4.3 EVALUATION OF MODELED CLOUD PROPERTIES FOR AIR QUALITY APPLICATIONS

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1. INTRODUCTION

About 60% of the earth is covered by clouds. They play an important role in production of oxidants and acids in the atmosphere through aqueous-phase chemical mechanisms. Once trace gases and aerosols enter cloud droplets, they can dissolve, dissociate and undergo chemical reactions (Seinfeld and Pandis, 1998). It is estimated that up to 80% of the total production of sulphate globally is contributed by aqueous-phase oxidation in the clouds (Barth et al., 2000). On the other hand, precipitation formed in clouds is one of the most efficient sinks for aerosols and other soluble tracers, which is known as wet deposition. Moreover, clouds also act as trace gas and aerosol redistributors. Vertical mixing transports trace gases from the more polluted lower levels to less polluted higher levels where ozone production may be more efficient (Renard et al., 1994; Wang and Prinn, 2000). Evaporation of clouds, especially for non-precipitation clouds, can also release cloud-processed tracers and aerosols to the atmosphere far from the source regions. Recent studies showed that about 50% of the global sulphate burden is contributed from aqueous-phase production (Barth et al., 2000; Rasch et al., 2000). Therefore, it is important to understand the impact of clouds on the gas and aerosol concentration and composition in the atmosphere.

Numerous model studies have been conducted in the past to investigate the role of cloud in processing of gases and aerosols in the atmosphere in a range of scales and topics, such as acid deposition in global and regional scales (e.g., Chang et al., 1987; Venkatram et al., 1988; Carmichael et al., 1991), impact of cloud processing on global sulphate burden and aerosol indirect forcing (e.g., Lohmann et al., 1999; Barth et al., 2000; von Salzen et al., 2000), and air quality related regional and small scale model studies (e.g., Bator and Collett, 1997; Jacobson et al., 1997; Ackerman et al., 1998; Gong et al., 2003; Gong et al., 2005). Although model evaluations have been done with various measurements, such as concentration of tracer gases near the surface and chemical components in precipitation (e.g., Bator and Collett, 1997; Jacobson et al., 1997; Gong et al., 2005), there is a lack of observations to undertake a comprehensive model evaluation for in-cloud processes, which are perceived to play an important role in determining atmospheric composition.

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Previous air quality model evaluation has shown that the ability of the meteorological model to predict cloud microphysics fields is critical to the modelling of tracer processing by clouds (Gong et al., 2004, 2005). Therefore, to evaluate the cloud chemical processing in air quality model, one question needs to be answered first is how well the cloud physical properties, such as cloud water content and cloud fraction, are represented by the meteorological model. In-situ observations by aircraft provide valuable datasets to evaluate model predicted cloud properties, and there are existing work attempting to verify modeled cloud properties using aircraft observations. For example, Guan et al. (2001) compared supercooled cloud water forecasts with in-situ aircraft measurements. They looked at hit rate (HR), false alarm rate (FAR), true skill statistic (TSS), and correlation between measured and forecasted cloud water along aircraft flight tracks. In their later paper Guan et al. (2002) used similar statistical measures to evaluate three different cloud forecast schemes in comparison with aircraft measurements. Although results showed that model had the skill to forecast the occurrence of clouds, forecasted cloud water agreed rather poorly with the observation. The poor agreement between the modeled and the observed cloud water is perhaps not too surprising because the modeled clouds can be temporally and spatially mismatched with what was observed along aircraft flight track. Recent studies also show that increasing model horizontal resolution generally increases the realism of the model results compared with observations in terms of temperature, precipitation and wind fields (Mass et al., 2002). The impact of model horizontal resolution on predicted cloud microphysical properties, however, is not yet well studied. More studies on evaluating model simulated cloud microphysical properties are needed.

During the summer of 2004, under the coordination of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT), a large field study was conducted over eastern North America, the North Atlantic, and Western Europe to provide a better understanding of some of the issues relating to air quality and climate change (http://www.al.noaa.gov/ICARTT). As a component of the ICARTT campaign, Meteorological Service of Canada (MSC), in collaboration with the National Research Council of Canada and Canadian Universities, conducted airborne studies from July 19, 2004 to August 20, 2004, using the NRC-IAR Convair 580 aircraft, focused on the interactions among trace gases, aerosols and clouds, as well as the transport of pollution into the Canadian Maritimes (http://www.msc-smc.ec.gc.ca/research/icartt/description_e.html).

In this paper, meteorological model performance with two spatial resolutions and different microphysical schemes will be evaluated against observations from radiosonde, satellite and aircraft. Section 2 briefly describes the model and its setup. Evaluation methods and results will be discussed in Section3. Some further discussions and conclusions will be given in Section 4.

2. MODEL DESCRIPTION

The air quality model under development at MSC, AURAMS (A Unified Regional Air-quality Modelling System), is a new, size- and composition-resolved, episodic, regional particulate matter modelling system (Moran et al., 1998). It is driven offline by a meteorological model - GEM (Global Environmental Multiscale) model (Côté et al., 1998a,b). The GEM model is a single highly efficient model that can be configured to either run globally at uniform-resolution, or to run with variable resolution over a global domain with uniform (core) mesh over a focused area of interest. The horizontal mesh can be of uniform or variable resolution varying from hundred kilometers down to single digit, and can be arbitrarily rotated. The vertical mesh is also variable. The GEM model is also able to be configured to run in a Limited Area Modelling (LAM) setup with the boundary conditions provided by the objective analysis or a coarser resolution forecast model. The regional operational GEM model is currently configured at 15-km resolution with the core domain centred over North America. In this study, GEM with LAM configuration at 15 and 2.5 km horizontal resolutions and 58 vertical levels will be evaluated. The runs are conducted in a cascade fashion: the initial and boundary conditions for the 15km resolution run are obtained from the best available objective analysis dataset, while those for the 2.5km resolution run are provided by the 15km LAM forecast. The 15 and 2.5 km horizontal resolution model domains used in this study are shown in Figure 1.

