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Assessing the uncertainty of soil-moisture impact on convective precipitation by an ensemble approach

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Abstract. Soil moisture influences the occurrence of convective precipitation. Therefore an accurate knowledge of soil moisture might be useful for an improved prediction of convective cells. But still the model uncertainty overshadows the impact of soil moisture in realistic cases even in 1 km resolution and therefore convection resolving models. Only drastic soil moisture changes can exhibit the model uncertainties but the systematic behaviour is still complex and depends strongly on the strength of soil moisture change.
Here we performed seven experiments with modified soil moisture using an ensemble approach for each experiment. Only a 50% soil moisture enhancement and a complete dried soil impact precipitation patterns considerably in structure, amplitude and location in certain analysis areas. Both, the enhanced and reduced soil moisture result in a reduced precipitation rate. Replacing the soil moisture by a realistic field from different days influences the precipitation insignificantly. We point out the need for uncertainty estimations in soil moisture studies.

1 Introduction

Convective precipitation changes rapidly in time and is very variable in space (Pedersen et al., 2010). The heterogeneity of convective precipitation and the interaction of different scales challenge atmospheric models on the global and regional scale. Nowadays regional climate models operate with a 1 km scale resolution to represent convective processes explicitly and to improve weather forecast (Mass et al., 2002). Nevertheless, precipitation formation undergoes a complex chain of atmospheric processes from the micro to the synoptic scale (Richard et al., 2007). Therefore precipitation remains a highly uncertain quantity. The final precipitation formation includes unresolved microphysical conversion processes, most often including the ice phase (Field and Heymsfield, 2015), that rely on complex parametrisations introducing a large uncertainty in the model. Many studies found buffering effects for those processes (Muhlbauer et al., 2010; Glassmeier and Lohmann, 2016). Such a modifying effect does not exist for the dynamical influence on convective precipitation, such as baroclinic and moist conditional instability. Soil moisture stands at the beginning of the convective precipitation formation that is highly sensitive to the aforementioned atmospheric stratification.

Soil moisture affects the partitioning of turbulent heat fluxes into sensible and latent heat, which once affects the surface temperature due to the latent heating. The surface temperature plays a crucial role in the initiation of convection. Second the soil moisture strongly influences the specific water content via latent heat flux. Furthermore, the specific water content in the lower troposphere modifies moist conditional instability. On the one hand high surface temperatures can be reached and initiate convection with a low soil moisture content. On the other hand, high soil moisture can destabilise the atmosphere by introducing water vapour in the lower troposphere favouring convection as well. These competing effects hamper the analysis on soil moisture influence. Many parameters to describe the atmospheric stability react on the soil moisture. A strong systematic effect on soil moisture changes exists for the latent and sensible heat fluxes, as well as equivalent potential temperature, lifting condensation level and convective energy, that following the process chain (Barthlott et al., 2011). Despite to the systematic effect on partitioning of the heat fluxes, precipitation reacts less systematically on soil moisture variations (Barthlott and Kalthoff, 2011; Hohenegger et al., 2009). The distribution and inhomogeneity of soil moisture patterns may initiate secondary circulation (Clark et al., 2004; Adler et al., 2011; Kang and Bryan, 2011; Dixon et al., 2013; Maronga and Raasch, 2013; Froidevaux et al., 2014).

Accordingly, there is no clear consent on soil moisture precipitation interaction in literature: Barthlott et al. (2011) found a strong dependency of precipitation with changes larger than 500% for a soil moisture variation of $\pm 25\%$ in regions with low mountain ranges and changes up to -75% for domains with higher mountain ranges. Significant differences between planetary boundary driven and synoptic forced conditions could not be detected. Further studies by Kalthoff et al. (2011) and Hauck et al. (2011) over orographic complex terrain investigate the role of orographic effects in the synergy of soil moisture-precipitation feedbacks. Hauck et al. (2011) determines large systematic differences between modelled and observed soil moisture. The influences on simulated precipitation is more complex and depends strongly on the chosen case and domain. A dependency of all convective indices on the equivalent potential temperature was found by Kalthoff et al. (2011) over different orographic terrains. However, convection was predominantly initiated over mountain, independent of the instability indices, but with smaller convective inhibition. The dependency of equivalent potential temperature on soil moisture was influenced by surface inhomogeneity. Barthlott and Kalthoff (2011) provide a sensitivity study, in which the soil moisture was increased by $\pm$ 50% in steps of 5%. While a systematic effect on the 24 hours precipitation sum for reduced soil moisture exists, precipitation does not react systematically in wetter simulations.

Diversity in the results may partly be attributed to model uncertainty. Hohenegger and Schär (2007) investigated the error growth of random perturbation-methods in cloud-resolving models using time shifted model simulations and perturbed temperature fields in the initial conditions. In their model study with a resolution of $2.2\,\mathrm{km}$ rapid error growth was found far away from perturbed regions, but growth of uncertainties is limited by the large-scale atmospheric environment. A further aspect of model uncertainties is provided by the model resolution especially in terms of convection. Different results of soil moisture-precipitation feedback occur for simulations with explicit and differently parametrised convection (Hohenegger et al., 2009). Hohenegger et al. (2008) found different results in sign and strength of the influence of soil moisture depending on the used model resolution. Simulations with explicitly resolved convection indicate a negative soil moisture-precipitation feedback, that is in consent with many other studies as Barthlott and Kalthoff (2011) summarised.

