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COSMO Priority Project "Tackle deficiencies in quantitative precipitation forecast (QPF)": Final Report

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1 Project report

1.1 Introduction

Quantitative precipitation forecasting (QPF) is an important reason to run a numerical weather prediction model - for forecasters and customers. Unfortunately, precipitation is also a very difficult parameter to quantitatively forecast. There are indications from verification and from forecasters in various COSMO countries, that the COSMO model - like other weather forecast models - has some serious deficiencies in quantitatively forecasting precipitation. This priority project aims at looking into the COSMO model deficiencies concerning QPF. The study is focused on the bias in area averaged accumulated precipitation rather than on local skill scores.

The QPF quality suffers from different sources of uncertainty such as inaccurate initial and boundary conditions, inaccuracies of numerical methods, and the incomplete description of physical processes. Especially, not all physical processes involved in the formation of precipitation are fully understood (Beard and Ochs, 1993), not to mention adequately represented in the model. Further limitations result from the fact, that some situations have a low predictability causing large errors in the precipitation forecast resulting from small errors in the initial conditions. This limited predictability especially occurs in situations which involve moist convection (Zhang et al., 2002; Walser et al., 2004; Hohenegger et al., 2006). The COSMO model, formerly known as Lokal Modell (LM, Steppeler et al., 2003), is a limited-area non-hydrostatic model that is developed within the consortium for small-scale modelling (COSMO). The model is designed for applications in the meso-β (20-200 km) and meso-γ (2-20 km) range and is used operationally at meteorological services in Germany, Greece, Italy, Poland, Romania, and Switzerland. A brief description of the model configuration and setup is given in Section 1.2. The objective verification of the operational forecasts as well as feedback by forecasters reveals deficiencies in the forecasts of precipitation. The kind of typical QPF error differs depending on the setup of the model for the operational forecasts in the different countries. The individual setups differ regarding size and location of the model domain, initial and boundary conditions as well as numerical methods or physical parameterizations. The aim of the present study is to investigate which parts of the modelling system have a significant impact on QPF. Investigations are focussing on numerical methods and physical parameterizations, while the effect of inaccurate initial and boundary conditions is disregarded in this study. Identifying the most important and/or weakest parts of the model will not necessarily lead to direct improvements, but can at least provide guidance for future research and development.

Investigations within the framework of this project are based on numerical sensitivity studies. Three to four test cases are selected for every implementation of the model representing typical forecast errors in the respective region. The test cases are selected such that the forecast error is unlikely to be caused by wrong synoptic conditions in the initial or boundary data. Altogether 25 test cases are selected that are representative for forecast errors in different geographical regions in Europe and for different meteorological situations (Section 1.3). For each of these test cases, 22 sensitivity studies regarding initial conditions, numerical methods and physical parameterizations (Section 1.4) are performed, and the effect and the importance of changes on the 24h area averaged precipitation is investigated (Section 1.5). The results and their implications are discussed in Section 1.6.

1.2 Configuration and setup of the COSMO model

The COSMO model is a non-hydrostatic limited-area atmospheric model developed within the Consortium for Small-scale Modelling (COSMO) for applications on the meso-β and meso-γ scale (Steppeler et al., 2003). The model is based on non-hydrostatic, fully compressible hydro-thermodynamical equations in advection form. The prognostic variables are horizontal and vertical wind components, pressure perturbation, temperature, specific humidity, cloud water and ice content, specific water content of rain and snow and turbulent kinetic energy. Generalized terrain-following height coordinates with rotated geographical coordinates are used.

The model equations are solved on an Arakawa C-grid with user-defined vertical grid staggering. They are spatially discretized with second-order finite differences. Time integration uses a second order leapfrog HE-VI (horizontally explicit, vertically implicit) time-split integration scheme including extensions proposed by Skamarock and Klemp (1992). A 4th order linear horizontal diffusion is calculated. 3-dimensional divergence damping and off-centering are applied in split time steps. Damping at the top of the model domain is done by Rayleigh damping in the upper layers. Data at the lateral boundaries are prescribed using a Davies-type one-way nesting.

Subgrid-scale turbulence is parameterized by a prognostic turbulent kinetic energy closure at level 2.5 including effects from subgrid-scale condensation and thermal circulations. The surface layer parametrization is based on turbulent kinetic energy and includes a laminar-turbulent roughness layer.

The formation of precipitation is described by a bulk microphysics parametrization including water vapor, cloud water and ice, rain and snow with a fully prognostic treatment of precipitation, i.e. three-dimensional transport of rain and snow is calculated. Condensation and evaporation are parameterized by saturation adjustment while depositional growth/sublimation of cloud ice is calculated using an explicit non-equilibrium growth equation. Subgrid-scale cloudiness used for radiation calculations is parameterized by an empirical function depending on relative humidity, ice content and height.

Moist convection is parameterized using a mass-flux scheme with an equilibrium closure based on moisture convergence following Tiedtke (1989). Radiation is calculated using a two-stream scheme for short- and longwave fluxes (eight spectral intervals) including a full cloud-radiation feedback. A multi-layer version of the soil model solving the heat conduction equation is applied. The simulations are performed using COSMO model version 3.19. Initial and boundary data are taken from GME forecasts (Majewski et al., 2002), no data assimilation is used. The horizontal grid size is 7 km and the number of vertical levels is varying between 40 and 45 for the different model implementations. The position of the model domain and its size also depends on the model implementation and is close to the operational setup of every involved meteorological service (Fig. 1).

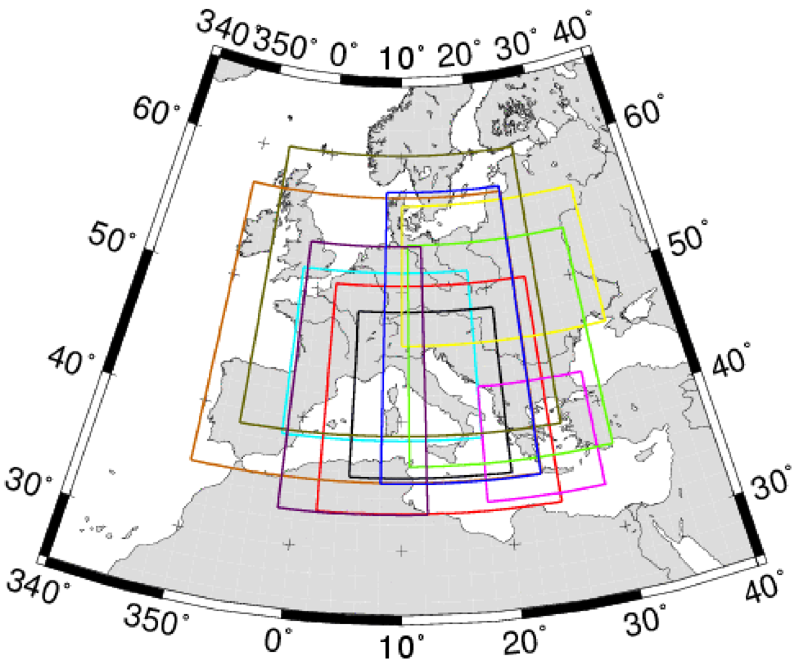

Figure 1: Position and size of the different model domains used for this study.

1.3 Selection and description of the test cases

The present study is focussing on the 24h precipitation sum of the first forecast day, that is, precipitation amounts between 6 and 30 hours lead time excluding the first 6 hours of the forecast (spin-up period). The first forecast day is chosen in order to ensure that initial and boundary conditions are close to reality and deficiencies of model forecasts are mainly due to numerical methods and physical parameterizations. The criterion for the test case selection is a poor forecast of the 24h precipitation sum on the first forecast day. The region of interest is specific for every involved meteorological service (Fig. 1).

The test cases are selected taking into account the typical QPF problems of the different regions of interest. No standard procedure for the selection is prescribed since operational verification procedures at the involved meteorological services are different. Based on operational QPF verification results and the experience of forecasters typical QPF errors are identified and single test cases are collected which reflect the most severe QPF errors and, hence, serve as a kind of prototype events for the observed QPF problems. In order to avoid wrong boundary forcing as a reason for bad QPF, the large-scale flow is checked to be reasonably well predicted. This selection resulted in a list of 53 test cases that were re-simulated with a COSMO reference version in order to exclude QPF errors due to out-dated model versions or inappropriate model settings. The reference version was COSMO model version 3.19, the newest version at that time, in the configuration described in Section 1.2. The boundary values for the reference simulations were taken from GME forecasts. If the QPF error disappeared or was completely changed in the re-forecast, the test case was excluded. The 25 test cases for which the original error was reproduced with the reference version remained on the list. Those test cases were characterized regarding the kind of QPF error (under-, overestimation), the kind of precipitation (mainly stratiform or convective) and the influence of fronts or orographic forcing. Three to four test cases per model implementation were selected by participants covering, if possible, different kinds of QPF errors. The test cases and their characteristics are summarized in Tab. 1.

The test cases fall into two main groups: underestimation of precipitation in convective weather situations (7 test cases) and overestimation of stratiform precipitation (9 test cases). There are 3 additional test cases with convective over- and 5 test cases with stratiform underestimation of precipitation and 1 test case that does not have a significant bias. The two dominant QPF errors correspond to specific geographical regions: 6 test cases of convective underestimation occur in regions where the weather is strongly affected by the vicinity to the Mediterranean Sea (Greece, Italy), and nine test cases of stratiform overestimation occur in countries in which the weather is less affected by the sea (Germany, Romania, Switzerland, and Poland). Thus, the geographical region and the kind of forecast error are closely related.

The QPF is evaluated based on the area averaged precipitation values calculated in evaluation regions that depend on the region of interest. The evaluation regions for the different test cases are defined in Section 4. The observed area averaged and maximum 24h precipitation values are compared with the simulated ones for all test cases (Fig. 2). Observed and simulated area averaged precipitation values are ranging from approximately 0.01 to 60 mm, differing strongly depending on the test case. Most of the test cases show significant differences between observed and simulated values except for the test cases 11 and 20, where the QPF error is not reflected by differences of area averaged or maximum precipitation values. Test case 11 is a situation with severe convective precipitation in the Piemonte region on the 17th of August 2006. The forecast error is underestimation of precipitation in the Toce catchment, while precipitation in the Ticino catchment is overestimated. The area averaged precipitation is calculated for a larger region and, thus, doesn't reflect the (large)

Table 1: Overview of selected test cases and their characteristics.

Case	Date	Meteorological service	Kind of error	Kind of precipitation	Fronts or orographic forcing
1	06.12.2004	Germany	overestimation	stratiform	warm sector
2	18.03.2005	Germany	overestimation	stratiform	cold front + orography
3	03.05.2005	Germany	overestimation	stratiform + convective	warm front
4	21.06.2005	Germany	underestimation	convective	cold front
5	02.02.2005	Switzerland	overestimation	stratiform	occluded front + orography
6	22.03.2005	Switzerland	overestimation	stratiform	warm front
7	12.07.2005	Switzerland	overestimation	convective	-
8	17.12.2005	Switzerland	overestimation	stratiform	orography
9	24.09.2004	Emilia Romagna	underestimation	convective	cold front + orography
10	10.04.2005	Emilia Romagna	overestimation	stratiform	occluded front + orography
11	17.08.2006	Piemonte	underestimation	convective	cold front + orography
12	09.09.2005	Campania	underestimation	convective	-
13	01.12.2005	Rome	underestimation	stratiform	cold front
14	03.12.2005	Rome	underestimation	stratiform	cold front + orography
15	17.12.2005	Rome	underestimation	stratiform + convective	cold front
16	15.09.2005	Greece	underestimation	convective	-
17	23.11.2005	Greece	underestimation	stratiform + convective	warm front
18	26.11.2005	Greece	underestimation	stratiform	orography
19	03.05.2005	Poland	underestimation	stratiform + convective	warm front
20	04.05.2005	Poland	average correct	stratiform	occluded front
21	10.06.2005	Poland	overestimation	stratiform + convective	-
22	09.08.2005	Poland	overestimation	stratiform	-
23	23.06.2005	Romania	overestimation	stratiform + convective	cold front
24	02.07.2005	Romania	overestimation	stratiform	cold front
25	12.07.2005	Romania	underestimation	stratiform	cold front

forecast error. A detailed description and discussion of this test case is given in Milelli et al. (2008). Test case 20 is a situation with stratiform precipitation on the 4th of August 2005. In the south-eastern part of Poland the forecast underestimates precipitation in a small region and north of this region the forecast overestimates precipitation. As a result, over- and underestimation are virtually canceling out and the area average is almost perfectly simulated. A discussion of both test cases is given in Section 4.

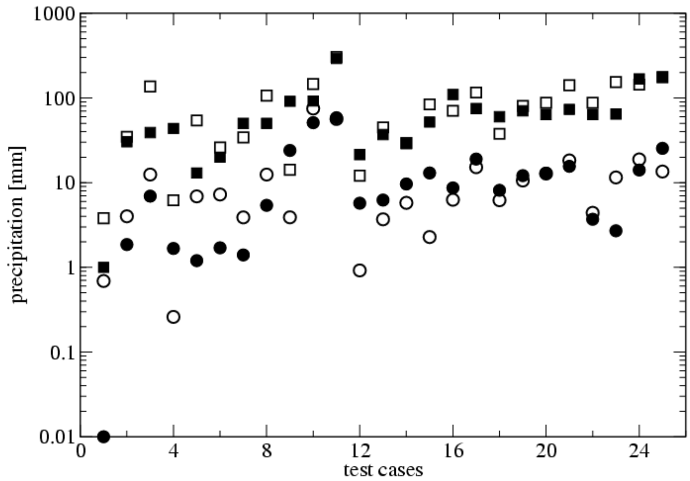

Figure 2: Observed (filled) and simulated (empty) area averaged (circles) and maximum 24h precipitation (squares).

Table 2: Overview of sensitivity studies regarding initial conditions.

No.	Sensitivity study	Expected	Kind of study
1	Reduction of soil moisture by 20%	Homogenous reduction of precipitation	idealized
2	Increase of soil moisture by 20%	Homogenous increase of precipitation	idealized
3	Reduction of initial humidity by 10%	Homogenous reduction of precipitation	idealized
4	Increase of initial humidity by 10%	Homogenous increase of precipitation	idealized

Table 3: Overview of sensitivity studies regarding numerics.

No.	Sensitivity study	Expected	Kind of study
5	Halved time step	Optimal case: nothing	idealized
6	Leapfrog, tri-cubic semi-Lagrange advection of QR and QS	Less diffusive advection of precipitation	option
7	Runge-Kutta, tri-cubic semi-Lagrange advection of QV, QC, QI QR and QS	Less diffusive, improved flow over terrain, improved advection of all moisture variables	option
8	Runge-Kutta, flux-form advection of QV, QC, QI, QR and QS	Less diffusive, improved flow over terrain, improve advection and mass conservation of all moisture variables	option
9	Runge-Kutta, flux form advection and T'-p' dynamics	Less diffusive, improved flow over terrain, improved advection and mass conservation and a better treatment of buoyancy terms	option
10	increased orography filtering	Slightly decreased orographic precipitation	idealized

1.4 Description of the sensitivity studies

Sensitivity experiments are divided into studies regarding initial conditions, numerical methods, and physical parameterizations. An overview of sensitivity experiments and expected changes is given in Tab. 2 to Tab. 4. The sensitivity experiments include idealized studies with changes that are not considered a possible configuration for operational applications (labeled 'idealized'), studies with optional schemes already included in the model ('option'), and studies with schemes that are currently under development and might be included soon ('development'). Sensitivity experiments regarding initial conditions, namely initial soil moisture and humidity are idealized studies. They are performed to have a reference in order to weight the effects of the other sensitivity experiments.

The sensitivity experiments regarding initial conditions are set up in an idealized way (Tab. 2). Soil moisture is increased (decreased) at all land grid points by 20%. The change is horizontally homogenous and is prescribed in all layers of the multi-layer soil model. The atmospheric water vapor mixing ratio is increased (decreased) by 10% in cloud free regions.

Table 4: Overview of sensitivity studies regarding physical parameterizations.

No.	Sensitivity study	Expected	Kind of study
Microphysics			
11	New warm rain scheme (Seifert and Beheng; 2001)	Reduced drizzle	option
12	Strong changes of ice microphysics and new warm rain scheme	Reduced drizzle and precipitation amount and increased transport of precipitation to mountain lee side	idealized
13	Moderate changes of ice microphysics and new warm rain scheme	Reduced drizzle and precipitation amount and increased transport of precipitation to mountain lee side	development
Convection			
14	Modified Tiedtke scheme	Weaker convection	development
15	Kain-Fritsch/Bechtold scheme	Modified convection	development
16	No parameterization of deep convection	Unrealistic up-scaling of convection, deteriorated forecast	idealized
Planetary boundary layer			
17/18	Decreased/increased scaling factor of height of laminar boundary layer for heat	Increased/decreased vertical exchange of heat and moisture	idealized
19/20	Decreased/increased stomata resistance	Increased/decreased vertical exchange of moisture	idealized
21/22	Decreased/increased laminar scaling factor for heat over sea	Increased/decreased vertical exchange of heat and moisture	idealized

Increased values might result in exceedance of the saturation value. In that test case the exceeding water vapor fraction is transformed to cloud water or cloud ice, respectively, but without considering latent heat release and, thus, a change in temperature.

Sensitivity experiments regarding numerical methods are changes of the time integration scheme in combination with different advection schemes (Tab. 3). For sensitivity experiments 7 to 9 the time integration scheme is changed from a leapfrog scheme to a two time-level 3rd order Runge-Kutta split-explicit scheme (Wicker and Skamarock, 1998). Advection of moisture variables in the reference simulation is calculated explicitly with a mix of various second-order spatial discretization, e.g., centered differences for moisture and cloud water, but upwind advection for cloud ice. Additional sensitivity studies are performed using a higher-order flux-form advection (Bott, 1989), a tri-cubic semi-Lagrange advection for water vapor and hydrometeors and a version using so-called T'-p'-dynamics, which is basically a reformulation of the dynamical core using perturbation temperature instead of total temperature. A sensitivity study with a halved time step is performed in order to confirm that the solution is insensitive against time step changes. The model orography is filtered in order to avoid numerically inaccurate solutions caused by mountain tops and valleys that are represented by only one grid point. The strength of filtering is increased in a sensitivity experiment in order to investigate its effect on orographically induced precipitation.

Sensitivity experiments regarding physical parameterizations are performed for microphysics, convection, and planetary boundary layer parameterizations. Microphysics studies include a sensitivity experiment using a one-moment variant of the warm rain scheme of Seifert and Beheng (2001) instead of the simpler Kessler-type formulation of autoconversion and accretion, and two studies with strong and moderate changes of ice microphysics (especially size, geometry of snow particles, and fall speed). Sensitivity experiments regarding convection include an idealized study without parametrization of deep convection, and a study using the mass flux Kain-Fritsch/Bechtold convection scheme (Bechtold et al., 2001) that is based on a CAPE closure instead of moisture convergence as used in the Tiedtke scheme. A further study is performed using the Tiedtke convection scheme with modifications regarding evaporation, turbulent entrainment and mixed-phase saturation adjustment. Three changes of the parameters of the planetary boundary layer parametrization change the vertical transport of heat and moisture. The vertical transport is decreased (increased) by a factor of 10 (50) in experiment 17 (18), by a factor of 3 (1.7) in experiment 19 (20), and by a factor of 20 (2) in experiment 21 (22). The change of stomata resistance affects the vertical exchange over land and is expected to be important for countries without strong influence by the sea (exp. 19/20). On the other hand, the change of the parameter affecting evaporation from the sea is expected to be important for countries with strong influence of the sea (exp. 21/22).

1.5 Results of the sensitivity experiments

The sensitivity experiments are performed and evaluated by the participating meteorological services. Model code and namelists are provided to everybody in order to ensure a consistent performance of sensitivity experiments. All sensitivity experiments (Tab. 2 to Tab. 4) are performed for all test cases (Tab. 1). However, some sensitivity experiments are missing for some test cases due to technical problems on different computational platforms.

A joint evaluation based on the area average of the 24h precipitation sum of lead times between +6 and +30 hours is performed. The area averaged precipitation value is calculated for the region of interest of every meteorological service. The evaluation regions are chosen sufficiently large in order to avoid changes by small-scale spatial shifts. The smallest evaluation region is about 100 km times 100 km. The evaluation regions are documented in

Section 4. The aim of the joint evaluation is an overview on the effect and its magnitude for different sensitivity experiments. Detailed investigations, e.g., of temporal development or small-scale spatial changes, are excluded from this joint evaluation. They are investigated by the participating groups individually. Due to the variety of details, these results are however not presented in this report.

