Response to Reviewer #1

We thank both reviewers very much for their time and effort. Please find point-by-point responses to the first reviewer below, with changes to the manuscript indicated in orange. Line numbers refer to the version with tracked changes.

We would also like to briefly summarize other changes that were made since our original submission. The MIMICA team revised their code to now consider radiative interaction with cloud ice, thereby updating MIMICA's FixN (mixed-phase) simulation, which affected Fig. 2, 4, and 6-12 (now 7-13).

Review of "The Cold-Air Outbreaks in the Marine Boundary Layer Experiment model-observation intercomparison project (COMBLE-MIP), Part I: Model specification, observational constraints, and preliminary findings" by Juliano et al. [MS No.: egusphere-2026-1237]

This paper presents a very useful LES and SCM model intercomparison project that simulates a strong cold-air outbreak (CAO) event. The models participated in the project run within a quasiLagrangian framework and are examined against a suite of ground observations, satellite data, and ERA5 reanalysis. The preliminary results are promising: LES models can broadly capture the evolution of observed cloud top height and liquid water path, along with the roll and open-cell structure of clouds in a km-scale domain. More insights into the role of ice microphysics are provided by comparing liquid-only simulations with mixed-phase simulations. The differences between LES and SCM runs and the source of modeling biases in longwave radiative fluxes at TOA and the surfaces are also investigated.

The paper is well written and organized, easy to follow. The initial conditions, large-scale forcings, and modeling setups are reasonably designed. One unique merit of this study is that they chose a very strong cold-advection event, manifested as more extreme surface fluxes forcing, so that cloud and radiative properties and their mesoscale organization along the CAO evolve significantly, providing a strong-signal test bed of CAOs for Earth system models, especially km-scale models. That said, the study could benefit from more discussions of the physical process involved, though the study focuses on presenting the preliminary modeling results. My comments and suggestions mainly concern some clarifications, and once they are addressed, I believe the paper would be suitable for publication in ACP.

Major comments:

1. The authors describe two methods for handling the large-scale wind forcings. I assume the presented simulations are based on the geostrophic adjustment approach, since wind speeds notably deviate from ERA5, as seen in Figure 4i. At 18:00 UTC on 03-13-2020, both ERA5 and the radiosondes show a wind speed peak between 1000 and 2000 m, indicating a strong wind shear in the PBL. This feature is not captured by the models, and the wind-shear driven turbulence may be missed as well, which could help explain why the simulated cloud-top heights are lower than those from ARSCL (Fig. 2f). Cloud-top heights also affect the LW

radiation fluxes. In this regard, did the authors compare the simulations from the above two approaches regarding cloud-top heights and LW radiative fluxes (TOA and surface)?

Throughout the paper we show simulations with geostrophic winds, which we prefer as forcing, as already motivated in Section 2.2.2. We are aware of some level of disagreement between simulations and observations, and attempted to decrease disagreement where deemed crucial. With respect to wind speed profiles, we find substantial variability in radiosonde profiles (Fig. 4i, green lines spanning +-6 hours). One crucial role of wind speed is to drive turbulent surface fluxes. We ascertained that the simulated surface energy fluxes are plausible through a comparison of simulations against ERA5 and observational products (Fig. 2b,d).

However, the reviewers raised another important role of wind speed profiles: they can drive the MBL's turbulence. During the forcing exploration, we tested the use of nudged winds. In response to the reviewer's concern, we now added an Appendix section that demonstrates forcing differences. Compared to a forcing with geostrophic winds, the below figure shows how nudged winds result in slightly smaller turbulent surface fluxes and cloud-top height during most of the simulation. Yet cloud condensate and radiative fluxes are largely insensitive to these differences: we see a slight decrease in LWP, IWP, and optical depth, but the outgoing TOA LW fluxes remain virtually unchanged. We included the below figure in our revised manuscript and added the following explanation:

In Section 2.2.2, we now add
ll. 203-204: In the remainder of the study we force models via geostrophic winds, as motivated in the following.
and
l. 226: (as shown in Appendix A for one model).
and
l. 227-229: While we find cloud and radiation fields to be largely insensitive to a forcing using nudged instead of geostrophic winds (Appendix A), we note that a reanalysis model's ability to plausibly represent vertical wind shear can create a potential limitation for any case setup.

