Soil moisture variability and its influence on convective precipitation over complex terrain

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Soil moisture monitoring data from the Convective and Orographically-induced Precipitation Study (COPS) 2007 are combined with operational and high-resolution simulations with the weather forecast system GME/COSMO-DE to analyse the discrepancies between observed and modelled soil moisture fields and their potential impacts on convective precipitation forecasts. We use data from the newly installed soil moisture monitoring network comprising 47 stations with soil moisture sensors installed at three different depths within the COPS area in southwest Germany. The obtained soil moisture fields are compared to their related representation within the global model GME interpolated with high-resolution soil and surface data to a 2.8 km resolution yielding soil moisture values on the same grid as the high-resolution model COSMO-DE. Systematic differences between modelled and measured soil moisture values are found and used to determine the potential impact of large soil moisture biases for the modelling of convective processes. This is achieved by conducting sensitivity tests using COSMO-DE, in which the initialisation fields of soil moisture are varied. Results show a general mean bias towards too dry soil conditions, both in GME during the whole COPS period, as well as in the high-resolution modelling of specific COPS IOPs with COSMO-DE. The influence of this bias on simulated precipitation is significant and non-trivial and depends on the specifics of the analysed case study. The results presented in this study demonstrate that soil moisture has a considerable impact on convection-related parameters over complex and heterogeneous terrain, but that no simple relationship regarding the sign of the soil moisture–precipitation feedback could be identified due to a complex interplay between various factors that favour or inhibit convection initiation.

Key Words: COPS; soil moisture monitoring network; COSMO model; Black Forest; convection initiation

1. Introduction

Quantitative precipitation forecasting (QPF) is a challenge for state-of-the-art numerical weather prediction (NWP) models. In particular, the prediction of convective precipitation over complex terrain under weak synoptic controls is still inadequate, one of the potential uncertainties being the influence of soil conditions, such as soil moisture and/or soil texture, and their relative importance in different regions. Under weak synoptic controls, low-level

and boundary-layer moisture inhomogeneities (Weckwerth, 2000) as well as convergence zones of different origin (e.g. Ulanski and Garstang, 1978; Wilson and Schreiber, 1986) can be important factors, but also spatial inhomogeneities of land use and/or soil moisture have been identified as important processes in recent years (Taylor and Ellis, 2006; Baldi *et al.*, 2008; Gantner and Kalthoff, 2010).

Soil moisture influences a number of processes concerning land–atmosphere interaction on different spatial and temporal scales (Seneviratne *et al.*, 2006; Fischer *et al.*, 2007). Observational and modelling studies have also shown how soil moisture can affect daily (Taylor and Lebel, 1998; Clark *et al.*, 2004) and weekly (Koster *et al.*, 2004) rainfall. Some of these processes concern the initiation of convection and the subsequent possibility of convective precipitation, such as the influence on the surface temperature and the availability of moisture in the planetary boundary layer (PBL) (e.g. Koster *et al.*, 2000; Hohenegger *et al.*, 2009). The PBL characteristics and their impacts on the triggering and/or dynamics of convective storms are strongly influenced by the partitioning of available radiation energy into sensible and latent heat, which itself is determined by soil moisture. Whereas for homogenoeus areas with scarce vegetation the impact of soil moisture on convection-related parameters and convective precipitation is well documented (e.g. Taylor and Lebel, 1998; Taylor *et al.*, 2007; Kohler *et al.*, 2010), it is generally not clear how large the influence of soil moisture for different geographic regions and seasons is, especially in complex (concerning e.g. surface characteristics and/or orography) terrain.

Concerning convective precipitation, the theory of the soil moisture–precipitation feedback (Pal and Eltahir, 2001) predicts an increase of the total energy of the PBL for wet soil conditions. This increase is expected to result in an increase of the convective available potential energy (CAPE). Similarly, regional climate simulations on the continental scale revealed that higher values of soil moisture lead to an enhanced amount of evapotranspiration, which is supposed to be responsible for more intense convective rainfall (Schär *et al.*, 1999; Koster *et al.*, 2004; Seneviratne *et al.*, 2006). It is assumed that a positive feedback mechanism between initial soil moisture and future rainfall exists: wet soils favour the build-up of shallow boundary layers with high values of low-level entropy by concentrating the surface fluxes of heat and moisture into a comparatively small volume of air (Schär *et al.*, 1999; Pal and Eltahir, 2001; Alonge *et al.*, 2007). This mechanism provides a source of convective instability.

In contrast to this, enhanced soil moisture may decrease the daily temperature range by increasing daytime surface evaporative cooling. By this, the probability for convective precipitation is decreased due to a lack of sufficient thermal forcing to initiate convection, especially for an already humid atmosphere (Pan *et al.*, 1996; Dai *et al.*, 1999). On larger spatial scales, mesoscale circulations generated from discontinuities in land-surface wetness can have a stronger impact than turbulent fluxes on the formation of clouds and subsequent precipitation (e.g. Schädler, 1990; Chen and Avissar, 1994; Taylor *et al.*, 2007).

Whereas the above statements are true for flat and comparatively homogeneous terrain, there are only few studies analysing the influence of soil moisture on convective precipitation over complex terrain. Hohenegger *et al.* (2009) presented a comparison of simulated soil moisture–precipitation feedback between a cloud-resolving

model with explicit convection and a model with 25 km grid spacing and parametrized convection. Significant differences between the two models were found, with a negative feedback for the former and a strong positive feedback for the latter system. It was shown that the sensitivity of convection to the presence of a stable layer on top of the PBL is much stronger for the cloud-resolving model, leading to a strong dependence of convection initiation (CI) on the presence of sufficient thermal forcing.

The uncertainty regarding the influence of soil moisture variability on atmospheric parameters on smaller scales concerns (a) operational forecast models, where soil moisture is often treated as a numerical parameter to constrain modelled 2 m temperature and humidity fields to observations, and (b) field observations, where the uncertainty of temporal and spatial soil moisture variability and its influence on atmospheric variables is high, as soil moisture is not directly operationally measured on a larger grid. However, with the increasing availability of soil moisture measurements, the use of realistic soil moisture initialisation is more often applied in long-range forecasting (e.g. Vitart *et al.*, 2008; Koster *et al.*, 2009), following from the assumption that such better initialisation will improve forecasts. Not surprisingly, it was found that larger initial soil moisture anomalies are more likely to contribute to a more accurate precipitation and air temperature forecast (Koster *et al.*, 2010). In this context, remote-sensing-based approaches such as the scatterometer (e.g. Naeimi *et al.*, 2009; Wagner *et al.*, 2009) or the newly launched Soil Moisture and Ocean Salinity mission (SMOS; Kerr *et al.*, 2001; Kerr, 2007) may improve the availability of initial soil moisture fields, as they can deliver global soil moisture with a regional-scale support. However, these approaches have usually a sensing depth of only a few cm whereas the soil moisture data of greatest relevance to many applications span a much larger depth. In addition, remotely sensed soil moisture products exhibit varying accuracy depending on the respective retrieval algorithms, the resulting soil moisture product, the calibration/validation procedure, and the region where the retrieval algorithm was validated. The scaling properties of soil moisture are usually highly variable in time, which implies that remotely sensed soil moisture fields obtained on specific spatio-temporal scales cannot be easily compared to surface measurements on other scales (Brunsell and Gillies, 2003; Jones and Brunsell, 2009).

As stated above, in most operational atmospheric models the simulated prognostic variable 'soil moisture' does not have an unambiguous meaning (Koster *et al.*, 2009). It is a strongly model-specific quantity with a dynamic range defined by the specific model formulation and the soil parameters such as porosity, hydraulic conductivity, wilting point, and layer depth, which are not known on the model scale. Whereas the absolute value of the quantity (soil moisture, saturation, wetness, water content of the root zone, etc.) has usually no direct observational analogue, its temporal variability at least tends to be similarly simulated by different models (Koster *et al.*, 2009). However, for regional to local scales, validation data from observations are usually lacking, leaving the assessment of the importance of correct initialisation fields of soil moisture for temperature and precipitation forecasts to be highly speculative.

To overcome this deficiency in systematic model and field studies over complex terrain, a soil moisture monitoring network was installed in southwest Germany during

Figure 1. The COPS domain in southwest Germany and eastern France with supersites V, R, H, M, S (see text for explanation) and additional radiosonde stations at Burnhaupt le Bas and Forschungszentrum Karlsruhe (FZK). The northern and southern Black Forest are separated by the Kinzig valley.

