The LM Cloud Ice Scheme

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1 Introduction and Background

Cloud processes take place on scales that are significantly smaller than those resolved by the grid boxes of a NWP-model. In large-scale models not only cumulus clouds but also precipitating stratiform frontal clouds are of subgrid nature and need to be represented by a suitable prognostic cloud fraction parameterization (e.g. Sundqvist, 1988; Smith, 1990; Tiedtke, 1993; Rasch and Kristjansson, 1998)). The formation of precipitation from subgrid stratiform clouds is further complicated by a necessary assumption on cloud overlap statistics (Jakob and Klein, 1999). This situation appears to be less complex in high-resolution mesoscale models with grid spacings of less than about 10 km. Frontal stratiform clouds are well resolved and bulk microphysical parameterizations similar to those used in cloud resolving models (e.g. Kessler, 1969; Lin et al., 1983, Rutledge and Hobbs, 1983) may be applied. In such grid-scale schemes, only the cloud condensate is predicted by budget equations and the cloud cover is set to 100% whenever condensate occurs.

Except cumulus convection, which is parameterized by dedicated schemes, all other non-resolved clouds in mesoscale models are of stratocumulus-type. A direct hydrological impact of these clouds may be neglected for NWP purposes, but not the interaction with radiation. In LM, we use a traditional scheme that diagnoses a cloud fraction and a corresponding liquid water content in terms of relative humidity, pressure and convective activity. Clearly, subgrid-scale cloudiness will become less important with increasing model resolution.

Ice-phase processes play a significant role in mid-latitude frontal cloud systems and their impact should be taken into account by parameterization schemes. Two mechanisms of precipitation enhancement are of particular importance: the Bergeron-Findeisen process and the Seeder-Feeder mechanism, which both are based on the presence of supercooled liquid water. Nucleation of ice in a water saturated environment will cause a rapid growth of the ice crystals by deposition (because of the ice supersaturation) and riming (because of the presence of supercooled cloud droplets). The ice particle growth is at the expense of liquid water, but if the cloud is kept at water saturation by thermodynamic forcings, high precipitation rates may result (Bergeron-Findeisen process). The Seeder-Feeder mechanism describes precipitation enhancement due to ice particles falling from a higher cloud into a lower cloud containing supercooled droplets. In this case, the droplets will also be converted into ice by deposition and riming, resulting in a more efficient removal of cloud water than by the collision-coalescence growth of water droplets.

Two gridscale cloud and precipitation schemes that include ice phase processes have been implemented in LM. They are described in the following sections and a shortcoming resulting from a simplified numerical treatment of precipitation fallout is also discussed. Both schemes neglect hail and graupel since these ice particle types are not relevant for precipitation formation in stratiform clouds at the current model resolution. The future application of LM on the mesoγ scale, however, will require a corresponding extension of the schemes.

2 The Operational Scheme

The default parameterization scheme for the formation of grid-scale clouds and precipitation is based on a Kessler-type bulk formulation and uses a specific grouping of various cloud and precipitation particles into broad categories of water substance. The particles in these categories interact by various microphysical processes which are parameterized in terms of the mixing ratios as the dependent model variables. Four categories of water substance are considered: water vapour, cloud water, rain and snow. Cloud water is treated a bulk phase with no appreciable terminal fall velocity relative to the airflow, whereas single-parameter exponential size-spectra and empirical size-dependent terminal fall velocities are assumed for raindrops and snow crystals.

To simplify the numerical solution of the budget equations for rain and snow, quasi-equilibrium in vertical columns is assumed by neglecting 3-d advective transport and by prescribing stationarity. The resulting balance between the divergence of the precipitation fluxes and the microphysical sources and sinks allows for a very efficient diagnostic calculation of P_r and P_s. While this assumption is well justified for large-scale models (Ghan and Easter, 1992), it is clearly not adequate for the meso-γ and smaller scales. Work on a prognostic treatment of the precipitation phases is in progress. With these key assumptions, the equations for the hydrological cycle read

