Development of a Kilometer-Scale NWP-System: LMK

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1 Overview

For very detailed short range forecasts, the Deutscher Wetterdienst (DWD) has started the development of a meso-γ version of the operational nonhydrostatic regional model LM. This new version, called LMK, will utilize a grid-spacing of 2-3 km with about 50 vertical layers and an integration domain of about 1300 x 1300 km^2 (see Fig. 1). LMK is aiming at the explicit prediction of deep convection and will provide 18-h forecasts for Germany eight times per day based on all observations available, including satellite and radar data. The development work is organized by an internal 3-years project from end 2003 to end 2006, with the operational implementation of the LMK system scheduled for late 2006. This project is embedded in a DWD programme (Aktionsprogramm 2003) aiming at an improvement of global and regional forecast systems and products.

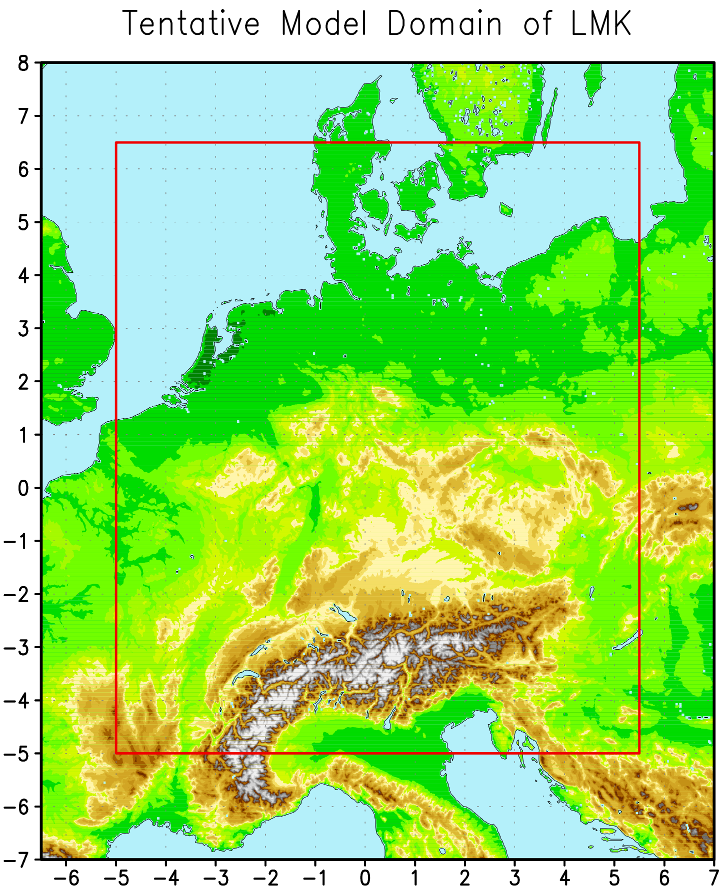

Figure 1: Tentative integration domain for LMK (red frame) with respect to a rotated lat-lon coordinate system (North pole at 40° N and 170° W). Using a grid-spacing of 2.8 km results in 421×461 grid points.

2 Background

With the new system, it is intended to fill the gap between traditional nowcasting methods for severe weather events (up to 3-6 hrs) and current short-range NWP with grid spacings of about 10 km and forecast ranges up to 48-72 hrs. In the time range of 18 hrs severe weather often forms in context with deep moist convection (such as super- and multi-cell thunderstorms, squall-lines, mesoscale convective complexes and mesocyclones) or due to interactions with fine-scale topography (such as fog, severe downslope winds, Föhn-storms, flash-floodings, etc.). As these events cannot be resolved with the resolution of present models, their prediction is in general very poor. However, there is a strong public demand for improved weather forecasts at finer scales and shorter ranges. An accurate prediction of extreme rainfall events or severe wind gusts in both time and space is especially required for hydrological, civil protection and environmental agencies to issue adequate warnings.

We expect a number of potential benefits of running a forecasts model routinely with a grid spacing better than 3 km on a quite large domain (to keep some internal predictability), since many more mesoscale weather systems and their scale interactions including local topographical effects can be properly resolved. Such a resolution will allow to simulate deep convective clouds directly and many deficiencies introduced by parameterized convection are removed. This means that the life-cycle of individual clouds can be represented in detail together with dynamic interactions and organization, resulting in features like supercell and squall-line formation or storm-cell initiation by gust fronts. It is expected that this will allow for much more realistic and hopefully more accurate forecasts of severe weather events.

