MESOSCALE SIMULATIONS OF CLOUD MICROPHYSICS WITHIN A WINTER STORM: SOME IMPLICATIONS FOR LARGE-SCALE ICE PHASE SCHEMES

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1. INTRODUCTION

The importance of clouds in weather and climate processes has been widely recognized. For example, the explicit amount of cloud water and cloud ice has an important influence on the results of large-scale numerical integrations, since it is closely related to the hydrological cycle and atmospheric radiation budget. Thus NWP models and GCM tend to upgrade from very crude diagnostic representation of clouds to more elaborate physically based prognostic schemes. Even if a number of cloud-resolving models (CRM) already include sophisticated representation of cloud microphysical processes, these schemes are expensive and computer limitations usually prevent their incorporation in large-scale models. For this reason, NWP models and GCM currently tend to implement more efficient cloud schemes such as proposed by Sundqvist (1989, 1993).

In this paper the implementation of a cloud microphysics parameterization scheme in a nonhydrostatic fully compressible numerical model is presented. Mesoscale simulations of a north Atlantic winter storm are next discussed. A comparison of the cloud microphysics simulations with the explicit mesoscale simulations using the scheme of Sundqvist is also discussed, and important differences in the treatment of ice phase within the two schemes are found. From a detailed analysis of the cloud microphysics simulations a simple physically based alternative for ice phase parameterization in large-scale applications is suggested.

2. MODEL DESCRIPTION

The numerical experiments discussed in this study are based on the fully compressible 3D nonhydrostatic semi-implicit semi-Lagrangian MC^2 (Mesoscale Compressible Community) model. The MC^2 model originated from a regional hydrostatic model (Robert *et al.* 1985). It was generalized to the Euler system by Tanguay *et al.* (1990), and successfully applied to synoptic storm simulations. Subsequently, the same model was used at fine-scale by Robert (1993) for bubble convection experiments. Tremblay (1994) used the model on the mesoscale for squall-line simulations, emphasizing the *universal* nature of this dynamical framework.

Some additional characteristics of MC^2 include: variable vertical resolution, modified Gal-Chen terrain-following scaled-height vertical coordinate, a limited-area one-way nesting strategy, and a complete physics package (Benoit *et al.*, 1989).

The inclusion of an explicit cloud microphysics scheme is particulary important for the present work. This scheme is based on the 2D kinematics cloud microphysics model of Zawadzki *et al.* (1993). The cloud microphysics model has been first generalized to 3D and then implemented interactively into the MC^2 dynamical framework. The model includes conservation equations for temperature, water vapor (q_v), cloud water (q_c), cloud ice (q_i), rain (q_r), snow (q_s) and graupel (q_g) for a total of 38 mass transfers between different water categories. The formulation of these mechanisms is mainly based on Lin *et al.* (1983) and Rutledge and Hobbs (1984), but some changes were introduced. Thus, the parameterization of solid precipitation processes is expressed in terms of the various moments of particle size distribution without specifying any particular functional form of the distribution. All the moments are related to the third moment of the snow size distribution ($\propto q_s$) using aircraft measurements

Another important feature of the model , in its mesoscale version, is an explicit treatment of condensation and clouds, based on Sundqvist *et al.* (1989). In this formulation, the cloud content is a prognostic variable of the model and existence of ice is parameterized in term of air temperature following Sundqvist (1993).

3. SIMULATIONS SETUP

The winter storm chosen for simulations occurred on the 14th of March 1992 over the north Atlantic, near the Canadian east coast. By 19 UTC, the storm was already developed, and SSM/I data for the region of interest were available. In order to help in the validation of cloud water simulations, retrieval of integrated liquid water content was performed using semi-empirical algorithm developed by Petty and Katsaros (1990).

To provide lateral boundary conditions needed for MC^2 simulations, the regional finite element model (Benoit *et al.*, 1989) was first integrated for 24 hours and the data were stored every 3 hours. For this simulation, 127×127 horizontal grid points were distributed in the hemisphere to obtain a 3500×3500 km region at a resolution of 50 km covering the region of interest. This information was next used to generate a MC^2 24 hour forecast over the same domain, but on different vertical levels (250 m in the first 5 km, increasing smoothly above). These data were stored at each hour, and used to initialize and drive higher resolutions nested simulations (at 20 km and 10 km in this work).

