Initial condition perturbations for the COSMO-DE-EPS

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1. Introduction

The numerical weather prediction model COSMO-DE, which simulates deep convection explicitly, is a configuration of the COSMO model with a horizontal grid size of 2.8 km [1]. It runs operationally at DWD since 2007, covering the area of Germany and producing forecasts with a lead time of 0-21 hours. A 20-members ensemble prediction system (EPS) based on COSMO-DE runs pre-operationally at DWD since December 9 2010. Operational use is envisaged to start in 2012, after an upgrade to 40 members and inclusion of statistical postprocessing. COSMO-DE-EPS includes perturbations of initial and boundary conditions, and model physics. This contribution describes the current implementation of initial perturbations in COSMO-DE-EPS.

The current setup of the lateral boundary conditions uses forecasts of different global models, while different configurations of the COSMO-DE model are used for the variation of model physics [4]. The perturbations of the initial conditions of the ensemble use two simple approaches: varying parameters during the Nudgecast (assimilation) phase of COSMO-DE and taking differences with members of a BC-EPS (boundary conditions EPS). The BC-EPS consists of 4 COSMO simulations with a 7km grid, driven by 4 different global models (GFS, GME, IFS and GSM) and the aim is to take into account the uncertainty at coarser scales to define initial perturbations. The concept of BC-EPS is based on the COSMO Short Range EPS (SREPS) developed at ARPA-SIMC [4], which is driven by the global models IFS, GME, GFS and UM. During the development phase of the COSMO-DE-EPS we have used SREPS boundary data, and all results presented in this contribution make use of COSMO-SREPS. The BC-EPS is the provider of boundary data during the pre-operational phase of COSMO-DE-EPS.

This contribution is organized as follows. A brief discussion of varying Nudging parameters is presented in Section 2. The setup of initial perturbations based on the BC-EPS is discussed in Section 3. The perturbations are filtered out close to the surface, and this is discussed in Section 4. Some numerical checks conducted on the perturbations are discussed in Section 5, and a method to hydrostically balance the perturbations is discussed in Section 6. Some preliminary results are presented in Section 7. The ensemble lacks variability close to the surface, and a way to remedy this can be to disturb soil moisture fields. Some sensibility studies on this regard are presented in Section 8.

2. Nudging perturbations

The current method for data assimilation in COSMO-DE is based on the Nudging technique, which is a very pragmatic approach with many parameters that control how the model relaxes to the observation increments [8]. The optimal values are empirically determined. We tested modifications of these parameters during the Nudgecast period of the ensemble forecast (first 1-1.5 hours). The most important parameters are the correlation length scale for the mass, wind and humidity observations (`rhinfl, rhvfac`, and `rhiflsu`), the coefficient of latent heat nudging (LHN) increments derived from radar observations (`lhn_coef`), parameters controlling the amount of geostrophic wind corrections for balancing the mass field increments (`qgeo` and `qgeotop`), and parameters controlling the amount of divergent and non-divergent wind increments (`fnondiv` and `cnondiv`). The default values of these parameters can be found in Schaettler et al. [6].

We have conducted several simulations modifying these parameters and found that they introduce variability only on the very small scales.

3. Initial condition perturbations based on BC-EPS

In order to introduce variability on the large scales we follow a multi-boundary technique. We have written a parallel program which calculates differences between undisturbed BC-EPS and COSMO-EU fields at start time, and adds them to the COSMO-DE analysis fields, using the formula

$$f = f_0 + W(k)(f_{BC} - f_{EU}), \tag{1}$$

where $f = (U', V', T', QV')$ are the disturbed fields, and $f_0 = (U_0, V_0, T_0, QV_0)$ are the undisturbed fields, while f_{BC} and f_{EU} denote the corresponding BC-EPS and COSMO-EU reference field respectively. All the fields have to be interpolated to the COSMO-DE grid using the operational `int2lm` routine [5]. The pressure perturbation PP' is calculated using the same equation but only on the last model level (see Section 6). A low pass exponential filter $W(k)$ is applied on every model level k, to the fields (U', V', T', QV').

