Answer to Reviewer 1:

We thank the referee for his/her valuable comments and suggestions, which will improve the paper. The responses to your comments are marked in blue.

General comments

1. I like the concept of distinguishing between random changes in precipitation and changes that result from soil moisture, but I have some concerns about the representativeness of the results. So far, I am not convinced that the simulation of one day and the evaluation on two comparably small evaluation domains is the right concept. For a more robust conclusion, more cases are necessary and the analysis of one evaluation area alone might be more meaningful. As the authors already mention in the Conclusions, further case studies are needed. If this paper is intended to be a proof-of-concept, the authors should clearly state that in the manuscript and be cautious with any general conclusions.
   As far as we know the concept of shifting the model domain has not been conducted in any model study so far. Furthermore, effects from soil moisture changes are rarely compared to other modifications to rate the soil moisture effects. Thus this study aims on proofing the concept of shifting the model domain as an estimate on model uncertainty and on comparing the concept to physically meaningful changes such as modifications in soil moisture. We recommend on enlarging the study to further cases as we could show that the shifted model domain is a useful tool for model uncertainty estimates and that this is necessary to validate the effect of soil moisture. However conducting further case studies is beyond the scope of this work. We will stronger emphases that the major goal was to introduce this concept. Before performing more case studies, one should be aware that the choice of evaluation domain might be crucial for the results and therefore this is a first necessary step before applying the concept to further cases.
2. My main criticism is due to the fact that nothing is being said about the physical processes that are responsible for these differences. The different model runs are compared to each other with the SAL method, but reasons for the differences remain unclear. As the paper is comparably short, I recommend to add a section on the physical processes responsible for the differences. For example, domain averaged time series of convection-related parameters could be shown here.
   We included a discussion of several quantities that react systematically on the soil moisture changes in contrast to precipitation.
3. When performing a sensitivity study, the control run has to be evaluated first to assure that it serves as a good basis for the sensitivity runs. I believe you need to insert a subsection on the synoptic controls, the observed precipitation and the results of the control run.
   This study aims on the comparison of simulations with different soil moisture and focuses on the differences between various simulations rather than finding the simulation that best fits observational data by model tuning.
   We included a section to describe the synoptically conditions and compared it to radar observations. A more detailed evaluation of the model in this case is beyond the scope of this work and would not improve the results of this work.
4. In many operational forecasting centers, soil moisture is already perturbed in their ensemble prediction systems. Some information about that and most importantly, the differences to the method used in this paper, should be added to the manuscript.
   Using soil moisture perturbation for ensemble prediction one need to know confidentially that this modification can generate an ensemble spread that is sufficiently large to capture possible realizations. That is exactly what this study addresses by comparing the effect from soil moisture perturbation to perturbation, which does not change physically meaningful parameters.
   We included this in the introduction and present some methods of soil moisture modification as conducted by weather services. However, they are not comparable to our soil moisture modification and the comparison to a different uncertainty estimate as they themselves present the uncertainty estimate/model spread.

Specific comments

1. What do you mean by model uncertainty? Please clarify. Again, later on: “Only drastic soil moisture changes can exhibit the model uncertainties...” Probably you mean similar uncertainties as in other ensemble systems where e. g. stochastic perturbations are inserted, tuning parameters changed, or different initial and boundary data from another model are used. This has to be made clearer at several locations in the manuscript
   We rewrote the abstract to make this clear

2. P1, L4: “...but the systematic behaviour is still complex...” Up to now, there is no consent about the existence of a systematic relationship of soil moisture to precipitation. I would rather write: “...but the response of precipitation to soil moisture changes is still complex...”
   included
3. P1, L6: Some details about the ensemble approach used in this work should be given here.
   included
4. P1, L23: Surface temperatures are dependent on the sensible heat flux, not the latent heat flux. Please rephrase.
5. You mean the water content of air? Then it’s probably better to write: “Secondly, soil moisture strongly influences the low-level humidity via the latent heat flux.”
   included
6. “...react on the soil moisture.” Better: “...depend on soil moisture due to its effects on low-level temperature and humidity.”
   included
7. What do you mean with the synergy of soil moisture-precipitation feedbacks?
   The role of orography in the soil-moisture feedback
8. Is shallow convection still parameterized? Which COSMO version do you use?
   Yes, Version 4.4
9. P3: Is the total drying of the soil the respective permanent wilting point?
   With the 50% increase in soil moisture, did you assure that you don’t have larger values than the porosity allows?
   Values of soil moisture are set to zero in the initial conditions and multiplied by a factor of 1.5 independent of wilting point and porosity, respectively
   You state in the manuscript that you want to show the full range of soil moisture influence. So why did you use just a 50% increase and not the maximum value possible for the respective soil type?
   It is right that an enhancement of 50% does not show the full range of possible soil moisture influence. We corrected this statement. Anyhow, the increase by 50% exceeds the increased that is reached by using the relatively wet soil moisture pattern from another day so that this state a large change as the realistic modifications. We included a figure to show this.
   Did you change all levels in the soil in the same way?
   Yes
   Did you make the changes at the model initialization time?
   Yes, we added this in the text.

10. P4, Figure 2: This figure is too pixelated, the text is hardly readable.
    Concerning your band pattern: Does the soil moisture changes from 1 grid point to the other or is there a smoother transition over a couple of grid points? Do these strong gradients introduce any thermal direct circulations?
    We do not have a smooth transition zone, but the initial soil moisture conditions also include strong gradients.
11. Which moist simulation do you refer to? I don’t agree with the statement that in the moist simulation, precipitation occurs mainly at places that are free of precipitation in the CNTRL run. At least, I don’t see that in Figure 3.
    We included a more detailed description of where precipitation occurs at the shown timestep

12. Figure 3: Instead of showing one time of day, a 24-h accumulated precipitation would be much more meaningful. Soil moisture may also influence the timing of cloud formation, so one snapshot might not be enough to show the overall effect. In addition, time series of domain-averaged precipitation should be shown as well
    We added the timeseries of accumulated precipitation.
13. Random perturbations are introduced by shifting the domain boundaries. Please explain in more detail, why you consider this as random perturbations. One way to prove that would be to insert stochastic perturbations e. g. in the initial temperature field. The authors should comment on that.
    With this method we can ensure, that we do not generate any other patterns, that are overlayed and do not change meaningful quantities such as temperature. We described this more detailed.

Technical comments

We corrected the manuscript as suggested in the technical comments

Answer to Reviewer 2:

We thank the referee for his/her valuable comments and suggestions, which will improve the paper. The responses to your comments are marked in blue.

Review on „Assessing the uncertaintiy of soil-moisture impact on convective precipitation by an ensemble approach" by O. Henneberg, F. Ament, and V. Grützun

In this article, the authors evaluate the impact of different soil-moisture initializations on the simulation of convective precipitation with the COSMO model, using a set of ensemble simulations for one case study. These consist of 8 uncertainty ensembles based on one soil-moisture ensemble.
The uncertainty ensembles consist of 11 simulations with a shifted model domain and in one case, on 6 additional simulations with a modified start time.
The underlying idea is that the uncertainty ensemble is a method to estimate model uncertainty, which is then used to assess the significance of different soil-moisture initializations. It is found that „only drastic soil moisture changes" can overcome the model uncertainties.
The idea to compare model uncertainty with soil-moisture induced uncertainty seems to be somehow neglected in recent literature and therefore the article is recommended for publication, even if it is not entirely clear if domain shifting can be regarded as a reliable measure to account for model uncertainty.