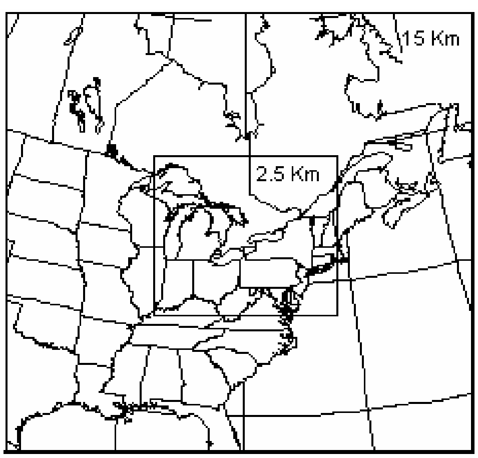

Figure 1 The GEM LAM domains of the 15 and 2.5 km horizontal resolution. The domain size for the 15 km resolution is 3750 x 3750 km, and for the 2.5 km resolution is 1250 x 1250 km.

Cloud condensation processes are parameterized differently for the 15 and 2.5 km resolution configurations. For the 15 km resolution, large scale stratiform condensation process, sub-grid scale deep convection and shallow convection are parameterized by a Sundqvist (sundqvist et al., 1989), a Kain-Fritsch (Kain and Fritsch, 1990; Kain, 2004), and a Kuo-transient (Wagneur, 1991), schemes, respectively. As for the 2.5km horizontal resolution, no sub-grid scale condensation processes were considered. Convections are assumed to be fully resolved at this resolution, and cloud microphysical processes are treated fully explicitly by Kong and Yau scheme (Kong and Yau, 1997).

3. MODEL EVALUATION AGAINST OBSERVATIONS

August 3, 2004 is chosen for a case study in this paper. Two Convair 580 flights were conducted on this day: one in late morning over southern Ontario (15:15 – 18:30 UTC) sampling mainly stratocumulus and the other one in later afternoon over northeastern Ohio sampling towering cumulus (20:30 -24:00 UTC). Figure 2 shows the GEOS visible (channel 1) image of clouds at 17:15 UTC on that day. Over eastern North America, clouds were mainly organized in two systems. One on the eastern coast is associated with Hurricane Alex. The second one is associated with a frontal system east of Hudson Bay extending into the Great Lakes.

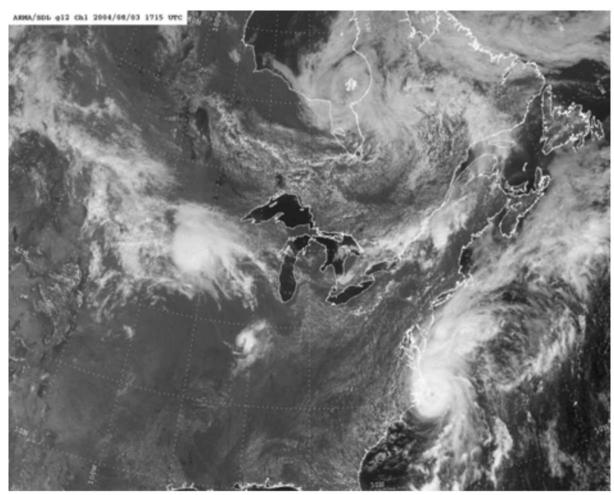

Figure 2 GEOS visibale image (channel 1) at 17:15 UTC on August 3, 2004.

GEM simulation at 15 km resolution is run for 36 hours with the first 12 hours as spin up starting at 12 UTC on Aug. 2, 2004. Output from the 15 km model simulation is used to drive the 2.5 km model simulation for a 24-hour forecast starting at 00 UTC on Aug. 3, 2004. Model predicted temperature, dew point depression (an indication of relative humidity), outgoing longwave radiation, and cloud liquid water content are compared with radiosonde, satellite and aircraft observations for the evaluation.

3.1 Evaluation against Radiosonde Observations

Temperature and dew point depression are observed at 00 and 12 UTC by radiosondes daily at upper-air stations globally. Ten stations are located within the smaller 2.5 km resolution model domain as shown in Figure 3.

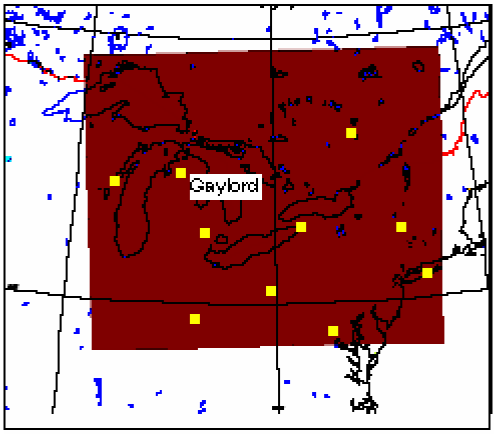

Figure 3 Radiosonde stations (yellow squares in the shaded area) located in the 2.5 km resolution model domain

Profiles of model predicted temperature and dew point depression are compared with the profiles observed by radiosonde at the time when radiosondes were launched. Overall model predicted temperature profiles agree very well with the observations at all stations for both 15 and 2.5km resolutions. As an example, Figure 4 shows the comparison of temperature profiles over Gaylord station at 12 UTC. Note that there are not many observations at lower altitude from these radiosonde measurements. Figure 5 shows the scatter plot of observed and model predicted temperature for all of the 10 stations. The data points distribute nicely along the 1:1 line in Figure 5. Correlation coefficients between model predicted and radiosonde observed temperature are very high for both 2.5 and 15km resolution (0.998 and 0.996, respectively). The temperature simulated at 2.5km resolution correlates slightly better with the observation than that simulated at 15km resolution. Furthermore, model with 2.5 km resolution is seen to reproduce some of the finer structures of the temperature profiles better, such as the inversion at the tropopause shown in Figure 4.