Several preliminary tests have been performed with the MC^2 model including the cloud microphysics scheme. These have proven the insensitivity of model results to timestep (halving the time step did not affected the results) and domain size and resolution (doubling the resolution and extending the domain neither produced additional features nor changed these already present).

Two simulations with two different cloud schemes incorporated in MC^2 were performed to follow the evolution of the 14 March storm. The domain was 1400 km by 2300 km and resolution 20 km. The MC^2 model with cloud microphysics scheme was integrated for 4 hours starting at 17 UTC. The MC^2 model with mesoscale Sundqvist scheme was integrated for 24 hours, starting at 00 UTC. The results of both simulations were compared at 19 UTC.

4. RESULTS

Vertically integrated water and ice contents for the two cloud schemes, superimposed with a frontal analysis, are depicted in Fig. 1. For the Sundqvist scheme, the partition between liquid and ice was obtained diagnostically using the temperature relationship of Sundqvist (1993). For the cloud microphysics scheme, the liquid phase is the sum of cloud water and rainwater, and the ice phase includes snow, graupel and cloud ice. In Fig. 1a, one recognizes the typical *T-bone* structure of the cloud field often associated with developing extratropical cyclones. An equivalent organization can be identified on satellite images of this storm (not shown). A comparison of Figs. 1a and 1c shows similitudes between the two schemes. For example, one can see the comma-shaped structure of the clouds associated with the developing low pressure center. This configuration is closely linked with the mesoscale pattern of vertical velocity in the model, with maximum values just ahead of the cold front, and upper-level occlusion near the low center. Within this region, the air is saturated, the cloud cover is unity, and both schemes give a maximum integrated liquid water of about 0.5 kg m^{-2}. This is significantly larger than 0.3 kg m^{-2}, a typical value retrieved from SSM/I for this specific case. There is however a great amount of uncertainties associated with the SSM/I retrievals of integrated liquid water, so the analogy should remain for moment mostly qualitative. A significant difference between the two schemes, is the greater spatial extent of the cloud water associated with the mesoscale cloud procedure, as indicated by the much larger area delimited by the 0.1 kg m^{-2} contour in Fig. 1a. This was attributed to the Sundqvist parameterization of statiform condensation that allows cloud formation for subsaturated grid points. In contrast, the cloud microphysics scheme needs supersaturation on the resolved scale, to initiate condensation.

A comparison of Figs. 1b and 1d shows clearly an important difference in the ice field generated by the two schemes. Although the general spatial morphology of this field is roughly equivalent for each case, there is large difference in the ice content values remaining in the atmosphere. Thus the mesoscale scheme (Fig. 1b) gives typical integrated ice content of about 0.1 kg m^{-2}, a value significantly smaller than 0.5 kg m^{-2} obtained from the full cloud microphysics integration (Fig. 1d). This emphasizes the fact that the modeling of ice physics in the two schemes is totally different. In the cloud microphysics simulation we model explicitly the physics of ice formation by considering all possible interactions between snow, graupel, cloud ice, rainwater and supercooled clouds. On the other hand, the mesoscale parameterization of ice is primarily based on the assumption that the amount of ice crystals in a volume with supercooled water is a function of temperature only. Thus, there is certainly a need to examine closely the appropriateness of this assumption.

