MISCELLANEA GEOGRAPHICA – REGIONAL STUDIES ON DEVELOPMENT
Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

Influence of Parameterization of Some Physical Processes in Soils on Numerical Meteorological Forecasts of Surface Fields

Abstract
Physical processes in soil-plant-water system are very complicated. Complex physical processes in soil, in particular interaction between soil-plant-water system have significant influence on processes in Planetary Boundary Layer. Changes of soil state can significantly modify processes in the PBL and meteorological fields . Since numerical models are to determine the forecast of high quality, the physical processes occurring in soil should be properly described and then appropriately introduced into a model. Every process in soil occurs on a smaller scale than original model's domain, so it should be described via adequate parameterization. Overall, soil parameterizations implemented in current numerical weather prediction (NWP) model(s) were prepared almost 40 years ago, when NWP models worked with very poor resolution mesh. Since nowadays NWP works over domains of high resolution, these "old" schemes parameterization must be adequately revised. In this paper preliminary results of changes of parameterization of soil processes will be presented.

Keywords
Soil-plant-water system • Hydrodynamics of porous media • Parameterization schemes • Multilayer soil model • Numerical weather prediction

Andrzej Mazur, Grzegorz Duniec

Department For Numerical Weather Forecasts
Institute of Meteorology and Water Management - National Research Institute
e-mail: andrzej.mazur@imgw.pl
e-mail: grzegorz.duniec@imgw.pl

Received: 26 January 2016
Accepted: 6 December 2016

Introduction

Very complex microphysical[1] and physical processes take place in soil. These processes can be divided into two categories: hydrological and thermal. The types of hydrological processes are, among others, directional-dependent, the heterogeneous flux of water, the freezing or thawing of water, evaporation from bare soil, water extraction by roots, infiltration, and percolation. Thermal processes in soil are, in general, thermal conductivity, ground heat flux, snow–soil heat exchange, heat released by freezing/melting, sensible and latent heat flux from the surface soil (Doms et al. 2011). These processes are very complex and interact with physical processes in the atmospheric Planetary Boundary Layer (PBL) and vice–versa (Hillel 1998; Stensrud 2007; Moene et al. 2014; Vila-Guerau de Arellano et al. 2015; Kędziora 1995). These microphysics processes occur on a smaller scale than any of the meteorological model(s) can deal with at the present, and thus must be parameterized. Until recently all parameterizations being used were prepared almost 40 years ago when model resolution was rather poor (Dickinson, 1984). Nowadays numerical meteorological models work in high resolution domains, but still with the "old" parameterization schemes implemented as far as the soil physics is concerned; hence, they must be changed and/or improved. Since processes in soil are very complex and are dependant on each other, and so the task is also complicated, it was decided to carry out this work in stages. At first, attention was focused on improving the physical processes for bare soil.

[1]physical processes in soil on a small scale

Summing up, all the reasons mentioned above (the obsolete character of parameterization, increased resolution etc.) set the main aim of this work – which is the improvement of the descriptions of physical processes in soil. This is very important from the point of view of the numerical forecasting model. The authors' intention was to check if the replacement of the old Dickinson's parameterization by the (improved) Darcy equation would have a positive influence on the quality of numerical forecasts. If the results are promising, meaning the forecast quality has tended to improve in comparison with forecasts using the old parameterization, new elements will be introduced to the parameterization schemes (e.g. the thermal aspect of soil and following this, vegetation).

In this paper a changed parameterization of water flux through the soil is described (the old Dickinson parameterization was replaced by Darcy equation). The new description was evaluated and the results were compared with observations. The preliminary results of the study on the parameterization change are presented in this paper.

Numerical experiments

The TERRA_ML (multilayer soil module) parameterization in the COSMO (non-hydrostatic, limited-area atmospheric model for numerical weather forecasts) model accounts for the five classes of soil texture: sand, sandy loam, loam, loamy clay and clay; additionally, peat, ice and rock are also considered as types of bedding (Doms et al., 2011). Basic soil texture classes in Poland,

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

as applied in the COSMO model, are shown in Fig. 1. One should keep in mind that for ice and rock, hydrological processes in the ground are not considered. Although potential evaporation is assumed to occur over ice surfaces, for this kind of ground the value of soil water content, related with vertical water flow, remains unchanged.

In the soil model, bare soil evaporation and plant transpiration are computed, and heat conduction and diffusion equations are solved. The calculation for melting snow is also included here. In TERRA_ML six layers are introduced for the water cycle and seven for thermal processes (Fig. 2, left chart; see Doms et al. 2011). An assumption accepted in the COSMO model is that the layer of thermally active soil has an overall thickness of 7.29 m, while hydrological active soil has 2.43 m. In this parameterization only hydrological (evapotranspiration, interception reservoir, infiltration of rain etc. Fig. 2, centre chart) and thermal (temperature of snow-free and snow-covered soil, snow albedo, melting and thawing etc. Fig. 2, right chart) processes are considered while capillary transport is neglected.

A detailed mathematical description of the parameterization of hydrological and thermal processes in TERRA_ML can be found in the COSMO model manual (Doms et al. 2011) as well as in previous work (Duniec and Mazur, 2015; Duniec and Mazur, 2016).