Major / general comments:

Before the article can be published, there is a strong need to clarify its structure. Moreover, the model setup is not well explained or even completely missing (the experiments can not be repeated at all with the given information) and a comprehensive overview of all performed and evaluated simulations is missing. Pieces of information can be gathered from different sections, but this makes it very hard to read.
It would be much more comfortable for the reader to have a section #2 called „Model setup" and a section #3 (or 2.2) called „Performed model simulations" to get a better overview at a first glance.
Following that, the case study should be described in its own Section. More work should be done on that – it is not sufficient just to say that it is a case of „convectively induced precipitation" (beginning of Section 2). The soil-moisture precipitation feedback can depend strongly on the strength of the synoptic-scale forcing. Thus it is essential for the reader to have some idea about the general synoptic conditions of this case.
We restructured the article as following:

- 2 Modelling approach
  - 2.1 Numerical Setup
  - 2.2 Soil moisture experiments
  - 2.3 Ensemble approach
- 3 Case description
- 4 Results
- 4.1 Estimate of model uncertainty ...

and extended the description of the synoptic situation
Related to this: It would be good to include a discussion on the question whether the domain shifting does generate / include new physical processes or not. In Figure 3, for example, LOC 10 00 is shown but not LOC 30 00. In LOC 30 00 and LOC 00 30, the domain is shifted by 30

km, which is not negligible. If a larger part of the ocean / coast is included in the shifted simulation for example, this could very well modify the simulation also in a physical way.
We agree, that a larger fraction of sea surface in the model domain includes physical processes due to different surface fluxes that affect precipitation formation. However we do not see any trend that a stronger shifting changes precipitation in one or the other direction and therefore consider the shifting to be suitable to generate changes. We included a discussion paragraph on that.
It is strongly recommended to separate the aims and the argumentation for the chosen comparisons from the description of applied methods. The SAL method should be described in a separate section (or subsection) with a clear description of which simulations / precipitation fields (15-min precipitation sums? which evaluation area?) are compared to which reference. Don't mix the argumentation for your method of generating uncertainty estimations into this Section.
We tried to make clearer that SAL is applied on every model output step of the precipitation rate. However, we tested the analysis for the 15min accumulated precipitation for the REAL ensembles and found the results are more sensitive to the chosen analysis area than the chosen output variable.
In contrast, a discussion of this point is missing in the introduction. Can you give some references / examples of other studies which use domain shifting to estimate model uncertainty?
We are not aware of any studies using this approach
Finally, the English language needs to be revised carefully as there are a large number of inaccuracies. Examples are given below.

We included the following comments either as suggested or as stated in blue:

Specific comments

1 Introduction

p. 1, l. 23-24: „Soil moisture affects the partitioning of turbulent heat fluxes …, which once affects

included

the surface temperature“; soil moisture rather directly affects the surface temperature
p. 2, l. 1-2: „in the lower troposphere“ → in the boundary layer?

included

p. 2, l. 2: „surface temperatures can … initiate convection“ → can influence the initiation of convection

included

p. 2., l. 7: „that following the process chain“ → that follow the…

included

p. 2, l. 34-35: „convective precipitation suffers strongly from model uncertainty such (as!) caused by initial and boundary data“ → uncertainties caused by initial and boundary data are not really model uncertainties, even if this is stated in Richard et al. (2007) – is it?

Reformulated

p. 3., l. 1: „many simulations“ → a large number of simulations

included

p. 3, l. 3: „the effect … can be ranged“ → can be assessed and quantified?

Included

2 Soil moisture perturbation and its influence on precipitation

The Section could be called „Model / experiment setup and overview of performed

simulations"
Please give a comprehensive description of the model setup: How many vertical levels did you use?

We give a more detailed model description

Are the chosen settings for the physics parametrizations similar to the operational ones? For example the parametrization of bare soil evaporation could be decisive for processes in the considered case of convection initiation. Model start time, length of the simulations?
p. 3, Figure 1: It would be great if you could show a larger domain with additional rectangles for used model domains (e.g. black solid line for ctrl domain, black dashed for LOC 00 30 and LOC 30 00).

We extenden the figure for simulation CTRL to a slighly larger domain, to show both analysis areas within this plot

p. 3, l. 6: „convective introduced precipitation" → convectively induced precipitation

included

p. 3, l. 8: „A 1 km resolution … provide(s!) a much more accurate simulation of convective precipitation" → more accurate than what?

Than simulations for which a convection pramatrization is required

p. 3, l. 11: „coarse-grid COSMO operational analysis" → 2.8 km is not really coarse; omit „coarsegrid"

included

p. 3., l. 15: „enhancement [of soil moisture] of 50 %" → did you apply this enhancement taking into account the underlying soil-type distribution?

No. Are there essential reasons to do so?

p. 3, l. 15: „red framed domain" → insert here „(hereafter, referred to as area „red")"

included

p. 3, l. 15 ff: „Those changes are first applied over whole model domain (DRY_a and MOI_a, Table 1) and second ...Another artificial modification is the redistribution … (BAND...)" → also give references to names in Table 1 in the following sentences

included

Figure 2: Is there a reason that you show only 6 out of 8 members of the soil-moisture ensemble?

We included a rectangle for the locally changed soil moisture. That differs from the allover changes by its local restriction.

p. 4, l. 2-3: „high uncertainty of convective precipitation on the initial and boundary data is accounted for by..." → sensitivity of conv. precip on?

reformulated

same sentence: better discuss the reasoning behind the method before – either in a separate (sub-)section „Aims and estimation of model uncertainties" or (better) directly at the end of the introduction

We included in the introduction that we used this estimate on model uncertainty to compare this to comparable strong soil moisture changes as soil moisture perturbations are also used in ensemble prediction.

p. 4, l. 4: „Those simulations"

included

p. 4, l. 5: „the simulation with a domain shifted by"

included

p. 4, l. 4 ff (starting with „Here we will focus on..."): This part should be moved into its own (sub-)section (see also general comments); but before, show Table 2 and give the corresponding explanations.
The new (sub)section could be called something like „Overview of convective precipitation event and influence of different soil moisture perturbations".

First, give a more general overview of the case study (Synoptic conditions? When did convection initiation occur? Which processes did contribute? Can you assume in the first place that soil moisture patterns had an influence at all? How much precipitation was observed over which period?).
Only afterwards, sensitivity experiments can be described.

We included a section on the synoptic description and show the occurrence of precipitation in the radar

p. 5, l. 1: „differences are predicated to" → presumably caused by? attributed to?

included

p. 5., l. 1: „brutal changes" → extreme changes?

included

p. 5., l. 2: „more obvious changes" → modifications / differences?

included

p. 5, l. 8: „similar order of magnitude as soil-moisture modifications"

included

Table 1, title: „which represents the shifting..."

included

Table 1, last column: The nomenclature „DRY_a ii jj" here is not really used in the text; could you give just „LOC ii jj"in this columns and refer to „CTRL-LOC ii jj"or „DRY_a-LOC ii jj" at places where it is explicitly referenced.

ii and jj is a replacement for all simulations in table to as described in the heading.

Figure 3, title: „Precipitation rate at 14:45" → this is misleading; I assume that this is the 15-min precipitation sum, recalculated to mm/h (assuming that you have output time steps of 15 min)?

It's the precipitation rate and results are very different chosing one or the other variable

Figure 3: Is there a good reason to use a logarithmic colour scale?

We decided to use a logarythmic scale to show precipitation detailes, which cant be seen with a linear scale (which is anyhow rather unusal for precipitation). And a logarythmic scale is still more intuitive than a irregular scale.

It would be great if you could include the blue rectangle as this evaluation area is used later.

Included

3 Estimation of model uncertainties

Section title could be „Determination of objective criteria for the given model uncertainty"
Which precipitation threshold did you use for the SAL (necessary to determine the precipitation objects, called „cells" in this article)?

The treshold for every object is calculated by the 5%-percentile of all precipitating grid points with rates higher than 1e-4 kg m-2 s-1

p. 5, l.12: „provide representative results by using the SAL score" → can you reformulate this sentence?

Changed

p. 5, l.13: „for every single time step" → you mean output time step? you also have to give it (15 min)?

changed

p. 5, l.13: „The SAL-score gives"

provides

p. 7, l. 25 to p. 8, l. 4: as said in the general comments, leave this passage out at this place (parts have to be included when you describe the aims, parts in the Section „Overview of performed model simulations").

The definition of the „uncertainty ensemble" would be clearer if it would be distinguished between the „CTRL-uncertainty ensemble" (shown in Table 2) and the other uncertainty ensembles for the simulations with perturbed soil moisture, e.g. the „DRY_a-uncertainty ensemble".

We renamed into reference simulation for ensemble and ensemble generating changes.

p. 8., l. 4 ff: Related to the previous comment, it is not easy to understand which simulation is compared to which reference (don't use „CTRL" in l. 8, p. 8 - that ambiguous here; additionally, in the given description of the SAL components, it is called „comp"). How do you count 122 simulations?

We changed the subscrips in SAL to ctrl and diff. There are 122 combinations to compare the different simulations. We corrected that.

Table 1: Columns headings: „lower-left corner" or „LL corner" with abbrev. given in title

included

Figure 4: Which evaluation area – red or blue?