3 Project Structure

Deriving the convective-scale LMK from the LM requires not only an adjustment of the existing schemes but also a development of new components within data assimilation, dynamics and numerics, physical parameterization, verification and validation. The project structure is organized along these points into four basic work packages (see below). Five new staff members are in employment on the project and additional support comes from collaboration within COSMO. Also, a more close collaboration is planned with NWP groups working on similar systems (ALADIN, UK-MetOffice, HIRLAM and WRF).

Work Package:	Main Issues
Radar Data	– Correction methods and quality control of 5-min DX-scans, – Generation of a 5-min DX composite using European radar sites, – Use of radar wind in the LMK assimilation cycle.
Latent Heat Nudging:	– Investigation of the latent heat nudging algorithm of LM, – Improvement and modification of the scheme to achieve a "long-lasting" impact of radar information.
Model Development	– Numerical Methods and basic model dynamics – Physical parameterization schemes – Lateral boundary conditions – Test Cases, sensitivity studies, model intercomparisons – Installation and evaluation of a LMK test suite
Verification	– Provision of model-derived remote sensing data (radar simulation model, pseudo satellite radiances) – Application of new verification methods (pattern recognition) – Standard surface and upper-air verification

4 Current Work and Plans

With respect to numerics, current work focuses on the implementation of a TVD-variant of the 3rd-order in time Runge-Kutta time integration. The scheme can easily be combined with the standard time-split forward-backward methods to integrate fast compression waves and furthermore allows for flexible use of high-order spatial advection operators. From the latter, we expect noticeable benefits for simulating processes such as deep convective cloud evolution which is at or close to the grid-scale. Using a 5th-order advection scheme, the new scheme allows for a time step almost twice as large as with the standard Leapfrog/2nd-order centered differencing scheme of LM. This advantage is somewhat reduced since the advection operator has to be calculated three times. The main reason for applying the new time scheme, however, is not to save CPU-time but to achieve a more accurate and thus much better converged numerical solution at neutral computational costs. For first results from the RK3 time integration see the paper by Förstner and Doms in this volume.

The equations for the hydrological cycle have also to be reconsidered for very high spatial resolution, since advective transport of precipitation particles (like rain and snow) may no longer be neglected as it is done in current schemes. Hence, the present diagnostic treatment of precipitation has to be replaced by an algorithm based on the full 3-d budget equations for rain and snow. For LMK and LM, a numerical algorithm to solve these prognostic equations has been constructed by combining a 3-d semi-Lagrangian advection scheme with an implicit treatment of precipitation fallout (see paper by Baldauf and Schulz, this volume) using a Marchuk time splitting technique. Tests of the scheme indicate that the horizontal transport of snow is essential for correcting an erroneous spatial distribution of precipitation of orographically forced rainfall in case of stable stratification. In case of high-resolution applications, the vertical advective transport of precipitation will be of crucial importance for describing the life-cycle of deep convective storms correctly.

Considering physical processes on the meso-γ scale, parameterization issues related to deep convection and gravity waved drag will disappear due to a direct simulation of these processes. Shallow convection, however, will still remain sub-grid scale and can play a significant role for initiating deep convection. At present, it is not clear if standard global-scale convection schemes based on steady-state plume cloud models with a moisture- or moist static energy convergence closure can cope with shallow convection at very high resolution. We plan to develop a shallow-convection scheme based on a dynamic cloud model, which allows for an explicit calculation of entrainment and detrainment, and a closure based on PBL turbulent kinetic energy.

Remaining parameterized physical processes are turbulent mixing, microphysics, radiation and surface fluxes. For the latter two, we initially rely on the standard parameterization used in LM. Turbulent transport becomes essentially 3-d at very high resolution, e.g. lateral exchange across cloud boundaries will be important for the evolution and organization of deep convection. A new 3-d turbulence scheme based on turbulent kinetic energy using a non-isotropic closure for fluxes has been developed (Herzog et al., 2003) and is currently implemented. A more comprehensive treatment of the ice-phase is also important when simulating deep clouds directly. In this aspect, we will upgrade the present microphysics scheme to include graupel (and later on hail) as an additional precipitation category.