The scatter plot of the model-predicted vs. observed dew point depression is presented in Figure 6 for both 2.5 (in blue) and 15 km resolution (in pink). The correlation coefficients are 0.762 and 0.646, and the slopes of the regression are 0.878 and 0.721 for 2.5 and 15 km resolution runs, respectively. The correlation is not as good as in the case of temperature. Again, the model simulation at 2.5 km resolution seems to perform better than the 15 km resolution run in terms of dew point depression.

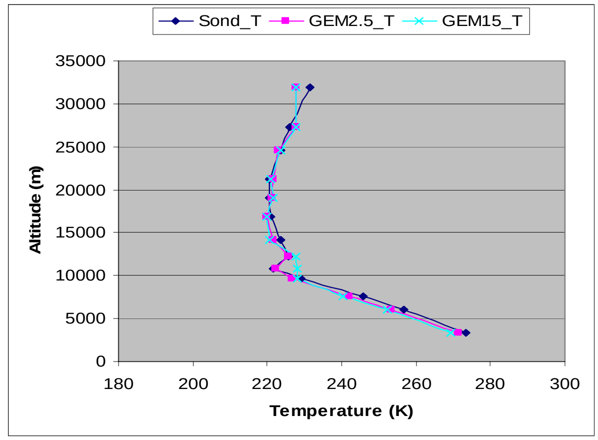

Figure 4 Radiosonde observed and model simulated profiles of temperature at the Gaylord station at 12 UTC

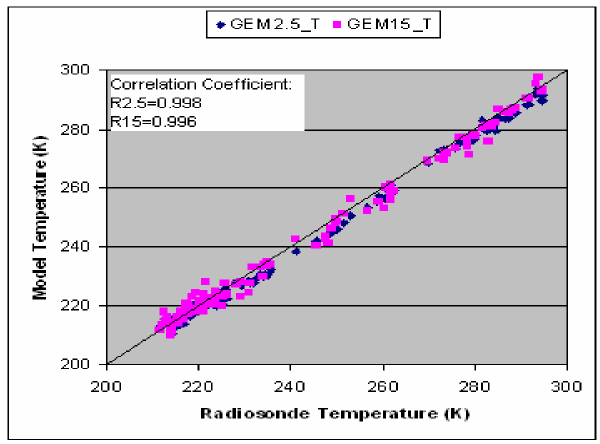

Figure 5 Scatter plot of radiosonde observed and model predicted temperature. R2.5 and R15 are the correlation coefficients for 2.5 and 15 km resolution, respectively.

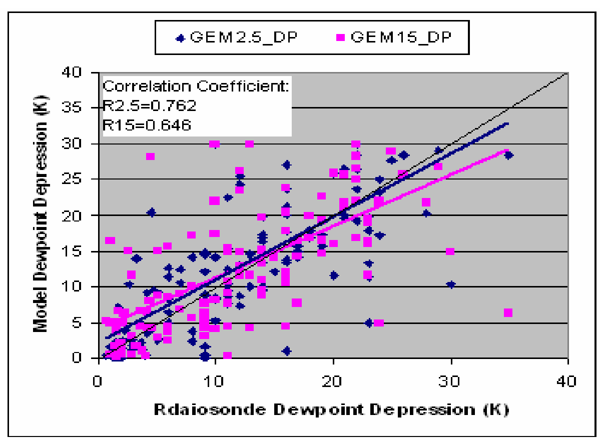

Figure 6 Similar as Fig. 5, but for Dew Point Depression. Linear regression lines are shown.

3.2 Evaluation against Satellite Observations

Geostationary satellites, such as GOES, have the ability to observe cloud field over a large domain at high frequency. They provide a unique way to evaluate the model simulation of clouds not only for large scale cloud distribution but also for the movement of the cloud system, although lower level clouds may not be observed in the visible and infrared channels if several levels of clouds coexist. In this section, model simulated clouds are evaluated by comparing with the GEOS observation at the time of the two Convair 580 flights.

Figure 7 shows the satellite observed infrared image of clouds (channel 4) at 15:15 UTC corresponding to the time when the first Convair flight of the day took off. In this image, higher clouds are represented by brighter tone. The height of clouds sampled by aircraft between Lake Erie and Lake Huron is relatively low.

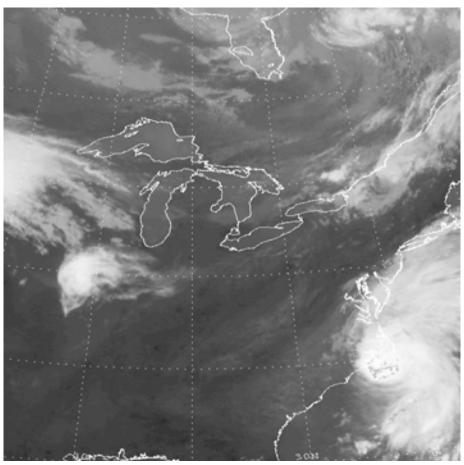

Figure 7 GEOS infrared channel image (Channel 4) over the 15 km resolution domain at 15:15 UTC on Aug. 3, 2004

Model simulated outgoing longwave radiation (OLR) at 15 km resolution at 15:00 UTC is shown in Figure 8. Model is able to capture the main cloud systems observed by satellite, especially the location and structure of Hurricane Alex. However, a seperate band of clouds, which was not observed by satellite, is seen from the modelled OLR at the northeastern edge of Hurricane Alex and the modelled cloud band along St. Lawrence River is moved northeastwardly compared to the satellite observation.