As Richard et al. (2007) already states, convective precipitation suffers strongly from model uncertainty such caused by initial and boundary data. This study provides an uncertainty estimation that enables to distinguish between random changes in

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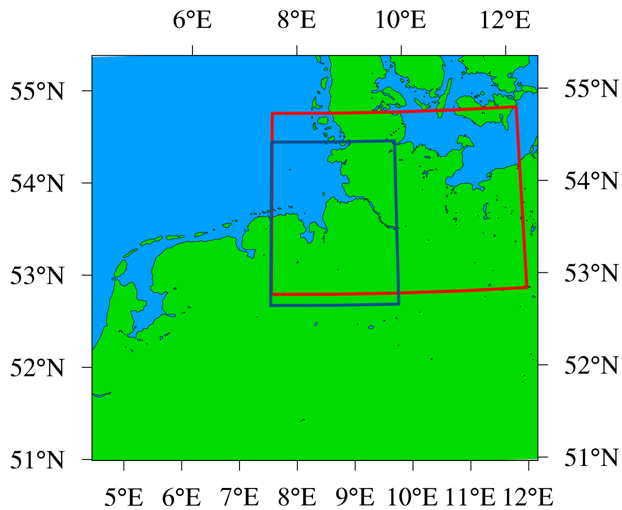

Figure 1. Complete model domain over Northern Germany for CTRL run. The two analysis areas are marked with red and blue rectangles.

precipitation and changes that results from differences in soil moisture. With this uncertainty estimation that is based on many simulations with slightly different model set-ups the effect of different soil moisture modifications on precipitation can be ranged and separated from random effects.

2 Soil moisture perturbation and its influence on precipitation

We simulate the convective introduced precipitation, observed on 03 August 2012, using the non-hydrostatic model COSMO (Schättler et al., 2009) with a resolution of 1 km over Northern Germany including 400 x 450 grid points (Fig. 1) with various simulation set-ups. A 1 km resolution allows an explicit representation of convection and provide much more accurate simulation of convective precipitation (Leutwyler et al., 2016, and references therein). Land surface processes are calculated by the interactive soil and vegetation model TERRA-ML and coupled to atmospheric processes (Doms et al., 2011). Boundary and initial conditions are provided by the coarse grid COSMO operational analysis with a resolution of 2.8 km.

A series of simulations include various soil moisture modifications of different strength and different realisations (table 1). Two classes of changes to the soil moisture field are applied: extreme artificial changes, that show the full range of soil moisture influence and realistic modifications (Fig. 2). Among the strong modifications are total drying of soil (Fig. 2c) and enhancement of 50% (Fig. 2d). Those changes are applied once over the whole model domain and secondly over the red framed domain in Fig. 1). A further artificial modification is redistribution into four alternating bands with 50% enhanced respectively reduced soil moisture (Fig. 2b). Realistic but less intense modifications are implemented by replacing the soil moisture patterns by those from another day (Fig. 2e and f). Therefore the soil moisture field from 20 August 2012 is used. On that day the soil moisture content in the uppermost layer (1.2 mm [H2O] averaged over all land points in the uppermost 10 mm) is 0.3 mm

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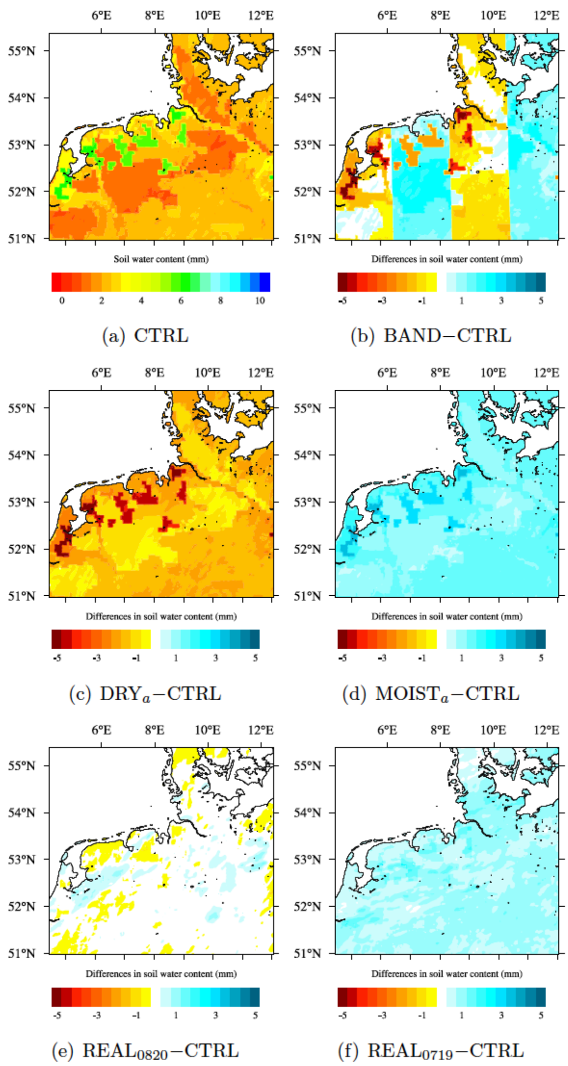