Red, we included it in the text now

Markers can be hardly distinguished – could you make two sub-plots?

included

p. 9, l.1-2: „Hence, a reduction in precipitation amplitude is related with too small and / or peaked precipitation objects … larger and / or shallower precipitation objects. … This agrees with...".

included

p. 9, l. 6: dependent … „Conclusively, no systematic behaviour can be detected for locally perturbed simulations, but for time-shifted simulations, which is caused by the differing precipitation onset."

included

p. 9., l. 9: „According to this definition"

included

4 Significant effects of soil moisture modification on precipitation

p. 9, l. 14 to p. 10, l.2: leave the passage out; as said above, overview of all simulations should be given in Section 2.2 / 3

deleted

p. 10, l. 3: „Each uncertainy ensemble will be compared to the CTRL-uncertainty ensemble, only comparing ensemble members with the same domain shifting. That yields again a ..." Again for all output time steps?

Yes included

p. 10, l. 6: „The percentage of the values exceeding the uncertainty range is ..."
p. 10, l. 11: „in only 5 % of all cases"
p. 10, l. 14: „soil moisture reduction in the whole domain (DRY_a) affects ..."
p. 10., l. 17: „soil moisture enhancement in a sub-domain only (MOI_p) ..."
p. 10, l. 19: „the redistribution of soil moisture as in BAND does not..."

all included

p. 10, l. 19-20: „The redistribution of soil moisture increases the large-area heterogeneity, but decreases the small-area heterogeneity" → do you mean that the heterogeneity on the length scale of the chosen band is increased by the perturbation itself while smaller-scale secondary circulations become less important?

Changed to: The redistribution of soil moisture changes the heterogeneity of the soil moisture by reducing small-scale structures, but induce stronger variations on the large scale.

Figure 6: Which time steps are analysed? The shading in the rectangles is not necessary and

blurs the images. Just give the frames. What are the dashed lines?

Shading was deleted, the dashes lines represent average values

5 Systematics

p. 12, l. 7: „in MOIST_p, significant but random changes occur" → are they really random or could the sign of A also be caused by the location of the patch relative to the shifted domain?

You mean accorind to the location of the modification (patch) relative to the domain boundaries? The location of the patch stays the same.

p. 13, l. 7: „According to the z-test [is it a z-test?], only two simulations [ensembles?] with overall modified soil moisture have a systematic effect..." → only two of this kind exist; do you mean „only two simulations have a systematic effect: DRY_a and MOI_a, i.e. the two simulations with overall..."

This had been formulated missleading. We reformulated this.

p. 13., l. 11 ff: I would be careful to call it „feedback" if it is not symmetric. Could the differences of the results found by Barthlott and Kalthoff (2011) compared to the results of others be caused by the influence of orography in their investigation?

What is menat by symmetric? There are mainly two feedback mechanism, one positive one negative resulting dependent on the conditions in either an overall positive or negative feedback. As in all reffered manuscripts this is called feedback we will stick to the term as well. The results from Barthlott are influenced from the orography.

Assessing the uncertainty of ~~soil-moisture~~ soil moisture impact on convective precipitation ~~by an~~ using a new ensemble approach

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Abstract. Soil moisture influences the occurrence of convective precipitation. Therefore, an accurate knowledge ~~of~~ about 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 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~~However, simulations with slightly changed model setup cause a large spread in model results that result from the chaotic behaviour of the atmospheric system and stochastic variability. By shifting the model domain, an estimate on the uncertainty of the model results can be calculated. This uncertainty estimate, which includes ten simulations with shifted model boundaries, is compared to the effects caused by soil moisture on precipitation. With this approach the effect if soil moisture is quantified.

~~Here we~~ We performed seven experiments with modified soil moisture ~~using an ensemble approach for each experiment. Only~~ to address the effect of soil moisture on precipitation. Each of the experiments consists of ten ensemble members. In three out of the seven experiments precipitation changes exceed the model spread in either amplitude, location or structure. This changes are caused by a 50% soil moisture enhancement ~~and a complete dried soil impact precipitation patterns considerably in structure, amplitude and location in different analysis areas. Both, the enhanced and~~ in either the whole or part of the model domain or dry-out of the whole model domain. Enhanced or reduced soil moisture ~~result in a reduced precipitation rate~~predominately result in reduced precipitation rates. Replacing the soil moisture by a realistic field from different days ~~influences the precipitationinsignificantly~~has an insignificant influence on the precipitation. We point out the need for uncertainty ~~estimations in~~ estimates in real-case 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 horizontal resolution of 1 km ~~scale resolution to~~ and can represent convective processes explicitly ~~and~~ to improve weather forecast (Mass et al., 2002). Nevertheless, precipitation formation ~~undergoes~~ results from a complex chain of atmospheric processes~~from the micro~~, which range from the microscale to the synoptic scale (Richard et al., 2007). Therefore precipitation remains Because many of these processes remain unresolved, precipitation states 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 Soil moisture sits at the beginning of the convective precipitation formationthat is highly sensitive to the aforementioned atmospheric stratification.

Soil moisture affects the partitioning of turbulent heat fluxes into sensible and latent heat, which once what affects the surface temperature due to the latent heatingand boundary layer temperature and the humidity in the lower boundary layer. 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, , whereas the specific water content in the lower troposphere boundary layer 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 convectionas well. These competing effects hamper the analysis on soil moisture influence. Many parameters to describe the atmospheric stability react on the soil moisture. A what also favours convection. Conclusively moistening and drying of the lower boundary can intensify precipitation and vice versa. Whereas, 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 follow 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 Furthermore, 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 There is no clear consent agreement on soil moisture precipitation interaction in the literature: Barthlott et al. (2011) found a strong dependency of precipitation, with changes larger than 500%, for a soil moisture variation of ±25% in regions with low mountain rangesand changes , and changes of up to −75% for domains with higher mountain ranges. Significant They could not identify significant differences between planetary boundary drivenand synoptic forcedconditions 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 , and synopticaly forced, conditions. Hauck et al. (2011) determined large systematic differences between modelled and observed soil moisture. The influences influence on simulated precipitation is more complex and depends in their study was complex and depended 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 crests, independent of the instability indices, but with smaller convective inhibition (CIN). The dependency of equivalent potential temperature on soil moisture was found to be influenced by surface inhomogeneity. Barthlott and Kalthoff (2011) provide a sensitivity study , in which the soil moisture was increased by ± 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~~ , using a model resolution of 2.2 km, a rapid error growth was found far away from the 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~~ parametrized 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~~ that depended on the model resolution. Simulations with explicitly resolved convection indicate a negative soil moisture-precipitation feedback, that is in ~~consent~~ agreement with many other studies~~as Barthlott and Kalthoff (2011)summarised~~, summerised by Barthlott and Kalthoff (2011).

Soil moisture perturbations are directly assessed to generate an ensemble spread in numerical weather forecasts. Weather services include soil moisture perturbation in data assimilation for their ensemble forecast systems as MeteoSwiss does by using the method from Schraff et al. (2016) in the COSMO model to achieve a model spread especially in summer (pers. com. Daniel Leuenberger, MeteoSwiss). The evaluation of the AROME-EPS ensemble prediction system from Bouttier et al. (2016), which also includes soil moisture perturbations, showed that a lack in precipitation spread remains. That rises the question if soil moisture perturbations can cause sufficient differences in precipitation. This question will be addressed in the present study. As Richard et al. (2007) already ~~states~~stated, convective precipitation ~~suffers strongly from model uncertainty such caused by initial~~ output strongly depends on model setup, such as the prescribed initial conditions and boundary data. ~~This studyprovides an uncertainty estimation that enables to distinguish between~~ In the present study, we provide an uncertainty estimate that allows random changes in precipitation and changes that results from differences in soil moisture. With ~~this uncertainty estimation that~~ a uncertainty estimate, which is based on ~~many~~ a large number of simulations with slightly different model ~~set-ups~~ setups, the effect of different soil moisture modifications on precipitation can be ~~ranged and~~ assessed and quantified. Furthermore, an effect caused by soil moisture can be separated from random ~~effects.~~ changes. This determines if soil moisture perturbations can provide a sufficiently large ensemble spread for ensemble forecast.

Model simulations are conducted with the regional model COSMO (section 2.1). The soil moisture experiments and the ensemble approach are presented in sections 2.2 and 2.3, respectively for a single case with convective precipitation. An overview of the synoptic conditions for this convective case is provided in section 3. An estimate on the model uncertainty based on the CTRL-ensemble is calculated in section 4.2. With the given uncertainty range, the significance of soil moisture changes compared to the model spread is assessed in section 4.1, and systematics in the soil moisture impact are investigated in section 4.1.

