Impact of soil moisture on convection-related parameters and convective precipitation over complex terrain: A numerical case study for COPS IOP 15a

Christian Barthlott and Norbert Kalthoff
Introduction

Barthlott, Hauck, Schädler, Kalthoff, Kottmeier (2011): *Soil moisture impacts on convective indices and precipitation over complex terrain*, Meteorol. Z. 20, 185-197:

⇒ investigate the impact of initial soil moisture (SOMO, ± 25%) on convection-related parameters for 7 COPS IOPs (PBL forcing: 2, synoptic-scale forcing: 2, combination: 3)

- systematic response to SOMO for a number of variables (sensible and latent heat fluxes, near-surface temperature, moisture, \(\theta_e\),...)
- considerable, but non-systematic dependance of precip on initial SOMO
- SOMO impact not systematically higher for PBL forcing
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Questions

- What kind of relationship exists between initial SOMO and subsequent precipitation in complex terrain?
- Is there an optimal SOMO content leading to a maximum in convective precipitation?
- Is there a threshold, where the atmosphere does not feel an additional increase in SOMO?
- Investigate contradiction between studies on the SOMO-precipitation feedback:

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COSMO simulations for 12 August 2007 (IOP 15a)

\[ \text{change initial soil moisture from } -50\% \text{ to } +50\% \text{ with respect to the reference run in steps of } 5\%, \text{ i.e. explore a large range of SOMO values in fine steps } \Rightarrow 21 \text{ runs} \]
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- COSMO v. 4.6
- grid spacing 2.8 km
  50 vertical levels
- deep convection resolved
  shallow convection parameterised
- initial and boundary data:
  7 km COSMO-EU analysis
- initial time: 0000 UTC
  integration time: 24 h
- initial SOMO modified in all soil levels in full model area
COPS domain

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<th>soil type</th>
<th>sand</th>
<th>sandy loam</th>
<th>loam</th>
<th>loamy clay</th>
<th>clay</th>
<th>peat</th>
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<td>porosity</td>
<td>0.364</td>
<td>0.445</td>
<td>0.455</td>
<td>0.475</td>
<td>0.507</td>
<td>0.863</td>
</tr>
<tr>
<td>permanent wilting point</td>
<td>0.042</td>
<td>0.100</td>
<td>0.110</td>
<td>0.185</td>
<td>0.257</td>
<td>0.265</td>
</tr>
<tr>
<td>percentage cover</td>
<td>3</td>
<td>9</td>
<td>61</td>
<td>22</td>
<td>4</td>
<td>1</td>
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1200 UTC COSMO-EU analysis: synoptic-scale ascent is weak ($\nabla \cdot \mathbf{Q}$ near zero), weak southwesterly winds, upper trough over the British Isles and its associated regions with significant upward vertical motion remain far away

$\Rightarrow$ triggering of convection is primarily controlled by soil-atmosphere interactions and boundary layer processes

- course of the day: weak advection of cold and moist air + moistening of middle trop. by low/mid-level clouds
Observations and reference run

- number of convective cells and their tracks oriented from southwest to northeast
- simulated maximum accumulated precipitation: 30 mm, obs: 27 mm
- timing of simulated precip: no precip in morning hours, relative amounts in afternoon lower, maximum precipitation at same time

⇒ not all cells simulated at right place, but model captures convective activity rather well
**24 h accumulated precipitation and mean cloud cover**

- drier runs: daily precip amount increases with SOMO, further increase: slightly lower precipitation amounts fluctuating at about 80-90% of REF
- maximum precip amount in +25%-run, but lower fraction of grid points with rain → reduced accumulated precip
- low-level cloud cover increases with increasing SOMO, mid-level cloud cover decreases, high-level and total cloud cover remain more or less constant, almost no sensitivity for SOMO > +20%
Time series of spatially integrated precipitation

First occurrence of precip between 0900 and 1000 UTC
Threshold of 50 mm: precip in wet simulations up to 4 h later
Until 1900 UTC: runs with reduced/increased SOMO \( \implies \) increased/reduced precip
Dry runs: short life-time of cells \( \iff \) wet runs: gradual increase of acc. precip
Evening: convection starts again also in the drier runs

Coloring:

-50\% -45\% -40\% -35\% -30\% -25\% -20\% -15\% -10\% -5\% REF +5\% +10\% +15\% +20\% +25\% +30\% +35\% +40\% +45\% +50\%
Energy balance components

- **a)** Differences in the heat flux (Q) between soil moisture reference, reduced, and increased conditions.
- **b)** Variations in the sensible heat flux (H) over time.
- **c)** Changes in the latent heat flux (V) across different soil moisture scenarios.
- **d)** Evolution of the Bowen ratio (β) with soil moisture conditions.

Each graph illustrates the impact of soil moisture on convection-related parameters over a 24-hour period (UTC), showing how different soil moisture conditions affect the energy balance components.
Near-surface meteorological variables

- RH2m (%)
- θe (°C)
- T2m (°C)
- QV2m (g kg⁻¹)

reference
soil moisture reduced
soil moisture increased
Dry/humid boundary layer?

