Simulations of Clouds and Sensitivity Study by Wearther Research and Forecast Model for Atmospheric Radiation Measurement Case 4

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Introduction

One of the large errors in general circulation models (GCMs) cloud simulations is from the mid-latitude, synoptic-scale frontal cloud systems (Zhang et al. 2004; Lin and Zhang 2004). Now, with the availability of the cloud observations from Atmospheric Radiation Measurement (ARM) 2000 cloud Intensive Operational Period (IOP) and other observational datasets, the community is able to document the model biases in comparison with the observations and make progress in development of better cloud schemes in models.

Xie et al. (2004) documented the errors in midlatitude frontal cloud simulations for ARM Case 4 by single-column models (SCMs) and cloud resolving models (CRMs). According to them, the errors in the model simulated cloud field might be caused by following reasons: 1) lacking of sub-grid scale variability; 2) lacking of organized mesoscale cyclonic advection of hydrometeors behind a moving cyclone which may play important role to generate the clouds there. Mesoscale model, however, can be used to better understand these controls on the subgrid variability of clouds. Few studies have focused on applying mesoscale models to the forecasting of cloud properties (Hartmann et al. 1999). Weaver et al. (2004) used a mesoscale model RAMS to study the frontal clouds for ARM Case 4 and documented the dynamical controls on the sub-GCM-grid-scale cloud variability.

Model Description and Setup

Weather Research and Forecast (WRF) model is used to simulate the ARM Case 4. The simulation was driven by ETA 3D analysis both for the initial time and lateral boundary condition at every 3h. The forcing data has horizontal resolution of 40km and 38 σ levels in vertical. The configurations of the model experiments are listed in Table 1 and Table 2. Cumulus scheme is not used for 4km domains. For detailed description of the physics scheme, refer to Chen and Dudhia (2002).

In WRF model, the cloud cover of a grid box is computed to be either 0 or 1, i.e. partly cloudy sky is not allowed. If the sum of the total cloud water and cloud ice mixing ratio of a grid box is greater than a threshold of 1e-6, it is flagged as cloudy sky; otherwise it is clear-sky.

Table 1. Model setups for experiments E1 and E2.

	E1	E2
Coverage	large domain	small domain
resolution (km)	12	same
Vertical levels	31	same
time step (s)	60	same
Initial	12Z 3/1	same
Microphysics	WSM 6-class	same
Boundary	MYJ TKE	same
Cumulus	Kain Fritsch	same

Table 2. Model setups for experiments E3, E4 and E5.

	E3	E4	E5
domains	3	Same	same
resolution(km)	36,12, 4	Same	same
Vertical levels	31	Same	same
time step (s)	180, 60, 20	Same	same
initial	12Z 3/1	0Z 3/3	same
Microphysics	WSM 6-class	Same	same
Boundary	MYJ TKE	Same	same
Cumulus	KF	Same	same
advection of hydrometeors	yes	Yes	no

Observations

Subperiod A of ARM Case 4 starts from 1730 UTC 3/1 and ends at 0Z 3/5. During this period, a cyclone developed and passed slightly south to the Southern Great Plains (SGP) site on 3/2-3/3. Figure 1 shows the synoptic configuration when the cyclone reaches its mature stage at 3Z on 3 March while it arrives at ARM SGP site. On the NWS surface weather map it is a mature wave cyclone, which had been developing since 12Z on 1 March. The low center is located over the south border of Oklahoma with typical cold and warm frontal configuration (figure not shown). During the passage of the cyclone, the minimum surface pressure at SGP site reaches 973mb. At 500mb, a short wave trough with closed center is located western KS and OK slightly to the northwest of the surface low. At 850mb, the low center is located in between the locations of the surface and the 500mb center.

The clouds related with this frontal system are the typical comma shaped clouds (Carlson 1980). The components of the cloud systems include 3 parts: the comma head which corresponds to the cloud shield north and west of the surface low system and its westward protrusion; the comma tail which extends a short distance toward the south and the dry intrusion which cuts off the cloud shield behind the comma head. The Central Facility measured the passage of the high prefrontal clouds, deep comma head frontal clouds, dry intrusion and deep post frontal cloud spiral in order as we can seen from temporal evolution of cloud in Figure 1. On 3/3 3Z, the cyclone located right over the SGP site on 850mb. At this time, the dry intrusion was passing the site.