1.5.1 Change of the area averaged precipitation relative to the reference simulation

We start with a joint evaluation based on the relative difference (Δrel) of the 24h area averaged precipitation of the sensitivity experiments (P_{exp}) with respect to the 24h area averaged precipitation of the reference simulation (P_{ref}):

$$\Delta rel = (P_{exp} - P_{ref})/P_{ref}. \tag{1}$$

The relative difference Δrel is very large for test cases 1, 4, and 12 because the area averaged value of the reference simulation P_{ref} is very small. Due to this dependency on the area averaged precipitation value of the reference simulation, relative differences are not comparable among different test cases. Thus, the relative difference allows comparing the effect of different sensitivity experiments, but not the test cases against each other.

An overview on the results for all sensitivity experiments and all test cases is given in Fig. 3, while Fig. 4 facilitates the comparison between different sensitivity experiments by condensing these results as follows: the sum for all test cases of the absolute values of the relative difference $\sum|\Delta rel|$ is shown as black bars whereas the sum of relative differences $\sum \Delta rel$ is given as grey bars. If a sensitivity experiment is causing an increase or decrease for most of the test cases, $\sum|\Delta rel|$ is about the same as $|\sum \Delta rel|$. On the other hand, the sum of absolute values is much higher than the sum of relative changes, if test cases with an increase and decrease of area averaged precipitation are canceling out.

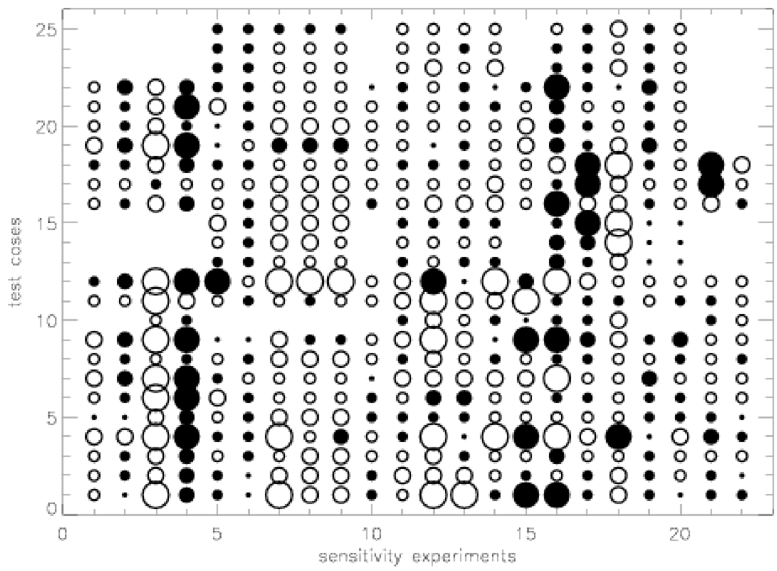

Figure 3: Difference of 24h area averaged precipitation in the sensitivity study and in the reference simulation relative to the 24h area averaged precipitation in the reference simulation Δrel [%]. Filled (empty) circles indicate an increase (decrease) of precipitation relative to the reference simulation. The big circles indicate a change bigger than 30%, medium ones between 10% and 30%, small ones between 0% and 10%, and tiny circles indicate cases with no change at all.

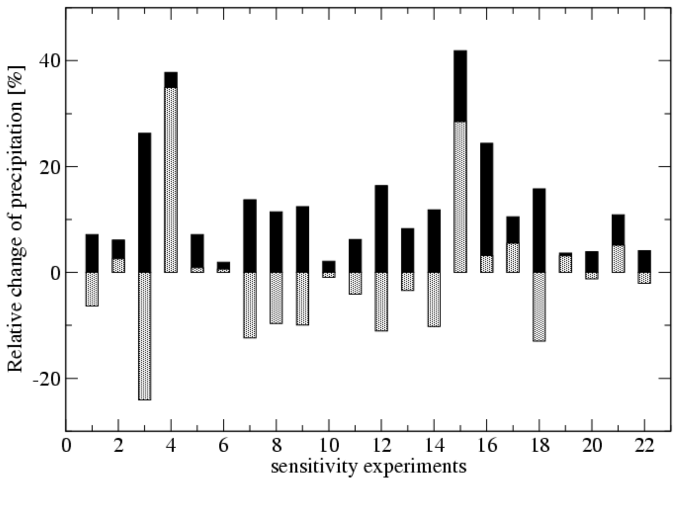

Figure 4: Relative difference of the 24h sum of area averaged precipitation in the sensitivity studies. The sum of the absolute values of the relative changes of area averaged values $\sum |\Delta rel|$ is given as black bars, whereas the sum of relative changes of area averaged precipitation $\sum \Delta rel$ is given as grey bars. The relation between grey and black bars indicates whether changes have predominantly one direction.

Initial conditions

Besides the Kain-Fritsch/Bechtold convection scheme (see below), the strongest changes in area averaged precipitation sums occur in the sensitivity experiments with changed initial humidity (exp. 3 and 4; cf. Fig. 4). The increase (decrease) of initial humidity by 10% causes an increase (decrease) of precipitation of more than 30% in about half of the test cases and between 10% and 30% for most of the other test cases (cf. Fig. 3). The change of initial humidity is predominantly acting as expected: an increase of initial humidity increases the average precipitation by 40% and a decreased initial humidity decreases it by 22%. Compared to the initial humidity changes, the average effect of the soil moisture changes by 20% results in a change in Δrel of less than 10% (exp. 1 and 2; cf. Fig. 3 and Fig. 4). The effect of initial soil moisture has a clear direction, and in those test cases where the change acts in the opposite direction, the effect is typically small. An explanation for the small effect of soil moisture changes might be that the first forecast day is evaluated. Soil moisture might act on a longer time scale and might be more important for longer forecast periods.

The strong impact of initial humidity is not surprising. Verifications of COSMO model results hint at an overestimation of atmospheric humidity. An example is the verification of the COSMO-EU model for the year 2007 using about 20 radio soundings in Europe. The comparison is carried out in the frame of the General Observation Period of the Priority Programme "Quantitative Precipitation Forecasts" of the German Research Foundation. Monthly bias and RMSE of mixing ratio are presented on the web page

http://gop.meteo.uni-koeln.de/gop/doku.php?id=data_quicklooks.

The monthly verification of the mixing ratio bias shows a great variety depending on radiosonde station and season. Examples for the radiosonde stations Lyon, Payerne, and Greifswald for January and July 2007 are shown in Fig. 5. The results show that the mixing ratio is overestimated above approximately 1000 m above ground in the model simulations during winter for these three radiosonde stations. The bias of initial humidity is generally relatively small, but increases significantly during the first 3 hours of simulation. In the summer months the overestimation of the mixing ratio in the model simulations is less pronounced. On the contrary, the mixing ratio bias at radiosonde stations in Italy and France show a tendency of underestimated humidity in the model simulations. Thus, over- and underestimation of simulated humidity might be an explanation for stratiform overestimation as well as convective underestimation. These results are only based on results of one model implementation, COSMO-EU, and for just one year, 2007. Still, the results motivate further investigations regarding the connection between simulated humidity and QPF deficiencies and possible reasons for over- or underestimated humidity in the COSMO model. The sensitivity studies confirm the expected great importance of simulated humidity for the precipitation forecast and, thus, it needs to be investigated if QPF deficiencies are partly based on wrong humidity.

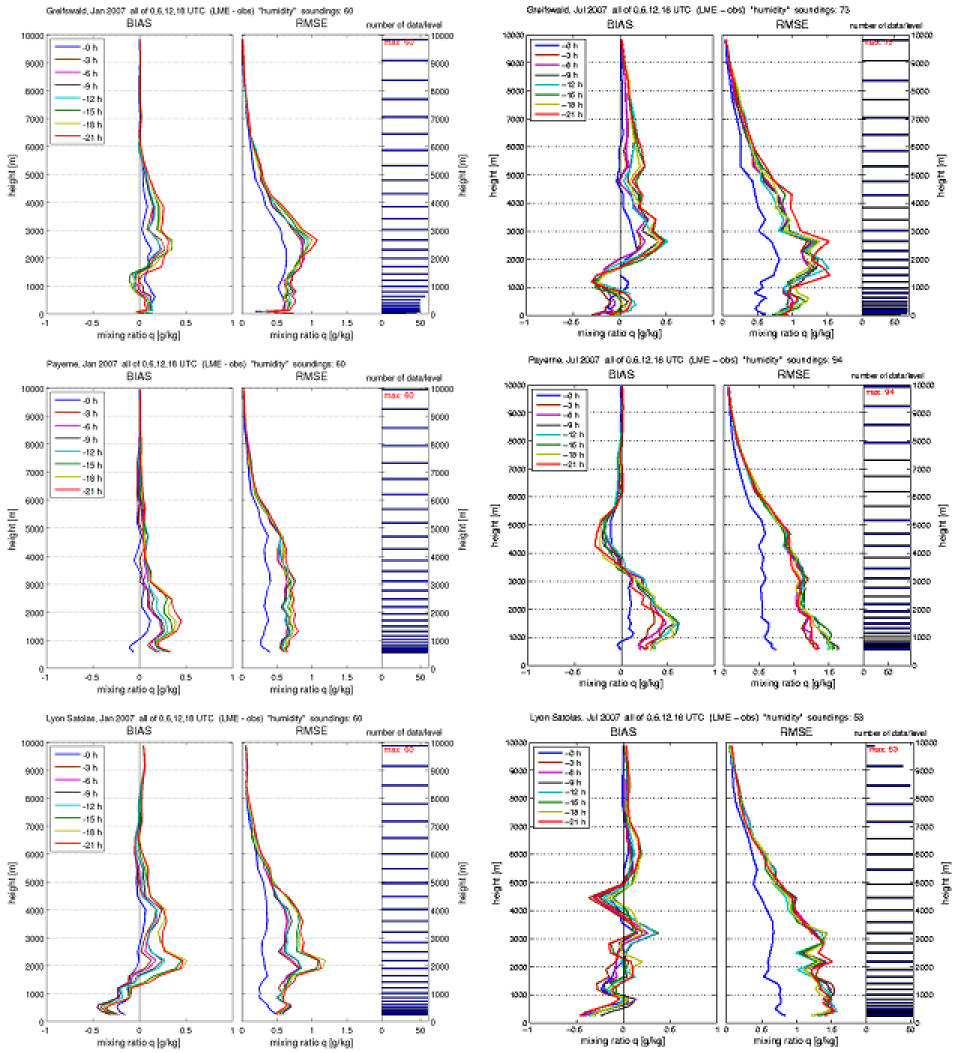

Figure 5: Monthly average Bias and Rmse for the observed and simulated vertical profile of mixing ratio at the radiosonde stations Greifswald (top), Payerne (middle), and Lyon (bottom) in January 2007 (left panels) and in July 2007 (right panels). The figures are taken from the GOP webpage: *http://gop.meteo.uni-koeln.de/gop/doku.php?id=data_quicklooks*.

Numerical methods

The strongest effect when changing numerical methods is the decrease of average precipitation when using the Runge-Kutta time integration scheme instead of Leapfrog (exp. 7 to 9; cf. Fig. 4). The Runge-Kutta scheme reduces the average precipitation amount by about 10%, for most of the test cases (cf. Fig. 4), stratiform as well as convective (cf. Fig. 3). The reason for this decrease has not yet been investigated. A possible explanation is that the centered differences, which are used in the reference simulation for advection of QV and QC, are not sufficiently accurate or lead to a significant mass error. Compared to this, the effect of the different variants of the Runge-Kutta scheme (exp. 7 to 9) is small. The effect is also small if the Leapfrog scheme is used with different advection schemes for mixing ratios of rain and snow (exp. 6; cf. Fig. 4), which leaves the improved advection of cloud and ice mixing ratios as the only possible explanation for the change in the average precipitation. Unfortunately, it was not possible to test this in a separate sensitivity experiment.

The impact of increased orography filtering and halved time step is negligible (exp. 5 and 10; cf. Fig. 4), i.e., changes remain below 10% for nearly all test cases. Only one test case with underestimated convective precipitation (test case 12) shows a significant relative increase of precipitation when changing the orography filtering, which is mainly due to the low area averaged precipitation value in the reference run. The absolute change from 0.92 mm in the reference run to 1.30 mm in the sensitivity experiment is small. Orography filtering and time step are part of the numerical methods and they should not have a significant impact on the results. Thus, insensitivity with respect to changes of orography filtering and time step is a positive result.

Physical parameterizations

The biggest change, besides the initial humidity changes, is caused by using a different convection scheme: Kain-Fritsch/Bechtold instead of Tiedtke (exp. 15). The sum of absolute values of relative changes of precipitation $\sum |\Delta rel|$ is about 40% resulting in an average increase of 30% (cf. Fig. 4). Changes are acting in both directions and there are many test cases with reduced average precipitation (cf. Fig. 3). Still, relative changes with increased average precipitation are bigger. This result is consistent with results from a comparison of the Kain-Fritsch/Bechtold and the Tiedtke scheme for Switzerland for summer 2006. The comparison showed that the Kain-Fritsch/Bechtold scheme tends to simulate higher area averaged precipitation values (Dierer and Schubiger, 2008). A test case with underestimated convective precipitation (case 4) is showing significantly better results with the Kain-Fritsch/Bechtold scheme which is triggering convection while the Tiedtke scheme misses the convective activity (Section 4).

Switching off convection causes average changes of 25% (exp. 16; cf. Fig. 4) with nearly neutral impact regarding increase or decrease of precipitation. There are some convective test cases where the lack of stabilization by the convection scheme causes an over-compensation by grid-scale precipitation (cases 9 and 16). In other convective test cases switching off the convection scheme reduces the average precipitation significantly or even inhibits precipitation (cases 4, 7, and 12). The effect for situations that are dominated by stratiform precipitation is typically small.

The sensitivity experiments with modified Tiedtke scheme tend to reduce the average precipitation by 11% (exp. 14; cf. Fig. 4) with the strongest impact on convective test cases. Regarding underestimation of convective precipitation, the other important QPF deficiency of the COSMO model besides stratiform overestimation, the modifications of the Tiedtke scheme seem not to improve QPF. The modified version of the Tiedtke scheme is further tested by DWD, e.g. exploring a revised formulation of evaporation of rain within the convection scheme.

The strongest effect when changing microphysical schemes is caused by combining the changes of the warm rain scheme with the substantial changes in snow physics (exp 12): this sensitivity experiment causes an average change of 15% and an average reduction of precipitation of 11%. The snow microphysics changes of this sensitivity experiment are probably not realistic and lead to a significant overestimation of cloud cover in some test cases. The moderate changes in the microphysics scheme (exp. 13) cause differences of 7% with an average reduction of 4% (cf. Fig. 4). The number of test cases with increased and decreased average precipitation is approximately the same, but the effect of reducing average precipitation is bigger. There is no evidence that the change is acting differently on stratiform and convective precipitation.

The effect of changing the vertical exchange of heat and moisture is generally small (exp. 17 to 22; cf. Fig. 4), and most of the test cases are quite insensitive to changes of the vertical exchange (cf. Fig. 3). Only a strong decrease in the vertical exchange of moisture and temperature by a factor of 50 (exp 18) results in a significant average reduction of precipitation of 12% (cf. Fig. 4). The test cases that show a significant sensitivity towards change in the vertical exchange of heat and moisture are cases 15, 17, and 18. Two of these test cases are mainly convective (cases 15 and 17) and one is mainly stratiform (18), and all of them are influenced by the sea. Consistently, parameters changing evaporation from the sea (exp. 21 and 22) cause strong differences for these cases (no results available for case 15), while changes of stomata resistance hardly affect the results (exp. 19 and 20).

The ratio of grid-scale to parameterized convective precipitation varies by about 4% for the different sensitivity experiments and, thus, is hardly affected (not shown). The only exception is the sensitivity experiment with the modified Tiedtke scheme (exp. 14). For this sensitivity experiment, the ratio of grid-scale to total precipitation is on average increased by 10%, while the amount of total precipitation is decreased by about 11% (not shown). Thus, it seems that the modified Tiedtke scheme produces less convective precipitation without compensating the loss by grid-scale precipitation.

The maximum precipitation values are changing similar to the area averaged precipitation values, that is, the relative differences of maximum and area averaged precipitation values for the same sensitivity experiment and for the same test case are typically comparable (not shown). There are a few sensitivity experiments that show a different behaviour for maximum precipitation than for area averaged precipitation. Simulations with a tri-cubic semi-Lagrange advection scheme (exp. 6 and 7), the changes of the warm rain scheme (exp. 11 and 13), and the increase of vertical heat and moisture exchange over sea (exp. 21) cause changes of maximum precipitation that are significantly different from the difference in the area averaged values. The effects on maximum precipitation values in the sensitivity experiments with changed advection or warm rain scheme do not show a consistent picture: maximum values are decreased as well as increased for convective as well as for stratiform test cases (not shown). The major effect of the sensitivity experiments with changed vertical exchange is an increase of maximum values in one stratiform and two convective test cases (cases 7, 17, and 18; not shown).

The above results reflect the fact that the sensitivity experiments were originally designed to mainly investigate cases of stratiform precipitation overestimation. Just a few sensitivity experiments have the potential to increase the simulated precipitation for test cases with convective underestimation.

1.5.2 Change of the bias relative to the reference simulation

In this section, the evaluation of the sensitivity experiments is based on the absolute value of the ratio of the 24h area averaged precipitation bias of the sensitivity experiments and the 24h area averaged precipitation bias of the reference simulation:

$$|bias_{exp}/bias_{ref}| = (P_{exp} - P_{obs})/(P_{ref} - P_{obs}). \qquad (2)$$

The evaluation of test case 20 is excluded from this evaluation, since the bias in the reference simulation is quasi-zero for this case. Test case 20 is discussed in Section 4.

The evaluation is focussing on some of the sensitivity experiments with significant relative difference Δrel, only: change of initial humidity (exp. 3 and 4), using Runge-Kutta (exp. 7 to 9), change of warm microphysical scheme and moderate snow physics changes (exp. 13), and using the modified Tiedtke (exp. 14) or Kain-Fritsch/Bechtold convection scheme (exp. 15). The idealized study of changed initial humidity is considered because of its strong impact on simulated precipitation and the hints that there are systematic errors of simulated humidity in the COSMO model. The other sensitivity studies considered are all realistic alternative options for running the model. The test cases are classified depending on their main characteristics: overestimation of stratiform and convective precipitation (Fig. 6, left) and underestimation of stratiform and convective precipitation (Fig. 6, right). The number of test cases in the different categories reflects the main QPF deficiencies found in the COSMO model. The two dominant errors are stratiform overestimation, which mainly occurs in countries not predominantly affected by the sea, and convective underestimation, mainly occurring in Mediterranean countries.