Figure 2. Soil moisture network during COPS and distribution according to soil texture (colour shading) in the COSMO model (3: sand, 4: sandy loam, 5: loam, 6: loamy clay, 7: clay, 8: peat). The black contours show terrain altitude (m). This figure is available in colour online at wileyonlinelibrary.com/journal/qj

the international Convective and Orographically-induced Precipitation Study (COPS) in summer 2007, where availability of additional atmospheric data was exceptionally high. In contrast to most atmospheric monitoring networks within COPS, the soil moisture network was installed for several years to allow also longer-term analyses of soil moisture–precipitation processes (Krauss *et al.*, 2010). In this study, we will focus on the three-month COPS period (1 June 2007–31 August 2007) to analyse systematic differences between modelled and measured soil moisture values and to analyse the potential impact of large soil moisture biases

for the modelling of convective processes. To investigate the impacts of soil moisture on the characteristics of convective storms, sensitivity tests are conducted using the Consortium for Small-scale Modeling (COSMO) model, in which the initialisation fields of soil moisture are varied.

2. Soil moisture monitoring network during COPS

The COPS study (Wulfmeyer *et al.*, 2008) was performed from 1 June to 31 August 2007 in southwestern Germany and eastern France (Figure 1). In summertime, this region

is often characterised by severe thunderstorm activity with low QPF skill. The overall goal of COPS was to advance the quality of forecasts of orographically induced convective precipitation by four-dimensional observations and modelling of its life cycle. Five supersites with a large number of different observation systems were deployed along a transect through the COPS region, named V (Vosges), R (Rhine valley), H (Hornisgrinde), M (Murg valley), and S (Dornstetten close to Stuttgart) (Figure 1). Two additional radiosonde stations at Forschungszentrum Karlsruhe (FZK) and Burnhaupt le Bas provided information about the vertical structure of the atmosphere at the northern and southern borders of the COPS region. An overview of the complete set-up of instruments operated is given by Kottmeier *et al.* (2008) and Wulfmeyer *et al.* (2008, 2011).

As part of COPS, an operational soil moisture monitoring network consisting of permanent and COPS-specific soil moisture stations was installed (Figure 2). The soil moisture network operated by the Institute for Meteorology and Climate Research (IMK) of the Karlsruhe Institute of Technology (KIT) included 47 soil moisture monitoring stations with more than 150 single soil moisture sensors deployed at three different depths (5, 20 and 50 cm) along a vertical profile at each station. (At some stations an additional near-surface sensor was installed.) For this, an innovative and cost-effective soil moisture sensor, the so-called Simplified Soil Moisture Probe (SISOMOP), was developed in co-operation with the Soil Moisture Group (SMG) of KIT. Measurement frequency is 10 min. The relative accuracy of the sensor has been estimated to lie within $\pm4\%$. As for all soil moisture sensors, the determination of absolute soil moisture values requires a soil-specific calibration, which is described in detail in a companion paper by Krauss *et al.* (2010), where also further details on the performance of the network are given.

3. Models and simulations

In order to perform both long-term comparison of the soil moisture measurements with model results over the whole COPS period, and process analyses using high-resolution simulations of individual case-studies, the complete model chain of the German Weather Service (Deutscher Wetterdienst, DWD) including the hydrostatic global model GME, and the two non-hydrostatic limited-area atmospheric prediction models COSMO-EU and COSMO-DE was used. Whereas both the GME and the COSMO-EU use a parametrization scheme for convective processes, convection is resolved in COSMO-DE.

The global model GME is a hydrostatic NWP model operating on a triangular grid with a mesh size of 40 km. The model has 40 layers as well as a 7-layer soil model including freezing/melting of soil water and a sea ice model. Majewski *et al.* (2002) provide a more detailed description of GME. GME model data were used to compare measured and modelled soil moisture values because, in contrast to the operational non-hydrostatic COSMO-EU, in GME no assimilation scheme is used which adjusts soil moisture such that errors in near-surface temperature are minimised. To compensate for the coarse spatial scale of the GME, GME data were interpolated on a grid with 2.8 km horizontal resolution using the interpolation routine *int2lm* of DWD. (Details of the interpolation scheme can be found in Schättler, 2009). Applying this procedure, a

number of important parameters, e.g. fraction of land, soil texture, surface height and roughness, plant cover and root depth were considered with 2.8 km resolution yielding soil moisture values on the same grid as the high-resolution model COSMO-DE. For the soil moisture comparison of this study, the operational analysis data of the GME runs during the COPS period were used.

The high-resolution simulations were performed with the non-hydrostatic limited-area atmospheric prediction model COSMO-DE (version 4.0) of the DWD (Schättler *et al.*, 2008), also in a version without artificial soil moisture adjustment. The model employs an Arakawa C-grid for horizontal differencing on a rotated latitude/longitude grid with a horizontal resolution of 2.8 km which allows for turning off the parametrization of deep convection. Shallow convection is parametrized using a modified Tiedtke scheme. The number of vertical layers in a generalised terrain-following coordinate is 50. A six-class graupel scheme is used for microphysics, a turbulent kinetic energy (TKE) scheme for turbulence, and a two-time-level Runge–Kutta method for the dynamics. The connection between soil and atmosphere is established through the energy balance equation, whereas the required soil parameters are calculated with the multi-layer soil model TERRA-M (Heise *et al.*, 2003; Doms *et al.*, 2007; Warrachi-Sagi *et al.*, 2008). Initial and hourly boundary data come from the COSMO-EU forecast with 7 km grid resolution, the initial time was 0000 UTC for all model runs and the simulation period was 24 h. Apart from Germany, Switzerland, and Austria, the simulation domain contains smaller parts of bordering countries covering an area of $\sim1200\times1300$ km^2 (421×461 grid points).

Simulations were conducted for various Intensive Observation Periods (IOPs) of COPS. Here, we focus on three well-documented case-studies, IOP 4b on 20 June 2007, IOP 8b on 15 July 2007 and IOP 9c on 20 July 2007, which are described in detail in Kottmeier *et al.* (2008) and which correspond to three different trigger mechanisms for CI: large-scale lifting of potentially unstable air masses (4b), locally initiated convection (8b) and convection near convergence lines (9c). After comparing the modelled and measured soil moisture values, additional sensitivity simulations with increased and decreased initial soil moisture values were conducted to analyse the impact of erroneous initial soil moisture values on the energy balance, convective indices and precipitation. Apart from a reference run with unchanged initial soil moisture fields, sensitivity experiments with dry (–25%) and wet (+25%) initial soil moisture were performed for the respective COPS IOP days. The value of 25% was selected because the mean (percental) bias between observed and modelled soil moisture lies in the range of 20–30% (see below). It has to be pointed out that this modification was not done by subtracting or adding 25% volumetric water content (VWC in %), but by multiplying the initial soil moisture values of the reference run with 0.75 and 1.25, respectively. In this focus on observed misfits between observed and modelled soil moisture values, our study differs from other model sensitivity approaches, where soil moisture is often varied between the possible minimum and maximal values, i.e. wilting point and field capacity, respectively (Jones and Brunsell, 2009).

4. Results

4.1. Comparison of soil moisture measurements with GME and COSMO-DE simulation results

4.1.1. Long-term temporal and spatial variability of soil moisture

3-hourly GME analysis data after interpolation on the COSMO-DE grid were compared to coincident soil moisture measurements at all stations of the network. Hereby, only measurement data passing a quality control protocol were chosen for comparison. From Figure 3(a), it can be seen that this is usually the case for 25–35 stations during most of the COPS period.

Figure 3 shows the temporal evolution of the mean bias (MB) and root mean square error (RMSE) over the whole COPS domain, where

$$MB = \frac{1}{N}\sum_{i=1}^{N}(\theta_{\mathrm{sim},i} - \theta_{\mathrm{meas},i})$$

and

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\theta_{\mathrm{sim},i} - \theta_{\mathrm{meas},i})^2} \, ,$$

where θ_{sim} and θ_{meas} are modelled and observed soil moisture (in % by volume) for each time instance and each soil moisture station i, and N is the number of available stations for each time step.

With a mean bias of minus 5–10% for the uppermost sensor, the differences are quite large, but are not surprising regarding the order of magnitude as the low-resolution forcing of GME cannot simulate the small-scale processes at the individual stations. In total, GME is too dry at all depths and this trend significantly amplifies with depth. Maximal underestimation can be found on/after days with high precipitation, implying a potential mismatch between soil properties in the model and at the measurement stations. The maximum mean bias values of –20% can be found right after the largest precipitation events between 7 and 10 August, when the near-surface soil is saturated and underestimated soil moisture values indicate an underestimated field capacity and/or an overestimated hydraulic conductivity (Krauss *et al.*, 2010). In addition, the temporal soil moisture variability is strongly underestimated in the model, as can be seen from the variances of model and measurements shown in Table I. Even though the decrease of variability with depth is correctly simulated, the variances of model and measurements differ by approximately a factor of 4. On the other hand, correlation coefficients are comparatively high, at least for the upper two sensors, showing that model and measurements roughly capture the same wet and dry periods.

