Toward a unified microphysics scheme for NWP models in Canada

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Abstract

A brief overview of current Canadian NWP models and planned development to 2017 is given. In particular, the microphysics schemes used in the Canadian forecast systems are summarized. Activities on the development of a unified microphysics package for different horizontal grid resolutions are described. The activities focussed on the implementation of sub-grid scale cloud and precipitation fractions in a two-moment microphysics representation and the consolidation of hydrometeor categories.

1. Overview of current Canada NWP and plans to 2017

Environment Canada is developing a suite of deterministic and probabilistic forecast and data assimilation systems based on the Global Environmental Multiscale (GEM) model (Cote et al. 1998a.b). At present, the operation suite consists of the GDPS (Global Deterministic Prediction System), the GEPS (Global Ensemble Prediction System), the RDPS (Regional Deterministic Prediction System), the REPS (Regional Ensemble Prediction System), and the HRDPS (High Resolution Deterministic Prediction System). The GDPS has initial conditions from 4D-Var, a grid spacing of 0.45° x 0.3° (~33 km at mid-latitudes), and a forecast lead time of 10 days. The GEPS consists of 20 members using initial conditions from an Ensemble Allmen Filter (EnKF), a grid spacing of 0.6° x 0.6° (~67 km at equator), and a forecast lead time of 16 days. The initial conditions of the RDPS are obtained using 3D-Var (soon 4D-Var), a grid spacing of 15 km (soon 10 km), and a lead time of 2 days.

On the regional scale, the REPS consists of 20 members with initial conditions interpolated from the global EnKF, a grid spacing of 33 km, and a lead time of 3 days. Currently, the HRDPS produces forecasts for 5 window regions over the country. Its initial conditions are interpolated from the RDPS. The grid spacing is 2.5 km, and the forecast lead time is 1 day. Operationally, there is no probabilistic high-resolution ensemble system.

A rapid upgrade of the systems is targeted for 2013-17, prompted partly by the results of Buehner et al. (2010a,b) who proposed a hybrid data assimilation method (En-Var) that combines the variational approach and the ensemble-based background error covariances. This method is deemed superior to existing data assimilation methods because the linear tangent and adjoint models are not required, also the advantages of 4D-Var and EnKF are combined, and the computational cost is low compared to 4D-Var when the ensemble exists.

By 2015, the global ensemble Kalman filter (GEnKF) will form the basis for global data assimilation (deterministic and ensemble-based). It will determine the initial conditions to the GEPS and provides

4-D background error covariances to En-Var to yield initial conditions for the GDPS. The Regional ensemble Kalman filter (REnKF) will form the basis for regional data assimilation (deterministic and ensemble-based). It will determine the initial conditions to REPS and provides 4-D background error covariances to En-Var to yield initial conditions for the RDPS and the HRDPS. The HRDPS at 2.5 km grid spacing is expected to cover the entire Canadian territory by 2013-14 (see Fig.1).