OLR simulated at 2.5 km resolution at 15:00 UTC is shown in Figure 9. Because the model with 2.5 km resolution is driven by the boundary conditions provided by the model at 15 km resolution, it is not surprising that the main cloud systems and their locations are similar to those forecasted from the 15 km resolution run but wirh finer details.

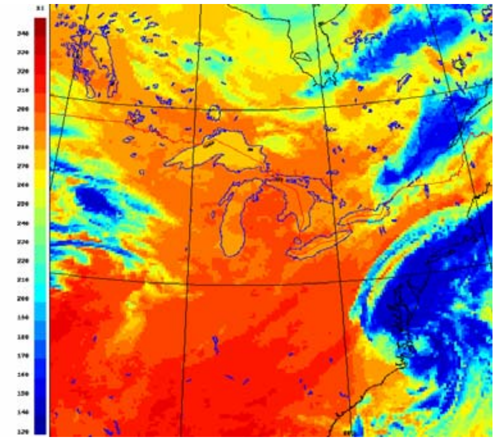

Figure 8 Outgoing Longwave radiation simulated by GEM at 15 km resolution at 15:00 UTC on Aug. 3, 2004

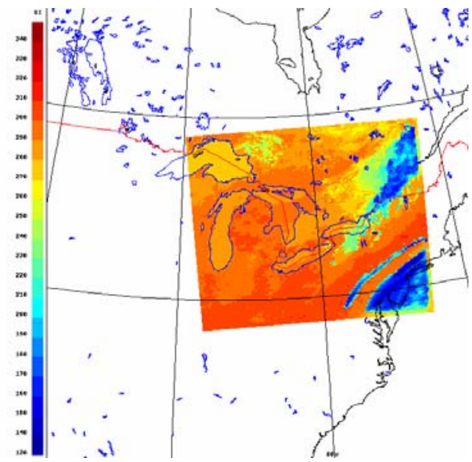

Figure 9 Same as Fig. 8, but for 2.5km resolution

Late that afternoon, a chain of individual towering cumulus (TCU) develped south of Lake Erie and Lake Ontario, extending from St. Lawrence river valley through upper state New York to eastern central Ohio as shown in the satellite image at 20:15 UTC (Figure 10). The TCUs over eastern central Ohio were sampled by the second Convair flight of the day.

Figure 11 shows the OLR simulated by model at 15 km resolution at 20:00 UTC. Again the main cloud systems are well captured by the model. The band of clouds south of Lake Erie and Lake Ontario coincides well with the chain of TCUs shown on the satellite image, but more spread out at 15 km resolution in comparison to the sperated TCU structure in Figure 10. The OLR simulated by model at 2.5 km resolution at 20:00 UTC shown in Figure 12 agrees noticeably better with the satellite observation than the simulation at 15 km resolution. The chain of indivival cumulus over eastern central Ohio is well simulated. This good agreement may be due to that these convective clouds are explicitly resovled and to that the trigerring mechanism associated with surface heating is better represented at this higher resolution.

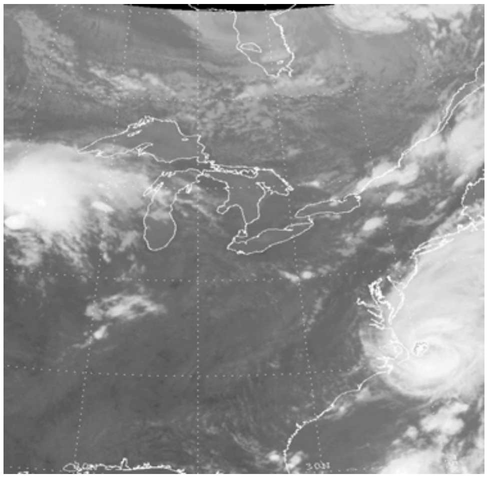

Figure 10 GEOS infrared band image (Channel 4) over the 15 km resolution domain at 20:15 UTC on Aug. 3, 2004

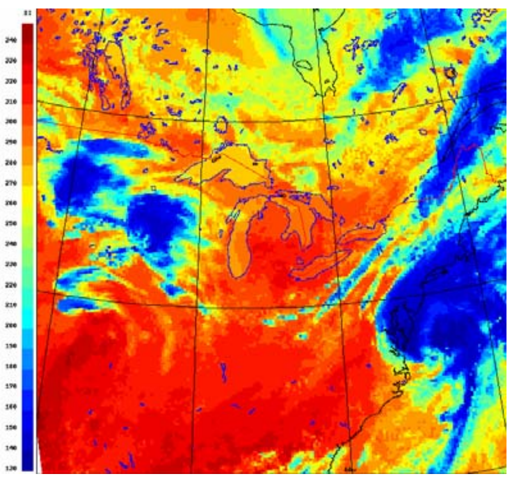

Figure 11 Outgoing Longwave radiation simulated by GEM at 15 km resolution at 20:00 UTC on Aug. 3, 2004