We now also include the above comparison of the two wind forcings in Appendix A:
ll. 648-657: Here we briefly describe the sensitivity of the DHARMA model to a forcing using nudged versus geostrophic winds. When compared to a forcing with geostrophic winds, we find nudged winds to result in slightly smaller turbulent surface fluxes and cloud-top height during most of the simulation, which cloud condensate and radiative fluxes are largely insensitive to: during the first half of the simulation, we find a slight decrease in LWP, IWP, and cloud optical depth, resulting first in slightly larger outgoing TOA LW fluxes before becomes slightly smaller in the second half of the simulation (Fig. A1). These results highlight a robustness of the forcing, with a preference for geostrophic winds for a more natural evolution (Sec. 2.2.2.)

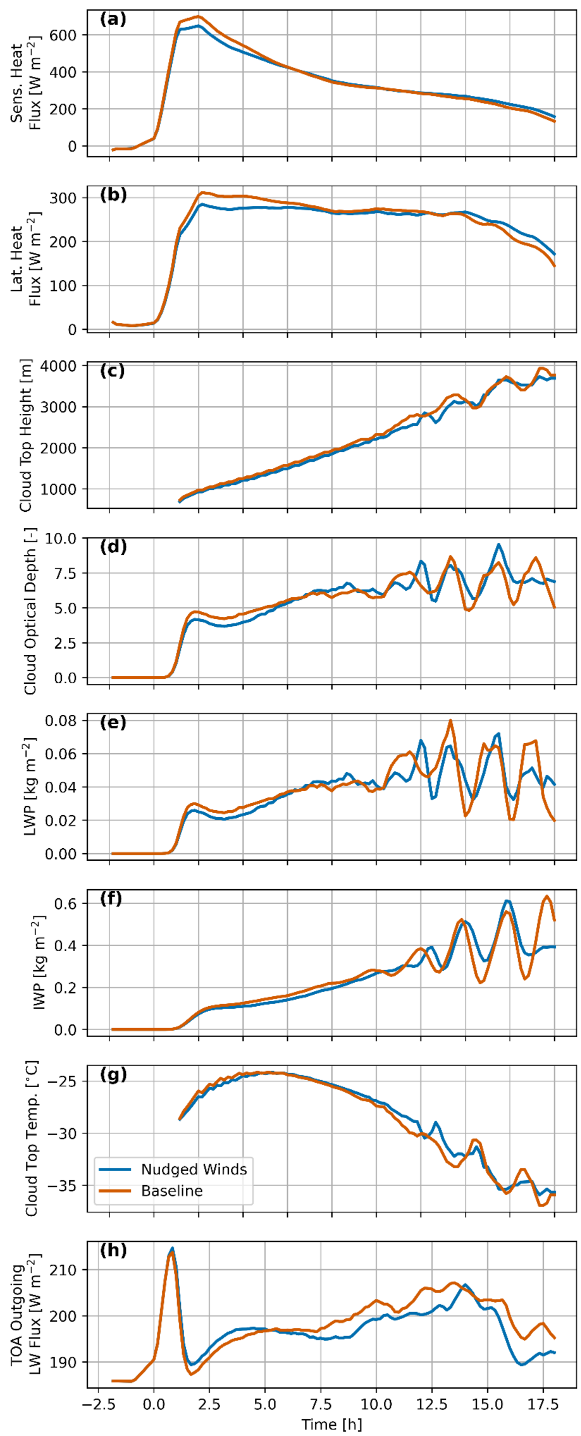
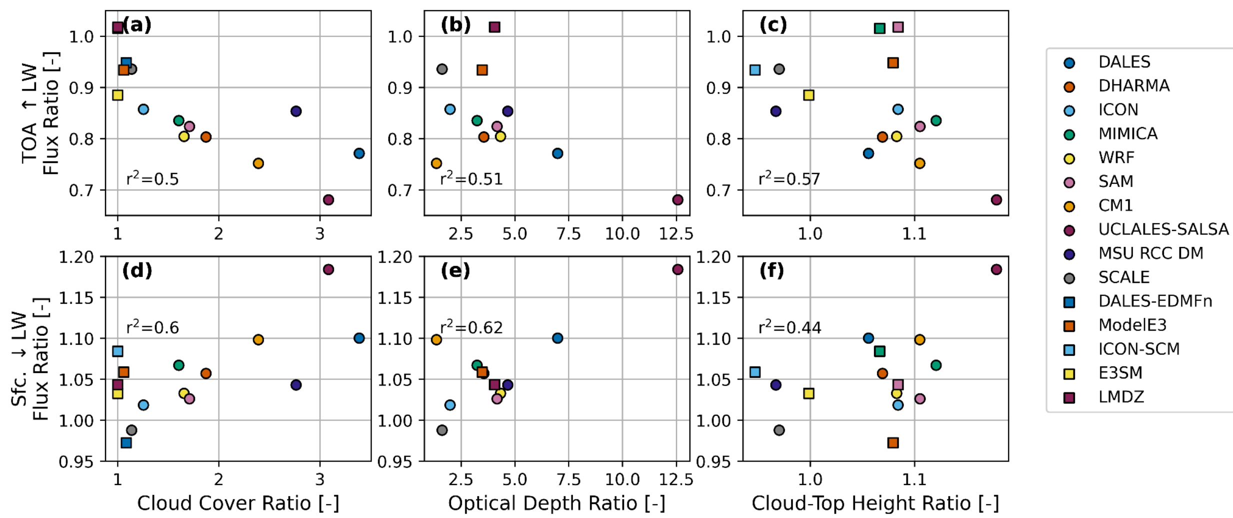