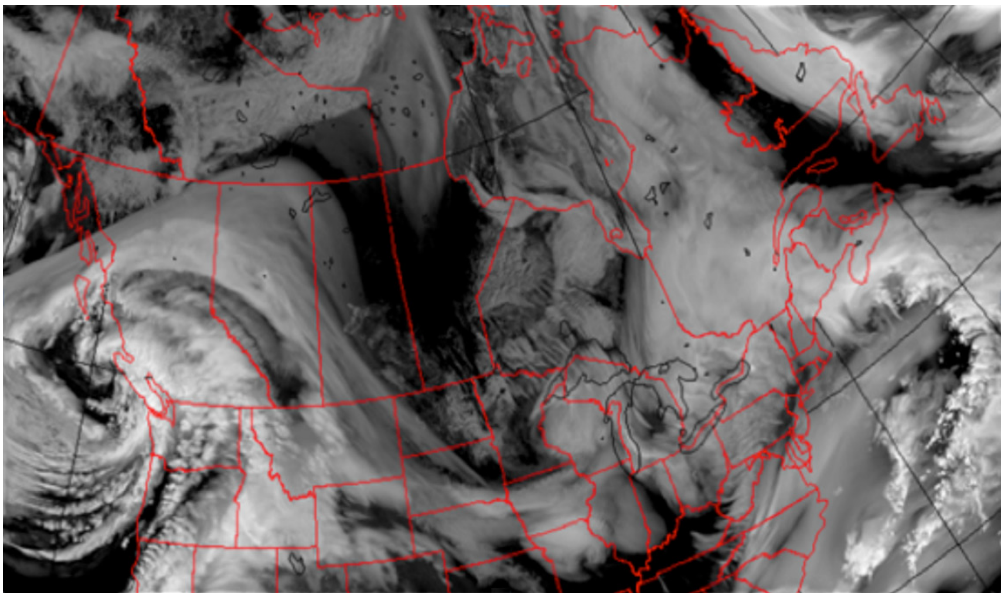


Figure 1: The 2.5 km national grid. A testing case of realistic cloud cover generated by the two-moment microphysics scheme. In a year or two, routine high-resolution (2.5 km grid spacing) model forecasts will be made over the entire Canadian territory.

During 2015-17, the REPS is targeted to reach 10 km grid spacing over North America and the lead time increases to 4-5 days. The lead time of the HRDPS will increase to 36 h or 48 h. A high-resolution analysis (2.5 km grid spacing) from the En-Var method with background error covariances from the REnKF is expected to become available. The HRDPS will likely take the role of the regional deterministic prediction system by then.

2. The microphysics schemes in Canadian NWP prediction systems

At present, the Sundqvist (Sundqvist et al. 1989) cloud scheme is used in all Environment Canada forecast systems other than the HRDPS. For high resolution deterministic forecasting, the two-moment Milbrandt and Yau (referred to as MY2, see Milbrant and Yau 2005a,b) explicit microphysics scheme is used. MY2 is the double-moment version of a multi-moment scheme in which the size distributions of hydrometeors are described by a three-parameter generalized Gamma function. To close the system and to determine uniquely the three parameters, prognostic equations are developed for three moments of the size distributions: the hydrometeor mixing ratios, total number concentrations, and radar reflectivity. Six hydrometeor categories are considered, including cloud droplets, rain drops, pristine ice crystals, snow flakes, graupel, and hail particles. In the operational implementation of MY2, one of the parameters of the Gamma function, the shape parameter, is assigned a constant value of zero. As a result, only two predictive moment equations, for total number concentration and total water mixing ratio, for each of the hydrometeor category are required.

3. Toward the development of a unified microphysics parameterization

It is highly desirable to have a similar microphysics representation across all model resolutions in the Canadian NWP systems. As the double-moment MY2 is developed for high resolution forecasting, and is more costly in terms of computational resources, some modification and optimization is called for before its implementation in coarser resolution models.

3.1. Sub-grid scale cloud and precipitation fractions

For coarser resolution models, cloud and precipitation may occupy only a fraction of the grid box. A sub-grid scale cloud fraction and a sub-grid scale precipitation fraction are required as part of the modified MY2 scheme. Chosson et al. (2013) implemented a simple sub-grid scale cloud and precipitation fraction based on a probability density function for total water. Tests in the context of a 1D kinematic updraft showed improved cloud and precipitation forecasts using MY2 with the inclusion of the cloud and precipitation fractions. A 3D case was also tested and the results indicate similar improvement as described below.

3.1.1. The 3D case

In this section, we compare the results for three GEM forecasts using the operational Sundqvist scheme, the MY2 scheme, and MY2 with sub-grid cloud and precipitation fractions (SCPF). The selected case occurred during the period 19-20 December 2008. Satellite cloud products from CALIPSO and CLOUDSAT were used as the observational basis for comparison.

3.1.2. Model description and setup

We use the limited area version of GEM (GEM-LAM). The simulated domain covers the whole North America. The horizontal grid size is about 15 km and the model time step is 450 seconds. The model is initialized at 1200 UTC December 19 2008 and a 36 h forecast was performed. Only the last 24h will be analyzed to avoid errors due to model spin-up. The evaluation is calculated for a single day, 20 December 2008, from midnight to midnight. The shallow and deep convection schemes are switched on and the detrained condensate and cloud fraction are included in the output cloud fields (cloud fraction, ice water content (IWC), and liquid water content (LWC)).