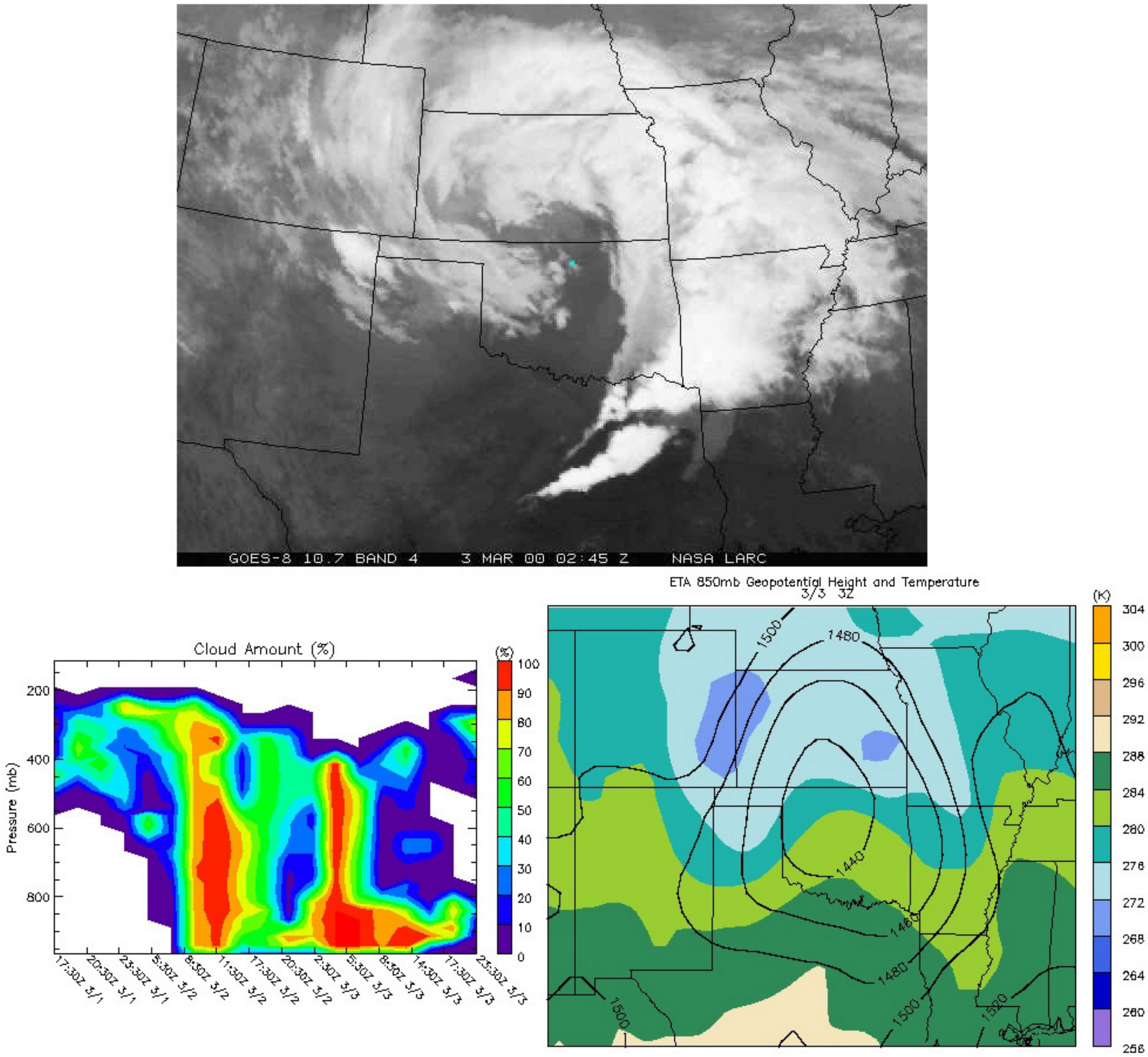

Figure 1. GOES infrared image at 2:45Z 3/3 (top), ETA analysis of temperature and geopotential height at 850mb at 3Z 3/3 (bottom right) and ARM observed cloud fraction at central facility for period A (bottom left).

Model Results

The impacts of boundary and initial condition on the WRF simulation and the contribution of advection of hydrometeors are presented here.