Figure A1: *DHARMA LES output using geostrophic winds (labeled "baseline") and nudged winds.*

2. As for the impact of ice microphysics on LW radiation fluxes, changes in cloud cover explain the LW radiation changes very well for the LES simulation, but not for SCM since both liquidonly and mix-phase SCM simulate overcast cloud decks, constraining the cloud cover ratio to near unity (Fig. 12c). In addition to cloud cover, the cloud-top height ratio might help explain the LW

radiative flux changes, given the influence of cloud top on LW radiation and the notably divergent cloud-top height/temperature differences between liquid-only and mix-phase simulations (Figs. 3e-f or 3g-h).

We appreciate the reviewer's suggestion and included a CTH component to Fig. 12 (now 13). The updated figure is inserted below and correlates best (0.57) with outgoing LW fluxes. We now also stress that our definition of cloud cover excludes optically thin portions that may be more prevalent in mixed-phase conditions.



We updated the caption accordingly:

Fig. 13: *Relationships between (top left) cloud cover ratio and TOA upwelling LW flux ratio; (top middle) optical depth ratio and TOA upwelling LW flux ratio, and (top right) cloud-top height ratio and TOA upwelling LW flux ratio; (bottom right) optical depth ratio and surface downwelling LW flux ratio; (bottom middle) cloud cover ratio and surface downwelling LW flux ratio, and (bottom right) cloud-top height ratio and downwelling LW flux ratio. LES models and SCMs are shown in circles and squares, respectively. Fractions of explained variance, r^2, are shown for only the LES models.*

We added the brief note to Section 2.4.3:

ll. 303-305: However, we select cloud cover (defined as the fraction of pixels with optical depth greater 2 over a (100 km)^2 domain) for solar zenith angles smaller than 75° as a target metric, under the assumption that pixel-scale retrieval accuracy is of secondary importance.

And we added the following text to Section 3.5:

ll. 578-582: Effects from cloud cover and cloud optical depth changes can be amplified by simultaneous changes in cloud-top height. Including ice decreases cloud-top height in most simulations, resulting in greater cloud-top temperature, which leads to greater upwelling LW radiation reaching TOA but leaves downwelling LW fluxes at surface largely unchanged (Fig. 13c,f). We note that the definition of cloud cover used here excludes optically thin layers (tau < 2) that can be more common in mixed-phase conditions.

3. The paper would benefit more if the authors could further clarify the physical processes involved: how including ice microphysical processes impact on cloud-top height and cloud cover. For the 1 first process, the authors argue that precipitation made the MBL more stratified, which hinders vertical mixing and thereby PBL deepening. However, comparing Fig. 2p with Fig. 2e, the surface precipitation does not increase and may even become weaker in the mixed-phase LES runs. This does not appear to support the authors' argument, unless there is evidence that sub-cloud evaporation becomes stronger in the mixed-phase run.

We appreciate the reviewer's suggestion and added the below figure to our manuscript. As the reviewer pointed out, surface precipitation rates are largely identical across liquid-only and mixed-phase LES runs. However, cloud-base precipitation rates in mixed-phase LES (grey) runs are larger compared to liquid-only LES runs (black), implying a greater loss through sublimation below cloud, as quantified in the left-hand side. The right-hand side shows how this increased loss in mixed-phase runs coincides with greater moisture stratification, as already explained in the text. The figure also lists two mixed-phase SCM runs (i.e., those models that reported precipitation flux profiles) and shows that the model with larger loss (ModelE) also shows larger stratification; we note the large spread in SCM moisture stratification.

