On the relationship between soil, vegetation and severe convective storms: Hungarian case studies

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A R T I C L E   I N F O
Article history:
Received 23 November 2007
Received in revised form 11 September 2008
Accepted 6 October 2008

Keywords:
Convective precipitation
Soil hydrophysical parameters
Stomatal functioning
Sensitivity
MM5
Hungary

A B S T R A C T
The effects of soil hydraulic parameter and stomatal functioning parameterization changes upon the precipitation fields of storms were compared and analyzed. The analysis was performed using results from the Penn State-NCAR MM5 Modeling System. Two sets of soil hydraulic parameters, from the USA and Hungary, were used. Stomatal functioning is parameterized as simply as possible using Jarvis’ approach. The days chosen for analysis (18th April 2005 and 7th August 2006) seemed to be favourable for local storms to form when the land-surface/air interaction is the strongest. Both days were wet, however, the prevailing moisture was somewhat larger on 18th April 2005. Precipitation fields were statistically analyzed in details. First, the simulated and observed fields were compared. The observed fields were estimated from rain-gauge data applying the ordinary block kriging interpolation technique. The agreement between the simulated and observed fields was estimated using categorical and continuous verification indices. Significance tests were done to estimate how large the obtained differences were. The results obtained indicate that precipitation fields are at least as sensitive to changes in soil hydraulic parameters as to changes in stomatal functioning parameterization. The simple Student t-test hypothesis was applied to estimate how large the precipitation differences obtained were. According to the estimates, the TSS differences obtained by soil parameter and stomatal functioning parameterization changes are significant on the 10% level. The acquired differences do not depend on the initialization of soil moisture. The results suggest that all weather and climate models used for regional purposes should prefer local soil data instead of some common globally used soil datasets. This is at least as important as the parameterization of stomatal functioning.

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1. Introduction

The formation and evolution of storms is determined by both the state of the atmosphere and the land surface. Atmospheric influence is significant through triggering (Benjamin and Carlson, 1986; Lanicci et al., 1987; Pielke et al., 1991; Avissar and Liu, 1996), instability (Betts et al., 1994; Betts and Ball, 1995) and interaction between cloud and environmental air (Siems et al., 1993; Zuidema, 1998; Zuidema et al., 2006). The impact of land-surface processes upon storm events is determined by land use (Bryant et al., 1990; Lyons et al., 1996; Wei and Fu, 1998; Mölders, 1999), surface heterogeneity (Segal et al., 1989; Rabin et al., 1990; Chang and Wetzel, 1991; Chen and Avissar, 1994) and by the thermal and hydrophysical properties (Delworth and Manabe, 1989; Jones et al., 1998; Grasso, 2000) of the soil-vegetation system. Among these effects, we are concentrating on the latter.

Land-surface/storm interaction processes are highly determined by the partition of available surface energy flux to
sensible and latent heat fluxes, that is, by the surface Bowen ratio (Betts et al., 1996). Both fluxes depend upon the state and type of the soil-vegetation system. Vegetation regulates this partition through its stomata, while soil by its hydrophysical properties, which controls water movement in both the soil and the vegetation. In mesoscale models, Jarvis' (1976) big leaf approach is one of the most popular parameterizations for simulating stomatal conductance. Jarvis' (1976) multiplicative formula specifies two governing relative stomatal conductances: one describing the atmospheric demand (relative stomatal conductance, $F_{\text{rad}}$); and one describing the available soil moisture (relative stomatal conductance, $F_{\text{sm}}$). The effect of atmospheric forcing (radiation, air humidity and temperature) upon stomatal functioning is condensed into $F_{\text{rad}}$. In most cases $F_{\text{rad}}$ is parameterized using different empirical formulae (Niyogi and Raman, 1997; Chen and Dudhia, 2001), but there are also parameterizations which do not use atmospheric forcing (De Ridder and Schayes, 1997). The available soil moisture for transpiration is represented by $F_{\text{sm}}$. $F_{\text{sm}}$ is mostly parameterized via soil moisture content using its linear dependence on soil moisture content, $\theta$ (Chen and Dudhia, 2001).

Soil hydrophysical properties are determined by hydrophysical functions (soil water retention, $\Psi(\theta)$ and soil water conductivity, $K(\theta)$) and by hydrophysical parameters (field capacity soil moisture content, $\theta_f$ and wilting point soil moisture content, $\theta_w$). The hydrophysical functions have to be estimated from field measurements. The empirical formulae fitted to the measurements range from the simpler (Clapp and Hornberger, 1978) to the more complex (van Genuchten, 1980). In meteorology, the Clapp and Hornberger (1978) parameterization is widely applied which refers to the soils in the USA. It is simple and uses only four fitting parameters: saturated soil water retention $\Psi_S$ (m, water column), saturated soil water conductivity $K_S$ (m s$^{-1}$), saturated soil moisture content $\theta_S$ (m$^3$ m$^{-3}$) and the pore size distribution index b. Using Clapp and Hornberger's (1978) parameterization in any other region of the world which is different from USA, we suppose that physical characteristics of the soil textures are independent from their geographical distribution. It is to be noted that this assumption is doubted by numbers of researchers (Hodnett and Tomassella, 2002).

