Closing report of the research program entitled: „The role of soil in different weather situations”

Regarding the original research plan the Mid-Nyírség test area was changed to the lowland area with the center of Observatory of Szeged. The reason of the change was to get measured PBL-heights data with higher reliability for the area. Soils of the Szeged test area is formed from loam texture chernozems with a sharp NW – SE boundary to sandy soils about 3.5 km from the Observatory in West direction. As it was planned 5 agricultural areas were selected for continuous soil moisture monitoring. Each selected sites were sampled for determining soil particle-size distribution, humus content, and hydro-physical properties as water retention (WR), hydraulic conductivity (HC). The soil properties were determined for top soil and sub soil layers. When the importance of soil temperature profiles in 30, 60, 90 cm depths as starting values of modelling turned out temperature monitoring of the five sites was also done in 2013. When it turned out that rather small and homogeneous agricultural fields will be the monitored areas we applied the conventional soil sampling instead of the 30-50 random collected samples of the research plan designed for the Nyírség test area.

It has been established that the parameter values calculated from the HUNSODA and USDA soil databases differ significantly. Soils described by the HUNSODA have 55mm/m higher available water storage than that of the USDA ones. Both the saturated soil moisture content (SMC) and the FC is higher (30-170mm/m) for other soil texture categories. Campbell’s soil porosity index of the USDA clay category soils is high (≈10-12) while in the HUNSODA soil’s it’s almost halve of that (≈5-6).

The effect of soil especially of its hydro-physical properties as water retention (WR) and hydraulic conductivity (HC) on precipitation amount had been analyzed. Calculations were made with the MM5 numerical weather prediction system on the 3700b supercomputer of the Hungarian Meteorological Service (HMS). The horizontal resolution of simulations was 6x6 km. The model area incorporated the Carpathian Basin. The area consisted from 49x115 horizontal grid cells. Model simulations started at 00 UTC (Coordinated Universal Time) and lasted for 30 hours. We compared precipitation spatial distributions calculated with soil parameter values estimated from the USDA (American) and HUNSODA (Hungarian) soil databases. Precipitation field’s sensitivity to field capacity (FC), wilting point (WP) and to the distribution of soil moisture content in a grid cell had also been analyzed. The simulated precipitation distribution was compared to one measured by the HMS. For proper comparison both measured and simulated precipitations have been interpolated to an 18x18 km grid. The comparison was based on the ETS (Equitable Threat Score) (Nurmi, 2003) verification index. This index was calculated to several precipitation amounts. The significance was defined with the non-parametric Spearman correlation.

It was established that simulated convective precipitation distributions didn’t showed any systematic difference to soil parameter values estimated from the USDA and HUNSODA databases. The amount of precipitation for the whole domain changed insignificantly. However the precipitation paths showed about 50 km shifting, caused by the changed surface energy budget. This resulted approx. ± 30 $mm \cdot day^{-1}$ difference in precipitation locally. The differences in soil parameter values resulted a 25% change in the ETS scores. From the hydro-physical soil properties the wilting point (WP) proved to be the most, and the field capacity (FC) the least significant. Difference between the simulated and measured precipitation fields were significant at p=0.02. Depending on its value the ETS changed about 20%. The measured and simulated precipitation difference was significant as well at p=0.11 level. (Breuer et al., 2011c, Breuer, 2012). Shifting of precipitation zones was detected when total or the relative available soil water content was changed as it was published by Pan et al. (1996).

These investigations were expanded to 16 days for studying sensitivities to initial soil moisture amount, differences in soil parameter's areal variation, convective cloud development, planetary boundary layer parameterization, and also to vegetation parameters (e.g. leaf area index, minimal stomatal resistance). Effect of vegetation on the convective precipitation was also demonstrable. In some cases vegetation effect was higher than those resulted from soil parameter values estimated from different soil databases. In these modeling studies vegetation parameters were changed more drastically than it is in the normal practice (Breuer, 2012).

