J3.7 VERIFICATION OF CLOUD FORECASTS WITH IN-SITU AIRCRAFT MEASUREMENTS

Hong Guan*, Stewart G. Cober, and George A. Isaac
Meteorological Service of Canada, Downsview, Ontario, Canada

1. INTRODUCTION

The Meteorological Service of Canada has conducted several winter field projects during the past decade, including the Second Canadian Atlantic Storms Program (CASP II), the First (CFDE I) and Third (CFDE III) Canadian Freezing Drizzle Experiments, and the Alliance Icing Research Study (AIRS). A common objective of each project was to improve the accuracies for cloud and aircraft icing forecasts in winter storms. Since in-situ aircraft based measurements include extensive microphysical parameters that are not normally measured at meteorological stations, these measurements were used to validate the predictions of meteorological fields that were made with the High Resolution Model Application Project (HIMAP) version of the Global Environmental Multiscale (GEM) model (Côté et al. 1998a). Specifically, forecasts of temperature (Ta), horizontal wind (V), dewpoint depression, cloud and supercooled cloud water (SCW) were compared with the in-situ aircraft measurements. The aircraft data were also used as a basis for intercomparisons of four cloud schemes and two SCW schemes.

2. MODEL AND CLOUD SCHEMES

The experimental HIMAP version of the GEM model had approximately 15-km horizontal grid spacing and 35 eta levels. Two uniform-resolution sub-domains, which were centered on the Quebec-Windsor corridor and St. John's, Newfoundland, respectively, were used for the simulations. Each simulation was started at 0006 UTC. The Canadian Meteorological Centre (CMC) objective analysis data were used to initialize the model, which in turn produced 6 to 24 hour forecasts.

The HIMAP version is fully coupled with the CMC physics library. The Fritsch-Chappell (Fritsch and Chappell, 1980) cumulus parameterization scheme is the current operational CMC scheme, and was used for all simulations. The resolved scale microphysics schemes tested include the Sundqvist (SUND) scheme (Sundqvist et al. 1989), explicit moisture scheme (HSIE) developed by Hsie et al. (1984), mixed-phase scheme (MIX) (Tremblay et al. 1996), and explicit microphysics scheme (KY) (Kong and Yau 1997). These parameterize the microphysics of clouds with different degrees of complexity. The SUND scheme is the CMC operational scheme and has only one prognostic variable, total cloud water (ice or liquid). The HSIE scheme explicitly predicts cloud and precipitation. The MIX scheme considers the total water content (TWC) as a basic prognostic variable. The TWC is diagnostically partitioned into solid and liquid phases at subfreezing temperatures. The KY scheme represents the most sophisticated microphysical scheme examined in this study and includes three prognostic equations for cloud water, rainwater, and ice+snow.

3. VERIFICATION METHODOLOGY

CASP II and CFDE I were based from Newfoundland, while CFDE III and AIRS were focused on the Great Lakes region. These represented maritime and continental environments respectively. These are the geographic regions with the highest frequencies of surface freezing precipitation in North America (Isaac et al. 1999). For this study, aircraft data collected during 77 research flights were used to validate the GEM model fields and cloud and icing schemes. The research aircraft employed during the four field programs was the National Research Council Convair-580, which was fully equipped for cloud microphysics measurements. A description of the instrument and measurements can be found in Cober et al. (2001a,b) and Isaac et al. (1998).

To compare model forecasts and aircraft measurements, the model fields at 1-h resolution were numerically interpolated along the 3D-time aircraft trajectories. The time series of Ta, dewpoint depression, and V were then quantitatively compared with averaged aircraft measurements at 1.5-km resolution. The accuracies for Ta, dewpoint depression, and V are evaluated based on root mean square (rms) errors. A different comparison technique was used to assess the cloud and SCW forecasts. The measured and forecast cloud and SCW at 15-km resolution were assessed as observed or not observed and forecast or not forecast based on certain thresholds. The threshold values for both the cloud and SCW were taken as 0.03 g m^{-3}. The hit rate (HR), false alarm rate (FAR), and true skill statistics (TSS) were calculated from 2 by 2 yes/no tables (Guan et al. 2001). HR (FAR) can be interpreted as the proportion of observed (not observed) events that were correctly (incorrectly) forecast. TSS is the difference between HR and FAR.