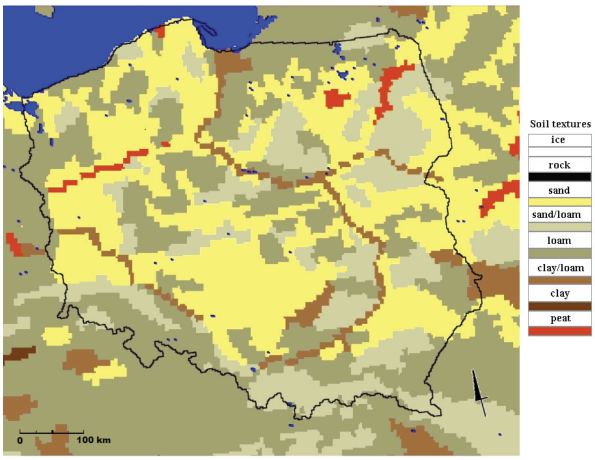

Figure 1. Basic soil texture classes in Poland, as applied within the domain of the COSMO model (pixelation occurs due to the finite spatial resolution of the model – 2.8 km x 2.8 km)

Theoretical assumptions for changes in parameterization can also be found in previous papers (ibidem).

An original description of the flux of water through soil (eq. 1; see Dickinson 1984) was replaced by a parameterization that was modified by introducing the soil temperature dependence of water flux (eq. 2). The basic assumption was that soil temperature was included in the scheme since it affects soil conditions by changing the soil viscosity. Hence, Dickinson's parameterization,

$$F_m = \rho_w \left(1 + 1550 \times \frac{D_{\min}}{D_{\max}} \times \frac{B - 3.7 + \frac{5}{B}}{B + 5} \right) \times 1.02 \quad D \quad s_u$$
$$\times 1.02 \times D_{\max} s_u^{B+2} \left(\frac{s_t}{s_u} \right)^{\left\{ 5.5 - 0.8B \left[1 + 0.1(B-4) \log \frac{K_0}{K_r} \right] \right\}} \frac{s_t}{\sqrt{z_u z_t}} \qquad (1)$$

was replaced with a modified scheme:

$$F = -\alpha(t) \cdot D(\theta) \cdot \exp\left(\frac{T}{T_0} \right) \nabla(\theta) \qquad (2)$$

where: $D_{min} = 2.5 \cdot 10^{-10}$m²/s – minimum soil diffusivity; $D_{max} = B\Phi_o K_o / \rho_{wm}$ – maximum diffusivity; $K_r = 10^{-5}$m/s; K_o – maximum hydraulic conductivity; $\Phi_o = 0.2$ m (maximum soil suction); $\rho_{wm} = 0.8$, fraction of saturated soil filled by water, nominally 0.5 (Dickinson 1984); B – non-dimensional parameter depending on the soil texture; s_u, s_t – the average of soil water content, normalized by the volume of voids for the uppermost layer (0.1 m thickness) and for the total active layer (1 m thickness) respectively; z_u, z_t uppermost layer and total active layer, respectively; $D(\theta)$ being the hydraulic diffusivity; parameter dependent on soil water content; T – being the actual soil temperature; $T_o = 273.15$K; α – correcting factor in the parabolic form to the Darcy equation (2).

$$\alpha(t) = -\frac{0.7}{t_z^2 - t_w^2} t^2 + \frac{1.5t_z^2 - 0.8t_w^2}{t_z^2 - t_w^2} \qquad (3)$$

t_w, t_z – the time of sunrise and sunset, respectively (Duniec and Mazur, 2015). This factor was applied to reduce the morning overestimation and afternoon underestimation of evaporation from the soil. The form of this factor comes from measurements showing that an overestimation of evaporation (of about 50%) from the soil is observed in the morning, while in the afternoon an underestimation of about 10 to 20% of evaporation from the soil

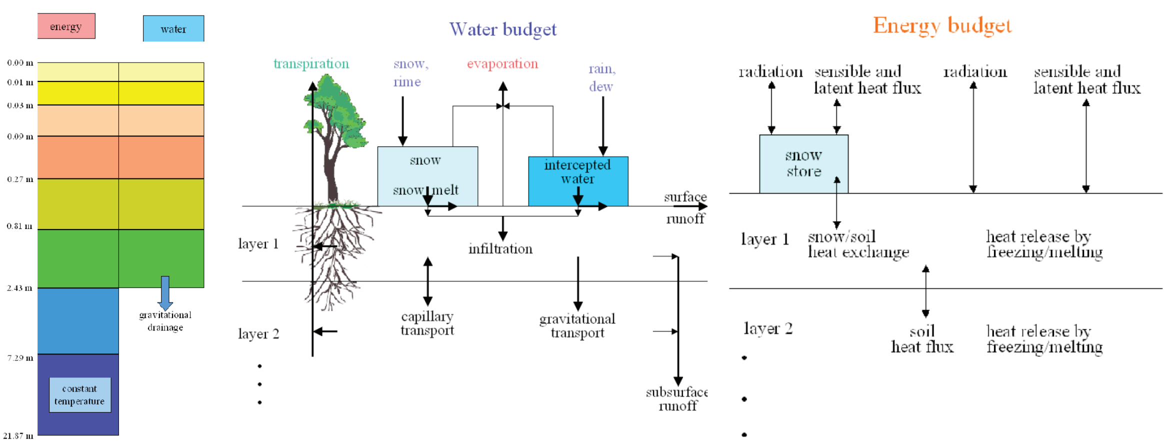

Figure 2. Allocation of water and energy process levels in the soil model (left chart). Hydrological and thermodynamic processes in the soil (center and right chart, respectively) included in TERRA_ML (Doms et al. 2011, Duniec and Mazur 2015). Source: Doms et al. 2011, changed

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

(Dickinson 1984) is observed. Thus, the "ad hoc" parabolic form was assumed in order to describe a dependence on the time elapsed between sunrise and sunset. In turn, parameter *a* was varied for different types of soil textures as in Table 1.

These values were adopted from experiments for defining the relationship between soil potential and volumetric water content (Stensrud 2007). Previous studies (Duniec and Mazur, 2015; Duniec and Mazur, 2016) have shown that adopting the same value for parameter *a* for all soil texture classes improves results, but this improvement depends strongly on the type of soil. Thus, it was decided to take into account the different values of parameter *a* at the same time and to check if this solution would bring about the desired result in terms of improving the numerical forecasts.