So far, the role of soil and vegetation has not been compared concerning the formation and evolution of storms. Vegetative control is considered using different stomatal parameterizations. The impact of soil was analyzed using two sets of soil hydraulic parameters: one of which was obtained in Hungary (Nemes, 2002) and the other in the USA (Clapp and Hornberger, 1978). Their effects upon storm events were studied by comparing precipitation fields. The analyses were made by the Penn State–NCAR MM5 Modeling System (Fifth-generation Mesoscale Model). The convective storms occurred on 18th April 2005 and on 7th August 2006. The chosen cases were analyzed in the region of the Carpathian Basin. The results obtained were also compared by surface accumulated precipitation data.

2. The nonhydrostatic model MM5

Numerical simulations were performed by Version 3 of the Penn State – NCAR MM5 (Fifth-generation Mesoscale Model) modeling system (Dudhia, 1993). Its general characteristics as well as relevant parameterizations which refer to the soil-plant system are presented in brief below.

2.1. General characteristics

The model applies a terrain-following sigma coordinate system. The predictice variables are: pressure perturbation, the three momentum components, temperature, specific humidity and the mixing ratio of the different types of hydrometeors (cloud water, cloud ice, rain, snow and graupel particles). The partial differential equation system is solved by using a relaxation lateral boundary condition and a radiation upper boundary condition. Model runs were performed using horizontal resolution of 6×6 km, and 26 vertical levels.

Grell's scheme (Grell et al., 1994) was applied for parameterization of convection based on rate of destabilization or quasi-equilibrium. A simple single-cloud scheme with updraft and downdraft fluxes and compensating motion determining heating/moistening profile was used. The formation of cloud and precipitation elements are simulated with an explicit bulk microphysical scheme (Reisner et al., 1998) with five different types of hydrometeors: cloud water, cloud ice, rain, snow and graupel particles. The collision coalescence processes between different types of hydrometeors, furthermore the diffusion of vapor, freezing of liquid elements and melting of ice particles are simulated. The equation of conservation is not only solved for the mixing ratios of hydrometeors but for the concentration of cloud ice as well.

The planetary boundary layer (PBL) is described by the non-local PBL scheme based on Troen and Mahrt (1986). Compared with other non-local or high-order closure schemes, this PBL scheme proved to be more efficient, because it needs less computer capacity.

2.2. Basic characteristics of the OSU LSM

Land-surface processes are simulated by the OSU LSM (Oregon State University Land-surface Model). It consists of a multilayer soil model (Mahrt and Pan, 1984) and a single-layer snow (Chen and Dudhia, 2001) and canopy model (Penman, 1948; Pan and Mahrt, 1987). Atmospheric stratification is simulated by applying the Monin-Obukhov similarity theory (Oncler and Dudhia, 1995). Recently, as in our simulations, the surface exchange coefficients for heat and moisture were given by using lookup tables. The soil and vegetation canopy processes are also considered in detail.

2.2.1. Soil and vegetation module

Soil temperature and moisture are calculated using the differential equation for heat flow (Campbell, 1985) and Richards's (1931) equation, respectively. Surface skin temperature $T_{\text{skin}}$ of the combined vegetation-ground layer is calculated by a linearized surface energy balance equation (see Sridhar et al., 2002, Eq. (4)). Soil moisture content prediction is performed using a four-layer soil hydrology module (Chen and Dudhia, 2001). Soil thermal characteristics (volumetric heat capacity and thermal conductivity) depend upon soil physical characteristics (Peters-Lidard et al., 1998) and soil moisture content (Chen et al., 1996).
Soil hydraulic properties (water retention and conductivity functions) are parameterized by Clapp and Hornberger’s (1978) empirical formulae. The formulae and the corresponding soil data refer to the USA though they are widely used in the global and regional simulations outside of the USA.

