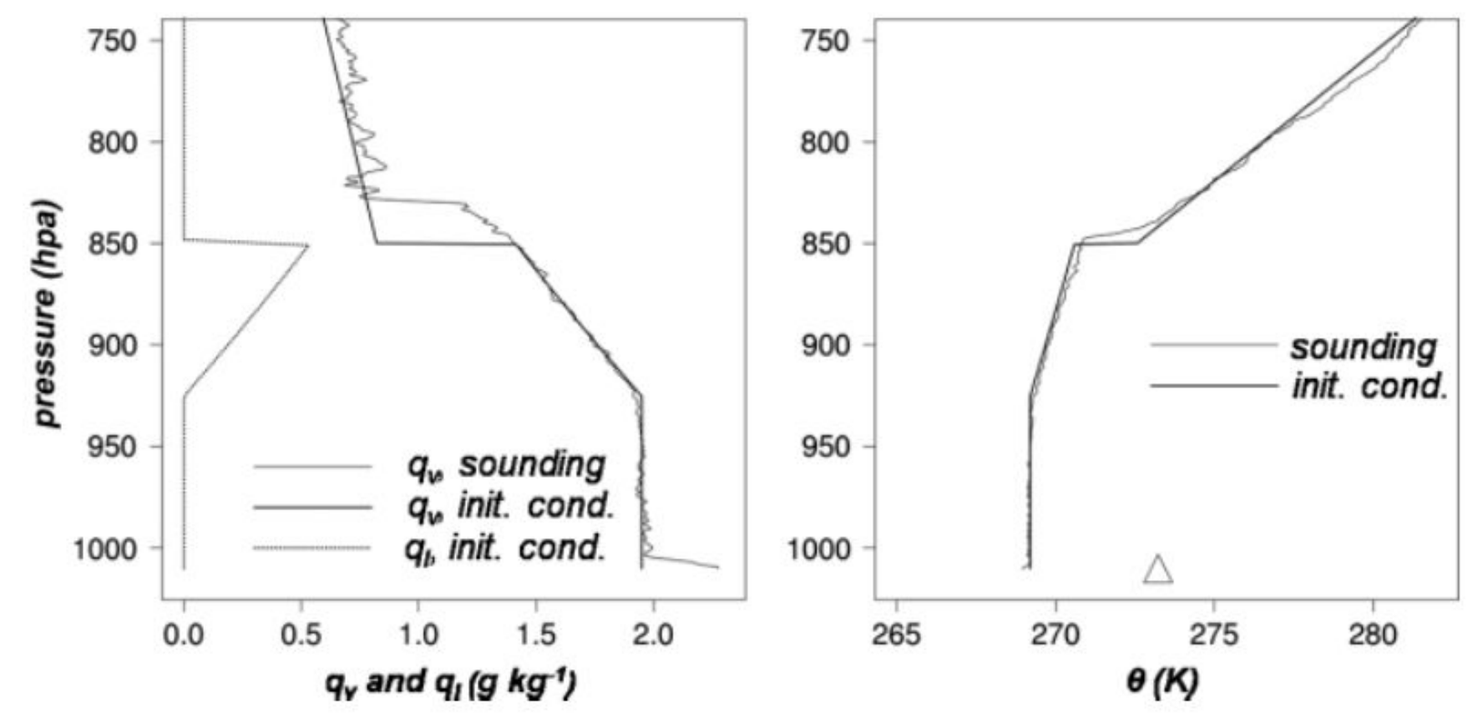


Figure 2: Soundings obtained during the M-PACE campaign, used as initial state for the MUSC experiments. From Klein et al. 2009.

Microphysics Schemes

ALARO: The ALARO microphysics scheme (Nemec et al., 2024) simulates 5 standard hydrometeors prognostically. Here, the single-moment version is compared to the double-moment version. The main difference is in the phase split between cloud water and cloud ice. This is done by the diagnostic function FONICE, based on temperature in the single-moment scheme. The double-moment option uses a prognostic treatment of cloud ice production from activation, freezing of droplets, secondary ice production, and depositional growth. The precipitating particles are assumed to follow a gamma distribution instead of a negative-exponential one, and snow is not assumed to be spherical and has variable density.