The soil properties can be ordered by their effects on the simulation results. Difference caused by the soil database was even greater than the effect of soil texture spatial distribution, coming in second place. This was followed by the effect of wilting point and field capacity. The smallest sensitivity related to the soil parameter distribution in a modeled grid cell (Breuer et al., 2011c; Breuer, 2012).

In soil physics (Schaap and Leij, 1998; Pachepsky and Rawls, 1999) it is known that better results can be achieved using a local soil database than a global one. In meteorological applications regarding to precipitation verification we came to the same conclusion. The simulated precipitation based on the soil textural distribution valid for Hungary, and soil hydro-physical parameter values estimated from Hungarian soil database showed significantly better agreement with measurements, than using the global (FAO and USDA) ones (Breuer, 2012).

Analyzing of planetary boundary layer (PBL) and the effect of soil hydro-physical properties, the sensitivity was investigated with both the MM5 and WRF models. Since 2011 the initially used MM5 model was switched to the WRF (Weather Forecast Research) model, which is recent and performs stable simulations in greater resolutions. When the sensitivity to different soil parameters are analyzed – for all model simulations -, the significance of difference is estimated taking the diurnal course of the meteorological parameter (e.g. PBL height, sensible heat flux) detrending it and afterwards treating it as an autoregressive process (Breuer et al. 2012a, b).

Simulations created with the MM5 included 6 case studies, where the spatial resolution of the model was 6 km. Regardless of the chosen PBL scheme (Janjic Eta-PBL (Janjic, 2002), MRF (Medium Range Forecast) (Hong and Pan, 1996)), radiation transfer calculation method or initial soil moisture content, the PBL height was significantly ($p < 0.01$) different in simulations where the USDA based soil parameters were changed to HUNSODA based ones. The differences occurred over soil textures (clay loam and clay) which showed higher differences in soil parameters. These analyses also showed that the energy budget affecting the PBL height is more dependent on the relative available soil moisture content than on actual soil moisture content. This means that the importance of FC and WP is higher than in the case of convective precipitation (Breuer et al. 2012a, b).

The analysis of the MM5 simulations was supplemented by a mixing diagram method (Betts, 1992; Santanello et al., 2009). This analysis showed that twice as much the surface sensible heat is determining the PBL height than the sensible heat mixing from the free atmosphere into the PBL. Drying effect of the free atmosphere in case of the HUNSODA origin soil parameter values was greater (Breuer et al., 2011b).

Using the Hungarian MARTHA soil physical database (Makó et al., 2012), new soil parameters values were calculated used in WRF simulations. The FC and WP values were higher for the HUNSODA based parameters than for the MARTHA based ones. Their differences cause less latent heat and higher surface temperature increasing the PBL height.

The comparison of soil parameters calculated from HUNSODA and MARTHA databases included WRF simulation with high horizontal resolution (3 km and 1 km) of 2 days, and WRF simulations with a coarser, 7.5 km grid for 31 consecutive days in August 2011. In both batch of simulations not only the sensitivity of PBL height but the sensitivity of sensible heat flux, latent heat flux and 2 m temperature were also investigated. Also PBL height were determined from windprofiler and radiometer measured data of the Observatory of Szeged which can be compared to simulations.

In all cases above cities and lakes there weren't notable diurnal PBL-H course, therefore for simulated grid cells the significance method was not applicable. Altogether it can be said that the differences in latent heat flux aren't showing a relation to the PBL-H differences. Significant sensible heat flux differences can found in about 80% of the grid points, while significant differences in PBL-H in about 65% (Breuer et al., 2011a, 2012c). The areas of significant differences are corresponding to soil textures. Over soil textures where there is a small amount of change between soil databases there are less cases for significant differences. E.g. from 31 days over loam texture soil 22-28, over clay loam texture soil 25-31 days differed significantly when considering PBL-H. The greatest differences on average were about 1.5°C for the daily average air temperature and about 300 m for the PBL height (Laza, 2012).

