Recent Changes to the Cloud-Ice Scheme

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1 Introduction

Ice-phase processes play a significant role in mid-latitude frontal cloud systems and their impact should be taken into account by parameterization schemes. Since liquid water and ice cannot coexist in thermodynamic equilibrium below the freezing point, three cloud states can be realized in this temperature range, depending on the local supersaturation with respect to ice (see Fig. 1):

– supercooled water clouds, existing at (or very close to) water saturation;
– mixed phase clouds, also existing at water saturation;
– ice clouds, existing at water subsaturation but ice supersaturation.

Mixed phase clouds at subfreezing temperatures allow for precipitation enhancement, where two mechanisms 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 (Seeder) cloud into a lower (Feeder) cloud containing supercooled droplets; in this case, the droplets within the Feeder cloud will be also converted into precipitating ice by riming in addition to the collision-coalescence

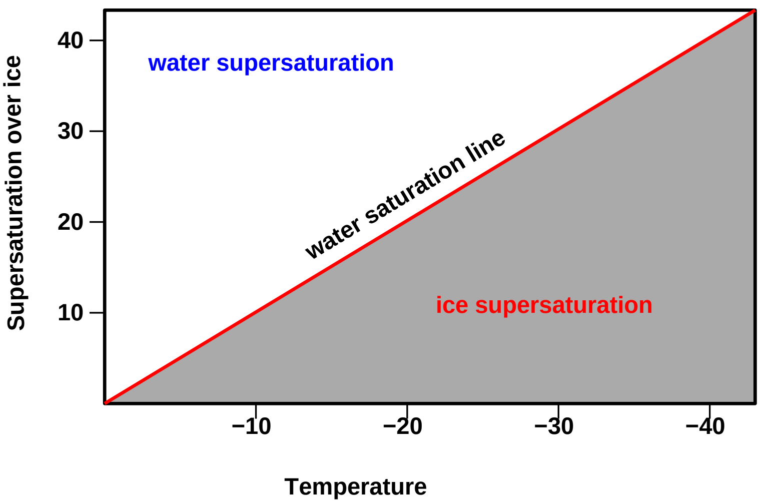

Figure 1: Supersaturation with respect to ice for a water-saturated state (red line) as function of subfreezing temperature. Both supercooled water clouds and mixed phase clouds exist at water saturation due to the presence of cloud droplets in equilibrium with water vapour. For specific humidities above or at ice saturation, but below water saturation, only ice clouds can be present (shaded area).

based warm rain precipitation formation. This results in a more efficient removal of cloud water and correspondingly higher precipitation rates than from both the Seeder and Feeder clouds alone.

The default (and former operational) parameterization scheme for grid-scale clouds and precipitation (HYDOR) is based on a Kessler-type bulk formulation where four categories of water substance are considered: water vapour, cloud water, rain and snow. Both the Bergeron-Findeisen process and the Seeder-Feeder mechanism are represented explicitly by this scheme through processes related to snow. 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 water or mixed phase clouds but no ice clouds are simulated below freezing point.

(b) The cloud ice-phase is neglected by assuming a fast 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.

To overcome these problems, a new scheme including cloud ice (HYDCI) in addition to the other categories, namely water vapour, cloud water, rain and snow, has been developed.

2 Parameterization Concept and Microphysical Processes

Many ice-phase schemes used in NWP-models solve only one prognostic equation for cloud condensate and the distinction of the water and the ice phase has to be determined diagnostically by assuming a prescribed liquid fraction as function of temperature. Such schemes have a number of conceptional drawbacks and rely on strange thermodynamic assumptions. Thus, the new LM parameterization scheme was designed to take into account cloud ice by a separate prognostic budget equation (Doms and Schättler, 1999; Doms, 2002). 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 with efficient formation of precipitation due to the Bergeron Findeisen process. In case of a comparatively weak forcing, however, 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 2 gives an overview on the hydrological cycle and the microphysical processes considered by the scheme.