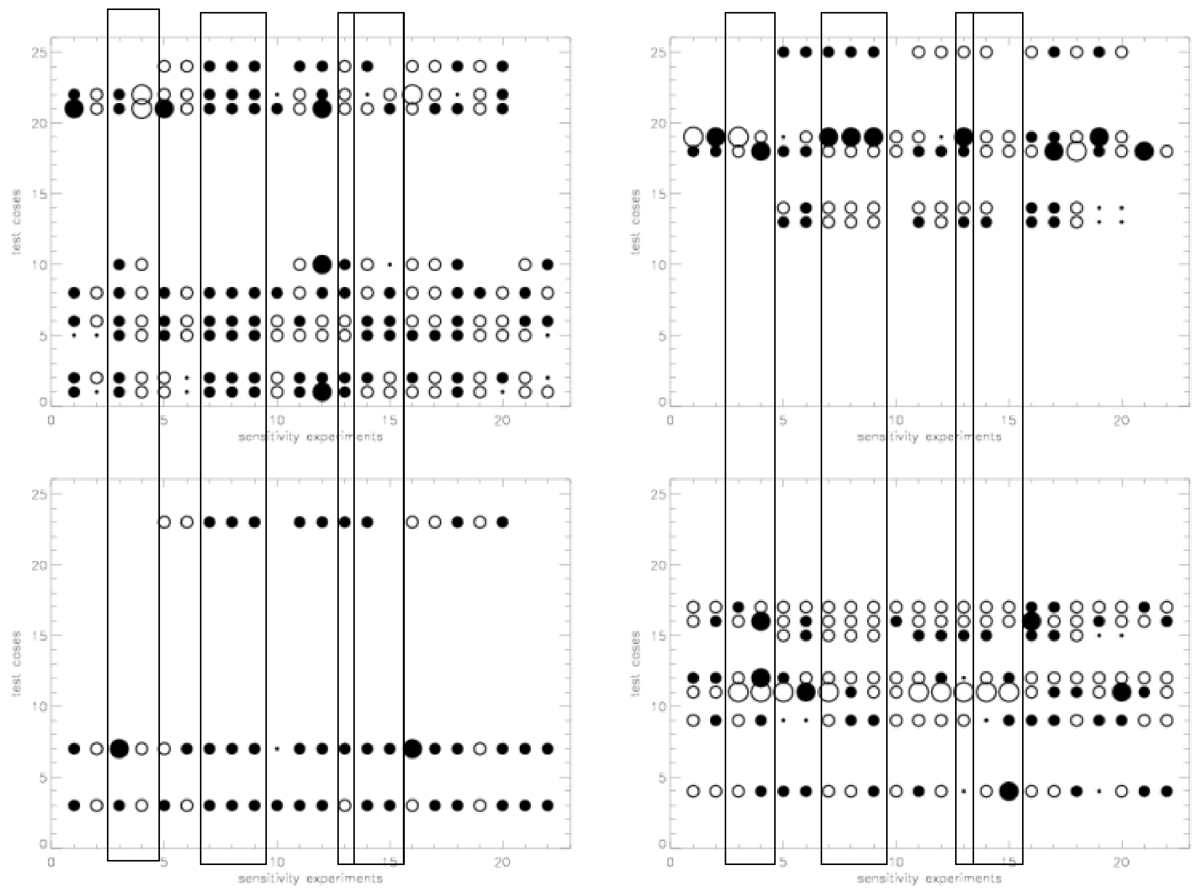

Figure 6: Ratio of the bias of the reference simulation and of the sensitivity study $|bias_{exp}/bias_{ref}|$ for cases with overestimation of stratiform (left, upper panel) and convective (left, lower panel) precipitation and with underestimation of stratiform (right, upper panel) and convective (right, lower panel) precipitation. Filled circles indicate a smaller bias, while empty circles indicate a higher bias than in the reference simulation. Big circles show a more than halved (doubled) bias and small circles an up to halved (doubled) bias. Points indicate no change. Case study 20 was excluded from this figure, because the bias was quasi-zero in the reference study.

Test cases with precipitation overestimation

The sensitivity experiments with decreased initial humidity and with Runge-Kutta time integration cause a decrease of area averaged precipitation for nearly all test cases (Section 1.5.1). For that reason, improved QPF for the test cases of overestimated precipitation can be expected. The decrease of initial humidity has a positive effect on all test cases with overestimation (Fig. 6, left), both for situations with stratiform as well as convective precipitation. On the other hand, an increase of initial humidity causes an even stronger overestimation. The Runge-Kutta time integration scheme, too, has a positive effect on all test cases with overestimated stratiform and convective precipitation. The sensitivity experiments with changes of warm rain scheme and moderate snow physics cause improvements but also worsening of QPF, the overall effect being slightly positive (Fig. 6). The effect of using the modified Tiedtke or the Kain-Fritsch/Bechtold scheme is small and mixed for the stratiform overestimation, but clearly positive for convective overestimation.

To summarize, reducing initial humidity and using Runge-Kutta time integration has a positive effect on overestimation of stratiform precipitation. These changes also have a positive effect on convective overestimation which are additionally reduced by using the modified Tiedtke scheme or the Kain-Fritsch/Bechtold convection scheme.

Test cases with precipitation underestimation

Increasing the initial humidity improves the QPF for most of the test cases. The results of the GOP (Section 1.5.1) show that there are stations in France and Italy where the COSMO-EU is underestimating the observed humidity. Since Italy is one of the countries with several test cases of underestimation, underestimated humidity in the atmosphere should be investigated as a possible reason affecting the underestimation of precipitation.

The Runge-Kutta time integration scheme tends to reduce the area averaged precipitation and, hence, gives overall worse results for the test cases with underestimated precipitation. Still, there are both convective and stratiform test cases with underestimated precipitation that are improved by using Runge-Kutta (4, 9, 19, and 25).

The change of warm rain scheme and moderate changes of the snow microphysics and the Kain-Fritsch/Bechtold scheme have a mixed impact, improving some (mainly stratiform cases for the former and mainly convective cases for the latter) and worsening other test cases. The modified Tiedtke scheme has a predominantly negative effect on QPF for test cases with precipitation underestimation.

Concerning convective underestimation, only, the sensitivity experiments don't reveal changes of numerical methods or physical parameterizations that have a clear positive impact on all these test cases. The sensitivity to the initial atmospheric humidity is however fairly large, and a good simulation of atmospheric humidity is mandatory for a decent QPF. Changing the convection scheme nevertheless has a significant impact on the results and, thus, further investigations regarding the convection scheme is the most promising step for these test cases. This is an ongoing task within COSMO: the IFS convection scheme has been implemented into the COSMO model and its performance is currently being tested.

The sensitivity experiments were also evaluated depending on the existence of fronts or orographic forcing of the precipitation, but no special characteristics were found. The characteristics of the sensitivity experiments described above remain valid independent of a frontal passage or orographic forcing.

Table 5: Overview of cross experiments.

No.	Sensitivity study
23	COSMO 4.0
24	COSMO 4.0 + 90% initial humidity + Runge-Kutta
25	COSMO 4.0 + Kain-Fritsch/Bechtold
26	COSMO 4.0 + 90% initial humidity + Runge-Kutta + Kain-Fritsch/Bechtold
27	COSMO 4.0 + modified Tiedtke scheme
28	COSMO 4.0 + 90% initial humidity + Runge-Kutta + modified Tiedtke scheme

1.5.3 Cross experiments

The cross experiments are set up to explore the positive effects of multiple changes. The focus is the overestimation of stratiform precipitation because several sensitivity experiments showed potential to improve this QPF deficiency. Changes of initial humidity, the Runge-Kutta time integration scheme, modified microphysics and modifications of the convection scheme had positive effects on test cases with overestimated stratiform precipitation. These changes are combined in the cross experiments that are described in Tab. 5. - Even if being highly idealized, the simulation with decreased humidity is included in the cross experiments due to indications that atmospheric humidity might be overestimated in the model and due to its great sensitivity to QPF.

The cross experiments are performed using version 4.0, the latest version of the COSMO model. This version is differing from the reference version (version 3.19) mainly by microphysics changes that are similar to the changes in the warm rain scheme and changes of snow physics in sensitivity experiment 13. The term 'reference version' will be used in the following for the reference simulation performed with COSMO 3.19. The modifications of the Tiedtke convection scheme for the cross experiments are, compared to the previous studies, expanded by an exchange of cloud water and cloud ice with grid-scale variables.

The comparison of simulated 24h area averaged precipitation values shows similar results with the reference version and with version 4.0 (Fig. 7). The simulations with version 4.0 reduce the average precipitation by 1 to 3 mm for most of the test cases. There are only two test cases (18 and 25) where the area averaged precipitation is significantly increased, and these are cases where (stratiform) precipitation is underestimated with the reference version. With the exception of the underestimated convective cases 9 and 11, this results in a neutral or slightly improved simulation of area averaged precipitation for all test cases. There are two test cases of stratiform overestimation that are clearly improved by using version 4.0 (cases 8 and 10). For test case 8 the overestimation is reduced by 2.5 mm, which is about 30%, and for test case 10 the overestimation is reduced by 11 mm, corresponding to 80% of the bias. Thus, COSMO version 4.0 has a significant positive impact on some test cases of overestimated stratiform precipitation and generally slightly improves the precipitation simulation.

The comparison of the results of the cross experiments to those of the reference version show a strong reduction of average precipitation for nearly all test cases and cross experiments (Fig. 8; compare with Fig. 3 for individual sensitivity experiments). Version 4.0 (exp. 23), as discussed before, has the tendency to reduce the area averaged precipitation, on average by 10 to 30%. The reduction of initial humidity and the use of the Runge-Kutta time integration scheme (exp. 24) reduce the area averaged precipitation by at least 10%, but for most of the test cases by over 30%. Comparing the effect of the cross experiment with reduced initial

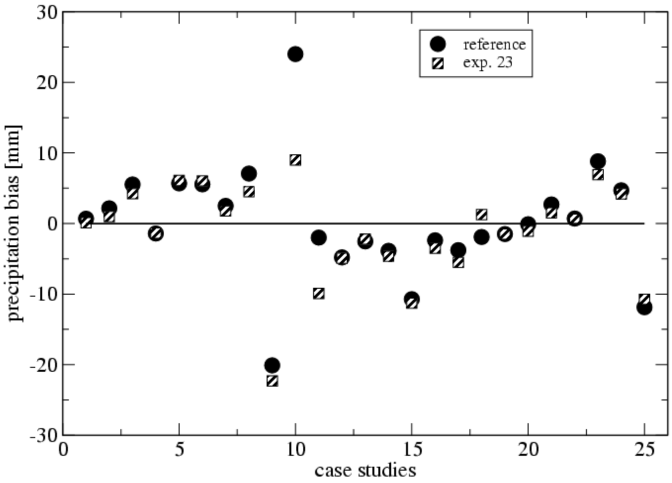

Figure 7: Bias of reference version (filled circles) and of the COSMO 4.0 version (striped squares).

humidity and Runge-Kutta scheme with their single effects leads to the conclusion that the effects of reduced initial humidity and Runge-Kutta time integration are adding up linearly without further non-linear amplification.

The test cases are again divided into cases with stratiform overestimation (Fig. 9) and cases with convective underestimation (Fig. 10) in order to study the effect of the cross experiments on different QPF deficiencies.

The results confirm that the cross experiments are reducing area averaged precipitation for most of the test cases and, thus, the bias of the test cases with overestimated stratiform precipitation is significantly improved for most of the cross experiments. 4 test cases have the best QPF results when using Kain-Fritsch/Bechtold, reduced initial humidity, and Runge-Kutta (exp. 26), 2 test cases when using only Kain-Fritsch/Bechtold (exp. 25) and 2 test cases when using the modified Tiedtke scheme, reduced initial humidity, and Runge-Kutta (exp. 28).

For test cases of underestimated convective precipitation the overall effect of the cross experiments is negative. Still, for two of the test cases (cases 4 and 16), the bias gets essentially zero if COSMO 4.0 is used together with the Kain-Fritsch/Bechtold scheme (exp. 25). For two other test cases (12 and 17), the bias is slightly improved using the Kain-Fritsch/Bechtold scheme. The increase of average precipitation in test case 12 is stronger than in the respective sensitivity experiment 15 that was performed with version 3.19 (Fig. 8 and Fig. 3) More generally, comparing the effect of using Kain-Fritsch/Bechtold in COSMO 3.19 and COSMO 4.0 seems to show that there is a tendency of a stronger impact of changing the convection scheme in version 4.0 (not shown). These results confirm that the convection parametrization is the most promising part of the model to concentrate on in order to improve the test cases with underestimated convective precipitation.

To summarize the effect of the cross experiments, 18 out of 25 test cases have been significantly improved by one of the cross experiments, including all 9 (3) test cases with overestimated stratiform (convective) precipitation. 5 test cases show the smallest bias if

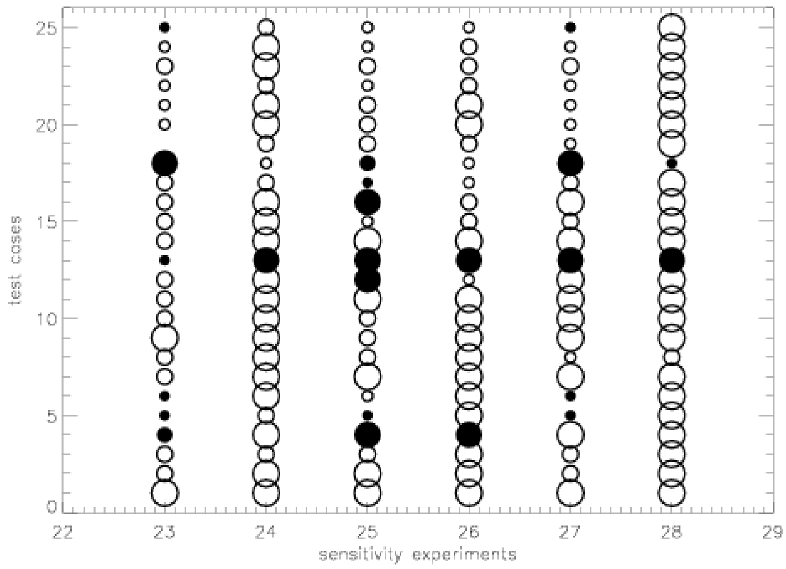

Figure 8: Difference of 24h area averaged precipitation in the cross experiments (23-28) and in the reference simulation relative to the 24h area averaged precipitation in the reference simulation Δrel [%]. Filled (empty) circles indicate an increase (decrease) of precipitation relative to the reference simulation. The big circles indicate an absolute change bigger than 30%, medium ones between 10% and 30% and small ones between 0% and 10%, tiny circles indicate cases with no change at all.

COSMO 4.0 is used with the Kain-Fritsch/Bechtold convection scheme. QPF of 3 test cases each is improved using reduced initial humidity, Runge-Kutta time integration, and Kain-Fritsch/Bechtold or modified Tiedtke scheme, respectively. 7 test cases are hardly affected or worse, 4 (3) of them being test cases of underestimated convective (stratiform) precipitation. The latter result is a consequence of the main focus of the cross experiments.

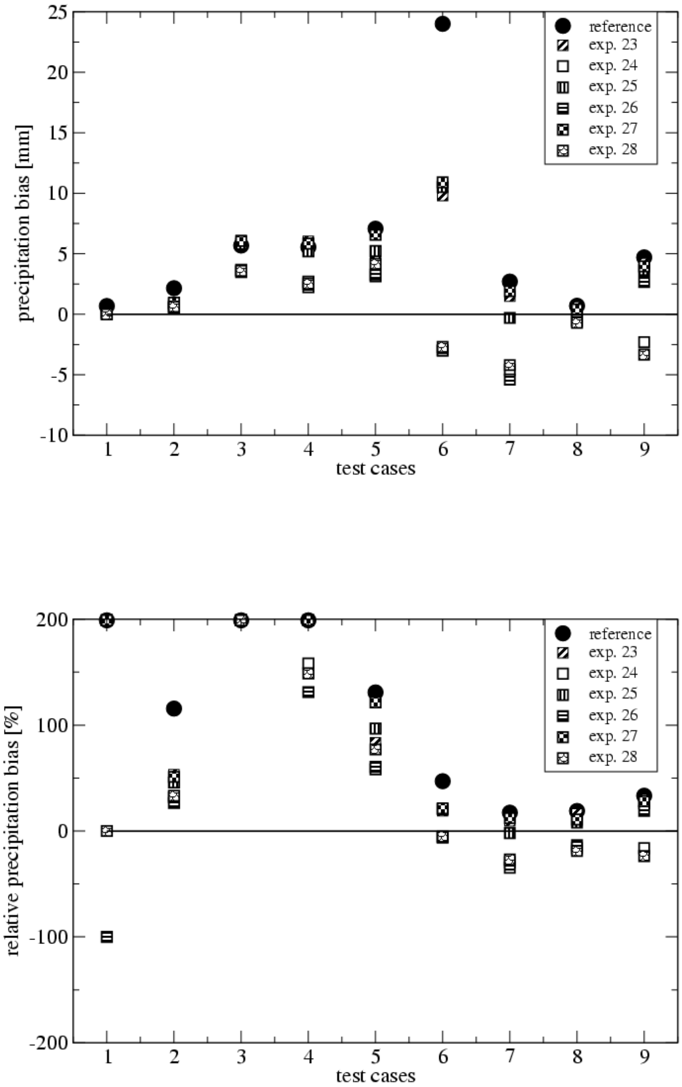

Figure 9: Absolute (upper panel) and relative (lower panel) precipitation bias (($P_{exp} - P_{obs}$) and $(P_{exp} - P_{obs})/P_{obs}$, respectively) of the reference simulation (black circles) and the cross experiments compared to the observations for cases with overestimation of stratiform precipitation. The test cases are 1, 2, 5, 6, 8, 10, 21, 22, and 24.

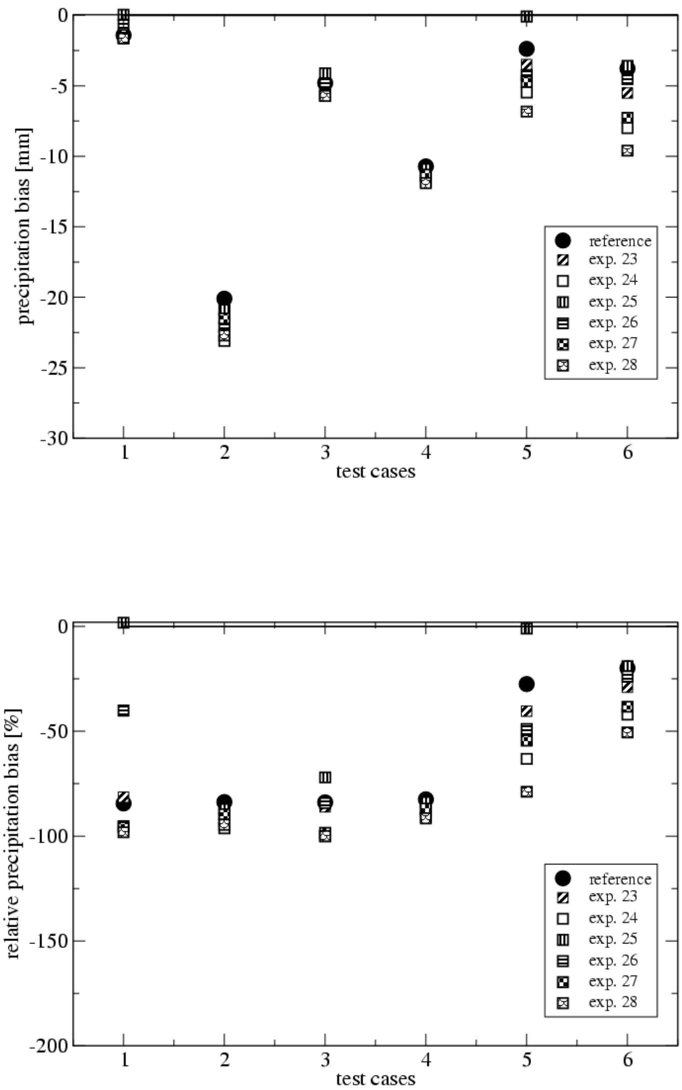

Figure 10: Absolute (upper panel) and relative (lower panel) precipitation bias (($P_{exp} - P_{obs}$) and $(P_{exp} - P_{obs})/P_{obs}$, respectively) of the reference simulation (black circles) and the cross experiments compared to the observations for cases with underestimation of convective precipitation. The test cases are 4, 9, 12, 15, 16, and 17.

1.6 Summary and conclusions

Quantitative precipitation forecasting (QPF) is difficult ! Verification results and forecaster feedback suggest that the operational implementations of the COSMO model (7 to 14 km horizontal grid spacing), like many other numerical weather prediction models, have some problems in quantitatively forecasting precipitation. This was the motivation to launch the COSMO Priority Project 'Tackle deficiencies in quantitative precipitation forecasts'. The aim was to determine which parts of the modelling system have a significant impact on QPF quality and, thus, might have the potential to improve QPF. The focus of the project was on numerical methods and physical parameterizations, while the effects of inaccurate initial and boundary data were largely neglected.

In the first step of the project test cases were selected that reflect typical forecast errors for the different regions of interest of the participating meteorological services. To ensure that the observed COSMO model forecast deficiencies are not due to an old model version or a specific local model implementation, all test cases were re-run with a COSMO model reference version using a 7 km grid spacing. From the test cases, for which the COSMO model reference version reproduced the reported QPF problem, a list of 25 test cases was selected. The selected test cases thereby fall into two prominent groups of forecast errors: 9 test cases with stratiform overestimation, mainly in Germany, Switzerland, and Poland, and 7 test cases of convective underestimation, mainly in Italy and Greece. As a second step, a set of sensitivity studies concerning initial conditions, numerics, and model physics has been prepared. The list includes 22 sensitivity experiments as well as 6 cross-sensitivity runs that are simulated for all test cases. All in all, some 700 simulations had to be performed and analyzed. The evaluation of the sensitivity experiments is based on the 24h area averaged precipitation for selected evaluation regions with a minimum size of 100 km times 100 km. Hence, the focus is on large scale over- or underestimation of QPF. Problems of wrong small-scale localization or wrong temporal simulation are not looked at. The results of these sensitivity studies provide a broad overview of which parts of the modelling system are most relevant for QPF and suggest potential model variants that may lead to better quantitative precipitation forecasts.

