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Numerical study of the effect of soil texture and land use distribution on the convective precipitation

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Abstract

In this study the Weather Research Model is used to analyse the sensitivity of convection to soil texture and land use distribution based on a heavy precipitation event. Both characteristics affect the latent heat flux and the near surface temperature distribution which are related to buoyancy. The model defaults Food and Agriculture Organization (FAO) soil texture and USGS (United States Geological Survey) land use have been replaced with more accurate databases in Hungary: soil texture based on the Digital Kreybig Soil Information System (DKSIS), land use based on the COoRdination of INformation on the Environment (CORINE). Regarding to soil texture the main changes are related on one hand to clay loam diversification to silty clay, loam, silty loam and sandy loam affecting area over 40 percent of Hungary, and on the other hand reclassification of sandy loam to sand. The difference between USGS and CORINE land use is sporadic, but significant. It is found that the diurnal latent heat flux is the highest at 12 UTC, at this peak the spatial average difference in latent heat flux is +6.5 W/m^2 and –4.3 W/m^2 with respect to soil texture and land use change, while the absolute differences range from –70 W/m^2 to +70 W/m^2 in all cases. As a result temperature at 2 m on average increased by 0.1 °C during soil texture and decreased by 0.15 °C during land use database comparison; the absolute differences are a magnitude higher. When comparing simulations regarding temperature at 2 m over main soil types and main land use categories results indicate –3 °C to +0.5 °C difference. It is found that the modification of both the soil texture and the land use have sometimes a compensating effect on latent heat flux and temperature change. Decrease in latent heat flux results an increase in buoyancy affecting convective precipitation. The formation of precipitation is also affected by large scale advection, therefore, no systematic changes can be seen on daily precipitation distribution. In spite of this, results indicate shifts in precipitation bands with about 30 km, and formation of new storm cells. Locally the replacement of soil texture and land use information to a more accurate one produced ±8 mm/day differences in precipitation.

Keywords: convective precipitation, soil texture, land use, numerical weather prediction

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Introduction

Land surface characteristics are playing an important role in the exchange of energy, water vapour and moment with the lower atmosphere. These exchange processes make the topic relevant also from a meteorological point of view and became increasingly important with the improvement of numerical weather prediction systems. The upward flux of water vapour – essentially the evapotranspiration – is affected by the vegetation and the available soil moisture. Relationships between the lower atmosphere and the soil moisture (Dickinson, R.E. 1984; Pielke, R.A. and Avissar, R. 1990), soil texture (Ek, M. and Cuenca, R.H. 1994; Alapaty, K. *et al.* 1997), soil parameters (Mölders, N. 2005; Breuer, H. *et al.* 2012), land surface heterogeneity (Avissar, R. and Liu, Y. 1996; Pielke, R.A. 2001) and vegetation (Pielke, R.A. *et al.* 1997; Adegoke, J.O. *et al.* 2007) have been extensively analysed in several aspects. Dry soils increase the sensible heat flux responsible for creating updrafts, while wet soils add moisture to the boundary layer (lower atmosphere) through evapotranspiration. Depending on the atmospheric conditions, the added moisture can either make the atmosphere more favourable for storms or more stable. These differences affect thermally driven local atmospheric circulations (Hong, X. *et al.* 1995) and convective precipitation formation (Teuling, A.J. *et al.* 2009).

The feedbacks between soil moisture and precipitation are controversial even in the case of measurements. Some studies have found that higher soil moisture increases the possibility of thunderstorm development by raising the convective available potential energy (CAPE) but the increased water vapour barely affects the convective inhibition (CIN) of the atmosphere (Pielke, R.A. and Zeng, Z. 1989; Eltahir, E.A. 1998). While others concluded that the increased vapour amount decreases the atmospheric temperatures creating greater inhibition (Taylor, C.M. and Ellis, R.J. 2006) resulting less precipitation. Taylor, C.M. *et al.* (2012) described even a higher precipitation formation over dry soils in the Sahel region. Depending on the geographical region, the effect of soil moisture can even negate the effect of atmospheric lower temperatures and higher moisture content. However, it has to be noted that through advection the precipitation occurrence is higher over dry soils when the wind transports additional atmospheric moisture from areas with greater evapotranspiration (deAngelis, A. *et al.* 2010).

Since soil moisture directly affects the water vapour flux to the atmosphere, and it depends on soil texture and land use, the spatial heterogeneity of soil texture and land use can significantly effects the precipitation. However, the joint analysis of both surface characteristics is rare. On climatological scale, the land cover change can affect the atmospheric circulation, especially in South-East Asia, North America and Europe, causing statistically significant changes in the regional distribution of temperature and precipitation without changing globally averaged temperature or rainfall (Chase, T.N. *et al.* 1996, 2000). Changes in either land use (Collow, T.W. *et al.* 2014) or soil texture (Khodayar, S. and Schädler, G. 2013) toward more realistic spatial distribution result more accurate surface heat fluxes and near surface temperatures. In turn, this has an effect on CAPE and convective precipitation formation.