$$\begin{aligned}
\frac{\partial T}{\partial t} &= A_T + \frac{L_V}{c_{pd}}(S_c - S_{ev}) + \frac{L_S}{c_{pd}} S_{dep} + \frac{L_F}{c_{pd}}(S_{nuc} + S_{rim} + S_{frz} - S_{melt}) \quad , \\
\frac{\partial q^v}{\partial t} &= A_{q^v} - S_c + S_{ev} - S_{dep} \, , \\
\frac{\partial q^c}{\partial t} &= A_{q^c} + S_c - S_{au} - S_{ac} - S_{nuc} - S_{rim} - S_{shed} \, , \\
-\frac{1}{\rho}\frac{\partial P_r}{\partial z} &= -S_{ev} + S_{au} + S_{ac} + S_{melt} - S_{frz} + S_{shed} \, , \\
-\frac{1}{\rho}\frac{\partial P_s}{\partial z} &= S_{nuc} + S_{rim} - S_{melt} + S_{frz} + S_{dep} \, .
\end{aligned} \tag{1}$$

The A_ψ-terms abbreviate advective and turbulent transport. L_V, L_S and L_F denote the latent heat of vapourization, sublimation and freezing, respectively. The other symbols have their usual meaning. The following microphysical mass-transfer rates S_x are considered by the scheme: condensation and evaporation of cloud water (S_c), autoconversion of cloud water to form rain (S_{au}), accretion of cloud water by rain (S_{ac}), formation of snow due to nucleation from cloud water (S_{nuc}), riming of snow (S_{rim}), shedding of rainwater from melting snow (S_{shed}), depositional growth of snow (S_{dep}), melting of snow to form rain (S_{melt}), heterogeneous freezing of rain to from snow (S_{frz}), and evaporation of rain in subcloud layers (S_{ev}).

Both the Bergeron-Findeisen process and the Seeder-Feeder mechanism are represented explicitly by this scheme. The calculation of cloud water condensation and evaporation is based on instantaneous adjustment to water saturation. From the latter assumption, however, a number of major drawbacks result:

(a) Clouds will always exist at water saturation independent of temperature. That is, only mixed phase clouds (cloud water, snow and rain) are simulated below freezing point.

(b) The cloud ice-phase is neglected by assuming a fast direct transformation from cloud water to snow. Thus, the glaciation of clouds cannot be simulated and cirrus will be at a wrong thermodynamic state. Also, the precipitation enhancement from the Bergeron-Findeisen mechanism may be overestimated.

(c) High-level clouds usually exist at or close to ice saturation. Since the scheme requires water saturation for cloud formation, the initial conditions must be artificially adapted to avoid long spin-up periods: In the analysis scheme, the specific humidity obtained from measurements is increased by the ratio of the saturation vapour pressure over water and over ice for temperature below $0°C$. This affects the high-level humidity structure in an unphysical way.

3 Description of the LM Cloud-Ice Scheme

To overcome these problems, a new scheme including cloud ice has been developed. Many ice-phase schemes used in NWP-models solve only one prognostic equation for cloud condensate. Hence, the distinction of the water and the ice phase has to be determined diagnostically. This is done by (i) prescribing the liquid fraction in the total condensate as a function f_l of temperature and (ii) assuming that both ice and water are in thermodynamic equilibrium with respect to a hypothetical saturation vapour pressure given by $e_s = f_l\, e_s^w + (1 - f_l)\, e_s^i$, where e_s^w and e_v^i are the saturation vapour pressure over water and ice, respectively.

The function f_l for the liquid fraction is usually chosen to be 1 for $T > T_0 = 0°C$ and 0 for temperatures below a threshold T_{ice} with a linear or quadratic decrease with temperature in the range $T_{ice} < T < T_0$. Various values for T_{ice} are assumed in different schemes, ranging from -15 $°C$ to - 40 $°C$. Observational data for the liquid fraction show a large scatter in the temperature range - 15 to $0°C$ (Ryan, 1996), and a climatology shown by Feigelson (1978) suggests that there is also plenty of supercooled water in the range - 15 to - 30 $°C$.

Ice-schemes with a prescribed liquid fraction are widely in use but have a number of conceptional drawbacks. First, the assumption of thermodynamic equilibrium of both water and ice at temperatures below T_0 is not in accordance with thermodynamic principles. Second, for $T < T_{ice}$ a saturation adjustment is done for the calculation of condensate; since the number of cloud ice crystals is very small, such an instantaneous adjustment has no physical basis. Third, effects from the Bergeron-Findeisen process cannot be considered explicitly, since the ice-phase is in thermodynamic equilibrium. Fourth, the Seeder-Feeder mechanism is not represented: deep clouds are more likely to be glaciated than thin clouds at the same temperature (Ryan, 1996). Also, ice falling from above into subfreezing layers is forced to melt in order to maintain the prescribed liquid fraction. This is not very realistic.

