Addressing Numerical Challenges Associated with WRF LES Modeling: Stratocumulus Cloud in the DYCOMS-II RF02 Case

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1. Introduction

A numerical issue in the Weather Research and Forecasting (WRF) model was raised by Yamaguchi and Feingold (2012), where large eddy simulations (LES) of stratocumulus clouds would not converge in terms of liquid-water path (LWP) unless a substantially smaller acoustic time step was used than required to meet the Courant–Friedrichs–Lewy (CFL) criterion (see Figure 1).

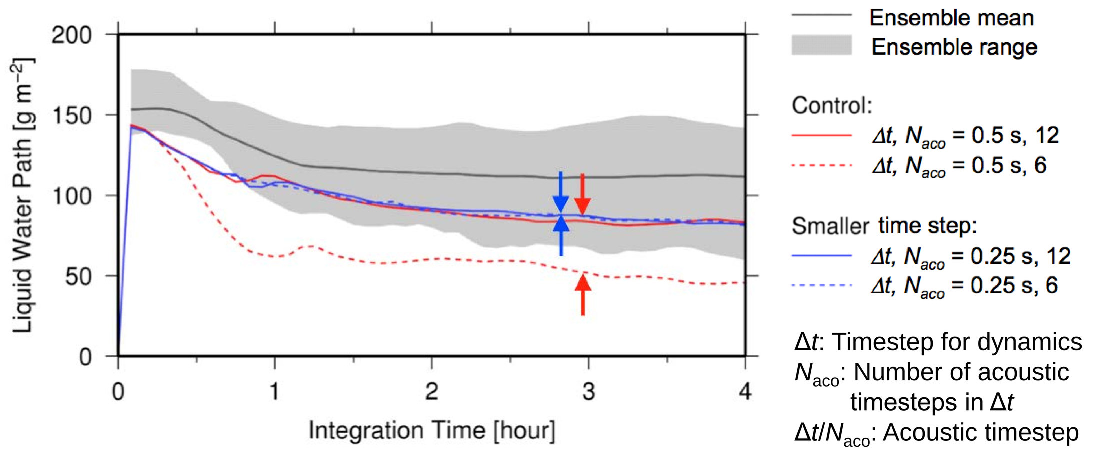

Figure1: The acoustic time-step dependency issue recreated from the DYCOMS-II RF02 case for precipitating marine stratocumulus clouds (colored lines). The ensemble mean (black line) and range (shaded) are from eight LES models in Ackerman et al. (2009). The convergence issue is indicated by the difference between the two red curves.

We investigate the convergence issue using WRF LES (WRF-FASTER package) for the DYCOMS-II RF02 (DRF02) stratocumulus case to understand the convergence issue and provide candidate solutions.

2. Understanding the convergence issue and conditions conducive to the issue

- Besides LWP, the convergence issue impacts bulk cloud properties (e.g., cloud fraction), meteorological variables, and turbulence statistics near the inversion (not shown).
- The non-convergence is associated with small-scale fluctuations in horizontal wind components (Figure 2) and other prognostic variables near the inversion that are not present in the converged runs.