It was shown that a more accurate soil texture distribution can improve the convective precipitation forecast (Breuer, H. 2012) and the effect of land use change has a notable effect as well (Drüszler, Á. 2011). To be able to improve model simulations, it is needed to examine the effect of the employment of different land use and soil texture distribution databases. In this preliminary study using WRF (Weather Research Forecast) model both the land use and the soil texture distribution are replaced with more accurate ones than the commonly used on the global scale. The aim is to assess the magnitude of the effects caused by both of the changes, and also to make a comparison to each other. Simulations are created for a single precipitation event, and are analysed discussing the surface characteristics/precipitation relationship.

Free convection

The atmospheric buoyancy is responsible for free convection, formed by the sun's shortwave radiation, which heats the land surface. The nearby atmospheric layers are warmed mostly by sensible heat flux. The warmer, ascending air is also controlled by the humidity and the thermal stratification of the atmosphere. When the ascending air is warmer than its surroundings the atmosphere is dynamically unstable (Horváth, Á. 2007). When the rising air contains enough moisture, condensation occurs, releasing latent heat of vaporization, lifting air mass higher.

There are different measures to estimate the instability of the atmosphere, like K-index, CAPE or CIN. CAPE (J/kg) is regarded as an indicator of the potential intensity of deep convection, and it is strongly controlled by the properties of the planetary boundary layer. CAPE is calculated from the temperature difference between the ascending air particle and its environment at each height level (e.g. model vertical levels) going from LFC (Level of Free convection) to EL (Equilibrium Level). LFC is the level, where the air particle becomes warmer than its surroundings for the first time, due to latent heat release. In the lower part of the atmosphere, under the LFC, the energy is negative as the particle requires this energy, named as the CIN. The CIN's value shows the atmospheric stability by giving the energy which must be overcome by the air particle to result convection. Neither the CAPE nor the CIN is a measure of possible precipitation, rather they express the potential possibility of free, non-forced (e.g. without the ascent forcing cold front) convective cloud forming if sufficient moisture is present in the atmosphere.

Model and its settings

The calculations were made with the WRF 3.4.1 model, developed by NCEP (National Centre for Environmental Prediction) and NCAR (National Centre of Atmospheric Research) (Skamarock, W.C. *et al*. 2008). This numerical weather prediction model system is a limited area, mesoscale, non-hydrostatical model, which is freely available on the internet, and for this study it was run on the Atlasz cluster of the Eötvös Loránd University. Spatial and temporal distribution settings can be varied in a wide range, the horizontal grid scale can be 1,000 km scaling down to 1 km. But with such fine resolution as a few kilometres, a nesting technique application is needed in the model area. This means the usage of several encompassing model domains with decreasing horizontal grid size in each nest.

In addition to calculating the hydro-thermodynamic equations governing the dynamics of the atmosphere, sub-grid processes (e.g. radiation-transmission, cumulus cloud convection, cloud microphysics, planetary boundary layer processes, soil-atmosphere interactions) were also calculated. The model uses terrain following, hydrostatic pressure vertical coordinate system and a staggered Lambert conformal horizontal grid.

The used nesting technique had an external model area with a 9 km horizontal resolution covering the Carpathian Basin, and a nested domain of 3 km covering Hungary (45.3°–49.8°N, 15.6°–23.6°E). For the simulations, 34 vertical levels were defined. The simulations were run by making changes to the WRF static data, such as soil texture and land use. The model reads the static data as binary files, which are used to create the model area. Four simulations were made: one using the original settings (FAO) soil texture and USGS land use (reference), the next by changing the soil type data (DKSIS) inside Hungary, another by modifying the land use cover (CORINE) and in the fourth applying both of the changed datasets (DKSIS&CORINE).

Meteorological initial and boundary conditions for the simulations were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) model which has a horizontal resolution of 15′ (approx. 25 km). From the available model levels only the lowest 12 standard pressure levels were selected for initialization, boundary conditions were updated in every 3 hours. These files contain the horizontal and vertical wind components, specific and relative humidity, dew point, geopotential height, surface temperature and pressure. Soil moisture and temperature is available in four layers.

Surface and soil data

Figure 1 shows the soil types over the model area based on the FAO database. The DKSIS database (Szabó, J. *et al.* 2000; Pásztor, L. *et al.* 2010) *(Figure 2)* over Hungary was also used in performing simulations, while outside the country no changes were made in the FAO distribution. In both cases the dominant soil texture of the model area is loam and its variants.

The most prominent difference is the appearance of sand in the Danube–Tisza Interfluve, and at the eastern part of the country. Most of the clay loam disappears, resulting in an about 45 percent reduction when changing from FAO to DKSIS. In the new distribution, silt and its variants appear to be scattered over Hungary. The used land use database was the USGS *(Figure 3)* and the CORINE 2000 (European Environmental Agency, 2002) *(Figure 4)*. The previous one was determined using AVHRR measurements in 1992–1993, while the latter one by using Landsat-7 imagery in 2000.