The reference simulation employs the Sundqvist cloud scheme in its operational configuration. The Sundqvist scheme is characterized by a single prognostic equation for total water. Precipitation is generated diagnostically. The partition between cloud liquid and cloud ice is determined using a prescribed relation which is a function of temperature and total water content (Boudala et al. 2004).

For the two forecasts using MY2, the microphysics package is calculated using a sub-time-step of 60s, resulting in 8 sub-time steps within each main model time step. The SCPF calculation employs the same relative humidity criterion as in the Sundqvist scheme.

3.1.3. The observation dataset

Recent active measurements from satellite provide a unique opportunity to evaluate cloud microphysics over both a large domain and a long time period, with high vertical resolution. The DARDAR-Cloud products (Delanoe and Hogan 2008, 2010) from the French ICARE thematic center are used in this study. The products are based on the combination of liDAR and raDAR measurements from the CLOUDSAT and CALIPSO satellites. A variational method is used to generate high resolution (1.1km in the horizontal, 60m in the vertical) cloud mask, IWC, effective radius and extinction along the satellites foot print. DARDAR-Cloud products have already been used to assess ECMWF and UK Met-Office NWP models (Delanoe et al., 2011) and have been compared with other remote and in-situ measurements (Delanoe et al., 2013).

3.1.4. The cloud masks

The satellite tracks crossed the simulation domain nine times on 20th December 2008 (Fig.2). The simulations outputs are projected onto the DARDAR grid and the closest corresponding points from the simulated output fields in space and time is selected for comparison.

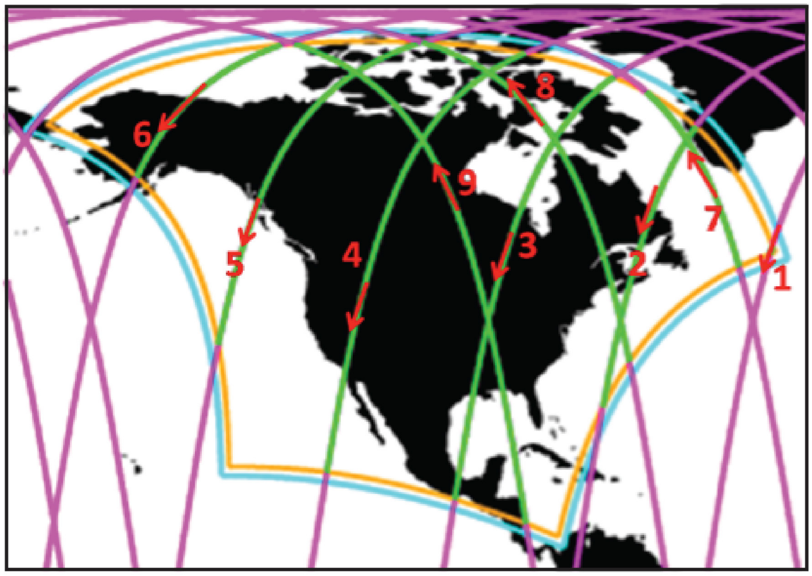


Figure 2: The GEM-LAM simulation domain. The foot prints of the CALIPSO and CLOUDSAT satellites on 20th December 2008 are shown in magenta. The points retained for comparison are highlighted in green, corresponding to the 9 trajectories crossing the domain (numbered).

Figure 3 shows the cloud masks from DARDAR and each of the 3 forecasts for the 9 satellite-tracks/domain crossings of the day. If a cloud is present, it can be either in the pure ice phase (green), pure liquid warm phase (deep blue), pure below 0°C (supercooled) liquid (light blue) phase, or a mixed phase (salmon). In the simulation with MY2 but no SCPF, the cloud fraction is either 1 or 0 if the total specific cloud condensate content is respectively above or below $1x10^{-3}$ g/kg. For the Sundqvist and MY2 with SCPF simulations, a point is considered cloudy if the cloud fraction exceeds 1% and the cloudy condensate (precipitation is ignored) exceeds $1x10^{-3}$ g/kg either in the ice or the liquid phase or both phases depending on the cloud mask category.