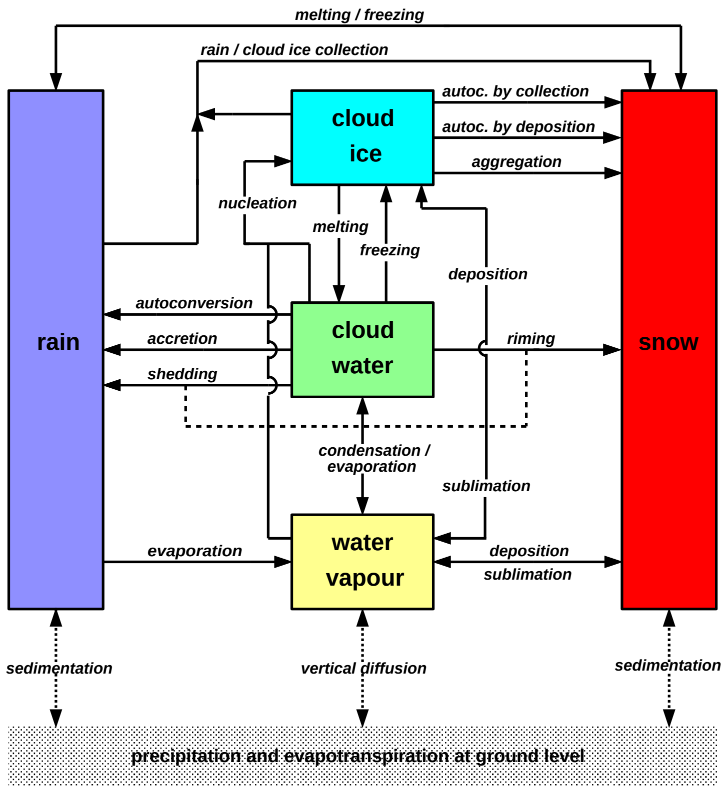

Figure 2: Hydrological cycle and microphysical processes in the LM cloud ice scheme

Since the Bergeron Findeisen process as well as cloud glaciation is described explicitly, no further parameterizations such as a liquid fraction are required and the cloud state will adjust freely to microphysical and dynamical forcings on a physical basis. Thus, the resulting cloud ice content will depend on the strength of the dynamical forcings maintaining ice supersaturation (mainly vertical ascent and radiative cooling) and the characteristic time scale of microphysical processes which decrease or increase cloud ice content. These time scales depend on details in the parameterizations of the microphysical conversion rates, and a variation of the rate coefficients within physical limits can be used to optimize the scheme for achieving a better cloud-radiation interaction. This type of tuning effort is described in the next section.

3 Some Modifications of the Scheme

The new cloud-ice scheme has been tested for a number of case studies as for extensive parallel suites of GME and LM during all seasons including data assimilation and forecasts. These test reveal a reasonable behaviour of the scheme with an improvement of the upper level humidity structure. Especially, the formation of high-level cirrus ice clouds due to vertical motion associated with fronts or due to deep convective forcing is represented explicitly. However, the test test suites with the GME/LM system indicated two major problems:

- The cloud ice content appears to be too high, especially in the tropics and in polar regions.
- There is substantial increase in high level cloudiness in LM, when compared to SYNOP observations.

A number of sensitivity experiments have been performed to cure these deficiencies. First, we focus on empirical parameters in microphysical conversion rates controlling the cloud-ice content. As a test case, we choose 8 September 2002, where high-level cirrus clouds related to a frontal system moved over France and Germany.