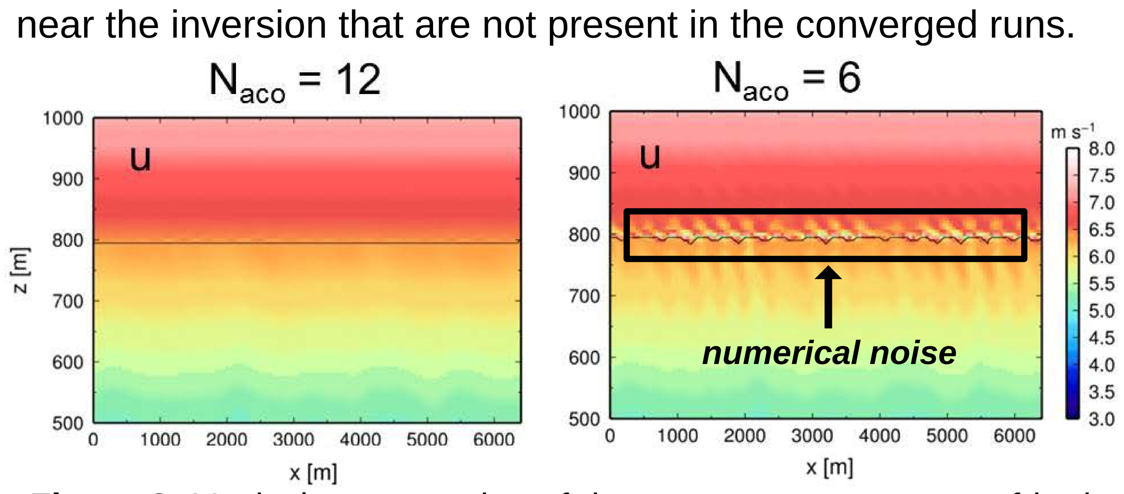

Figure 2: Vertical cross section of the east-west component of horizontal wind, u (m s^{-1}) in the simulations using N_{aco} = 6 and 12 with dynamical time step Δt = 0.5 at 30 min into the DRF02 simulation period. Thin black line indicates cloud top.

- We found that the dependency on acoustic time step is sensitive to the initial horizontal wind speed (not shear) near the inversion height (not shown) and water vapor difference across the inversion (Figure 3).

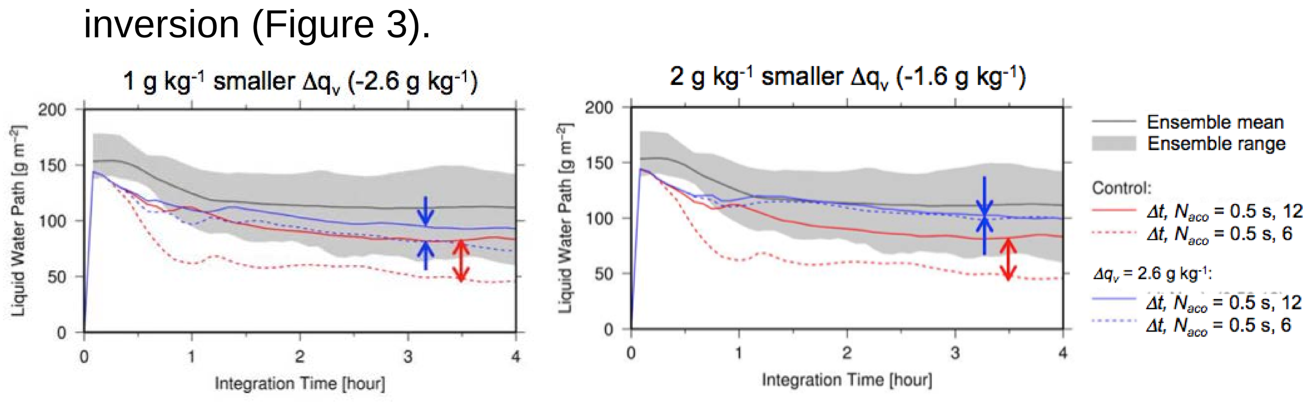

Figure 3: As in Figure 1 but for the sensitivity tests of the initial moisture jump, Δq_v (-3.6 g kg^{-1} for the control run [red]; -2.6 or -1.6 g kg^{-1} for the sensitivity runs [blue]). Differences between the solid and dashed lines indicate the presence of the convergence issue and the lack of difference by Δq_v = -1.6 g kg^{-1} indicates convergence.

When a large acoustic time step is used under the condition of large wind speed and moisture jump at the inversion, the advection scheme fails to correctly advance wind and produces spurious wind fluctuations (numerical noise) that leads to a thinner stratocumulus cloud, with less liquid water path and cloud fraction.

3. Method to detect noise and the convergence issue

- We developed a methodology to detect the numerical noise that leads to the convergence issue. We quantified the magnitude of the spurious wind fluctuations through the variance of u after it has been high-pass filtered to remove wavelengths longer than the scale of the spurious fluctuations (400 m) (Figure 4).
- Using the maximum filtered-wind variance as a measure of the spurious wind fluctuations, the acoustic time step dependency is examined in a 2-D parameter space of wind speed and moisture jump at the inversion height for DRF02 using 3-D simulations (Figure 5).