Figure 2. a) soil moisture for CTRL run and differences between CTRL run and b) run BAND, c) run DRY$_a$, d) run MOI$_a$,e) run REAL$_{0820}$ and f) run REAL$_{0719}$ in the uppermost soil layer.

lower than on 03 August 2012. On 19 July 2012 soil moisture content was high (1.9 mm [H2O]) and therefore this day was used to simulate 03 August 2012 with realistic but higher soil moisture. The high uncertainty of convective precipitation on the initial and boundary data (Richard et al., 2007) is accounted by an ensemble approach conducting additional simulations with shifted boundaries by ten to 30 grid points. Those simulation will be explained in detail in Sect. 3. Here we will focus on the simulation with shifted domain by ten grid points first.

In comparison between the CTRL run (Fig. 3a) and the simulation with shifted boundaries (Fig. 3b) differences in the single cells in the West, partly over the North Sea, and in the structure of the large precipitation pattern in the East become obvi-

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Table 1. Model simulations with modified soil moisture (SM). Simulations are named by the applied soil moisture modification and with a for whole model domain and p for modification in a subdomain (partly). Simulations with additional random changes are denoted with ii and jj what represents the shifting of the model domain in grid points (For details see table 2).

simulation	Characteristics		additional random changes	
	modification	area		
CTRL			LOC*ii jj*	TIME*tt*
DRY_a	dry out	whole model domain	$DRY_a ii\, jj$	
DRY_p	dry out	area “red”	$DRY_p ii\, jj$	
MOI_a	50% increased SM	whole model domain	$MOI_a ii\, jj$	
MOI_p	50% increased SM	area “red”	$MOI_p ii\, jj$	
BAND	four bands	whole model domain	BAND*ii jj*	
$REAL_{0820}$	SM from 20.08.12	whole model domain	$REAL_{0820} ii\, jj$	
$REAL_{0719}$	SM from 19.07.12	whole model domain	$REAL_{0719} ii\, jj$	

ous. These differences are predicated to the shifted boundary conditions by ten grid points (10 km). The brutal changes in soil moisture cause even more obvious changes in the precipitation patterns. The enhancement of soil moisture in either the whole domain or a sub domain changes the location of the precipitation for the chosen time dramatically (Fig. 3e and f). In the moist simulation precipitation occurs mainly at places, that are free of precipitation in the CTRL run, and vice verse. Moderate changes in soil moisture, such as applied by using realistic moisture fields, result in smaller changes in precipitation. The general pattern observed in the CTRL run remains in $REAL_{0820}$ and $REAL_{0719}$ (Fig. 3f and g).
Figure 3 shows results of a single output time step only, but gives evidence that random perturbations in the simulations may influence precipitation in a similar order of magnitude as effects due to soil moisture modifications. Detailed and statistically reliable results for an extended estimation of the model uncertainty by a sufficient number of simulation and an analysis method over all time steps is required. Both methods will be introduce in the following section.

3 Estimation of model uncertainties

The comparison of precipitation patterns between 10:00 UTC and 18:00 UTC for multiple simulations provide representative result by using the SAL-score (Wernli et al., 2008) for every single time step. The SAL-score calculates a rate for the differences in structure S, amplitude A and location L of precipitation patterns.
Amplitude A yields the differences of precipitation amount over the whole analysed domain:

$$A = \frac{D(R_{\mathrm{mod}}) - D(R_{\mathrm{comp}})}{0.5[D(R_{\mathrm{mod}}) + D(R_{\mathrm{comp}})]} \quad (1)$$