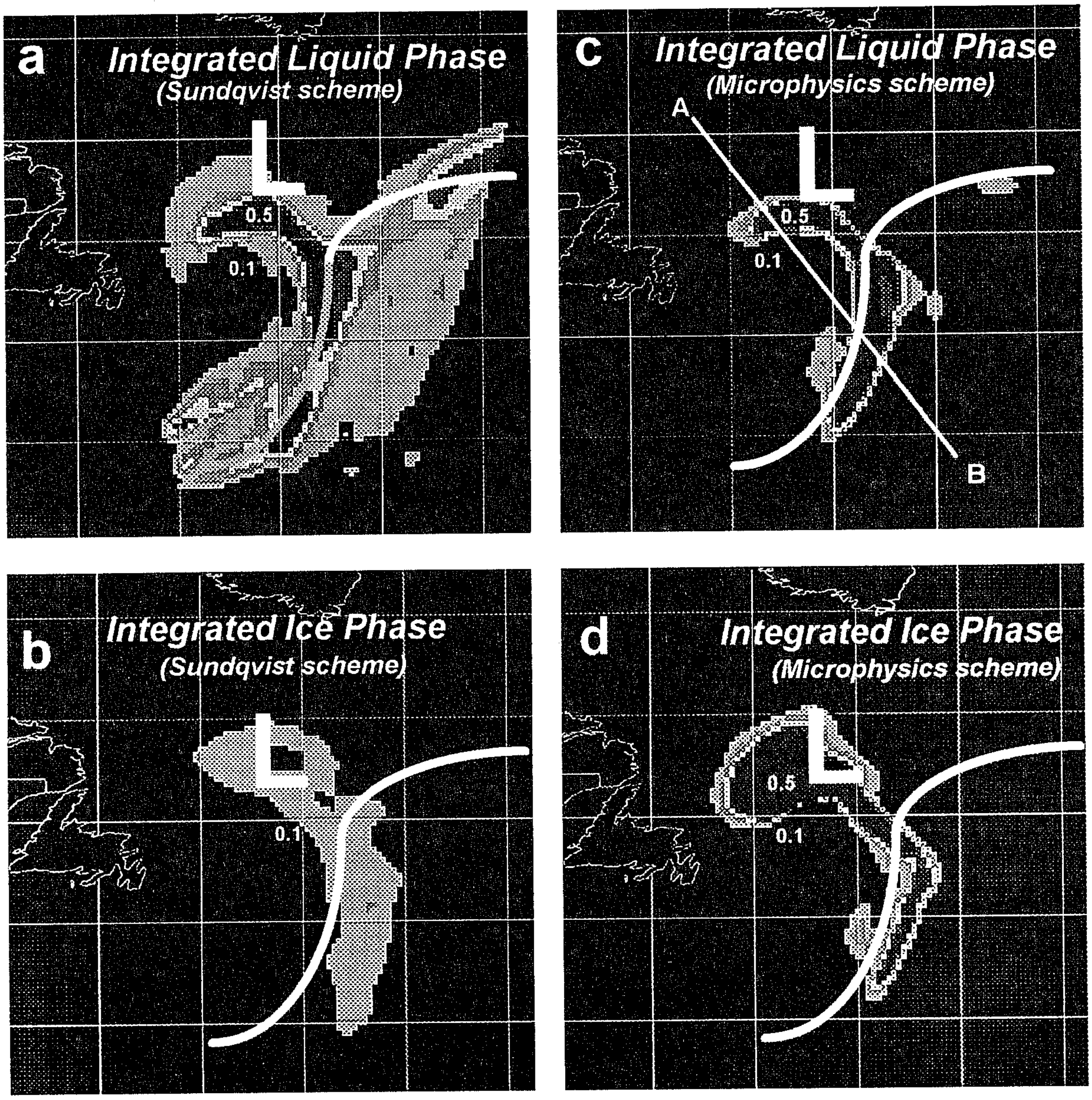

Fig 1: Integrated liquid water content and ice water content for cloud microphysics and Sundqvist scheme integrations valid at 19 UTC 14 March 1992.

Fig. 2a displays a composite map of hydrometeors mass distribution superimposed with isotherms in a vertical plane along the line segment AB shown in Fig. 1c. The figure demonstrates that precipitation processes are active in association with both upper-level (left) and surface (right) cold fronts. Only snow, cloud water and rain appear in Fig. 2a since graupel and cloud ice did not accumulate significantly in this simulation. The slanted cloud tower is associated with the updraft at the upper-level cold front. This updraft structure supports condensation and there is a growth of snow crystals by deposition and riming at the expense of the supercooled cloud. The snow is subsequently advected out of the updraft core by the horizontal wind, leading to the large cloud-free area apparent in the figure. For temperatures above freezing, cloud is converted to rain and there is a strong interaction with falling snow as discussed below. Similar arguments can also be invoked to discuss the structure of the hydrometeors mass associated with the surface cold front (right).