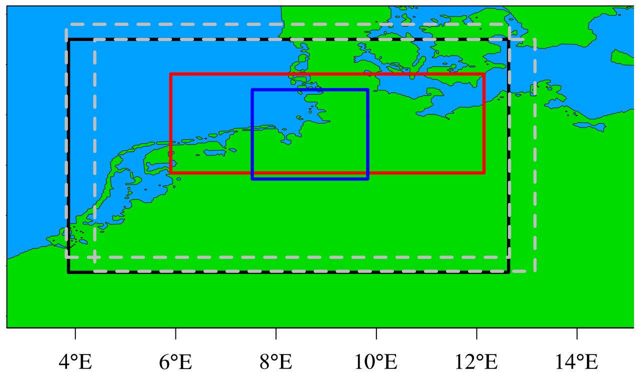

Figure 1. Complete model Model domain over Northern Germany given by the black rectangle for the CTRL run. Dashed gray rectangles describe the model domain, which is shifted by 30 gridpoints to the north and to the east, respectively. The two analysis areas are marked with red and blue rectangles.

2 Soil moisture perturbation and its influence on precipitationModelling approach

2.1 Numerical setup

We simulate the convective introduced precipitation , observed on 03 We performed 24-hour simulations to simulate the convectively induced precipitation on 3 August 2012 over the area around Hamburg, using the non-hydrostatic model COSMO (Schättler et al., 2009) with a resolution of (Version 4.22, Schättler et al., 2009) with a horizontal resolution of 0.1° (≈1 kmover Northern Germany including). The chosen domain covers 400x $\times$ 450 grid points over Northern Germany (Fig. 1)with various simulation set-ups. A . 50 vertical hybrid Gal-Chen levels range from the surface to a height of 22 km. The lowest level has a vertical resolution of 20 m. The boundary and initial conditions are provided by the COSMO operational analysis with a resolution of 2.8 km.

The horizontal resolution of around 1 km resolution allows allows for an explicit representation of convectionand provide , and thus provides much more accurate simulation simulations of convective precipitation than resolutions, which require convection parametrizations (Leutwyler et al., 2016, and references therein). Shallow convection is parametrized by the Tiedke Scheme (Tiedtke, 1989). 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 2.8the atmospheric module (Doms et al., 2011). The coupled soil model includes seven

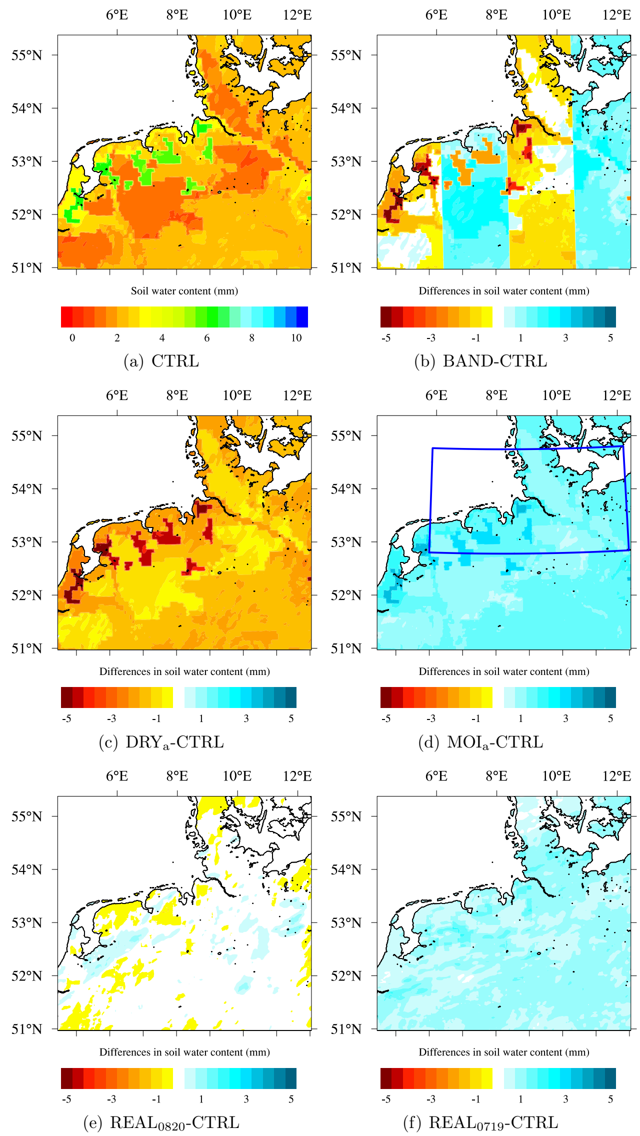

Figure 2. (a) ~~soil~~ Soil moisture for CTRL run and differences between CTRL run and (b) ~~run~~ BAND run, (c) ~~run~~ DRY$_a$ run, (d) ~~run~~ MOI$_a$ run, (e) ~~run~~ REAL$_{0820}$ run and (f) ~~run~~ REAL$_{0719}$ run in the uppermost soil layer. Blue rectangle indicates the region where soil moisture was changed in DRY$_p$ run and MOI$_p$ run.

soil levels from the surface to a depth of 14.58 m with the uppermost layer having a vertical extension of 5 mm.

2.2 Soil moisture experiments

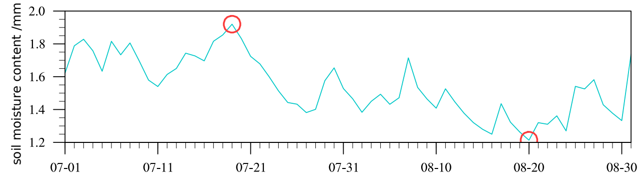

Figure 3. Time series for soil moisture content in the uppermost soil level averaged over the analysis domain "red". Red circles indicate the soil moisture values, which were used to perform simulations with soil moisture from another day.

A series of simulations include various soil moisture modifications of different strength and different realisations To address the potential effect of soil moisture on precipitation, the soil moisture content provided in the initial conditions was modified (Table 1). Two classes of changes to in the soil moisture field are were applied: extreme artificial changes, that show the full which show a large range of soil moisture influence and modifications in a physically feasible range (Fig. 2). Among the strong modifications are is the total drying of soil by setting the soil moisture content to zero (Fig. 2c)and . Soil moisture increase is achieved by an enhancement of 50% (Fig. 2d) in all soil layers. Those changes are applied once first over the whole model domain and (DRY_a and MOI_a, Table 1, Fig. 1) and secondly over the red framed domain in Fig. 1. A further , hereafter referred to as area "red" (DRY_p and MOI_p, Table 1). Another artificial modification is achieved by a redistribution into four alternating bands with 50% enhanced respectively and reduced soil moisture, respectively (Fig. 2b). Realistic but less intense A large range of possible soil moisture effects is covered with this modifications. More realistic, but slightly less intense, modifications are implemented by replacing the soil moisture patterns by those pattern by one from another day (Fig. 2eand f). Therefore, the soil moisture field from 20 August 2012 is used . (Fig. 3). On that day the soil moisture content in the uppermost soil layer (105 mm) is around 1.2 mm [H2O] [H_2O] averaged over all land points. That , what is 0.3 mm lower than on 03 August 2012. the simulated day (3 August 2012). On 19 July 2012 soil moisture content was high (1.9 [H2O])and therefore slightly below the 50%-artificial enhancement (Fig. 3). Therefore, the soil moisture was higher than on 3 August and thus this day was used to simulate 03 3 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. ??. Here we will focus on the simulation with shifted domain by ten grid points first. Precipitation rate at 14:45 UTC for (a) CTRL run , (b) LOC 10 00 and (c-h) different soil moisture modified simulations. In comparison between the CTRL run (Fig. 10a) and the simulation with shifted boundaries (Fig. 10b) 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 obvious. These differences are predicated to the shifted boundary conditions by ten grid points (10). 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. 10e 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 $REAL_{0820}$

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 jjwhat , , which represents the shifting number of gridpoints by which the model domain in grid points is shifted (For details see Table 2).

simulation reference simulation for ensemble	Characteristics		ensemble generation	
	modification	area		
CTRL			LOCCTRL-LOC*ii jj*	TIME*tt*
DRY$_{a}$a	dry out	whole model domain	DRY$_{a}$a-LOC*ii jj*	
DRY$_{p}$p	dry out	area "red"	DRY$_{p}$p-LOC*ii jj*	
MOI$_{a}$a	50% increased SM	whole model domain	MOI$_{a}$a-LOC*ii jj*	
MOI$_{p}$p	50% increased SM	area "red"	MOI$_{p}$p-LOC*ii jj*	
BAND	four bands	whole model domain	BANDBAND-LOC*ii jj*	
REAL$_{0820}$	SM from 20.08.12	whole model domain	REAL$_{0820}$-LOC*ii jj*	
REAL$_{0719}$	SM from 19.07.12	whole model domain	REAL$_{0719}$-LOC*ii jj*	

and REAL$_{0719}$ (Fig. 10f and g). Figure 10 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

2.3 Ensemble approach

To quantify the relevance of the results from the 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 provides representative results 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:

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

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:

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

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.