It is planned to run the LMK every 3 hours from a continuous data assimilation stream based on the LM observational nudging technique (Fig. 2). Such a rapid update cycle will require a short data cut-off (less than 30 min) and the successful use of available non-synoptic remote sensing data. In this respect, the assimilation of radar reflectivities using the latent heat nudging (LHN) technique is under evaluation (see the paper by Klink and Stephan, this volume) and satellite data will be assimilated by using profiles obtained with 1-D var retrievals. The LHN will be based on 5-min reflectivities, which requires the development of corresponding data correction algorithms and data quality control methods as well as the development of a European composite.

Verification and validation of high-resolution model forecasts is very difficult as representativity errors, spatial and temporal variability, and lack of suitable data become important - resulting in a less meaningful applicability of traditional quantitative scores. In the LMK project, we will focus on the use of a radar simulation model (to compare directly with radar measurements) and pseudo satellite images in various channels, combined with new verification tools such as pattern recognition methods. These activities go along with the development of appropriate diagnostic tools and derivation of necessary products for customers.

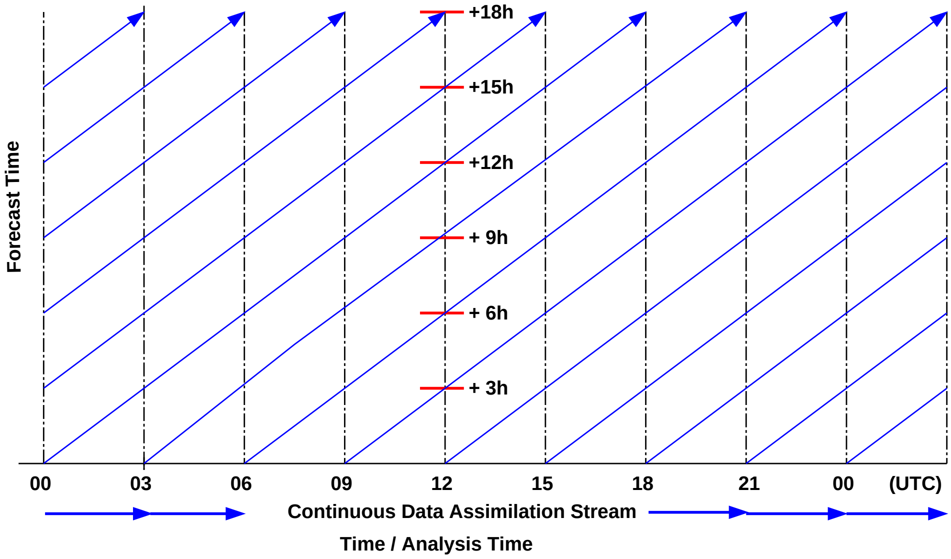

Figure 2: Planned update/forecast cycle with forecasts every 3 hours (right). At a given time, 6 forecasts are available, allowing to generate some lagged averaging ensemble products.

5 A First LMK Test Suite

In order to investigate the general behaviour of the LM at the meso-γ scale, a first test suite has been installed at DWD. Some preliminary case studies on a number of convective situations have shown a certain skill of the model to predict severe weather conditions as e.g. squall-line formation at the presence of large scale forcing (Doms et al., 2002). The behaviour of the model for 'normal' non-convective situations, however, is not yet known and a number of deficiencies and problems may be present. The LMK test suite aims at the detection of such problems at an early stage of the project.

The set-up of the test suite is quite simple: We start from interpolated initial and boundary conditions from the operational LM using the interpolation program LM2LM, i.e. there is no data assimilation for LMK yet. The dynamics and physics is the same as in LM at DWD, except that the convection scheme is switched off. LMK is integrated for the domain shown in Fig. 1 using a 2.8 km grid spacing and 50 vertical layers, where the hybrid Gal-Chen coordinate is used as vertical coordinate. The time-step is set to 16 sec for the Leapfrog time-integration. The test suite started at 18 December 2003 and was run until 29 February 2004, performing two 18-h forecasts a day stating at 00 and 12 UTC.