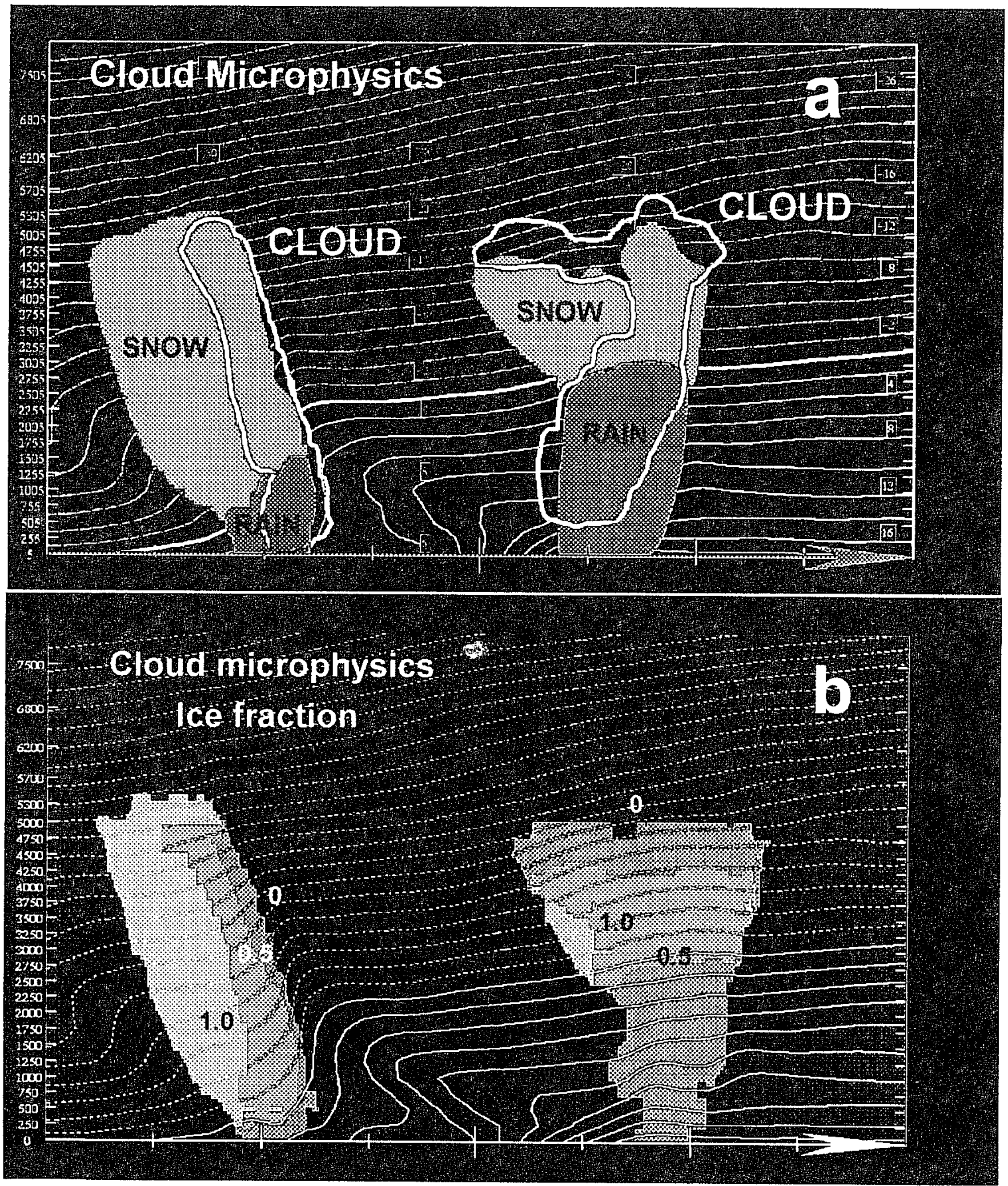

Fig. 2: Vertical cross-sections along line segment AB (Fig. 1c) of a) outline of snow, rain and cloud water > 0.01 g m^{-3}; b) ice fraction calculated from the cloud microphysics simulation.