**Corresponding Author address:*
Hong Guan
Cloud Physics Research Division
Meteorological Service of Canada
4905 Dufferin St.
Downsview, Ontario, Canada, M3H 5T4
E-mail: Hong.Guan@ec.gc.ca

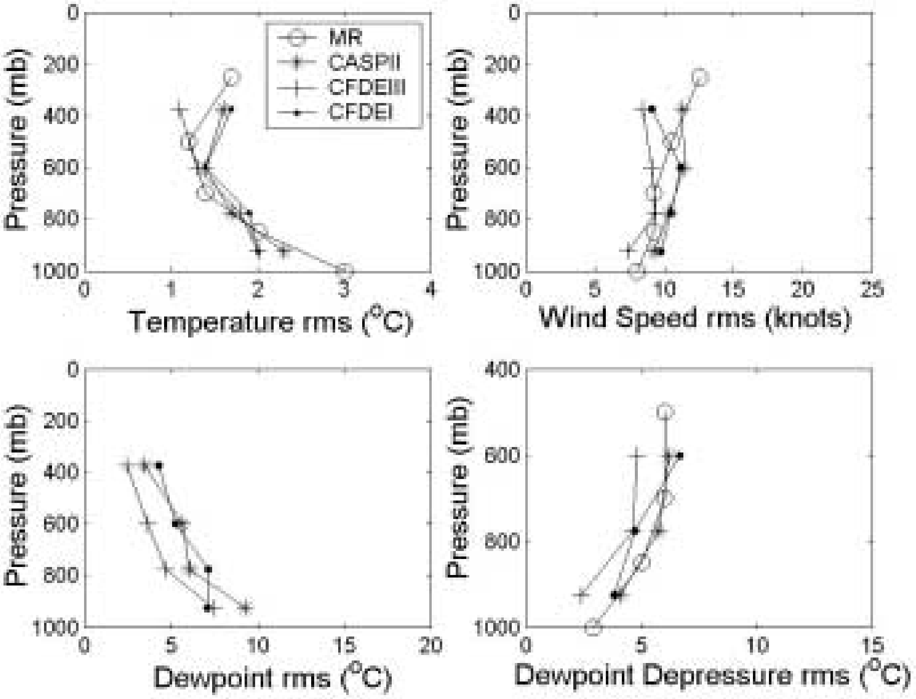

Fig. 1. Vertical rms errors for Ta, V, dewpoint, and dewpoint depression for CASP II, CFDE I, and CFDE III. MR indicates the results from the model-radiosonde comparisons.

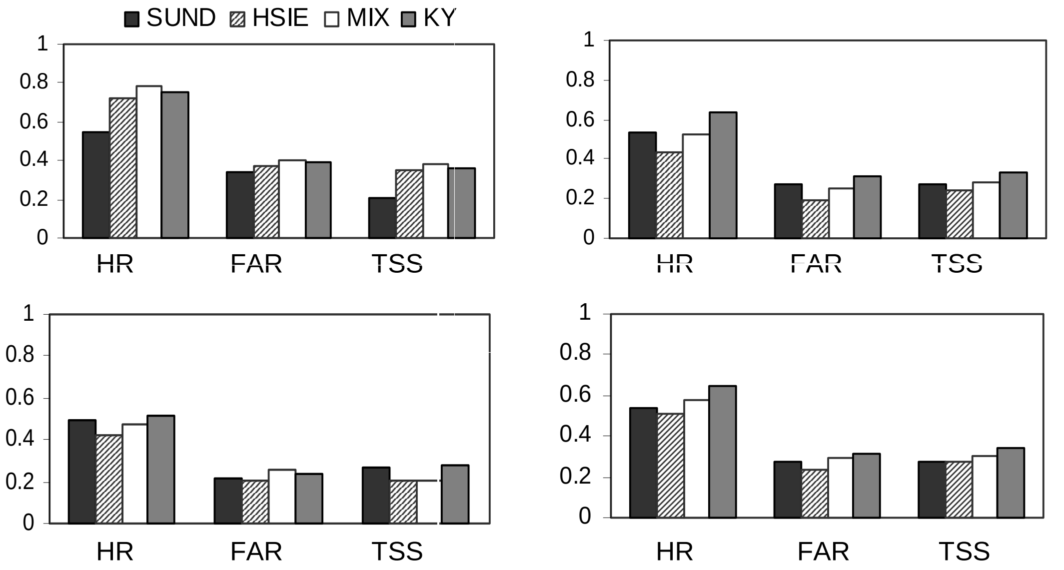

Fig. 2. Histograms of the HR, FAR and TSS for the four cloud schemes, for CFDE I, CFDE III, AIRS, and the total dataset (Total). The number of data points of observed cloud/no-cloud cases for CFDE I, CFDE III, AIRS and Total are 540/553, 1116/1193, 401/713 and 2057/2459, respectively.