(a) Modification of Ice-Crystal Number Density

The depositional growth rate of specific cloud ice content q^i is calculated explicitly from

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

where N_i is the number density of cloud ice, $m_i = \rho q^i N_i^{-1}$ is the mean mass of ice crystals, c_i is a thermodynamic factor depending on the shape of the crystals, q^v is specific humidity and q^v_{si} is the specific humidity at ice saturation. The number density N_i is prescribed as a function of temperature according to

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

N_i is a disposable empirical parameter, and Eq. (2) was derived by fitting data obtained by aircraft measurements in stratiform clouds (Hobbs and Rangno, 1985; Meyers et al., 1992). Other schemes often use the classical Fletcher relation (Fletcher, 1962)

$$N_i^F \; = \; N_0^F \exp\{\, 0.6\,(T_0 - T)\} \, , \qquad N_0^F \; = \; 0.01 m^{-3} \, , \tag{3}$$

which gives about 3 orders of magnitude higher values for the ice crystal number density at low temperatures of about -40 °C and about two orders of magnitude lower values at high temperatures of about -10 °C. Interestingly, the cloud ice content changes not very on much on average despite these large differences. Fig. 3 (middle) compares the vertical distribution of domain and time average cloud ice content for two formulations of the autoconversion rate. The impact of using Eq. (3) instead of (2) is relatively small, the Fletcher relation results in somewhat higher values a all model levels. Smaller values for N_i than from Eq. (2) would reduce the average cloud ice content somewhat, but smaller number densities can

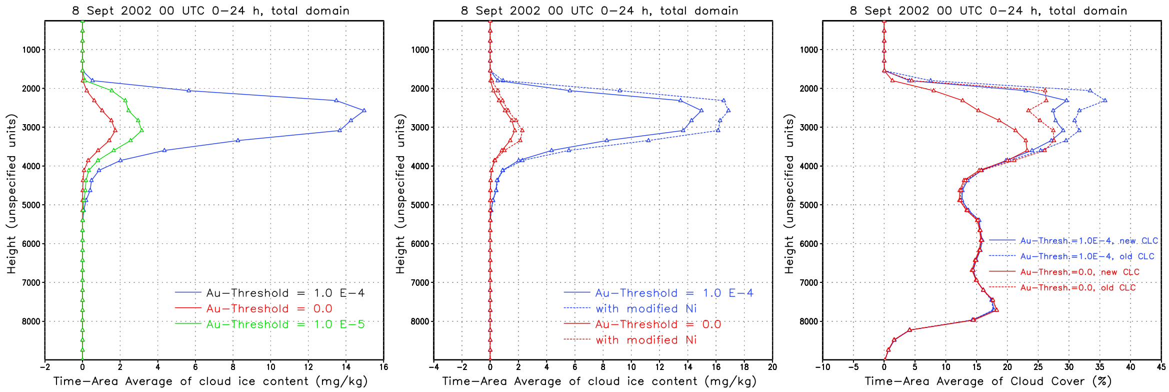

Figure 3: Left: Vertical distribution of domain and time averaged cloud ice content on model layers for three values of the autoconversion threshold value as indicated. Middle: Vertical distribution of domain and time averaged cloud ice content on model layers for two autoconversion threshold values as indicated, using the standard equation (2) for N_i and the modified equation (3). Right: Vertical distribution of domain and time averaged cloud cover, using the former and the modified diagnosis of cloud cover. All figures refer to a LM simulation starting on 8 September 2002 00 UTC, the time average is from 0 to 24 hours integration time.

hardly be justified from observations. We thus still rely on the Eq. (2) to parameterize N_i in the cloud ice scheme.