We added the following text to our manuscript:
ll. 411-415: *While surface precipitation rates are largely unchanged between liquid-only and mixed-phase simulations, we note that cloud-base precipitation rates are greater in mixed-phase simulations (not shown), implying a greater sub-cloud sublimation compared to sub-cloud evaporation in liquid-only simulations (Fig. 6a), which results in a greater vertical moisture stratification in mixed-phase simulations, measured as the difference in water vapor mixing ratio at 25% and 75% of the cloud-top height (Fig. 6b).*

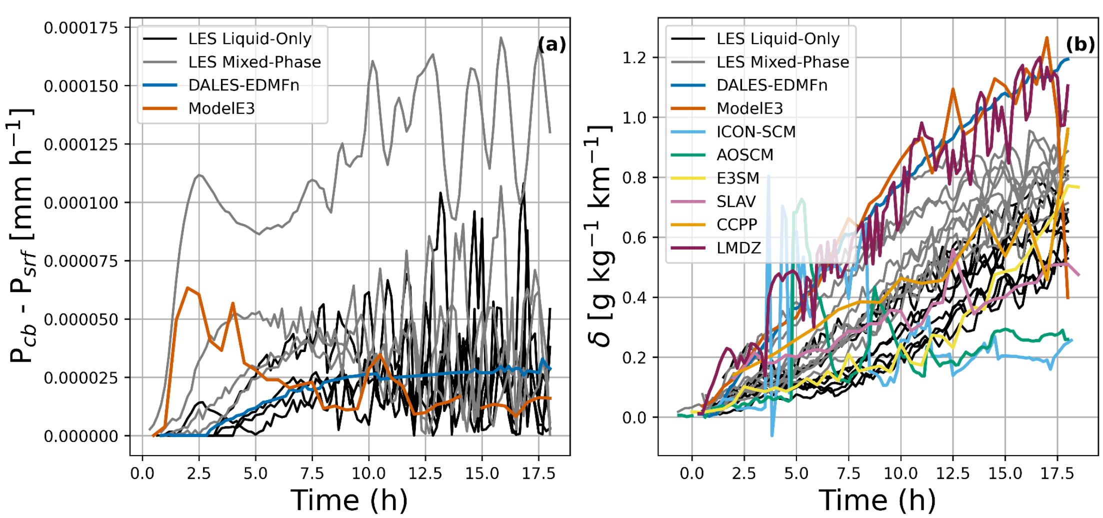


Fig. 6: *Cloud-base minus surface precipitation rate (left) and water vapor mixing ratio difference between the bottom and top of the MBL (i.e., 25% and 75% of cloud-top height, respectively) (right) over time. LES Liquid Only and LES Mixed-Phase simulations are shown in the black and*

gray lines respectively, with each line representing results from a single model, while the mixed-phase SCMs are colored according to the legend, noting that not all models reported precipitation flux profiles.

We now also note other differences between liquid-only and mixed-phase simulations that can impact temperature profiles and help further explain differences in MBL deepening:
ll. 420-425: Differences in cloud condensate amount and phase also modify temperature profiles via cloud radiative effects and microphysical latent heat release (e.g., shown illustratively in Fig. D1). Specifically, mixed-phase simulations exhibit reduced cloud-top longwave cooling and enhanced warming below cloud-top. Simultaneously, microphysical latent heat release warms the cloud layer while cooling the region below cloud base, resulting in stronger temperature stratification. Ultimately, these combined changes in radiative forcing and latent heating can further suppress cloud-top entrainment and vertical mixing in mixed-phase simulations.