4. VERIFICATION RESULTS

4.1 Validation Of Meteorological Fields

Figure 1 shows a comparison between the aircraft validation results and the Côté et al. (1998b) radiosonde-model validation results, the latter based on 120 North American stations. Their rms error profiles were derived for 12-h forecasts, comparable with the average validation time for the results presented here. The results indicate that the overall performances for both sets of validations are very similar. The rms errors for V and dewpoint depression for CFDE III are slightly smaller than those in the radiosonde-model validation. Conversely, the rms errors for Ta and V for CASP II and CFDE I are slightly larger than the radiosonde-model results. The consistency of the aircraft-model comparison with the radiosonde-model comparison of Côté et al. (1998b) demonstrates that the aircraft-model comparison methodology is an equally feasible approach to model validation. The aircraft-model comparison technique allows the opportunity to evaluate the model accuracy for parameters such as liquid water content (LWC) and TWC, which are not measured with the radiosondes.

4.2 Intercomparisons Of Four Cloud Schemes

The HR, FAR, and TSS of cloud forecasts for CFDE I, CFDE III, AIRS, and the total (CFDE I + CFDE III + AIRS) dataset, for each of the four cloud schemes, are shown in Fig. 2. For CFDE I, the HR, FAR, and TSS values for the three more advanced schemes (HSIE, MIX, and KY) are very similar, with the TSS ranging between 0.35 and 0.38. Conversely, the SUND scheme has a much lower TSS of 0.21, which is primarily associated with a low HR value. For CFDE III and AIRS, the differences in TSS values between the four cloud schemes were relatively small, ranging from 0.21 to 0.33. Overall, the KY scheme demonstrates the highest HR and TSS, which is expected given its more advanced microphysics algorithms.

4.3 SCW Verifications

The SCW verification results for the MIX and KY forecasting schemes for the total (CFDE I + CFDE III + AIRS) dataset are shown in Fig. 3. The HR, FAR, and TSS values for the KY scheme are approximately a factor of two higher than those for the MIX scheme. To see why the KY scheme has a better performance for SCW forecasts, the numbers of liquid-, mixed-, and glaciated-phase cloud cases forecast with both schemes are compared to the aircraft measurements. The observed cloud phases were accessed following Cober et al. (2001b). The results are shown in Fig. 4. Both schemes over (under) predict glaciated-phase (mixed-phase) cloud cases. The KY scheme overestimates the number of liquid-phase cloud cases, while the MIX scheme underestimates liquid-phase cases. The KY scheme more closely parallels the aircraft observations. There are several possible reasons for the differences between the two schemes. The KY scheme requires that the temperature has to be <-5ºC in order for nucleation to start (Kong and Yau, 1997), while the MIX scheme starts the ice nucleation process at 0ºC. The aircraft observations are more consistent with the KY scheme, and considering that 51% of the in-situ observations were made between -5 and 0ºC, this may account for a significant portion of the differences between the two schemes. In addition, the supercooled warm rain process (SWRP) in a supercooled precipitating cloud is not included in the MIX scheme (Tremblay and Glazer, 2000). Cober et al. (2001a) showed that most of the observed supercooled large drops during CFDE I and CFDE III were formed through a condensation and collision-coalescence process. Therefore, neglecting SWRP in the MIX scheme may lead to an underestimation in liquid-phase cloud number, relative to the KY scheme forecasts.

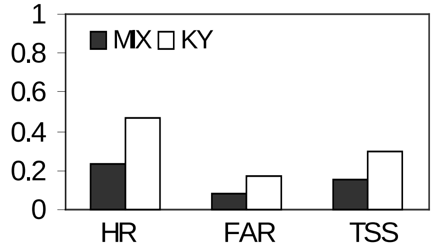

Fig. 3. Comparisons of HR, FAR, and TSS for SCW forecasts for the MIX and KY schemes. The numbers of observed cloud cases with SCW and with no SCW were 1316 and 2586 respectively.

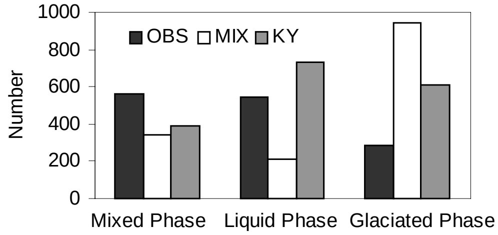

Fig. 4. Histograms of the number of observed and forecast cloud conditions for liquid, mixed and glaciated phase cases at T < 0ºC.