Actual evapotranspiration is parameterized by using the so-called $\beta$-approach based on the moisture availability concept; $\beta$ depends on both the land-surface and the atmospheric characteristics (see Chen and Dudhia, 2001, Eq. (15)). Canopy resistance $r_c$ is formulated after Jarvis (1976) as follows:

$$r_c = \frac{r_{st,\text{min}}}{LAI \cdot F_{ad} \cdot F_{ma}}.$$ \hspace{1cm} (1)

where $r_{st,\text{min}}$ is the minimum stomatal resistance, $LAI$ is the leaf area index, $F_{ad}$ and $F_{ma}$ are the atmospheric demand and the moisture availability effect on stomatal functioning respectively. The functions range between 0 and 1. After Noilhan and Planton (1989) $F_{ad}$ is split into three effects in a multiplicative manner:

$$F_{ad} = F_{wr} \cdot F_{ah} \cdot F_{at},$$ \hspace{1cm} (2)

where $F_{wr}$, $F_{ah}$ and $F_{at}$ expresses the influence of absorbed visible radiation, air humidity and temperature. There are many forms of these relative stomatal conductivity functions, we used those which are described in Chen and Dudhia (2001). At the same time, according to De Ridder and Schayes (1997)

$$F_{ad} = 1.$$ \hspace{1cm} (3)

According to this parameterization there is no atmospheric stress effect upon stomatal functioning at all. $F_{ma}$ is parameterized as

$$F_{ma} = \sum_{j=1}^{3} F_{ma,j} \cdot \frac{\Delta z_j}{z_{\text{root}}},$$ \hspace{1cm} (4)

where $F_{ma,j}$ is the moisture availability function for layer $j$, $\Delta z_j$ is the thickness of layer $j$ and $z_{\text{root}}$ is the root layer depth. As we see, $F_{ma}$ is weighted according to soil layer thicknesses, in other words, no root density distribution change with depth is assumed. $F_{ma,j}$ depends on soil moisture content $\theta$. Following general rules, it can be parameterized as

$$F_{ma,j} = \begin{cases} \frac{\theta_j^{2.5}}{1 - e^{3 \theta_j}} & \text{convex form,} \\ \frac{\theta_j}{\theta_f - \theta_w} & \text{linear form,} \end{cases}$$ \hspace{1cm} (5)

where $\theta_j = \frac{\theta_j - \theta_w}{\theta_f - \theta_w}$, $\theta_j$ is the actual soil moisture content in the $j$th soil layer ($j = 1, 2, 3$), $\theta_w$ is the wilting point, while $\theta_f$ is the field capacity soil moisture content. In most cases, the linear form of $F_{ma,j}$ is used (Noilhan and Planton, 1989; Chen and Dudhia, (2001).

![Fig. 1. Station positions and measured precipitations together with the model domain on 8th August 2006.](image-url)
several thunderstorms formed and some of them caused occurred, causing convective instability. During the afternoon basin, meanwhile on higher levels (500 hPa) cold advection slowly moving cyclone with its center situated above the 3.2. The synoptic situations

situation is presented by Horváth (2005).

During the day many convective storms were also observed over the plane regions. A detailed description of the synoptic situation is presented by Horváth (2005).

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Table 1
USA soil parameters in the OSU LSM. Symbols: θ_s = saturated soil moisture content, Ψ_s = saturated soil water retention, K_s = saturated water conductivity, b = pore size distribution index, θ_f = field capacity soil moisture content and θ_w = wilting point soil moisture content.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>θ_s (m³ m⁻³)</th>
<th>Ψ_s (m)</th>
<th>K_s (m s⁻¹)</th>
<th>b</th>
<th>θ_f</th>
<th>θ_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Sand</td>
<td>0.319</td>
<td>0.069</td>
<td>4.60·10⁻³</td>
<td>2.79</td>
<td>0.236</td>
<td>0.010</td>
</tr>
<tr>
<td>2) Loamy sand</td>
<td>0.421</td>
<td>0.036</td>
<td>1.41·10⁻⁵</td>
<td>4.26</td>
<td>0.283</td>
<td>0.028</td>
</tr>
<tr>
<td>3) Sandy loam</td>
<td>0.434</td>
<td>0.141</td>
<td>5.23·10⁻⁶</td>
<td>4.74</td>
<td>0.312</td>
<td>0.047</td>
</tr>
<tr>
<td>4) Silt loam</td>
<td>0.476</td>
<td>0.759</td>
<td>2.81·10⁻⁶</td>
<td>5.33</td>
<td>0.360</td>
<td>0.088</td>
</tr>
<tr>
<td>5) Silt</td>
<td>0.476</td>
<td>0.759</td>
<td>2.81·10⁻⁶</td>
<td>5.33</td>
<td>0.360</td>
<td>0.088</td>
</tr>
<tr>
<td>6) Loam</td>
<td>0.439</td>
<td>0.355</td>
<td>3.38·10⁻⁶</td>
<td>5.25</td>
<td>0.329</td>
<td>0.096</td>
</tr>
<tr>
<td>7) Sandy clay loam</td>
<td>0.404</td>
<td>0.135</td>
<td>4.45·10⁻⁶</td>
<td>6.66</td>
<td>0.314</td>
<td>0.067</td>
</tr>
<tr>
<td>8) Silty clay loam</td>
<td>0.464</td>
<td>0.617</td>
<td>2.04·10⁻⁶</td>
<td>8.72</td>
<td>0.387</td>
<td>0.120</td>
</tr>
<tr>
<td>9) Clay loam</td>
<td>0.465</td>
<td>0.263</td>
<td>2.45·10⁻⁶</td>
<td>8.17</td>
<td>0.382</td>
<td>0.103</td>
</tr>
<tr>
<td>10) Sandy clay</td>
<td>0.406</td>
<td>0.098</td>
<td>7.22·10⁻⁶</td>
<td>10.73</td>
<td>0.338</td>
<td>0.100</td>
</tr>
<tr>
<td>11) Silty clay</td>
<td>0.468</td>
<td>0.324</td>
<td>1.34·10⁻⁶</td>
<td>10.39</td>
<td>0.404</td>
<td>0.126</td>
</tr>
<tr>
<td>12) Clay</td>
<td>0.468</td>
<td>0.468</td>
<td>9.74·10⁻⁷</td>
<td>11.55</td>
<td>0.412</td>
<td>0.138</td>
</tr>
</tbody>
</table>