(b) Modification of Ice Autoconversion

Other disposable empirical parameters controlling the cloud-ice content are the coefficients in the autoconversion rate S^i_{au} of ice to snow (due to crystal aggregation):

$$S^i_{au} = \max\{c^i_{au}\,(q^i - q^i_0)\,,\,0\}\,. \qquad (4)$$

Here, q^i_0 is a threshold value of specific cloud ice content which is set to 10^{-5} kg/kg by default. The rate coefficient is set to $c^i_{au} = 10^{-3}$ s^{-1} for cloud ice and corresponds to a decay time scale of 1000 s which gives a rather quick conversion of cloud ice into snow. Since we do not want to further decrease this time scale because of physical reasons, the threshold value was varied in sensitivity experiments. Increasing the default threshold to $q^i_0 = 10^{-4}$ kg/kg resulted in a dramatic increase of the average cloud ice content, whereas a reduction resulted in smaller ice contents. For $q^i_0 = 0$ kg/kg, the average cloud ice content is reduced by about a factor of two (see Fig. 3, left) on all model levels. Additional experiments with GME for various combinations of q^i_0 and c^i_{au} revealed best results with the standard value $c^i_{au} = 10^{-3}$ s^{-1} and $q^i_0 = 0$ kg/kg by evaluating the radiation balance at the top of the atmosphere and at the surface as well as the bias of near-surface temperatures. Thus we switched to a zero threshold value in the cloud-ice autoconversion rate for the operational application.

(c) Modification of Cloud-Cover Diagnosis

The problem of high-level cloudiness could be tackled by rescaling the cloud cover (both grid and sub-grid scale) which is diagnosed in terms of relative humidity and grid-scale cloud ice. Usually, the cloud cover is set to 100 % whenever cloud ice exists, otherwise a fractional cloud cover and a sub-grid scale cloud ice content are diagnosed. However, below a certain threshold value (q^i_{min} = 0.1 mg/kg) cirrus clouds are not detectable by a ground-based observer. If the cloud ice content exceeds q^i_{max} = 10 mg/kg, the impact on the visible part of the radiation spectrum is so large that the sky appears to be obscured by high clouds. In between these two values, the cloud cover obtained from standard diagnosis (clc_d) is now rescaled by an empirical function f_s which depends logarithmically on cloud ice content to

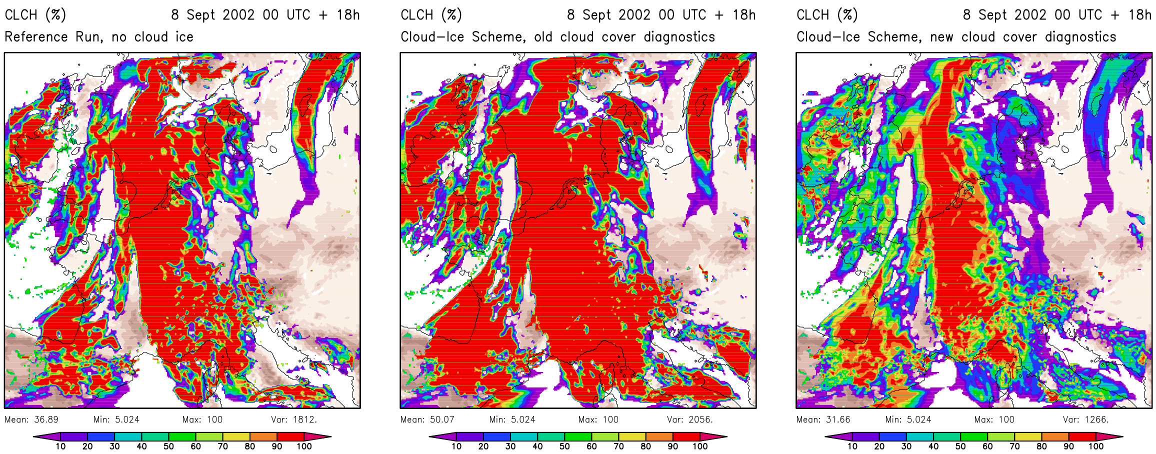

Figure 4: 18-h LM forecast of high cloud cover (%) valid at 18 UTC on 8 September 2002. Left: Reference run using the old cloud microphysics scheme (no cloud ice). Middle: Run using the cloud ice scheme but with standard cloud cover diagnosis. Right: Run using the cloud ice scheme but with modified cloud cover diagnosis.