Scatter plots of model observations and aircraft measurements of supercooled LWC (SLWC) and ice water content (IWC) are shown in Fig. 5 for the MIX and KY schemes. There is generally a poor correlation between model and aircraft observations. In general, the MIX scheme underestimates SLWC, while the KY scheme tends to overestimate SLWC. There are very few aircraft measurements with SLWC more than 0.4 g

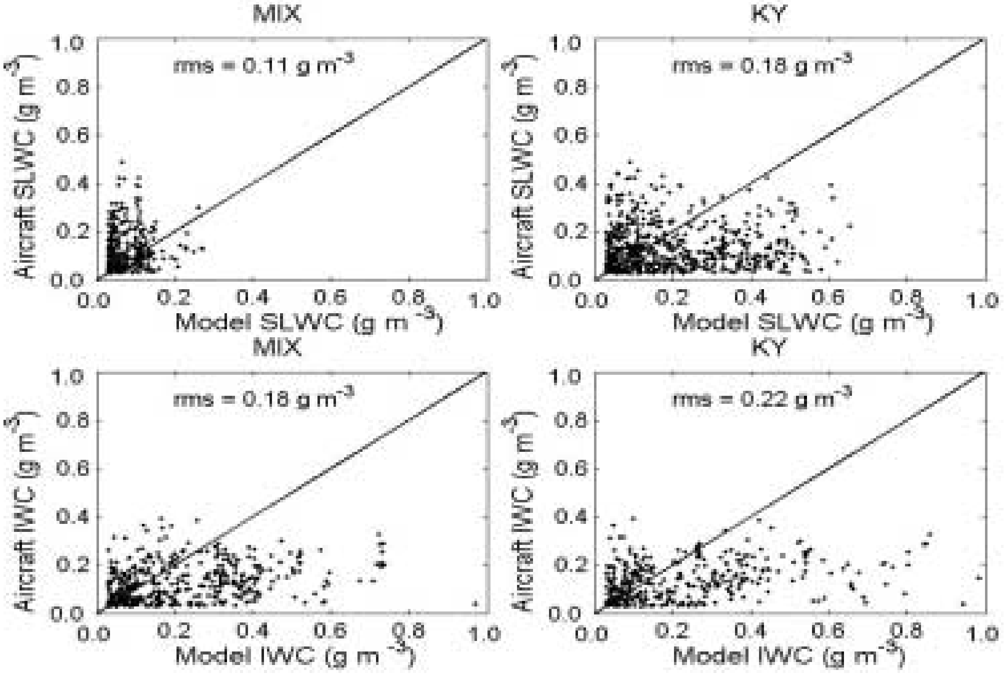

Fig. 5. Comparison of measured and forecast SLWC and IWC for the MIX and KY schemes.

m^{-3}. Conversely, the KY scheme produces numerous cases with SLWC > 0.4 g m^{-3}, while only a few points with SLWC > 0.15 g m^{-3} are observed for the MIX scheme. The behavior for the MIX and KY schemes may arise from the different rain auto-conversion thresholds used in the models. These thresholds are 0.1 g m^{-3} and 0.5 g kg^{-1}, for the MIX and KY schemes respectively, which correspond with the observed SLWC limits of 0.15 and 0.6 g m^{-3}. This suggests that matching the auto-conversion threshold with in-situ observations may provide quantitative improvements in the forecast accuracies for both schemes. The IWC observations for KY and MIX schemes are similar, with both schemes on average overestimating IWC in comparison to the aircraft measurements.

4.4 Comparison Of Precipitation

To demonstrate differences in the auto-conversion thresholds for precipitation, the mean accumulated surface precipitation along the aircraft flight tracks are shown in Fig. 6. There is a significant difference in the mean accumulated surface precipitation for the KY scheme. For the total dataset, the KY scheme forecast value is approximately 50% lower than the other schemes. The use of a higher rain threshold (0.5 g kg^{-1}) in the KY scheme to initiate sedimentation could partially explain the lower mean accumulated surface precipitation. The HSIE scheme does not produce a lower mean accumulated surface precipitation although it uses a similar rain threshold to the KY scheme. This is because the HSIE scheme does not have the ability to predict SCW. Therefore, the surface precipitation is mainly contributed by solid phase, which would be otherwise dominated by SCW. These observations partly explain why the KY scheme predicts more supercooled cloud cases and higher values of SLWC, than the MIX scheme, since more hydrometeor mass remains in the form of SCW in the KY scheme.