As mentioned above, a key ingredient in the mesoscale parameterization of ice phase, is the dependence on temperature of the fraction of ice (f_{ice}) in a given volume . To investigate the physical argumentation underlying this assumption, Fig. 2b displays f_{ice}, computed directly from the cloud microphysics integration. When $0 \le f_{ice} \le 0.5$ supercooled cloud dominates, for $0.5 < f_{ice} < 1$ the mixed-phase cloud is mostly ice and for $f_{ice} = 1$ the cloud is glaciated. Clearly, one sees in the numerical solution abundant mixed-phase clouds and large regions with $f_{ice} = 1$. Interestingly, f_{ice} is a highly structured field, but its dependence on temperature is very weak. For example one can see at the upper-level front, a large region of ice cloud but no temperature stratification is apparent. Thus, f_{ice} is more related to the interaction between cloud microphysical processes and mesoscale dynamics rather than to the temperature field.

Fig. 3 illustrates the relationship between f_{ice} and temperature. From this figure, one can see that an important amount of snow was generated within the temperature range $-10C \leq T \leq 0C$, as indicated by the high density of data points with $f_{ice} > 0.8$ within this range. It is also apparent that a significant amount of supercooled cloud water is present in the numerical solution around $T = -15C$, since there is a large number of points with $f_{ice} < 0.2$ in this region. The ice phase is also found for $T > 0C$ due to unmelted particles, and virtually no supercooled water exists at temperature below -20. Fig. 3 shows clearly, that there is no correlation between f_{ice} and T, and that using a functional dependence for f_{ice} as in the mesoscale scheme may be inappropriate. This suggest that this parameter must rather be deduced from a detailed analysis of coupled cloud-microphysics/cloud-dynamics systems.

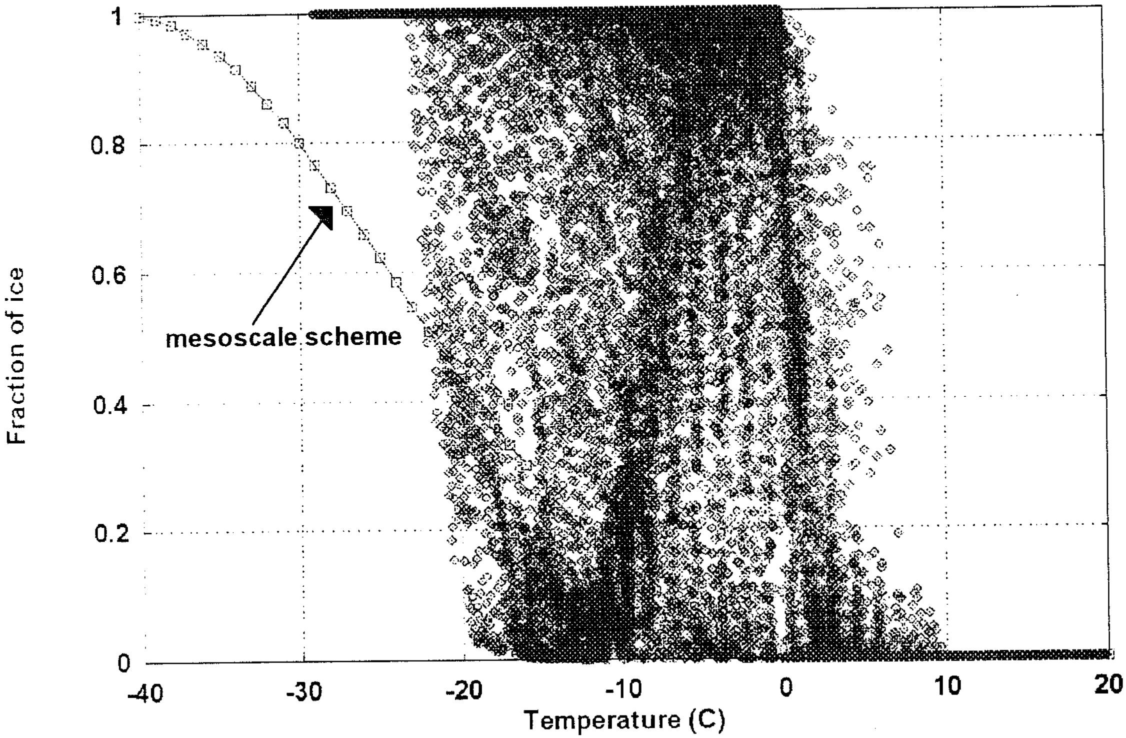

Fig 3: Distribution of ice fraction with respect to temperature calculated from the cloud microphysics simulation.