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

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

$$r(R) = \frac{\sum_{n=1}^{M} R_n \, |\mathbf{x} - \mathbf{x}_n|}{\sum_{n=1}^{M} R_n}.$$

and compared:

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

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:

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

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

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

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

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

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 (LL) corner of the simulation domains is given in geographical (rotated) coordinates with the north pole being shifted to 40° N and -170° E.

run	LL corner in ° N	LL 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

~~compared to each other respectively.The significance of soil moisture impact is proven by facing with uncertainty estimations. Random perturbations are~~ and variability is estimated with a novel and simple approach. Perturbations are introduced by shifting the domain boundaries by ten to 30 grid points north- and eastwards (Table 2~~). Those~~ , Fig. 1). These perturbations provide an ~~estimation~~ estimate 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 input fields and does not create errors on a scale that can interact with the analysed processes eg by creating small scale secondary circulation. Furthermore, ~~shifted start time~~ shifting start times of the simulations (Hohenegger and Schär, 2007) provide an additional degree of uncertainty. A time shift of one to six hours is also applied to the CTRL run to ~~extend the uncertainty estimation~~fairly compare uncertainty estimates. The ensemble, further called the ~~uncertainty-ensemble~~CTRL-ensemble, delivers 17 independent model simulations including the ~~CTRL run~~ reference simulation (CTRL-run) to estimate the uncertainty. The ensemble approach, including all simulations with shifted model domains, was applied on every simulation with the modified soil moisture pattern (Table 2). ~~Using the SAL-score an~~

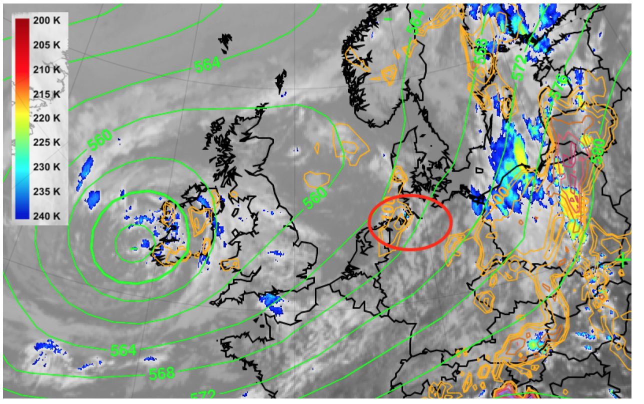

Figure 4. EUMEtrain infra-red satellite image of Europe on 3 August 2012 at 12:00 UTC. Colours are cloud top temperatures showing high clouds. Green contours are geopotential height at 500 hPa and orange contour lines are CAPE-values provided from ECMWF NWP (www.eumetrain.org). The area of interest is marked with a red circle. Note the CAPE values within the marked area and the high clouds, which correspond to the intense precipitation.

~~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~~

3 Convective case-study and the effect of soil moisture

The chosen convective case on 3 August 2012 was affected by a low pressure system in the north Atlantic, west of Great Britain (Fig. 4). The associated cold front passed over Germany and resulted in heavy precipitation over Poland where air masses converged. Next to the major precipitation events in the east, another local precipitation cell developed close to Hamburg where a slight enhancement in convective available potential energy (CAPE)-values and high clouds occurred (Fig. 4). This locally strong precipitation was detected by the rain radars over Hamburg at 14:11 UTC with rain rates between 10 to ~~every other simulation with~~ $100\,\mathrm{mm\,h^{-1}}$ (Fig. 5). The simulations showed maximal values of $12\,\mathrm{mm\,h^{-1}}$ between 13:00 to 17:00 UTC. The simulated precipitation onset is at around 10:00 UTC (Fig. 6a). Before the precipitation onset, high CAPE-value confirms the convective nature of the precipitation (Fig. 6b). High CAPE-values enable strong convective precipitation formation, when CIN can be exceeded.

4 Results

4.1 Soil moisture influence on convective related variables

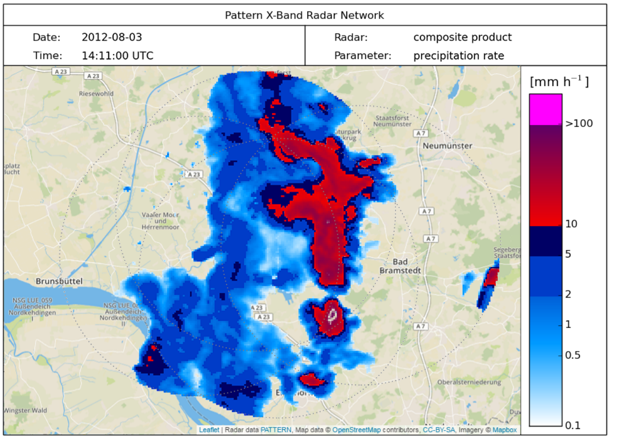

Figure 5. Radar composite from high resolution radars (Lengfeld et al., 2014) showing the precipitation rate over Itzehoe on 3 August 2012 at 14:11 UTC.

While the passing front stated the main mechanism for the lifting of air masses, soil moisture is important for the stability of the atmosphere and thus affecting the precipitation, which initially was triggered by the synoptic system. In complete dry conditions (DRY_a and DRY_p), no latent heat fluxes transport heat from the surface. Thus, sensible heat fluxes need to balance the heat differences between surface and atmosphere (Fig. 7). Without latent cooling, the temperatures at 2 m altitude in the simulation with dry soil conditions (DRY_a and DRY_p) are the highest, whereas dew point is the lowest (Fig. 7c and d). With more humidity in the atmosphere, less adiabatic cooling due to lifting is required for condensation. The resulting shift in the condensation level to lower altitudes can reduce CIN and increase CAPE. CIN only reduces in the first hours of the simulation before solar radiation heats the surface (Fig. 7). When the surface heats up, in simulations with low soil moisture content, CIN values are continuously lower than in simulations with higher soil moisture content. The further development of CIN is strongly affected by the feedback from precipitation.

All mentioned quantities react systematically on changes in soil moisture (Fig. 7). Convective precipitation is more likely with reduced CIN and its strength depends on CAPE. However, the changes in precipitation amount does not systematically react on the soil moisture. The main reason in literature for this systematic behaviour is due to the CIN dependency on the soil moisture (Kalthoff et al., 2011). Even though the changes in precipitation with changing soil moisture are more complex, precipitation is influenced by the soil moisture. However, that the changes in precipitation caused by soil moisture changes compared to the synoptic forcing are less significant will be shown in the following sections.

4.2 Estimate of model uncertainties

An estimate of the model uncertainty is determined from the CTRL-ensemble. The statistical tool, which was applied for this purpose, is the SAL-score (Wernli et al., 2008), which assigns values for differences in structure, S, amplitude, A and location, L, of precipitation patterns at every single output-timestep (15 min).