Figure 4 shows the mean bias between model and measurements, now for each station separately averaged over the whole COPS period. Again, the general underestimation of the soil moisture values by the model is clearly seen, as well as the increase of the bias with depth. Only at a few stations is the mean bias positive, corresponding to an overestimation by the model. Interestingly, most of these stations are situated close to each other in the southern part

Table I. Mean RMSE, correlation coefficient and variance of measured and GME-simulated soil moisture values, averaged over all stations and over the whole COPS period.

Depth (cm)	RMSE (% by vol.)	Correlation coefficient	σ^2_{meas}	σ^2_{sim}
5	10.8	0.52	23.3	6.2
20	12.2	0.56	11.7	4.1
50	17.4	0.38	7.9	1.8

of the COPS area on the Black Forest crest and on its lee side, which could hint at a systematic and precipitation-related effect.

In addition to the stations with comparable bias values, there are stations with specifically high or low values. Low biases are for example found for station Nagold in the lee of the Black Forest, whereas a strongly increasing bias with depth is shown for Durbach-Ebersweier on the western, windward side of the Black Forest. The COPS supersite M of the ARM mobile facility (AMF, situated in the Murg valley) shows a negative bias at the surface, but positive bias at larger depth, and the highest bias values can be found for the COPS supersite H at Hornisgrinde, on the highest mountain top of the northern Black Forest. Figure 5 shows the comparison of modelled and measured soil moisture evolution for these four stations.

Modelled and measured soil moisture at station Nagold show very good agreement at all depth levels (Figure 5(a)). For the near-surface sensor at 5 cm depth, both the 2 cm and 6 cm model level were compared (dotted and solid black lines). The two model levels are very similar, so that they cannot be distinguished in Figure 5(a). On closer inspection, not all precipitation events (visible through a marked increase in soil moisture) happened simultaneously in model and measurements, but most larger wetting and drying periods are captured correctly. Furthermore, the absolute soil moisture values correspond with a mean bias of less than 2%. As the COPS period was characterised by frequent synoptic-scale precipitation events, no real dry period took place until the end of August, when the lowest soil moisture values of the period were measured. Maximal values in the model were around 39%, and 35% in the measurements, which is near the field capacity for the sandy loam soil texture to be found at this site (Krauss *et al.*, 2010). The two datasets are in similar agreement for the two deeper levels. Even though the measurements show a higher variability, both datasets react to the same infiltration events from the upper levels and have the same wetting and drying characteristics, especially at 20 cm depth.

Similar results can be seen for the uppermost level at station Durbach (Figure 5(b)). The absolute values differ slightly more than for Nagold, but again measured and modelled soil moisture react to the same precipitation events, as seen best for a period during the second half on June. In contrast to Nagold, the two datasets for the two deeper levels do not correspond as well. Whereas the modelled values decrease with depth, the measured values at 20 and 50 cm depth increase and reach values around 40% (almost double the simulations), which is most probably due to the clayey silt soil texture with high water retention capacity, although the characteristics of the curves are similar.
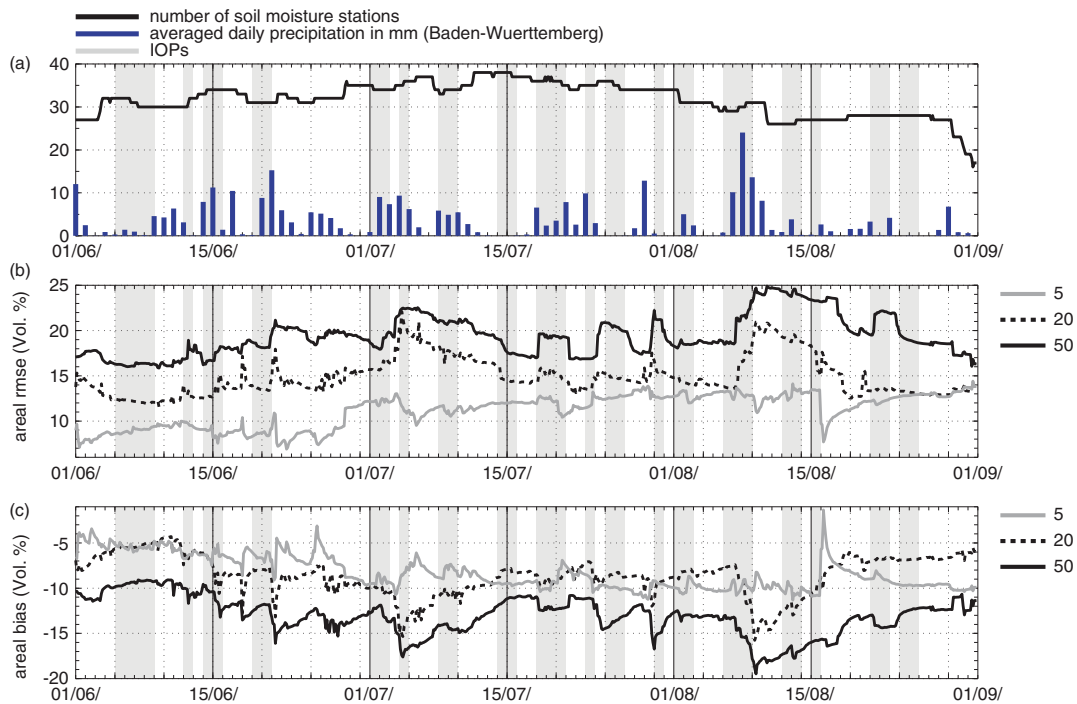
Figure 3. Temporal evolution of (a) spatially averaged daily precipitation (mm) in Baden-Württemberg (southwest Germany) taken from the precipitation network of the DWD, (b) mean root-mean-square error between soil moisture observations and GME model results, and (c) bias of GME model results for the three sensor depths averaged over the COPS domain. The solid black line in (a) denotes the number of soil moisture stations used for the analysis. Intensive Observation Periods (IOPs) are marked by grey vertical shading. This figure is available in colour online at wileyonlinelibrary.com/journal/qj
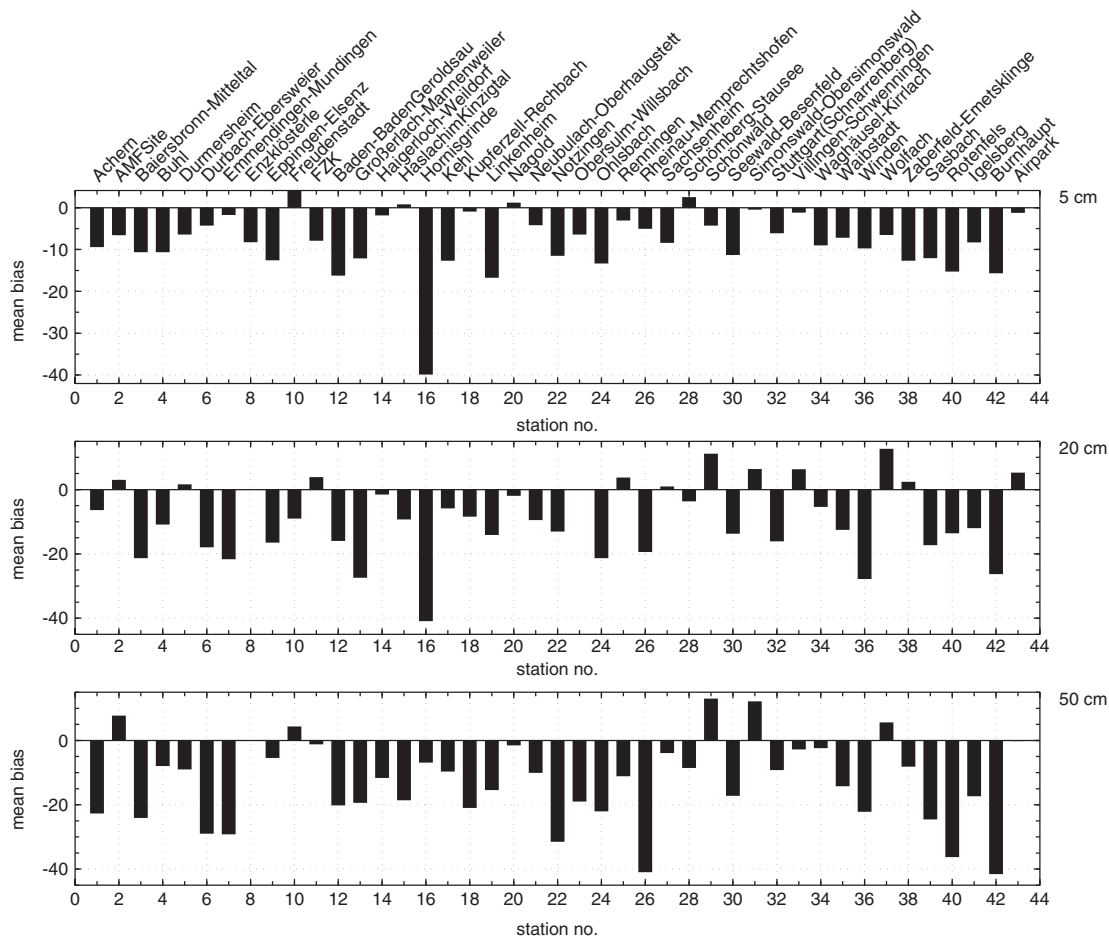
Figure 4. Mean bias between GME model and soil moisture measurement data for all stations in the network and at all depths during the COPS experiment.

