SENSITIVITY OF SIMULATED CLOUD PROPERTIES TO METEOROLOGICAL MODEL CONFIGURATIONS

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1. INTRODUCTION

Clouds are important in the processing and cycling of chemicals in the atmosphere through complex processes. On one hand, aerosol particles, a key ingredient of air pollution, play an important role in the formation of clouds by acting as cloud condensation nuclei and ice nuclei. On the other hand, clouds provide a favored environment in which heterogeneous chemical reactions can take place, which in turn alters the concentrations of gases and particles in the atmosphere. Clouds also affect photochemical processes in the atmosphere by modulating radiation intensity, and they can remove gases and particles through precipitation processes. Previously studies shows that the ability of the air quality model to simulate cloud processing of aerosols and gases depends largely on the accuracy of the modelled cloud microphysics fields [e.g., Gong et al., 2006a and 2006b].

In order to evaluate cloud processing in the Canadian air quality model AURAMS (A Unified Regional Air-quality Modelling System [Moran et al., 1998]), the performance of AURAMS's meteorological driver model – GEM (Global Environmental Multiscale model, [Côte´ et al., 1998a,1998b; Mailhot et al., 2006]) was evaluated previously for its ability to predict cloud microphysical properties under summer continental conditions against the aircraft observations conducted during the 2004 International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) field study (Zhang et al., 2007). Results from that evaluation showed that the GEM model generally captured the observed vertical distribution of liquid water content (LWC) in the towering cumulus and also reproduced the observed variation of LWC among different flights. However, model at both 15- and 2.5km resolutions overestimated the in-cloud water content.

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Recently significant efforts have been made to develop the next generation of GEM model – GEM version 4 (Girard et al., 2011, GEM4 hereinafter). Amongst various important changes, the single-moment explicit bulk cloud microphysical scheme (Kong & Yau, 1997, "KY-SD" hereinafter) is being replaced by a double-moment scheme (Milbrandt and Yau, 2005, "MY-DM" hereinafter) for high-resolution simulations. This study examines the performance of GEM4 in predicting cloud fields for the ICARTT period. In the following, model setup will be briefly described in Section 2; model simulated LWC under different model setups will be discussed in Section 3; discussions and conclusions will be given in Section 4.

2. MODEL SETUP

The model setup is similar to the High Resolution Deterministic Prediction System operating in the Canadian Meteorological Center (CMC). It is a one way cascade of nested LAM (Limited Area Model) version of the GEM with increasing resolutions (Milbrandt et al., 2013). In this study, model simulations were conducted at two resolutions: 15-km and 2.5-km, the same as in Zhang et al. (2007).The boundary conditions are provided by either an objective analysis (in the case of the 15-km run for the continental domain) or a coarser resolution model forecast (in the case of the nested 15-km and 2.5-km runs). The model was first run with 15-km resolution on a continental domain using Sundqvist microphysical scheme [Sundqvist et al., 1989] for condensation at grid-resolved scale and Kain-Fritsch parameterization [Kain and Fritsch, 1990] for sub grid-scale clouds due to deep convection. This run is piloted by the objective reanalysis available at 00, 06, 12 and 18 UTC. This is then followed by an intermediate 15-km resolution run on a smaller domain using the MY-DM scheme (in place of the Sundqvist scheme) and the Kain-Fritsch scheme, piloted by the continental 15-km run. Finally the 2.5-km resolution run is conducted with the explicit MY-DM scheme only, piloted by the intermediate 15-km resolution run. Figure 1 shows the cascading model domains.