give the final cloud cover clc:

$$clc = clc_d \cdot f_c\,, \quad f_c = \min\left(1\,,\ \max\left\{0.2\,,\frac{\ln q^i - \ln q^i_{min}}{\ln q^i_{max} - \ln q^i_{min}}\right\}\right) \tag{5}$$

The introduction of the scaling factor f_c results in significant reduction of high-level cloud cover when compared to the standard diagnosis (see Fig. 4, right). The spatial distribution now corresponds better to both the results from the old microphysics scheme and to ground based observations at SYNOP stations (see Section 4).

4 Verification Results of GME/LM Testsuites

The cloud-ice scheme has been tested in extensive parallel suites of GME and LM including data assimilation. The verification of this test suites generally showed only modest improvements of forecast accuracy over the operational model versions.

(a) Vertical Profiles

The verification of vertical profiles of LM forecasts for a test suite during May 2003 using the cloud ice scheme with modified ice-autoconversion reveals an almost neutral impact for wind and geopotential with a slightly reduced temperature bias. A more noticeable improvement

Routine Experiment

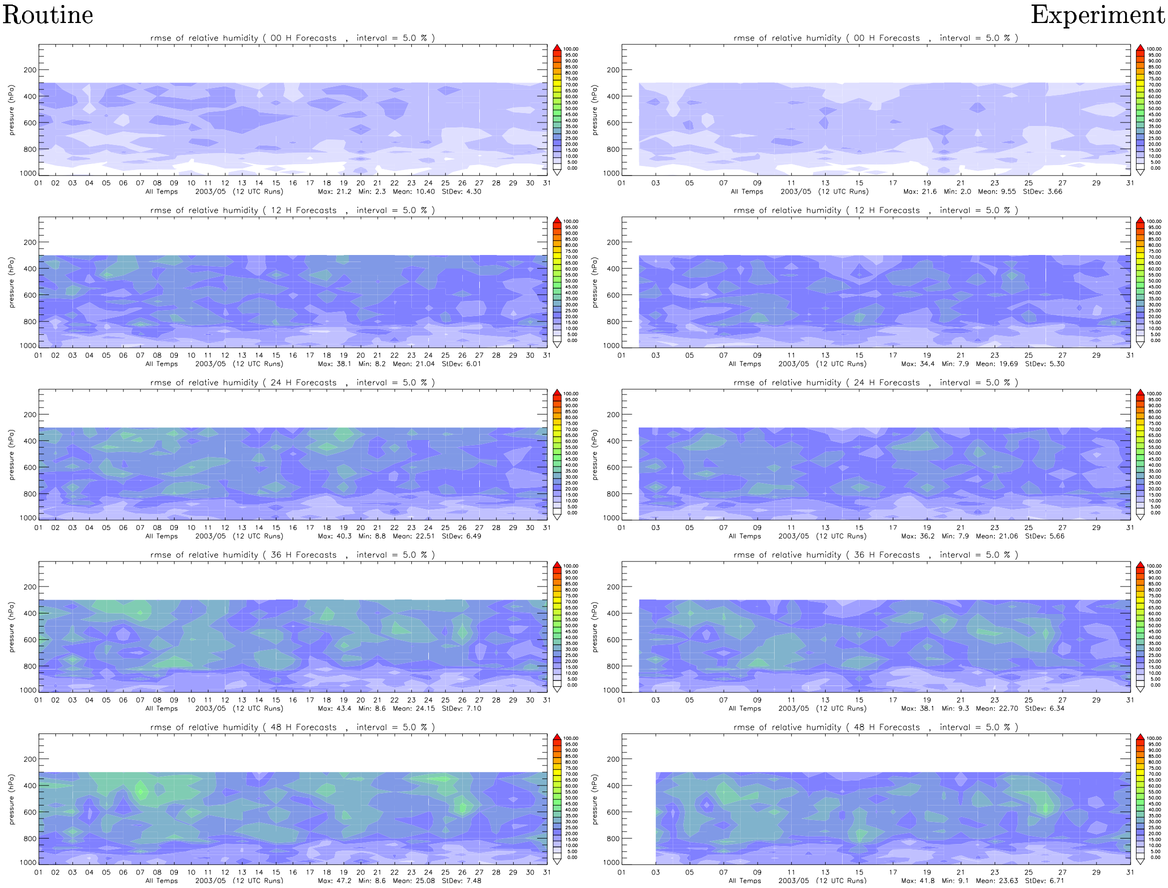

Figure 5: Time Series (1 - 31 May 2003) of relative humidity RMS errors for 12 UTC LM forecasts against radiosonde data. From top to bottom: Analysis, 12-h, 24-h, 36-h and 48-h forecast time. Left: operational runs at DWD without cloud ice. Right: Runs with cloud ice using the modified autoconversion rate with zero threshold.