The comparison of PBL-H measurements to model simulations is not as exact as in case of precipitation. Several evaluation methods exists for determination of the PBL height. About 15 was tested for the available measured data, but only 6 were found to be useful. From the 6 applicable methods the potential temperature gradient and Ri number ones gave acceptable maximum PBL heights, between 1100-1600 m. (Laza, 2012). The usually applied particle method gave far higher PBL values. For the high resolution simulation the differences between simulations and measurements were about 500 m for both studies during the PBL maxima (Breuer et al., 2012c). For the coarser resolution model runs some model simulated values (temperature, air humidity, horizontal wind speed and direction) were compared to the daytime measurements (radiometer and windprofiler) at Szeged. The model showed considerably different wind speed related to the north-south wind speed component. Applying the method used in the measured data evaluation for the WRF simulations the PBL heights were on average about 300-400 m higher. The simulated PBL heights over 2000 m were significantly greater than the ones determined from measurements. Comparing simulated and modeled PBL heights, the potential temperature gradient based method proved to be the best. In the afternoon simulations and measurements differed about 50-100 m. However in the morning, the modeled values showed a fast increase which isn't found in measurements. The difference averaged of 200-400 m (Laza, 2012).

The HUNSODA defined soils have generally lower available soil moisture amount than that of the MARTHA. As such the PBL heights indicated a dryer environment; the PBL heights were 50 m higher in average for the HUNSODA. This difference is less than the average PBL height caused by its determination method. Consequently, the PBL height estimation is more method than soil database dependent. Still these results also suggest that the PBL processes are sensitive to the soil parameters values (Breuer et al., 2012c, Laza, 2012).

The simulations for the whole month of August have also been subjected to a principal component analysis. The PBL height evolution during the day can be divided into a build-up (6-12 UTC) and a collapse (14-17 UTC) phase. When the whole daytime period is considered the principal component is the 2 m temperature (19%) for the build-up and the vertical gradient of temperature in the lowest 150 m (25%). In the collapsing phase it is the wind shear near the PBL height (20%). The secondary component is the water vapor amount at the top of the PBL (12%), the latent heat flux (11%) and the vertical gradient of temperature in the lowest 150 m (13%). The third component isn't determined because it only explains 2-7% of the PBL height diurnal course. The complexity of the PBL evolution is described well by the fact that for accounting 80% of PBL variations about 25 variables are needed. Since both 2 m air temperature, the latent heat flux and vertical gradient in the lowest atmosphere depends highly on the surface and soil properties their determination is important in PBL investigations (Breuer et al., 2012d).

The diurnal variation of the PBL height was investigated with the WRF-SCM[Rev21] (Single Column Model) model. For this analysis the average on a dry, 3 months long period was considered. The main results are as follows: 1. around noon time the simulated PBL heights (2400-3000 m) are generally higher, than the observation determined ones (1300-2000m); 2. around noon time the variation (approx. 700 m) of the methods used to calculate the measured PBL height is comparable to variations of the simulated PBL heights with different PBL schemes. The found difference comes from the different measured and simulated atmospheric profiles (Breuer et al., 2013b; Breuer et al., 2014). It also has to noted that simulations were created for different cultivations. During the analyzed period the soil moisture content was usually below the WP. When a small amount precipitation increased the soil moisture over WP, about 500 m differences in PBL-H were found for different cultivations.

These investigations lead to not only to soil but to surface analyses as well. Effects of soil texture and landuse spatial distribution were analyzed. High resolution (3x3 km) WRF simulations were made for convective precipitation (four 24 hour long) simulations. The incorporated FAO texture distribution in the WRF model was changed to the DKSIS (Digital Kreybig Soil Information System), and the USGS land use built system was replaced with the CORINE (COoRdination of INformation on Environment) one for Hungary

The effect of soil texture change on model results was greater than the land use change. In the latent heat this difference was almost twice as much on average due to soil texture change (20-50 W/m^2), than for land use change (15-25 W/m^2). The latent heat surplus in the DKSIS simulation compared to FAO one the temperature was lower. Large differences in latent heat and the lower temperature is corresponded. The temperature difference was around 0.5°C. The surface heat surplus have a great role in the CAPE (convective available potential energy) describing the atmospheric instability, and effecting cloud development. The latent heat surplus in the DKSIS simulation resulted 50-60 J/kg higher CAPE. Compared to the effect of soil texture change in a large area, the land use change effect was more equalized. Based on model simulations there wasn't significant difference in accumulated precipitation over the model area. Differences were more local, especially over Hungary where the changes were made (Göndöcs, 2013).