In the WRF model the USGS land use is available at a 0.5°, while the CORINE was implemented at a 30″ horizontal resolution. According to USGS, two-thirds of the investigated area is "dryland cropland and pasture" and this suffers the greatest change, around 10 percent, when the USGS is replaced by CORINE. Areas occupied by deciduous broadleaf forests appear mostly on mountain ridges. The previously scattered cropland/woodland areas disappear almost entirely within the

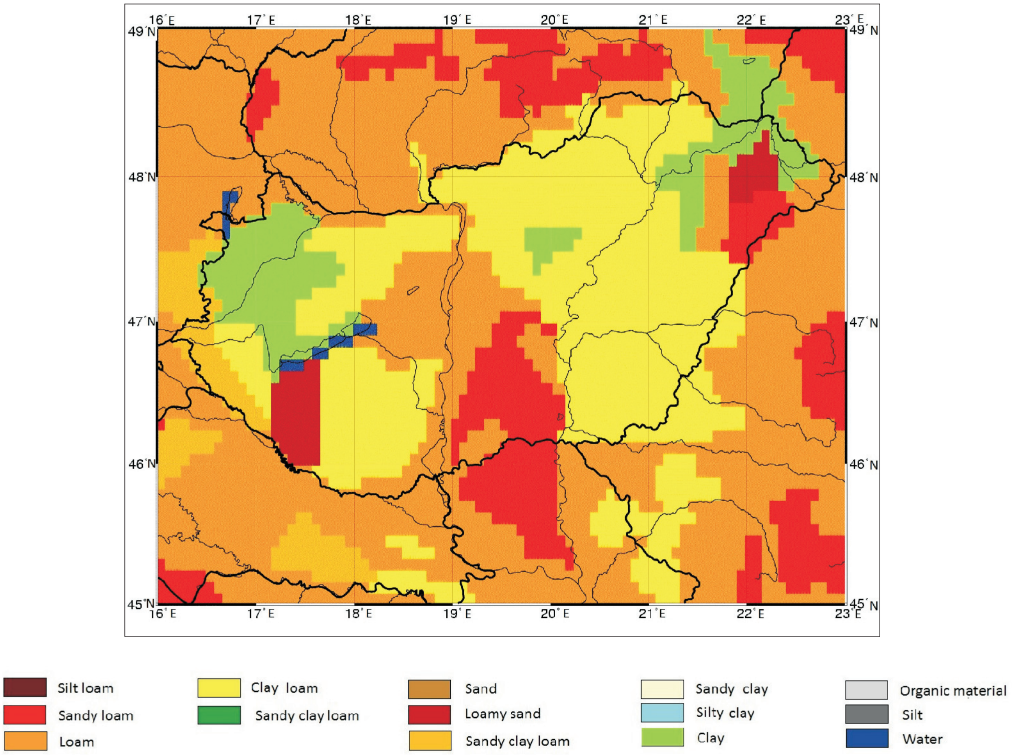

Fig. 1. Soil type over the model area based on FAO database

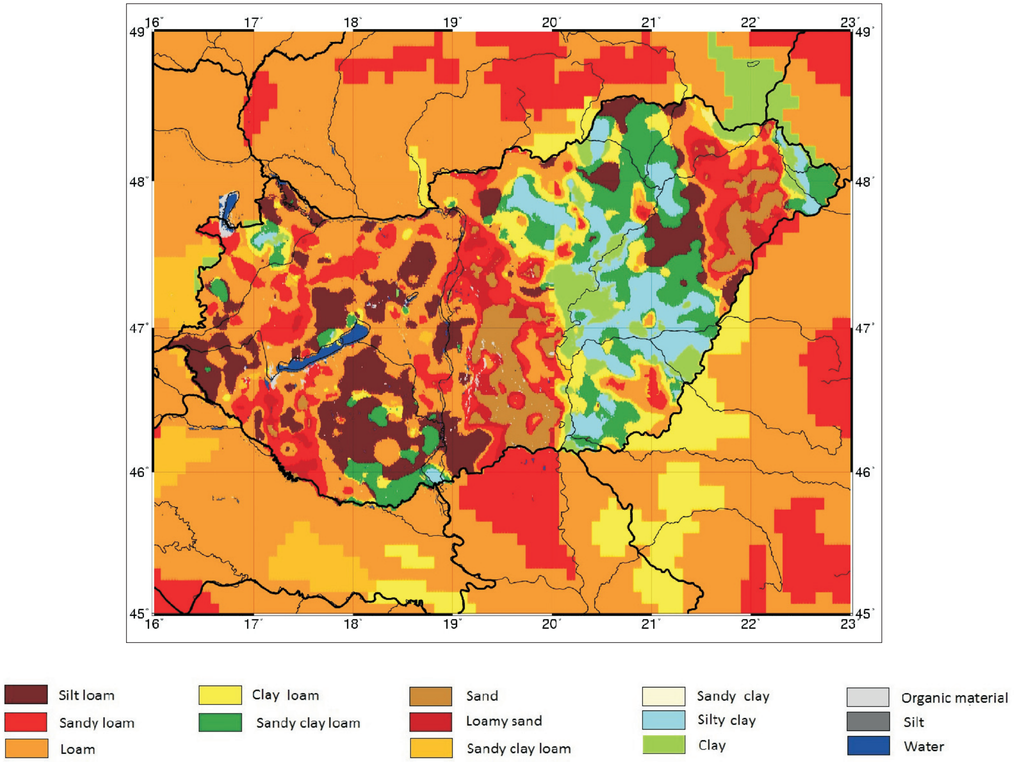

Fig. 2. Soil type over the model area based on DKSIS database in Hungary. Outside the country FAO database is used

country borders. The grass- and shrublands are more apparent in *Figure 4*. The ratio of urban and built-in land areas increased as well as the area of larger cities, such as Budapest and Bratislava, has become more visible. The size of water-covered areas is constant.