AROME-MF: The operational microphysics scheme in AROME-MF cy49 is ICE3 (Pinty et al., 1998). It is a bulk mixed-phase one-moment scheme with prognostic equations predicting the mass mixing ratios (MMRs) of water vapor, droplets, rain, pristine ice, snow, and graupel. An adjustment to saturation for liquid/solid phase is performed, meaning that there is deposition of all of the excess vapor on cloud droplet/pristine ice particles in warm/cold clouds. Sub-grid variability for adjustment is accounted for through turbulence. For the MPACE case, the surface mass closure of the shallow convection scheme had to be lowered from 0.065 to 0.03 to avoid instabilities. Collection, sedimentation and deposition/evaporation processes from ICE3 then act.

LIMA (Vié et al., 2016) is a two-moment bulk microphysical scheme that includes a prognostic representation of aerosols and their interactions with clouds. Aerosol modes are characterised by their chemical composition, particle size distribution (PSD), and their ability to act as cloud condensation nuclei (CCN). The scheme builds upon the six water species defined in ICE3. However, in the configuration used here, only the number concentrations of rain droplets, ice crystals, and cloud droplets are prognostic. In contrast, the deposition and sublimation rates of ice crystals are explicitly computed as a function of both their MMR and number concentration, allowing supersaturation with respect to ice to evolve freely. Several microphysical processes have been adapted in LIMA to account for number concentrations. For instance, processes such as evaporation, melting, and homogeneous freezing have been modified accordingly.

HARMONIE-AROME: The base microphysics scheme in HARMONIE-AROME cy49 is ICE3 as in AROME-MF. A major modification called OCND2 was added to the scheme and is used in operations in the UWC countries (Müller et al. 2017, Bengtsson et al. 2017, Gleeson et al., 2024). The main purpose of the development of OCND2 was to allow for more mixed-phased clouds, as well as a reduction in ice fog. The main changes include separating the fast liquid-phase processes from the slower ice-phase processes, reducing the speed of the sublimation of ice particles.

OCND2 resulted in an improved representation of mixed-phased clouds, but supercooled liquid cloud water is still underestimated. Engdahl et al. 2020 added another major modification to the microphysics scheme, called ICE-T. This introduces elements from the Thompson et al. 2008 microphysics scheme, such as stricter conditions for ice nucleations, less efficient collision-collection of liquid by solid hydrometeors, and a variable rain size distribution.

Abbreviation	Physics	Microphysics
AL1M	ALARO	ALARO 1-moment
AL2M	ALARO	ALARO 2-moment
HARE	HARMONIE-AROME	ICE3+OCND2 (1-moment)
HAIT	HARMONIE-AROME	Is ICE-T within OCND2 and ICE3 (1-moment)
ARI3	AROME-MétéoFrance	ICE3 (1-moment)
ARLI	AROME-MétéoFrance	LIMA (2-moment for cloud droplets, rain and pristine ice)

Table 1: List of experiments

Results

ALARO: single-moment vs. double-moment

- The prognostic treatment of cloud ice evolution in AL2M leads to a significant increase in the cloud water mass fraction and a reduction in cloud ice.
- AL2M creates a maximum of cloud water in the upper part of the cloud, while the total ice water content peaks lower, which is an often observed profile of Arctic planetary boundary layer (PBL) clouds capped by inversion.
- As ice supersaturation is allowed in AL2M, a little less total condensate is created, which also reduces the initial intensive precipitation after the simulation is initialized.
- The snow processes are altered too. The main source of snow in AL2M is deposition followed by collection of cloud water, while autoconversion dominates in AL1M.