4. Vertical filter

Sudden changes in model levels for the perturbed variables can arise during the interpolation process from COSMO-EU and BC-EPS to COSMO-DE resolution, since these models use a coarser resolution. This is especially true closer to the surface, where model levels are adapted to the local orography. The surface temperature and surface humidity may not be consistent if all the fields are perturbed in the same way, especially close to the boundary layer. This can result in spurious surface fluxes and humidity adjustments, and sudden condensation or evaporation. Our aim is to introduce a large scale perturbation without disturbing the surface layer and without triggering internal boundary layer fluxes. One way to achieve this is by keeping the surface layer undisturbed, slowly increasing the perturbation with height, using a low-pass exponential filter

$$W(k) = \exp\left(-\left|\frac{k}{N_{ke}}\right|^{\gamma} \ln\epsilon\right), \quad 0 \le |k| \le N_{ke}, \tag{2}$$

where N_{ke} is the number of model levels (N_{ke}=50 for COSMO-DE), $\epsilon = 2.2 \times 10^{-16}$ is the machine zero, and γ is the (integer) order of the filter. A small value ($\gamma < 16$) indicates strong filtering of the perturbations on lower levels, while a high value ($\gamma > 16$) indicates soft filtering. Typically, 5-10 levels closest to the surface are undisturbed. Figure shows the behaviour of $W(k)$ as a function of model level k, for $8 \le \gamma \le 24$. The curves correspond, from right to left, to $\gamma = 24, 20, 16, 10$ and 8.

5. Numerical check on QV and QC

Occasionally, it may happen that taking simple differences between the BC-EPS and EU fields produces unphysical values of the specific humidity QV$'$ (i.e., QV$' < 0$). In order to

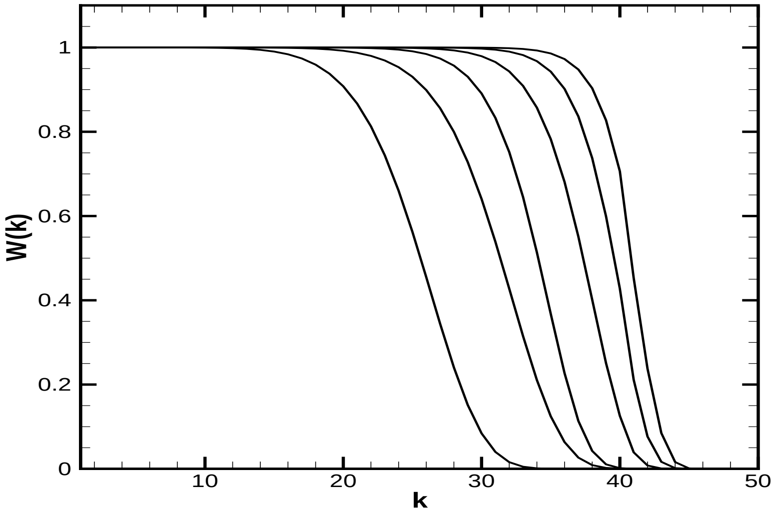

Figure 1: Vertical filter $W(k)$ as a function of model level k, for $\gamma = 24, 20, 16, 14, 10$ and 8 (from right to left).

avoid this situation a numerical check is performed on this variable, so that QV′ is in the range $R_{min}\, QV^* \leq QV' \leq R_{max}\, QV^*$, where R_{max} and R_{min} are adjustable parameters (currently set to 1.15, and 0.05 respectively) and QV^* is the specific humidity for saturated water vapour pressure, calculated analytically using the formula

$$QV^* = \left(\frac{R_d}{R_v}\right) \frac{P_v}{P_a - (1 - R_d/R_v)P_v} \tag{3}$$

where P_v is the saturation water vapour pressure (in Pa), P_a is the air pressure (in Pa) and R_v and R_d are the gas constants of water vapour and dry air (in J/(kg K)). The saturation water vapour pressure is given by the Magnus Formula:

$$P_v = b_1 \exp\left(\frac{b_{2w}(T - b_3)}{T - b_{4w}}\right) \tag{4}$$

where T is the temperature and b_1, b_{2w}, b_3 and b_{4w} are constant parameters. The Magnus Formula also requires the air pressure as input. The air pressure is calculated using the COSMO-DE routine `reference_atmosphere` [5]. In some upper levels the air pressure can be too small, and the Magnus Formula can lead to negative values for QV^*. To avoid this situation the calculation is limited to levels in which P > 100 hPa. For levels in which P < 100 hPa QV′ is also checked, and set to $QV' = 10^{-6}$ if $QV' < 0$.

Finally, the specific cloud water content QC is also checked and set to 0 if $QV' < 0.95\, QV^*$. The variable QC is only checked in this way to be consistent with QV, and it is not disturbed in any other way.