The weather on 7th August was determined by a matured small cyclone, which moved NW to SE and drifted above the eastern part of the Carpathian-basin. Between 12 and 18 UTC the cyclone center, indicated by the sea level pressure field, was situated in the eastern part of Hungary. On the 500 hPa level the axis of the cold air drop got above the surface cyclone center and this configuration resulted in a larger value of convective instability. The frontal systems of the cyclone were not sharp, in this way thunderstorms were not forced to develop on one significant squall line but appeared sporadically around the cyclone center, influenced by local orographical and surface trigger effects.

3.3. Initializations

The initial conditions for the MM5 model run were obtained from the ECMWF analysis and forecast. For both days 00 UTC data were used. For the top level of the MM5 model the 100 hPa layer was chosen. Initial soil data (temperature and soil moisture) were also taken from the ECMWF analysis. According to soil moisture content values (about 250–300 mm m⁻³) in the vadose-zone, both days can be treated as wet (see θ_f values in Table 2). However, on 18th April 2005 the prevailing moisture was somewhat greater than on 7th August 2006. In comparison experiments we also used artificially chosen initial soil moisture content values. These were created from the ECMWF analysis values, lowering them by 20 % in all four soil layers.

3.4. Basic land-surface parameters

The USGS-25 category land use dataset was used. The vegetation characteristics in the model domain for April and August are as follows: the vegetation cover veg (vegetated part of one complete grid cell) changes between 0.5 and 0.7 in April and between 0.5 and 1 in August. In the Carpathian Basin, the prevailing vegetation type is type 2, “Dryland Cropland and Pasture”. The lowest veg values can be found in the case of type 2. Towards mountain regions the “Grassland” type increases. In the Carpathian mountains, the “Deciduous Broadleaf Forest” is prevailing, but there is also

Table 2
Hungarian soil parameters in the OSU LSM. Symbols: θ_s = saturated soil moisture content, Ψ_s = saturated soil water retention, K_s = saturated water conductivity, b = pore size distribution index, θ_f = field capacity soil moisture content and θ_w = wilting point soil moisture content.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>θ_s (m³ m⁻³)</th>
<th>Ψ_s (m)</th>
<th>K_s (m s⁻¹)</th>
<th>b</th>
<th>θ_f</th>
<th>θ_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Sand</td>
<td>0.507</td>
<td>0.060</td>
<td>3.26·10⁻⁵</td>
<td>3.02</td>
<td>0.325</td>
<td>0.029</td>
</tr>
<tr>
<td>2) Loamy sand</td>
<td>0.598</td>
<td>0.126</td>
<td>2.52·10⁻⁵</td>
<td>3.09</td>
<td>0.479</td>
<td>0.080</td>
</tr>
<tr>
<td>3) Sandy loam</td>
<td>0.476</td>
<td>0.143</td>
<td>1.14·10⁻⁵</td>
<td>3.99</td>
<td>0.379</td>
<td>0.064</td>
</tr>
<tr>
<td>4) Silt loam</td>
<td>0.487</td>
<td>0.182</td>
<td>2.73·10⁻⁶</td>
<td>4.18</td>
<td>0.408</td>
<td>0.080</td>
</tr>
<tr>
<td>5) Silt</td>
<td>0.496</td>
<td>0.223</td>
<td>2.00·10⁻⁶</td>
<td>3.54</td>
<td>0.437</td>
<td>0.069</td>
</tr>
<tr>
<td>6) Loam</td>
<td>0.468</td>
<td>0.224</td>
<td>4.58·10⁻⁶</td>
<td>4.20</td>
<td>0.406</td>
<td>0.088</td>
</tr>
<tr>
<td>7) Sandy clay loam</td>
<td>0.439</td>
<td>0.132</td>
<td>7.98·10⁻⁶</td>
<td>4.21</td>
<td>0.354</td>
<td>0.061</td>
</tr>
<tr>
<td>8) Silty clay loam</td>
<td>0.491</td>
<td>0.234</td>
<td>6.20·10⁻⁷</td>
<td>5.04</td>
<td>0.435</td>
<td>0.119</td>
</tr>
<tr>
<td>9) Clay loam</td>
<td>0.580</td>
<td>0.207</td>
<td>3.05·10⁻⁶</td>
<td>4.74</td>
<td>0.479</td>
<td>0.139</td>
</tr>
<tr>
<td>10) Sandy clay</td>
<td>0.500</td>
<td>0.890</td>
<td>4.58·10⁻⁶</td>
<td>3.58</td>
<td>0.340</td>
<td>0.055</td>
</tr>
<tr>
<td>11) Silty clay</td>
<td>0.453</td>
<td>0.324</td>
<td>1.05·10⁻⁶</td>
<td>4.06</td>
<td>0.340</td>
<td>0.113</td>
</tr>
<tr>
<td>12) Clay</td>
<td>0.541</td>
<td>0.228</td>
<td>8.00·10⁻⁷</td>
<td>6.21</td>
<td>0.489</td>
<td>0.147</td>
</tr>
</tbody>
</table>
the “Mixed Forest” type. Typical minimal stomatal resistance values are $40 \, \text{s m}^{-1}$ in the Carpathian Basin and $100 \, \text{s m}^{-1}$ in the Carpathian mountains. Leaf area index LAI is estimated on the basis of veg. The details concerning the specification of vegetation parameters are described in the work of Chen and Dudhia (2001).