The entire 2013 year was chosen for the numerical tests, with the results for both warm and cold seasons discussed. The monthly average values of atmospheric fields were also analysed. The measurement data (from synoptic stations) and results of the COSMO Model (reference runs, and runs with the changed parameterization) were compared to each other. Sixty-one meteorological stations were chosen for this experiment, with air temperature values at 2 m above ground level (AGL), dew point temperature at 2 m AGL and wind speed at 10 m AGL.

The specially defined function, Ψ, was designed to compare results. This function consisted of two parts:

$$\Psi = \left|X_{obs} - X_{ref}\right| - \left|X_{obs} - X\right| \quad (4)$$

The first part was an absolute value for the difference between observations carried out at meteorological stations, X_{obs} and the reference results from the COSMO model, X_{ref} (i.e. the forecast from COSMO models with old parameterization for water flux). The second part was an absolute value for the difference between the observation from meteorological stations, X_{obs} and forecasts obtained after the implementation of the changed parameterization, X. If $\Psi>0$ (areas marked with the colour red in figures 3, 6, 8, 10, 12 and 14) – forecasts improved, however, if $\Psi<0$ (areas marked with the colour green) – forecasts worsened with respect to the reference. The COSMO model results, with the changed description of soil processes, were compared with the observations and with reference runs, then divided into two groups: "the best" and "the worst". The best results indicate an improvement in meteorological forecasts – this means that the forecasted meteorological values were closer to the real values, measured at the stations, than those obtained from the reference numerical forecasts. The worst case indicates that numerical forecasts worsened due to the implementation of the new parameterization scheme(s).

Results and discussion

The results from the COSMO model are shown in figures 3, 6, 8, 10, 12 and 14. In order to illustrate the overall state of the atmosphere for this period, the monthly sums of precipitation, the deviation from the monthly mean air temperature and the monthly average air temperature are shown in figures 4, 5, 7, 9, 11, 13 and 15.

From the results of the COSMO model (Fig. 3) and their comparison with the observations one may point out that the numerical weather forecasts improved. Forecasted values for dew point temperatures at 2 m AGL are closer (area coloured with red in the Fig. 3) to the observed values in areas where monthly total precipitation was below the monthly average; thus making soil moisture below the monthly average (Fig. 4 and 5, monthly average values and deviations from long-term mean values). In the case of extremely dry soils, no improvement in forecasts for (average) dew point temperatures at 2 m AGL was observed. However, an improvement in the numerical forecasts of dew point temperatures was observed at a time when air temperatures exceeded the monthly average value for air temperatures at

Table 1. Values for parameter a for different types of soil texture. See detailed explanation in text

Type of soil texture	Value of parameter a
Sandy loam	4.74
Sand	2.79
Loam	5.25
Clay loam	8.17
C lay	11.00

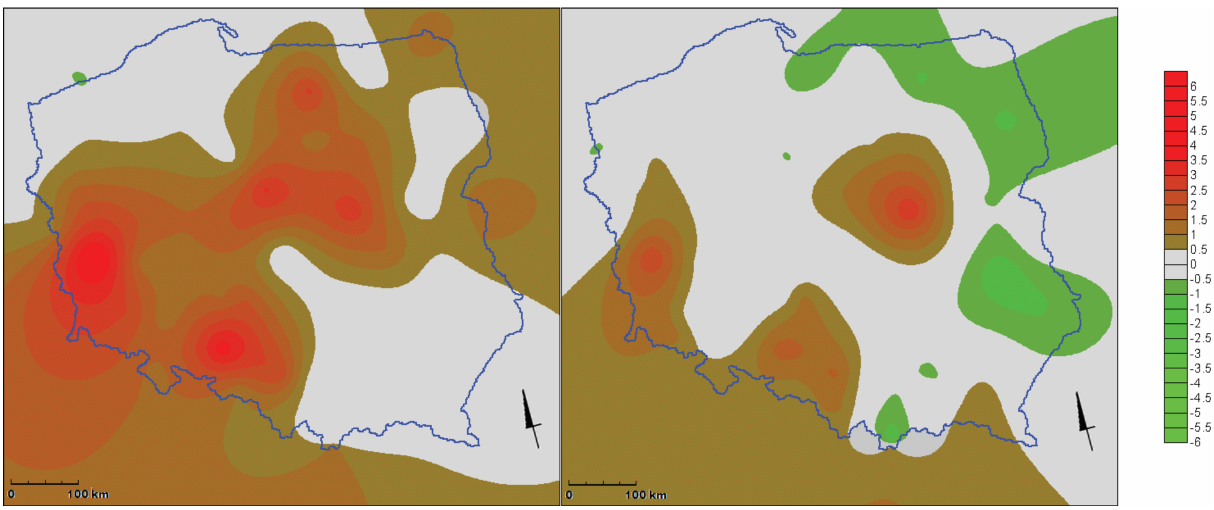

Figure 3. The best results for COSMO model forecasts for dew point temperatures at 2 m AGL. Monthly average of 00 UTC runs for August 2013 (left) and of 12 UTC runs for July 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