6. Calculation of the pressure perturbation PP'

In order to avoid direct sources of vertical wind, the total analysis perturbations should be balanced hydrostically. This is achieved by using the hydrostatic equation derived from the vertical momentum equation, neglecting subgrid scale processes and setting the total derivative of vertical wind to zero. Integrating this equation for the analysis increments $\Delta P'$ of pressure perturbation, a recursive equation is obtained, that gives the pressure increments as a function of reference pressure, T' and QV', calculated in the way described in the previous Section (see equation (3.87) in Schraff and Hess [7]). The pressure increments are calculated from the last to the first model level. Since the equation is recursive, $\Delta P'$ at the model level N_{ke} is needed. This is given as $(\Delta P')_{N_{ke}} = C(PP' - PP_0)$, where C is an empirically chosen factor (currently set to 0.7) and PP_0 the undisturbed analysis field.

During the interpolation from BC-EPS to the COSMO-DE grid some artificial artifacts can appear in the pressure fields close to the surface (this is particularly true when doing the interpolation from the GFS members of BC-EPS to COSMO-DE). Therefore $(\Delta P')_{N_{ke}}$ is additionally smoothed on each model level by replacing its value at a particular grid point by the mean of the values on a box with N×N grid points. Typically, N =20 is enough to ensure a smooth field. The pressure perturbation PP' is finally calculated as $PP' = PP_0 + \Delta P'$ from model $k = N_{ke} - 1$ to $k = 1$ (note that no vertical filter is applied on PP').

7. Effect of the perturbations on a forecast

Several example 24 hours forecasts were conducted, all starting at 00 UTC. These simulations make use of 4 members of the COSMO-SREPS, 1 for each global model, corresponding to COSMO-SREPS members 1 (IFS), 5 (GME), 9 (GFS) and 13 (UM).

Figure shows the effect of using different vertical filters on the spatial mean of the vertical velocity field at 850 hPa. Member 1 corresponds to a reference (undisturbed forecast), and members 2-5 correspond to an initial perturbation using equation (1) with SREPS member 1, 5, 9 and 13 respectively. Spurious gravity wave oscillations are triggered when the surface boundary layer is disturbed (Figure d, γ = 24), and greatly reduced for stronger filtering (Figure a-c, γ = 8-14).

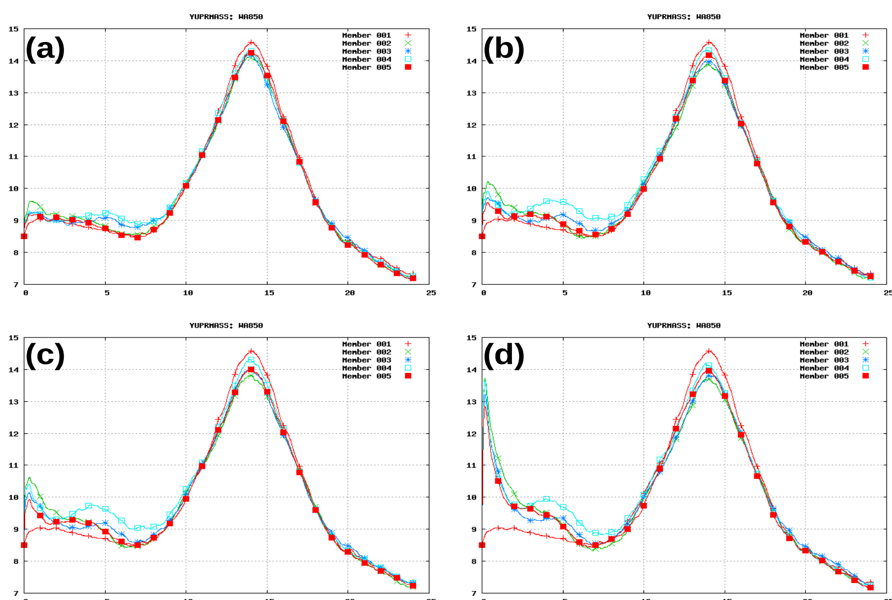

Figure 2: Spatial mean of the vertical velocity at 850 hPa (in m s^{-1}) as a function of forecast time for (a) $\gamma = 8$, (b) $\gamma = 12$, (c) $\gamma = 14$ and (d) $\gamma = 24$. Member 1 corresponds to a reference (undisturbed forecast), and members 2-5 correspond to an initial perturbation using equation (1) with SREPS members 1, 5, 9 and 13 respectively.