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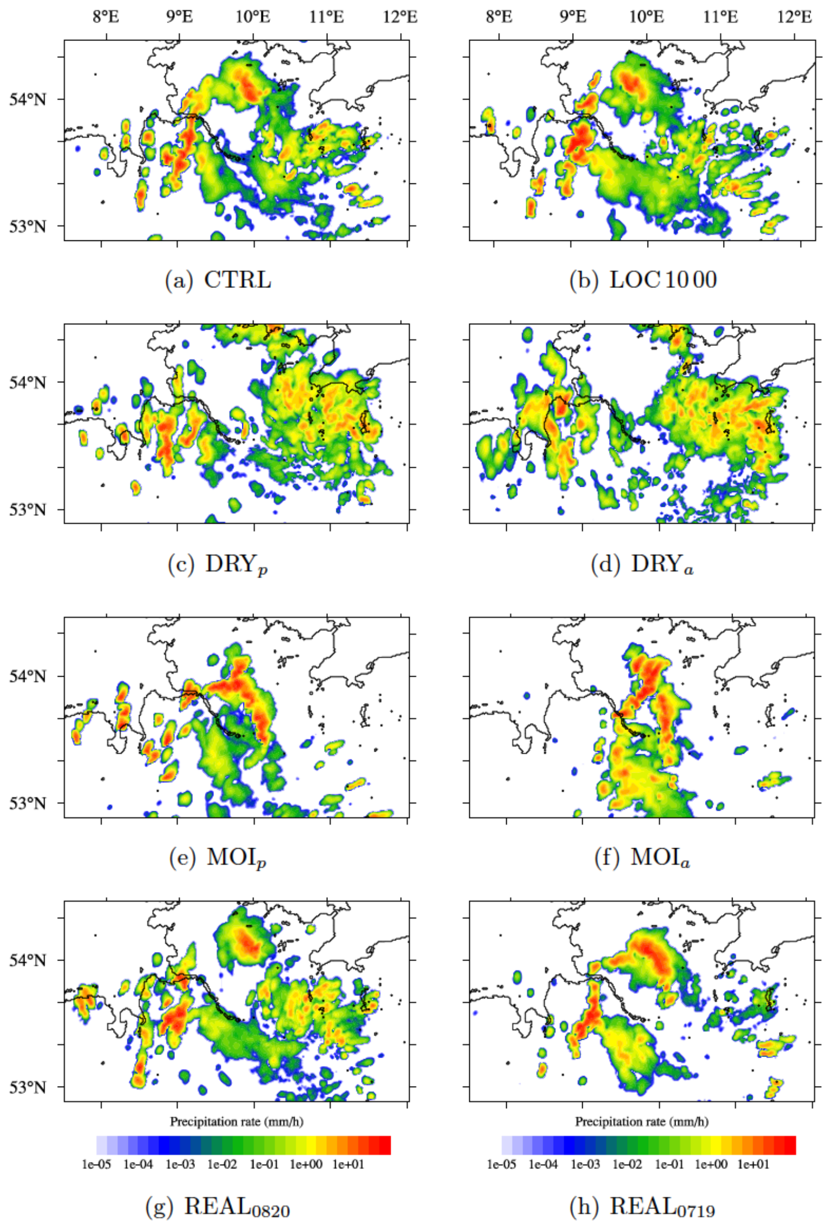

Figure 3. Precipitation rate at 14:45 UTC for a) CTRL run , b) LOC 10 00 and c - f) different soil moisture modified simulations.

with D(R) the averaged precipitation amount for modified model simulation denoted with mod and the compared simulation that is mostly the CTRL run denoted with comp:

$$D(R) = \frac{1}{N_{\mathrm{GP}}} \sum_{(i,j)\in\epsilon} R_{ij} \tag{2}$$

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with the precipitation rate R_{ij} within a grid point that is given by the indices i,j and the number of all grid points N_{GP} in the analysed domain. Component location L compares the location of precipitation in the two model simulations in two steps. First the normalised distance of the centres of mass $\mathbf{x}(R)$ of the precipitation patterns in each model simulation is calculated.

$$L_1 = \frac{|\mathbf{x}(R_{\mathrm{mod}}) - \mathbf{x}(R_{\mathrm{comp}})|}{d}, \tag{3}$$

where d denotes the maximal distance within the analysed domain.

Secondly the distances from the centre of mass of all M individual cells $\mathbf{x}_n$ to the centre of mass fore the whole precipitation field $\mathbf{x}$ is calculated

$$r(R) = \frac{\sum_{n=1}^{M} R_n \left|\mathbf{x} - \mathbf{x}_n\right|}{\sum_{n=1}^{M} R_n} \tag{4}$$

and compared:

$$L_2 = 2\left[\frac{|r(R_{\mathrm{mod}}) - r(R_{\mathrm{comp}})|}{d}\right]. \tag{5}$$

Both components of L are added.

Structure component S gives a hint whether the precipitation patterns tend to more convective precipitation with small but more peaked rain objects or shallow precipitation with larger but less precipitating objects. Therefore a volume $V(R)$ is calculated by the sum of precipitation $\mathcal{R}_{ij}$ over all grid cells ϵ within a precipitation cell n and the maximal precipitation R_n^{max} within this cell:

$$V_n = \sum_{(i,j)\in\epsilon} \frac{\mathcal{R}_{ij}}{R_n^{max}}, \tag{6}$$

$$V(R) = \frac{\sum_{n=1}^{M} R_n V_n}{\sum_{n=1}^{M} R_n}. \tag{7}$$

With $V(R)$ the volume over all precipitation cells M the structure component can be calculated similar to Eq. (1):

$$S = \frac{V(R_{\mathrm{mod}}) - V(R_{\mathrm{comp}})}{0.5[V(R_{\mathrm{mod}}) + V(R_{\mathrm{comp}})]}. \tag{8}$$

For more detailed information on SAL see Wernli et al. (2008).

To address the dependency of SAL-score on the chosen analysis area two different analysis areas are chosen (Fig. 1). The blue framed area in Fig. 1 includes mainly the small convective cells and the red framed area includes the whole precipitation field. For those two analysis areas two simulations are compared to each other respectively.