The most important cloud microphysical processes can be inferred from an analysis of detailed budget parameters. Thus, the time-evolution of the domain-averaged mass for each hydrometeor category is displayed in Fig. 4a. Basically, this figure shows that the cloud microphysics model has a spin-up time of about 2 hours. During this time interval the microphysics variables, initially set to zero, simply adjust to the mesoscale forcing, and this part of the numerical solution has likely no physical meaning, since it is strongly influenced by initial conditions. After this adjustment period, the cloud microphysics scheme responds smoothly to the

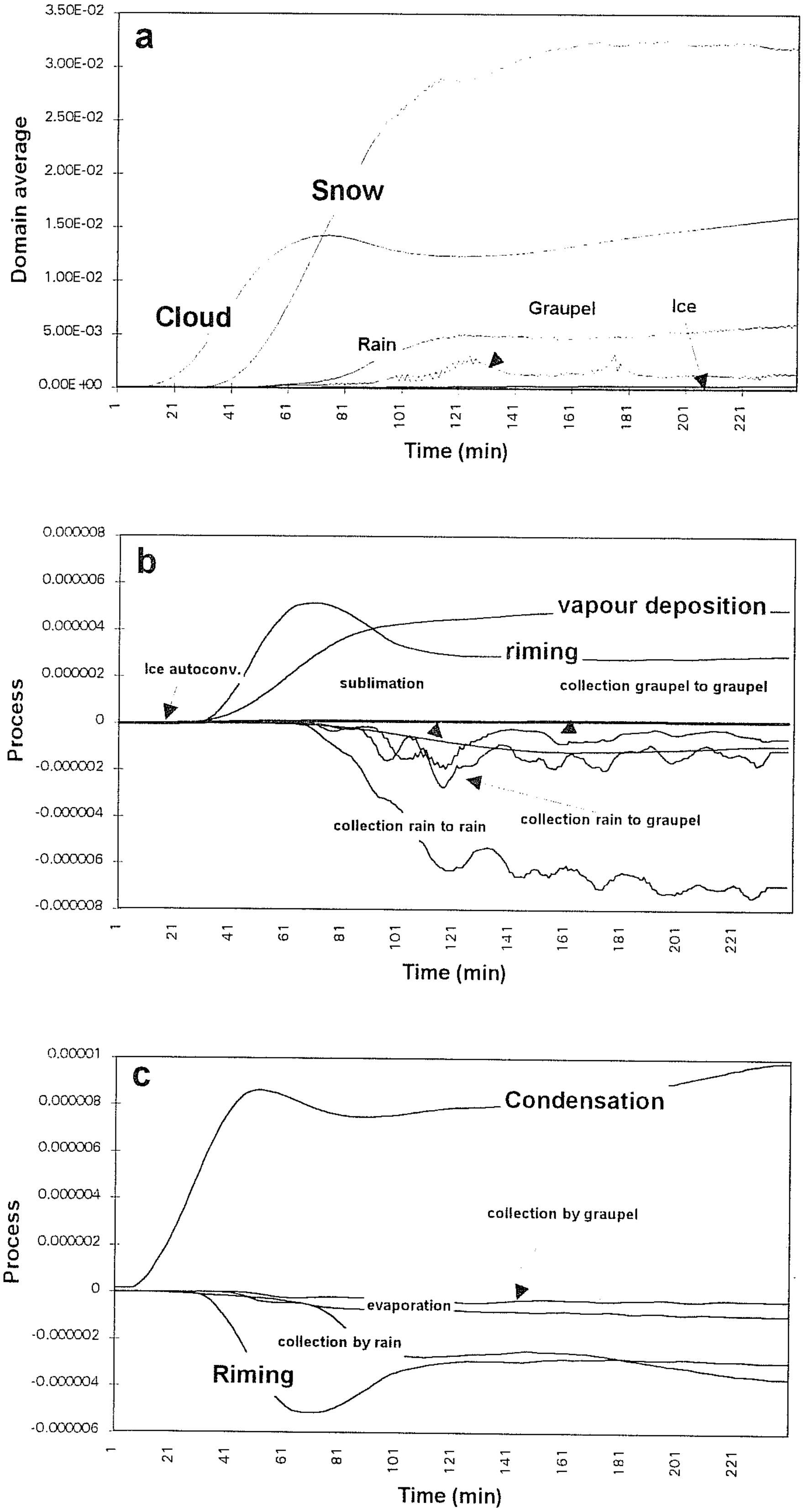

Fig. 4: Time series of: a)domain-averaged hydrometors mass; b) microphysical processes for snow; c) microphysical processes for cloud water.

mesoscale signal, and this portion of the solution can be used to discuss microphysical processes related to ice/supercooled clouds. Near the end of integration, snow and cloud water are the most important species within the simulation domain. Graupel and cloud ice do not accumulate significantly, and rain exists mainly for temperatures above freezing. Thus, as a first order approximation, one can consider mixed phase clouds simply as combination of snow and supercooled cloud water.

Fig. 4b illustrates the source/sink terms that maintain the snow mass. Initially, snow is initiated from the ice autoconversion process. Next, it starts to grow quickly by riming of preexisting cloud water, and simultaneously, the vapor deposition process is activated. Snow falling to temperatures above freezing, is efficiently collected by rain. Clearly, at the equilibrium stage for subfreezing temperatures, snow mostly grows by riming and vapor deposition, but depletion by graupel and sublimation are second-order processes.

A similar argumentation can be invoked to discuss cloud water processes. Thus, from Fig. 4c, one can see that cloud water is generated by condensation and depleted by riming and scavenging by rain. Evaporation and collection by graupel remain typically one order of magnitude smaller than these dominant processes.

The above discussion can be summarized by the following simplified microphysics equations for the 2 dominant species within mixed clouds at subfreezing temperatures:

$$\frac{dq_c}{dt} \approx C - R - A \tag{1}$$

$$\frac{dq_s}{dt} \approx D + R - S \tag{2}$$