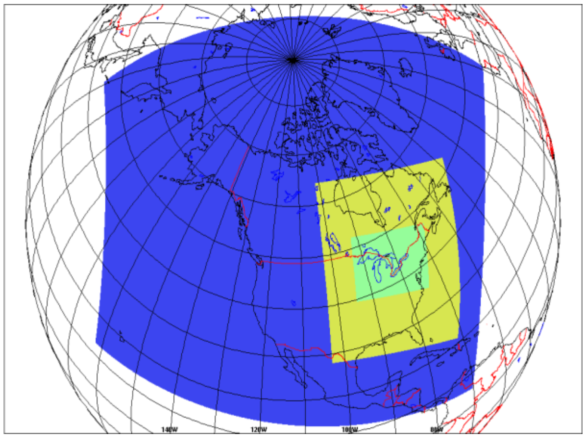

Fig. 1. Cascaded GEM domains: continental 15-km (blue), regional 15-km (yellow), and 2.5-km (light green).

3. MODEL SIMUALTIONS AND RESULTS

The case studied here is based on two research flights during the ICARTT field campaign, when gases and particles were sampled in and below clouds along two north-south lines to investigate the cloud processing of plumes originated from the Chicago area on August 10, 2004, between 17 and 24 UTC [Gong et al., 2013]. Fig. 2 shows the GOES satellite visible images at 18:15Z on Aug10, 2004. The study area was mostly covered by stratocumulus clouds ahead of an advancing cold front.

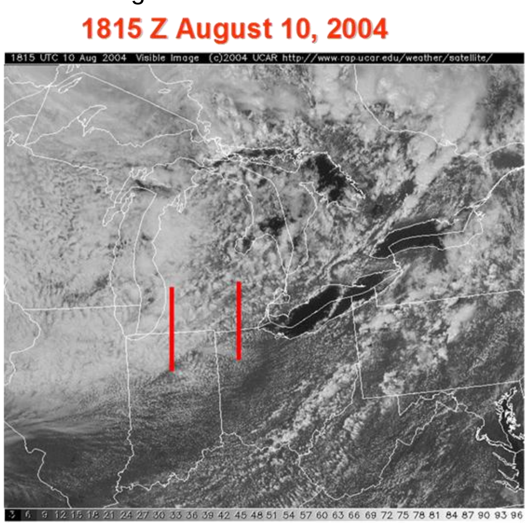

Fig. 2. GOES satellite image at 18:15Z on August 10, 2004; red lines denote the flight tracks (*Gong et al., 2013*)

Figure 3 shows the simulated LWC, from the previous model run (at 2.5-km resolution) with the older version of GEM (version 3; hereafter GEM3), at 18:00Z on August 10, 2004 at roughly 1400m above surface, a level where most of the clouds were encountered and sampled by the aircraft. The clouds over the aircraft sampling areas were simulated reasonably well by the model.

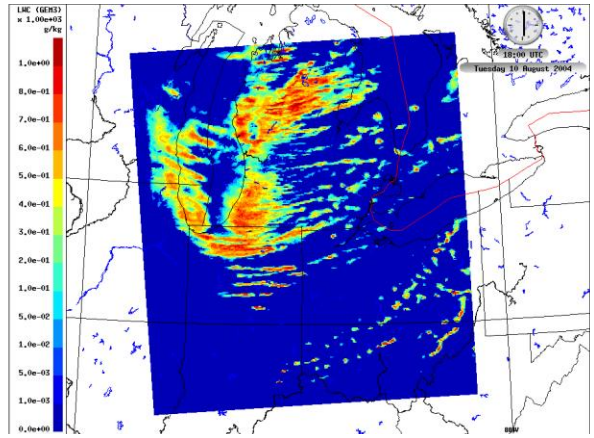

Fig. 3. Liquid Water Content (LWC) simulated by the old version of GEM – GEM3 at 18:00Z on August 10, 2004 at an altitude about 1400m above surface.

Figure 4 shows the simulated LWC from the new model run, using GEM4 at 2.5-km resolution, for the same time and altitude as Fig.3. In comparison, the new model simulation produced significantly less cloud.