The sensitivity experiments show that the strongest influence on QPF is caused by changes of the initial humidity and by using the Kain-Fritsch/Bechtold convection schemes. Both sensitivity experiments result in average relative differences of the area averaged precipitation values in the range of 30-40%. Using the Runge-Kutta time integration scheme instead of the Leapfrog scheme, applying a modified warm rain and snow physics scheme or a modified Tiedtke convection scheme all change the area averaged precipitation by roughly 10%. Finally, but only for the Roman and Greek test cases, which all have a strong influence from the sea, the heat and moisture exchange between surface and atmosphere is of great importance and can cause changes in the range of up to 25%.

The great importance of *atmospheric humidity* for the area averaged precipitation is not surprising. Still, these studies re-affirm this fact and the necessity to investigate the effect of humidity regarding QPF errors. There are indications from verification that there are indeed deficiencies in the humidity simulation. The comparison of radiosonde data and COSMO-EU profiles of mixing ratio performed in the frame of GOP shows that the model systematically overestimates atmospheric humidity, especially in the northern part of Europe. It also shows underestimation, especially in summer, in the southern part of Europe. These errors in the simulated atmospheric humidity field may strongly correspond to prevailing QPF errors of overestimated stratiform precipitation and underestimated convective precipitation. No detailed analysis of this interrelation has been performed that would allow to draw firm conclusions, but the results of the sensitivity experiments provide motivation to have a closer look at the simulation of atmospheric humidity in order to prove or disprove its influence on QPF deficiencies.

The other important parameter influencing QPF, the *convection parametrization*, is also an expected one. The Kain-Fritsch/Bechtold scheme gives better results for 9 and worse results for 8 test cases. Test case 4, a case of underestimated convective precipitation, is significantly improved by using the Kain-Fritsch/Bechtold scheme. The scheme was tested in a quasi-operational test chain at MeteoSwiss in 2006 and showed promising results, especially regarding the diurnal cycle of precipitation. However, the test chain also revealed deficiencies. Further adaptations in order to avoid spin-up effects and overestimation of low precipitation amounts are required. Since no institute is currently developing this scheme or using it operationally, it was decided to implement and adapt the operational IFS convection scheme rather than continuing work on the very similar but unsupported Kain-Fritsch/Bechtold scheme. The other convection scheme used in the sensitivity experiments is the modified Tiedtke scheme which over all has a slightly negative impact on QPF. It improves the simulation of test cases with overestimated convective precipitation and has a neutral effect on overestimated stratiform precipitation, but it worsens test cases with underestimation of precipitation. This variant of the Tiedtke scheme is currently being revised and tested at DWD. Investigations regarding convection in the COSMO model are hence going on and it will be interesting to see how the new or further modified schemes perform in the COSMO model.

Using the *Runge-Kutta* time integration scheme instead of the Leapfrog scheme shows astonishing results: the area averaged precipitation values are significantly reduced,(by typically 10%) for most of the test cases. It is not yet fully understood why the scheme is predominantly reducing the precipitation amount, but it might be related to insufficient accuracy of the centered differences which are used in the reference simulation for advection of humidity and cloud water. Few test cases show an increase of area averaged precipitation with the Runge-Kutta scheme, and for those test cases it is a change in the right direction. Thus, the Runge-Kutta scheme has a positive effect on QPF for all cases with overprediction of precipitation as well as for some cases with underprediction of precipitation, and *is recommended for use.*

The *microphysics* changes similar to sensitivity experiment 13 are already included in COSMO version 4.0. They showed a positive impact on QPF for many test cases. The positive effect is confirmed by the comparison of COSMO version 4.0 to version 3.19 that shows a neutral or slightly positive impact on QPF for almost all the test cases when using the new model version.

The *cross experiments*, mainly targeted at the cases with overpredicted stratiform precipitation, confirm the main findings summarized above: Use of COSMO version 4.0 and the Runge-Kutta time integration scheme is encouraged, and more work on the simulation of atmospheric humidity as well as on further improvement of the convection schemes in needed to obtain better quantitative precipitation forecasts.

There are some limitations of this study which have to be kept in mind. To give just one example, all simulations were based on the same initial conditions, which can lead to an overestimation of the model sensitivity, since in a full NWP system that includes data assimilation, the initial conditions will always adjust to the new model physics or numerics. This effect of somewhat inconsistent initial conditions might, for example, contribute to the strong sensitivity of the accumulated precipitation which was found for the new microphysics in COSMO 4.0. Some of the reduction might be caused by the inconsistency of the old initial conditions, which are based on COSMO 3.19, and only the rest by the new microphysics in

COSMO 4.0. Still, the sensitivity studies shown here can provide some guidance and insight for improving or at least tuning the model to give better QPF results.

2 Workshops and meetings

- LM User Seminar, Langen, Germany, 8 March 2006
- COSMO General Meeting, Bucharest, Romania, 18 September 2006
- LM User Seminar, Langen, Germany, 8 March 2007
- Visit of Axel Seifert at MeteoSwiss, 24-25 April 2007
- COSMO General Meeting, Athens, Greece, 21 September 2007

3 Presentation of QPF results

- Silke Dierer et al.: LM User Seminar, Langen, Germany, 6-8 March 2007
- Federico Grazzini et al.: National Meeting of Geophysics, Ischia, Italy, 11-15 June 2007
- Massimo Milelli et al.: EMS, San Lorenzo de El Escorial, Spain, 1-5 October 2007
- Silke Dierer et al.: COSMO General Meeting, Athens, Greece, 19 September 2007
- Silke Dierer et al.: SRNWP Workshop, Bad Orb, Germany, 5-7 November 2007
- Antonella Morgillo et al.: SRNWP Workshop, Bad Orb, Germany, 5-7 November 2007

4 Test cases description

4.1 Germany

Simulation domain: 333 x 333 grid points, 7 km grid spacing, startlat = -9.75, startlon = -12.75, pollat = -40, pollon = -170

Evaluation domain: Germany

Responsible scientists: Uli Damrath (Task 1), Axel Seifert (Task 2)

Test case 06.12.2004

QPF problem: widespread overestimation of drizzle

Best sensitivity study: COSMO 4.0 with RK solves the problem. COSMO 4.0 with LF gives similar results. The main effect is due to the modification of the cloud microphysics in COSMO 4.0, especially the autoconversion rate.

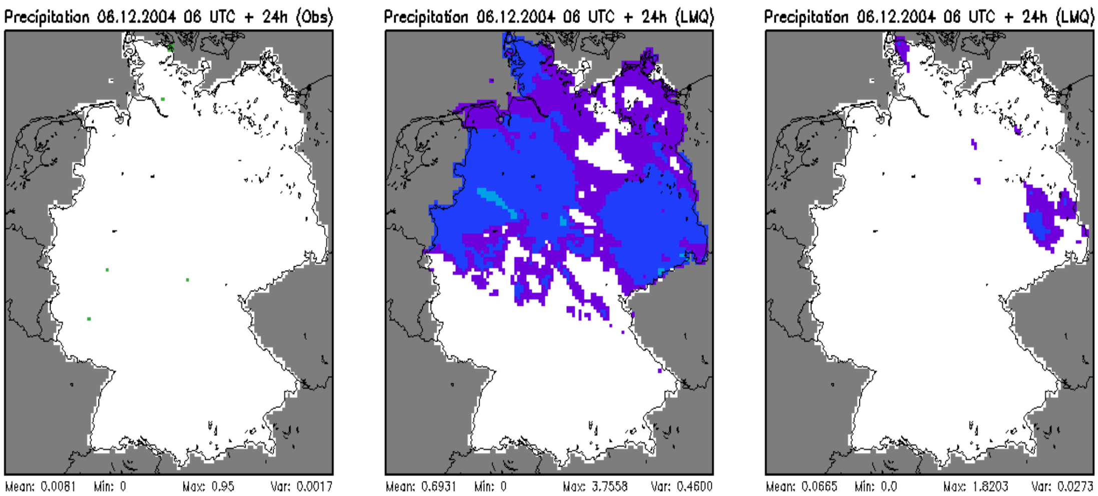

Figure 11: 24h precipitation sum from 06.12.2004, 06 UTC - 07.12.2004, 06 UTC from surface observations (left), the reference simulation (centre) and the sensitivity study with COSMO 4.0 and Runge-Kutta time integration (right).

Test case 18.03.2005

QPF problem: overestimation of stratiform precipitation

Best sensitivity study: no single sensitivity study was able to solve this case. The best improvement can be achieved by a combination of modifications which help to reduce the precipitation amounts in general, e.g. the cross-experiment A4 using COSMO 4.0 with Runge-Kutta core, KFB convection scheme and a reduction of the initial humidity.

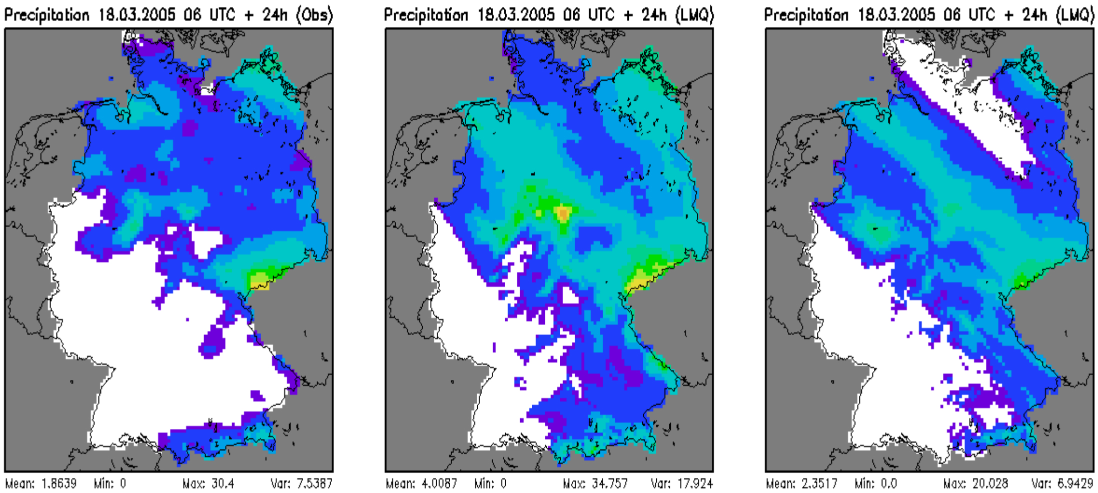

Figure 12: 24h precipitation sum from 18.03.2005, 06 UTC - 18.03.2005, 06 UTC from surface observations (left), the reference simulation (centre) and the sensitivity study with COSMO 4.0, Runge-Kutta time integration, KFB convection scheme and reduced initial humidity (right).

Test case 03.05.2005

QPF problem: overestimation of precipitation in a summertime event due to 'double-counting' of grid-scale and convective precipitation. Mean and maximum values are much too high. Probably caused by upscaling of convective motions to the grid-scale.

Best sensitivity study: COSMO 4.0 with Runge-Kutta and the modified Tiedtke convection scheme. The COSMO 4.0 with Runge-Kutta and KFB convection scheme does also a good job, but in this setup more of the overestimation of precipitation remains in the forecast. Detrainment of condensate from the convection scheme seems to help in this case.

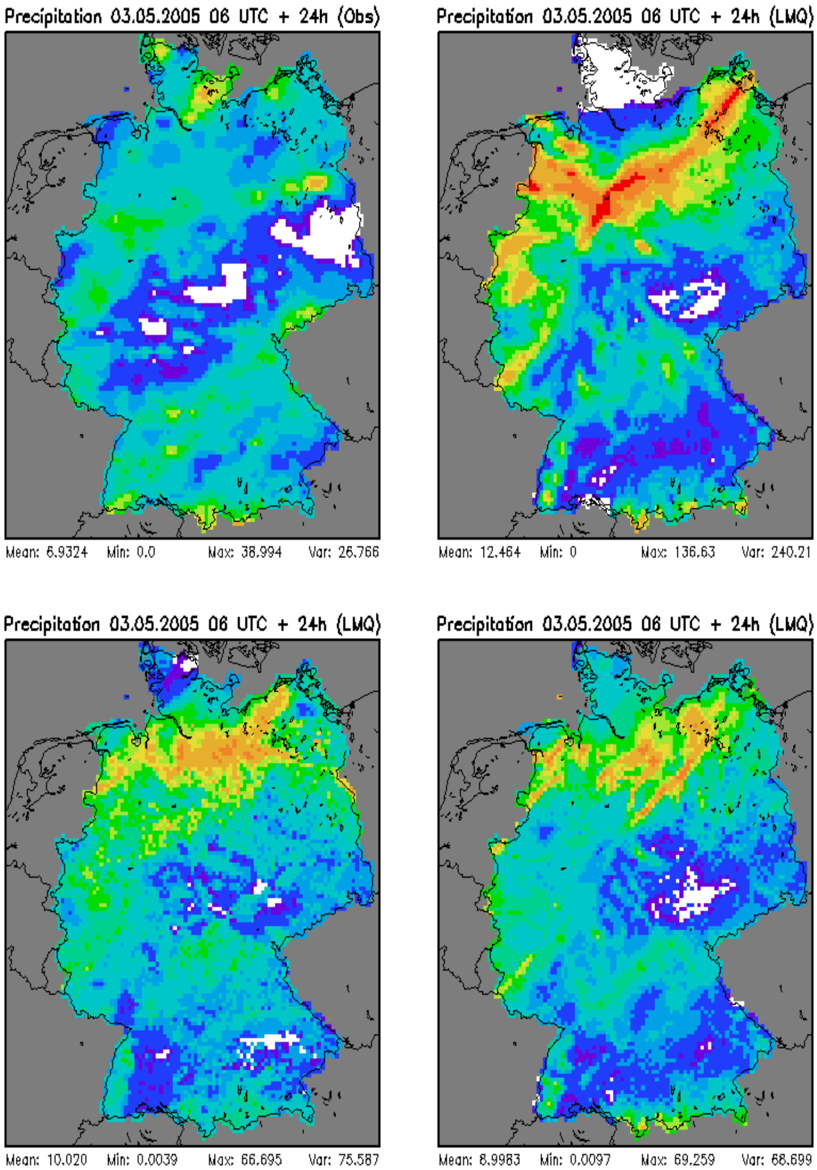

Figure 13: 24h precipitation sum from 03.05.2005, 06 UTC - 03.05.2005, 06 UTC from surface observations (upper left), the reference simulation (upper right), the sensitivity study with COSMO 4.0, Runge-Kutta time integration and KFB convection scheme (lower left) and an additional cross-sensitivity study COSMO 4.0 + Runge-Kutta + modified Tiedtke scheme.

Test case 21.06.2005

QPF problem: underestimation of the amount of precipitation in a convective event.

Best sensitivity study: the KFB scheme captures this event very well leading to a good forecast. This is a robust result independent from other choices, e.g. using RK vs LF or COSMO 3.19 vs 4.0.

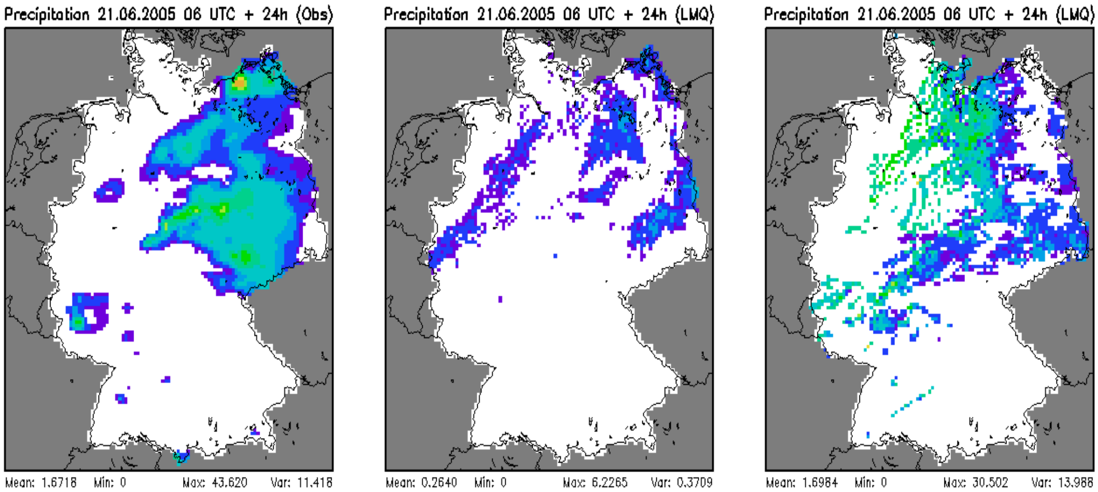

Figure 14: 24h precipitation sum from 21.06.2005, 06 UTC - 22.06.2005, 06 UTC from surface observations (left), the reference simulation (centre) and the sensitivity study with COSMO 3.19 and the KFB convection scheme (right).

4.2 Switzerland

Simulation domain: latitude 35.17/57.50; longitude -8.0/23.24

Evaluation domain: latitude 45.8/47.7; longitude 6.0/10.5

Responsible scientists: Silke Dierer and Francis Schubiger (Task 1), Silke Dierer (Task 2)

Test case 02.02.2005

QPF problem: northerly flow at 500 hPa, occluded front passing northeast of Switzerland. In the morning snow starting from north, locally rain. In the afternoon decaying snowfall. Overestimation of precipitation at the northern slopes of the Alps and in the mountains. Typical error pattern for situations with northerly flow.

Best sensitivity study: Runge-Kutta (independent of advection, in this case flux-form advection, exp. 8)

Best cross experiment: COSMO 4.0 with Kain-Fritsch/Bechtold, Runge-Kutta and reduced initial humidity (exp. 26)

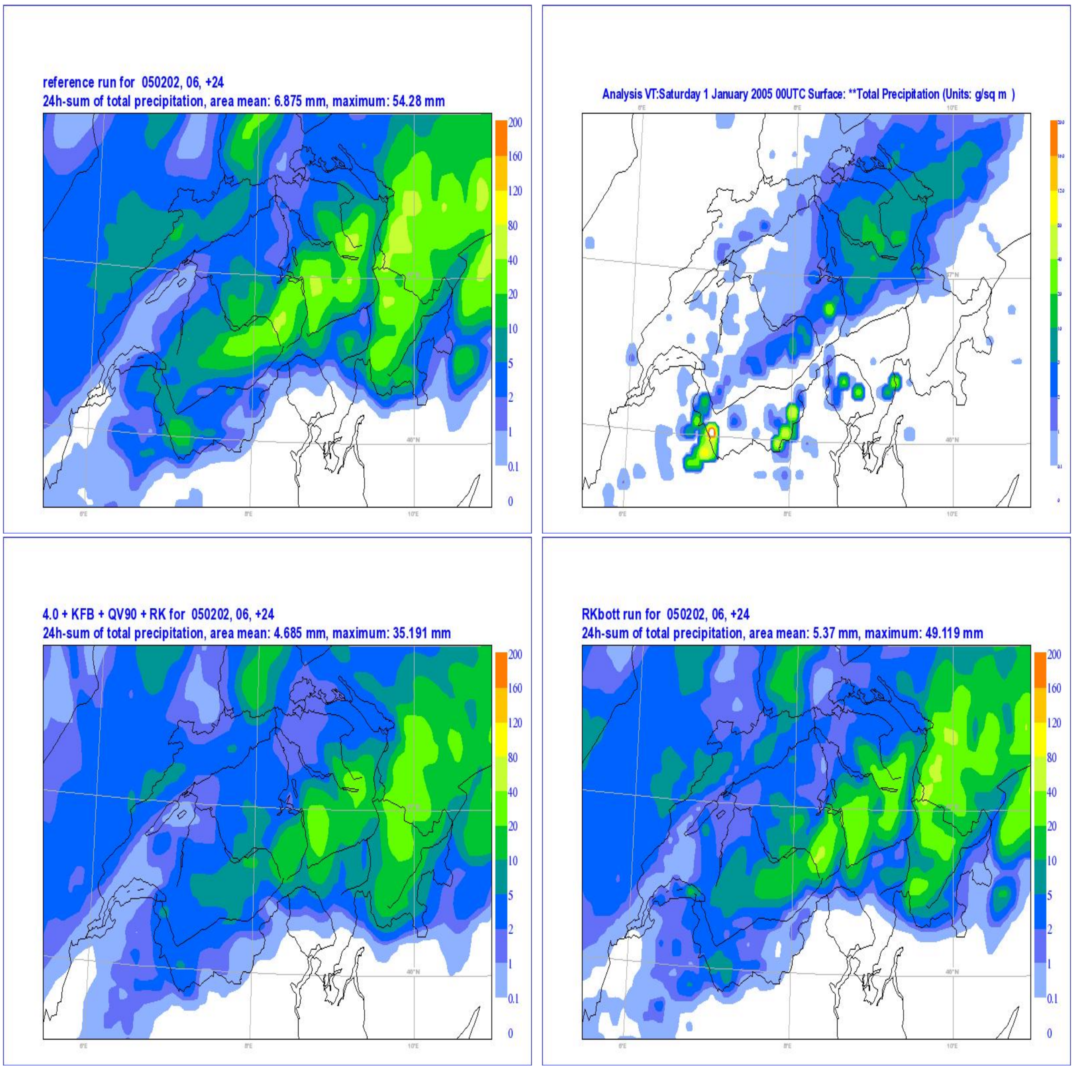

Figure 15: 24h precipitation sum from 02.02.2005, 06 UTC - 03.02.2005, 06 UTC from radar observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with Runge-Kutta and flux-form advection (exp. 8, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold, Runge-Kutta and reduced initial humidity (exp. 26, lower panel, right).