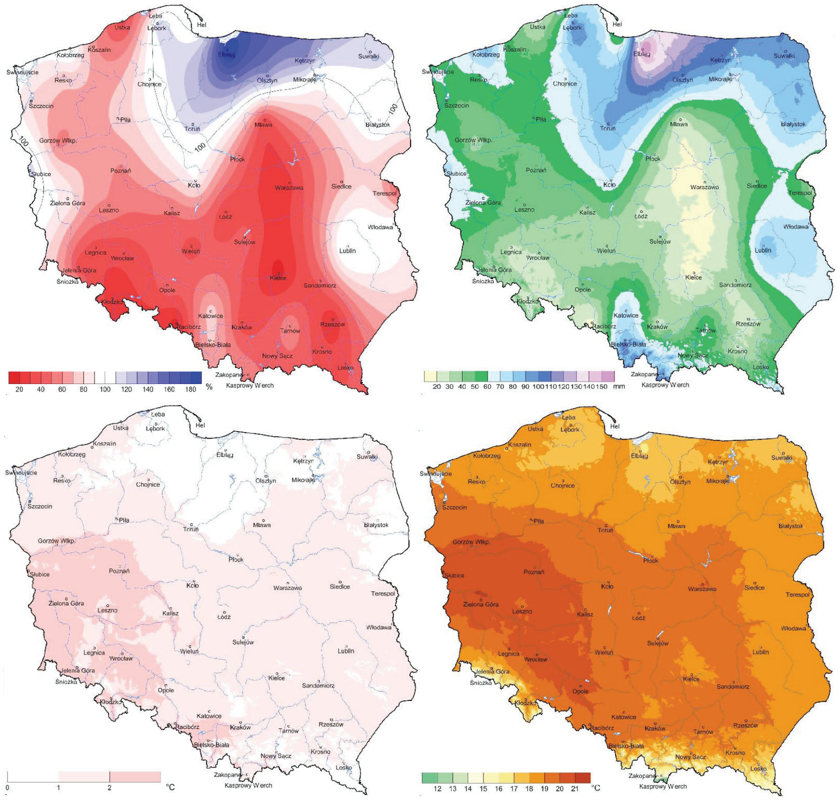

Figure 4. July 2013, from left to right: deviation of monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

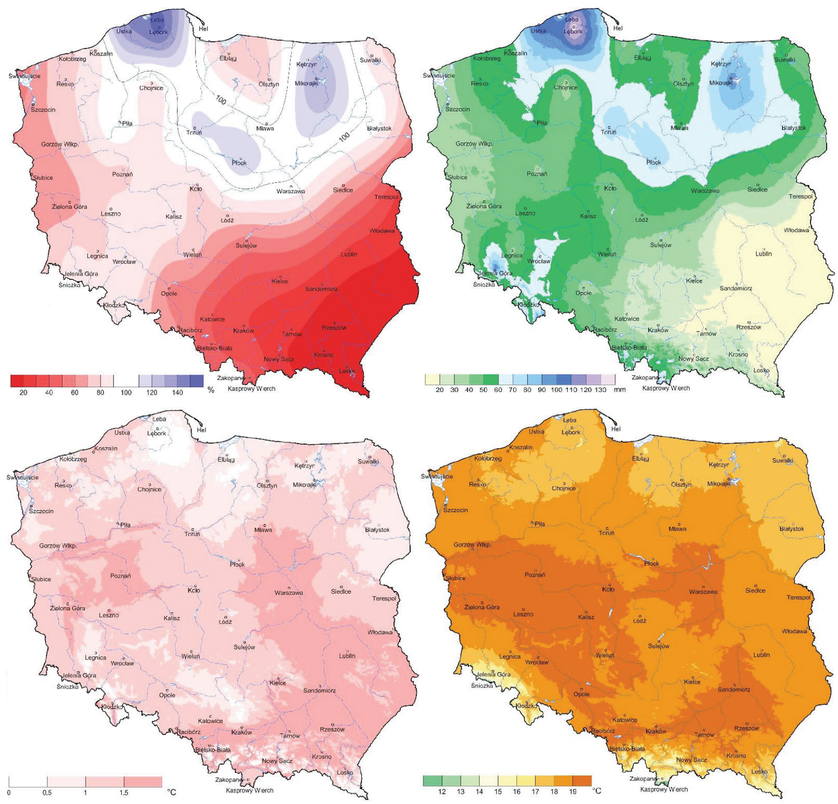

Figure 5. August 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

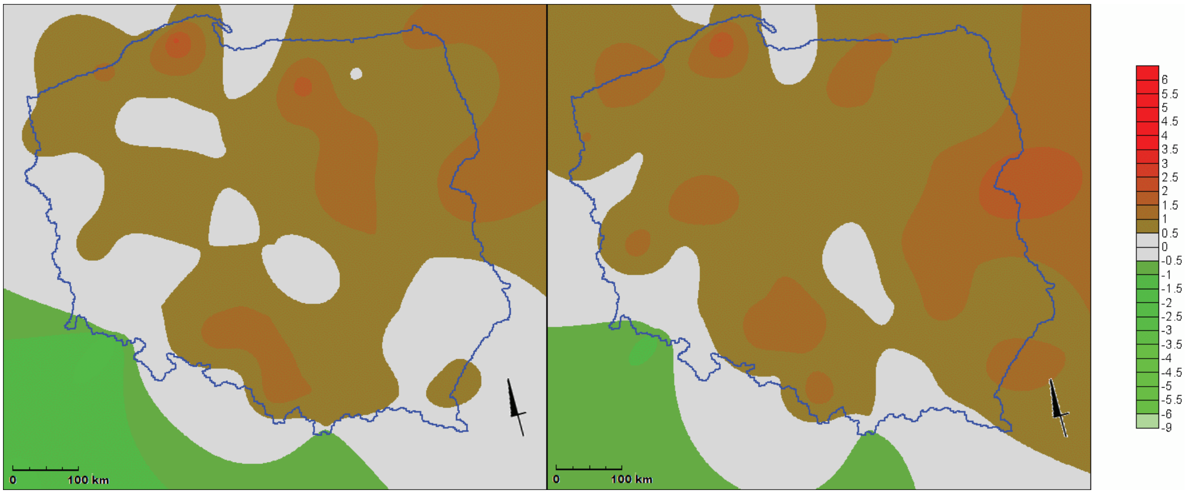

Figure 6. The best results for COSMO model forecasts for air temperatures at 2 m AGL. Monthly average of 00 UTC runs for July 2013 (left) and of 12 UTC runs for April 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