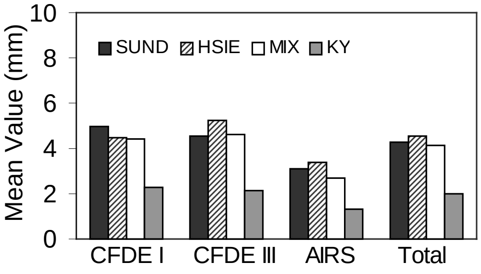

Fig. 6. Histograms of mean accumulated surface precipitation for each cloud scheme along the aircraft flight tracks.

5. CONCLUSIONS

In this paper, in-situ aircraft measurements made during 77 flights from four field programs were used to validate the GEM HIMAP model and intercompare four cloud and two SCW schemes. The model data were interpolated along 3-D time trajectories. The forecast accuracy of temperature, horizontal wind, and dewpoint depression agreed closely with the results from radiosonde-model validation experiments, which gave confidence in the aircraft-model validation methodology.

Intercomparisons of the four explicit cloud schemes with the aircraft data gave similar TSS values, varying between 0.27 for SUND and 0.34 for KY. The TSS for SCW forecasts was 0.15 and 0.30 for the MIX and KY schemes respectively. Comparisons with the number of aircraft measurements of liquid, mixed, and glaciated phase clouds, demonstrate that the MIX and KY schemes over (under) predict the number of the glaciated (mixed) phase conditions. The KY scheme tends to overestimate the number of liquid phase clouds, while the MIX scheme underestimates it. The predictions from the KY scheme are closer to the aircraft observations than the MIX scheme. The KY scheme has several advantages over the MIX scheme including additional microphysics processes, inclusion of a supercooled condensation and collision-coalescence process, and an ice nucleation threshold that corresponds more closely with aircraft observations. Consequently, it predicts a more realistic number of liquid phase cloud cases. The average IWC for the KY and MIX schemes are larger than the average aircraft measurements, while the average SLWC was overestimated by the KY scheme and underestimated by the MIX scheme.

The forecasts of mean accumulated surface precipitation for the KY scheme were approximately 50% lower than the other schemes. This is caused by a higher auto-conversion threshold, and helps explain why the KY scheme predicts more supercooled-cloud cases and higher SLWC values than the MIX scheme.

Acknowledgements

This research was funded by the Canadian National Search and Rescue Secretariat, Environment Canada, the National Research Council of Canada and Transport Canada.

References

Cober, S. G., G. A. Isaac, and J. W. Strapp, 2001a: Characterizations of aircraft icing environments that include supercooled large drops. Submitted to *J. Appl. Meteor*.

Cober, S. G., G. A. Isaac, A. V. Korolev, and J. W. Strapp, 2001b: Assessing cloud phase conditions. Accepted by *J. Appl. Meteor.*

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

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

Fritsch, J. M., and C. F. Chappell, 1980: Numerical prediction of convectively driven mesoscale pressure systems. Part I: Convective parameterization. *J. Atmos. Sci*., **37**, 1722-1733.

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

Hsie, E.-Y., R. A. Anthes, and D. Keyser, 1984: Numerical simulation of frontogenesis in a moist atmosphere*. J. Atmos. Sci*., **41**, 2581-2594.

Isaac, G. A., S. G. Cober, A. V. Korolev, J. W. Strapp, A. Tremblay, and D. L. Marcotte, 1998: Overview of the Canadian Freezing Drizzle Experiment I, II and III. Preprints, *Cloud Physics Conf.*, Everett, WA, Amer. Meteor. Soc., 447-450.

Isaac, G. A., S. G. Cober, A. V. Korolev, J. W. Strapp, A. Tremblay, and D. L. Marcotte, 1999: Canadian Freezing Drizzle Experiment. *37th Aerospace Sci. Meeting and Exhibit*. Reno, NV, AIAA 99-0492.

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

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

Tremblay, A., and A. Glazer, 2000: An improved modeling scheme for freezing precipitation forecasts*. Mon. Wea. Rev*., **128,** 1289-1308.

Tremblay, A., A. Glazer, W. Yu, and R. Benoit, 1996: An explicit cloud scheme based on a single prognostic equation. *Tellus*, **18A**, 483-500.