Test case 22.03.2005

QPF problem: Switzerland is influenced by a high pressure system at 500 hPa with a weak south-westerly flow. A warm front is crossing Switzerland and, later, a cold front is crossing in the north. Overestimation of precipitation, mainly in the middle and eastern part of Switzerland.

Best sensitivity study: reduced initial humidity (exp. 3). Reducing the amount of precipitation to realistic values. Still, the location of precipitation remains wrong.

Best cross experiment: all studies with reduced initial humidity and Runge-Kutta very similar, lowest bias with reduced initial humidity, Runge-Kutta and Kain-Fritsch/Bechtold (exp. 26). Reducing the amount of precipitation to realistic values. Still, the location of precipitation remains wrong.

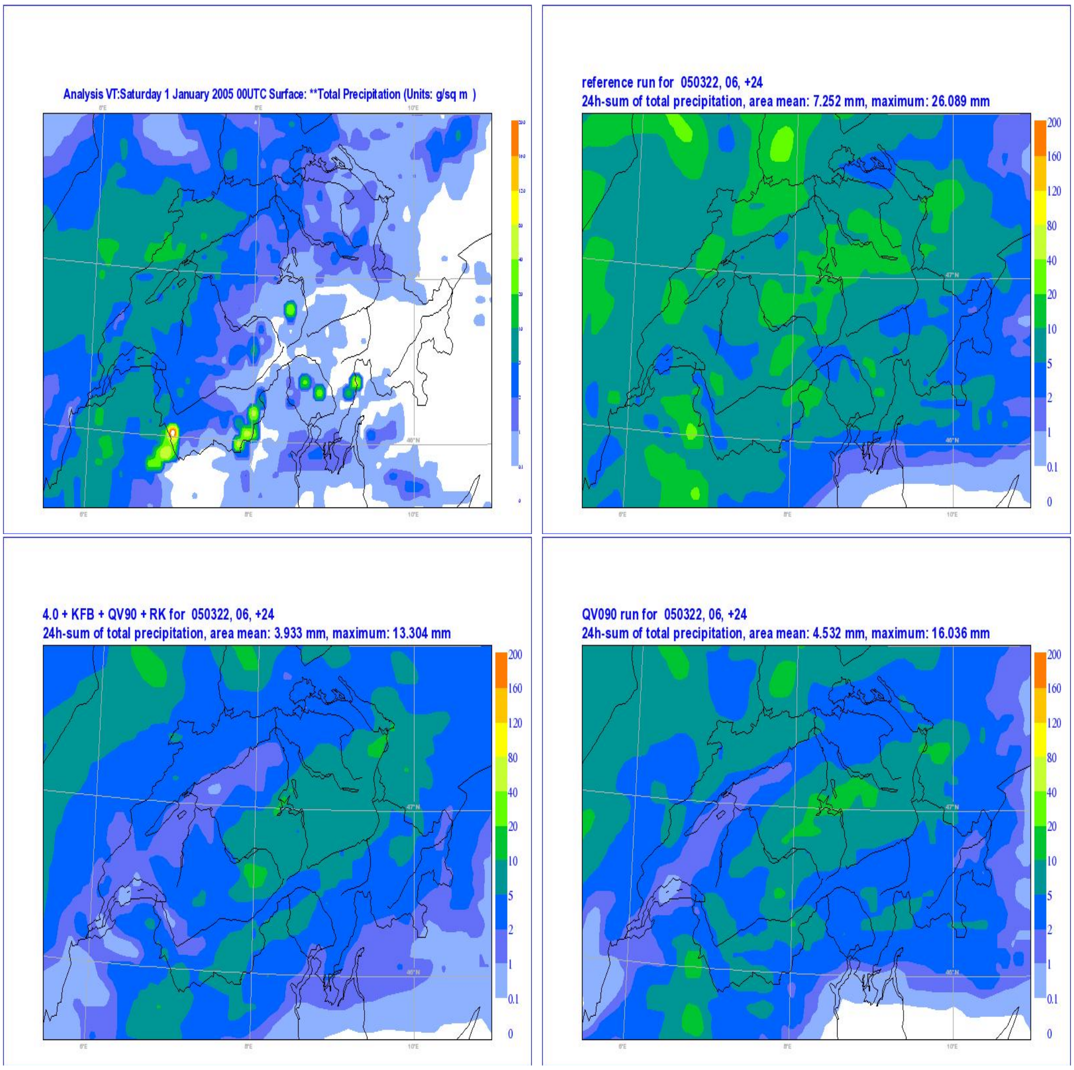

Figure 16: 24h precipitation sum from 22.03.2005, 06 UTC - 23.03.2005, 06 UTC from radar observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with reduced initial humidity (exp. 3, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold, Runge-Kutta and reduced initial humidity (exp. 26, lower panel, right).

Test case 12.07.2005

QPF problem: low pressure system at 500 hPa over Croatia and influence of an Atlantic high pressure ridge towards Ireland: north-easterly flow at 500 hPa over the Alpine area. In the afternoon thunderstorms in Jura and Tessin. Those are hardly captured by the model. Wrong simulation of precipitation in the northern and eastern part of Switzerland.

Best sensitivity study: reduced initial humidity (exp. 3). Reducing and, thus, improving the amount of precipitation. Still, the location of precipitation remains wrong.

Best cross experiment: simulation with COSMO 4.0, reduced initial humidity, Runge-Kutta and Kain-Fritsch/Bechtold (exp. 26) improves the simulation of the precipitation north of Switzerland slightly improves the simulation of precipitation in the Tessin. Simulation of precipitation in the eastern part is reduced, but did not disappear.

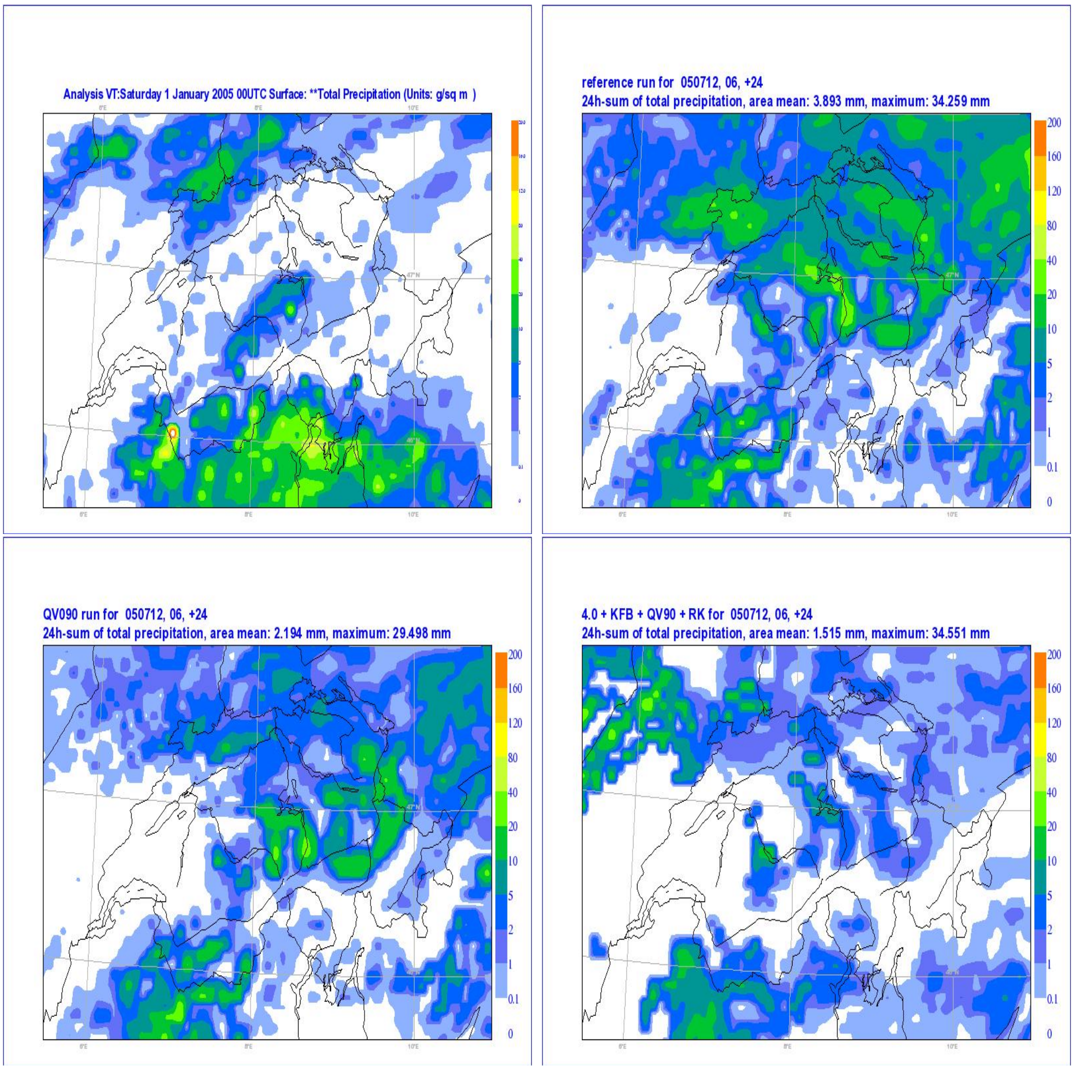

Figure 17: 24h precipitation sum from 12.07.2005, 06 UTC - 13.07.2005, 06 UTC from radar observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with reduced initial humidity (exp. 3, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold, Runge-Kutta and reduced initial humidity (exp. 26, lower panel, right).

Test case 17.12.2005

QPF problem: northwesterly flow at 500 hPa, strong jet from Island to the Alps, very strong temperature gradient at 500 hPa over Switzerland. In the Alps and at the northern slopes constant snowfall, snow shower in the flat regions of Switzerland. Overestimation of precipitation in the middle and in the southern part of Switzerland. Typical error pattern for situations with northwesterly flow.

Best sensitivity study: Runge-Kutta (independent of advection, in this case flux-form advection, exp. 8). The average precipitation is reduced, but the region of precipitation remains too big.

Best cross experiment: COSMO 4.0 with reduced initial humidity, Runge-Kutta and Kain-Fritsch/Bechtold (exp. 26). Using COSMO 4.0 already gives a good reduction of the overestimation and using Runge-Kutta additionally increases this effect. While the amount of precipitation is in much better agreement now, there is still wrong simulation of precipitation in the Jura and in Graubünden.

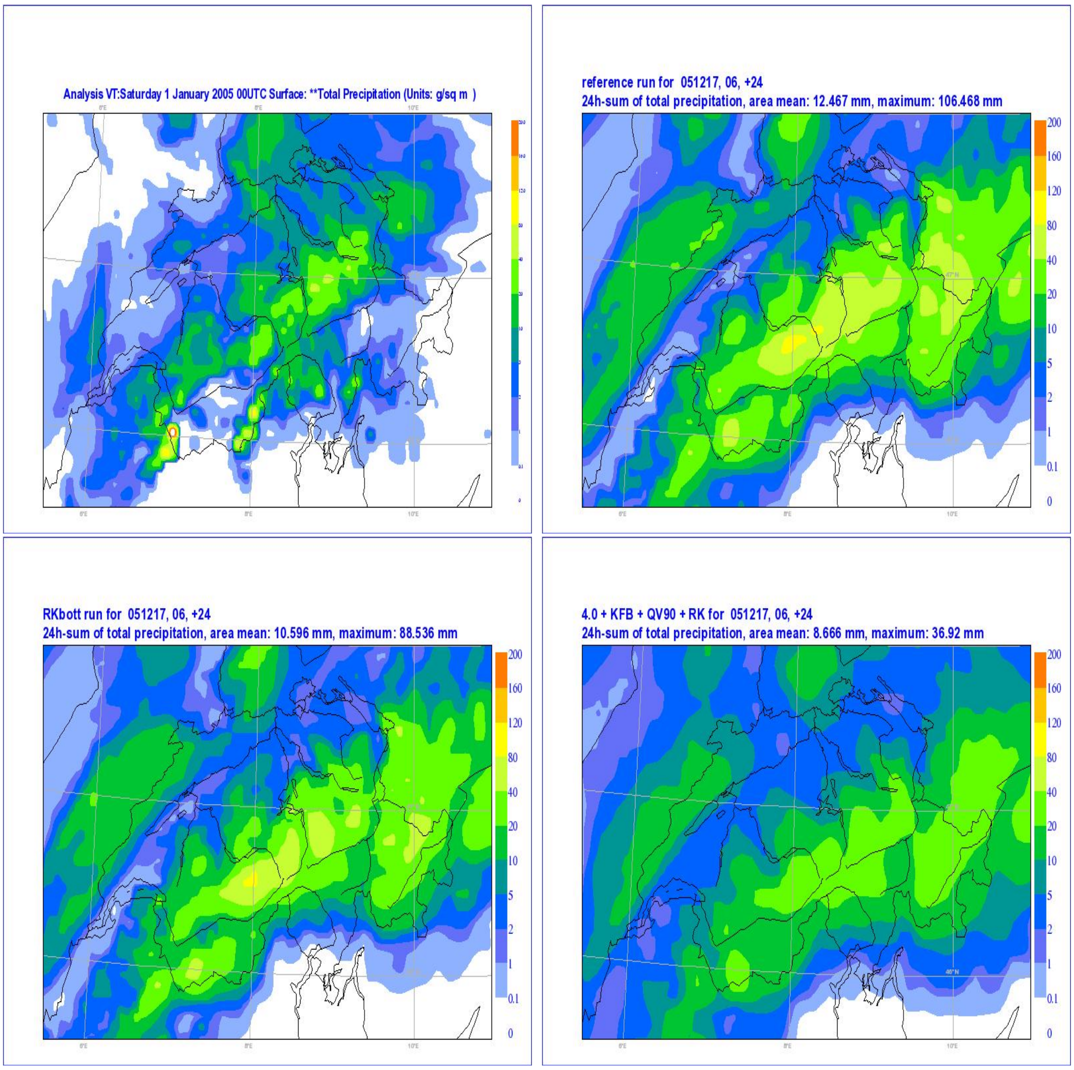

Figure 18: 24h precipitation sum from 17.12.2005, 06 UTC - 17.12.2005, 06 UTC from radar observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with reduced initial humidity (exp. 3, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold, Runge-Kutta and reduced initial humidity (exp. 26, lower panel, right).

4.3 Emilia Romagna, Piemonte, Campania

Test case 24.09.2004

Simulation domain: latitude 32.81/50.51; longitude 2.16/24.76

Evaluation domain: latitude 43.75/45; longitude 10.5/12.2

Responsible scientists: Federico Grazzini (Task 1), Paola Mercogliano (Task 2)

QPF problem: deficiencies in the convection triggering caused by complex orography

Best sensitivity study: the best results for this test case (with stratiform and convective precipitation) has been found: increasing the initial humidity, switch off the convective parametrization; for the two runs in which has been Increased the vertical exchange of heat and moisture (on the soil and on the sea).

Best cross-experiment study: COSMO 4.0 with increased initial humidity, Runge-Kutta scheme for the numerics and Kain-Fritsch for the convection scheme (This particular experiment has not been reported in this paper but it has been considered only for this particular convective test case with strong underestimation).

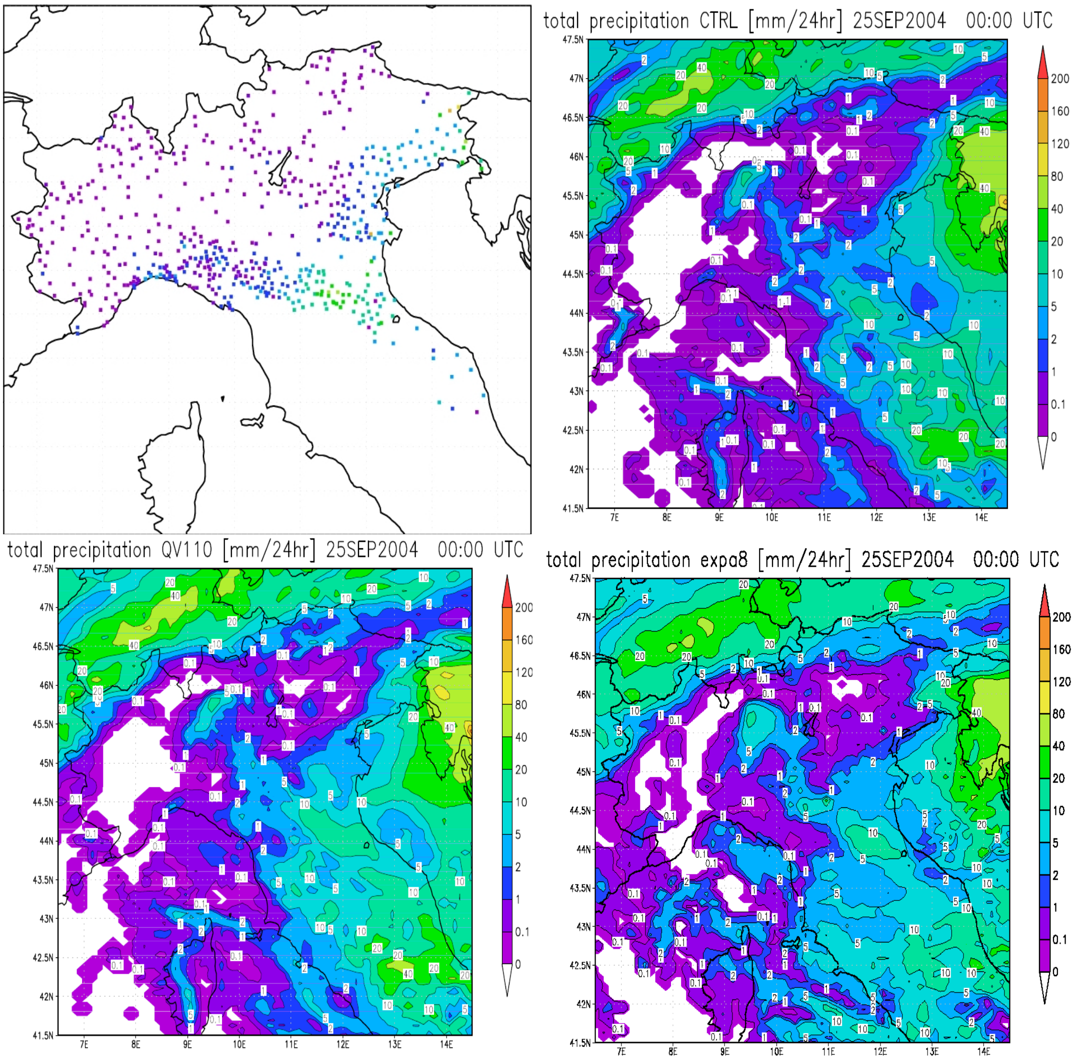

Figure 19: 24h precipitation sum from 24.09.2004, 00 UTC - 25.09.2004, 00 UTC from in situ observations of (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with increased initial humidity (exp. 4, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold, Runge-Kutta and increased initial humidity (lower panel, right).