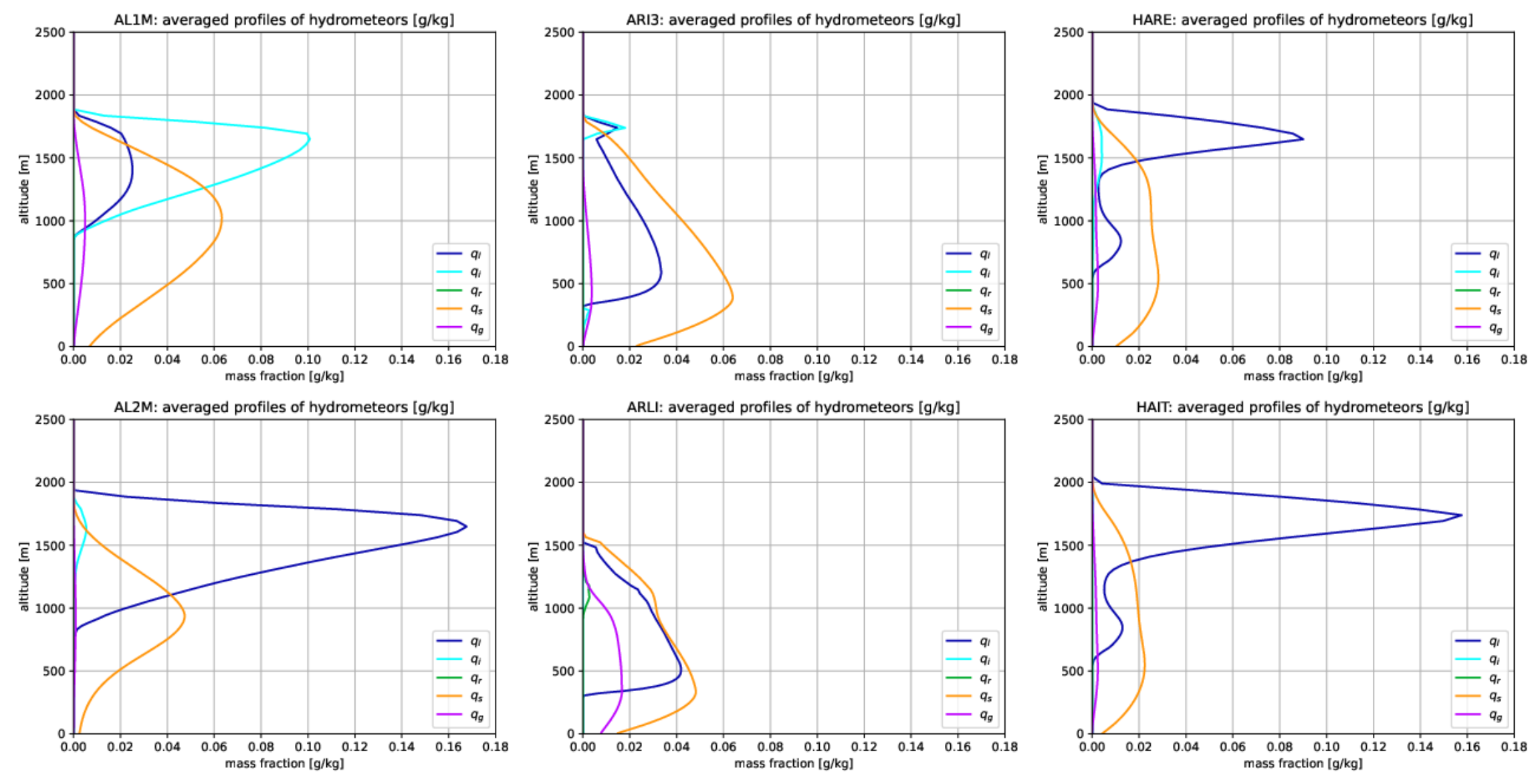
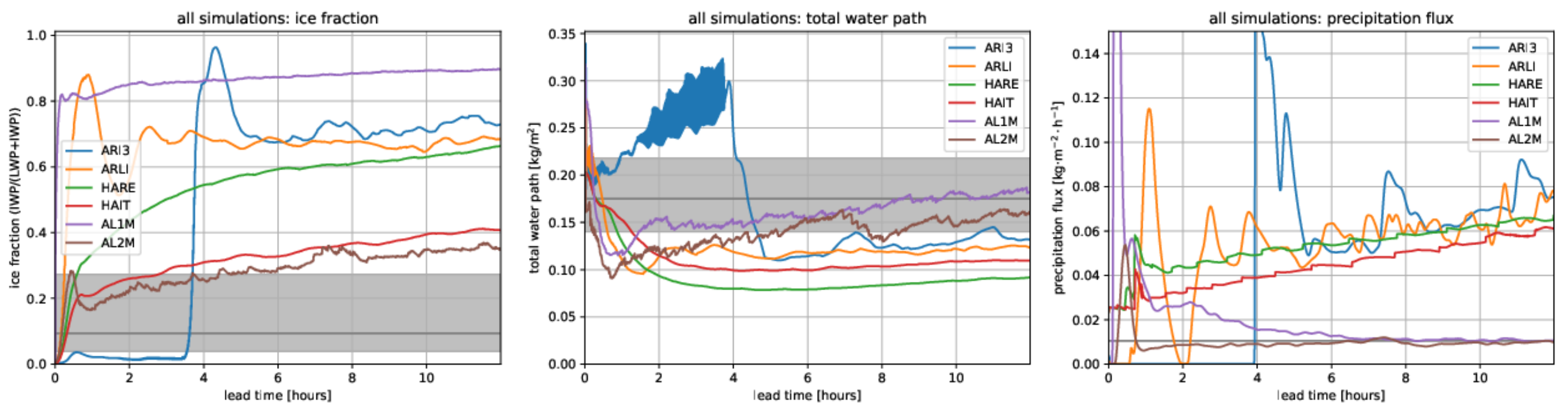