A. Prefrontal

For the prefrontal clouds, we conducted 2 runs, E1 and E2. The main difference is the domain coverage. E1 runs over a large domain while E2 runs over a small domain. They are a pair of experiments to test the boundary effect. In E1, the horizontal cloud cover is overestimated. It doesn't show banded structure as seen on satellite image. Further examination of the relative humidity fields showed it is well overestimated too. We suspect the WRF model did not well simulate the sub-grid dynamic control, which caused large biases in the clouds. So E2 is designed with a smaller domain to be more constrained to ETA analysis at the boundary. Figure 2 shows the temporal and vertical evolution of cloud amount, vertical velocity from E1, E2, ARM observation or analysis. The results from E2 showed improvements. First, high cloud amounts are reduced a lot comparing with that in E1; second it captured the cloud minimum at midlevel at 5:30Z 3/2; third, it well captured the gradually decreased altitude of the cloud base. The dynamic forcing, i.e. the evolution of vertical velocity of E2, follows the ARM analysis more closely. From these two runs, we can see that the boundary condition plays very important role in this prefrontal cloud simulation.

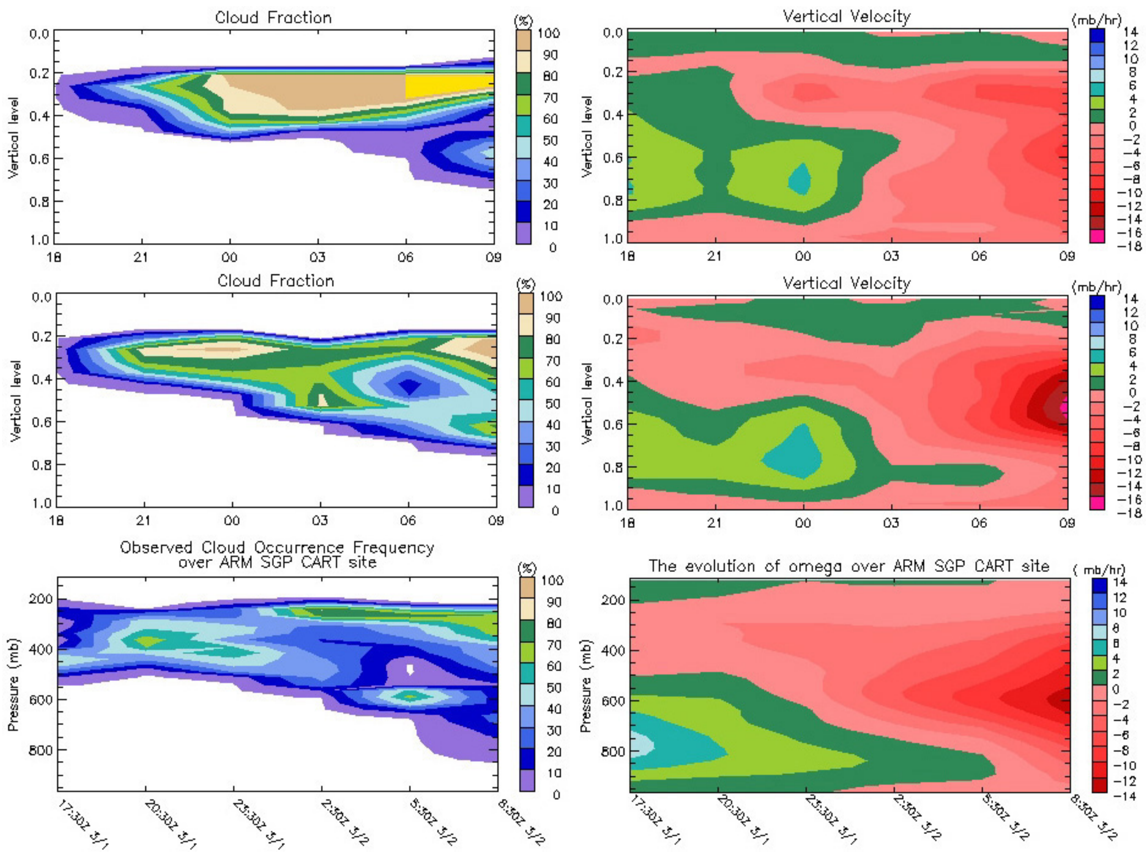

Figure 2. Top panel: cloud fraction and vertical velocity of E1; middle panel: cloud fraction and vertical velocity of E2; bottom panel: ARM measured cloud fraction and analysis of vertical velocity.