Weather

The convective precipitation was examined for 20 August 2006, when all weather conditions were favourable for its formation. The weather in Europe had been influenced by a large, well-developed cyclone, whose cold front has reached Hungary. The convective instability was further increased by the 25 m/s wind and the cold advection at the 500 hPa level. Above the Carpathian Basin a jet stream was flowing. The thunderstorm line has reached the Carpathian Basin in the late afternoon. The cold front reached Hungary at 16 UTC (Coordinated Universal Time) and has left it by 00 UTC on 21 August. Precipitation occurred in the northern part of the country, and local showers occurred Southeast. The majority of the precipitation occurred in the Northwest, the highest measured precipitation in Hungary was 17 mm at Kapuvár. The maximum temperature in Hungary was between 28 °C (North-Northwest) and 34 °C (Southeast) (Horváth, Á. 2006).

Results: temperature, latent heat flux

By changing soil texture map without changing meteorological (initial and boundary) conditions, the water holding capacity will also change, which defines the rate of evapotranspiration. Land use change results changes in the minimum stomatal resist-

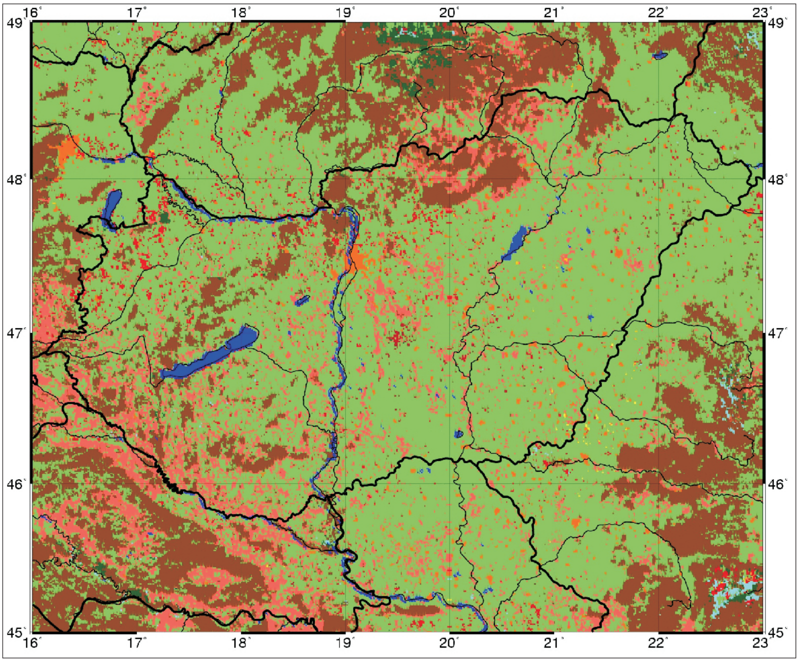

Fig. 3. Land use cover over Hungary based on USGS database

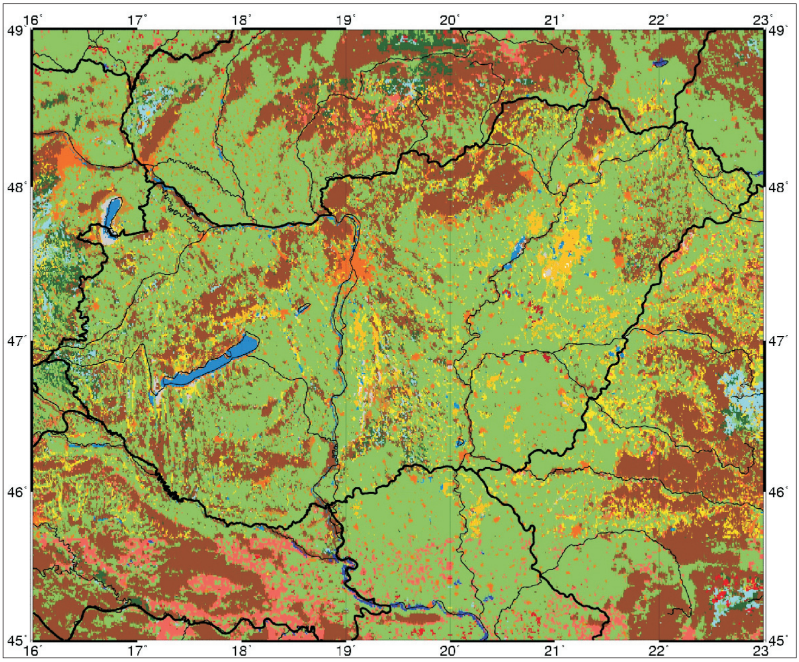

Fig. 4. Land use cover over Hungary based on CORINE database

ance also affecting the evapotranspiration. Furthermore changes in surface affect the albedo. These effects have an impact on near surface temperatures and atmospheric moisture content.