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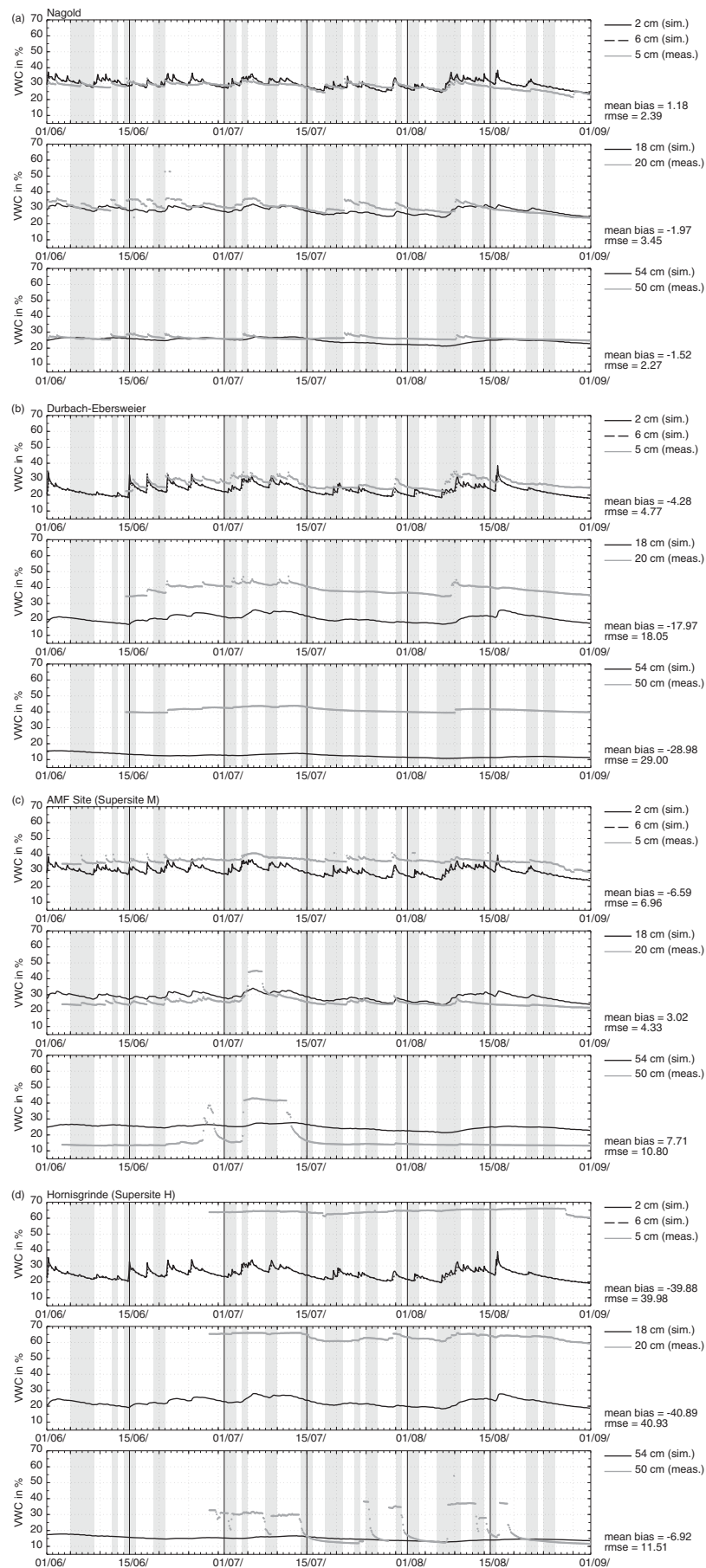
Figure 5. Comparison of modelled and measured soil moisture evolution at three different depths for the stations (a) Nagold, (b) Durbach, (c) AMF (supersite M) and (d) Hornisgrinde (supersite H). The grey shaded areas mark Intensive Observation Periods (IOPs) during COPS.

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For the AMF station (Figure 5(c)), the agreement is again comparatively good for the soil moisture in the uppermost layer with deviations between 5 and 15%. For the sensor at 20 cm depth, the agreement is similar, except for a short period in the beginning of July, when the measured soil moisture increased sharply from 25 to 45%. Because this event was even stronger and with longer duration at 50 cm depth (where also an additional sharp soil moisture increase can be seen end of June), it is not interpreted as a measurement error, but as an increase due to a raised ground water level. The station is situated in the valley bottom near to the river Murg, and a raised groundwater level would show first at larger depths, which is exactly what is observed in Figure 5(c).

Finally, Figure 5(d) shows the results for COPS supersite H, on top of the Hornisgrinde mountain, the highest point of the northern Black Forest. As could also be seen from Figure 4, measurement and simulation show the largest bias of all stations, due to exceptionally high soil moisture values for the uppermost two sensors (between 60 and 70%). Apart from the difficulties of good sensor calibration for such high water contents, this phenomenon is due to the specific environment at Hornisgrinde, located within a upland moorland with a supersaturated surface layer during most of the year. Whereas this specific situation cannot be taken into account by the soil model used operationally, it is an important boundary condition for the analysis of surface–atmosphere exchange processes or energy balance calculations using data from this COPS supersite. Energy balance measurements during COPS showed that, due to its specific environment, neither the partitioning of the net radiation into sensible/latent heat flux nor the evolution of the near-surface equivalent potential temperature had any dependence on the soil moisture (Kalthoff *et al.*, 2011).

Almost all the remaining stations fall into one of the four categories, as exemplified by Figure 5:

(a) good match at all levels (example Nagold, total 8 stations);
(b) good match at the surface but underestimated modelled soil moisture at greater depth (example Durbach, total 13 stations);
(c) good match at the surface but measurements show much more soil moisture variability at greater depths than the simulations (example AMF, total 15 stations); and
(d) poor match because a station-specific surface or subsurface condition could not be modelled adequately (example Hornisgrinde, total 5 stations).