Where C symbolizes the condensation rate, R riming, D vapor deposition of snow, A interaction of cloud with rain and/or graupel, and S the interaction of snow with rain and/or graupel.

Based on similar considerations, Tremblay *et al.* (1995) have demonstrated, that within mixed clouds, the steady-state version of

$$\frac{dq_v}{dt} \approx Q - C - D \tag{3}$$

was valid. In the above, Q is the rate at which supersaturation is available by adiabatic ascent. This equation simply translates mathematically the fact that supersaturation in the atmosphere always remains small. Based on the above equation, it was shown (Tremblay *et al.*, 1995) that the existence of supercooled cloud water in presence of snow depends not only on temperature, but on vertical velocity and snow content as well.

The above equations have interesting implications for ice phase parameterization schemes on the large-scale. Thus, a more refined analysis of the present results suggests that the term A in equation (1) is significant only at temperatures above freezing. This, when combined to the steady-state assumption for q_c and with (3), provides an algebraic equation for the two unknowns and q_c and q_s. Thus, in principle the knowledge of the total water content such as in the Sundqvist's scheme may be sufficient to infer f_{ice} on a physical basis.

5. SUMMARY

A universal cloud-resolving model, based on the general Euler system including sophisticated atmospheric physics, was coupled with a cloud microphysics scheme. The model algorithms are built on recent advances in numerical technology and benefit from high computational efficiency of the semi-implicit and semi-Lagrangian schemes. The model was successfully applied to the simulation of a north Atlantic winter storm, and the results show a consistent physical picture of cloud and precipitation processes with the cloud microphysics scheme. A comparison between the results obtained from the elaborated cloud microphysics simulation and the results obtained using the Sundqvist scheme has demonstrated a significant inconsistency in the simplified mesoscale treatment of ice phase. It was shown that the partition between supercooled and glaciated clouds within a given volume, cannot be inferred from a knowledge of temperature alone, but instead one must consider the interaction between cloud microphysical processes and mesoscale dynamics as well. A simple alternative was briefly outlined, but further research is still needed to complete this investigation.

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