Both temperature and latent heat flux reach their daily maximum in the early afternoon, first the latent heat, then approximately an hour later the temperature caused by turbulent mixing. *Figure 5* shows latent heat flux (LH) and 2 m temperature (T2) differences between simulations obtained at 12 UTC, when the T2 changed from 28 °C to 34 °C over flat terrain, and the LH was between 200 W/m^2 and 360 W/m^2.

After changing soil type, the LH increased by 6.5 W/m^2 in spatial average *(Figure 5,* a*).* The T2 changed inversely with an average of 0.12 °C *(Figure 5,* b*).* Daytime average change was +3.48 W/m^2 and 0.1 °C, respectively. At the Danube–Tisza Interfluve, at the Small Plain (Kisalföld) and at Nyírség area the latent heat values increased. The cause of this is that the hydraulic properties of soils altered resulting in a decreased ability to hold moisture and therefore prompting an intensified evaporation. At the Kisalföld, clay has been modified to sandy loam or loam, while at Kiskunság sandy loam altered to sand. Over these areas the LH had increased by 20–40 W/m^2. In opposition to this, there was an observed decrease of 10 W/m^2 at Körös region due to more moisture being able to remain in the soil. Evaporation distracts heat from its surroundings leading to cooling, as it was seen at Kiskunság where the T2 change was approximately 1°C.

Areas outside Hungary, where the soil texture is unchanged, differences were caused by advection and especially North to Hungary this had an effect on cumulus cloud formation over the mountains resulting great differences in LH.

After switching the land use cover *(Figure 5,* c, d*),* warming of the model area by an average of 0.15 °C, and an approximate of 8 W/m^2 decrease in the LH was observed (daytime averages: +0.12 °C, –4.3 W/m^2). Following the modification North to Lake Balaton, the broadleaf forest coverage increased, which caused a decrease in evaporation and in LH, mainly causing the increasing of the minimum stomatal resistance from 40 s/m to 100 s/m and the decrease of radiation stress function coefficient from 100 to 30. These areas show a decrease in the LH as indicated by red and orange dots.

At the Danube–Tisza Interfluve the T2 rose since the albedo decreased and the minimum stomatal resistance became stronger. The effect of the built-in areas reached its maximum at the early evening, when the T2 was 2.5–3 °C higher and the LH was 60–70 W/m^2 lower than the reference. The modification of soil types affected the results more than changes in the land use cover especially over areas where sandy texture replaced loam or clay. All four simulations show that the location of the changes moved slightly to the East because of the daylong westerly winds at the Hungarian Great Plain (Alföld), while these relocations shifted south at the northern parts of the country due to strong northerly winds.

Model used 12 different soil texture and 16 land use categories appearing in Hungary during calculations. In order to make the comparison, simpler groups of land use and soil texture with similar physical properties were created *(Table 1.* and *2*).

In each case, the altered land use was compared to the reference, shown in *Figures 6.* and *7.* By changing sand and its variants, a warming was caused (average 0.5 °C, max. 2 °C) before sunrise and after the arrival of the front. The initial amount of soil moisture during the simulations remained the same, thus by replacing e.g. loam with sand the available soil moisture increased. Due to the increment of water resources, a more intensive evaporation was caused and therefore a slight (approx. 0.4 °C average) cooling during the day.

Table 1. Created groups of soil type categories

Sand	Loam	Clay
Sand Sandy clay loam	Silt loam Loam Loamy sand Sandy loam	Clay Silty clay Clay loam Sandy clay loam