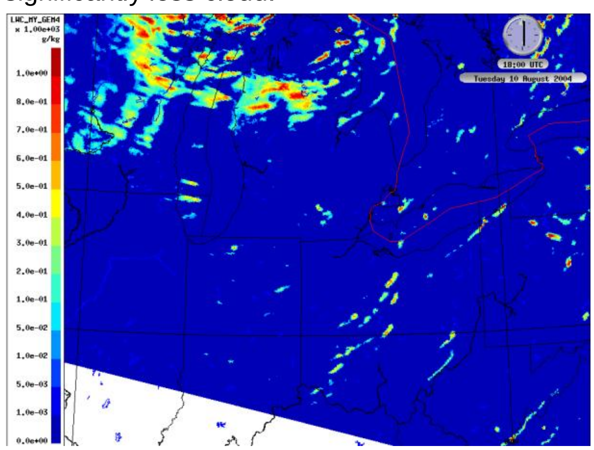

Fig. 4. The same as Fig. 3, but simulated by the new version of GEM – GEM4.

To investigate the reasons for the under prediction of LWC in the new simulation, several sensitivity tests have been carried out and are discussed below.

3.1 Sensitivity to Microphysical Scheme

A first test is to see the impact of a different microphysics scheme. For this test the double-moment MY-DM scheme was replaced by the single-moment KY-SM scheme as in the GEM3 simulation. The LWC simulated using the KY-SM in GEM4 is shown in Fig. 5 and Fig. 6 shows the difference between the two schemes.

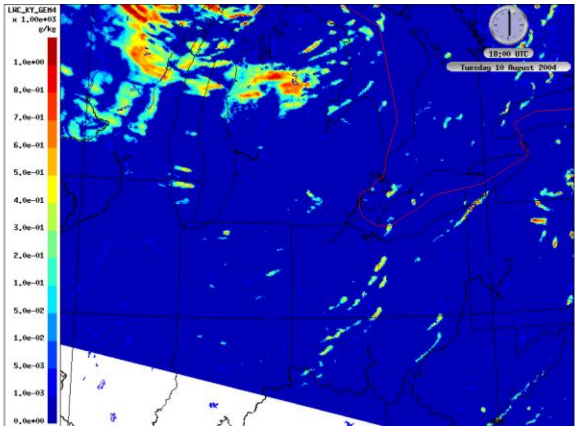

Fig. 5. The same as Fig. 4, but KY-SM scheme was used instead of MY-DM

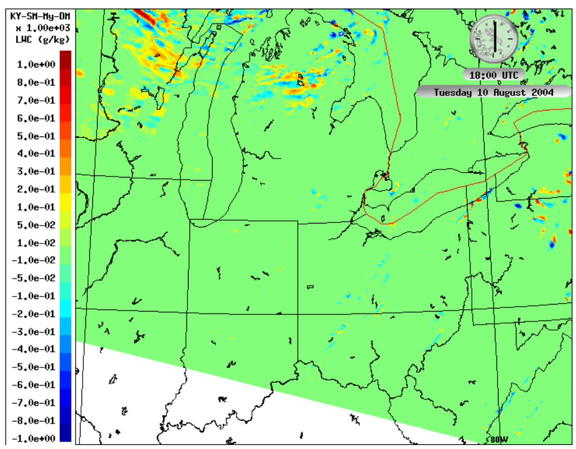

Fig. 6. Difference of simulated LWC between the KY-SM and MY-DM scheme (KY-SM – MY-DM)

It is apparent from comparing Fig. 4 and 5, and also from Fig.6, that the two different explicit schemes did not lead to much difference in the predicted cloud (as far as LWC is concerned) in this case, especially in the area where aircraft observation was conducted. As a result, the KY-SD scheme is used for the remaining sensitivity runs to be consistent with the previous GEM3 simulations.