Humidity index $\text{HI}_{\text{low}}$ in the form used by Findell and Eltahir (2003) as the sum of the dewpoint depressions at 950 and 850 hPa:

$$\text{HI}_{\text{low}} = (T_{950} - T_{d950}) + (T_{850} - T_{d850})$$

$\text{HI}_{\text{low}} > 15 \text{ K} \implies$ not enough low-level humidity to allow for rainfall or shallow clouds

Convective precipitation is simulated despite $\text{HI}_{\text{low}}$ being larger than 15 K in the driest runs $\implies$ strong trigger mechanism required
Convective indices

- **a)** Precipitation (100 l)
  - Reference: Black line
  - Soil moisture reduced: Red line
  - Soil moisture increased: Blue line
- **b)** EL (km agl)
- **c)** CIN (J kg\(^{-1}\))
- **d)** LFC (km agl)
- **e)** CAPE (J kg\(^{-1}\))
- **f)** LCL (km agl)
Low-level convergence

divergence of 10 m wind field → only convergent contributions are accumulated

\[ w_{CIN} = \sqrt{2 \cdot CIN} \]
\[ w_{\text{diff}} = w_{\text{max}}(\text{below LFC}) - w_{CIN} \]
> 0 → CAPE can be released

dry simulations: due to stronger thermal forcing and thermally induced circulations with accompanied low-level convergence \(\Rightarrow\) higher number of grid points where \(w_{\text{diff}} > 0\)

wet simulations: low-level convergence and number of grid points \(w_{\text{diff}} > 0\) is smaller
Mid-level humidity

700 hPa specific humidity

700 hPa relative humidity

Normalized saturation deficit NSD (Chaboureau et al., 2004) to quantify the occurrence of deep clouds:

$$\text{NSD} = \frac{r_{\text{sat}} - r}{\sigma r_{\text{sat}} - r}$$

relates the saturation deficit to the domain variability of water vapor (=stddev of the saturation deficit)

After 1700-1800 UTC: NSD is below the threshold of 2 indicating suitable conditions for persisting deep convection
precipitation amounts in the afternoon of the wet simulations are lower than in the reference run or the dry simulations  \(\Rightarrow\) negative correlation between SOMO and precipitation

small convective cells present \(\Rightarrow\) intensify and persist because of higher CAPE and more humid middle troposphere (increase of RELHUM, NSD below 2) \(\Rightarrow\) dry simulations: positive correlation wet simulations: non-systematic
Impact of soil moisture is different for the initiation and modification of convective precipitation.
Conclusions

- response of 24-h accumulated precipitation:
  - **dry soils**: systematic positive relationship of precipitation to SOMO
  - **wet soils**: influence of increasing SOMO much weaker, no general response anymore

⇒ reason for differing SOMO-precipitation relationships in previous studies: depending on the position of reference SOMO, a further increase can lead to both, an increased or reduced precipitation amount

- relative contribution of precipitation during the initiation and modification phase of convection significantly influences the dependance of 24-h accumulated precipitation on the initial soil moisture

- no lower threshold for the atmospheric response on soil moisture, each reduction up to -50% affected precipitation and other parameters clearly; response considerably smaller for SOMO larger than +25% (VWC = 41 Vol%, RWC = 85%)

- complex orography plays an important role by its thermal effects - dry simulations: strengthened thermally induced circulations are obvious from stronger low-level convergence and increased number of grid points where CIN can be overcome

- single case study → not sufficient for general statements because the behavior depends on the initial atmospheric conditions too, but results demonstrate high impact of initial soil moisture on the forecast of convective precipitation (considering the mean dry bias of 20-30% between measurements and numerical results found in the same region by Hauck et al., QJRMS, 2011)
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**Content:**
- Cumulus formation, Cu hum to Cu med, distant Cb (initiated near Villingen-Schwenningen)

**Viewing direction:**
- from Baden-Airpark (Rhine valley) towards southeast (Black Forest)

**Time period:**
- 14:04 - 17:07 CEST

**Time step:**
- 15 s

**Length:**
- 00:48, 15 pictures/s – this and other movies available at [www.cops2007.de](http://www.cops2007.de)
Initial soil moisture

\[ \text{RWC} = \frac{\text{VWC} - \text{WP}}{\text{PO} - \text{WP}} \]

RWC : relative water content  
VWC : volumetric water content  
WP : wilting point  
PO : porosity

- domain-averaged SOMO uppermost level: 33 Vol\% (REFRUN) equals monthly mean in August 2007 measured by network (Krauss et al., Meteorol. Z., 2010)
- mean minimum and maximum measurements for that month: 25 and 41 Vol\% (stddev of 5 Vol\%) ⇐ COSMO simulations 17-48 Vol\%
Reference run: rainwater content (10-24 UTC, dt=30 min)
Optimum CI-conditions: CAPE > 600, CIN < 10 J kg$^{-1}$

- daily sum of grid points increases with increasing SOMO
- time evolution: again positive relationship to SOMO

convective precipitation is simulated also in the driest runs $\Rightarrow$ strong trigger mechanism required