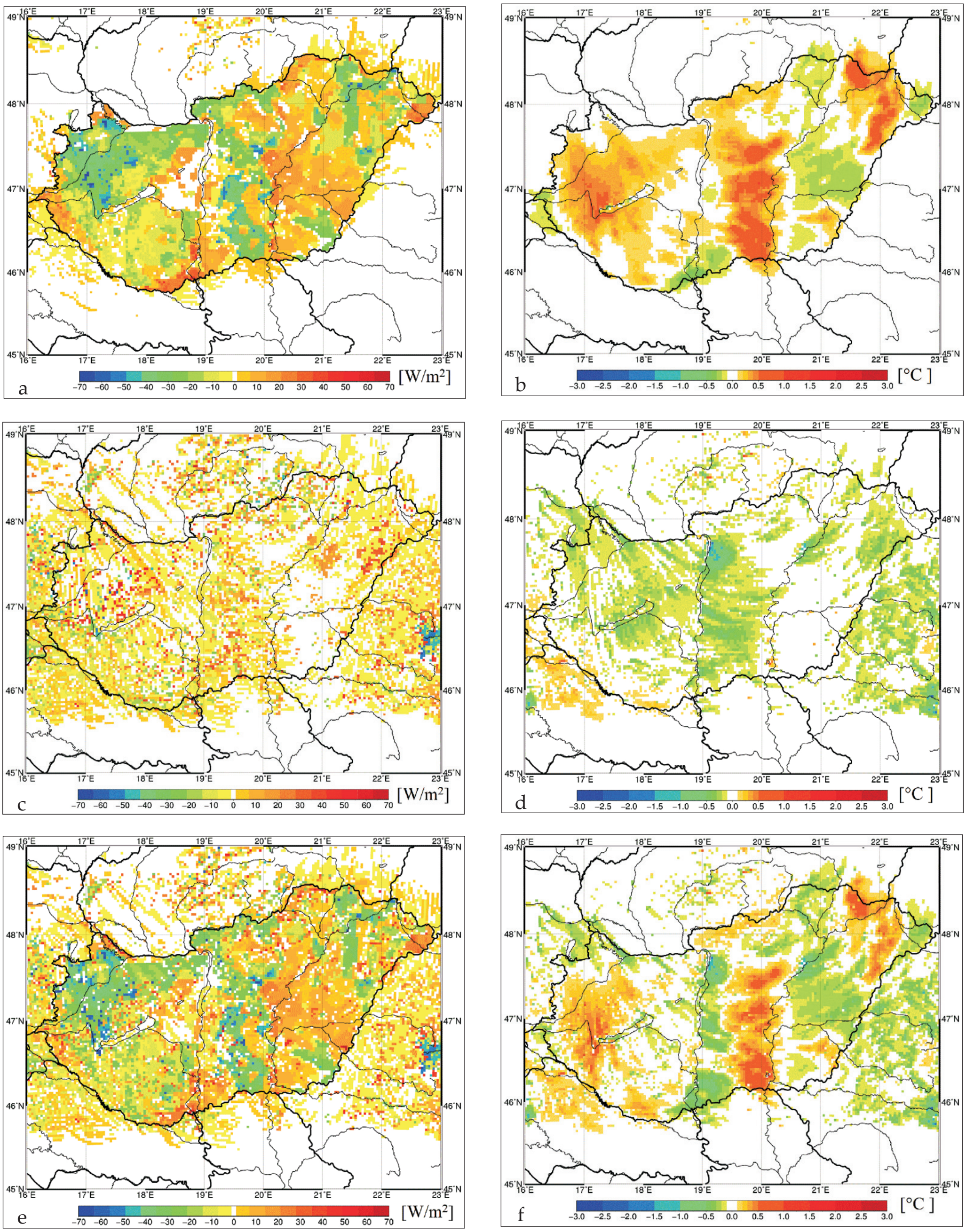

Fig. 5. Latent heat flux and 2 m temperature difference between REF-DKSIS (a, b), REF-CORINE (c, d) and REF-DKSIS&CORINE (e, f) simulations on 20th August 2006 at 12 UTC

the entire day, there was less intensive evaporation over the appearing grass vegetation type resulting in surface air warming with maximum at approximately 2 °C. In the case of the forested areas a difference of 0.5–1 °C can be observed.

Table 2. Created groups of land use categories

Urban, built-up area	Woodland	Shrubland	Grassland
Urban and built-up land	Deciduous broadleaf forest Evergreen needle leaf forest Mixed forest Wooded wetland	Shrubland Mixed shrubland/ grassland	Dryland, cropland and pasture Irrigated cropland and pasture Cropland/grassland mosaic Cropland/woodland mosaic Grassland

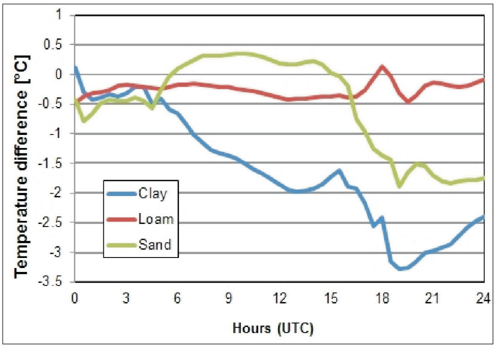

Fig. 6. 2 m temperature difference between reference and DKSIS in the case of combined soil textures on 20th August 2006

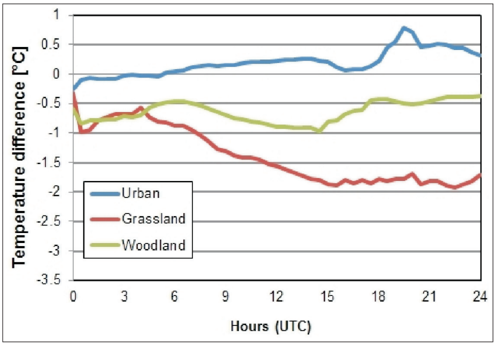

Fig. 7. 2 m temperature difference between reference and CORINE in the case of combined vegetation types on 20th August 2006

The steep change at around 16 UTC denotes the arrival of the cold front. At the loam categories no significant temperature difference was observed (avg. –0.3 °C), because the spatial ratio and distribution of this type remained approximately constant. The clay type had the biggest impact on the temperature with an average 3 °C warming. During

Convective Available Potential Energy (CAPE)

Convective Available Potential Energy is used to estimate the instability of the atmosphere through temperature and humidity of the atmosphere, which is partly controlled by the land surface. *Figure 8* shows the CAPE values at 12 UTC. The calculated values were 0–750/2,000 J/kg. The drier and colder air mass preceding the front had a CAPE of 0 J/kg (stable stratification, less possibility of storm). As the figures show, the CAPE has increased for DKSIS simulation, while the area by stable stratified air mass has decreased for CORINE.