3.2 Sensitivity to Initialization and Length of Forecast

The new GEM4 and the previous GEM3 runs also differ in start time: the GEM3 run was initialized at 00Z, August 10, 2004, while the GEM4 run was initialized at 12Z, August 10, 2004. As a consequence, the LWC shown in Fig. 3 (from GEM3) is an 18-hour forecast, but the one in Fig. 4 (from GEM4) is a 6-hour forecast. Although a 6-hour spin-up is usually considered sufficient for mesoscale forecast [http://www.drjack.info/INFO/model_basics.html), studies have shown that initial conditions and spin-up hours can have significant impacts on model prediction of cloud microphysical properties and precipitations [e.g., Kristjfinsson, 1991]. Therefore, a test was conducted to start the simulation with GEM4 at 00Z, the same as the previous simulation with GEM3. Shown in Fig. 7 is the GEM4 simulated LWC as in Fig. 5 but with an 18-hour lead time. It is seen that significantly more cloud (higher LWC) is predicted with longer lead time (or spin-up time). This result inicates a spin-up longer than 6 hours is required in this case.

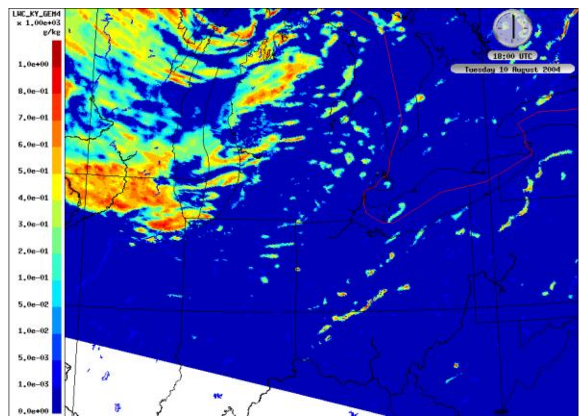

Fig. 7. The same as Fig. 5, but GEM4 was initialized at 00Z, Aug. 10, 2004, the same as GEM3 in Fig.3

Fig. 8 and Fig. 9 compare the GEM4 predicted LWC at 22Z after 10 (initialized at 12 Z) and 22 hours (initialized at 00 Z) of simulation, respectively. The two model predictions of LWC are now quite comparable indicating a spin-up (or model lead time) of 10 hours may be sufficient for this case.

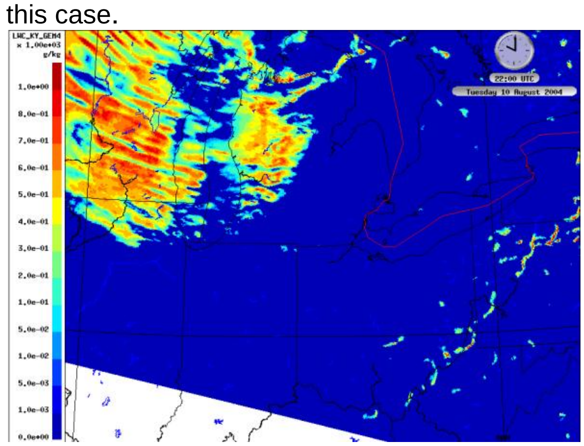

Fig. 8. GEM4 predicted LWC valid at 22Z after 10 hours of simulation.

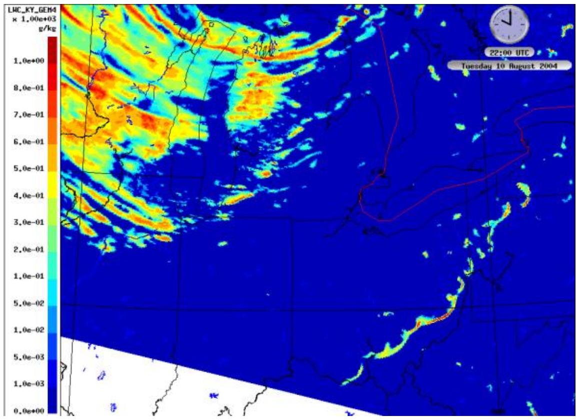

Fig. 9. GEM4 predicted LWC valid at 22Z after 22 hours of simulation.