The significance of soil moisture impact is proven by facing with uncertainty estimations. Random perturbations are introduced by shifting the domain boundaries by ten to 30 grid points north- and eastwards (table 2). Those perturbations provide an estimation of the uncertainty caused by the chaotic behaviour of the atmospheric system and are superimposed on all systematic and physical changes caused by the soil moisture perturbations. This method conserves the structure of all meteorological

Table 2. Uncertainty-ensemble with randomly changed model simulations by model domain shifting, denoted with LOC and the number of shifted grid points, and by shifting the model start time denoted with TIME. The shifted time is given in hours. The lower left corner of the simulation domains is given in geographical (rotated) coordinates with the north pole being shifted to 40° N and -170° E.

run	corner in ° N	corner in ° E	starttime (UTC)
CTRL	50.87 (1.0)	15.55 (3.5)	0:00
LOC 00 10	50.97 (1.1)	15.56 (3.5)	0:00
LOC 00 20	51.07 (1.2)	15.57 (3.5)	0:00
LOC 00 30	51.17 (1.3)	15.59 (3.5)	0:00
LOC 10 00	50.88 (1.0)	15.39 (3.4)	0:00
LOC 10 10	50.98 (1.1)	15.40 (3.4)	0:00
LOC 10 20	51.08 (1.2)	15.42 (3.4)	0:00
LOC 20 00	50.89 (1.0)	15.23 (3.3)	0:00
LOC 20 10	50.98 (1.1)	15.25 (3.3)	0:00
LOC 20 20	51.08 (1.2)	15.26 (3.3)	0:00
LOC 30 00	50.89 (1.0)	15.08 (3.2)	0:00
TIME 01	50.87 (1.0)	15.55 (3.5)	1:00
TIME 02	50.87 (1.0)	15.55 (3.5)	2:00
TIME 03	50.87 (1.0)	15.55 (3.5)	3:00
TIME 04	50.87 (1.0)	15.55 (3.5)	4:00
TIME 05	50.87 (1.0)	15.55 (3.5)	5:00
TIME 06	50.87 (1.0)	15.55 (3.5)	6:00

input fields and does not create errors on a scale that can interact with the analysed processes. Furthermore, shifted start time of the simulations (Hohenegger and Schär, 2007) provide an additional uncertainty. A time shift of one to six hours is also applied to the CTRL run to extend the uncertainty estimation. The ensemble, further called the uncertainty-ensemble, delivers 17 independent model simulations including the CTRL run to estimate the uncertainty. Using the SAL-score an uncertainty estimation with the uncertainty-ensemble will be done by comparing the simulations within the uncertainty-ensemble to each other. Therefore all simulations with shifted model domain are compared to every other simulation with shifted model domain. Those with shifted model start are compared only to the CTRL run. Positive or negative amplitude arises just as an effect of which simulation is used as the CTRL run. To avoid an uncertainty range tending more to one direction, all comparisons are done also in the reversed direction. This approach provides a symmetric distribution for the deviation range. The uncertainty estimation (Fig. 4) encompasses a sample of 122 (number of simulations) times 32 (time steps) values even though, not all of them are independent from each other.

Negative deviations in amplitude are mostly connected to negative deviations in structure and vice versa. Hence a reduction in

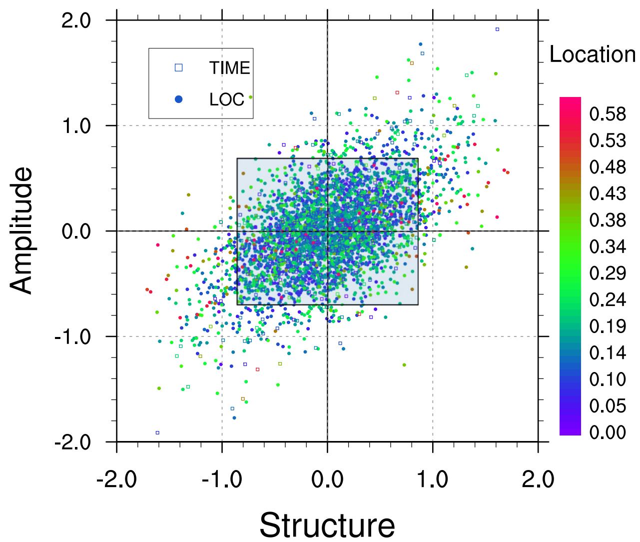

Figure 4. SAL results for the uncertainty-ensemble between 10:00 UTC and 18:00 UTC. Structure is represented on the x-axis, amplitude on y-axis and location by marker colours. Every marker presents a comparison between two model simulations at a single time step. Simulations with shifted model domain are presented by filled dots and those with shifted model start time by rectangles. The borders of the grey rectangle are calculated by 5% and 95% percentile of structure and amplitude.

rain's amplitude arises by too small but peaked rain objects, whereas an increase in precipitation goes along with larger and shallow rain objects. Largest deviations arise in the first hour until 11:30 UTC of the analysis time (Fig. 5). This accords with the beginning of the precipitation event in the different simulations. The onset of precipitation differs in all simulations (not shown) and therefore causes the largest uncertainties. The end of the precipitation event is not considered in the chosen time range. A large shift in model start time leads to higher uncertainties. The random changes due to the shifted model domain do not dependent on how much the boundaries are shifted. Conclusively, there are no systematics for locally perturbed simulations but for time shifted simulations.