Prior to the front's passage through the country, the DKSIS values were by 60–80 J/kg greater than the reference, while the CORINE's values remained below the reference by 120–160 J/kg. In the case of CORINE, the changes are consistent throughout the entire country, contrary to DKSIS, which concentrates on the sites of modification similarly to *Figure 5*, b. Due to wind the difference formed in band shapes. In the case of the DKSIS&CORINE simulation the absolute values of the changes did not exceed the maxima of the previous simulation differences, which was 240 J/kg. At some areas soil texture had a more significant effect on CAPE. At some parts of the model area, the processes of the two simulations amplified each other's effect.

The convective inhibition changed parallel as CAPE, the increasing latent heat resulting greater values of CIN. At around noon, the average values of CIN reached in absolute terms 60 J/kg. At the western part of the model area the inhibition was smaller, thus less CAPE was enough to form convective cloudi-

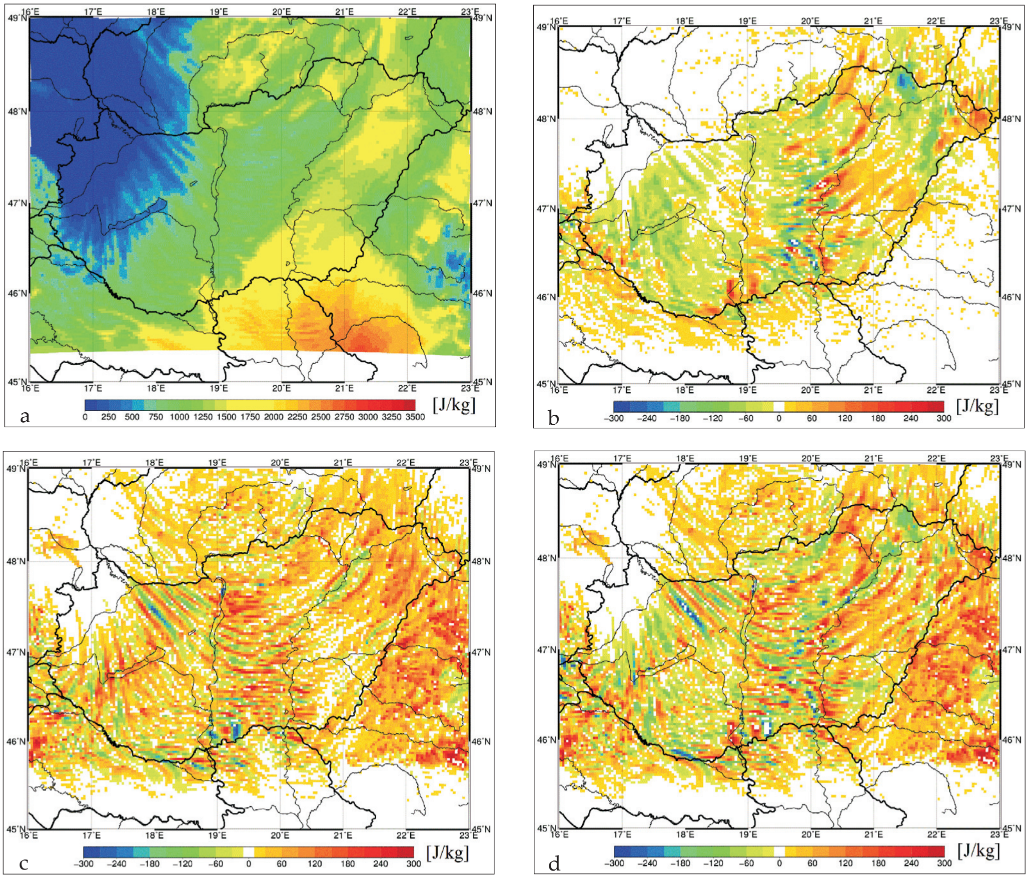

Fig. 8. Convective available potential energy CAPE (J/kg) for reference run (a), CAPE difference between REF-DKSIS (b), CAPE difference between REF-CORINE (c), and CAPE difference between REF-DKSIS&CORINE (d) at 12 UTC on 20th August 2006

ness. On the other part of the country the modification resulted greater CIN in each simulation. In case of breakthrough of CIN, stronger thunderstorms and precipitation may occur, when the CAPE's value is sufficiently large. That process has been observed at the central area, while CIN increased by 20–40 J/kg.

Precipitation *Figure 9* (a) shows the 24-hour accumulated precipitation. In the western parts of the country, there is a smaller deviation between the simulation and the actual measurements (not shown), however, East of the Danube these differences became larger, and translocated cells can be observed by the Northeast border. Southern part of the Alföld measurements showed the development of local convective systems, which didn't appear on the simulation even though the amount of CAPE would have allowed the formation.