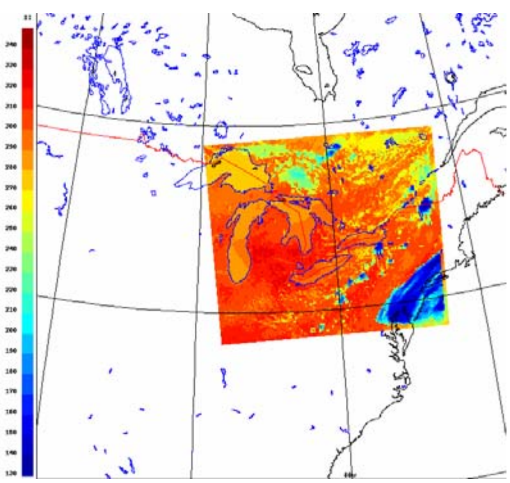

Figure 12 Same as Fig. 11, but for 2.5km resolution

3.3 Evaluation against Aircraft Observations

The flight paths of the two Convair 580 flights are shown in Figure 13 and 14. Along with the suite of aerosol and trace gas measurements, Convair 580 was equipped with extensive instrumentations for cloud microphysics measurement.

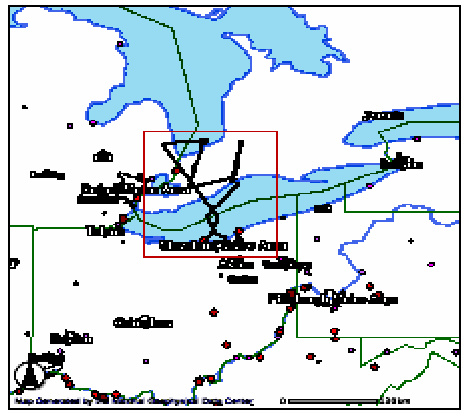

Figure 13 The first flight path duirng the day of Aug. 3, 2004 (red box is a subdomain chosen for LWC comparison)

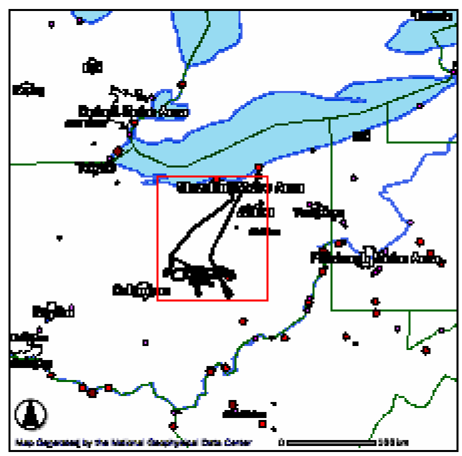

Figure 14 The second flight path duirng the day of Aug. 3, 2004 (red box is a subdomain chosen for LWC comparison)

As discussed in the introduction, model simulated cloud microphysical properties have not been well evaluated so far due to the lack of suitable observational dataset. Although in situ measurement can be used to evaluate model simulation, how to evaluate using aircraft measurement is still a big challenge. Clouds evolve quickly in time and space, unlike the more continuous fields such as temperature, and aircraft observations are at very different temporal and spatial scales with what a meteorological model can directly simulate.

Guan et. al. (2001, 2002) evaluated model simulated cloud water/ice along aircraft tracks using objective evaluation methods (hit rate, false alarm rate and true skill statistics) which are commonly used in model evaluations. However, due to the high temporal and spatial variation of clouds and the relatively low spatial coverage of flight tracks, a good one-to-one comparison (in space and time) between model predicted and aircraft observed cloud properties is unlikely. Figure 15 shows the comparison of aircraft observed and model simulated in-cloud (grid mean cloud water content divided by cloud cover fraction, in the case of model prediction) liquid water content (LWC) along one section of the first flight path (the length is about 110 km).

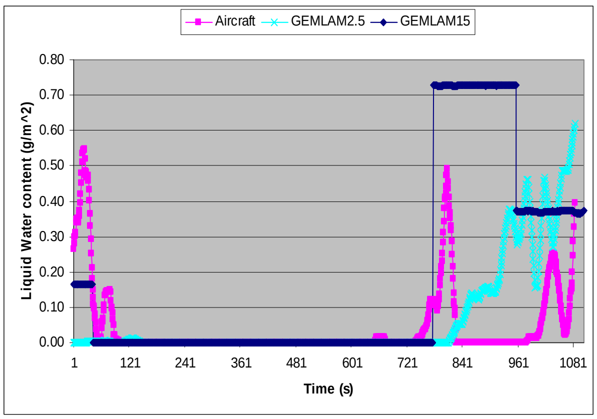

Figure 15 Comparison of aircraft observed liquid water content with what was simulated by model at 15 and 2.5 km resolutions.

We can see that model with 15 km resolution is not able to resolve the variation of cloud water content observed by the aircraft. The model simulation with 2.5 km resolution reproduces the kind of variation as observed by the aircraft, but the model predicted LWC time series along the flight track does not compare well with the observations. Correlation coefficient between model simulation and aircraft observation is very low (not shown). The low correlation between the model and the aircraft observation from this one-to-one comparison agrees with the findings from Guan et al. (2002). Hence, in this study we will be using a different evaluation approach – a statistical comparison of the model simulated cloud water content with aircraft observations over two sub-domains that cover the aircraft tracks (see the boxes outlined by red lines in Figs. 13 and 14) rather than just along the flight tracks.

Figure 16 shows the time series of aircraft altitude and the observed LWC for the two flights on Aug. 3, 2004. During the first flight (Fig. 16a), stratocumulus between 500 m and 1500m were sampled. The observed LWCs in these boundary-layer clouds were low. Most of the time the LWC was lower than 0.8 g/m^3 and hardly exceeded 1 g/m^3. During the second flight (Fig. 16b), convective clouds sampled were mainly between 1800m and 3100 m. The LWCs in these convective clouds were higher than those observed during the first flight. This observation is consistent with the fact that the LWC in convective clouds is usually larger than that in stratiform clouds due to greater updraft (Cotton and Anthes, 1989).