The occurrence of (c) and (d) cases is not surprising, as such small-scale processes can of course not be included on the coarse GME model grid. However, for the analysis of site-specific case-studies these effects cannot be disregarded. The general underestimation of the soil moisture especially at larger depths (case (b)) may on the other hand have a more serious influence on modelled surface–atmosphere exchange processes. Its possible importance will be analysed in more detail below using high-resolution COSMO-DE simulations for individual IOP case-studies.
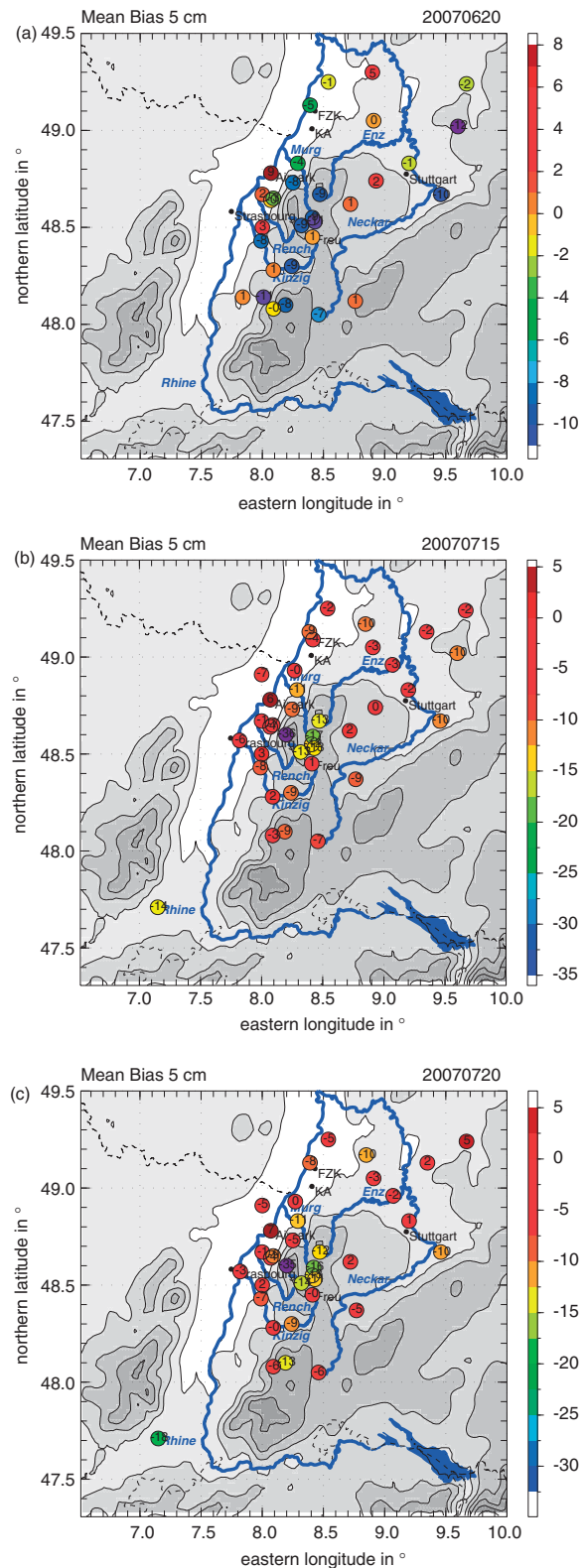

Figure 6. Spatially distributed bias between measured and modelled (COSMO-DE) near-surface soil moisture for three COPS IOPs: (a) IOP 4b, (b) IOP 8b and (c) IOP 9c. Note the different colour scales for the three cases. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

4.1.2. Short-term temporal and spatial variability of soil moisture

To analyse the accuracy of the soil moisture representation in a high-resolution model, simulations of individual COPS
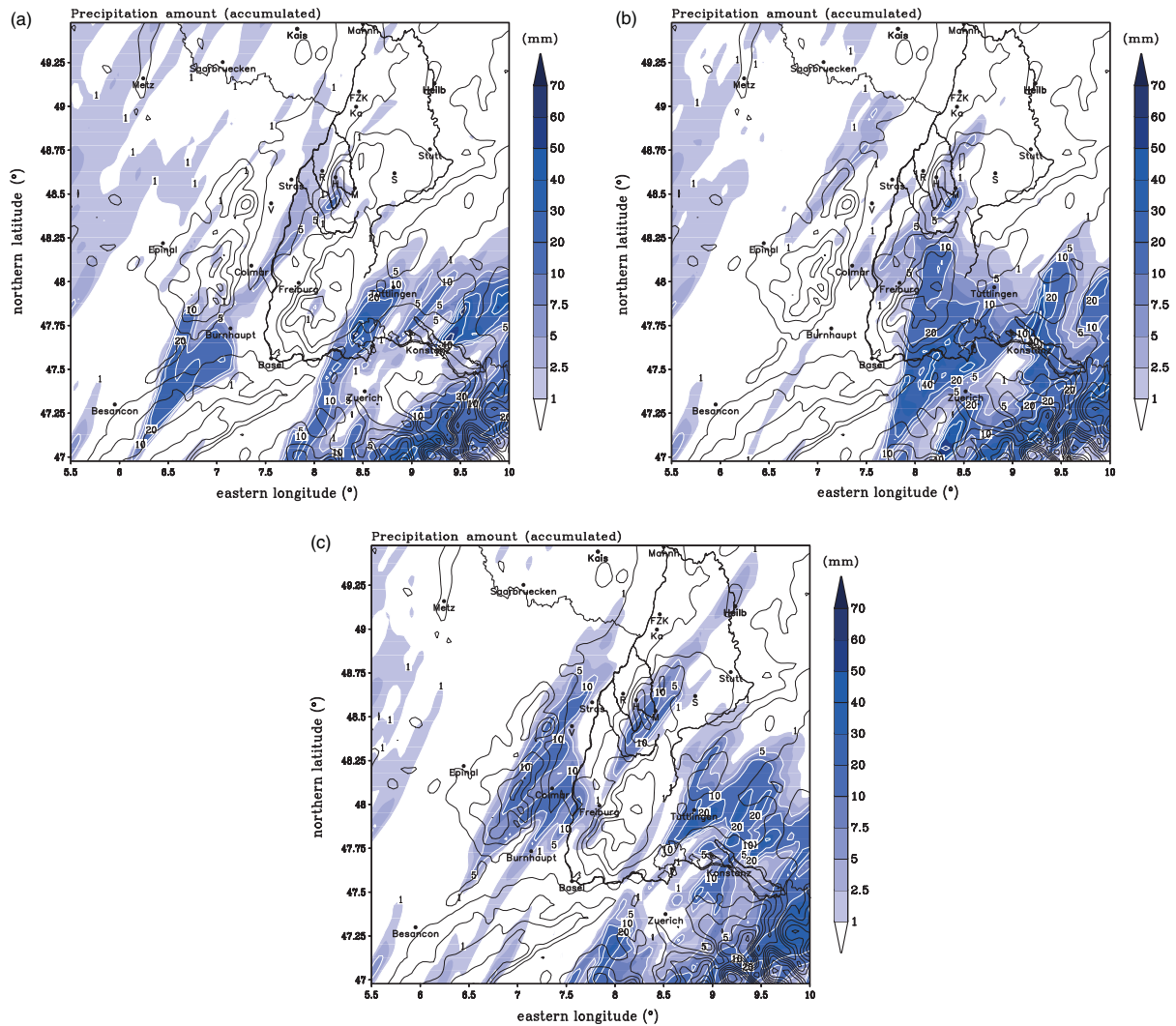
Figure 7. Accumulated daily precipitation for a simulation of COPS IOP 4b (20 June 2007) with initial soil moisture content (a) increased by 25% and (c) decreased by 25%. (b) shows unchanged soil moisture conditions as the reference. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

IOPs were conducted with COSMO-DE and the operational TERRA subsurface model. The mean daily bias between observed and modelled near-surface soil moisture values are shown in Figure 6 for the three IOPs discussed in detail in Kottmeier *et al.* (2008).

As for the GME comparison shown above, there are large differences between measured and simulated soil moisture to be seen in the COSMO-DE simulations. Simulated soil moisture for the near-surface sensor is systematically too low for the two July case-studies (Figure 6(b) and (c)) in the whole COPS domain and for IOP 4b (Figure 6(a)) in the Black Forest region. Generally, the bias is largest for the Black Forest region with an underestimation of soil moisture of up to 15%. (The extraordinary high bias values of 35% are due to the special location of Hornisgrinde, as discussed above.)

This trend is similar for the two deeper levels (not shown), even though they exhibit more spatial variability of the bias between model and measurement.

### 4.2. Influence of soil moisture on convective precipitation

To analyse the potential impact of a general soil moisture under- or overestimation in the model, sensitivity studies using artificially increased/decreased soil moisture values were conducted for the above IOPs. For this, soil moisture values were increased/decreased by a fixed percentage over the whole model domain. Data analyses include the difference in simulated precipitation values as well as a closer inspection of the energy balance and atmospheric variables known to be important for the initiation of convection and corresponding convective precipitation. As an approximate upper bound of biases between simulated and observed soil moisture, the initial soil moisture values were increased and decreased by 25%.