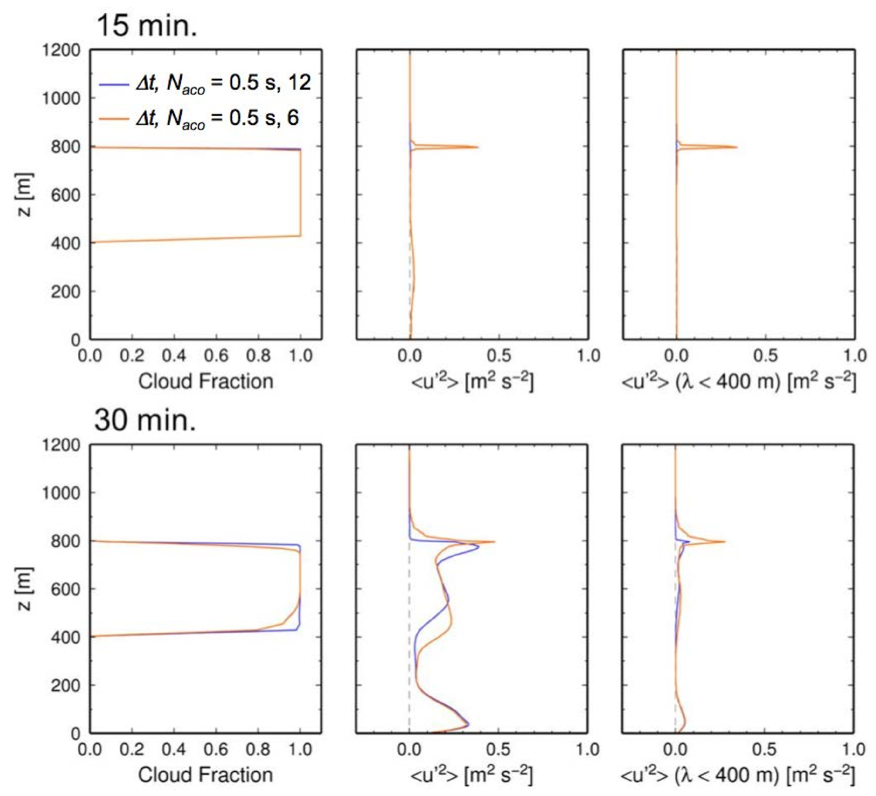

Figure 4: Vertical profiles of cloud fraction, and unfiltered and filtered u variances at 15 and 30 min into the integration period for the DRF02 case using N_{aco} = 6 and 12. The filtering removes wavelengths longer than 400 m and make the signal from the spurious fluctuations more apparent.