For comparing the MM5/WRF model results to measured meteorological variables the models used Noah surface scheme. The Noah model by itself can simulate soil moisture and temperature from atmospheric variables and initial soil conditions. The sensitivity to vegetation parameter values was investigated with it as well for different soil textures. From land use types the agricultural land, shrub land, deciduous and evergreen forests were considered. The greatest differences between these land-use/vegetation types were found in the evapotranspiration and soil moisture content. The minimal stomatal conductance had the greatest effect from the parameter values, but leaf area index (LAI) and optimum temperature were also important. The modelled vegetation types differed 50-100 W/m^2 of the latent heat. Comparison of model simulated and measured soil moisture contents haven't been done, since in 2012 there were several local showers only at one monitored site at a time, which are not in the meteorological data of the HMS Observatory. These small showers affected the soil moisture contents significantly, which caused incomparable differences in model results (Forgács, 2014).

Effect of surface cover on the PBL height was studied with the WRF model. In these studies shallow convection was dominant as a result of a high pressure system. In the comparisons the model area was characterized with only one land use at a time, to filter out the inhomogeneity of spatial distribution. The reference simulation was created with USGS land use distribution and FAO soil texture. In the simulations sand and clay soil texture types, agricultural lands and deciduous forests land use types were applied. The plant available soil moisture amount affects the distribution of latent and sensible heat. Change of the land use causes not only physical (albedo, roughness) but ecophysical (e.g. minimal stomatal resistance) changes, which also affect the surface energy balance. Over the cloudless areas the texture can cause about 500-1000 m and the land use can cause about 300-600 m differences in the maximum of PBL height. The SNR (Signal to Noise Ratio) and parcel methods calculated PBL-H diurnal course showed significant difference ranging between -1000 and 1500 m. The parcel method and the WRF simulated PBL height diurnal course difference was considerably smaller. Averaged over space and time, the PBL heights between 11-15 h showed greater differences for single changes than for accumulated ones. The greatest difference (494 m) caused the soil texture change to clay. Similar great differences occurred for single land use changes e.g. forest to grass. In most of the cases the PBL height diurnal course are significantly different. However, the variation of PBL heights is greater for the validation dataset than for any of the simulated ones (Ács et al., 2013, Ács et al., 2014).

The soil moisture content measured at the five locations near to Szeged at 10-40 cm depth are considerably less (on average 0.1 m^3/m^3) than the down scaled initial values of the model (Fig. 1). The precipitation in autumn 2012 only appears in the upper 10 cm layer of soil in the simulation. In modelling the initial conditions refer to a 7.5x7.5 km grid in which the measurements took place from July 4, 2012 to October 8, 2012. The WRF model simulations used the measured soil moisture data as initial conditions. In 2012 year the soil moisture content was below wilting point according to the measurements. In the WRF database at this grid point the soil texture is loamy sand which could allow lower soil moisture content since its wilting point value is 0.047 m^3/m^3.