Test case 10.04.2005

Simulation domain: latitude 35.4/48.5; longitude 5/20.5

Evaluation domain: approximately 44.8N/43.8N, 10E/12.5E

Responsible scientists: Federico Grazzini (Task 1 and Task 2)

QPF problem: precipitation overestimation in a occluded front linked to a Mediterranean cyclone over Tirrenian Sea.

Best sensitivity study: the largest impact for our case of stratiform precipitation has been found with changes in the microphysics (Micro experiments) and with the introduction of version 4.0. In particular these versions contributed to reduce the overestimate of precipitation. A strong positive impact has been found in SEA40 and QV090.

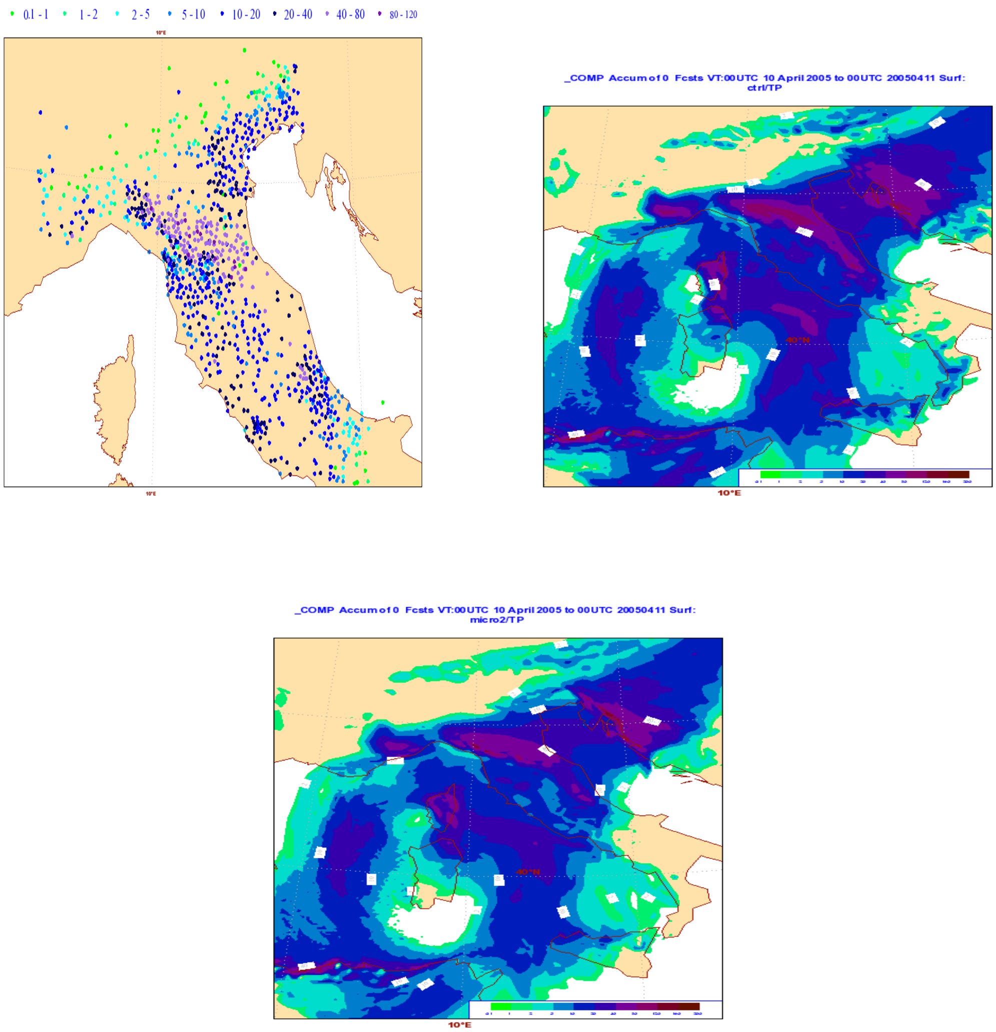

Figure 20: Observed precipitation (upper panel, left), in the reference run (upper panel, right), in the micro2 experiment (lower panel.

Test case 17.08.2006

Simulation domain: latitude 38.52N/51.48N; longitude 1.92W/17.98E

Evaluation domain: latitude 45.3N/46.6N; longitude 7.5E/9.3E

Responsible scientists: Elena Oberto (Task 1), Massimo Milelli (Task 2)

QPF problem: south-westerly flow at 500 hPa; cold frontal system with thunderstorms. Localized underestimation in the northern part of the region, both in the mean and in the maxima over the warning areas. Slight shift of the precipitation peak towards Tessin where the maximum value has been forecasted.

Best sensitivity study: actually it is difficult to find a simulation that gives better results than the ctrl. The stand-alone modifications (RK or QV or microphysics) do not improve the results.

Best cross experiment: a modification of Exp 24 (4.0 + QV090 + RK) in which humidity has been increased by 10% (fak=1.1) instead of being reduced by 10%. It has been called exp a7 (4.0 + QV110 + RK). Only in this case the relative error of the precipitation over the considered area is reduced (slightly) with respect to the other runs. Second place for the ctrl.

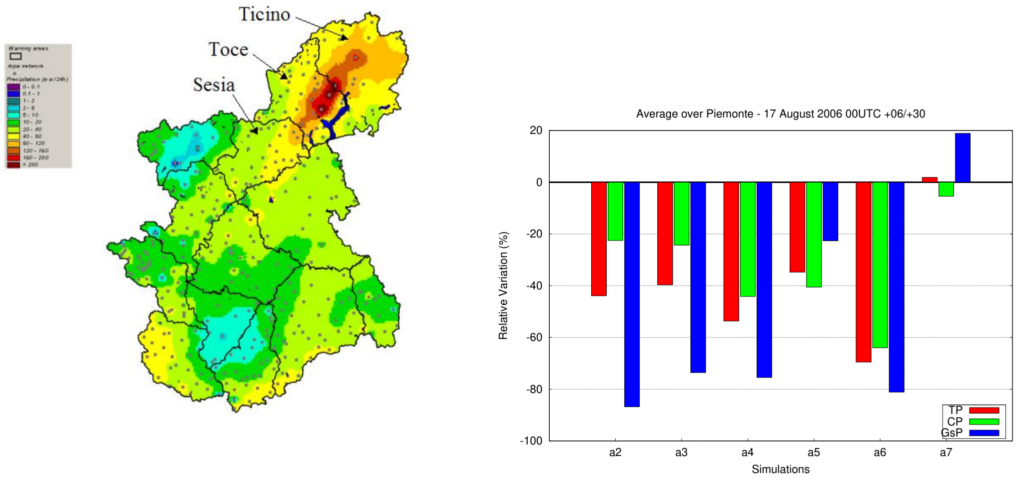

Figure 21: Left: observed rainfall depths in the North-Western Italy. The panel refers to the 24 h cumulated rainfall depth (06 UTC 17 August - 06 UTC 18 August). The rain gauges are plotted in grey and the warning areas in black. The affected areas, indicated with arrows, are Ticino (CH), Toce and, marginally, Sesia. Right: relative bias (%) of the different simulations with respect to the Ctrl run (a1) for different domains in the +6h/+30h time interval. Average performed over Piemonte region. Total Precipitation in red (TP), Convective Precipitation in green (CP) and Grid-scale Precipitation in blue (GsP). See Milelli et al. (2008) for more details.

Test case 09.09.2005

Simulation domain: latitude 32.81/50.51; longitude 2.16/24.76

Evaluation domain: latitude 40.5/41.5; longitude 13.8/15

Responsible scientists: Paola Mercogliano (Task 1 and Task 2)

QPF problem: deficiencies in the triggering of the afternoon convection along the coast line.

Best sensitivity study: the large impact on this convective case on the Italian coastal area has been obtained increasing the initial humidity, and changing the microphysics (in particular the experiment MICRO2).

Best cross-experiment study: COSMO 4.0 with increased initial humidity and using Runge-Kutta scheme fits well the average and the maximum value on the area (This particular experiment has not been reported in this paper but it has been considered only for this particular convective test case with strong underestimation).

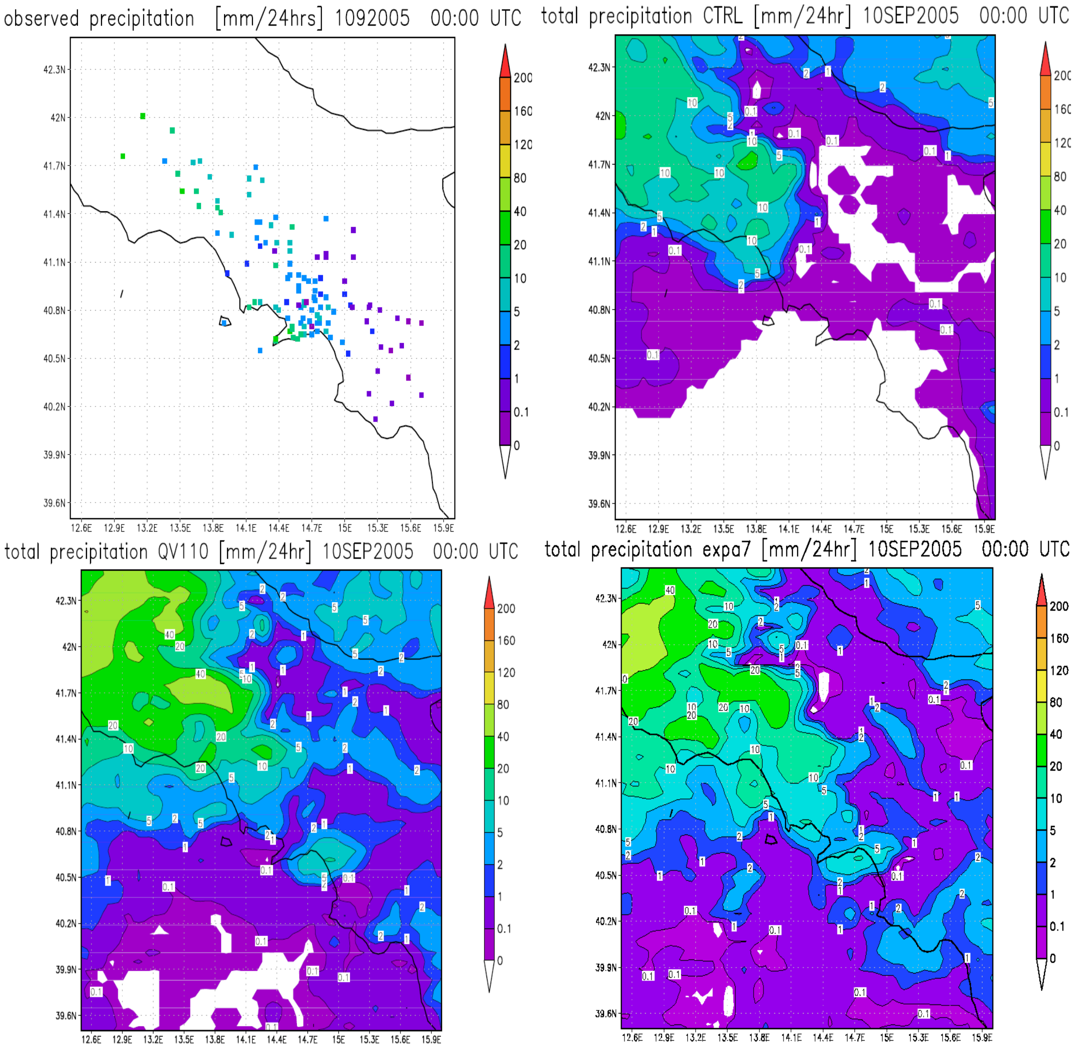

Figure 22: 24h precipitation sum from 09.09.2005, 00 UTC - 10.09.2005, 00 UTC from in situ observations of (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with increased initial humidity (exp. 4, lower panel, left) and in the cross experiment with COSMO 4.0, Runge-Kutta and increased initial humidity (lower panel, right).

4.4 Rome

Simulation domain and evaluation domain: dlat=0.0625, dlon=0.0625, ielm_tot=321, jelm_tot=321, kelm_tot=40, pollat=40, pollon=-170.0, startlat_tot=-16.5, startlon_tot=-10.0

Responsible scientists: NN (Task 1), Rodica Dumitrache (Task 2)

Test case 01.12.2005

QPF problem:

- Sicily: 250 l/m^2 observation vs 25-50 l/m^2 model
- Ionian part of Calabria: 5 l/m^2 observation vs 25-50 l/m^2 model

Best sensitivity study: CTR, microphysics, numeric and surface simulations for Standard version tests

Best cross experiment: A1, A2, A6 for the LM 4.0 tests

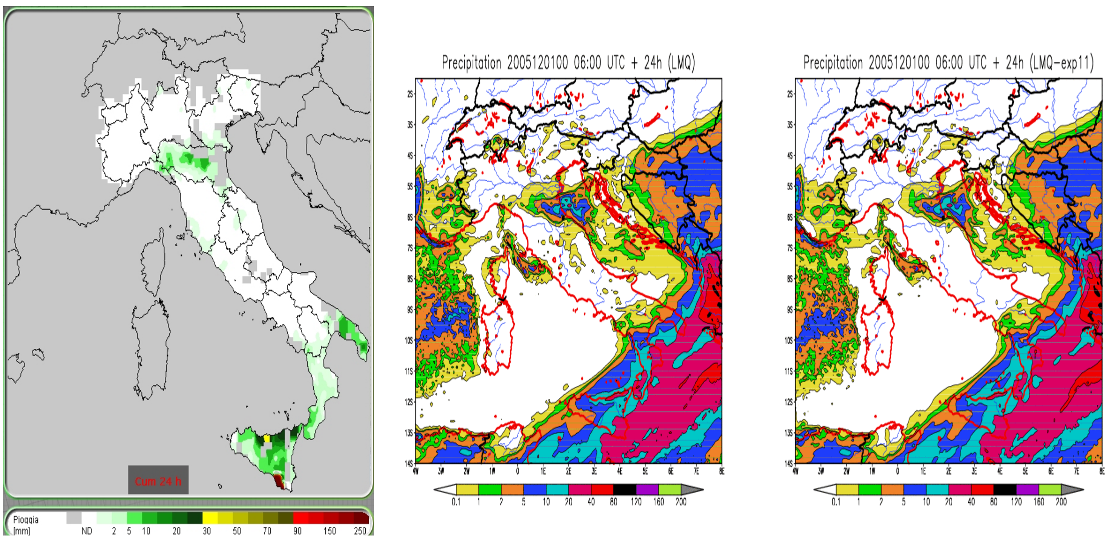

Figure 23: 24 h cumulated precipitation observation (left); 24h cumulated precipitation CTRL run (middle); 24h cumulated precipitation exp11 (right).

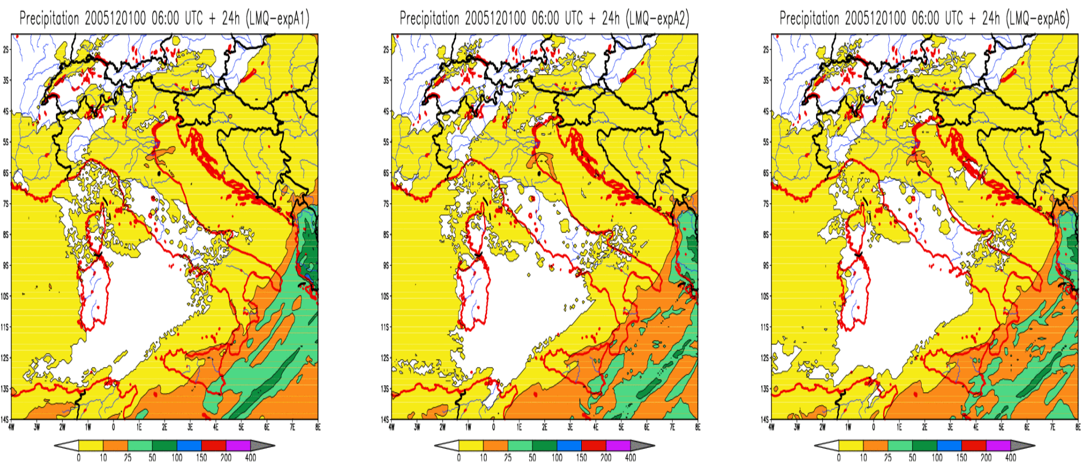

Figure 24: exp A1 (left); exp A2 (middle); exp A6 (right).

Test case 03.12.2005

QPF problem: east part of Liguria and north Toscana: 250 l/m^2 observation vs 0-10 l/m^2 model

Best sensitivity study: RLAM 50

Best cross experiment; CTRL 4.0

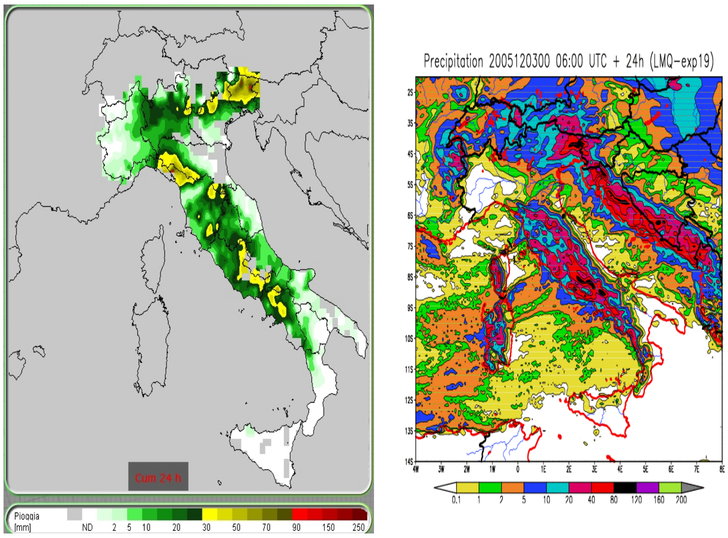

Figure 25: 24 h cumulated precipitation - observation (left); 24h cumulated precipitation exp 19 (right).

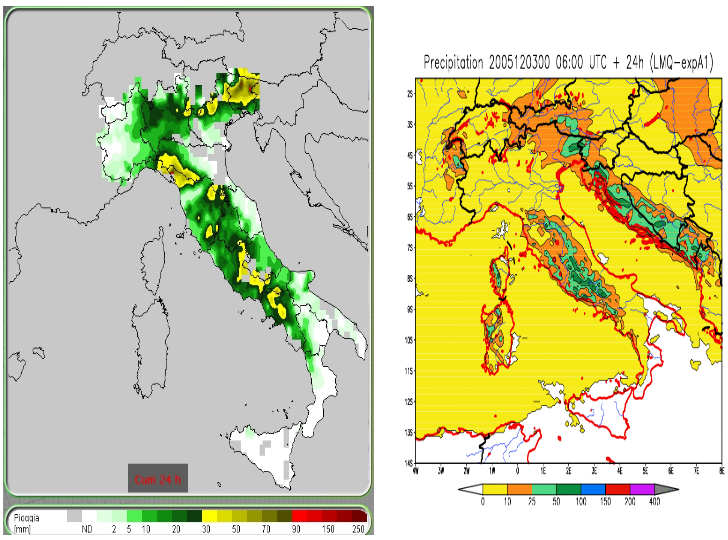

Figure 26: 24 h cumulated precipitation - observation (left); 24h cumulated precipitation exp A1 (right).

Test case 17.12.2005

QPF problem: Tyrrhenian part of Calabria: 10-50 l/m^2 observation vs 250-100 l/m^2 model

Best sensitivity study: numeric and surface simulations.

Best cross experiment: exp A3, A5.