4.2.1. Precipitation

Figure 7 shows the resulting daily accumulated precipitation values for the example of IOP 4b from 20 June 2007. This IOP was characterised by widespread convection in different parts of the COPS area caused by

(i) initiation from the surface (southern and northern part),
(ii) triggering by orographic effects (but only weak thermally driven wind systems), and

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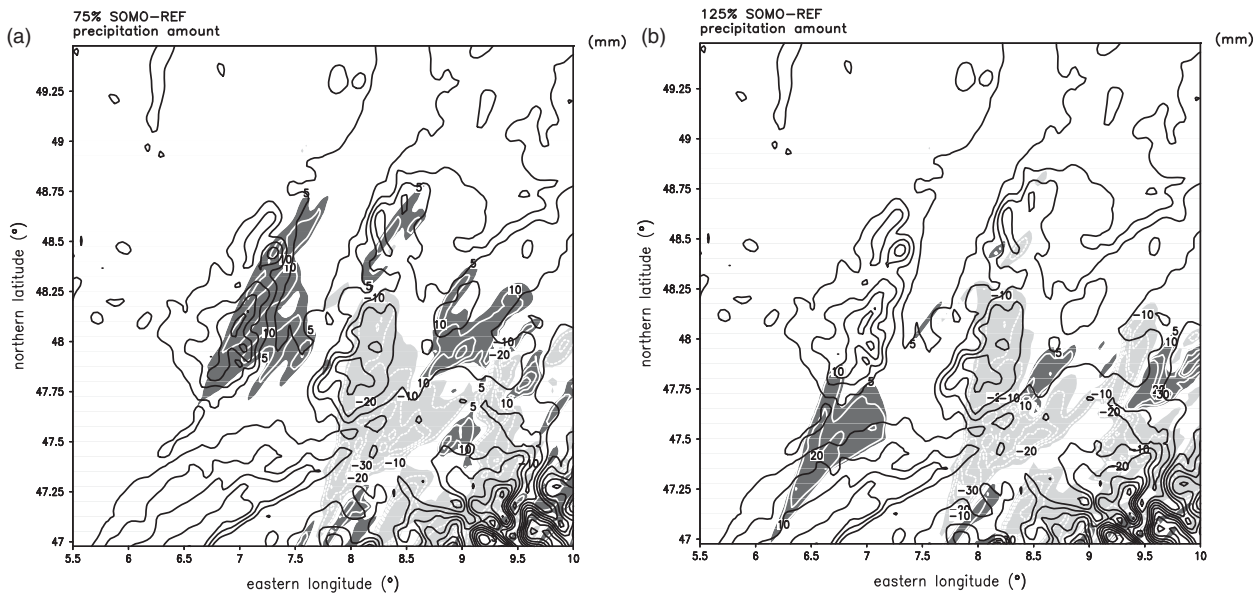
Figure 8. Plots of precipitation difference taken from Figure 7. (a) shows Figure 7(c) minus 7(b), and (b) shows Figure 7(a) minus 7(b). Positive and negative values are shown in dark and light grey, respectively.

(iii) mid-tropospheric lifting, mainly in the southwestern part (Kottmeier *et al.*, 2008).

Precipitation occurred mainly along and on the leeside of the mountain ranges of the Vosges and Black Forest mountains as well as in the southeastern part, while the Rhine valley was free of deep convective clouds.

In good agreement with the observed precipitation, accumulated precipitation in the reference simulation (Figure 7(b)) is highest in the southeastern part of the COPS area and over the Black Forest. Almost no precipitation is found in the Rhine valley and in the northeastern part of the COPS area. In contrast, for reduced initial soil moisture conditions, precipitation is increased on the lee side of the Vosges mountains and in the Rhine valley and decreased over the southern Black Forest, whereas it is decreased over the whole Black Forest for increased soil moisture conditions (Figures 8(a) and (b)). Even though the moisture content in the PBL was predominantly influenced by the large-scale flow on this day, simulations show that different soil moisture conditions may influence convection through modifying the surface temperature and hence the potential for reaching the convective temperature, one of the possible trigger mechanisms for CI.

The above result for the Vosges mountains and the Rhine valley is in good agreement with other high-resolution studies over complex terrain (Hohenegger *et al.*, 2009), where reduced soil moisture did tend to increase CI, as the convective temperature was reached more easily for drier soil surfaces. The fact that both the reduced and increased soil moisture runs result in a decrease of precipitation over the Black Forest possibly suggests that the reference soil moisture field of that day acts as a kind of maximum threshold value, where the convective temperature is just reached and convection was initiated over the Black Forest. A further increase inhibited convective activity due to a lack of thermal forcing, whereas a decrease led to a reduction of CAPE, which similarly inhibited convective activity.

In contrast, a positive effect was observed for the increased soil moisture run of IOP 9c, with a precipitation increase by up to 50% outside the Black Forest (Figure 9(c)). Here,

convection was initiated along a convergence line, with a reduced sensitivity to thermal forcing, but an enhancement of convection through the additional availability of moisture (Kottmeier *et al.*, 2008). A reduction of soil moisture led to a small precipitation increase over the Black Forest (Figure 9(b)), where no precipitation was observed in the control run (Figure 9(a)), due to the higher thermal forcing in accordance to the results for IOP 4b.

Almost no precipitation was simulated for IOP 8b (not shown) which is consistent with observations, since only an isolated cell was detected over the Black Forest (Kalthoff *et al.*, 2009). Due to consistently high convective inhibition (CIN) values, no CI was simulated in all three sensitivity runs, even though a large sensitivity of the turbulent fluxes, the near-surface temperature and moisture on changed soil moisture was observed (Barthlott *et al.*, 2010, and next section).

4.2.2. Energy balance and convective indices

Figure 10 shows the various components of the energy balance as well as some convective indices for the case of IOP 8b (15 July 2007), where locally initiated convection took place over the Black Forest (Kottmeier *et al.*, 2008; Kalthoff *et al.*, 2009; Barthlott *et al.*, 2010). On this day the warm but very dry air mass did not allow early and widespread convection to develop.

Generally, the amount of net radiation available for transformation into sensible and latent heat flux is larger for high than for low soil moisture conditions, as soil moisture reduces outgoing short- and long-wave radiation via albedo and surface temperature, respectively. However, for IOP 8b the impact of a reduced or increased soil moisture on the radiation budget is low (Figure 10(a)). This is in good accordance with energy balance measurements during the COPS period, where the dependence of the albedo on soil moisture was found to be weak (Kalthoff *et al.*, 2011), probably because soil moisture variation was too weak during COPS. On the other hand, all other model variables shown in Figure 10 with the exception of CIN
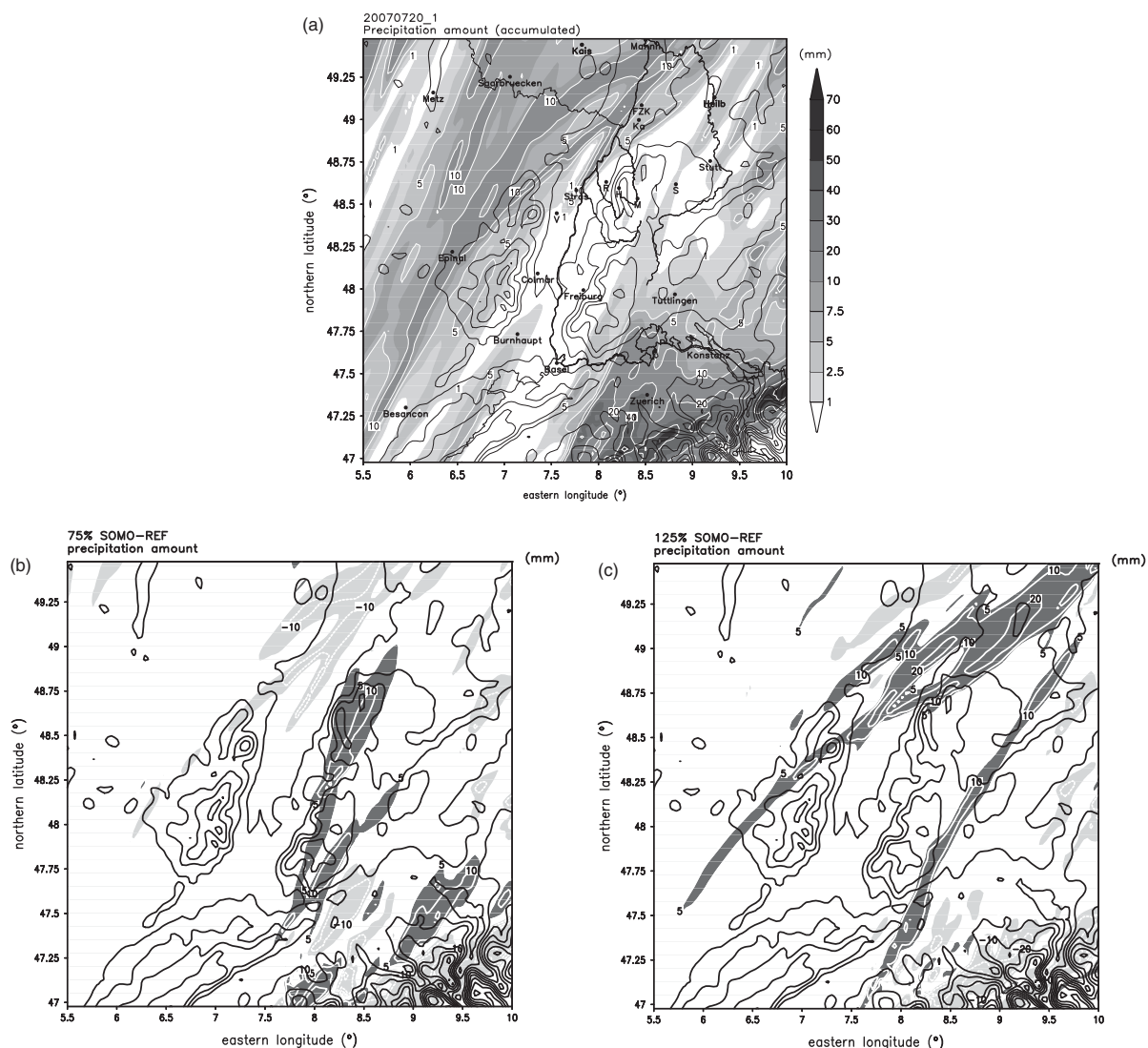
Figure 9. (a) Accumulated daily precipitation for the reference simulation of COPS IOP 9c (20 July 2007) with unchanged soil moisture conditions, and precipitation difference plots for (b) 25% decreased and (c) 25% increased soil moisture minus the reference. Positive and negative values in (b) and (c) are shown in dark and light grey, respectively.