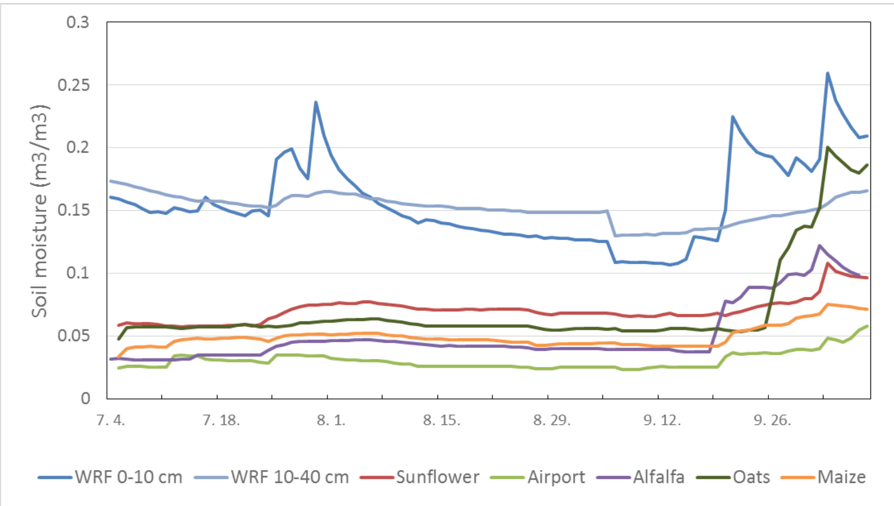

Fig 1: Measured and model initial soil moisture during the measurement period in 2012. The measurements refer to 10-40 cm depth.

The WRF model initial conditions for soil moisture in 2013 showed a better representation compared to the measurements. This year the average difference of measured and model generated soil moisture contents was still 0.05 m^3/m^3.

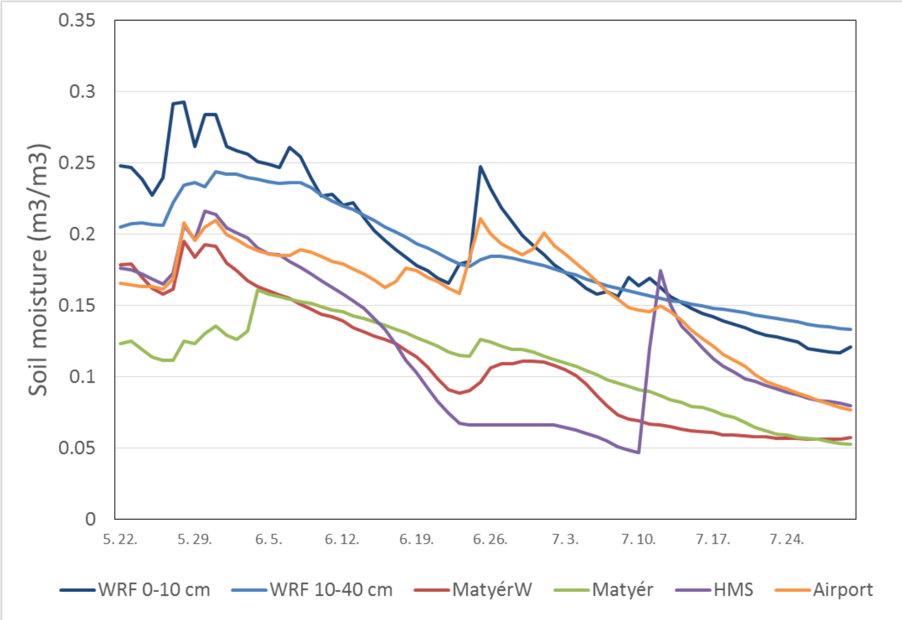

Fig. 2: Measured and model initial soil moisture during the measurement period in 2013. The measurements refer to 10-40 cm depth.

The temperature in the upper soil level (0-10 cm) of the model shows a good relationship with the ones measured at 30 cm depth in the beginning of the 2013 measurement period, especially with the ones close to the HMS observatory and at the airport. However in the 10-40 cm model layer the temperature is lower on average with 4-7°C than measured ones. This is resulted by on one hand from the difference in soil moisture content and on the other hand it allows the conclusion that the soil thermal conductivity in the model giving the initial and boundary conditions is wrong despite that the same Noah model is used in the MM5 and WRF models (Ács et al., 2014).

