A Prognostic Cloud Ice Scheme for NWP-Models

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Most grid-scale cloud 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 for temperatures below the freezing point $T_0 = 0°C$. This is usually done by (i) prescribing the liquid fraction in the total condensate as a function f_l of temperature and (ii) assuming that both cloud ice and cloud 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 $T > T_0$ 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 $-40°C < T_{ice} < -10°C$ are assumed in different schemes.

A class of cloud schemes simply neglects the cloud ice phase ($f_l = 1$ for all temperatures) as for instance done in the operational schemes of the global model GME and the regional model LM of DWD. This strategy, however, results in a wrong thermodynamic state of cirrus clouds (always water clouds at water saturation) with corresponding errors the cloud-radiation feedback, and in a large positive bias of upper-level humidity. On the other hand, ice-schemes with a prescribed temperature dependent liquid fraction have also 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 physical 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. And fifth, ice falling from above into sub-freezing layers is forced to melt in order to maintain the prescribed liquid fraction – this is not very realistic.

Bearing in mind these difficulties, a new parameterization scheme was designed to take into account cloud ice and cloud water by a separate prognostic budget equations. 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. The explicit calculation of cloud ice depositional growth is based on the mass-growth equation of single pristine crystals. By prescribing cloud ice particles as thin hexagonal plates with a monodispers size distribution, the total growth rate of cloud ice mixing ration q_i due to deposition (sublimation) may then be derived as

$$(\dot{q}_i)_{dep} \;=\; c_i\,(N_i)^{2/3}\,(\rho q_i)^{1/3}\,q_v^{si}(\,S_i - 1,) \qquad (1)$$

in terms of the ice-supersaturation (subsaturation) $S_i = q_v/q_v^{si}$, where q_v is the specific humidity and q_v^{si} is its saturation value over the ice. c_i is a slowly varying function of temperature and pressure, which is approximated by a constant value of of $1.5 \cdot 10^{-5}$ (in corresponding SI-units). The number density $N_i(T)$ of cloud-ice particles is parameterized as a function of air temperature using the relation $N_i(T) = N_0^i \exp\{\,0.2\,(T_0 - T)\}$ with $N_0^i = 1.0 \cdot 10^2 m^{-3}$, which is an empirical fit to available data from aircraft measurements in stratiform clouds. 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 $-37°C$. For heterogeneous nucleation, we simply assume that $N_i(T)$ ice forming nuclei with a very small initial mass are activated within a time step and that the temperature is below a nucleation threshold (set to $-7°C$). According to results from field experiments, we require water saturation for the onset of cloud ice formation above a temperature threshold T_d (set to $-25°C$). For temperatures below T_d, deposition nucleation may occur for any ice supersaturation. All other conversion rates are parameterized in a similar way as in standard cloud microphysics schemes.

Ice crystals which nucleate in a water saturated environment will grow very quickly by vapour deposition due to a high ice supersaturation S_i according to (1). Depending on local thermodynamic conditions, the existing cloud water will either evaporate completely, or will be resupplied by condensation. The first case is expected for weak dynamical forcings, where the initial mixed-phase cloud will rapidly glaciate to become an ice cloud existing at or near ice saturation. The second case is expected for strong dynamical forcings along fronts or in the vicinity of convection, where water saturation with mixed phase clouds can be maintained. Thus, the liquid fraction will physically adjust and an empirical specification is not required. Moreover, precipitation enhancement mechanisms such as the Bergeron-Findeisen or the Seeder Feeder process are represented explicitly and additional parameterizations are avoided.