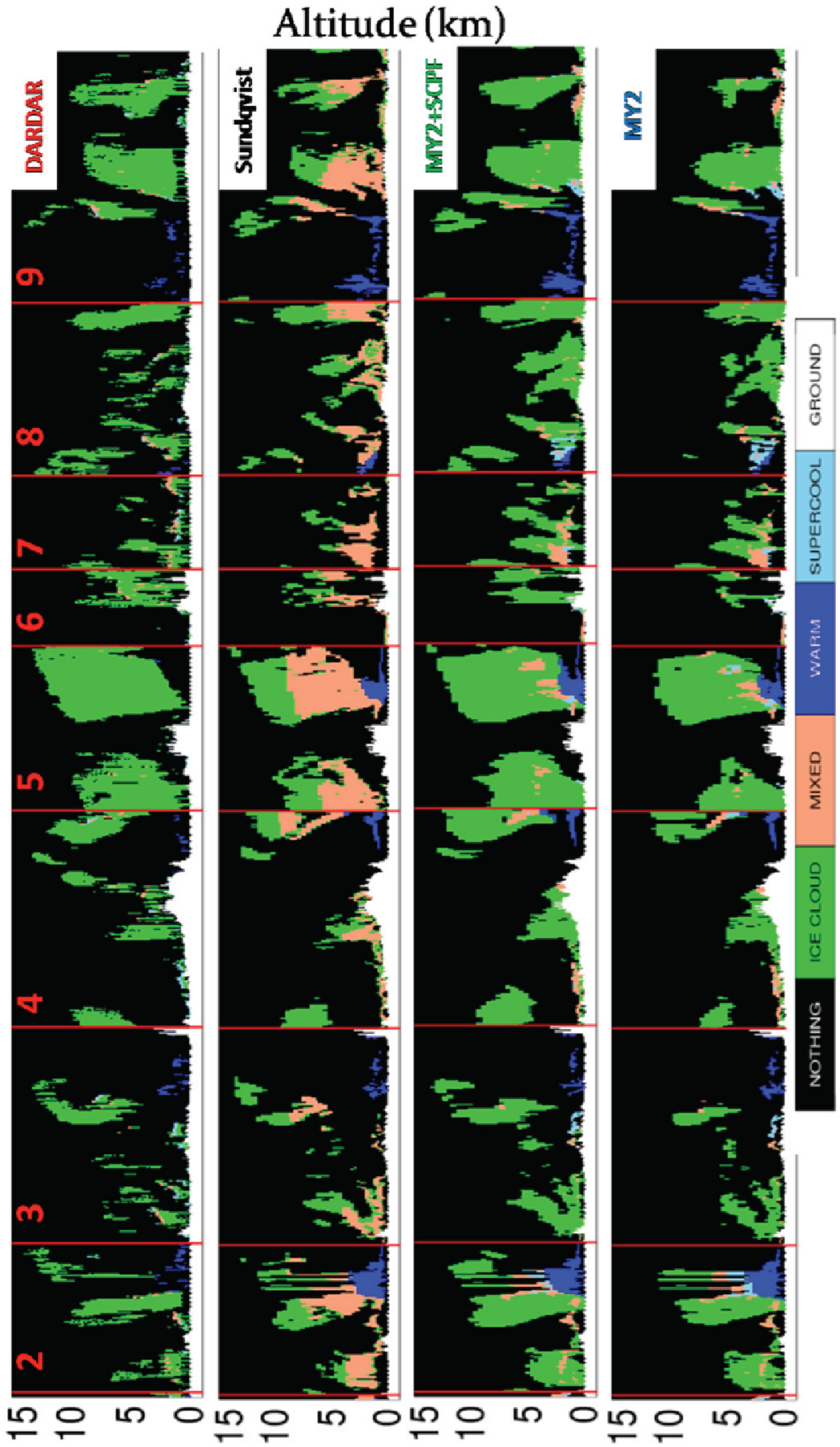


Figure 3 Time height sections of cloud masks along the 9 tracks crossing the model domain (see Fig.2). From top: DARDAR, GEM-LAM with ng Sundqvist, GEM-LAM with MY2 and SCPF scheme, and GEM-LAM with MY2 but no SCPF.