Although there is great improvement from E1 to E2, overestimations still exist in the high clouds. We examined the differences between the forcing data and the ARM data, and it was found that the water vapor mixing ratio of ETA analysis had large biases at high levels. It is much larger than 100% at those levels for the whole prefrontal period (Figure 3). This could very likely contribute to the overestimation of high clouds in E2.

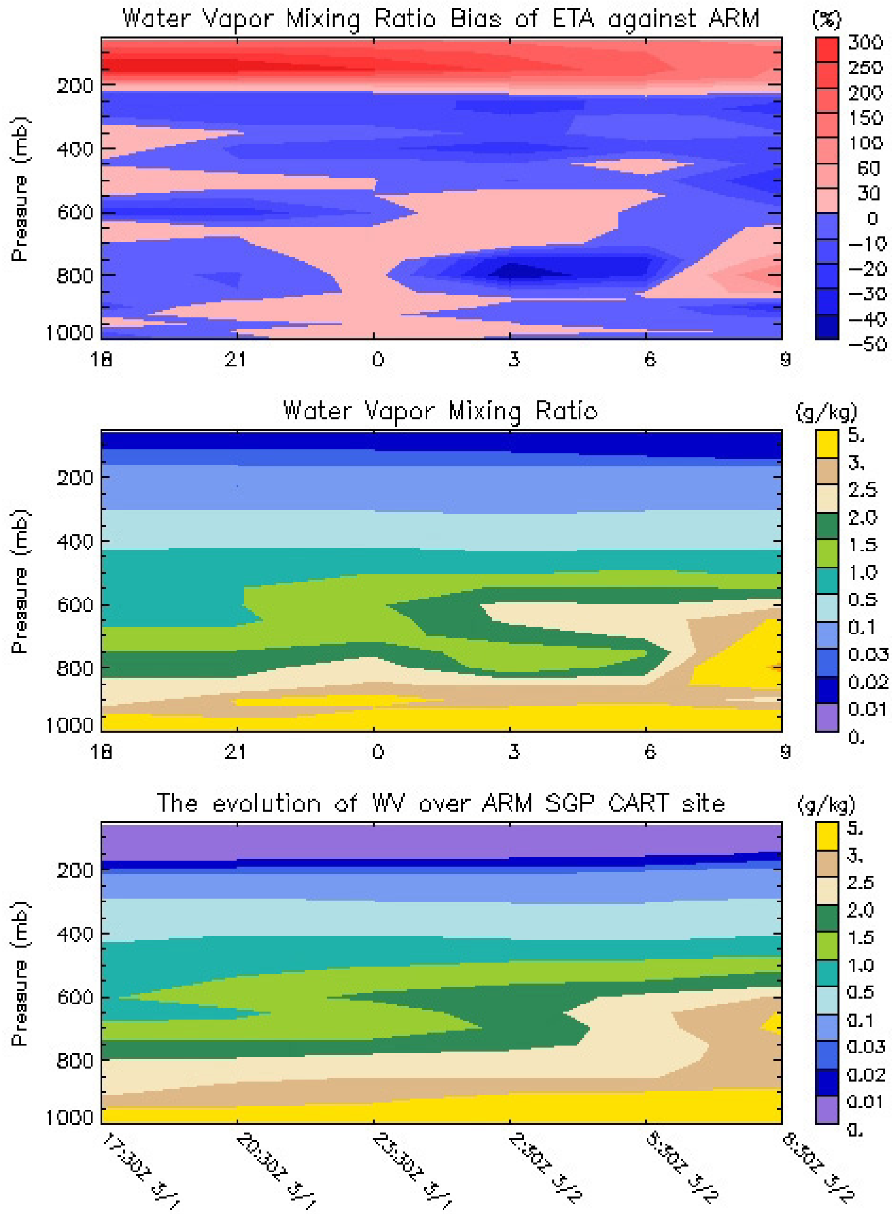

Figure 3. Water vapor mixing ratio of ETA analysis (middle), ARM analysis (bottom) and their difference percentage (up).

B. Post-frontal Clouds

Another pair of experiments E3 and E4 is conducted to show the impacts of the initial condition. We examined the horizontal morphology of the cloud top temperature at time when the cyclone reached its mature stage at 3Z 3/3. At 3Z 3/3, E3 is 39hrs into the simulation and E4 is 3hrs into the simulation. It is obvious that the morphology of the cloud cover of E4 is much closer to satellite image than that of E3 (Figure 4). This indicates the importance of the initial condition in generating the reasonable clouds from WRF model.