A first tentative validation with the global model GME running in 'climate' mode revealed that the inclusion of cloud ice greatly improves the outgoing longwave radiation due to different radiative properties of cloud ice compared to cloud water. Meanwhile, a parallel test suite including data assimilation has been established. First verification results show slightly improved scores for 2m-temperature and 500 hPa geopotential height correlation, and a better representation of the upper-level humidity and cloud structures. As an example, Figure 1 compares the relative humidity over water at 250 and 500 hPa resulting from 24-h GME runs with the operational and with the cloud-ice scheme. At the 250 hPa level, the routine scheme results in unrealistic high humidities close to water saturation in equatorial and mid-latitude regions associated with tropical convection and frontal systems, respectively. With the cloud-ice scheme, the relative humidity is significantly reduced in these regions – down to values around 60-70%, which indicate ice-saturation. Only for a few gridpoints in tropical regions or along frontal clouds mixed-phase at water saturation are simulated. At the warmer 500 hPa level, the spatial distribution of relative humidity from the two forecasts is very similar – except for cold high latitude regions, where cloud-ice scheme again results in a drastic reduction of relative humidity.

Given a successful completion of the test suite, an operational introduction of the cloud-ice scheme is scheduled for May 2003. At the same time, the new scheme will also be switched on in the regional model LM as well as in LMs at MeteoSwiss (Switzerland), ARPA-SMR (Italy), HNMS (Greece) and IMGW (Poland), and in ten HRMs running world wide.

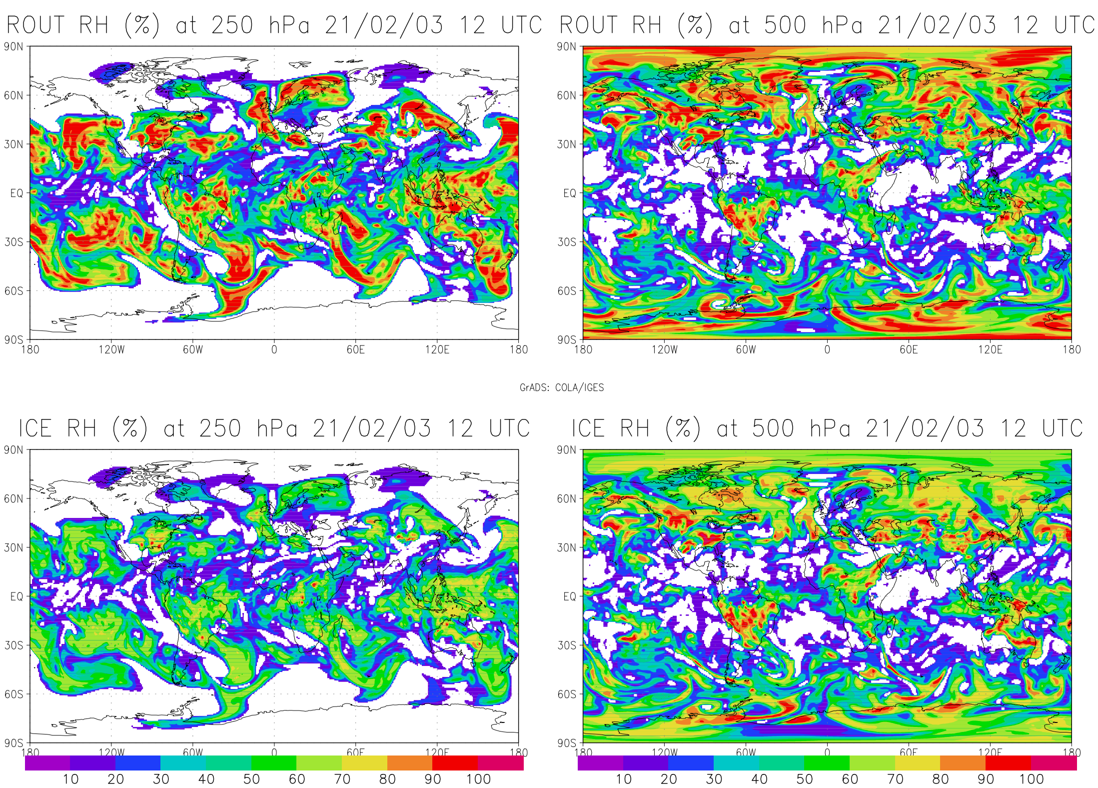

Figure 1: Relative humidity at 250 hPa (left) and 500 hPa (right) for theoperational cloud scheme (top) and the new cloud-ice scheme (bottom). 24-h GME forecasts starting from 20 February 2003 12 UTC.