(Figure 10(f)) show a systematic response, that is they show consistently increasing/decreasing values for either increasing or decreasing soil moisture conditions. A reduced soil moisture would therefore lead to a strongly increased Bowen ratio, a reduced CAPE and an increased LI. The decreasing effect on CAPE is strongest for the Black Forest, where a 25% reduction in soil moisture leads to a reduction of maximal CAPE values from 1500 to 700 J kg^{-1}. This effect is much smaller for the Rhine valley (reduction from 600 to 400 J kg^{-1}).

As a further potential influence of soil moisture, the timing of CI at the surface is dependent on how fast the surface temperature can reach the convective temperature, both being dependent on the near-surface soil moisture. Figure 11 shows the influence of soil moisture on temperature, equivalent potential temperature and convective temperature at four COPS stations and for several IOPs. Heselbach (= AMF site) is a station within the Black Forest, whereas FZK and Achern are located in the northern and southern parts of the Rhine valley, respectively. For IOP 8b, the results show that a reduced soil moisture would lead to an increase in the convective temperature of around 0.6 K (AMF) and 0.7 K (Achern), and to an increase of 2 m

temperature of around 1 K for both sites. An increased soil moisture would lead to a decrease in convective temperature by 0.8 K (AMF) and 0.6 K (Achern), and a decrease in 2 m temperature by 0.8 K (AMF) and 0.7 K (Achern).

Kottmeier *et al.* (2008) found that the maximum 2 m temperature of 33 °C on that day was a little less than the necessary convective temperature of 34 °C in the northern Rhine valley near Karlsruhe. Thus, CAPE could not be released by buoyancy in this case. The results from Figure 11 indicate that the net influence of soil moisture on the surface temperature and convective temperature is systematic but small (less than 0.5 K), so that for IOP 8b no improvement of the modelled precipitation could be shown by using a more realistic soil moisture initialisation. However, combined with a significant difference in the amount of CAPE, especially over the Black Forest, there is a clear benefit of using improved soil moisture initialisation.

A general analysis of the results of the sensitivity experiments for several COPS IOPs showed that wet soil conditions in the model indeed lead to moister and cooler boundary layers as well as lowered lifting condensation levels and levels of free convection, facilitating the development of deep convection (not shown). In particular, the interplay
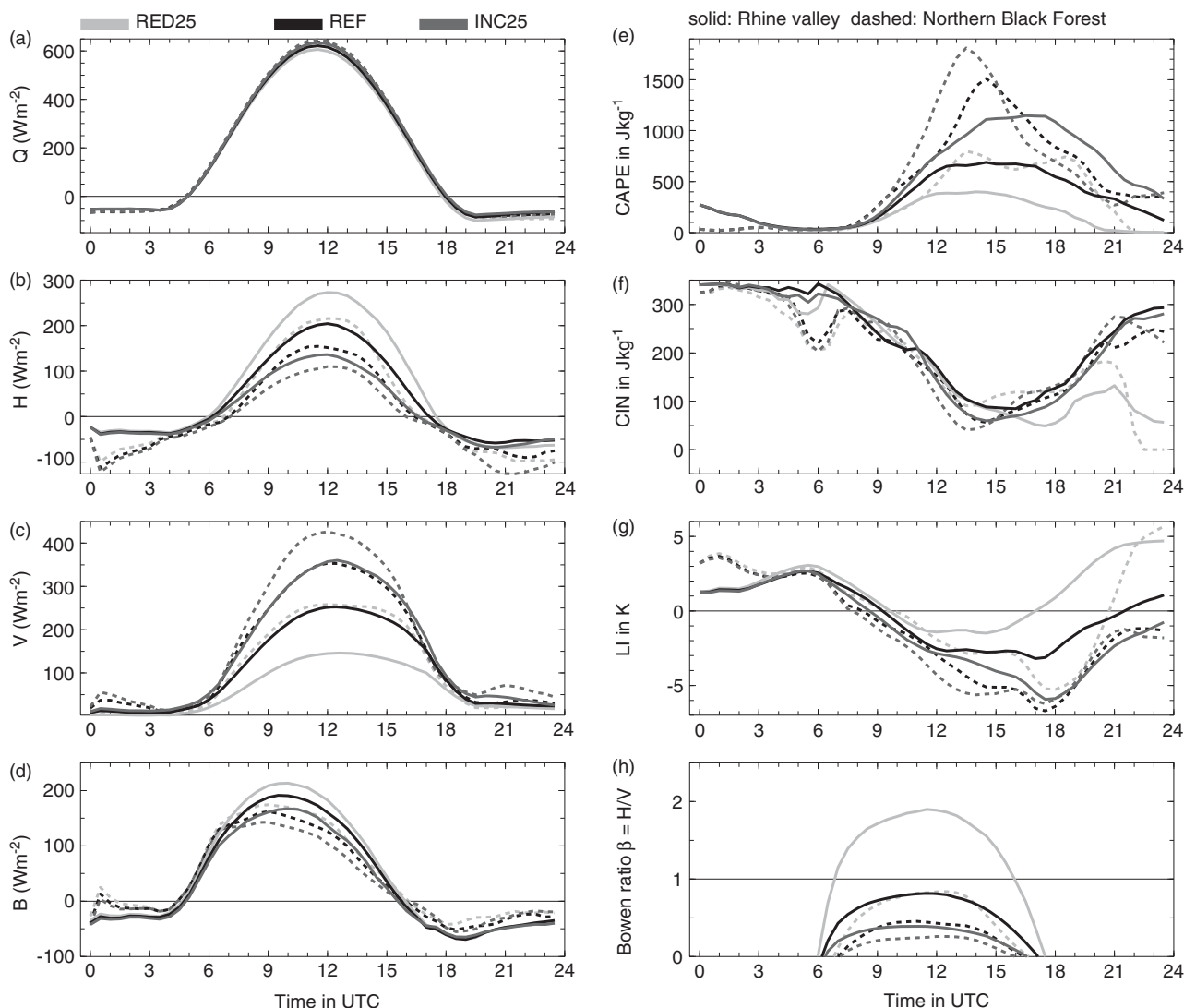
Figure 10. Areal mean values for the energy balance and convective indices for the simulation of IOP 8b (15 July 2007) with increased and decreased initial soil moisture values. Mean values for the Rhine valley (solid) and northern Black Forest (dashed) regions are shown. (a) Net radiation, (b) sensible het flux, (c) latent heat flux, (d) ground heat flux, (e) CAPE, (f) convective inhibition (CIN), (g) lifted index (LI) and (h) Bowen ratio.

between CAPE, which may depend strongly on surface fluxes, and CIN, being more dependent on upper-level processes, plays a major role in the impact of soil moisture in complex terrain (see also Kalthoff *et al.*, 2011). However, for most mid-tropospheric forcing cases of convection, the soil moisture plays no (or only a very minor) role, because the humidity in the PBL (which strongly influences the above-mentioned variables) is advected from upstream and does not depend on the soil characteristics. This was the case for about 21 IOP days during COPS, as opposed to 14 days with (at least partly) locally initiated convection (Kottmeier *et al.*, 2008).