Bearing in mind these difficulties, the new LM parameterization scheme was designed to take into account cloud ice by a separate prognostic budget equation. Cloud ice is assumed to be in the form of small hexagonal plates that are suspended in the air and have no appreciable fall velocity. As a novel feature of the scheme, we formulate the depositional growth of cloud ice as a non-equilibrium process and require, at all temperatures, saturation with respect to water for cloud liquid water to exist. Ice crystals which are nucleated in a water saturated environment will then grow very quickly by deposition at the expense of cloud droplets. Depending on local dynamic conditions, the cloud water will either evaporate completely, or will be resupplied by condensation. For strong dynamical forcings it is expected that water saturation will be maintained, resulting in a mixed phase cloud. In case of a comparatively weak forcing, the cloud will rapidly glaciate to become an ice cloud existing at or near ice saturation (i.e. at subsaturation with respect to water). Figure 1 gives an overview on the hydrological cycle and the microphysical processes considered by the scheme.

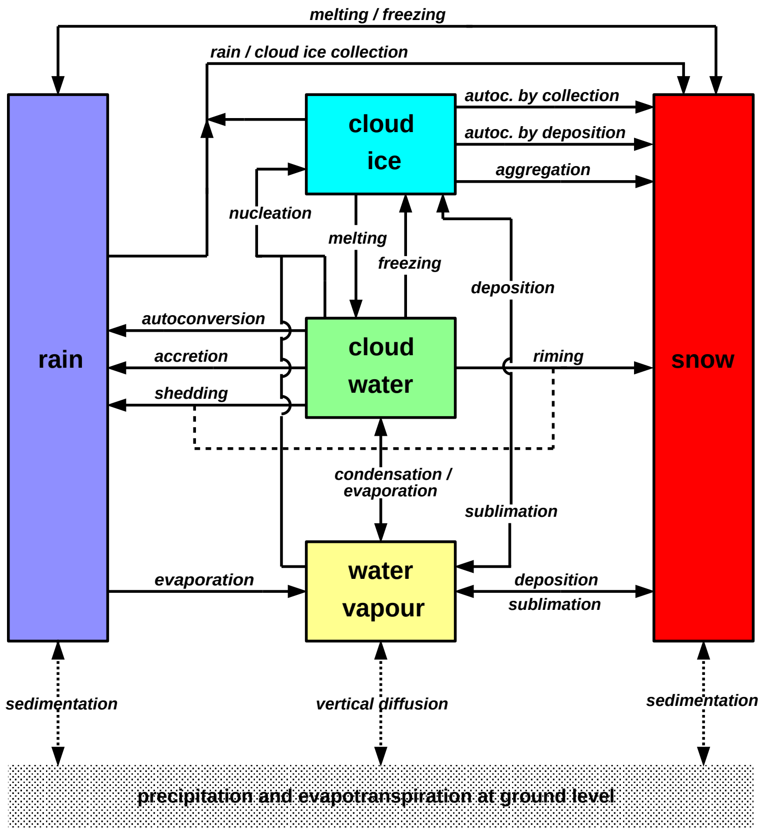

Figure 1: Hydrological cycle and microphysical processes in the LM cloud ice scheme

The explicit calculation of cloud ice depositional growth as a non-equilibrium process is based on the mass-growth equation of a single pristine crystal and requires some basic assumptions on the shape, size and number density of the ice crystals. Here, we assume a monodispers size distribution for cloud ice particles with the mean crystal mass

$$m_i \;=\; \rho q^i N_i^{-1}\,, \tag{2}$$

being diagnosed from the the predicted mixing ratio q^i and the number density N_i of cloud ice particles. The number density $N_i(T)$ of cloud-ice particles is prescribed as a function of ambient air temperature using the relation

$$N_i(T) \;=\; N_0^i \exp\{\,0.2\,(T_0 - T)\}\,, \qquad N_0^i \;=\; 1.0 \cdot 10^2 m^{-3}\,, \tag{3}$$