Two soil datasets were used: the so called USA and HU datasets. The former is based on the data gathered from about 1000 samples in the USA. Some details of this dataset are described in the work of Clapp and Hornberger (1978), but also in the work of Ek and Cuenca (1994). The HU dataset comprises soil data from 576 samples collected in Hungary. The dataset does not contain information about the single map units, that is, we do not know how large the area to which they are representative is. Therefore it is impossible to upscale this data. The dataset is described in

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**Fig. 2.** a) Pore size distribution index and b) saturated soil moisture content values for different soil textures as obtained from Hungarian and USA datasets.
3.5. Experimental design

To be able to do a comparative analysis, four runs were performed. The conditions used in the runs are presented in Table 3. Run 1 is the reference run. In this run HU soil parameters and original parameterization (as it is defined in the OSU LSM) of \( F_{ma} \) and \( F_{ad} \) functions were used. Run 2 differs from Run 1 in that USA soil parameters were used. Run 3 and Run 1 are different only in the parameterization of the \( F_{ma} \) function. In Run 3, the linear form of \( F_{ma} \) was replaced by its convex form. The non-convex form of \( F_{ma} \) was also tested; these results are not considered at all because the differences obtained are small. Run 4 differs from Run 1 in the parameterization of \( F_{ad} \) function. Comparing the results of Run 1 and 2 (comparison 1), we can analyze how important the soil parameter differences are. Comparing the results of Run 1 and 3 (comparison 2), we get an insight into how important the parameterization of the \( F_{ma} \) function is. Comparing the results of Run 1 and 4 (comparison 3), we get an insight into how important the parameterization of \( F_{ad} \) is.

4. Results

Storm events occurring on 18th April 2005 and 7th August 2006 were analyzed. The model was running for 30 h to ensure a 6 h spin-up time. In both cases, the model was started at 00 UTC. 24-hour accumulated precipitation fields were obtained from +6 and +30 h accumulated precipitation fields. The domain considered has 115 \times 49 grid points. It covers the Carpathian Basin and some parts of the Carpathian mountains (the coordinates of the domain’s lower left and upper right points are 45.6°N/15.6°E and 49.3°N/22.8°E, respectively). Precipitation fields were statistically analyzed in detail. First, the simulated and observed fields were compared. Observed fields were estimated from rain-gauge data applying the ordinary block kriging interpolation technique. In the second step, the agreement between simulated and observed fields was estimated using a categorical and a continuous verification index. At the end, significance tests were also done to estimate how large (important) or small (unimportant) the obtained differences are.

Kriging interpolation technique was used because this method is an approved method for interpolating precipitation data Rubel (1996). Among the various categorical verification indexes true skill statistics (TSS) was chosen. It is based on the two dimensional contingency table (Table 4). The TSS is computed as

\[
TSS = \frac{hz - fm}{(h + m) \cdot (f + z)}.
\]

The TSS changes from minus one to plus one. For perfect simulation, it tends towards plus one. This is a perfect verification measure because it is independent from the fraction of rain/no rain events. Root mean square error (RMSE) was chosen as the continuous verification index. Significance

\[
Table 4
\begin{tabular}{|c|c|c|}
\hline
Estimated & Observed & \hline
YES & h & f \\
NO & m & z \\
\hline
YES & hits & false & h+f \\
NO & misses & zero & m+z \\
\hline
h + m & f + z & n = h + f + m + z \\
\hline
\end{tabular}
\]
tests were made by using the Student t-test hypothesis. This is appropriate for independent, small-number samples with Gaussian distribution. In the following, we will be dealing with the validation and the sensitivity experiments for each day separately.