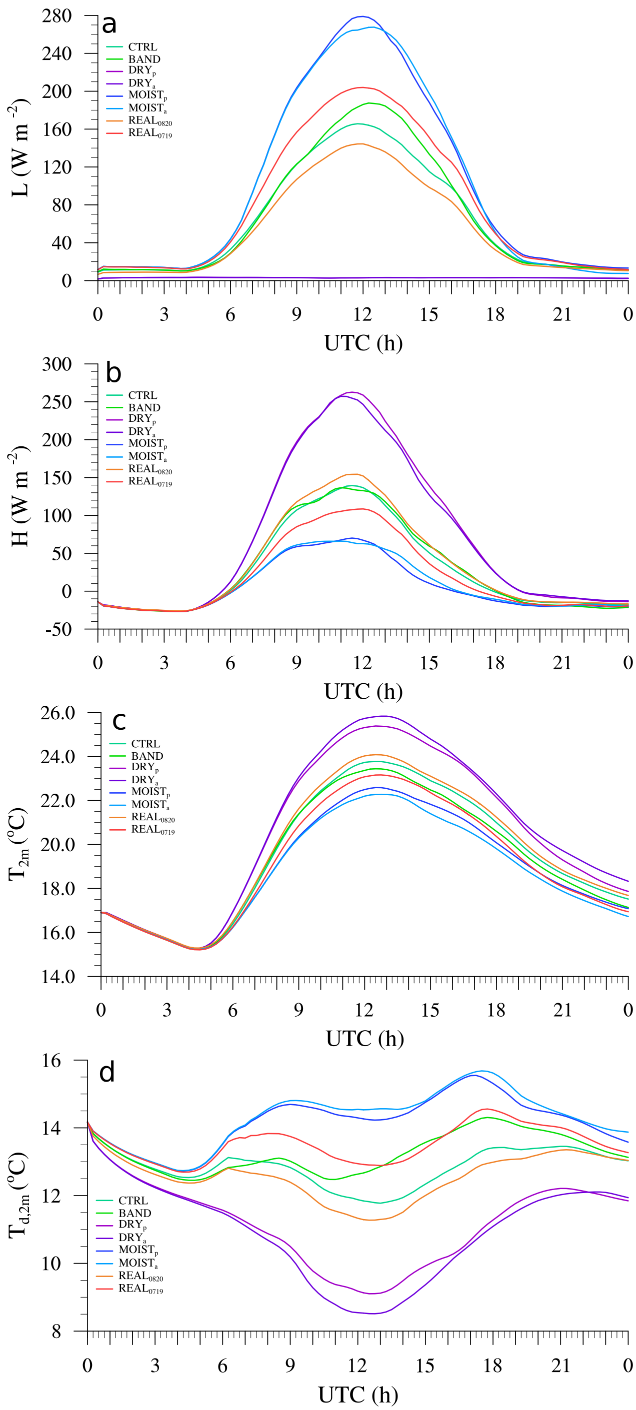

Figure 6. Timeseries of (a) latent heat fluxes, L, (b) sensible heat fluxes, H, (c) 2m-temperature and (d) dew point temperature, T_{d} in the reference simulations of the ensembles with different soil moisture modifications for 3 August 2013. Averaged over area red.

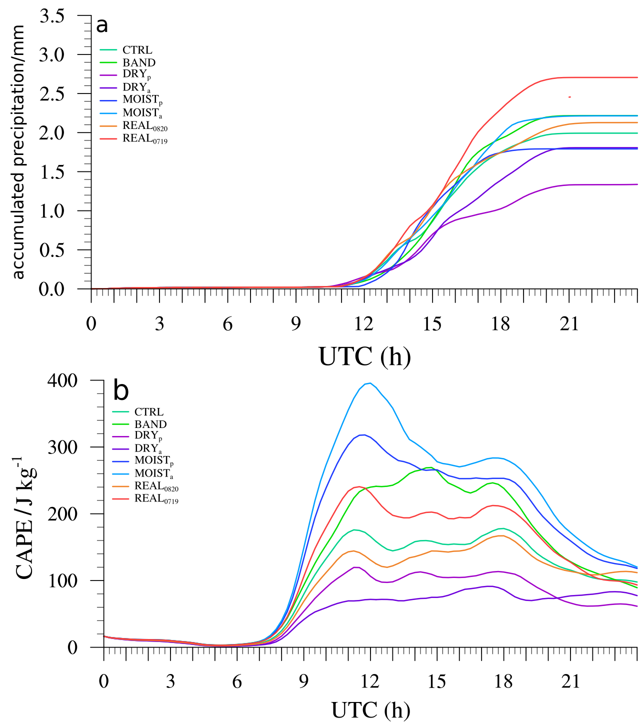

Figure 7. Timeseries of (a) accumulated precipitation and (b) CAPE for different model simulations for 3 August 2013. Averaged over red area.

Amplitude A yields the differences of precipitation amount over the whole analysed domain:

$$A = \frac{D(R_{\mathrm{dif}}) - D(R_{\mathrm{ctrl}})}{0.5[D(R_{\mathrm{dif}}) + D(R_{\mathrm{ctrl}})]} \tag{1}$$

with the averaged precipitation amount, $D(R)$, for shifted simulation from the CTRL-ensemble denoted with dif and the compared simulation that is the not shifted reference simulation from the CTRL-ensemble denoted with ctrl:

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

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.

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

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 for 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:

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

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:

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

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

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

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

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

The numerous simulations were compared in the time range from 10:00 UTC and 18:00 UTC, covering the precipitation event. Those with a shifted model ~~domain. Those with shifted model~~ start are compared ~~only~~ to the CTRL run. Positive or negative ~~amplitude arises just~~ amplitudes arise as an effect of which simulation is used as the ~~CTRL run~~reference run, denoted with ctrl or comparison run, denoted with dif. 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~~in reverse additionally, providing a symmetric uncertainty distribution. The uncertainty ~~estimation~~ estimate (Fig. 8) encompasses a sample of 122 (~~number of simulations)times~~ permutation of simulation couples) $\times$ 32 (time steps) values~~even though, not all of them are independent from~~ , although they are not all independent of each other.

~~Negative deviations in amplitude are mostly connected to negative deviations in structure and vice versa.~~ A and S are correlated (Fig. 8). Hence a reduction in ~~rain's amplitude arises by too small but peaked rain~~ precipitation amplitude is related to too small

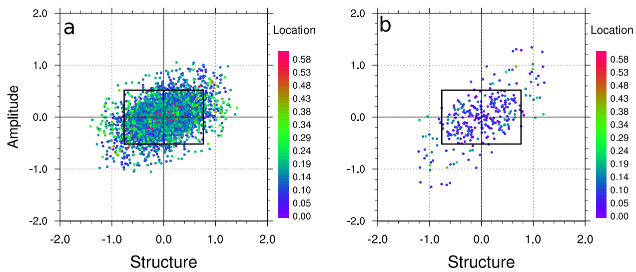

Figure 8. SAL results for the uncertainty-ensemble CTRL-uncertainty-ensemble between 10:00 UTC and 18:00 UTC separated for uncertainties generated by the shifted model domain (a) and by the delayed model start (b). Structure is represented on the x-axis, amplitude on y-axis and location by marker colours. 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.

and/or peaked precipitation objects, whereas an increase in precipitation goes along with larger andshallow /or shallower rain objects. Largest The largest deviations arise in the first hour until hours from 10:00 to 11:30 UTC of the analysis time (Fig. 9). This accords agrees with the beginning of the precipitation event in the different simulations . The because the onset of precipitation differs in all simulations (not shownFig. 6) 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 (Fig. 9). 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. depend on the distance of the boundary shift. The deviations from CTRL for simulations with shifted boundaries are not caused by a direct change of physical parameters such as temperature in a first instance but the differences emerge because synoptic systems, such as low pressure systems, are included in the model boundaries differently. Differences are further caused by changes in the lower boundaries such as including a larger area of sea- or landcover. For example, a model domain with north- or westward shifted boundaries includes more grid points over sea surface. The simulation with the strongest westward shift (LOC3000) causes the largest changes in precipitation amplitude (Fig. 9), whereas the strongest northward shift by 30 km (LOC3000), which also includes a larger fraction of sea surface, affects precipitation amplitude less strongly than a shifting by 20 km north (LOC2000) (Fig. 9).

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. 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 According 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

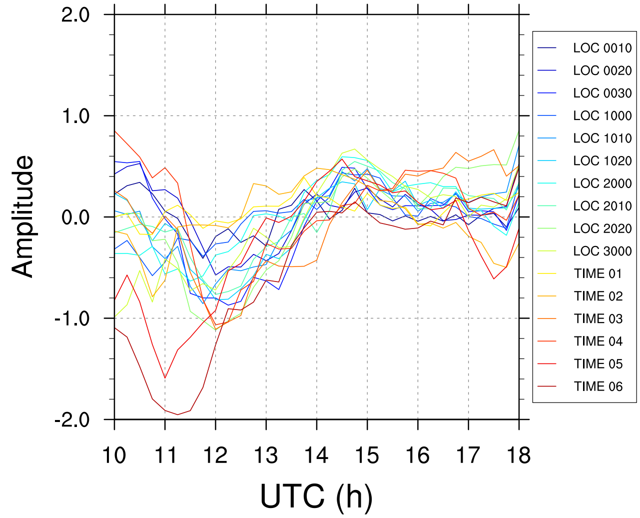

Figure 9. Amplitude values from Fig. 8 for comparisons to the CTRL run only on the single time steps.

not a result of soil moisture modification. In comparison between the CTRL run (Fig. 10a) and the simulation with shifted boundaries (Fig. 10b), 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 obvious. These differences are caused by shifting the boundary domain by ten grid points (10 km). The extreme modifications in soil moisture cause even more obvious differences 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. 10e and f). In the moist simulations (MOI_a and MOI_p), the strongest precipitation occures north-east of the estuary. This region is mainly free of precipitation in the dry simulations (DRY_a and DRY_p) and in the CTRL simulations (CTRL and LOC1000) the precipitation occurs even further north-east of this particular region. 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. 10f and g).