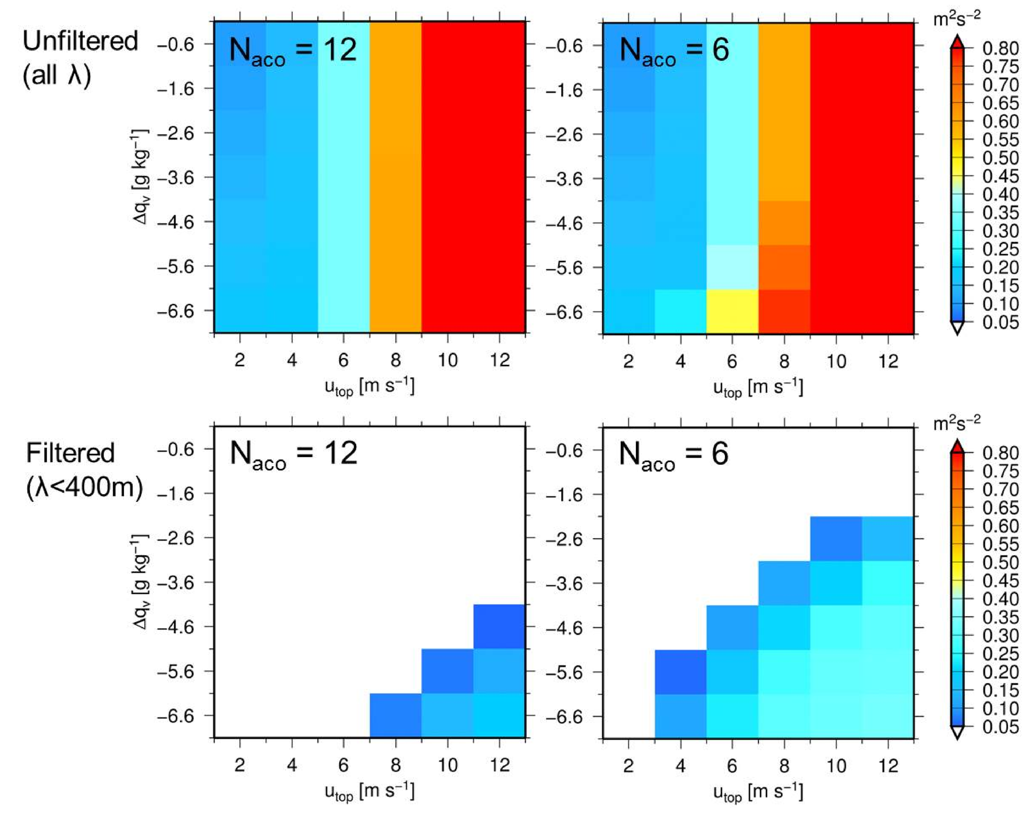

Figure 5: Unfiltered and filtered maximum u variances (color) as a function of initial wind speed at the inversion top (u_{top}) and the moisture jump at the inversion, $\Delta q_v = q_{bot} - q_{top}$.

4. Candidate solutions

Solution 1: Galilean transformation

A Galilean transformation, which simulates dynamics on a moving coordinate (at a relative motion, $\mathbf{V}_c$) instead of static coordinate, can be used to reduce the effective wind speed in the advection calculation and reduce the acoustic time step dependency (Figure 6).

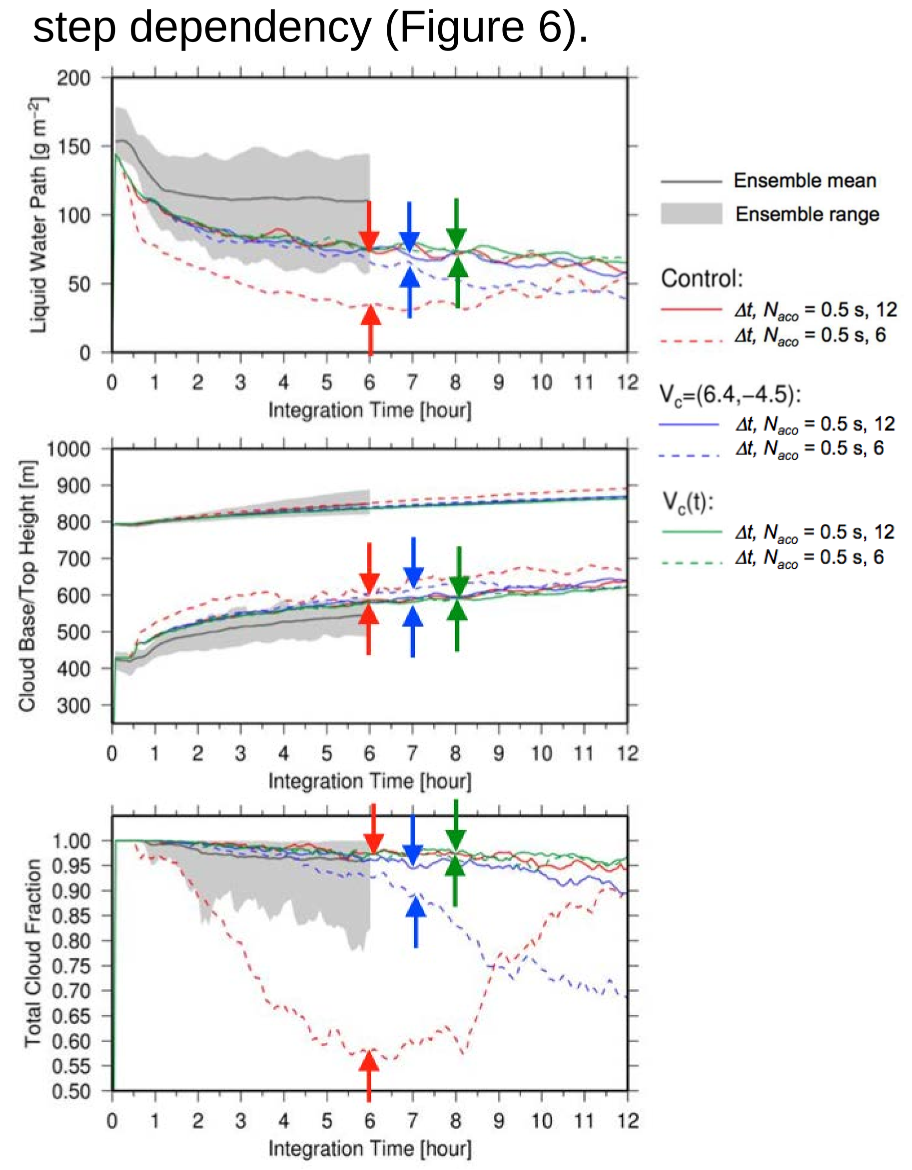

Figure 6: Time series of LWP, cloud top and cloud base heights, and cloud fraction from the simulations testing Galilean transformations with a fixed $\mathbf{V}_c$ (blue) and temporally varying $\mathbf{V}_c$ updated by sampling 800-m wind (green).