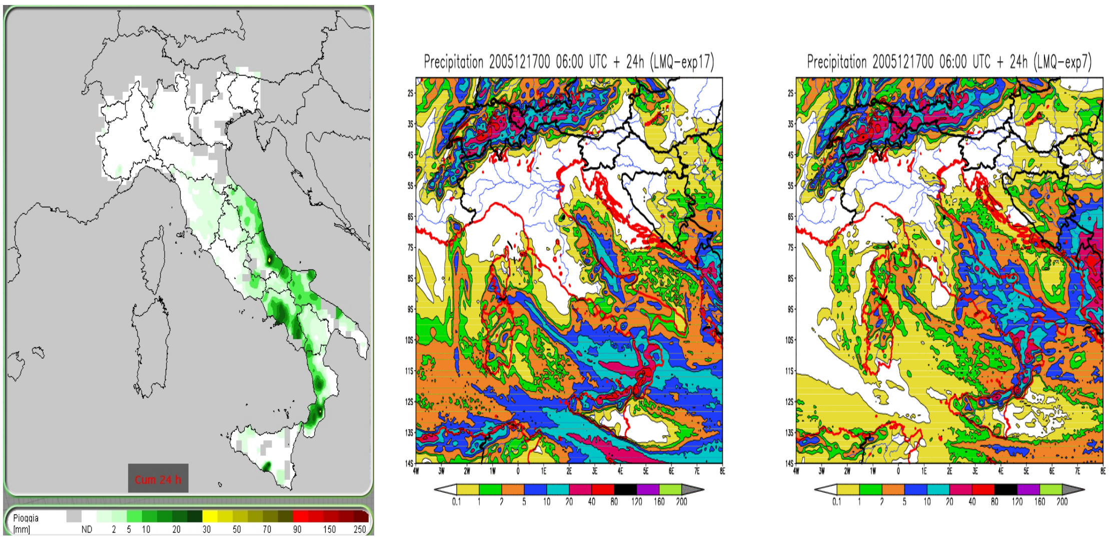

Figure 27: 24 h cumulated precipitation - observation (left); 24h cumulated precipitation exp 17(middle); 24h cumulated precipitation exp 7 (right).

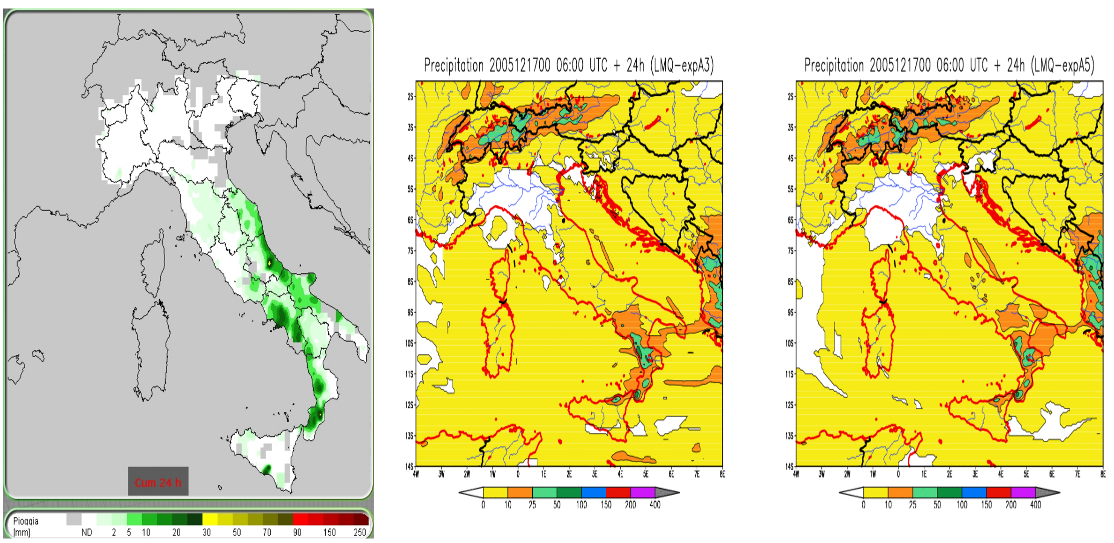

Figure 28: 24 h cumulated precipitations - observation (left); 24h cumulated precipitation exp A3 (middle); 24h cumulated precipitation exp A5 (right).

4.5 Greece

Simulation domain: latitude 33.5/42.5; longitude 18.0/29.0

Evaluation domain: latitude 34.5/41.5; longitude 19.0/28.5

Responsible scientists: P. Fragkouli (Task 1), E. Avgoustoglou (Task 2)

Test case 15.09.2005

QPF problem: trough over Southeast Europe, strong overestimation of precipitation over Crete.

Best sensitivity study: increase of atmospheric water vapor mixing ratio by 10% (exp.4). The average and the distribution of precipitation is improved, but the secondary precipitation centre over Central Aegean is missed.

Best experiment based on COSMO 4.0: in this case, the control run with COSMO 4.0 (exp. 23) showed rather significant preponderance over all cross experiments, however the overall precipitation simulation is poor.

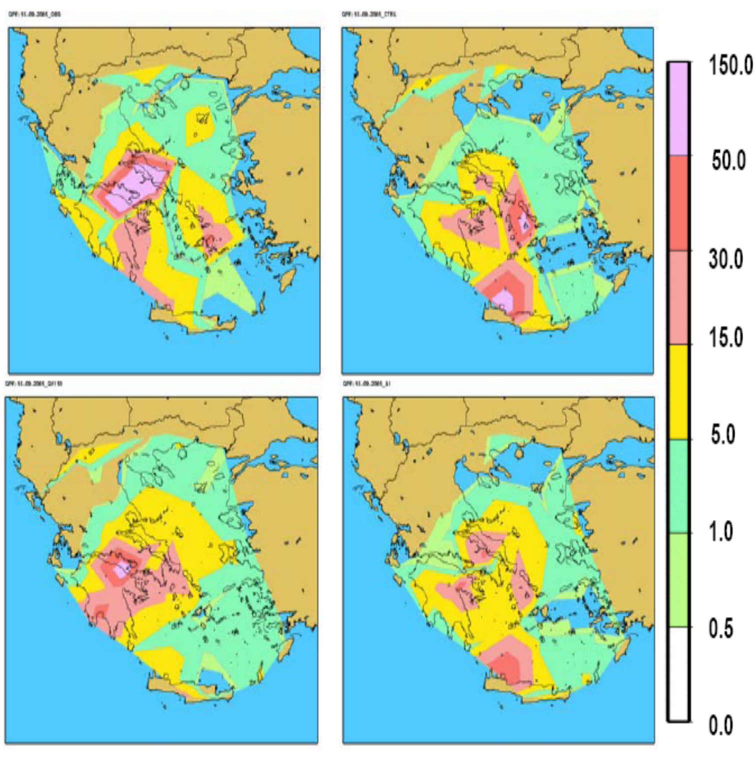

Figure 29: 24h precipitation sum in from 15.09.2005, 06 UTC - 16.09.2005, 06 UTC in the isohyet graphs based on synoptic observations from 63 meteorological stations (upper panel, left), in the reference simulation (upper panel right), in the sensitivity study with increase of water vapor mixing ratio (exp. 4, lower panel, left) and in the control experiment with COSMO 4.0 (exp. 23, lower panel, right).

Test case 23.11.2005

QPF problem: overestimation of precipitation in parts of Northern and Western Greece, eastwards moving fronts with extreme precipitation over Athens.

Best sensitivity study: increase of atmospheric water vapor mixing ratio by 10% (exp.4).The precipitation over the eastern and north-eastern parts of Greece is improved nevertheless underestimated over the central and western parts of the country.

Best cross experiment: COSMO 4.0 with Kain-Fritsch/Bechtold scheme (exp. 25).

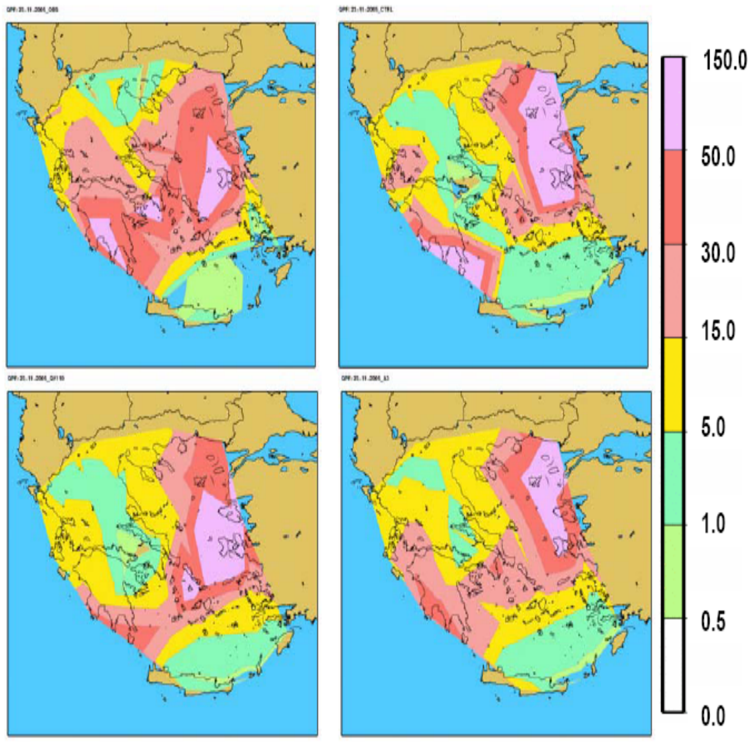

Figure 30: 24h precipitation sum in from 23.11.2005, 06 UTC - 24.11.2005, 06 UTC in the isohyet graphs based on synoptic observations from 60 meteorological stations (upper panel, left), in the reference simulation (upper panel right), in the sensitivity study with increase of water vapor mixing ratio (exp. 4, lower panel, left) and in the cross experiment with COSMO 4.0, Kain-Fritsch/Bechtold (exp. 25, lower panel, right).

Test case 26.11.2005

QPF problem: overestimation of extreme precipitation by a factor of 5 for the first forecast day.

Best sensitivity study: increase of atmospheric water vapor mixing ratio by 10% (exp.4). The average precipitation is improved but the simulation is wrong.

Best cross experiment: COSMO 4.0 with modified Tiedtke scheme (exp. 27).

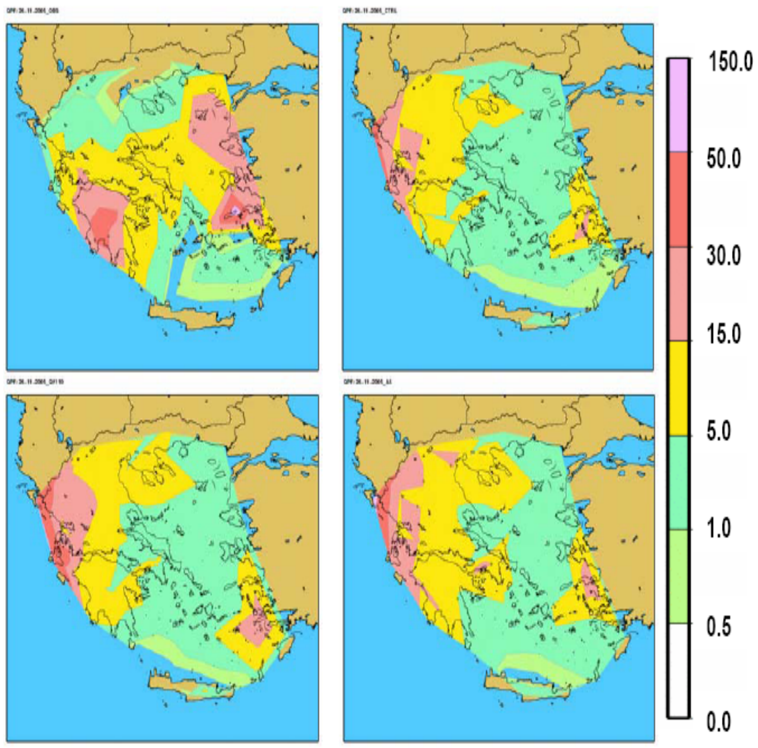

Figure 31: 24h precipitation sum in from 26.11.2005, 06 UTC - 27.11.2005, 06 UTC in the isohyet graphs based on synoptic observations from 59 meteorological stations (upper panel, left), in the reference simulation (upper panel right), in the sensitivity study with increase of water vapor mixing ratio (exp. 4, lower panel, left) and in the cross experiment with COSMO 4.0, modified Tiedtke (exp. 25, lower panel, right).

4.6 Poland

Simulation domain: latitude 45.9/56.5; longitude 10.0/32.8

Evaluation domain: latitude 49.0/54.3; longitude 12.8/26.1

Responsible scientists: Katarzyna Starosta (Task 1 and Task 2)

Test case 03.05.2005

QPF problem: a low with warm front is moving north of Poland from west to east. In the south-east of Poland a second low arises related with heavy precipitation in south-eastern part of the country. Underestimation of precipitation mainly in the south-eastern part of Poland is observed.

Best sensitivity study: the best result which reduces maximum precipitation and increases the average of precipitation to realistic values is observed in experiment 9 (Runge-Kutta, flux form and T'-p' dynamics).

Best cross experiment: these experiments do not increase average precipitation. Experiment with modified Tiedtke scheme reduces maximum precipitation (exp. 27), but the region without precipitation in south-east remains.

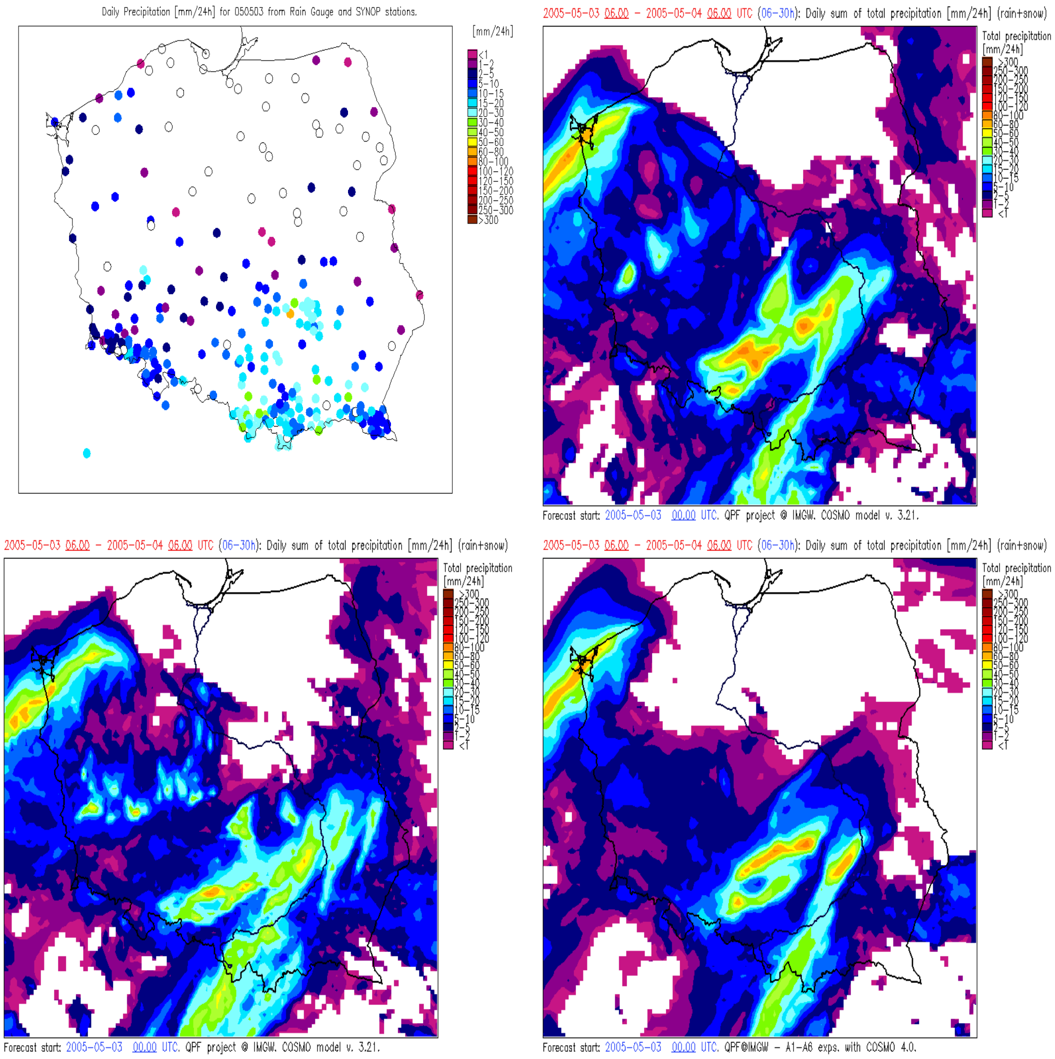

Figure 32: 24h precipitation sum from 03.05.2005, 06 UTC - 04.05.2005, 06 UTC from rain gauges observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with Runge-Kutta and T'-p' dynamics (exp. 9, lower panel, left) and in the cross experiment with COSMO 4.0, modified Tiedtke scheme(exp. 27, lower panel, right).

Test case 04.05.2005

QPF problem: low over Ukraine moves from south to north provoking heavy precipitation in the south, centre and east of the Polish territory. In the south of the region there is underestimation of precipitation, but over central and eastern parts of territory there is an overestimation. The maximum of precipitation is overpredicted. Locally the difference of maximum precipitation is significant, but taking into account an average precipitation this difference disappears.

Best sensitivity study: the experiment with microphysics reduces the maximum of precipitation (exp. 11, exp. 13). Location of precipitation values still remains wrong.

Best cross experiment: reduction of initial humidity + Runge-Kutta (exp. 24) decreases in general the maximum of precipitation. Still, the location of precipitation values remains wrong.

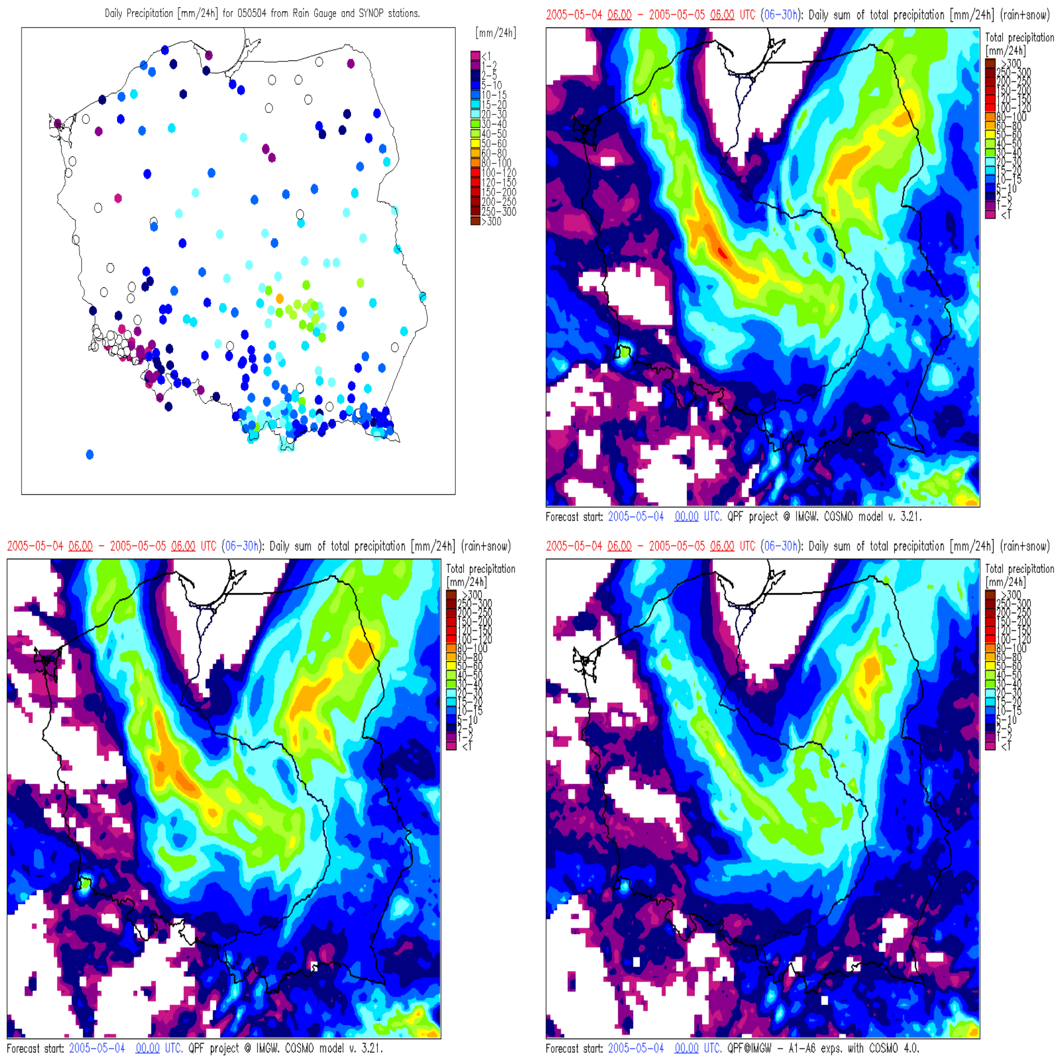

Figure 33: 24h precipitation sum from 04.05.2005, 06 UTC - 05.05.2005, 06 UTC from rain gauges observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with new warm rain scheme (exp. 11, lower panel, left) and in the cross experiment with COSMO 4.0, Runge-Kutta and reduced initial humidity (exp. 24, lower panel, right).