4.1. Validation experiments

4.1.1. 18th April 2005

TSS distributions for different threshold limits obtained by using a reference run (Run 1) on 18th April 2005 are presented.
in Fig. 3. Threshold limits denote precipitation intervals from the threshold to its maximum value. Fig. 3a refers to the areal distribution of soil texture as originally used in MM5; this is briefly referred to as US texture. Note that all simulations considered in the sensitivity tests were performed using US texture. In spite of this, Fig. 3b refers to the areal distribution of the soil texture which exists in Hungary. This is referred to as HU texture. The two fields are similar, but they differ considerably in some places. Irrespective of which areal distribution of soil texture was used, the TSS values obtained were quite similar. Note that TSS values obtained for HU texture were somewhat larger than those obtained for US texture, especially for larger threshold limits (from 17 mm day$^{-1}$). Three ranges can be separated. For small threshold limits (small and large precipitation together), the TSS values are quite high, above 0.3. For large threshold limits (referring to large precipitation events), the TSS values obtained are about 0.3. In between, the TSS values estimated are the smallest, about 0.1–0.2. The RMSE values for different threshold limits are presented in Fig. 4. Note that RMSE is small (about 8 mm day$^{-1}$) for larger and large (about 11 mm day$^{-1}$) for smaller TSS values.

### 4.2. Comparison experiments

Carrying out comparison experiments, first of all we wanted to analyze the sensitivity of precipitation field prediction to soil parameter differences (comparison 1, see Section 3.4) and to the parameterization of stomatal functioning (comparison 2 and 3). After this, we will also briefly discuss the sensitivity of precipitation fields to soil parameter uncertainties and initial soil moisture content fields.

#### 4.2.1. Soil effect

Comparing the results of Run 1 and 2 (comparison 1), we can analyze the effect of soil parameter differences upon precipitation field prediction. This is presented in Figs. 3a and 5a, for the April and August cases, respectively.

#### 4.2.2. 18th April 2005

For all threshold limits except threshold limit 2, the TSS values obtained by Run 2 (US soil texture, USA soil parameters) are larger than those obtained by Run 1. In general these

![Root Mean Square Error - 04.18.2005](image)

**Fig. 4.** Distribution of the root mean square error obtained using Run 1 (Hungarian soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) and Run 2 (USA soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) for different precipitation threshold limits on 18th April 2005. Threshold limits denote 24-hour accumulated precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture.
differences are about 0.05, but from large threshold limits (about 15 mm day$^{-1}$) they are about 0.1. Since the average TSS value is about 0.25, the obtained TSS differences between Run 1 and 2 are not small. Note that the largest differences are obtained for large precipitation threshold limits.

4.2.3. 7th August 2006

For almost all threshold limits, the TSS values obtained by Run 1 (HU soil texture, HU soil parameters) are larger than those obtained by Run 2. But these differences are somewhat smaller with respect to the previous day. The largest

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**Fig. 5.** a) Distribution of the True Skill Statistics obtained using Run 1 (Hungarian soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) and Run 2 (USA soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) for different precipitation threshold limits on 7th August 2006. Threshold limits denote 24-hour accumulated precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture. Fig. 5b: As in Fig. 5a, but for HU areal distribution of soil texture.
differences were obtained for precipitation threshold limits of 7.8 and 9 mm day$^{-1}$, they amount to about 0.05. Contrary to the former case, the obtained differences are small for large precipitation threshold limits.

We could pose the question, whether the TSS differences obtained between the Run 1 and 2 are significant. The simple Student t-test hypothesis was applied to estimate this. According to the estimate the TSS differences obtained are significant on the 10% level.

4.2.4. Vegetation effect

Comparing the results of Run 1 and 4 (comparison 3), we can get an insight into the effect of the parameterization of $F_{ad}$ upon precipitation field prediction. Similarly, comparing the results of Run 1 and 3 (comparison 2), we can see the effect of the parameterization of $F_{ma}$ upon the goodness of the precipitation prediction. These two effects constitute the so-called vegetation effects.

4.2.5. 18th April 2005

The TSS distributions for different threshold limits obtained by using Run 1 and 4 on 18th April 2005 are presented in Fig. 7a. For almost all threshold limits, except threshold limits 3, 9 and 10 mm day$^{-1}$, there are TSS differences. In general, the TSS values obtained by Run 4 are larger than those obtained by Run 1. That is, precipitation prediction is somewhat better when we suppose that atmospheric conditions do not limit stomatal functioning. This can be observed especially for large precipitation threshold limits (from 13 mm day$^{-1}$). In these cases, the TSS differences obtained can reach 0.05.