Solution 2: Advection Treatment

The Weighted Essentially Non-Oscillatory (WENO) advection scheme is designed to inhibit overshooting and undershooting of the numerical solution. It can inhibit the generation of spurious wind fluctuations and attain convergence (Figure 7).

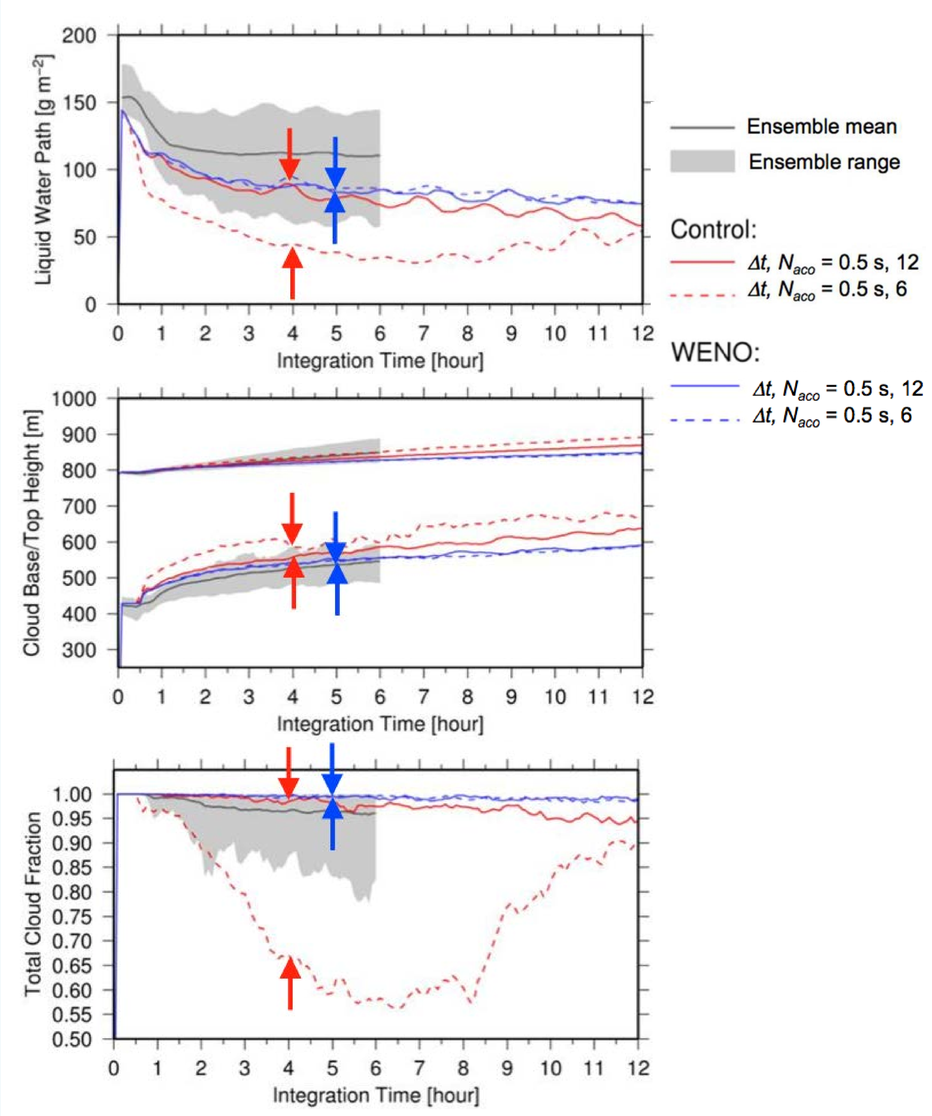

Figure 7: As in Figure 6, except for simulations testing the WENO advection scheme (blue).

Solution 3: Fix Dynamical Core

Based on discussions with WRF developers, θ is replaced by moisture-weighted θ in the fast mode calculations. The runs converge with different acoustic time steps and produced results similar to the converged run using the original advection scheme (Figure 8).