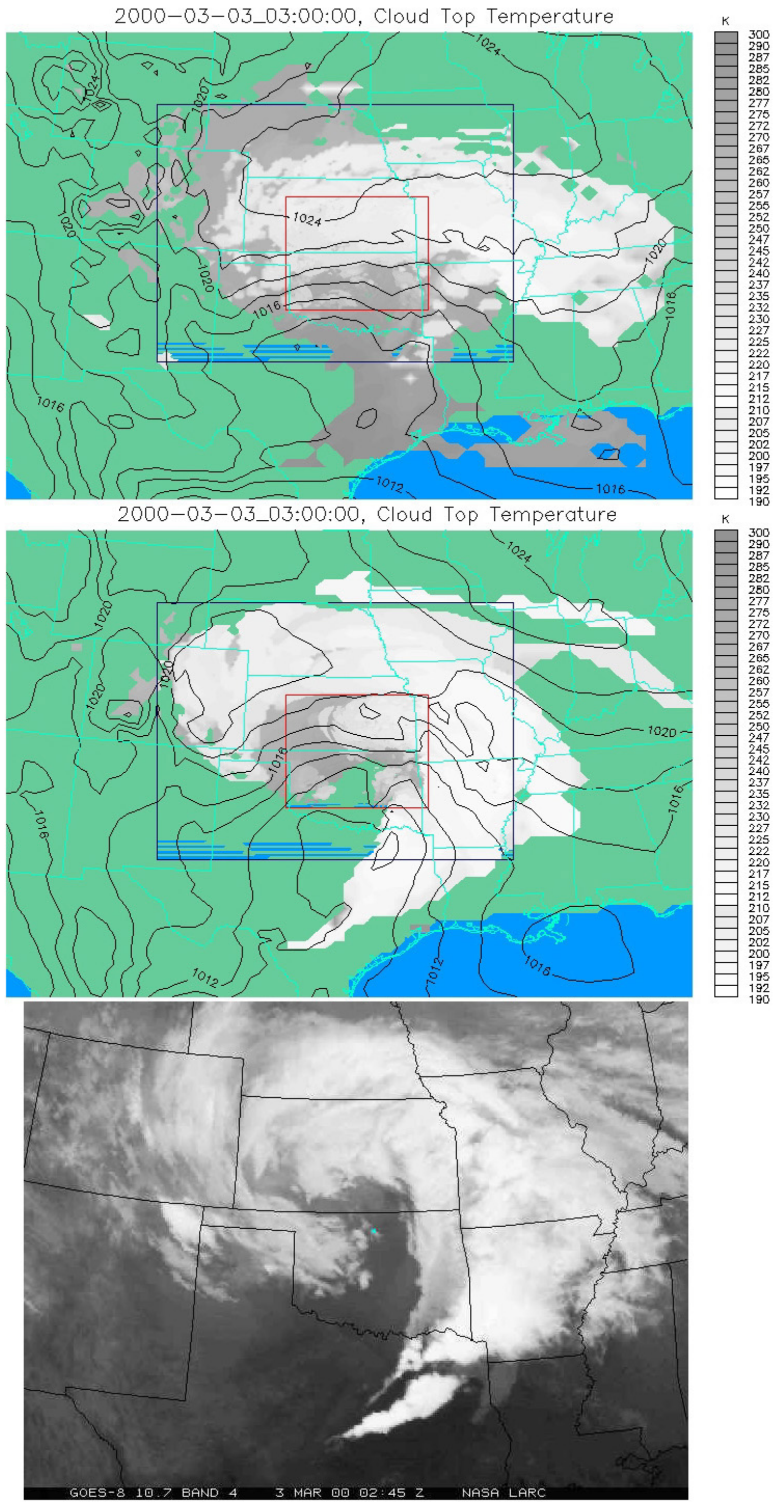

Figure 4. Cloud top temperature from E3 (top), E4 (middle) and GOES image (bottom) at 3Z on 3/3. Leading time for E3 is 39 hrs, for E4 is 3 hrs.

In Xie's paper, they suspect that the advection of hydrometeors is important in the postfrontal clouds formation. As a follow up study, we conducted another experiment E5 which was exactly the same as E4 except that it suppressed the advection of hydrometeors. The results show that the advection of hydrometeors contributes to the generation of middle clouds (Figure 5).