Test case 10.06.2005

QPF problem: the heavy precipitation in the east is related to a low over Ukraine. The precipitation in western of Poland is connected with cold front. Overestimation is larger in maximum precipitation than in average precipitation. Over south-eastern parts of Poland there is a region where precipitation is not predicted. The region with maximum precipitation is located to the east and not to the south of the country.

Best sensitivity study: the experiments QV090 (exp. 3) and Mikro2 (exp. 12) reduce maximum precipitation but not ideally. Still, the location of precipitation in south-east remains wrong.

Best cross experiment: the experiment Kain-Fritsch/Bechtold (exp. 24) reduces average precipitation, and experiment 28 (reduced initial humidity + Runge-Kutta + modified Tiedtke scheme) reduces maximum value to realistic one, but decrease average value. Wrong location of maximum precipitation and the region with missing precipitation still exists.

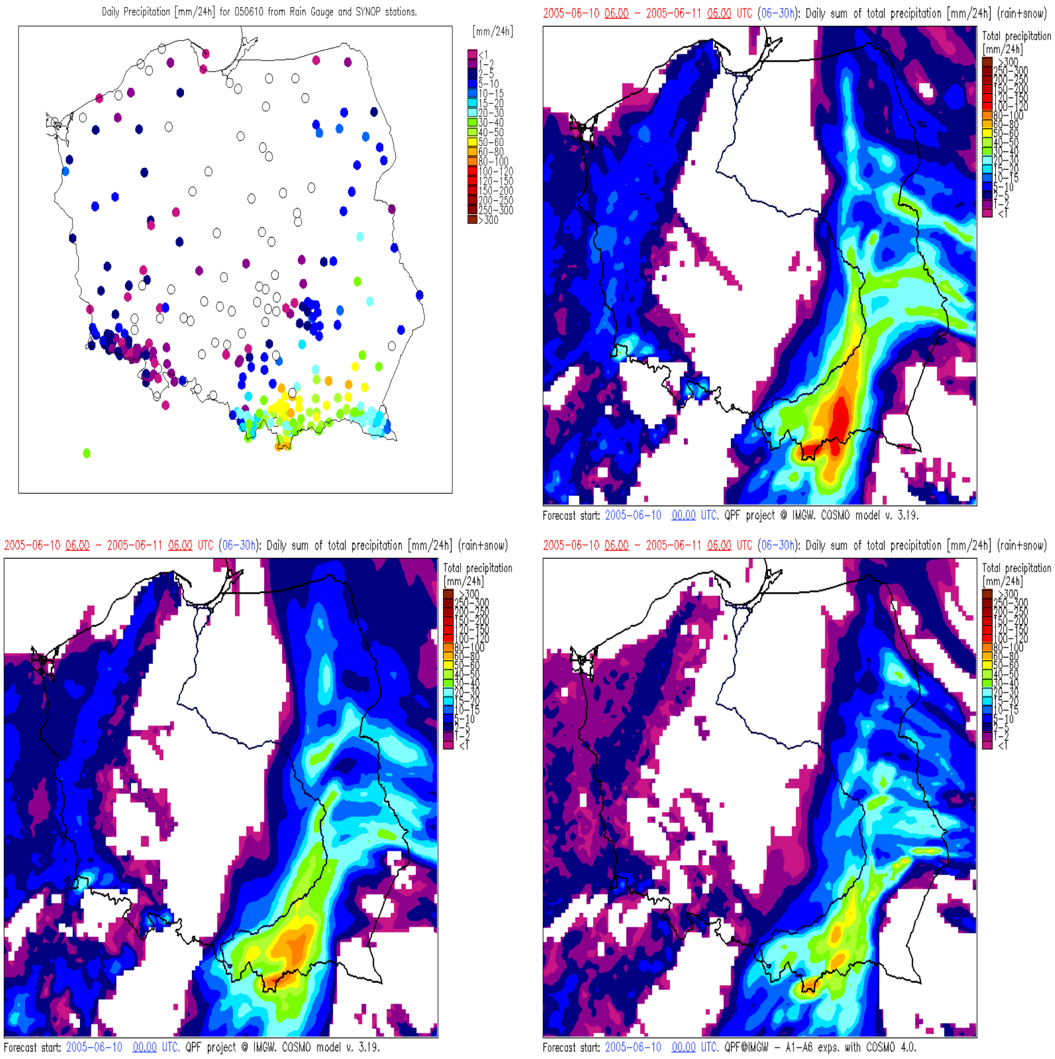

Figure 34: 24h precipitation sum from 10.06.2005, 06 UTC - 11.06.2005, 06 UTC from rain gauges observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with changes of ice microphysics and new warm rain scheme (exp. 12, lower panel, left) and in the cross experiment with COSMO 4.0, modified Tiedtke scheme, Runge-Kutta and reduced initial humidity (exp. 28, lower panel, right).

Test case 09.08.2005

QPF problem: low moving from Belarus to Latvia. Overestimation recorded especially in north-east of Poland, while underestimation in south-east of Poland.

Best sensitivity study: the experiment with microphysics (exp. 11, 12) reduces the maximum value to realistic one.

Best cross experiment: the model version 4.0 improves the results.

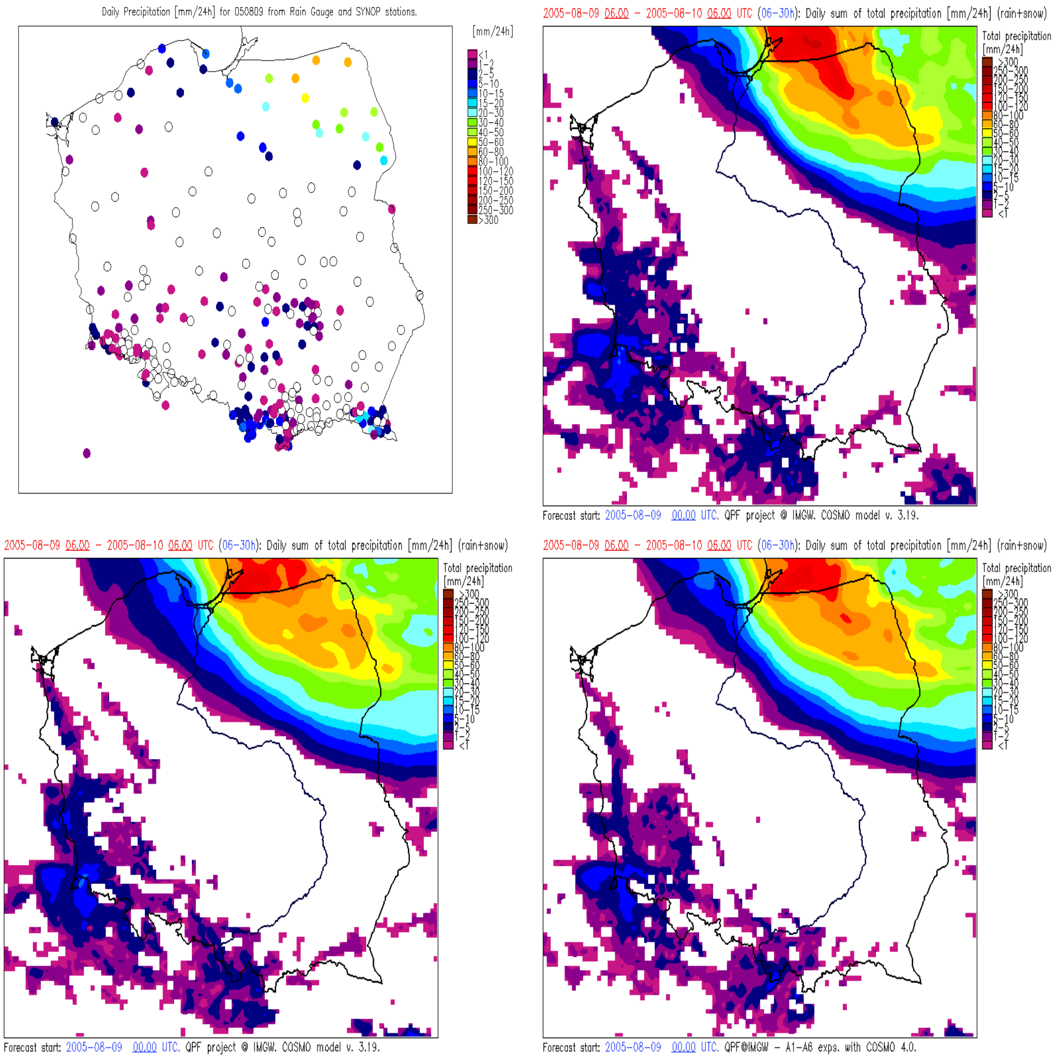

Figure 35: 24h precipitation sum from 09.08.2005, 06 UTC - 10.08.2005, 06 UTC from rain gauges observations (upper panel, left), in the reference simulation (upper panel, right), in the sensitivity study with changes of ice microphysics and new warm rain scheme (exp. 12, lower panel, left) and in the cross experiment with COSMO 4.0, (exp. 23, lower panel, right).

4.7 Romania

Simulation and evaluation domain: dlat=0.0625, dlon=0.0625, ielm_tot=301, jelm_tot=301, kelm_tot=40, pollat=40, pollon=-170.0, startlat_tot=-13.5, startlon_tot=0.625.

Responsible scientists: Rodica Dumitrache (Task 1 and Task 2).

QPF problem:

- E and central Moldova 50-100 l/m^2 observation vs 40-80 l/m^2 model;
- SE 25-50 l/m^2 observations vs 120-160 l/m^2 model overestimation;
- Littoral area 10-25 l/m^2 observations vs 40-80 l/m^2 model overestimation;
- NW - not observed – not simulated;
- SW not observed – 40-80 l/m^2 model overestimation;
- Center 25-50 l/m^2 observations vs 40-80 l/m^2 model.

Best sensitivity study: cloud microphysics, numeric and convective scheme simulations.

Best cross experiment: A2, A6.

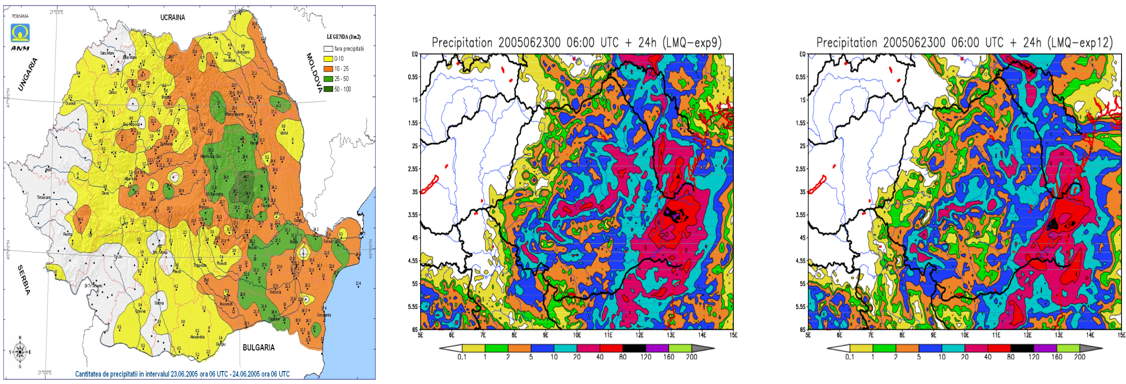

Figure 36: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp 9 (middle); 24h cumulated precipitation exp 12 (right).

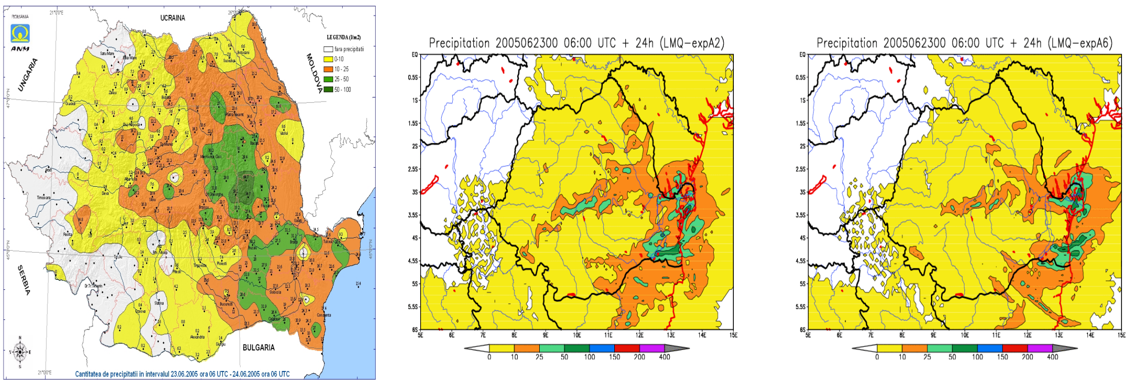

Figure 37: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp A2 (middle); 24h cumulated precipitation exp A6 (right).

Test case 02.07.2005

QPF problem:

- NE-E of the country (40 l/m^2 simulated vs no observed precipitation);
- West, SE and Carpathian region (120-160 l/m^2 simulated vs 25-50 l/m^2 observed);
- South of the country (20 l/m^2 simulated vs 66-110 l/m^2 observed).

Best sensitivity study: exp 18- RLAM 50.

Best cross experiment: exp A1, A6.

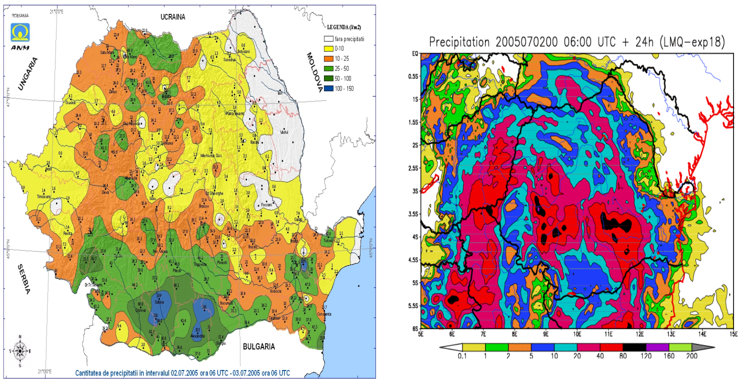

Figure 38: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp 18 (right).

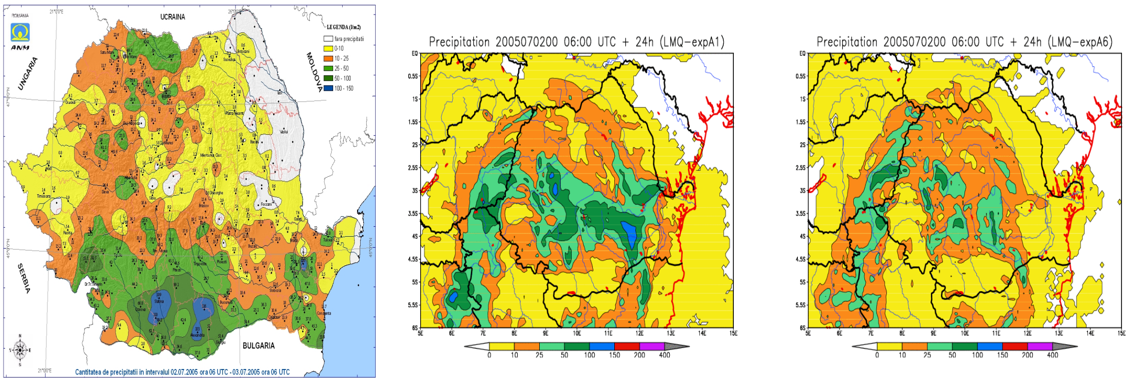

Figure 39: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp A1 (middle); 24h cumulated precipitation exp A6 (right).

Test case 12.07.2005

QPF problem:

- W 1-2 l/m^2 observations vs 20-40 l/m^2 model;
- SW 50-100 l/m^2 observations vs 2-5 l/m^2 model;
- SE 100-150 l/m^2 observations vs 10-20 l/m^2 model;
- Littoral area 1-2 l/m^2 observations vs 40-80 l/m^2 model.

Best sensitivity study: exp 17.

Best cross experiment; exp A1, A6.

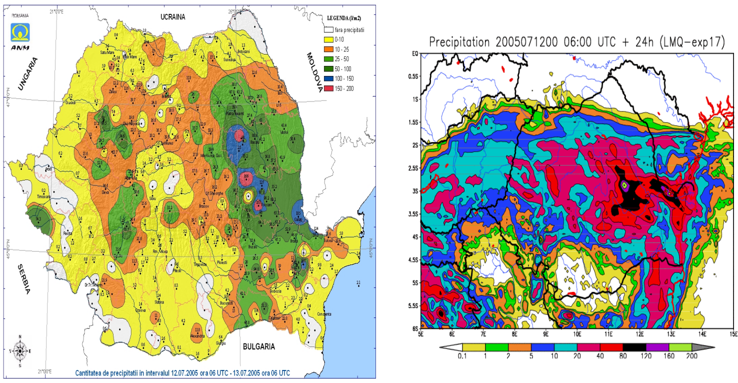

Figure 40: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp 17 (right).

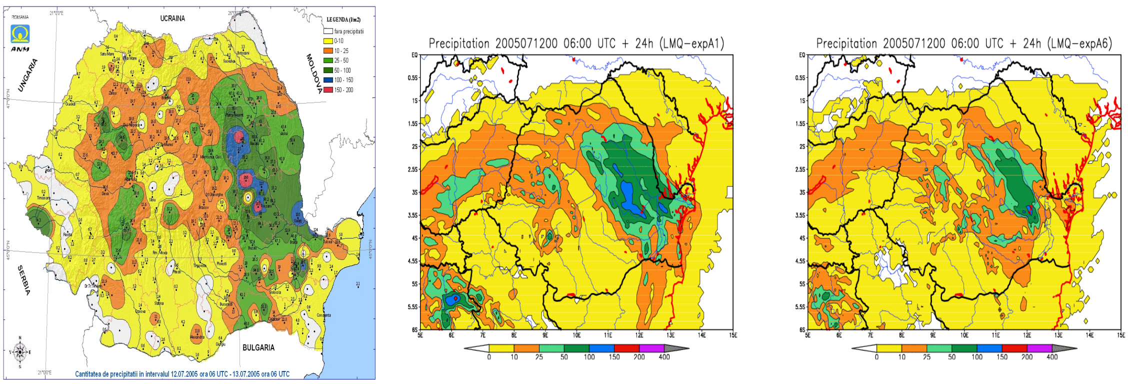

Figure 41: 24 hour cumulated precipitation - observation (left); 24h cumulated precipitation exp A1 (middle); 24h cumulated precipitation exp A6 (right).

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Issues of the COSMO Technical Reports series are published by the *COnsortium for Small-scale MOdelling* at non-regular intervals. COSMO is a European group for numerical weather prediction with participating meteorological services from Germany (DWD, AWGeophys), Greece (HNMS), Italy (USAM, ARPA-SIMC, ARPA Piemonte), Switzerland (MeteoSwiss), Poland (IMGW) and Romania (NMA). The general goal is to develop, improve and maintain a non-hydrostatic limited area modelling system to be used for both operational and research applications by the members of COSMO. This system is initially based on the COSMO-Model (previously known as LM) of DWD with its corresponding data assimilation system.

The Technical Reports are intended

- for scientific contributions and a documentation of research activities,
- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

The purpose of these reports is to communicate results, changes and progress related to the LM model system relatively fast within the COSMO consortium, and also to inform other NWP groups on our current research activities. In this way the discussion on a specific topic can be stimulated at an early stage. In order to publish a report very soon after the completion of the manuscript, we have decided to omit a thorough reviewing procedure and only a rough check is done by the editors and a third reviewer. We apologize for typographical and other errors or inconsistencies which may still be present.

At present, the Technical Reports are available for download from the COSMO web site (www.cosmo-model.org). If required, the member meteorological centres can produce hard-copies by their own for distribution within their service. All members of the consortium will be informed about new issues by email.

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