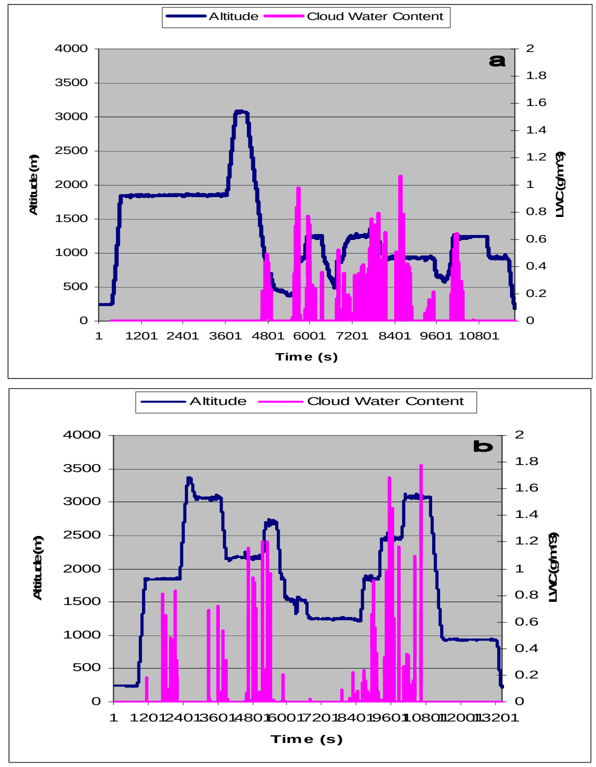

Figure 16 Aircraft altitude (m) and measured liquid water content (g/m^3) during the Flight 1 (a) and 2 (b)

The frequency distributions of LWC observed during these two flights are shown in Figure 17. Both types of clouds have high frequency of low LWC. At LWC smaller than 0.8 g/m^3, the frequency of observed LWC at a given interval is generally smaller in TCUs than that in stratocumulus. However at values greater than 0.8 g/m^3 the opposite is true. Table 1 lists the mean and standard deviation (STD) of LWC in the two types of clouds. Both the mean and the STD of LWC are larger in the TCUs than those in the stratocumulus.

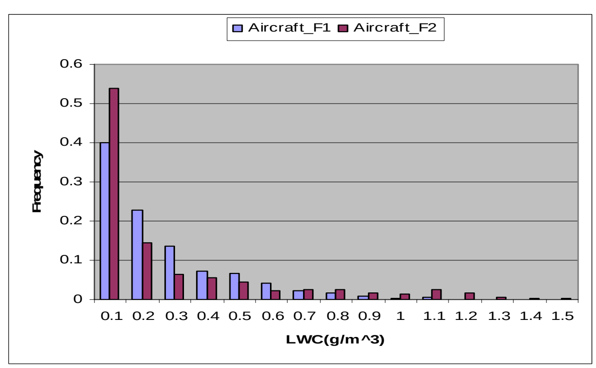

Figure 17 Distribution of liquid water content measured in stratocumulus (F1) and TCUs (F2)

Table 1 Mean and Standard Deviation of LWC from aircraft observations and model simulations at 15 and 2.5 km horizontal resolutions during the Flight 1 and 2

		Mean LWC (g/m^3)	STD (g/m^3)
Flight 1	Aircraft	0.204	0.198
	GEM15	0.338	0.290
	GEM2.5	0.274	0.260
Flight 2	Aircraft	0.245	0.339
	GEM15	0.245	0.262
	GEM2.5	0.352	0.363

Model simulated LWCs within the two sub-domains between the altitudes and time period of aircraft observations are considered in the comparison with the observations. The frequency distributions of the model simulated LWC are shown in Figure 18 for the 15 km resolution run and Figure 19 for the 2.5 km resolution run. At both resolutions, the model predicted lower frequency at small LWC (<0.1 g/m^3) than observed (Figure 17). The model at 15km resolution simulated higher frequency than observed at larger LWC for stratocumulus, and does not show the distinction between the two types of cloud as in the observations. In contrast, the model at 2.5 km resolution predicted more occurrences of LWC greater than 1.0 g/m^3 for Flight 2 than for Flight 1, which is in agreement with the observed distinction between the two types of clouds.

Accumulative frequencies (at given LWC intervals) for both aircraft observations and model simulations are shown in Figure 20. Clearly there are considerable discrepancies between the modeled and the observed LWC frequency distributions. In general, the model tends to under-predict the occurrence of lower LWC and over-predict the occurrence of higher LWC. Nonetheless the difference in the observation between the two types of cloud is qualitively reproduced by the model at 2.5 km resolution.