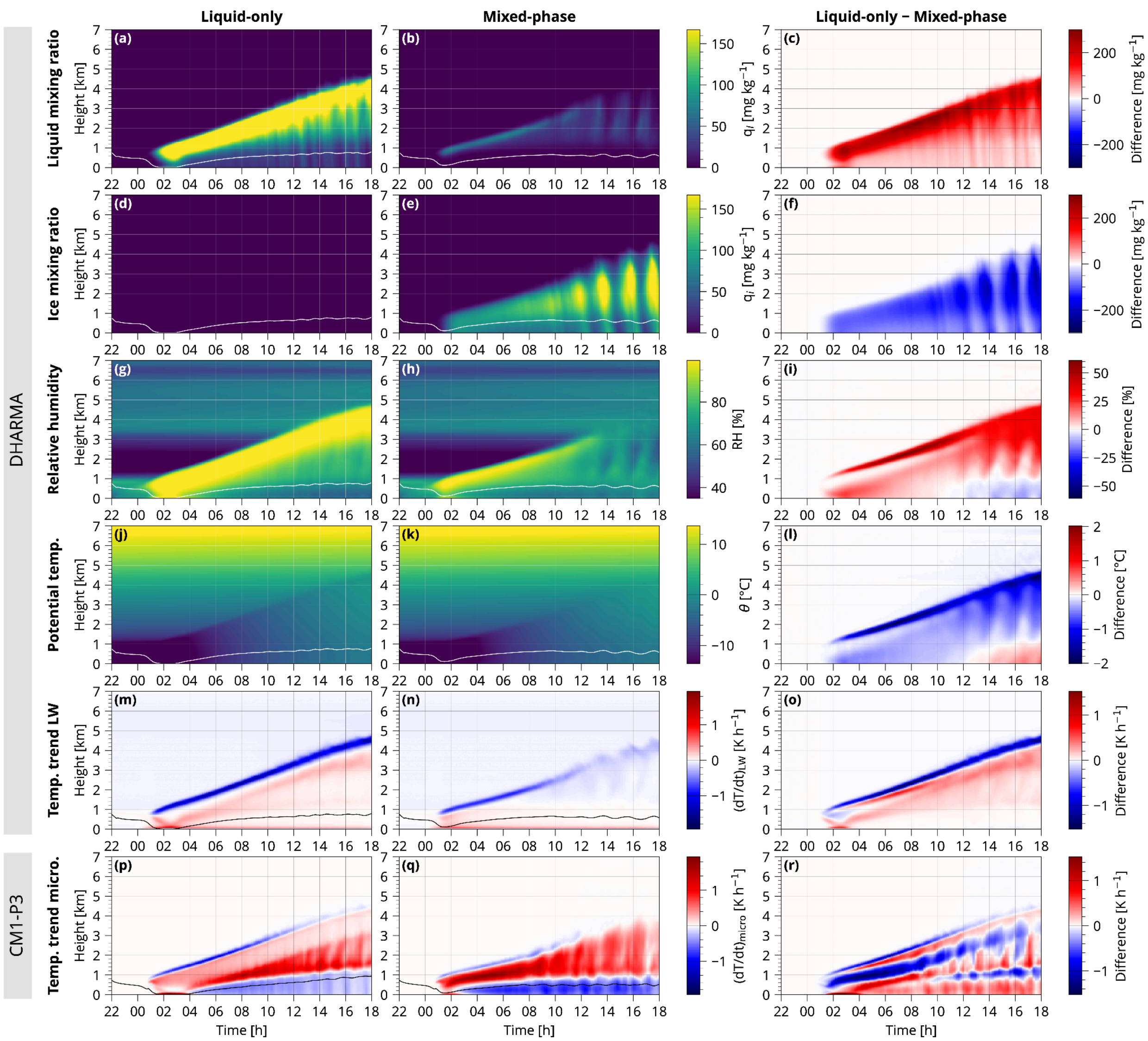


Fig. D1: *Curtain plots of liquid and ice mixing ratios (cloud plus precipitation), relative humidity (relative to liquid), potential temperature, temperature trend due to longwave radiation, and temperature trend due to microphysics in the DHARMA and CM1-P3 simulations for the liquid-only case, mixed-phase case, and their difference. The white and black lines show the lifting condensation level.*

To this extent, we added an appendix section that demonstrates these changes using two LES codes:

ll. 708-719: ***Appendix D Supplementary curtain plot analysis***

Here we provide additional curtain plots that demonstrate cloud condensate, relative humidity, and temperature differences across liquid-only and mixed-phase simulations using exemplary models. The use of two models (i.e., DHARMA and CM1-P3) is needed as neither model provides all variables fully. Given the relatively uniform response to configurations across LES codes, these plots offer a general idea of scenario differences that somewhat differ between LES codes.