which is an empirical fit to data obtained by aircraft measurements in stratiform clouds (Hobbs and Rangno, 1985, and Meyers et al., 1992). For a given temperature, the experimental data may scatter by about two orders of magnitude. Nevertheless, we assume that (3) represents a meaningful average value for the cloud ice crystal concentration in cold stratiform clouds. Cloud ice crystals are assumed to be in the form of thin hexagonal plates with diameter D_i and thickness h_i, where the maximum linear dimension D_i is smaller than about 200 μm. This constant aspect ratio growth regime yields the following relation to calculate the size D_i of cloud ice particles from the diagnosed mean mass m_i,

$$D_i \;=\; (m_i)^{1/3}\,(a_m^i)^{-1/3}\,, \tag{4}$$

where $a_m^i = 130$ kgm^{-3}. A temperature dependency of the form factor a_m^i is neglected.

Using (2), (3) and (4) in the mass-growth equation for a single crystal, the total deposition rate of cloud ice, $S^i_{dep} = N_i \dot{m}_i / \rho$, may then be formulated by

$$S^i_{dep} = c_i \, N_i \, m_i^{1/3} \, (q^v - q^v_{si}) \tag{5}$$

in terms of ice supersaturation $q^v - q^v_{si}$ (or subsaturation for sublimation). The factor $c_i = 4G_i d_v \sqrt[3]{a_m}$ varies slowly with temperature and pressure due to the Howell factor G_i and the water vapour diffusivity d_v. Here, c_i is approximated by the constant value of $1.5 \cdot 10^{-5}$.

Cloud ice is initially formed by heterogeneous nucleation or homogeneous freezing of supercooled droplets. The latter process is parameterized by instantaneous freezing of cloud water for temperatures below $-37°C$. To formulate heterogeneous nucleation, we simply assume that the number of ice forming nuclei activated within a time step Δt is given by Eq. (3) and that the temperature is below a nucleation threshold (set to $-7°C$). We will also neglect nucleation whenever ice is already present since this has been found to be of minor importance. Recent field experiments show that ice nucleation is not likely to occur in regions of the atmosphere which are subsaturated with respect to water, except for very low temperatures. In the present version of the scheme we thus require water saturation for the onset of cloud ice formation above a temperature threshold T_d (set to $-30°C$). For temperatures below T_d, deposition nucleation may occur for ice supersaturation. All other conversion rates are parameterized in a similar way as in the operational scheme. For 3-dimensional advection of cloud ice, the positive definite Lin and Rood (1996) algorithm is used.

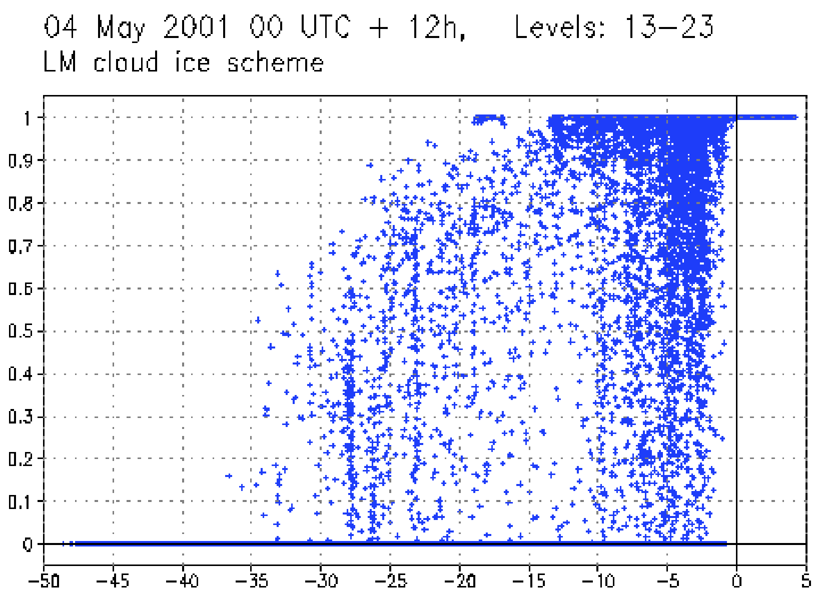

Figure 2: Variation with temperature of the liquid fraction for 4 May 2001 00 UTC + 12 h.