The results indicate that all three GEM-LAM simulations capture well the general distribution of cloud systems relative to the observations. The correlation in space and time between the cloud patterns is rather good although some differences are evident.

The Sundqvist simulation exhibits too much cloud diagnosed as mixed phase, even at altitude as high as about 9 km. This can be traced to the problem arising from the liquid/ice partition function used in the model (Boudala et al., 2004).

Compared to DARDAR, the simulations using MY2 exhibit a good distribution of cloud types. In particular, there is a realistic proportion of mixed phase clouds and the presence of a thin overlying mixed phase or even supercooled liquid layer on the top of some deeper ice clouds.

The inclusion of SCPF in MY2 leads to a slightly higher cloud fraction, especially for ice clouds. The main difference arises from the absence of high altitude ice clouds in the MY2 simulation without SCPF.

3.1.5. Ice water content

Figure 4 depicts the IWC from DARDAR and the simulations wherever a cloud is diagnosed as detailed in the previous sub-section. The values from the simulations are grid mean values.

Whenever the clouds pattern exhibits similar feature between DARDAR and the simulations, the vertical distributions of IWC are in general agreement. However, it is clear that the Sundqvist IWC is considerably lower than DARDAR. The agreement is much better with the MY2 simulations. Note that whenever the cloud pattern is similar in both MY2 simulations, the IWC fields are almost identical, in agreement with the notion that MY2 with SCPF converges to MY2 without SCPF when grid mean saturation is achieved.

3.1.6. Mean profiles

Figures 5 presents the mean vertical profiles of cloud fraction (all cloud types), ice water content, and in-cloud IWC (IWC divided by the cloud fraction for each point where the cloud fraction exceeds 1%), averaged over all nine along-track cross sections during this day.

For the case study, the Sundqvist simulation exhibits too low values of cloud fraction in the troposphere relative to DARDAR, except for altitudes above 12 km. It is interesting to note that even though the relative humidity criterion is the same as in the SCPF scheme and that the subgrid cloud fraction diagnostic estimations are similar, the Sundqvist mean cloud fraction is significantly lower than in the MY2 with SCPF. As stated in the previous sub-section, the Sundqvist simulation produces far too low ice condensate. The lack of cloud fraction is not sufficient to compensate for the lack of cloud condensate below 8 km and the Sundqvist mean in-cloud IWC profile shows significantly lower values than the DARDAR restitutions.