Figure shows an example of the effect on total precipitation after 3 hours of forecast, using different COSMO-SREPS members to disturb the initial conditions. The plots show differences in total precipitation between a reference (undisturbed) forecast and a forecast with initial condition perturbations using COSMO-SREPS member: (a) 1, (b) 5, (c) 9 and (d) 13, with the vertical filter set to $\gamma = 14$.

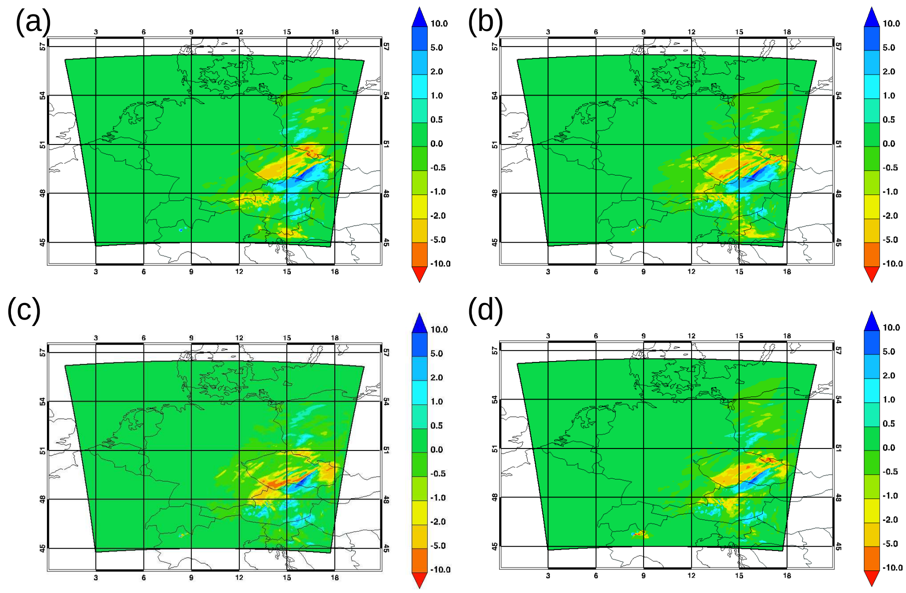

Figure 3: Difference in total precipitation (in mm) after 3 hours between a reference (undisturbed) forecast and a forecast with initial condition perturbations using COSMO-SREPS member: (a) 1, (b) 5, (c) 9 and (d) 13.

Figure shows the individual effect of using initial, boundary, and model physics variations. Each curve represents the spatiotemporal mean of the spread calculated for a period of 29 days (between May 20 and July 27 2009), as a function of forecast time. The solid curve shows the spread for a 10 members ensemble with initial condition perturbations based on equation (1), using COSMO-SREPS 1,5,9 and 13 (members 2-5), and disturbing the Nudging parameters indicated in Section 2. The dashed curve shows the spread of a 10 members ensemble with only model physics perturbations (parameters changed can be found in Gebhardt et al. [4]). The dotted curve with circles shows the spread of a 8 members ensemble with only boundary condition perturbations. The smaller number of members of this last ensemble comes from selecting pairs of COSMO-SREPS global models (1, 4, 5, 8, 9, 12, 13, 16, or two per global model). Most of the gain from disturbing the initial conditions occurs during the first 6 hours of the forecast. After that, the boundary condition perturbations dominate.

The effect of combining initial and boundary conditions, and model physics perturbations in one 15 members ensemble can be appreciated in Figure , which shows the spatiotemporal mean as a function of forecast time for a period of 15 days, between October 7 and November 24 2009 (solid curve). This ensemble uses COSMO-SREPS members 1,5, 9 for the initial and boundary condition perturbations and a selected number of COSMO-DE parameters disturbing the model physics [4]. As a comparison, the dashed curve in Figure shows the spread for a 15 member ensemble excluding initial condition perturbations (only boundary conditions and model physics). After ~ 6 hours both curves are almost identical.