4 Preliminary Results

The LM cloud ice scheme has been tested for a number of case studies. Figure 2 shows the variation with temperature of the liquid fraction $f_l = q^c/(q^c + q^i)$ generated by the scheme. The values of f_l were obtained from a single time step after the model was run for 12 h starting from the 4 May 2001 00 UTC analysis. For temperatures warmer than about $-10°C$, there are cloudy grid-boxes which are composed of either liquid water or ice, and there is a large number of boxes indicating a mixed phase state. Below $-10°C$, there is still a large number of mixed phase clouds with supercooled droplets, but the liquid fraction drops off with temperature. Below about $-35°C$ only ice clouds exist. There is a good qualitative agreement with the observations for stratiform clouds (Ryan, 1996), but the model indicates a larger number of mixed phase clouds for temperatures below about $-15°C$. A reason for this behaviour is that in Figure 2 not only stratiform clouds but all cloudy grid points are counted. For the convective 4 May 2001 case, a large number of gridpoints from anvils and embedded cold frontal convection contribute to the scatter plot. At such points, strong dynamical forcing can keep the air at water saturation allowing for mixed phase clouds at low temperatures. This example shows also that with the new scheme the liquid fraction adjusts reasonable in response to dynamical forcing and microphysical processes.

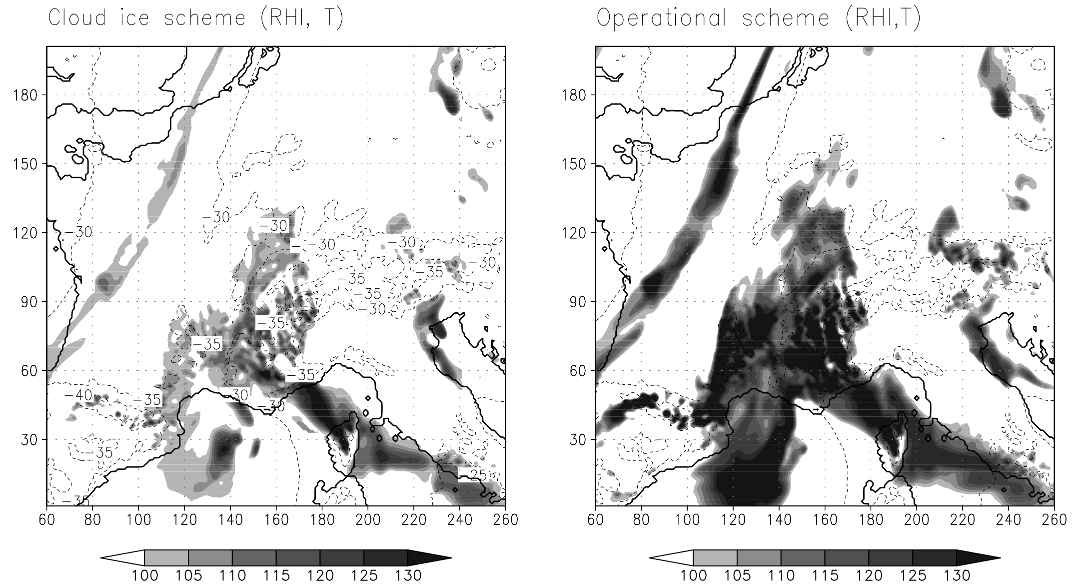

Figure 3: Relative humidity over ice (shaded, in %) and temperature ($°C$, isolines) for 4 May 2001 00 UTC + 12 h at model level 14. Left: cloud ice scheme. Right: operational scheme.