The TSS distributions for different threshold limits obtained by using Run 1 and 3 on 18th April 2005 are presented in Fig. 7b. Note that there are practically no TSS differences between Run 1 and 3. That is, in this case, the precipitation field prediction was not sensitive to the parameterization of $F_{ma}$.

4.2.6. 7th August 2006

The TSS distributions for different threshold limits obtained by using Run 1 and 4 on 7th August 2006 are presented in Fig. 8a. In general, the TSS differences obtained are somewhat smaller than in the previous case; their amount is about 0.02. However, similarly to the previous case, the largest TSS difference is about 0.05 (see threshold 8 mm day$^{-1}$). Note that TSS values obtained by Run 4 are smaller than those obtained by Run 1. This relationship remains for larger threshold limits too, which is just the opposite of the former April case.

The TSS distributions for different threshold limits obtained by using Run 1 and 3 on 7th August 2006 are presented in Fig. 8b. Contrary to the former April case, the TSS differences obtained are obvious. The largest TSS differences amount about 0.05, which is about 24% of the average TSS value of 0.21. Note that the sensitivity of

Table 5

<table>
<thead>
<tr>
<th>Estimated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>91.08%</td>
</tr>
<tr>
<td>NO</td>
<td>3.76%</td>
</tr>
</tbody>
</table>

The calculation was made for USA areal distribution of soil texture.

Fig. 6. Distribution of the root mean square error obtained using Run 1 (Hungarian soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) and Run 2 (USA soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) for different precipitation threshold limits on 7th August 2006. Threshold limits denote 24-hour accumulated precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture.
Fig. 7. a) Distribution of the True Skill Statistics obtained using Run 1 (Hungarian soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) and Run 4 (Hungarian soil data, original $F_{ma}$ and changed $F_{ad}$ parameterizations) for different precipitation threshold limits on 18th April 2005. Threshold limits denote 24-hour accumulated precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture. Fig. 7b: Distribution of the True Skill Statistics obtained using Run 1 (Hungarian soil data, original $F_{ma}$ and $F_{ad}$ parameterizations) and Run 3 (Hungarian soil data, changed $F_{ma}$ and original $F_{ad}$ parameterizations) for different precipitation threshold limits on 18th April 2005. Threshold limits denote 24-hour accumulated precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture.
prediction skill to the parameterization of $F_{ma}$ is apparent even for larger precipitation threshold limits.

As in the former case, the simple Student t-test hypothesis is applied to estimate whether TSS differences are significant or not. This is proved for TSS differences obtained between Run 1 and 4. According to the results, these differences are also significant on the 10% level.

4.2.7. Soil data uncertainty effect

The soil parameter values used in the tests represent “average” values. The scatter around the “average” values can be quite large like, for instance, in the case of USA soil parameters (see Fig. 2a and b). Therefore, we could pose the question, to what extent is the precipitation field sensitive to changes in soil parameters? To prove this sensitivity, we

**Fig. 8.** a) As in Fig. 7a, but on 7th August 2006. Fig. 8b: As in Fig. 7b, but on 7th August 2006.
simulated precipitation for plus-minus one standard deviation about the mean values of the soil parameters. Tests were carried out for the case on 7th August, and made using HU soil parameters, since these parameters were used in the reference runs to express regional soil characteristics.

The results obtained are presented in Fig. 9. Fig. 9 shows that some sensitivity of precipitation to soil parameter uncertainties exists, but this sensitivity does not seem to be large, at least for the day proven and the soil data used. For small threshold limits, differences between the precipitation obtained for the mean and for the plus-minus one standard deviation about the mean value of every soil parameter are much smaller than the difference between the precipitation obtained for the mean value of every soil parameter and the measured precipitation. Nevertheless, these differences decrease with increase of the precipitation threshold limits. It can be noted that similar investigations were also made by Ek and Cuenca (1994). Instead of precipitation, they tested the sensitivity of turbulent heat fluxes using USA soil parameter values. They found a more considerable sensitivity, which is not surprising seeing that the scatter of the USA soil parameter values is unequivocally larger than the scatter of the HU soil parameter values (see Fig. 2a and b).

4.2.8. Initialization effect of the soil moisture

Atmospheric forecasts are sensitive not only to the state of the soil-vegetation system but also to the initialization of soil moisture content Hu et al. (1999).