Compared to mixed-phase clouds, liquid-only simulations gain warm-phase condensate (Fig. D1a-c) at the expense of frozen one (Fig. D1e-f). We find relative humidity with respect to liquid to increase inside the cloud layer and decrease below cloud (Fig. D1g-i). This relative humidity response is largely explained by changes in potential temperature that decreases inside the cloud and increases below cloud (Fig. D1j-l). The in-cloud response is partially caused by increased LW cooling near cloud-top (Fig. D1m-o) and decreased microphysical latent heat release (Fig. D1p-r). Below cloud, the liquid-only simulation shows smaller microphysical latent heat absorption (from decreased hydrometeor evaporation) compared to the mixed-phase simulation (where sublimation acts), resulting overall in greater sub-cloud temperature tendencies in liquid-only simulations. Section 3.2 examines all LES and SCM codes more widely.

It would also help if the authors could elaborate on why ice microphysics leads to more cloud breakup or a smaller cloud fraction in LES models. If precipitation changes do not account for this, any other processes might be responsible? Relatedly, since cloud cover is an important variable during CAOs, can the authors also add cloud cover evaluations to in Figs. 2 and 3 if possible?

The newly added metrics (see above point) largely tie decreased cloud cover to increased MBL stability from increased sub-cloud moistening in mixed-phase simulations. We anticipate additional analysis in the second part of the MIP, looking closer at sensitivities of cloud and precipitation properties to interactive aerosol treatment and model-specific choices of primary and secondary ice formations..

We appreciate the reviewer’s suggestion to add cloud cover. We updated Fig. 10 (now 11) and its caption accordingly.