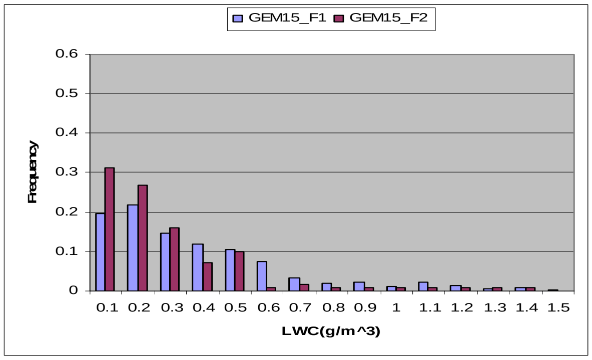

Figure 18 Distribution of LWC simulated by model at 15 km resolution during the periods of Flight 1 and 2

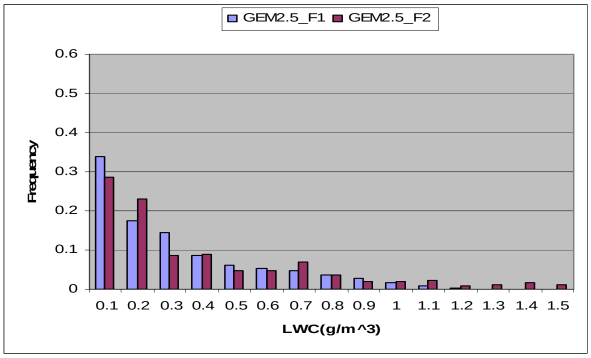

Figure 19 Same as Fig. 18, but for 2.5 km resolution

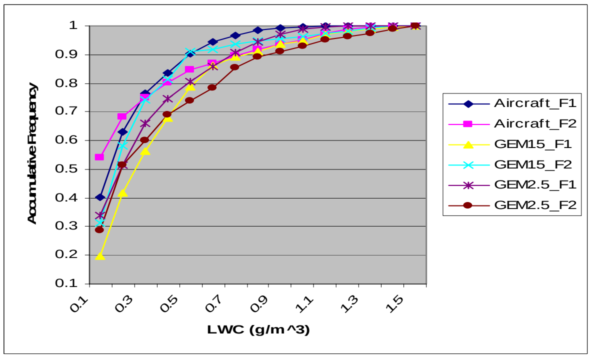

Figure 20 Accumulative frequency of LWC for all observations and model simulations during the two flight periods

The mean and STD of LWC from the model simulations over the two flight areas (i.e., subdomains) are also included in Table 1. It is seen that in the case of boundary-layer stratocumulus (the first flight) the model at both resolutions overpredicted the mean and STD of LWC. The 2.5 km resolution run did slightly better than the one at 15 km resolution. In the case of TCUs (the second flight), the run at 15 km resolution predicted the mean LWC well but underpredicted the STD, while the run at 2.5 km resolution overpredicted the mean LWC but predicted the STD reasonably well. Again, the observed characteristic differences between the two types of cloud (i.e., higher LWC and greater variability for TCUs in comparison to stratocumulus) seem to be picked up by the model run at 2.5 km resolution but not by the one at 15 km resolution.

4. DISCUSSIONS AND CONCLUSIONS

To provide a basis for analyzing cloud processing of gases and aerosols in air quality model, the performance of a meteorological model (GEM model) at two horizontal resolutions, 15 km and 2.5 km, is evaluated against radiosonde, satellite and aircraft observations with a focus on cloud properties. Overall, the model simulations agree well with observations in terms of temperature, dew point depression, and large scale cloud distribution (or the clouds associated with major synoptic systems). However, timing and placement errors can exist for these clouds as shown in the comparison with satellite observations.

Increasing horizontal resolution from 15km to 2.5 km improves the model simulation of dew point depression, but only improves the simulated temperature field slightly. Increase of model resolution also improves the model's ability to better resolve small scale convection. It needs to be pointed out that different cloud microphysics parameterizations are used for model simulations at different horizontal resolutions, since parameterization schemes are often scale dependent. For example, Kong and Yau scheme is designed to explicitly resolve cloud scale microphysical processes and is not suited for use with coarse resolutions.

Due to the disparity in scales (spatial and temporal) between the aircraft observation and the model simulation, it is difficult to quantitatively compare model predicted cloud water content with aircraft observation on a strictly one-to-one basis. Statistically, the model with 2.5 km resolution reproduces the difference between stratocumulus and TCU observed by the aircraft, but the LWC simulated by the model is generally larger than observed by the aircraft for both flights. At the coarser 15 km resolution, the model does not seem to be able to reproduce the observed characteristic differences between these two cloud types.

In this study, we only examined two particular flight cases (corresponding to two types of clouds). We will be looking at more flight cases from the ICARTT campaign and will further investigate the Impact of horizontal resolution and microphysics parameterization on modeled cloud properties. We will also be looking into their subsequent impact on air quality modeling.

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REFERENCES:

Ackerman, I.J., H. Hass, M. Memmesheimer, A. Ebel, F.S. Binkowski, and U. Shankar, 1998: Modal aerosol dynamics model for Europe: Development and first applications. *Atmos. Environ.*, **32**, 2981-2999.

Barth, M.C., P.J. Rasch, J.T. Kiehl, C.M. Benkovitz, and S.E. Schwartz, 2000: Sulfur chemistry in the National Center for Atmospheric Research Community Climate Model: description, evaluation, features, and sensitivity to aqueous chemistry. *J. Geophys. Res*., **105**, 1387-1415.

Bator, A. and J.L. Collett, Jr., 1997: Cloud chemistry varies with drop size. *J. Geophys. Res.*, **102**, 28071-28078.

Carmichael, G.R., L.K. Peters and R.D. Saylor, 1991: The STEM-II regional scale acid deposition and photochemical oxidant model – I. an overview of model development and applications. *Atmos. Environ*., **25A**, 2077-2090.

Chang, J.S., R.A. Brost, I.S.A. Isaksen, S. Madronich, P. Middleton, W.R. Stockwell and C.J. Walcek, 1987: A three-dimensional eulerian acid deposition model. Physical concept and formulation. *J. Geophys. Res*., **92**, 14681-14700.

Charlson, R.J., J.H. Seinfeld, A. Nenes, M. Kulmala, A. Laaksonen, and M.C. Facchini, 2001: Reshaping the theory of cloud formation. *Science*, **292**, 2025-2026.