Figure 3: Vertical profiles of time-averaged hydrometeors for 1-moment ALARO (top left), 2-moment ALARO (top center), AROME-MF ICE3 (top right), and AROME-MF LIMA (bottom left), HARMONIE reference (bottom center), HARMONIE ICE-T (bottom right)

AROME-MF: ICE3 vs LIMA

- The different ice initiation processes in ARLI and ARI3 lead to distinct temporal evolutions of pristine ice formation in the two experiments.
- In ARLI, sufficient pristine ice is present from the beginning, allowing for early formation of snow and then graupel. In contrast, in ARI3, this formation occurs only after approximately four hours.
- Once snow and graupel are formed, they begin to collect cloud droplets. Differences in collection efficiency between the two schemes are partly related to the representation of cloud droplets, which follows a two-moment approach in LIMA.
- When collection processes become strongly active, this results in a rapid increase in both the ice fraction and the precipitation flux.
- Both simulations exhibit an enhanced cloud droplet mixing ratio near the cloud top, consistent with observations of Arctic PBL clouds capped by a temperature inversion.
- Recent developments in ICE3 and LIMA, particularly regarding the representation of snow PSD (Wurtz et al., 2023), ice initiation and collection processes (Dupont et al., 2024; July-Wormit et al., 2026) are expected to improve the representation of mixed-phase clouds.

Figure 4: Ice fraction (left) and total water content (middle) and precipitation flux (right) with time for all experiments. Gray shadings and line represent the observed values.