5 ~~Significant effects of soil moisture modification on precipitation~~

4.1 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 moistureare conducted additionally with shifted domain boundaries as already applied to the CTRL run (uncertainty-ensemble, see table 1). This huge amount~~ The huge number of model simulations (a complete ensemble for each soil moisture modification) and the uncertainty ~~estimation~~ estimate from Sect. ~~??~~ 4.2 accounts for a quantitative evaluation of the significance of soil moisture influence on precipitation.

~~For all soil modified ensembles every ensemble member~~ Each ensemble with modified soil moisture will be compared to the ~~corresponding ensemble member (same shifting) from the uncertainty-ensemble. That delivers again a huge sample of SAL values (Fig. 11).~~ CTRL-uncertainty ensemble by comparing ensemble members with the same shift of the model domain for every output-step. Within every ensemble the values are divided into those that exceed the uncertainty range (blue ~~transparent filled~~ rectangle in Fig. 11) ~~, that~~ what is given by the uncertainty-ensemble, and those that are within. The percentage of the ~~uncertainty range exceeding values~~ values exceeding the uncertainty range 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~~ the DRY_p-ensemble exceeds the uncertainty in only 5% of all cases (Fig. 11a 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~~ to DRY_p modifications, but for L in area “red” ~~only~~(Table 3). In contrast, the soil moisture reduction in the whole domain (DRY_a-ensemble) affects the precipitation significantly (Fig. 11b). More than 50% of A exceed the uncertainty range ~~and some of them exceed it by far~~in some cases with values for A down to -1.8. 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~~ (MOI_p-ensemble), results in significant ~~precipitation changes , contrary to the drying in the sub domain~~ changes in precipitation (Fig. 11c). ~~Again the~~ As already seen for the DRY_a-ensemble, the modification over the whole domain results in ~~stronger response in precipitation~~ a stronger precipitation response.

The redistribution of soil moisture (BAND-ensemble) does not lead to any significant ~~effects~~ effect (Fig. 11e)~~but in location in~~ , except for L in area “blue”. The redistribution of soil moisture ~~increases the large-area heterogeneity , but decreases the small-area heterogeneity.~~ changes the heterogeneity of the soil moisture by reducing small-scale structures, but induce stronger variations on a large scale. Thus, secondary circulation can develop on a different scale. This is in accordance with Adler et al. (2011); Kang and Bryan (2011) ~~,~~ who found an influence of redistribution of soil moisture on the location of convective ~~inition~~initiation. 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~~ performed by using different ~~initialisation for~~ initialisations of soil moisture, lead 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 in the present case. Accordingly, ~~slight and~~ physically feasible 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~~setup.

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~~ uncertainty-ensemble 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~~$_p$~~$_\text{p}$	5.79	0.02 ± 0.0034	3.58	~~-0.13 ± 0.0011~~ **-0.13 ± 0.0011**	**25.34**
DRY~~$_a$~~$_\text{a}$	**23.14**	~~0.30 ± 0.0063~~ **0.30 ± 0.0063**	**22.31**	~~-0.26 ± 0.0023~~ **-0.26 ± 0.0023**	**53.72**
MOI~~$_p$~~$_\text{p}$	**15.98**	-0.12 ± 0.0051	**18.73**	-0.05 ± 0.0042	8.26
MOI~~$_a$~~$_\text{a}$	9.92	-0.10 ± 0.0043	**23.42**	~~-0.18 ± 0.0043~~ **-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~~$_p$~~$_\text{p}$	4.85	-0.10 ± 0.0033	9.39	~~-0.29 ± 0.0091~~ **-0.29 ± 0.0091**	5.76
DRY~~$_a$~~$_\text{a}$	**11.82**	0.08 ± 0.0058	**51.21**	~~-0.60 ± 0.0068~~ **-0.60 ± 0.0068**	**30.61**
MOI~~$_p$~~$_\text{p}$	**14.85**	-0.19 ± 0.0053	**12.12**	0.00 ± 0.0039	**12.42**
MOI~~$_a$~~$_\text{a}$	**15.76**	~~-0.27 ± 0.0058~~ **-0.27 ± 0.0058**	**19.70**	~~-0.28 ± 0.0044~~ **-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

5 ~~Systematics~~

4.1 Systematics

After determining the significance of the strength of ~~precipitation changes~~ changes in precipitation, this section handles the systematics of changes. Significant changes do not necessarily imply systematic changes. While in DRY~~$_a$~~$_\text{a}$ (Fig. 11b) predominantly negative amplitude changes occur, in ~~MOIST$_p$~~ MOI$_\text{p}$ (Fig. 11c) significant, but random changes occur. Structure and amplitude change in both positive and negative directions. In none of the soil moisture experiments S and A are correlated (Fig. 11). 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. ?? the~~ The sample for the SAL results for the uncertainty-ensemble is symmetric and therefore the average is zero. A significant difference of the averaged values from zero hints at the systematics. Whether the averaged values differ significantly from zero is tested statistically by:

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

$\overline{x}_1$ and $\overline{x}_s$ $\overline{x}_2$ 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, $\hat{\sigma}^2(\overline{x}_1 - \overline{x}_2)$ $\hat{\sigma}^2[\overline{x}_1 - \overline{x}_2]$ 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 The averaged structure differs significantly from zero only for the ensemble DRY_a and MOI_a by analysing over area red and blue respectively (Table 3). The 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 feedbacks, 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 shows a positive feedback for decreased soil moisture. But, enhanced soil moisture can lead to an increase or decrease in precipitation, dependent on the strength of soil moisture enhancement. In contrastCheng and Cotton (2004); Ek and Holtslag (2004); Martin and Xue (2006); Hohenegger et al. (2009); Weverberg et al. (2010) all , Cheng and Cotton (2004); Ek and Holtslag (2004); Martin and Xue (2006); Hohenegger et al. (2009); Weverberg et al. (2010) 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. The selected case study for 03

5 Conclusions

In the present case study we conducted seven ensembles of simulations with different perturbations in soil moisture. The letter include strong artificial changes and changes in a feasible range by replacing with real soil moisture patterns from another day. The ensembles were conducted over slightly different model domains, which were shifted 10 to 30 km to each other to deliver slightly changed boundary conditions. That caused a large spread in the convective case because the day (3 August 2012analysed by the) was synoptically forced by a low pressure system over the Atlantic. Conclusively, only in two ensembles soil moisture caused significant changes in intensity, local distribution and amount of convective precipitation what was assessed with the SAL-scoreprovide 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 . The amplitude, determining a difference in amount of precipitation, is most often systematically reduced within an ensemblewith 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 . Thus, no overall systematic was found because wetting and drying of soil result in reduced precipitation amount. The structure, which describes the difference in intensity in precipitation, can be either enhanced or decreased at different times and in different ensemble members what can also be caused by a time delay caused by 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 A local displacement in the precipitation cells is found for three and four out of five artificially changed soil moisture patterns in the two different analysis regions, respectively. The changes in precipitation for the simulations with realistic soil moisture patterns are not significant.

Limitations in the present study are 1) the restriction to 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 resultswill be compared to high resolved radar data (Lengfeld et al., 2014). With Thus, no general valid results could be found. However, this study presents a proof of concept and can be conducted with further cases, which are less affected by frontal systems. In those cases a stronger influence of soil moisture can be expected. 2) The dependency of the results on the chosen analysis area, which in turn shows the complexity of the results. 3) The dependency of the uncertainty estimate on synoptic forcing and size of the model domain. The ensemble spread might become smaller with weaker synoptic forcing and with a larger model domainthe 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. . However, a expected smaller model spread would strengthen the importance of soil moisture influence as it is expected in this cases.