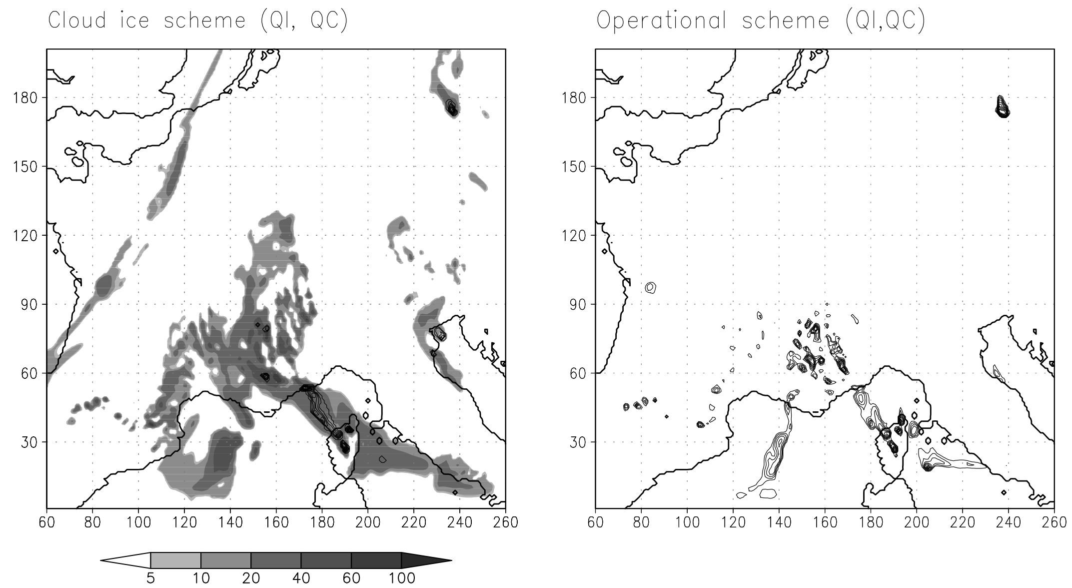

Figure 4: As in Fig. 3 but for specific cloud ice content (shaded, in mg/kg) and cloud water content (isolines at 10 mg/kg intervals).

There is also a large impact to the humidity structure of the upper atmosphere. To illustrate this, the relative humidity over ice obtained from runs with the cloud ice and the operational scheme is shown in Figure 3 for the same case and forecast time. Figure 4 displays the corresponding specific cloud ice and cloud water contents. The fields are plotted for a model subdomain at level 14, corresponding to a height of about 7000 m with temperatures ranging from -30 to $-40°C$. The operational run reveals high ice supersaturation of about 20 - 40 % in two regions: a band-like structure over western France which is associated with a cold front, and a more unstructured region in the warm sector ahead of the front. Here, widespread deep convection occurs which by vertical transport generates and maintains high humidity.

With the operational scheme, there is no ice but only cloud water by definition (Fig. 4, right). Since saturation with respect to water is required for grid-scale cloud formation, cloud water is found only at those gridpoints where dynamic forcing by convection drives the atmosphere to water saturation (at a temperature of $-35°C$, this will occur at about 35 % ice-supersaturation). However, these points are rather scattered whereas satellite images indicate a region of merged anvils above the northern Mediterranean Sea and southern France (not shown). This high level cloudiness is simulated much more realistic by the cloud ice scheme (Figures 3 and 4, left). Here, cloud ice is initially formed also at gridpoints which are at or near water saturation. Subsequently, however, it can be advected into regions which are ice-supersaturated but are below water saturation. In these regions, cloud ice will continue to grow by vapour deposition, thereby reducing the humidity to values more close to ice saturation (Fig. 3, left). Thus, a much larger region with grid-scale anvils – mostly composed of ice – is simulated than with the operational scheme. In the warm sector region, some mixed-phase clouds do also exist at gridpoints, where strong convective forcing maintains water saturation. Also, high-level ice clouds appear along cloud front.

Besides such single case tests, the new scheme was run in a parallel forecast suite with full data assimilation for two three-week periods in winter and spring 2002. The verification against radiosonde data showed a significant positive impact on temperature (reduction of a negative bias) and on relative humidity (reduction of a strong positive bias in the upper troposphere) when compared to the operational runs. The verification of parameters from surface observations revealed a neutral (precipitation) to slightly positive (2-m temperature) impact of the ice-scheme – except for high-level cloudiness which is increased to too high values. This deficiency is expected to be cured by future fine-tuning of the scheme.

5 Summary and Plans

A new microphysics parameterization scheme including cloud ice has been developed and successfully tested in LM. The main advantage of the scheme is a more physically based representation of ice and mixed-phase clouds, allowing for a direct simulation of cloud glaciation. The phase composition of high-level clouds appears to be well captured, which is important for a better cloud-radiation interaction. And in particular, the formation, growth and spreading of grid-scale anvil clouds can be simulated explicitly.

Following further testing it is planned to introduce the cloud ice scheme operationally in spring 2003. To provide consistent boundary conditions from the driving model, the scheme has also been implemented in our global model GME. A rerun of a one-year period during 2001/2002 revealed an overall benefcial impact of the cloud ice scheme, with a significant reduction of current imbalances in the average radiation an water budgets.

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