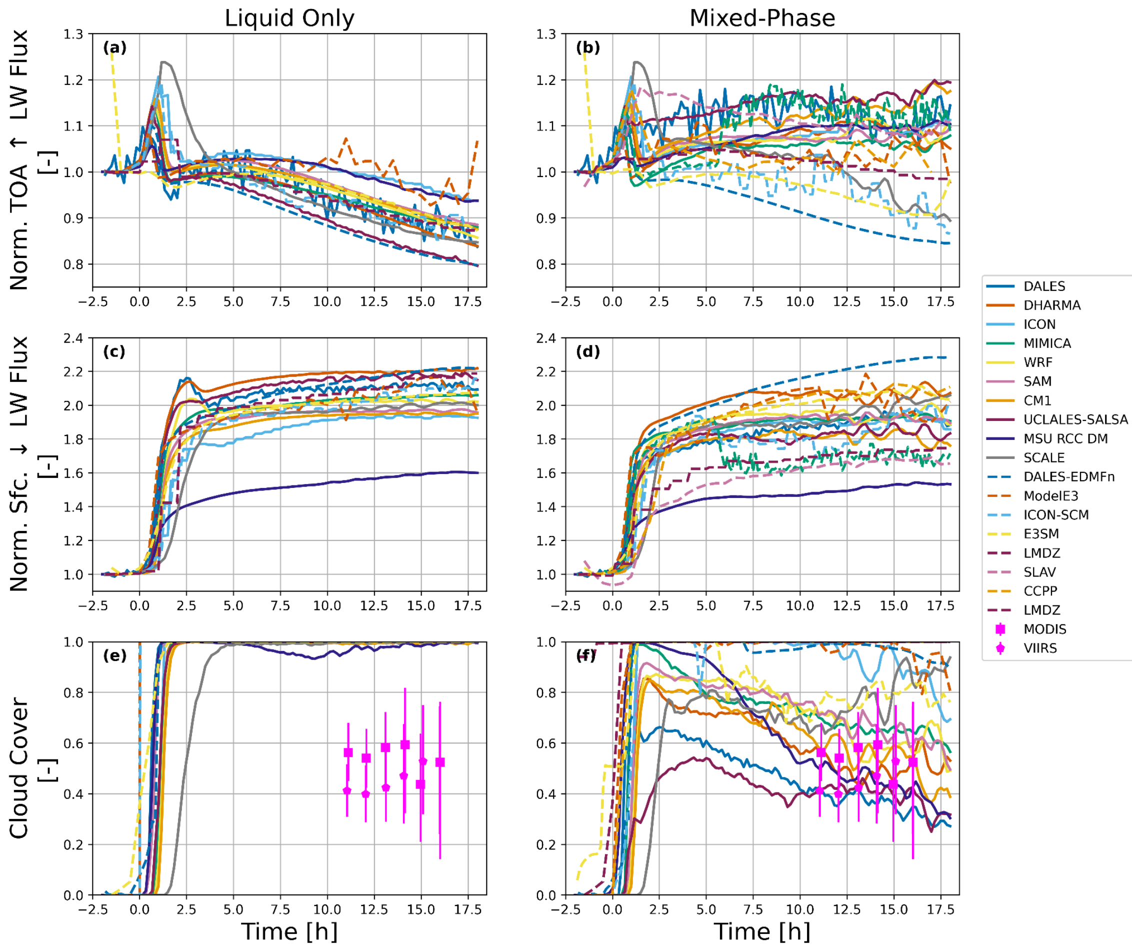


Fig. 11: *As in Fig. 10, except showing only model results that are normalized by the pre-cloud (t=-1 h) values. In the bottom-most row, we also show the modeled cloud cover together with observational targets, inferred from satellites carrying MODIS and VIIRS instruments. Identical to LES, cloud cover is computed as the portion of pixels with a cloud-optical depth greater 2.0.*

4. For open research, would the authors also consider sharing the simulation setup files? This would allow readers to reproduce the simulations if they are interested in specific cases and would facilitate the extension of the study with additional sensitivity tests.

We note that our webpage already provides initial conditions and forcing files (https://arm-development.github.io/comble-mip/main_configuration.html), which each modeling group has translated according to their code-specific input format. Prompted by this concern, we now stress the availability of these setup files in the Code and Data Availability section and also provide an archived version of the GitHub repository:

ll. 642-644: Analyzed observational data sets, initial and boundary conditions for LES and SCM model as well as their results, and analysis scripts are publicly accessible via GitHub. A version archived during the revision stage can be found at https://zenodo.org/records/21246964.

Minor comments:

L68: Relative to “surface heterogeneities”? Please clarify.
We deleted “relative” here to avoid confusion.

L79: Revise “atmospheric scales” to “atmospheric motions”
Revised as suggested..

L150: In Table 1, please also add the “SW radiation” setup
We updated Table 1 as suggested.

L172: The phrase “started from” seems to fit better here than “reached”.
Revised as suggested.

L174: Please clarify how the trajectory is computed, e.g., initial height, whether it is run on an isobaric level, and the time resolution of the trajectory.
We added the following:
ll. 176-178: The back trajectory is initiated at 1800 UTC, 13 March, 2020, at the ARM site (69.141ºN, 15.519 ºE) with an initial height of 1 km above sea level. The trajectory is calculated based on model velocity with hourly resolution (Wu and Ovchinnikov, 2019).

L178: Since ERA5 data are used for the initial profiles, please note that ERA5 sometimes has lower boundary layer heights due to its coarse resolution, which could result in a shallower simulated boundary layer due to this initial bias. I suggest adding a caveat up front to give readers proper context.
We added the following sentence to Section 2.2.1:
ll. 184-185: We note that ERA5's coarse resolution can produce MBL depth biases.

L195: Are both nudging methods applied? Please clarify which one is used in the following simulations.
Great point. As explained in the first major concern, we now clarify this in Section 2.2.2.

L324: Suggest mentioning the two modeling setups (liquid-only vs. mixed-phase) earlier, possibly in Section 2.2.4.
Great point. We added the following sentence to Section 2.2.4:
l. 268: In addition to mixed-phase simulations, this study will also examine liquid-only simulations with identical N_d.

L355: Suggest narrowing the y-axis range in Fig. 3l for better visibility.
We considered the reviewer’s suggestion, but found it to complicate comparability across LES (Fig. 2) and SCM (Fig. 3) simulations. Axis ranges in Fig. 2 and 3 are intentionally aligned.

L395: “2e-d” should be “2e-f”?
We thank the reviewer for catching the typo and revised it as suggested.

L417: Revise “(Young et al., 2002, , their Fig. 4)” to “Young et al. (2002) (see their Fig. 4)”
Revised as suggested

L569: Please clarify the fixed numbers in the modeling setups, as well as the translation speed.
We added the following information:
ll. 592-595: …tighter specification of fixed droplet number concentration and ice formation processes (in the simulations presented here using N_d=25 cm^{-3} and N_{i0}=25 L^{-1}) enable LES results to diverge far less in total LWP and IWP evolution. Additionally, we use a quasi-Lagrangian domain (translating at ~25 m s^{-1}).