The overall impression from the test runs (an automatic generation of plot products with posting on the DWD Intranet has been established) is quite encouraging: The model runs stable (no blow-ups) and no grid-point storm like effects have been observed; also, the severe winter storms during January were robustly integrated. The spin-up time for the dynamical adaptation to the new high-resolution topography is in general less than one hour, but amplitudes can be quite high over the Alps. Another spin-up effect comes from the time needed to build up convective cells explicitly, which can also be noticed along the lateral inflow boundaries for unstable weather situations. This type of lateral boundary spin-up will not be removed by future continuous data assimilation.

Two main deficiencies have been detected during the experiment: One is related to the pressure field at the lateral boundaries, and the other with a missing shallow convection scheme. To illustrate these problems we consider two cases from the test suite. The first is related to the winterstorm on 13 January 2004, the second to a thermal unstable situation on 28 February 2004.

For the first case, Fig. 3 displays the vertically integrated water vapour and the vertically integrated cloud condensate (cloud water and cloud ice) for the LMK run and the corresponding operational LM run at 12 UTC. High values of the latter indicate deep clouds and can be associated with resolved stratiform or convective clouds – depending on the spatial cloud scale. The frontal cloud structures over the northern and eastern parts of Germany look quite similar in both simulations, except that some convective scale cloud structures are embedded within the front. In the cold air in the rear of the front (over the North Sea, the Netherlands and Belgium), explicit convective cells are simulated in the LMK run - which are not visible in the LM run since these are represented only as subgrid-scale clouds in parameterized form. There is also some type of organization into cloud-bands both along

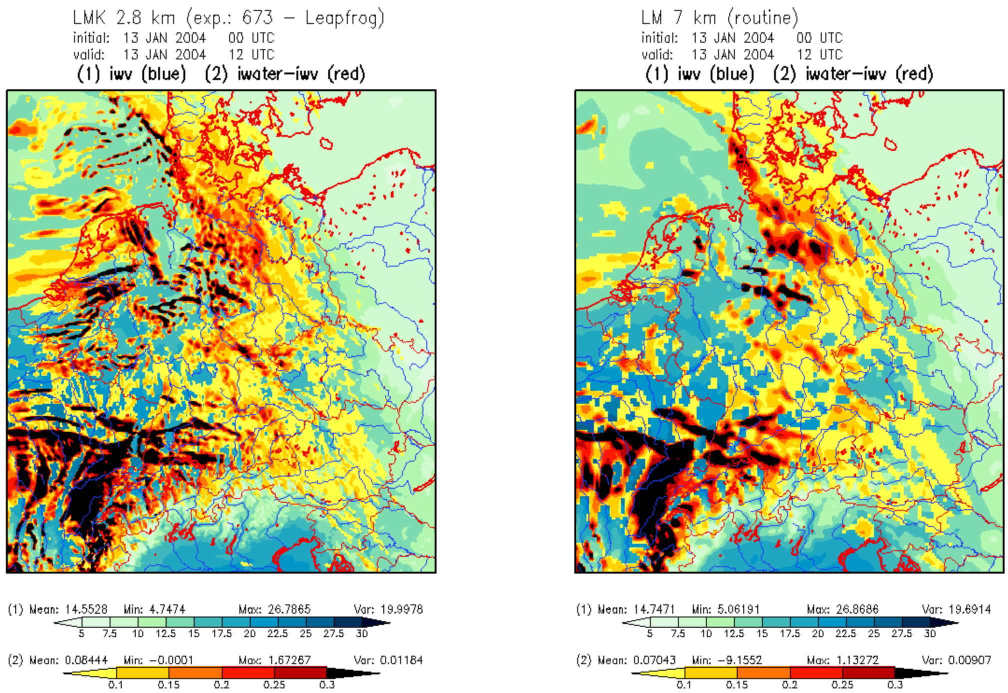

Figure 3: Vertically integrated water vapour (green-blue colors) and vertically integrated cloud water and ice (yellow-red colors) for 13 January 2004 00 UTC + 12 h. Left: LMK (total domain). Right: Operational LM with 7km grid spacing on the corresponding subdomain.