24-hour accumulated precipitation was 8.75 mm on average-based on the reference simulation. The DKSIS simulation positively deviated from that value by 0.30 percent (*Figure 9*, b), while the DKSIS&CORINE (*Figure 9*, d) predicted a value 1.56 percent lower. The modification of land use cover (CORINE) caused a temperature increase resulting in higher vertical velocities leading to an overall 1.70 percent increase of precipitation (*Figure 9*, c) compared to the reference. Though this difference is neg-

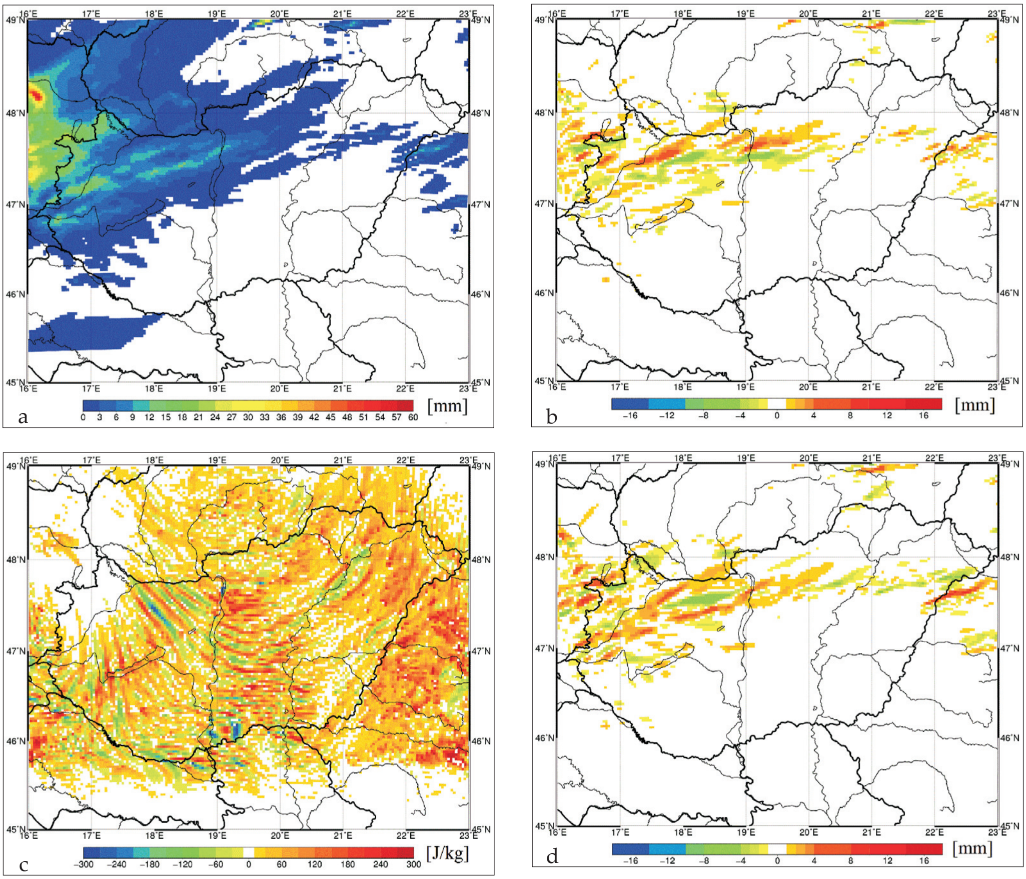

Fig. 9. 24-hour accumulated precipitation (PREC) reference run (a), PREC difference between REF-DKSIS (b), PREC difference between REF-CORINE (c) and PREC difference between REF-DKSIS&CORINE (d) on 20th August 2006

ligible, the migration of the precipitation band was faster with 30 minutes, leading to an East-west directional shift. Similar shift was noticeable in case of soil texture modification but it was in the North–South direction.

As it could be seen on accumulated precipitation differences, even if the total precipitation does not change significantly in the whole domain, locally ±8 mm/day changes can be seen which reaches 50 percent difference. These are usually related to a shift in precipitation cells with about 30 km; in most cases new precipitation cells appeared which weren't present in the reference run (e.g. northern border of the Alföld in *Figure 9*, d).

Conclusions

This study examined the effect of the land use cover and soil texture distribution change on convective precipitation, and on alterations in state variables affecting that. In the four simulations, the boundary conditions of the model area were modified. The evaluated data relates to the Hungarian land area over a 24-hour time period. In regard to the examined variables, the differences, in comparison to the reference, were larger in the case of the DKSIS than for the CORINE simulation.

At the middle of the day, the absolute values of the differences in latent heat for the DKSIS were mostly close to 25–50 W/m^2, while for the change to CORINE they were around 15–25 W/m^2. Furthermore it has to be noted, that the DKSIS simulation was characterized by both a latent heat flux decrease and increase, while the CORINE simulation showed only decrease in latent heat flux over the model area. Simultaneously, the latent heat excess, a decrease in temperature was observed, resulting in an average of 0.5 °C temperature difference between the two simulations.

The combined effect of soil texture and land use change negated each other over some areas, but where the soil became more saturated the effect of soil texture change was dominant. For CAPE values a similar tendency could be observed. The CAPE values were 50–60 J/kg greater in the case of the soil texture modification than for the altered land use cover due to the latent heat difference. Considering precipitation there were no significant alterations in the 24-hour accumulated precipitation over the whole model area. However, the location of storm cells with the highest intensity shifted toward south in case of soil texture change, and an East–West horizontal tilt and shift was observable in case of land use change. As a result locally ±8 mm/day precipitation differences occurred. Also mostly in the case of land use change, new cells formed as a result of higher temperatures.

It can be stated that even though this weather event and the related precipitation was mainly related to cold front passage, the effect of switching to a more realistic soil texture and land use distribution is not negligible, not only for near surface temperatures but also for precipitation forecast. To determine whether the realistic distribution results more accurate forecast further analyses, using radar precipitation verification are needed.

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