The main objective of the OTKA K81432 project was to analyze the effect of soil on convective precipitation and planetary boundary layer. The analyses were primarily planned with numerical simulations since most of the meteorological processes cannot be measured in adequate spatial density.

The soil affects the atmospheric processes mainly through evapotranspiration. Most of the sunshine originated available energy at the surface is partitioned to evaporation (latent heat) and heating (sensible heat). The ratio of these two is affected by the soil moisture and the surface's ability to evaporate controlled by the incoming solar radiation. When the evaporation is great, then the sensible heat is smaller. This situation isn't favorable for upward motions creating convective precipitation. When the convective precipitation is induced by atmospheric fronts, the moisture from the near surface atmosphere can increase the amount of precipitation reaching the surface. In case of great evaporation furthermore the top of the PBL is situated lower, since the atmospheric buoyancy is smaller. In numerical weather and climate models calculation of soil moisture requires soil hydraulic parameters.

Therefore in our investigations we were mainly dealing with these soil parameters and their effects. The hydraulic parameters can be determined using functions determined for soil data bases or determining an average for each soil textures from these functions. In meteorological models – assuming that the soils particle distribution (texure) and the hydrophysical properties has a relationship valid on average – Campbell (1975) and Cosby (1984) parameters are used globally. The Campbell method determined soil hydraulical properties for Hungarian databases as the HUNSODA (Nemes, 2003) and the MARTHA

(Makó and Tóth, 2008; Makó et al., 2011) differed considerably in several cases. As e.g. the definition of field capacity is not conventional it is analyzed separately.

From the hydraulical properties, the water conductance is affected by the organic carbon content. Therefore the organic carbon content was considered using Nemes (2005) calculation method. However the model simulations weren't affected by the effect of organic carbon. The main reason is probably that the simulations are only 30 hours long. From this reason we didn't continue our planned program in this direction. However, it can be assumed that in climatological models the organic carbon resulted difference in water conductivity wouldn't be negligible. According to our statistical analysis convective precipitation simulations using soil parameters calculated from the Hungarian database result a less diverging result from measurements than using the global values.

Aside from the hydraulical properties the soil texture distribution is also dominant. The soil texture distribution found the model was replaced with the one in the Digital Kreybig database (Bakacsi et al., 2010, Pásztor et al., 2011). The effect of differences in soil texture distribution can be as great as the differences caused by using different soil databases.

One of the most important sides of atmospheric numerical modeling is the knowledge of appropriate initial conditions. Without them the prediction cannot be accurate. In the research project in 2012 and in 2013 near Szeged at 5 sites measured soil moisture was compared to the global model providing initial data for the atmospheric model used, the difference was about 0.1 m^3/m^3. So the difference is quite notable, and can reach 50%. This difference is sometimes greater than the difference resulting from database application. For simulations of convective precipitation 20% change in initial soil moisture condition caused as great alterations as the ones from different database parameters.

The evapotranspiration is not only affected by the soil, but through the transpiration the surface covering vegetation as well. In the WRF model, the globally used land use distribution have been changed to the newer CORINE database. In some analyses aside from inhomogeneous spatial distribution uniform distribution was also assumed.

According to the model simulations in most cases the convective precipitation difference was not attributed to the whole model domain precipitation amount, but rather to a shifting of the trails with 40-60 km.

The PBL studies showed that the simulated PBL height is more sensitive to relative available soil moisture and land use. Comparing the measured and simulated PBL height is not as unequivocal as the case of precipitation. Radiometer and windprofiler measured air temperature, air humidity, wind speed and refraction measurements of the HMS at Szeged was used to estimate PBL height, for which several methods are available. In our analyses it was showed that the differences resulting from using different estimation methods are generally larger than any simulation differences. If only one method is used consequently, the soil texture and land use change causes significant differences in PBL height.

In our research the main aspect was to explore the effect of soil on the atmosphere. Even though the surface effects were investigated in smaller numbers it is evident that the surface properties have at least equal effect on weather than the soil.

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