Côté, J., J.-G. Desmarais, S. Gravel, A. Méthot, A. Patoine, M. Roch, and A. Staniforth, 1998a: The operational CMC-MRB Global Environment Multiscale (GEM) model. Part I: Design considerations and formulation. *Mon. Wea. Rev.,* **126**, 1373 – 1395.

Côté, J., J.-G. Desmarais, S. Gravel, A. Méthot, A. Patoine, M. Roch, and A. Staniforth, 1998b: The operational CMC-MRB Global Environmental Multiscale (GEM) Model: Part I - Design considerations and formulation, Part II – Results. *Mon. Wea. Rev.*, **126**, 1397-1418.

Cotton, W. R. and R. A. Anthes, 1989: Storm and Cloud Dynamics. Academic Press, Toronto, 5-10pp.

Gong, W., A.P. Dastoor, V.B. Bouchet, S. Gong, P.A. Makar, M.D. Moran and B. Pabla, 2003: Cloud processing of gases and aerosols in a regional air quality model (AURAMS) and its evaluation against precipitation-chemistry data, *Proc. Fifth AMS Conference on Atmospheric Chemistry*, 2.3 (CD-ROM), Feb. 9-13, Long Beach, California, American Meteorological Society, Boston.

Gong, W., A.P. Dastoor, V.S. Bouchet, S. Gong, P.A. Makar, M.D. Moran, B. Pabla, S. Ménard, L-P Crevier, S. Cousineau, and S. Venkatesh, 2005: Cloud processing of gases and aerosols in A Regional Air Quality Model (AURAMS). *Atmos. Res.*, accepted.

Gong, W., V. S. Bouchet, P. A. Makar, M. D. Moran, S. Gong, A. P. Dastoor, B. Pabla1, and W. R. Leaitch, 2004: Cloud Processing of Gases and Aerosols in a Regional Air Quality Model (AURAMS): Evaluation Against Aircraft Data, to appear in "Air Pollution

Modelling and Its Application XVII", edit. C. Borrego and A. Norman, Kluwer Academic/Plenium Publishers.

Guan, H., S.G. Cober, and G. A. Isaac, 2001: Verification of supercooled cloud water forcasts with in situ aircraft measurements. *Wea. Forecasting*, **16**, 145-155.

Guan, H., S.G. Cober, G. A. Isaac, A. Tremblay, and A. Méthot, 2002: Comparison of three cloud forecast schemes with in situ aircraft measurements, *Wea. Forecasting*, **17**, 1226-1235.

Jacobson, M.Z., 1997: Development and application of a new air pollution modeling system. Part 1: gas-phase simulations. *Atmospheric Environment,* **30B**, 1939–1963.

Kain, J.S., 2004: The Kain-Fritsch Convective Parameterization: An Update. *Journal of Applied Meteorology*, **43**, 170-181.

Kain, J. S. and J. M. Fritsch, 1990: A one-dimensional entraining-detraining plume model and its application in convective parameterization, *Journal of the Atmospheric Sciences*, **47**, 2784 – 2802.

Kong, F.Y. and M.K. Yau, 1997: An explicit approach to microphysics in MC2. *Atmos. Ocean*, **35**, 257-291.

Lohmann, U., K. von Salzen, N. McFarlane, H.G. Leighton and J. Feichter, 1999: Tropospheric sulfur cycle in the Canadian general circulation model. *J. Geophys. Res.*, **104**, 26,833- 26,858.

Mass, C.F., D. Ovens, K. Westrick, and B.A. Colle, 2002: Does increasing horizontal resolution produce more skillful forecasts?. *Bull. Amer. Meteor. Soc.*, **83**, 407-430.

Moran, M.D., Dastoor, A.P., Gong, S.-L., Gong, W., and Makar, P.A., 1998: Conceptual design for the AES unified regional air quality modelling system (AURAMS), Internal Report, 100 pp., Air Quality Research Branch, Atmospheric Environment Service. [Now Met. Service of Canada]

Rasch, P.J., M.C. Barth, J.T. Kiehl, S.E. Schwartz and C.M. Benkovitz, 2000: A description of the global sulphur cycle and its controlling processes in the National Center for Atmospheric Research Community Climate Model, Version 3. *J. Geophys. Res.*, **105**, 1367-1385.

Renard, M., N. Chaumerliac and S. Cautenet, 1994: Tracer redistribution by clouds in West Africa: numerical modeling for dry and wet seasons. *J. Geophys. Res*., **99**, 12,873-12,883.

Seinfeld, J.H. and S.N. Pandis, 1998: Atmospheric chemistry and physics. Wiley-interscience, New York, 1326pp

Sundqvist, H., E. Berge and J.E. Krisjansson, 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev.*, **117**, 1641-1657.

Venkatram, A., P.K. Karamchandani and P.K. Misra, 1988: Testing a comprehensive acid deposition model. *Atmos. Environ.*, **22**, 737-747.

von Salzen, K., H.G. Leighton, P.A. Ariya, L.A. Barrie, S.L. Gong, J.-P. Blanchet, L. Spacek, U. Lohmann and L.I. Kleinman, 2000: Sensitivity of sulphate aerosol size distributions and CCN concentrations over North America to SO_x emission and H_2O_2 concentrations, *J. Geophys. Res.*, **105**, 9741-9765.

Wagneur, N., 1991: Une évaluation des schémas de type Kuo pour le paramétrage de la convection. MSC Thesis, Université du Québec à Montréal, 76 pp.

Wang, C. and R.G. Prinn, 2000: On the roles of deep convective clouds in tropospheric chemistry. *J. Geophys. Res*., **105**, 22,269-22,297.