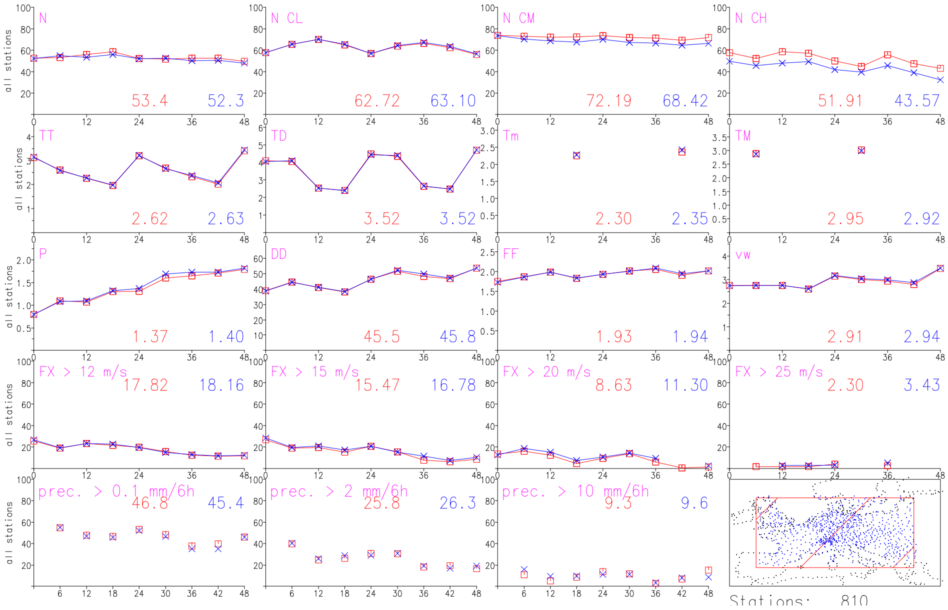

Figure 6: Verification of forecasts for local weather elements from operational LM 12 UTC runs (red) and from experimental runs with cloud ice (blue) using the modified autoconversion rate but the old cloud cover diagnosis, against SYNOP observations for 2 - 31 May 2003 as a function of forecast time. Percent correct for cloud covers (top row: total (N), low (NCL), medium (NCM) and high (NCH) cloud cover), TSS for precipitation (bottom row, for 6-h precipitation amounts above indicated thresholds), ETS for wind gusts (4th-row, for gusts (FX) above indicated thresholds), RMS errors for other elements (2nd row: 2m-temperature (TT), 2m dew-point (TD) , minimum 2m- (Tm) and maximum 2m-temperature (TM); 3rd row: mean sea-level pressure (P), 10m wind direction (DD), 10m wind speed (FF) and 10m wind vector (vw).

is found for relative humidity. Fig. 5 shows the root mean square (RMS) error for the test period for analysis and various forecasts times. Between 300 hPa and 600 hPa (i.e. for temperatures well below 0 °C), the RMS errors are significantly reduced in the analysis and for all forecast ranges when compared to the verification of the operational runs. Similar results are found from the GME verification.