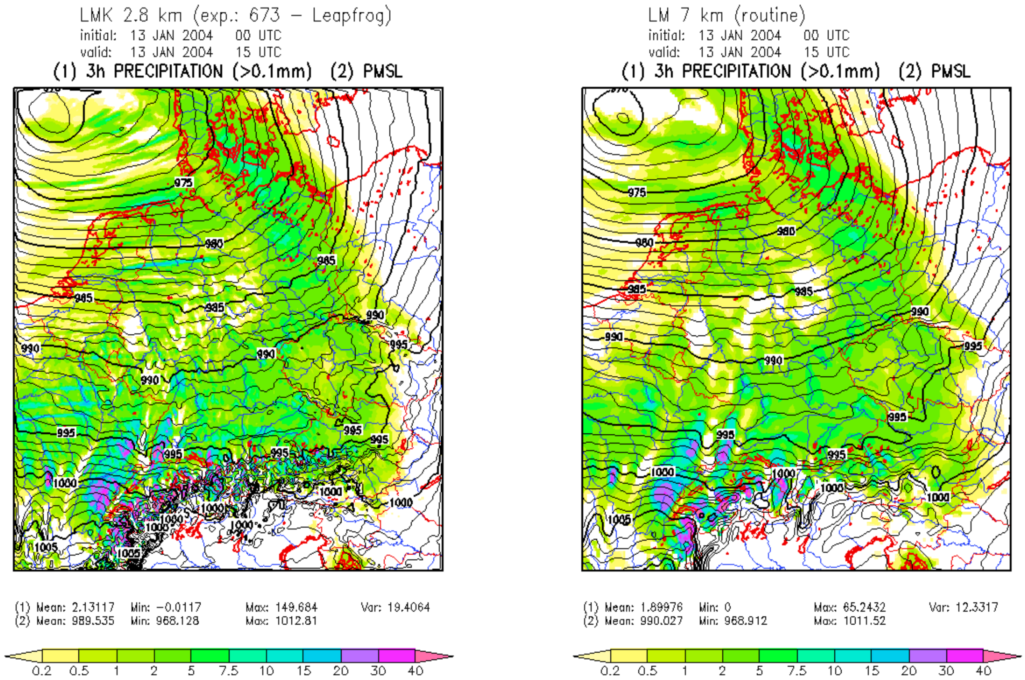

Figure 4: 3-h precipitation amount from 12 UTC to 15 UTC for forecasts starting on 13 January 2004 00 UTC. The contour lines indicate the mean sea level pressure at a 1 hPa interval. Left: LMK (total domain). Right: Operational LM with 7km grid spacing on the corresponding subdomain.

and cross to the mean wind direction. A comparison with satellite images, however, has not yet been done. In the southwestern part of the integration domain we see deep orographic grid-scale cloudiness, which is quite similar in both runs, except that the cloud structures are more sharp and more detailed in the LMK run.

The corresponding precipitation amount from 12 to 15 UTC is displayed in Fig. 4. There is not much difference in the precipitation patterns from both runs, the LMK gives a somewhat higher area mean precipitation amount and obviously much too high peak values related to orographic rain in the Alps. The latter effect is expected from the steeper orography and will probably be removed when using the prognostic precipitation scheme later on. In the northwest of the integration domain some tracks of precipitation from explicit convective cells are visible, which is consistent with the cloud structure shown in Fig. 3.

The pressure problem along the lateral boundaries mentioned above is clearly visible in Fig. 4. There is a drop in pmsl – and in the pressure perturbation on model levels – of about 0.5 to 1.0 hPa from the boundary value to the inner domain within the relaxation zone. This results in a correspondingly lower level of surface pressure in the whole inner LMK domain when compared to the driving LM. The pressure difference forms within the first hour of simulation time and then stays at about the same level for the rest of the integration. Moreover, this effect is not case dependent, i.e. it is noticeable in every simulation performed in the test suite. The cause for this behaviour is not yet clear. First experiments have shown that the distribution of vertical levels is quite sensitive to the formation of the pressure drop (indicating a substantial impact of the method used for vertical interpolation), but also the Rayleigh damping layer has a noticeable impact. Another reason might come from errors introduced from a too narrow set-up of the lateral relaxation zone (Herzog et al., 2002). A further possible source for this behaviour from the interpolation of nonhydrostatic pressure in LM2LM instead of using an equilibrium condition (hydrostatic pressure) as in GME2LM can be excluded, since a similar error shows up when the GME2LM is applied to provide initial and boundary conditions for LMK form the global model GME. Clearly, a detailed investigation of this problem is on the work plan of the project for the next months.