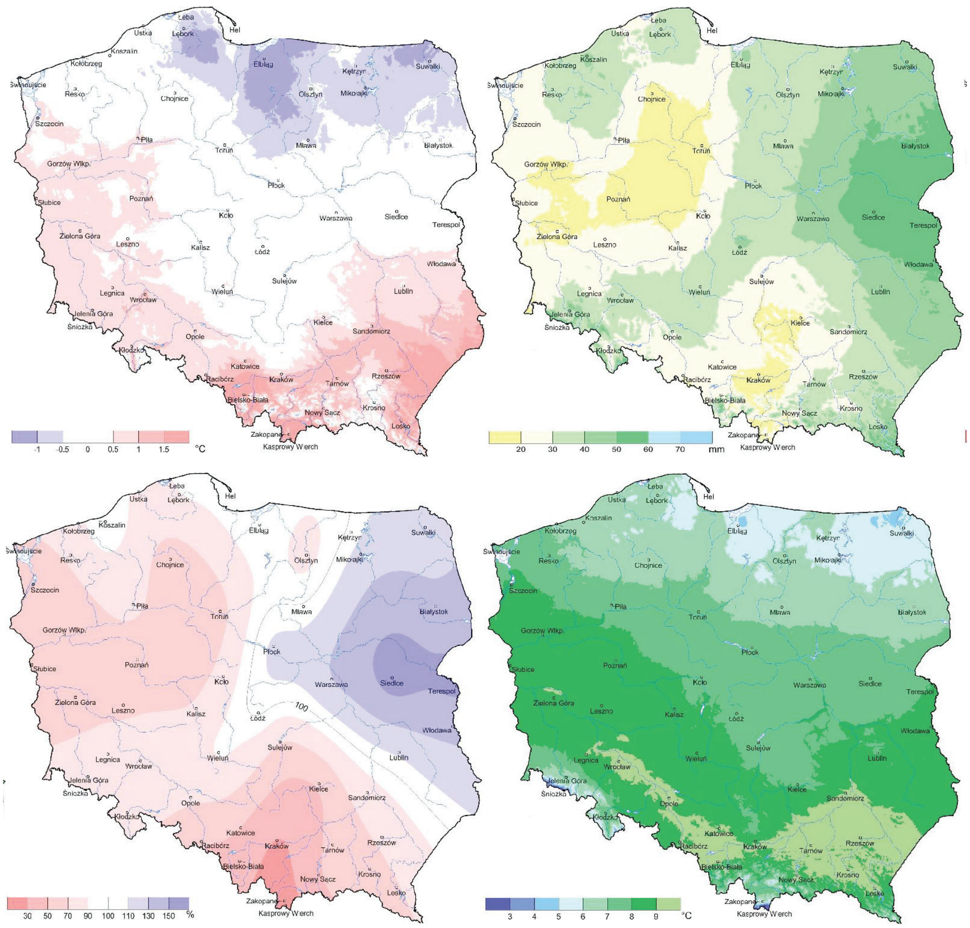

Figure 7. April 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

2 m AGL. Yet, it is difficult to find a spatial correlation between areas where forecast improvement is observed, and soil texture classe. This may be due to the fact that none of these soil texture classes is "favoured" as far as changes (i.e. improvements) are concerned.

Improved forecasts for air temperatures at 2 m AGL were obtained in areas where air temperatures at 2 m AGL were observed to be below (Fig. 6, 7) monthly average values. As above, it was difficult to make a judgement about a spatial correlation between areas of improved forecasts and soil texture.

In January 2013, the average numerical forecast for wind speeds (Fig. 8) was improved in areas where the average amount of monthly precipitation was above the climatological average precipitation, and the average air temperatures were below the average level or at the same level (Fig. 9). In April, however, the situation was more complicated, since the improvement in numerical forecasts for wind speed was observed in areas where precipitation and air temperature were above average levels (which meant, that soil moisture was also above the average; Fig. 7).

The worst results were received for dew point temperatures for March 2013, for air temperatures at 2 m AGL for May 2013 and for wind speeds for September 2013.

A worsening of the numerical weather forecast for dew point temperatures in March 2013 (Fig. 10) was observed for the whole area. The observed precipitation was close to the climatological monthly average, while air temperature at 2 m AGL was below the climatological monthly mean (Fig. 11) for this area.

Numerical weather forecasts for air temperature at 2 m AGL (Fig. 12) worsened in May 2013, as it was observed that air temperatures at 2 m AGL were higher than the climatological monthly mean (Fig. 13).

Finally, in September 2013 the worst results for the numerical weather prediction of wind speeds were observed (Fig. 14). Air temperatures at 2 m AGL were below the climatological monthly average (Fig. 15). For all the cases analysed above it was rather difficult to find a correlation between areas with worse forecasts for dew point temperatures, for air temperatures at 2 m AGL and for wind speeds; and soil texture.