In summary, we could proof the concept of shifting the model domain to achieve a sufficient large model spread without being influenced by generated patterns. Such an estimate of the model spread is necessary in soil moisture studies to assure the results from soil moisture changes. We further showed that under synoptically driven situation the effect of soil moisture remains uncertain and further investigations are necessary. To proceed the present study further cases studies should be conducted.

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Data availability

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

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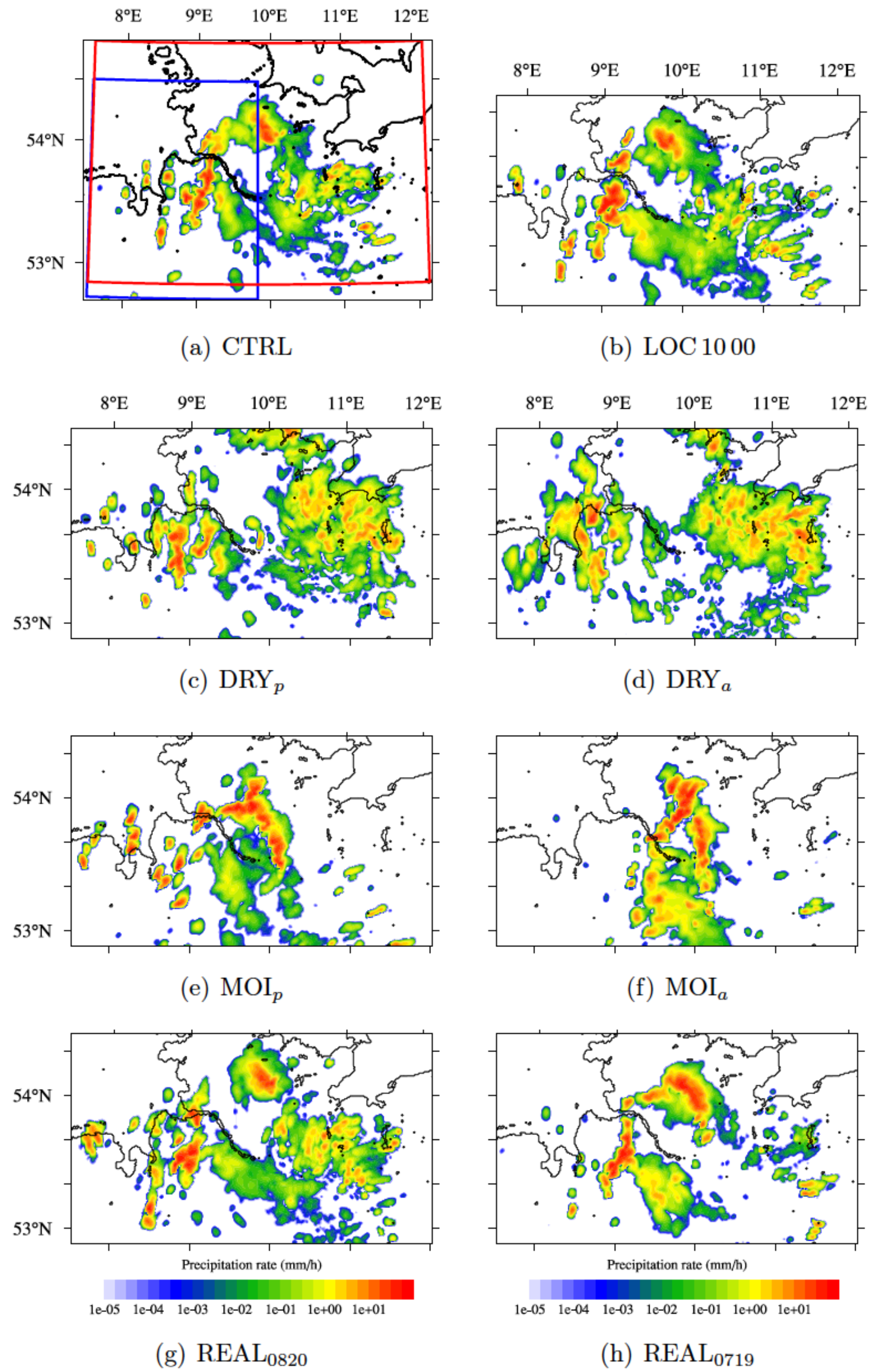

Figure 10. Precipitation rate at 14:45 UTC for (a) CTRL run , (b) LOC 10 00 and (c-h) different soil moisture modified simulations.

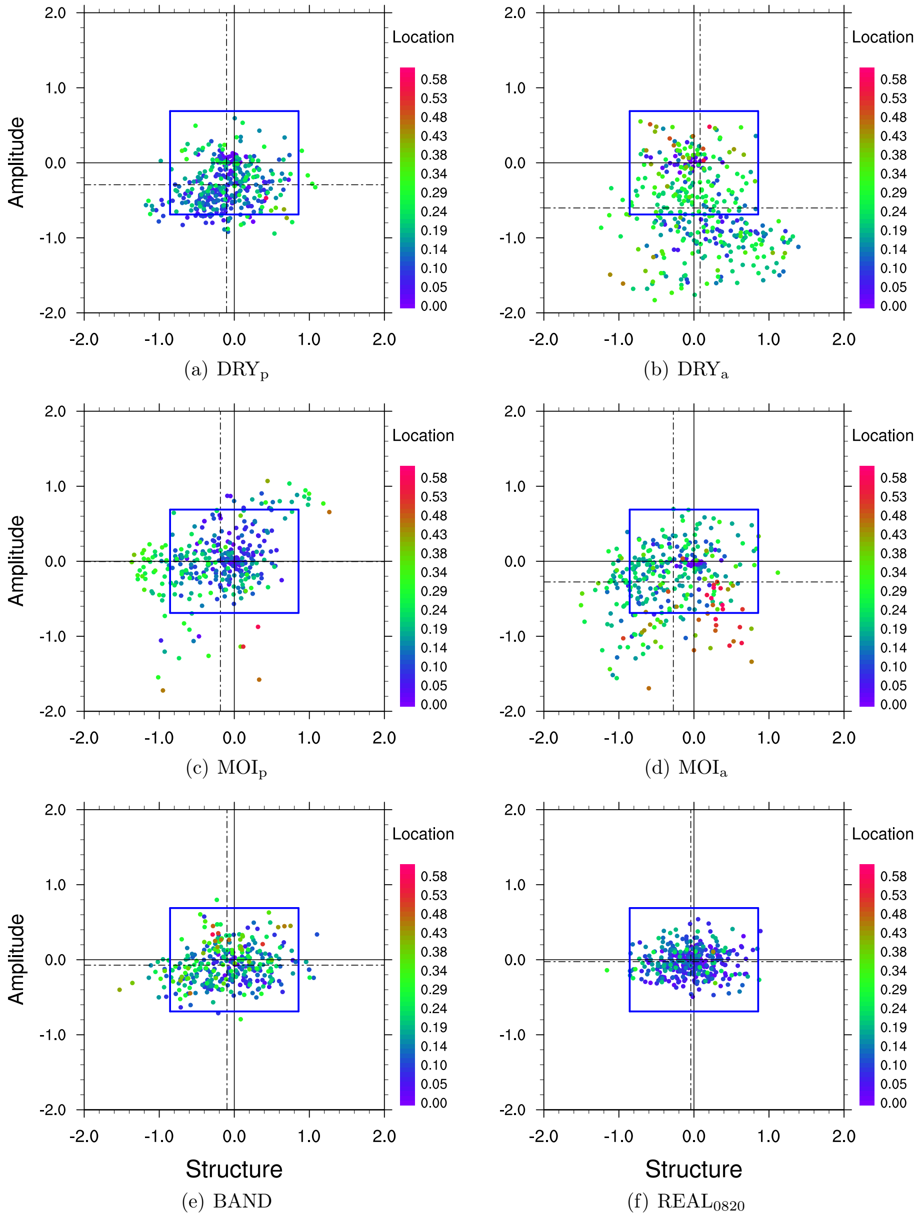

Figure 11. SAL scatter plot: Comparison of ensembles (a) $\mathrm{DRY_p}$, (b) $\mathrm{DRY_a}$, (c) $\mathrm{MOI_p}$, (d) $\mathrm{MOI_a}$, (e) BAND and (f) $\mathrm{MOI_{0820}}$ with the uncertainty-ensemble for area "blue". Dashed lines represent the averages.