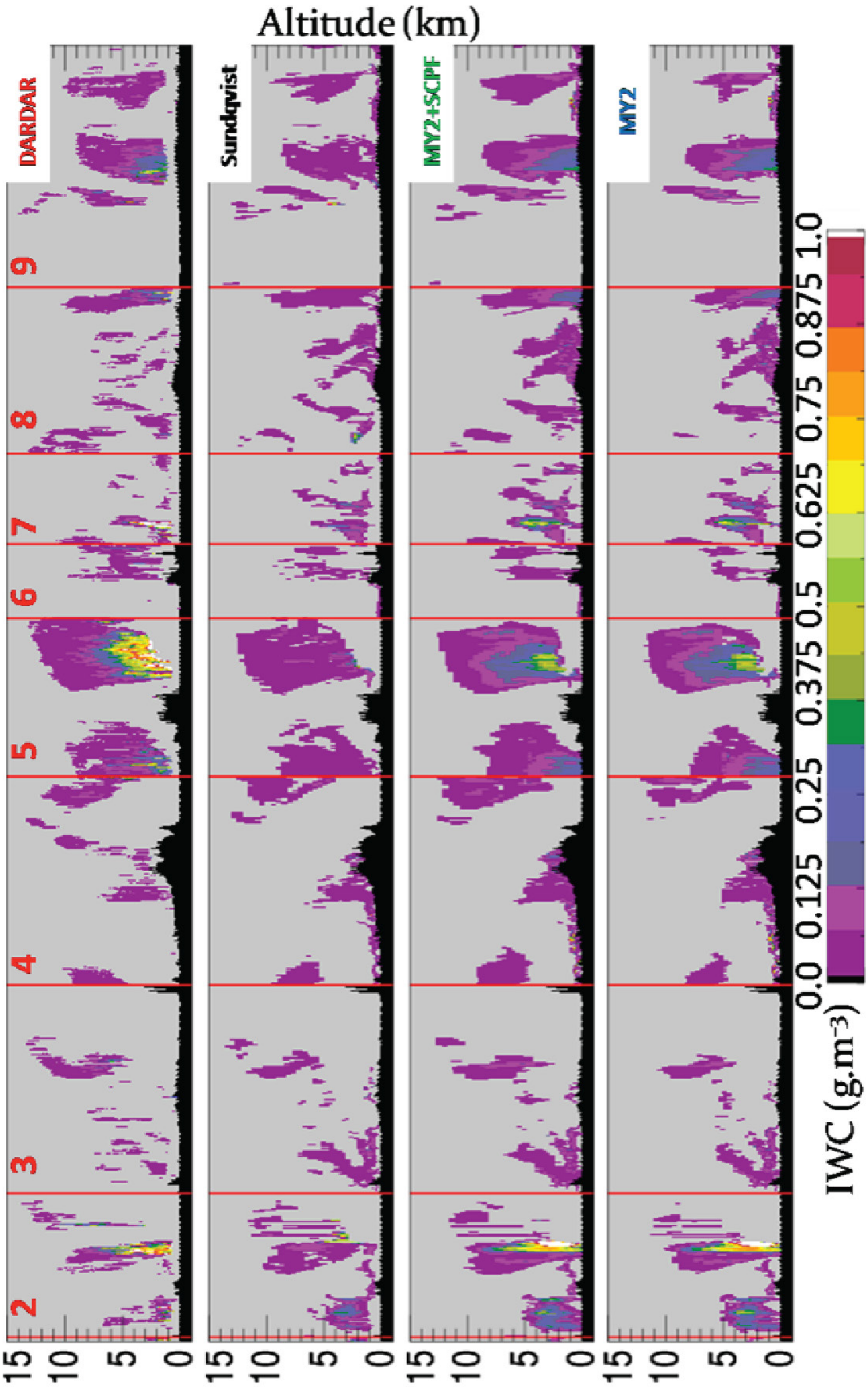
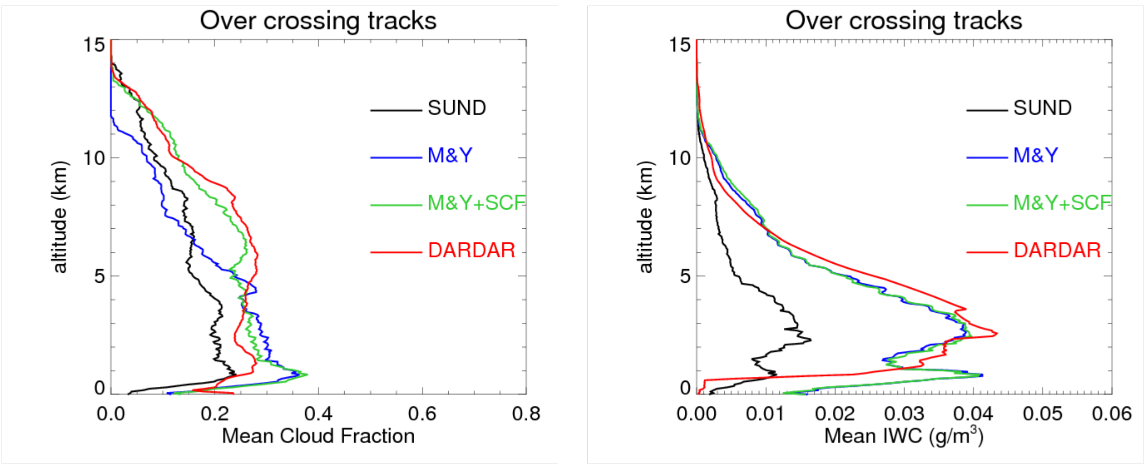


Figure 4: Same as Fig.3 but for IWC.