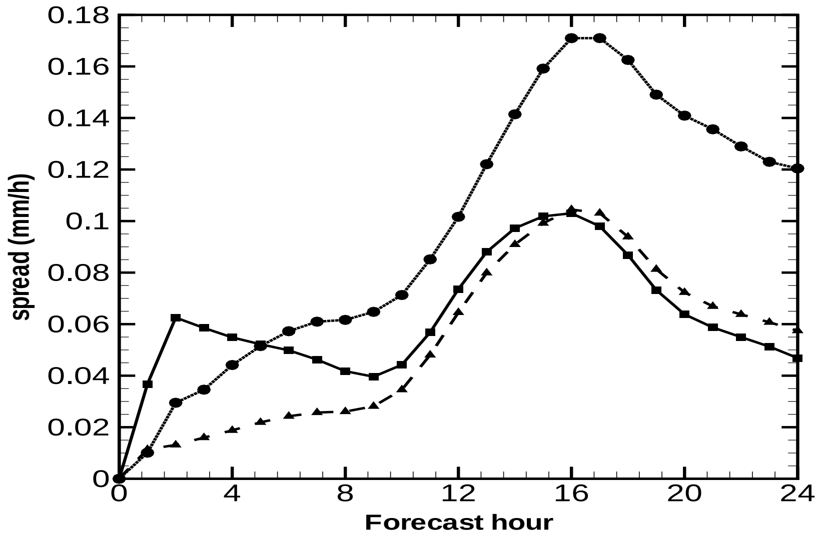

Figure 4: Spatiotemporal mean of the spread for a period of 29 days (between May 20 and July 27 2009) as a function of forecast time. The different curves correspond to a 10 members ensemble with only initial condition perturbations (solid, squares), a 10 members ensemble with only model physics perturbations (dashed, triangles) and an 8 members ensemble with only boundary condition perturbations (dotted, circles).

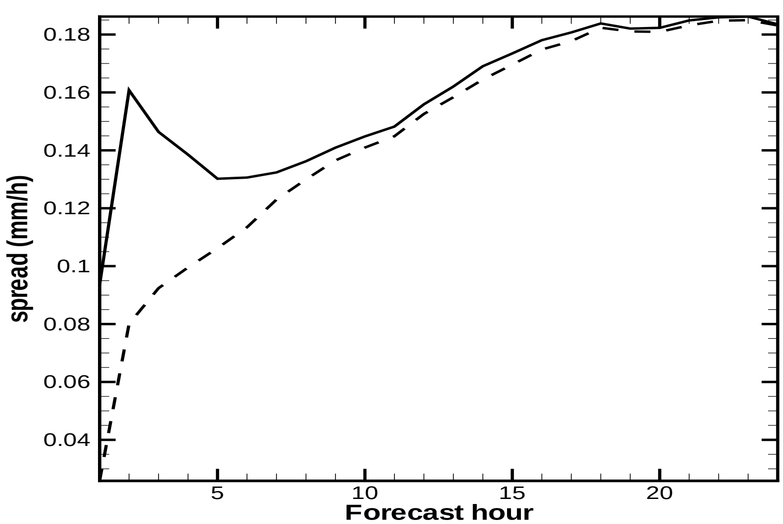

Figure 5: Spatiotemporal mean of the spread for a period of 15 days (between October 7 and November 24 2009) as a function of forecast time. The different curves correspond to a 15 members ensemble with combined model physics, initial and boundary condition perturbations (solid curve) and with only model physics and boundary condition perturbations (dashed curve).

8. Disturbing soil moisture fields

The current setup of the COSMO-DE-EPS suffers from a lack of perturbations of the soil and on levels closest to the surface. This lack of variability is also present in COSMO-SREPS. Recently, [3] have developed a technique to tackle this deficiency by disturbing soil moisture fields in COSMO-SREPS using an approach similar to Sutton and Hamill [9]. In the same spirit, we are currently conducting non-EPS simulations to test the effect of disturbing soil moisture fields in COSMO-DE.

We briefly report here some sensibility studies using a very simple method to disturb the soil water content W_SO. There are eight layers, with the lowermost layer containing the climatological water content (1, 2, 6, 18, 54, 162, 486 and 1458 cm). No soil analysis is performed in the COSMO-DE routine. Therefore, we retrieve the soil moisture field W_SO from the COSMO-EU analysis and interpolate it to the COSMO-DE grid. This field is then inserted into the COSMO-DE analysis and a forecast is run with this perturbed field, starting at 00 UTC. The original W_SO field can be totally replaced by the interpolated COSMO-EU-analysis W_SO field, or a fraction of W_SO can be added or subtracted.