3.3 Sensitivity to the Location of the upstream boundaries

Although Fig. 7 shows a significant improvement in the simulated LWC after longer spin-up time, the model still predicted too small amount of LWC in the area south-east of Lake Michigan where clouds were sampled by aircraft. Another difference between the previous GEM3 and the new GEM4 simulations is the location of the upstream boundaries for the high-resolution domain. Fig. 10 shows the 2.5-km resolution model domains for the GME3 (black box) and GEM4 (red box) simulations superposed on the LWC field predicted by the pilot model GEM4 at 15km resolution.

We can see that the upstream boundaries (i.e., the upper eastern and northern boundaries) of the old GEM3 2.5-km domain are located in the middle of the cloud system, while the upstream boundaries of the new GEM4 2.5-km domain are located somewhat at the edge of the system. This could imply that the lack of predicted cloud from the new GEM4 2.5-km run may be due to inadequate moisture supply from the lateral boundaries. Therefore, the old GEM3 2.5-km domain was used for the simulation with GEM4 so that its eastern boundary is placed in the middle of the cloud system. The simulated LWC with the modified domain is shown in Fig. 11. We can see that, comparing to Fig. 7, more LWC is predicted in the area east of Lake Michigan at 18Z after 18 hours of simulation.

Since the cascading modeling system was designed in a way that the 2.5-km model domain and the piloting regional 15-km model domain have the same rotation, for the new 2.5-km run in the revised domain the intermediate regional 15-km domain (for piloting) was also changed accordingly. A comparison between the model predicted cloud fields from the two piloting runs (at 15-km resolution with different rotation) showed very little difference (not shown here), indicating that the difference seen between Fig. 11 and 7 are due to the differences in upstream boundary placement only in this case (rather than differences in piloting fields).

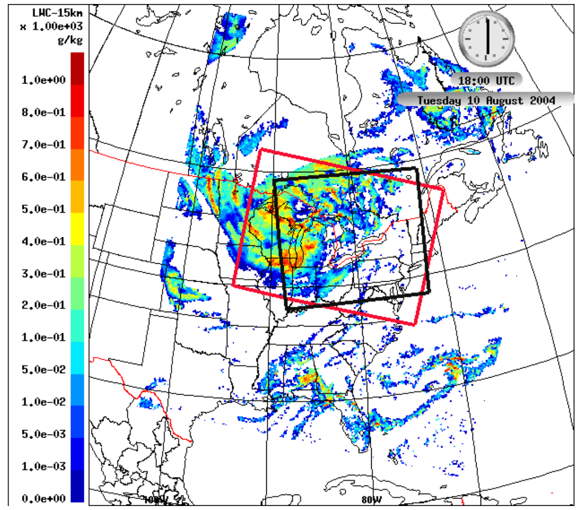

Fig. 10. LWC simulated by GEM4 at 15km resolution and the two 2.5km model domains: red - new GEM4 domain and black – old GEM3 domain

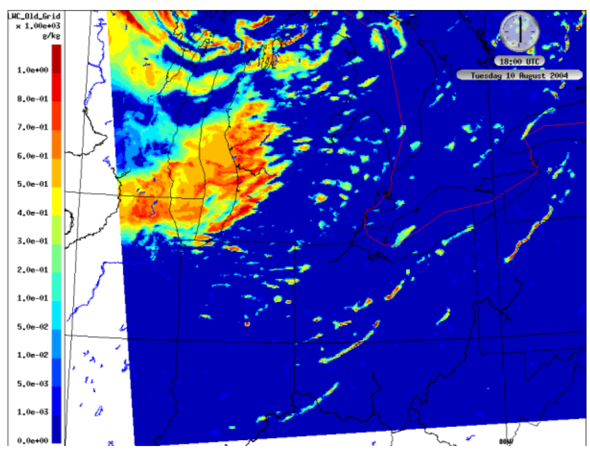

Fig. 11. The same as Fig. 7, but with the old GEM3 2.5km domain.