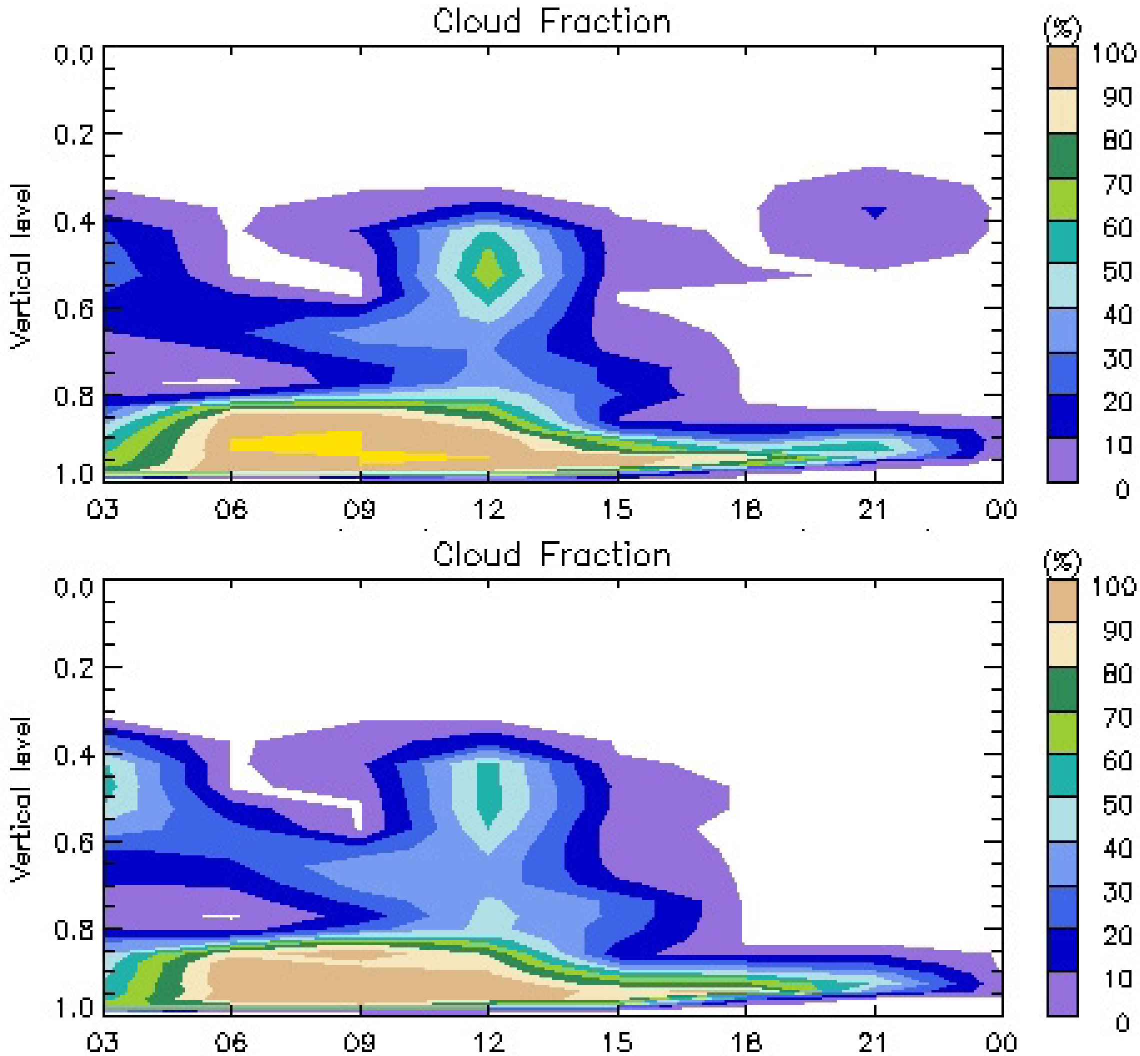

Figure 5. Cloud Fractions from E4 (top) and E5 (bottom). E5 suppresses the advection of hydrometeors.

Summary

For the prefrontal clouds, the boundary condition (dynamic constrains) plays important role in generating reasonable prefrontal clouds. Biases in the forcing data may contribute to the overestimation of the high clouds.

For post frontal clouds, the initial condition shows large impact on the cloud morphology. The advection of hydrometeors contributes partially to the generation of the postfrontal clouds.

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