Conclusions

Evaporation from the soil surface requires a continuous supply of heat, which aides the latent heat needed to change the water into a vapour. In addition, the water vapour pressure in the atmosphere must be lower than the pressure of the vapour from the evaporating soil surface. These two factors are due to meteorological causes (solar radiation, air temperature, dew point, wind speed etc.). They determine the maximum amount of water that can be evaporated from the soil surface. The third very important factor in the evaporation of water from the soil surface is the amount of water (contained in the soil) delivered to the surface. The transport of water within the soil is a process that occurs on a scale smaller than the resolution of the numerical grid and so must be parameterized. In the COSMO model, the parameterization was developed by Dickinson based on physical conditions, empirical results and numerical experimentation. However, this parameterization does not necessarily reflect the real state of the process. Water flux in the soil is either overestimated (in the morning) or underestimated (in the afternoon). These over- and underestimations of the quantity of water supplied to the soil surface will result in reduced or increased evaporation from the surface, which will affect the forecast for the structure of the boundary layer and of meteorological fields such as air temperature and dew point temperature.

In the literature, many parameterization schemes for water flux in the soil have been developed. For example, Chen and Dudhia (2001), have developed a scheme, whereby the amount of evaporated water depends on the texture of soil and its transpiration potential. It has been shown that the evaporation described by the above parameterization does not reflect reality, since soil moisture decreased too slowly, and Ek has had to make adjustments to previous parameterization (see Ek. et al., 2003). However, according to Santanello and Carlson (2001), the corrections applied resulted in an overestimation of the drying out of the soil. In the schema developed by Noilhan and Plato (1995), Mahfouf (1991), and Viterbo and Beliaars (1995) the drag coefficient of the atmosphere was also considered. In Chen's parameterization (1996) water flux is described with the Darcy equation taking into account thermal conductivity, but without taking into account the effect of soil temperature on its value as a result of changes in water viscosity. Sellers (Sellers et al., 1986) developed a parameterization

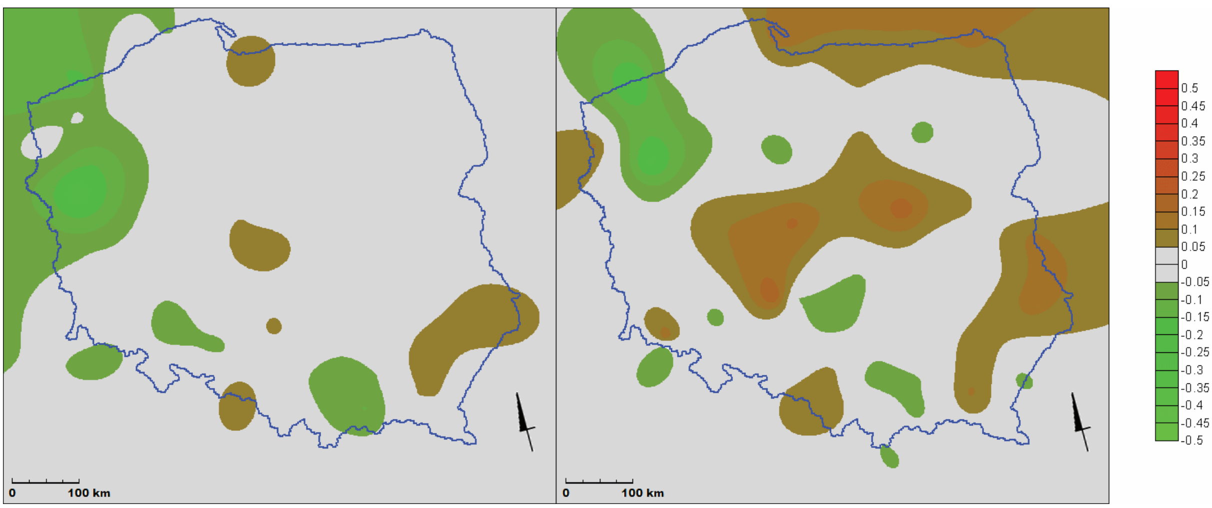

Figure 8. The best results for COSMO model forecasts for wind speeds at 10 m AGL. Monthly average of 00 UTC runs for January 2013 (left) and of 12 UTC runs for April 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