(b) Surface Weather Elements

The verification of predicted surface weather elements of a test suite for May 2003 using the cloud ice scheme with modified ice-autoconversion and the standard (old) cloud cover diagnosis showed an almost neutral impact for all elements, except for high-level cloudiness (see Fig. 6): The percent correct value for high-level clouds decreases noticeable for all forecast ranges, from 51.9% to 43.6% on average. This result was the reason for introducing a modified cloud cover diagnosis as proposed by Eq. (5). Using this new diagnosis, another test suite for a period in September 2003 was run. The verification results shown in Fig. 7 reveal a significant improvement of the predicted high-level cloudiness, which now has a better score than from the operational runs. Interestingly, noticeable improvements are also achieved for 2m-temperature, 2m dew point temperature and precipitation.

5 Summary and Outlook

A new microphysics parameterization scheme including cloud ice has been developed and successfully tested in GME and LM. Since 16 September 2003, this new scheme is used operationally in both models at DWD, as well as in all LM applications at COSMO Centres

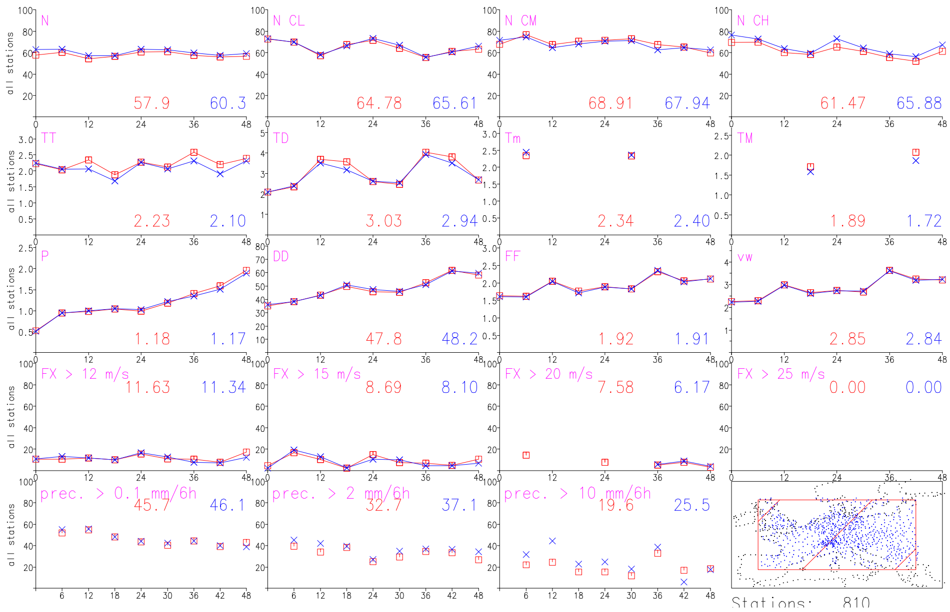

Figure 7: As in Fig. 6, but for a test period from 1 - 9 September 2003 using the new cloud cover diagnosis (5).

and in the HRM (High-resolution regional model) of DWD, which is used operationally at more than 13 national weather services world wide.

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.

Further fine-tuning of the cloud-radiation interaction and the present interpretation of fractional cloudiness for low cloud ice content might be necessary. Also, further improvements or optimizations of cloud microphysical conversion rates are possible. Another issue for future work is the inclusion of sub-grid scale sources of cloud ice due to detrainment of ice from parameterized convective clouds. In context with the introduction of prognostic precipitation within the operational Leapfrog time-integration, the source terms have been reformulated with the mixing ratios instead of the precipitation fluxes and a stable numerical scheme for precipitation fallout has been formulated.

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