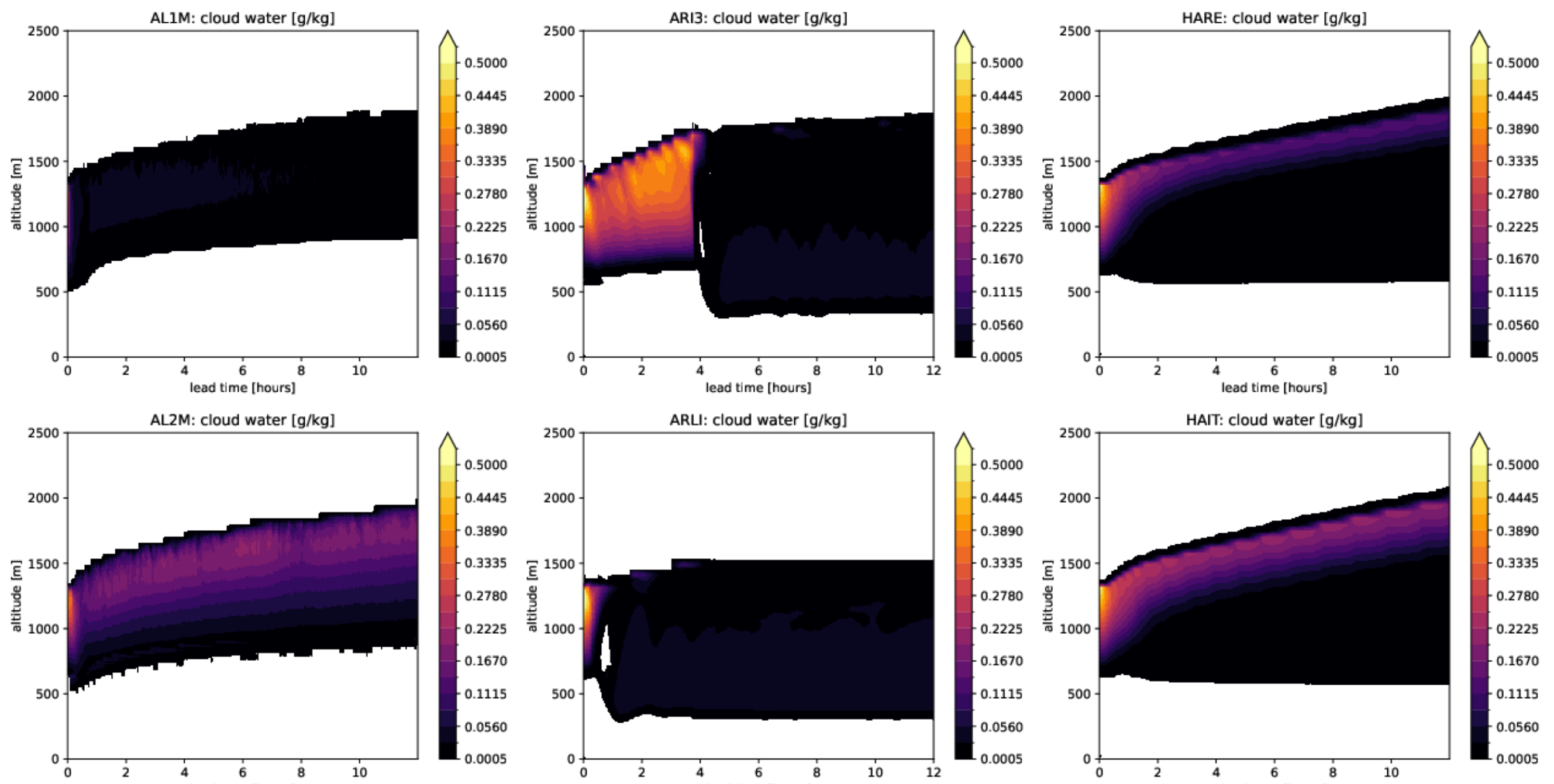
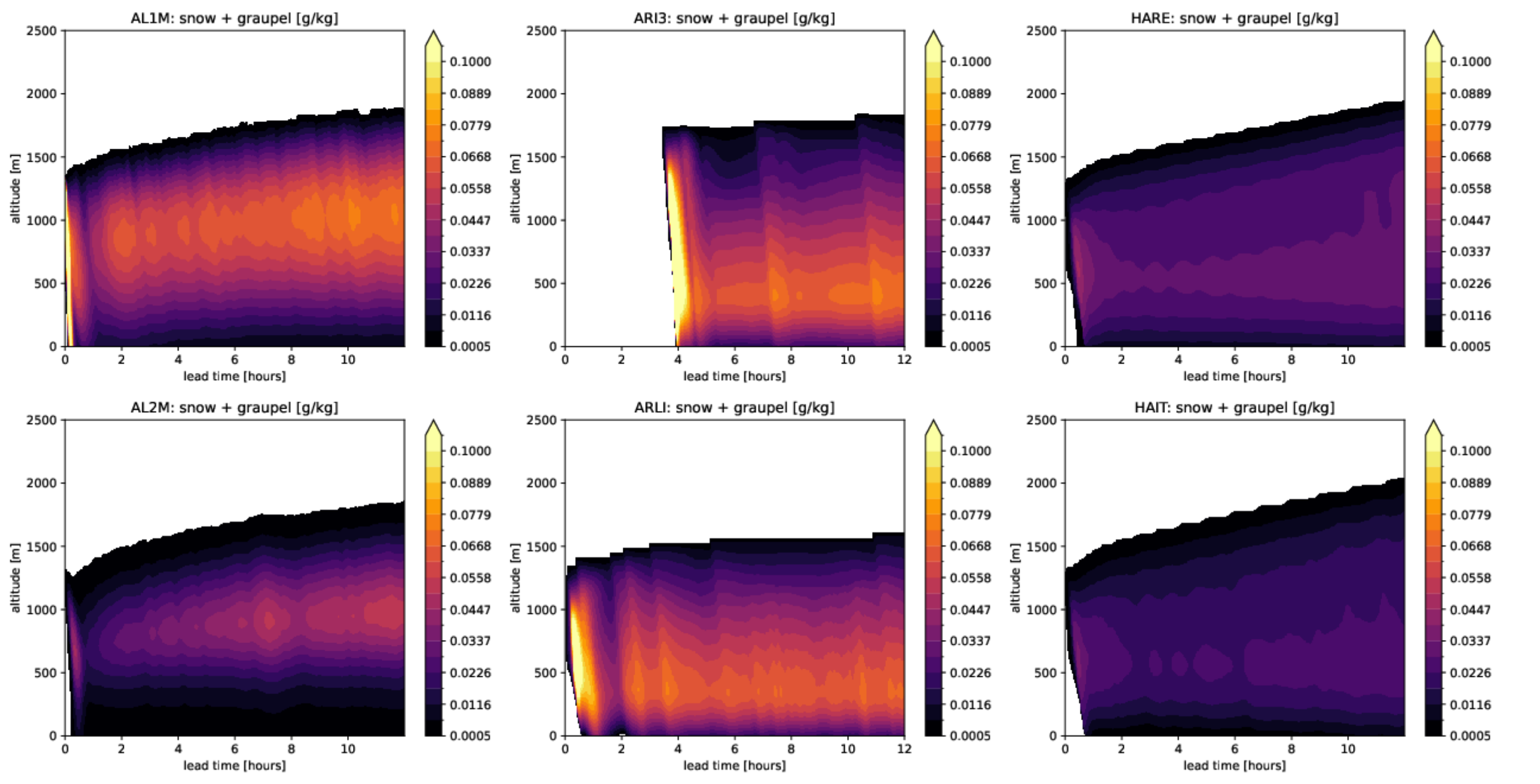