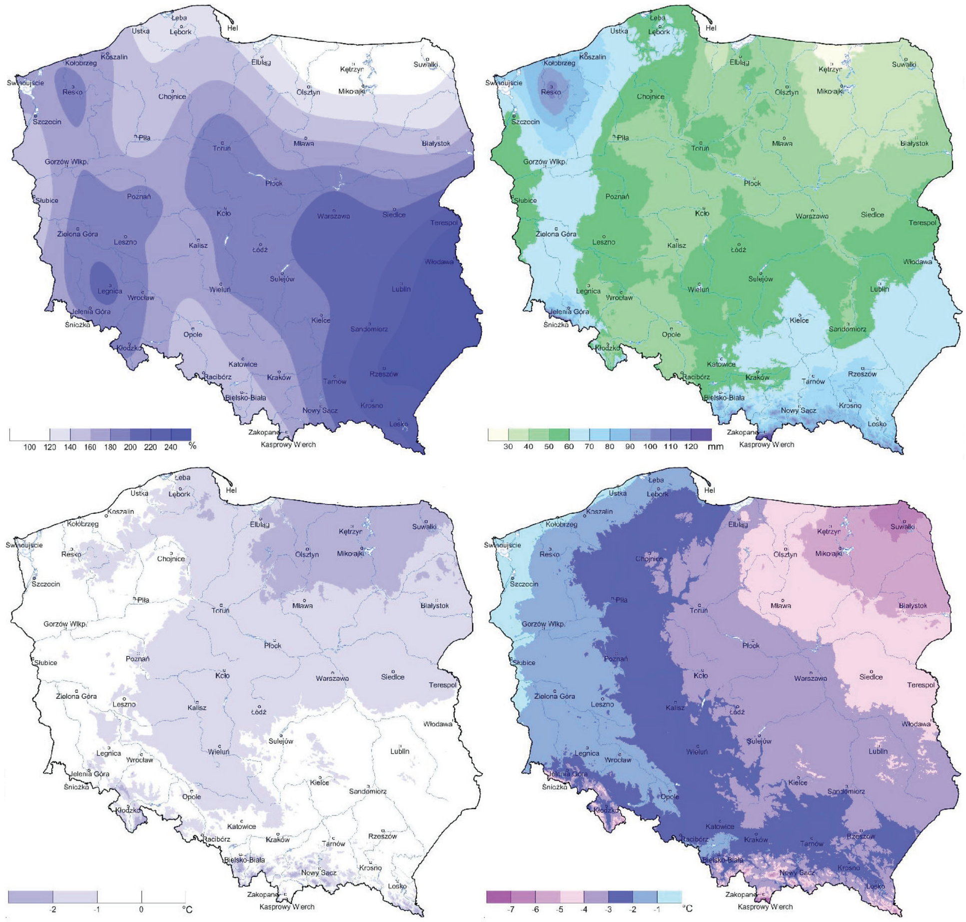

Figure 9. January 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

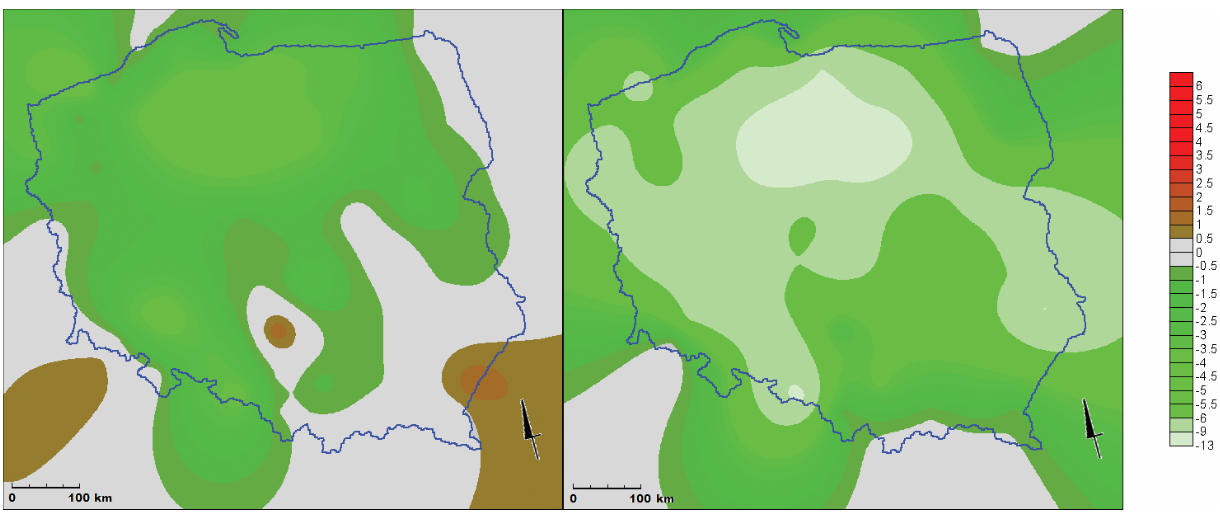

Figure 10. The worst results for COSMO model forecasts for dew point temperatures at 2 m AGL. Monthly average of 00 UTC runs for March 2013 (left) and of 12 UTC runs for March 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