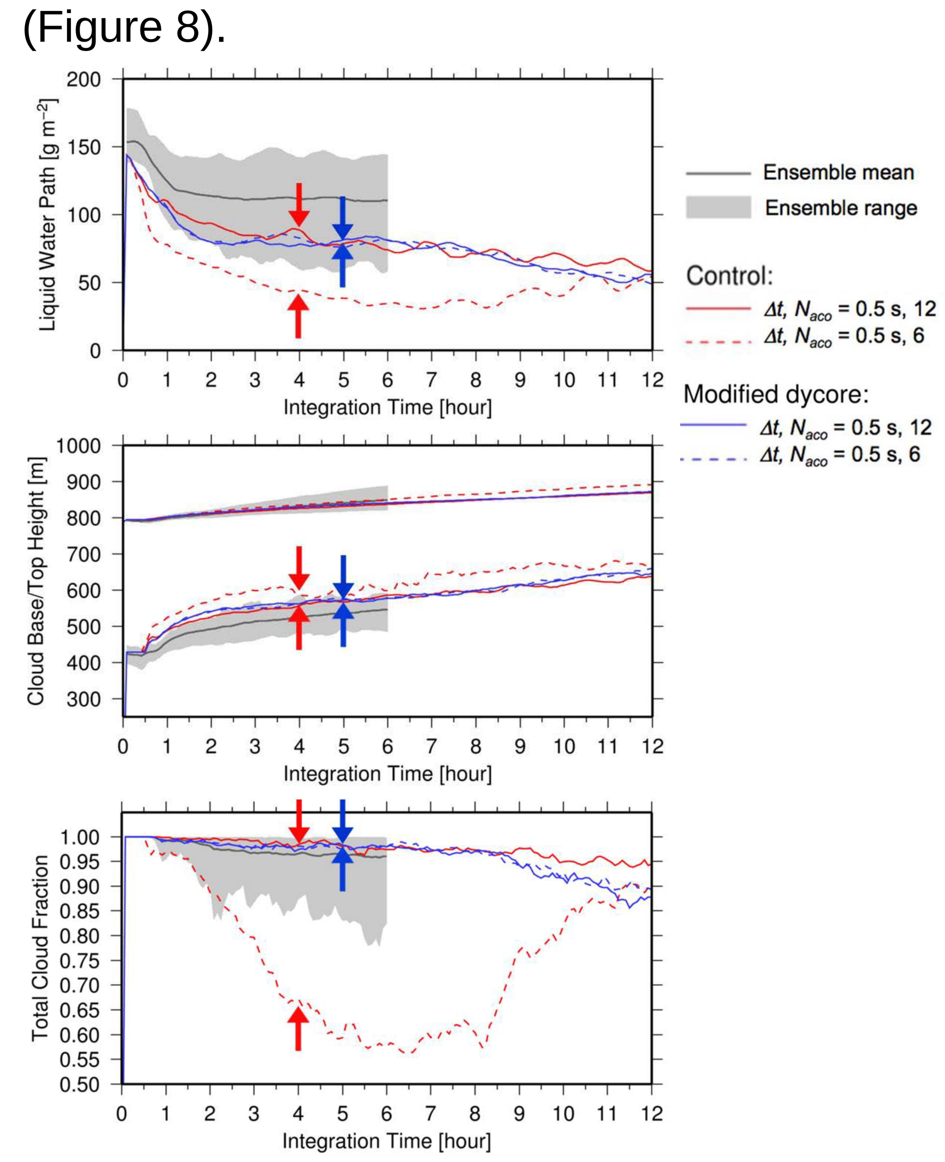

Figure 8: As in Figure 6, except for the simulations testing the modified dynamical core (blue).

5. Summary

- We investigated the acoustic time dependency (convergence issue) of WRF LES in DYCOMS-II RF02 stratocumulus case, which can potentially impact low-cloud simulations at the ARM sites.
- We found that the spurious wind fluctuations (numerical noise) occur near the inversion in the un-converged run, and are responsible for the convergence issue.
- We found that the acoustic time step dependency is sensitive to the wind speed and moisture jump at the inversion height.
- A methodology is developed to quantify the spurious fluctuations related to potential occurrence of the convergence issue.
- We found three candidate solutions that attain convergence even with a large acoustic time step. From them, modifying the dynamical core to use moisture-weighted θ is the recommended solution.
- The problem and solutions are also examined using low-cloud cases at the ARM SGP site. See Fast et al. poster.

Acknowledgments
This research was supported by the DOE ASR Program.

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