Figure 5: Time-height evolution for cloud liquid water for 1-moment ALARO (top left), 2-moment ALARO (top center), AROME-MF ICE3 (top right), and AROME-MF LIMA (bottom left), HARMONIE -AROME reference (bottom center), HARMONIE-AROME ICE-T (bottom right).

Figure 6: Time-height evolution for snow and graupel for 1-moment ALARO (top left), 2-moment ALARO (top center), AROME-MF ICE3 (top right), and AROME-MF LIMA (bottom left), HARMONIE reference (bottom center), HARMONIE ICE-T (bottom right).



HARMONIE-AROME: ICE3 + OCND2 vs ICE-T

- Both runs create a mixed-phase cloud with liquid at the top, and a peak of solid hydrometeors at about 500m.
- The cloud water decreases with time, especially during the first few hours due to evaporation.
- The snow content increases at the beginning due to the deposition of water vapour on snow and collection of cloud droplets, but after two hours the conversion of large crystals to snow and sublimation are the two main processes.
- ICE-T yields higher values of cloud water, and lower values of solid hydrometeors. The increased cloud water is in accordance with previous studies, where ICE-T significantly increases the amount of supercooled liquid.
- However, the decrease in frozen particles is not seen in previous studies, and likely stems from reversing changes to the mass-diameter and fall-speed relations in ICE-T, leading to higher fall speed of graupel and snow.
- HAIT has a much lower ice fraction than HARE. This is closer to the observed values, but still too high after 3h.
- Both simulations have a total water content that is too low, HARE less than HAIT, which is then essentially a lack of cloud liquid water.
- The resulting precipitation flux is similar in both simulations, HAIT slightly lower than HARE, and increases with lead time.
- Both simulations overestimate the precipitation. It is found that the shallow convection scheme is responsible for most of the rain and more than half of the solid precipitation.

Discussion and future plans

The results from these simulations show that the two HARMONIE-AROME simulations and AL2M yield similar results, with a clear liquid topped cloud and low values of solid hydrometeors consistent with the observations. The other three experiments show a clear tendency towards high values of solid hydrometeors at the expense of cloud liquid water.

So far we have only considered the MPACE case, with all physics active. Future plans include running several other idealised cases with only microphysics switched on. We also have the possibility to extract the tendencies from each process involved.

As the results are highly sensitive to the many tunable variables in the physics, this approach is useful for comparing the schemes, and figuring out why the differences occur. In the end, we aim for a tool that can help in improving all schemes.