We define the model uncertainty for this study as the range from 5% percentile to 95% percentile for structure and amplitude and by 90% percentile for location. Concerning to this definition, the uncertainty range is ±0.77 (±0.86) in structure, ±0.54 (±0.69) in amplitude, and up to 0.20 (0.29) for analysis area "red" ("blue"). Changes are defined as significant when the response to the soil moisture modification is larger than the generated background noise. A residual probability of 10% remains that the latter are not a result of soil moisture modification.

4 Significant effects of soil moisture modification on precipitation

Significant effects from soil moisture perturbations will be carved out with a comprehensive set of model simulations. All simulations with modified soil moisture are conducted additionally with shifted domain boundaries as already applied to the CTRL run (uncertainty-ensemble, see table 1). This huge amount of model simulations (a complete ensemble for each soil

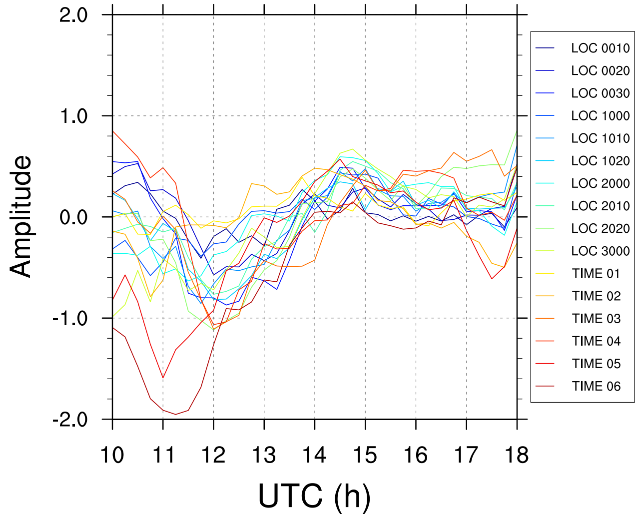

Figure 5. Amplitude values from Fig. 4 for comparisons to the CTRL run only on the single time steps.

moisture modification) and the uncertainty estimation from Sect. 3 accounts for a quantitative evaluation of the significance of soil moisture influence on precipitation.

For all soil modified ensembles every ensemble member will be compared to the corresponding ensemble member (same shifting) from the uncertainty-ensemble. That delivers again a huge sample of SAL values (Fig. 6). Within every ensemble the values are divided into those that exceed the uncertainty range (blue transparent filled rectangle in Fig. 6), that is given by the uncertainty-ensemble, and those that are within. The percentage of the uncertainty range exceeding values is calculated to decide whether a soil moisture modification leads to significant changes in precipitation (table 3). Changes caused by a soil moisture modification will be treated as significant if more than 10% of the values exceed the uncertainty range. The threshold is set to 10% because the uncertainty range was calculated by the 5% and 95% what remains a 10% probability that an exceeding value can still be caused by model uncertainties.

The structural change of precipitation on soil moisture modification as in DRY_p exceeds the uncertainty in only 5% (Fig. 6a and table 3). For both scores S and A the percentage of exceeding values lies beneath the 10% threshold. Therefore, precipitation does not respond significantly on DRY_p modifications, but for L in area “red” only. In contrast, the soil moisture reduction in the whole domain affects the precipitation significantly (Fig. 6b). More than 50% of A exceed the uncertainty range and some of them exceed it by far. For S only 11% of the values exceed the range. Nevertheless, this is enough to be treated as a significant impact.

The soil moisture enhancement in a sub domain only, already results in significant precipitation changes, contrary to the drying in the sub domain (Fig. 6c). Again the modification over the whole domain results in stronger response in precipitation.

The redistribution of soil moisture does not lead to any significant effects (Fig. 6e) but in location in area “blue”. The redistribution of soil moisture increases the large-area heterogeneity, but decreases the small-area heterogeneity. This is in accordance