Another deficiency – but case dependent – was detected for meteorological situations with a moist-convective unstable boundary layer. As an example, Fig. 5 shows the low-level cloud cover for 28 February 2004 at 18 UTC from LM and LMK forecasts starting at 00 UTC. The operational LM predicts low-level cloudiness in the southeastern part of the domain, but an almost cloud-free sky for northern and western regions – except for a meso-cyclone which formed over Belgium and the Netherlands during the day and moved eastwards in the evening (with heavy snowfall during the night). In contrast, the LMK predicts an almost closed low level cloud cover in the northern and western part of the domain.

On this day, a convectively unstable situation prevailed with some snow showers from shallow convective clouds during the afternoon. Shallow convection, however, cannot be resolved correctly with 2.8 km gridspacing. As it is not parameterized so far, moisture can be accumulated within the boundary layer during the day resulting in high relative humidity and correspondingly high subgrid-scale cloud cover (which is interpreted from relative humidity) on the lower model levels. Also, the relative humidity on the 850 hPa level is smaller in LMK than in LM (not shown), indicating that an efficient exchange mechanism between the boundary layer and the free atmosphere is missing in the LMK simulation for this case.

In order to test the sensitivity of the simulation to shallow convection, we rerun this case with a simple parameterization scheme for shallow convection. This was realized in an ad-hoc approach by just switching on the Tiedtke scheme but storing back the convective tendencies only when the resulting convective cloud depths are less than 2000 m. Fig. 6 compares the

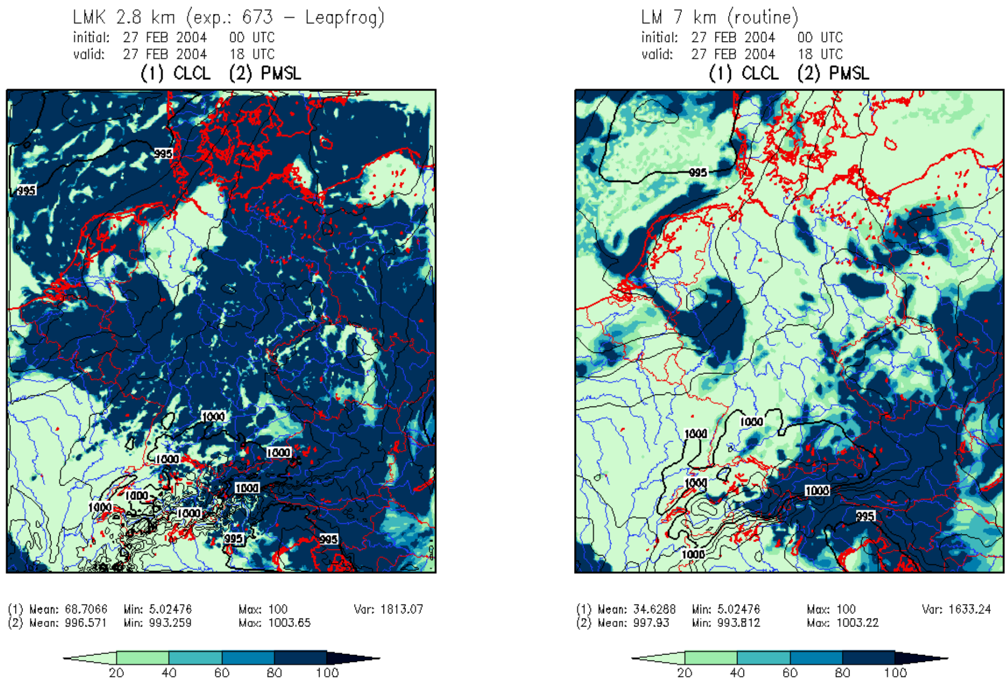

Figure 5: Low-level cloud cover valid for 27 February 2004 00 UTC + 18 h. Left: LMK (total domain). Right: Operational LM with 7km grid spacing on the corresponding subdomain.