5. Discussion and summary

We presented a comparison of modelled and observed soil moisture values in the near subsurface with the aim of analysing systematic discrepancies of soil moisture variability and their potential impacts on the simulation of convective processes over complex terrain. The soil moisture dataset consists of data from a newly installed soil moisture monitoring network in southwest Germany. These data were compared with operational long-term

analysis data from the GME model of the DWD as well as with case-study simulations with the high-resolution non-hydrostatic model COSMO-DE (2.8 km resolution). The large-scale GME model data were used because, in contrast to the operational non-hydrostatic COSMO-EU, in GME no assimilation scheme is used that adjusts soil moisture such that errors in near-surface temperature are minimised.

To analyse the potential impact of systematic soil moisture errors in the model, sensitivity simulations with increased and decreased soil moisture were conducted for three case-studies from the Convective and Orographically-induced Precipitation Study (COPS).

Key results from this study using this new (and for the region unique) soil moisture dataset are as follows:

- Large differences between GME-simulated and observed soil moisture values can be observed. The model is generally too dry at all depths and this trend amplified with depth. Mean bias values are between –5% and –10% by volume at the surface and maximum discrepancies are around –20%. In addition, temporal soil moisture variability is underestimated in the model.

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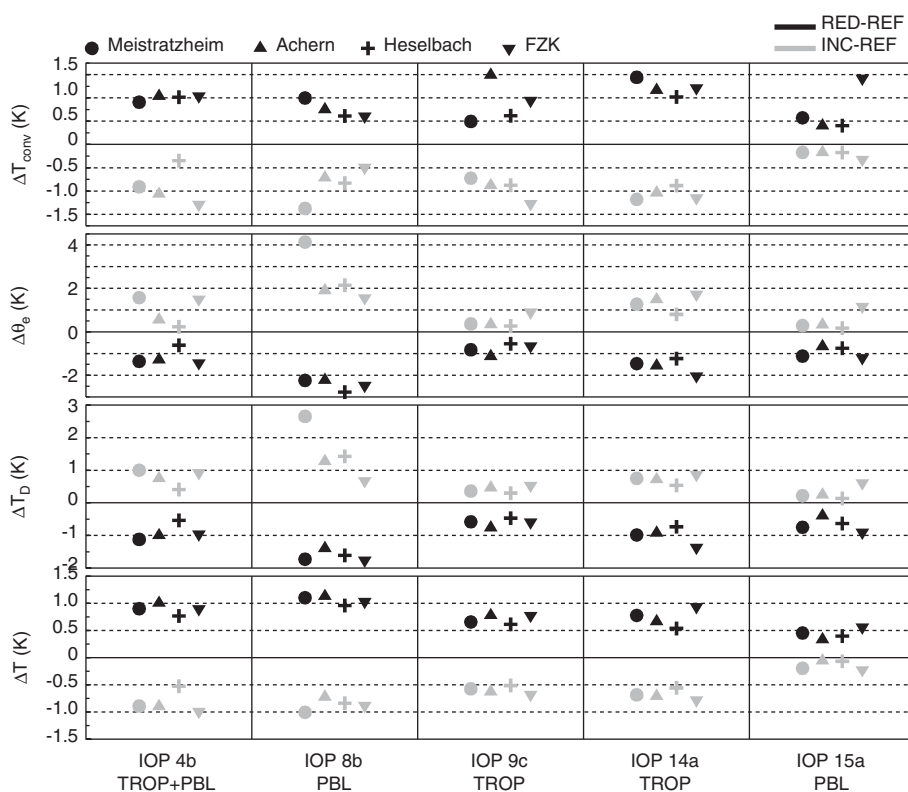
Figure 11. Temperature differences from reference values arising from increased (light points) and decreased (dark points) soil moisture: (a) convective temperature, (b) equivalent potential temperature, (c) dew point temperature, and (d) 2 m temperature for four COPS stations with energy balance data and for five IOPs.

- Detailed analyses of simulation minus observation discrepancies for individual stations revealed four distinct groups of stations: (a) those with a good match at all levels (8 stations), (b) those with a good match at the surface, but underestimated soil moisture at greater depth (13 stations), (c) those with a good match at the surface, but higher soil moisture variability in the measurements at greater depth (15 stations) and (d) those with a poor match, because a site-specific (sub-)surface condition could not be modelled adequately (5 stations).

- High-resolution modelling of specific days such as the COPS IOP 8b with COSMO-DE also showed a mean bias towards too dry soil conditions, especially on the windward side and on the crest of the Black Forest, where precipitation is maximal. Generally, soil moisture values in COSMO-DE simulations were too low with the largest biases near the surface and for the Black Forest region (up to 15% underestimation).

- The influence of this bias on simulated precipitation is non-trivial and potentially large, and depends on the specifics of the analysed case-study. For example, sensitivity simulations for COPS IOP 4b with increased soil moisture showed decreased precipitation over the whole Black Forest, whereas decreased soil moisture simulations showed increased precipitation in the Rhine valley and the Vosges mountains and decreased precipitation in the southern part of the COPS region. In contrast, the opposite effect was observed for IOP 9c, where convection was initiated along a convergence line. There, precipitation outside the Black Forest was enhanced for increased soil moisture values through the additional availability of moisture.

- The simulations presented in this study demonstrate that soil moisture has a considerable impact on convection-related parameters in complex and heterogeneous terrain. Sensitivity experiments showed significant dependences of convection-related parameters such as CAPE, Bowen ratio and surface temperature on soil moisture, but no systematic influence on convective precipitation due to a complex and regionally different interplay with convection inhibiting factors, such as CIN.

Following Koster *et al.* (2009), we point out that the value of modelled soil moisture in operational weather prediction models lies not in its absolute magnitude but in its time variations, as soil moisture is often treated as an adjusting variable to produce realistic near-surface temperatures (as e.g. in COSMO-DE). Similarly, in GME, where no adjustment is performed, small-scale and site-specific processes cannot be modelled on the coarse GME grid. The site-specific discrepancies between GME modelled and observed soil moisture found in this study are therefore not surprising. Koster *et al.* (2009) emphasised that the existence of *in situ* data does not guarantee their usefulness as measurements are highly localised, and differences in soil properties can cause important differences in the mean and variance of soil moisture, even over small distances.

However, the general underestimation of soil moisture may have a significant influence on modelled surface–atmosphere exchange processes, as was shown also in a number of previous studies (e.g. Georgescu *et al.*, 2003; Jones and Brunsell, 2009). On the other hand, observed land-surface exchange processes during COPS were studied in detail in

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a companion paper using soil moisture, turbulence, and energy balance data (Kalthoff *et al.*, 2011). There it was found that latent heat fluxes and conditions in the convective boundary layer were barely dependent on soil moisture in the mountainous regions of the Black Forest, but weakly dependent in the Rhine valley. Assuming that large-scale advection affected the whole COPS domain uniformly, the results indicate that contributions from mesoscale advection and entrainment processes were more important over complex terrain during COPS. In contrast to the model results, Kalthoff *et al.* (2011) found no significant correlations between the convection-related parameters (such as CAPE and CIN) and the soil moisture measurements during the COPS period, due to the observed weak correlation between soil moisture and the surface fluxes and between the surface fluxes and the boundary-layer conditions.

This observed lack of sensitivity of fluxes to soil moisture over the Black Forest contrasts with the model behaviour. This suggest that the model behaviour overestimates the influence of soil moisture which may be caused by an inadequate description of soil textures and/or land-surface exchange processes. It has to be kept in mind that IOPs during COPS were predominantly performed during warm and humid conditions and that the COPS summer was wetter than climatology (Wernli *et al.*, 2010; Wulfmeyer *et al.*, 2011), which may also have influenced the reduced dependence of the PBL on energy supply from the surface.

The considerable sensitivity of precipitation to soil moisture in complex terrain as shown in the model examples of this study demonstrates the particular importance of accurate initial soil moisture fields in NWP models. A potential benefit of a more realistic representation of soil moisture in those models could be an improvement of quantitative precipitation forecasts, a hypothesis which would have to be tested using a series of sensitivity experiments *and* observational evidence over a longer time span than the COPS period. This has not been addressed so far and would have been beyond the scope of this contribution.

Future work will therefore include model simulations that are initialised with observed soil moisture fields to evaluate the potential of improvement of the simulation of CI by using operational soil moisture data.

Acknowledgements

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