3.4 Sensitivity to Land Surface Parameterization

The sensitivity test discussed in Section 3.3 demonstrated that the model predicted cloud fields are very sensitive to the boundary locations where moisture is supplied laterally. Another important source of moisture is from the surface through vertical diffusions. The land surface scheme also has impacts on surface heat balance and thermal forcing at the surface. Studies have shown that land surface parameterization has significant influences on model predicted precipitation [e.g., Beljaars et al. 1996; Paegle et al. 1996]. Therefore, sensitivity of model simulated cloud LWC to land surface modeling systems is examined in this subsection.

In the current operational GEM model, the ISBA (Interaction Soil Biosphere Atmosphere) [Noilhan and Planton, 1989] land surface scheme has being used since 2002 [Bélair et al., 2003]. It replaced a simplified force-restore land surface model [Mailhot et al., 1997; Benoit et al., 1989]. To study the impact of land surface parameterization on the formation of clouds, the ISBA scheme in GEM was switched back to the force-festore model. Since the LWC predicted with the old GEM3 2.5-km model domain compared better with the satellite and aircraft observations, the old domain was used for this sensitive test. Fig. 12 shows the difference of LWC predicted using the ISBA land surface scheme and the force-restore scheme (ISBA – Force-Restore). We can see the land surface parameterization does have a noticeable impact on the simulated cloud fields, e.g., the model predicted slightly more clouds over an area south-east of Lake Michigan using the ISBA scheme than the Force-Restore scheme.

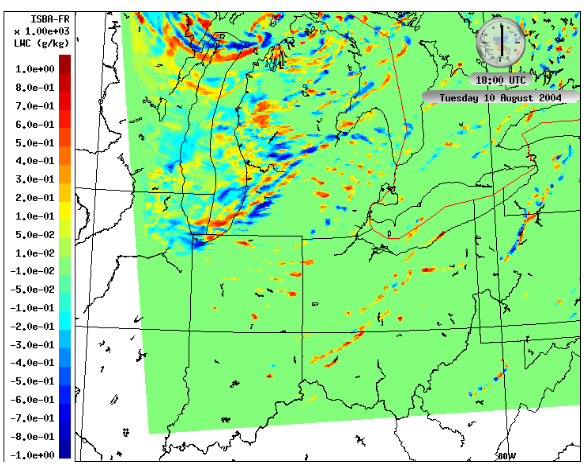

Fig. 12. Difference of LWC predicted by model using ISBA and Force-Restore land surface scheme (ISBA-Force-Restore)

4. DISCUSSIONS AND CONCLUSIONS

Cloud processing is very important in air quality modeling. The ability of air quality model to accurately represent this process depends significantly on the ability of the meteorological model to adequately predict the cloud fields. The sensitivity tests done in this study emphasize the complexity and difficulty of simulating cloud fields in the meteorological model. However, they also shed some light on where one needs to pay attention to the setup (and configuration) of the meteorological model for simulations.

Cloud microphysical schemes are important in parameterizing cloud fields, especially when detailed cloud information is needed, such as cloud-aerosol interaction where both cloud water content and cloud droplet number concentration are desired (e.g., Gong et al., 2013). However, changing from double-moment cloud scheme to single-moment cloud scheme has little impact on simulated LWC for the case studied here. The selection of the location of model domain, i.e., the locations of the upstream boundaries, can be important for simulation of clouds over a small model domain. The land surface scheme also impacts the cloud formation due to its role in determining the moisture and heat balance at the surface. To allow clouds to develop, enough spin-up time is also needed. The often used 6-hour spin up does not seem to be long enough for cloud simulation, a 10- to 12-hour spin-up may be sufficient based on the sensitivity test done in this study.

This study only tested limited number of processes and parameters, other processes such as model's vertical structure and vertical diffusion may play roles also in cloud formation. These factors will be investigated in our future study.

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