To date, the impact of these two factors upon atmospheric forecasts is investigated separately. However, the question could be posed, does sensitivity to the soil-vegetation system depend upon the initialization of soil moisture content. The answer is: in general no. This can be observed by taking a look at Fig. 10, which refers to the day 7th August 2006. Fig. 10a was obtained by using initial soil moisture content values which were originally taken from the ECMWF. This is referred to as 1 ini. In spite of this, Fig. 10b was obtained using initial soil moisture content values which were 20 % less than those originally used. This is referred to as 0.8 ini. The results are presented for all four runs together with the measurement results. Soil effect can be seen comparing precipitation between Run 1 and 2. Vegetation effect can be observed comparing precipitation between Run 1 and 4 on the one hand and between Run 1 and 3 on the other. Differences obtained between Run 1 and 2 equally exist for both the 1 and 0.8 ini conditions. The same is valid for the differences obtained between Run 1 and 4. Precipitation differences are, of course, not equally large for 1 and 0.8 ini conditions, but they do not vanish.

5. Discussion and conclusion

The impact of soil hydraulic parameter and vegetation parameterization changes upon the precipitation fields of storms was compared and analyzed. The analysis was performed using the simulation results of the Penn State-NCAR MM5 Modeling System on 18th April 2005 and 7th August 2006. On both days, the soil was wet.
The model was running for 30 h to ensure a 6 h spin-up time. In both cases, the model was started at 00 UTC. 24-hour accumulated precipitation fields were obtained from +6 and +30 h accumulated precipitation fields. The domain considered has $115 \times 49$ grid points. It covers the Carpathian Basin and some parts of Carpathian mountains (the

Fig. 10. a) Distribution of the 24-hour accumulated precipitation obtained using Run 1 (Hungarian soil data, original $F_{\text{max}}$ and $F_{\text{at}}$ parameterizations), Run 2 (USA soil data, original $F_{\text{max}}$ and $F_{\text{at}}$ parameterizations), Run 3 (Hungarian soil data, changed $F_{\text{max}}$ and original $F_{\text{at}}$ parameterizations) and Run 4 (Hungarian soil data, original $F_{\text{max}}$ and changed $F_{\text{at}}$ parameterizations) for different precipitation threshold limits on 7th August 2006. Threshold limits denote precipitation intervals from the threshold to its maximum value. The calculation was made for USA areal distribution of soil texture. The initial soil moisture content values are taken from ECMWF (identified as 1 ini). Fig. 10b: As in Fig. 10a, but initial soil moisture content values are 20 % less (identified as 0.8 ini).
coordinates of the domain’s lower left and upper right points are 45.6° N/15.6° E and 49.3° N/22.8° E, respectively). The precipitation fields were statistically analyzed in detail. First, the simulated and observed fields were compared. The observed fields were estimated from rain-gauge data applying the kriging interpolation technique. The agreement between simulated and observed fields was estimated using categorical and continuous verification indices. Significance tests were done to estimate how large (important) or small (unimportant) the obtained differences are. The precipitation fields were also visually examined (not presented) in the eastern part of Hungary, in the region between the Tisza river and the Hungarian/Romanian border where USA/HU soil parameter differences are the largest.

According to the results

- MM5 simulates in an acceptable manner the formation of precipitation in Hungary. For 18th April 2005, the TSS values obtained are about 0.3 on average, while for 7th August 2006 about 0.2. Note that the results presented in the contingency table for the August case (see Table 5) are very good.

- The sensitivity of precipitation fields to soil parameter changes is comparable to, and what is more, is as large as, the sensitivity of precipitation fields to the parameterization of stomatal functioning. The TSS differences obtained by soil parameter and stomatal functioning parameterization changes are significant on the 10% level. This is a little surprising because one would suppose that vegetation has a stronger forcing effect for severe convective storms than soil. The sensitivity observed (visual comparisons, not presented) is at the meso-γ scale (20–20 km) according to Orlanski (1975).

- The sensitivity of precipitation to soil parameter uncertainties in the HU soil dataset is not large, at least for the day proven. The largest deviations are about 10%.

- The sensitivity of precipitation fields to soil and vegetation effects does not depend upon the initialization of soil moisture.

- It should be noted that the highest sensitivity of precipitation fields to soil parameter changes is obtained (visual comparisons, not presented) in clay loam and clay areas. This result is in accordance with Mölders’s (2005) results, which came to the same conclusion independently doing Gaussian error propagation analysis using the MM5 modeling system with the HTSVS (Hydro-Thermodynamic Soil Vegetation Scheme) land-surface model.

According to our opinion, in the regional simulation of weather and climate events, local soil parameters should be preferred contrary to the common so-called “global” soil parameters that are used, for instance, Clapp and Hornberger’s (1978) parameters for the USA. This is especially valid for finer soil texture areas, which is independently confirmed not only by the meteorological (Mölders, 2005) but also from the soil physical (Hodnett and Tomassela, 2002; Acş and Drucea, 2003) aspect. A definite conclusion on the relative importance of soil parameter and stomatal functioning parameterization in the formation and evolution of storms cannot be drawn; further tests are needed.

These results obtained refer to only 2 days. The analyses should be extended using many more case studies.

Acknowledgements

The study is financially supported by the National Program for Research and Development (Project Number NKFP3-00022/2005).

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