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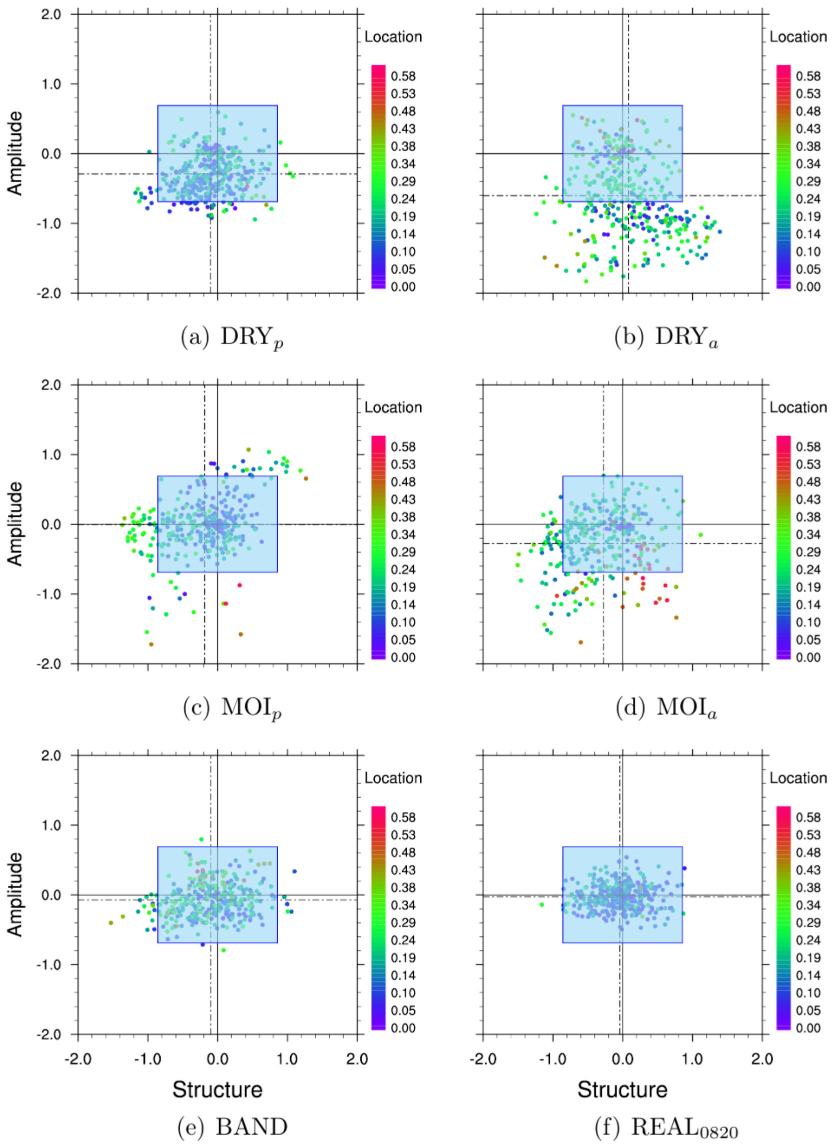

Figure 6. SAL scatter plot: Comparison of ensembles a) DRY$_p$, b) DRY$_a$, c) MOI$_p$, d) MOI$_a$, e) BAND and f) MOI$_{0820}$ with the uncertainty-ensemble for area "blue".

with Adler et al. (2011); Kang and Bryan (2011), who found an influence of redistribution of soil moisture on the location of convective inition. Therefore, area "blue", mainly containing small convective cells, is more influenced than area "red" with the large advected precipitation band.

Even slight modifications of soil moisture, as Klüpfel et al. (2011) did by using different initialisation for soil moisture, lead

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Table 3. Percentages (p_S, p_A, p_L) of values S, A and L that exceed the model uncertainty by 90%. Uncertainties are in a range from $[-0.767, 0.767]([-0.857, 0.857])$ in structure, $[-0.538, 0.538]([-0.690, 0.690])$ in amplitude and $0.200(0.288)$ in location for analysis area "red" ("blue"). Bold values exceed model uncertainties in more than 10%. Averaged values and its deviation ($\overline{S} \pm \hat{\sigma}^2$, $\overline{A} \pm \hat{\sigma}^2$). Bold values are those mean values that differ significantly from the mean of the uncertainty-ensembleafter after Eq. (9) for an confidence interval of 90%.

Ensemble	Structure		Amplitude		Location
	p_S	$\overline{S} \pm \hat{\sigma}^2$	p_A	$\overline{A} \pm \hat{\sigma}^2$	p_L
analysis area "red"					
DRY_p	5.79	0.02 ± 0.0034	3.58	-0.13 ± 0.0011	**25.34**
DRY_a	**23.14**	0.30 ± 0.0063	**22.31**	-0.26 ± 0.0023	**53.72**
MOI_p	**15.98**	-0.12 ± 0.0051	**18.73**	-0.05 ± 0.0042	8.26
MOI_a	9.92	-0.10 ± 0.0043	**23.42**	-0.18 ± 0.0043	**26.72**
BAND	3.03	-0.04 ± 0.0025	0.55	0.00 ± 0.0001	6.61
$REAL_{0820}$	3.31	-0.03 ± 0.0022	0.28	-0.02 ± 0.0006	0.55
$REAL_{0719}$	2.48	0.05 ± 0.0024	1.65	0.09 ± 0.0008	1.65
analysis area "blue"					
DRY_p	4.85	-0.10 ± 0.0033	9.39	-0.29 ± 0.0091	5.76
DRY_a	**11.82**	0.08 ± 0.0058	**51.21**	-0.60 ± 0.0068	**30.61**
MOI_p	**14.85**	-0.19 ± 0.0053	**12.12**	0.00 ± 0.0039	**12.42**
MOI_a	**15.76**	-0.27 ± 0.0058	**19.70**	-0.28 ± 0.0044	**27.58**
BAND	7.27	-0.10 ± 0.0045	0.91	0.07 ± 0.0014	**21.52**
$REAL_{0820}$	0.91	-0.04 ± 0.0026	0.30	-0.03 ± 0.0007	1.21
$REAL_{0719}$	1.21	-0.01 ± 0.0026	0.30	0.07 ± 0.0010	1.21

to different precipitation patterns. Using soil moisture from another day also changes precipitation. But those changes do not exceed the model uncertainty in more than 10% of all values. Accordingly, slight and realistic changes in soil moisture lead to changes in precipitation not larger than changes that can also be caused by choosing a slightly different model set-up.