For the MY2 simulations, in the lower part of the troposphere from about 1.5km up to 5km, the mean cloud fraction from both simulations are similar and in good agreement with DARDAR. In the lowest part of the atmosphere (boundary layer), the disagreement increases. However, in the boundary layer the satellite measurements are often too attenuated by overlying clouds and the simulations may be significantly affected by the shallow convection scheme. The two MY2 simulations diverge above 5 km, where the mean cloud fraction decreases to zero at around 12 km if SCPF is not included. On the contrary, the simulation with SCPF continues to be in good agreement with the DARDAR mean cloud fraction up to 14 km. Note that the two MY2 simulations produce nearly identical mean ice water content profiles, both in very good agreement with DARDAR, although with slight overestimation of IWC from 7 km to 12 km and slight underestimation of IWC below 7 km. Consequently, the mean in-cloud IWC profiles agrees quite well with DARDAR up to 5 km high, and even at higher levels in the simulation using the MY2 with SCPF scheme. There is an overestimation from 5 km to 12 km in the MY2 simulation without SCPF.



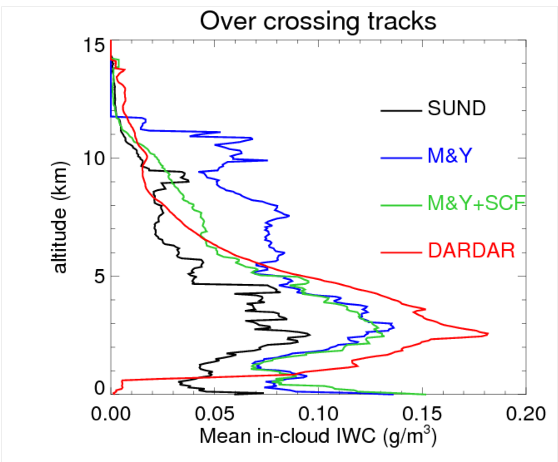


Figure 5: Mean vertical profiles of all-type cloud fraction (upper left), ice water content (upper right) and in-cloud ice water content (lower left), averaged over the overlapping tracks on 20th December 2008, for DARDAR (red) and simulations using Sundqvist (black), MY2 with (green) and without (blue) the subgrid cloud and precipitation fraction schemes.

3.2. Consolidation of hydrometeor categories

To allow the MY2 with SCPF scheme to be used for longer term forecasts, the efficiency of the scheme needs to be improved. Toward this end, attempt is started to consolidate certain hydrometeor categores to decrease the number of predicted categories. Milbrandt and Morrison (2013) proposed to combine the graupel and hail categories by adding a predictive equation of bulk density of graupel ρ_g in MY2. The simulation of graupel using the modified scheme is evaluated through idealized simulations of a mesoscale convective system using a 2D kinematic model with a prescribed flow field and different peak updraft speeds. The results indicated that as a result of the direct feedback of ρ_g to the terminal fall speed, the modified scheme produces a much different spatial distribution of graupel and can produce solid precipitation at the surface in the convective region without a separate hail category. The work is of promise as it is shown that a single rimed-ice category is capable of representing a realistically wide range of graupel characteristics under various atmospheric conditions without the need for *a priori* parameter settings.

4. Future work

Future work planned include

a) Testing of sub-grid scale cloud and precipitation fractions to horizontal resolution of about 40 km;

b) Consolidation of ice crystal and snow categories;

c) Better treatment of sub-grid scale vertical motion and sedimentation;

d) Improvement of microphysics in convective parameterization scheme and proper interface between convection, microphysics, and radiation.

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