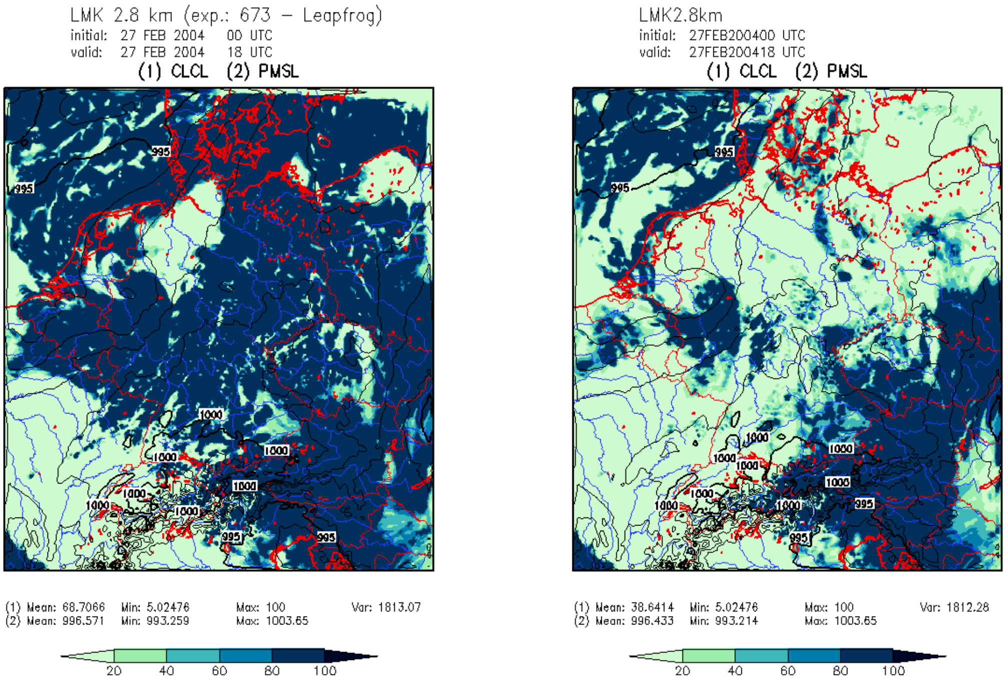

Figure 6: Low-level cloud cover valid for 27 February 2004 00 UTC + 18 h. Left: LMK (total domain). Right: LMK with a simple shallow convection scheme.

low-level cloud cover from this test run against the standard LMK simulation. As can be noticed, shallow convection has a profound impact on the low-level humidity structure: Almost all low-level cloudiness over northern Germany and the Baltic Sea has vanished, and now the meso-cyclone appears as a distinguished feature. When compared to the operational LM 7 km run shown in Fig. 5, a somewhat higher low-level cloudiness remains over the North Sea. This is related to explicit deep convection simulated by the LMK in this region and is consistent with the LM 7km run, where parameterized convections indicates cloud depths of about 8000 m.

This test experiment demonstrates that a parameterization for shallow convection is of crucial importance to properly represent non-local vertical exchange processes between the boundary layer and the free atmosphere. The current ad-hoc approach of applying a large-scale scheme is of course not suitable: First, the method is computational expensive and second, the closure condition which relates cloud-base mass flux to sub-cloud moisture convergence is certainly not scale-adequate. We plan to develop a new scheme based on a more sophisticated cloud model which will allow to determine entrainment and detrainment as diagnostic quantities in terms of convective available buoyant energy.

6 Outlook

As a next step, we plan to rerun the testsuite for January 2004 with the new TVD-RK3 integration scheme and 5th-order discretization of horizontal advective transport, combined with the prognostic precipitation scheme. Later on the testsuite will be gradually upgraded according to new developments in the dynamics/numerics and physical parameterizations.

For the more long-term planning, the following milestones have been defined.

- Summer 2004:
  A prototype version of the LMK-System (new time integration including 3-d turbulence, graupel microphysics and shallow convection) with data assimilation but without latent heat nudging is running in a test environment.
- Summer 2005:
  The prototype version of the LMK-System with latent heat nudging is running in a quasi-operational mode. Further testing, evaluation and development of new numerical schemes and physical parameterizations.
- Early 2006:
  Start of a pre-operational test-phase and begin of fine-tuning and final evaluation of all components of the system.
- End 2006:
  Start of the operational application.

7 References

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