5 Systematics

After determining the significance of the strength of precipitation changes, this section handles the systematics of changes. Significant changes do not necessarily imply systematic changes. While in DRY_a (Fig. 6b) predominantly negative amplitude changes occur, in $MOIST_p$ (Fig. 6c) significant but random changes occur. Structure and amplitude change in both positive and negative directions. To carve out any systematic effects the averaged value of amplitude and structure are compared to the average of the uncertainty-ensemble. Systematics in L are not analysed as this quantity provides no direction. As explained in Sect. 3 the sample for the SAL results for the uncertainty-ensemble is symmetric and therefore the average is zero. A significant

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difference of the averaged values from zero hints at the systematics. Whether the averaged values differ significantly from zero is tested statistically by:

$$\widehat{z}_{\mathrm{sys}} = \frac{\overline{x}_1 - \overline{x}_2 - E[\overline{x}_1 - \overline{x}_2]}{\sqrt{\hat{\sigma}^2(\overline{x}_1 - \overline{x}_2)}}. \tag{9}$$

$\overline{x}_1$ and $\overline{x}_s$ denotes the averaged values of S or A for the two compared simulations, $E[\overline{x}_1 - \overline{x}_2]$ is the expected value for the differences between the two simulations and is expected to be zero for the null hypothesis, $\hat{\sigma}^2(\overline{x}_1 - \overline{x}_2)$ is the variance of averages.

Only two simulations with overall modified soil moisture have a systematic effect in precipitation structure (table 3). A positive deviation of structure implying less convection is found in the case with reduced soil moisture for the analysed area “red”, whereas a negative deviation is found in a case with enhanced soil moisture in region “blue”. Precipitation’s amplitude reacts more often systematically in the analysis for both regions. Modifications of soil moisture by increasing and decreasing result both in reduced precipitation rates. This implies negative and positive feedback respectively. The positive feedback by decreasing the soil moisture is in consent with Barthlott and Kalthoff (2011). The case study from Barthlott and Kalthoff (2011) show positive feedback for decreased soil moisture. But enhanced soil moisture can lead to increase or decrease in precipitation, dependent on the percentage of soil moisture enhancement. In contrast Cheng and Cotton (2004); Ek and Holtslag (2004); Martin and Xue (2006); Hohenegger et al. (2009); Weverberg et al. (2010) all found a negative feedback in convection resolving simulations.

The strength of deviation depends on the strength of modification. While a partly increased soil moisture does not lead to systematic changes the overall enhancement has a systematic effect. The effect of dry soil exceeds the effect of soil moisture enhancement and shows systematic effects for both implementations. The effects are stronger for overall modifications. Comparing the results for both regions the averaged differences calculated for region “blue” exceed those of region “red” because convective cells are more influenced by soil moisture changes.

6 Conclusion and outlook

The selected case study for 03 August 2012 analysed by the SAL-score provide some results on strength and systematic of soil moisture influence on precipitation:

- Intensive soil moisture modification via artificial enhancement and reduction of soil moisture results in significant changes in precipitation. Large-area modifications show stronger effects than modification in sub domains.
- Unsystematic changes often occur in structure within an ensemble with same soil moisture modification. Systematic changes occur often in amplitude within an ensemble with same artificial soil moisture modification.
- No systematic in amplitude for all different soil moisture modifications exists. Increase as well as decrease will lead to systematic negative deviations. Changes in structure show too few systematic changes to allocate an all over systematic.

- No deviations exceeding the model uncertainty arise by redistributing soil moisture in four bands in this case study. For differences in precipitation's location a significant change can be determined for analysis in the smaller terrain.
- Precipitation differences between the CTRL run and simulations with realistic soil moisture modification can not be proofed as caused by the soil moisture modification. That again shows the difficulties to carve out resilient soil moisture influence.

The results of the two analysis areas differ especially in the percentage of differences exceeding the uncertainty. Having a look on another precipitation quantity or over a different time interval the results will also look a little different. Furthermore, these results base on a single case study. Further case studies with less precipitation in the CTRL run and different synoptic forcing might bring some more different results, especially in systematics of precipitation. To proceed this study the results will be compared to high resolved radar data (Lengfeld et al., 2014). With a larger model domain the uncertainty from the boundary data could be reduced. If soil moisture effects can be better carved out, model simulation with calculated soil moisture from radar data will show the possibility to improve simulation of convective precipitation.

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Data availability

Model output data are stored at DKRZ computers and can be provided on demand.

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