Figure shows W_SO (at 1 and 6 cm depth), 1 h after the start of the forecast for the operational COSMO-DE and for a simulation in which the COSMO-DE field W_SO was completely replaced by the interpolated W_SO field from COSMO-EU. The forecast was started at 06 UTC, for July 2 2009. The humidity is slightly higher for the disturbed simulation. The relative difference is ~ 9.4 % at 1 cm and ~ 8.7 % at 6 cm. Interestingly, the differences are quite small considering that COSMO-EU uses a soil-moisture analysis, while W_SO quantity develops completely free in COSMO-DE. Figure shows the total precipitation after 6 hours of an undisturbed forecast using COSMO-DE (left) and introducing the W_SO fields from COSMO-EU (right). Differences are very localized and on small scales. Additional simulations were conducted, adding or subtracting a fraction of the W_SO field from COSMO-EU, giving similar results.

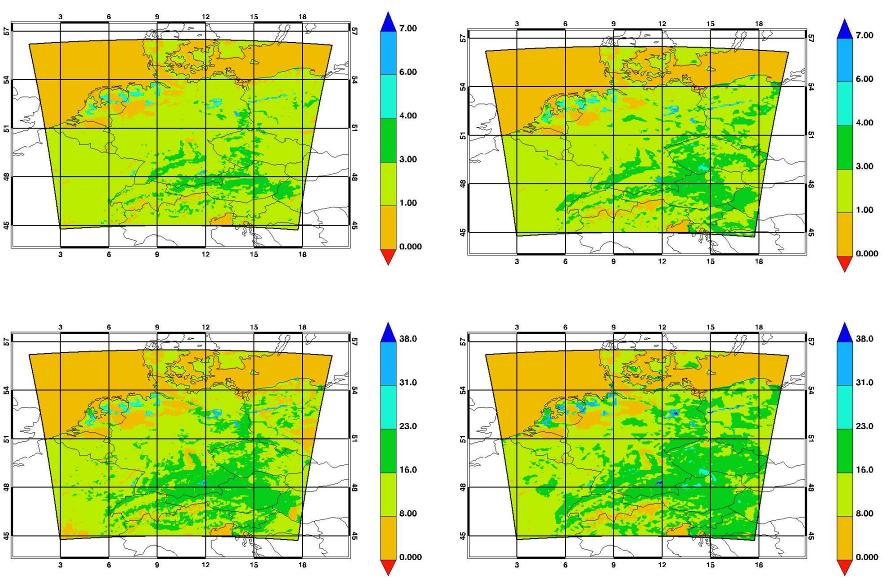

Figure 6: Soil moisture W_SO (in kg m^{-2}) for the operational COSMO-DE and a disturbed forecast using W_SO from COSMO-EU at 1 cm depth (upper row, left to right) and at 6 cm (lower row, left to right). The fields are shown 1hr after the start of the forecast.

9. Summary and Outlook

The inclusion of initial conditions in COSMO-DE-EPS has a positive effect, increasing the spread during the first 6 hours of the forecast. Later on, the spread is similar to the one introduced by boundary and model physics variations. However, note that this is true only

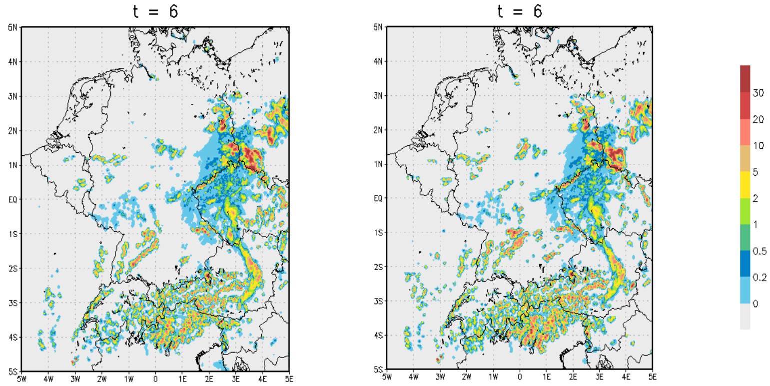

Figure 7: Total precipitation (in mm) after 6 hours for the operational COSMO-DE (left) and a disturbed forecast using W_SO from COSMO-EU (right).

on average, and not in general for each individual case.

One way to introduce spread at the surface boundary layer is to disturb soil moisture field. Disturbing soil moisture fields by interpolating the W_SO from COSMO-EU to the COSMO-DE grid and replacing this field (or a fraction of it) at the beginning of the forecast produces localized differences in total precipitation. No soil moisture perturbations have been included in COSMO-DE-EPS.

A more detailed study describing the combined effect of initial and boundary conditions perturbations and variations of model physics (including verification) will be reported elsewhere.

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