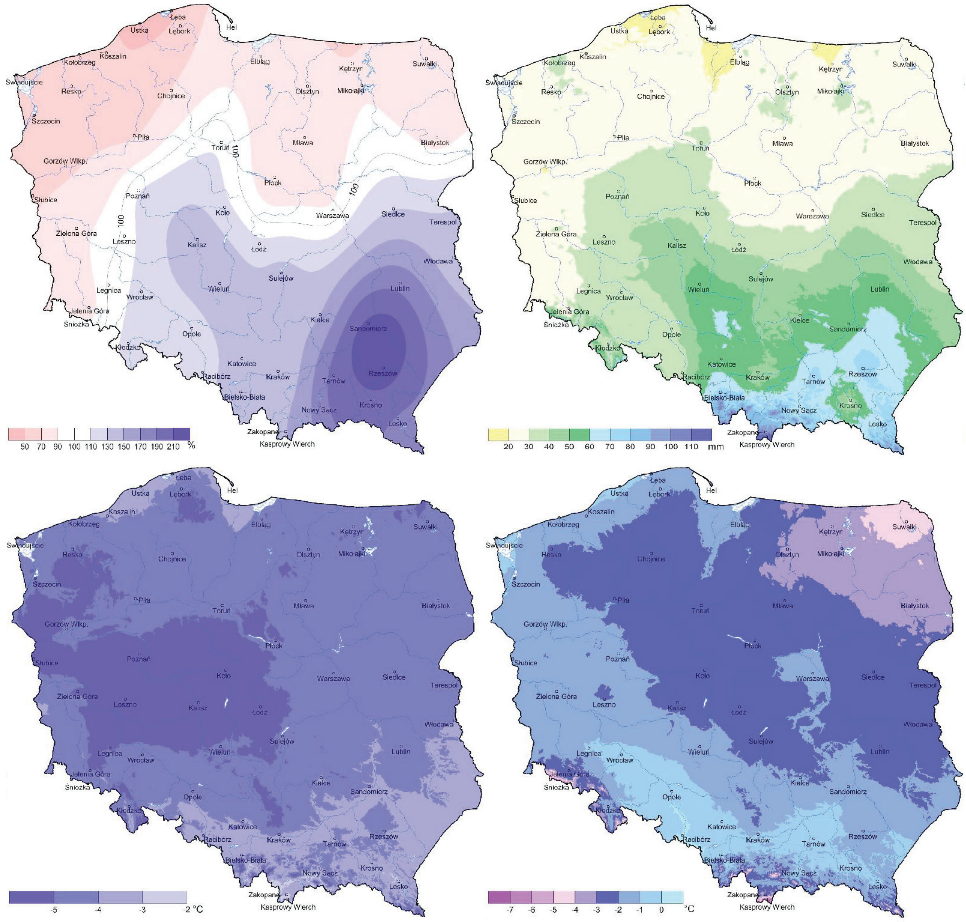

Figure 11. March 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

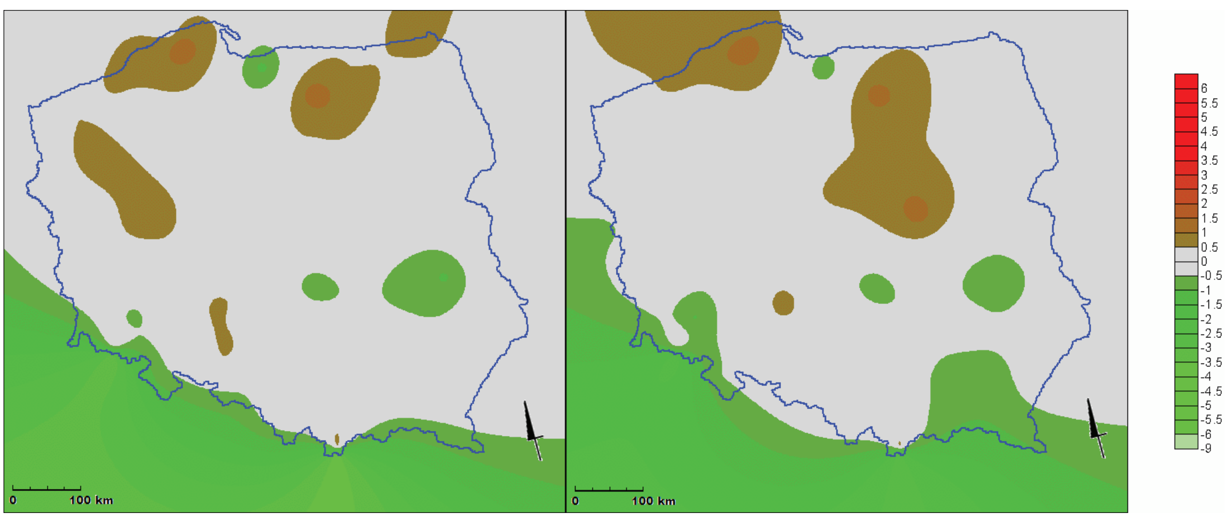

Figure 12. The worst results for COSMO model forecasts for air temperatures at 2 m AGL. Monthly average of 00 UTC runs for May 2013 (left) and of 12 UTC runs for May 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

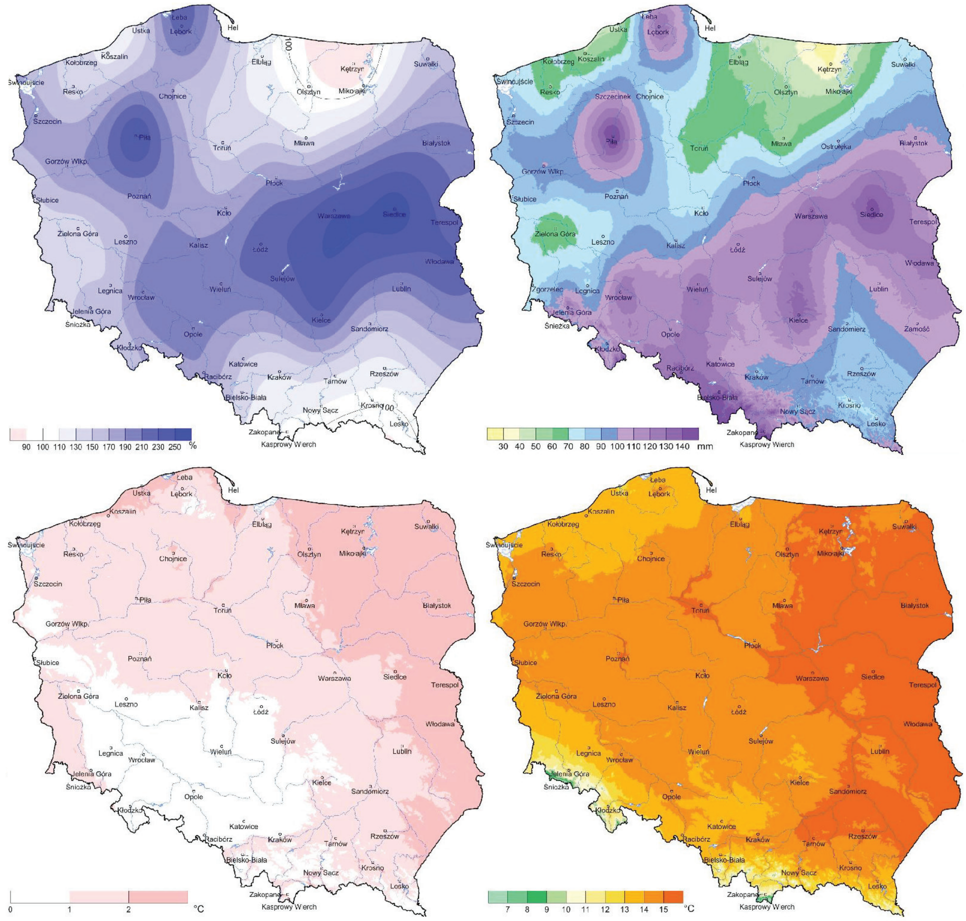

Figure 13. May 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

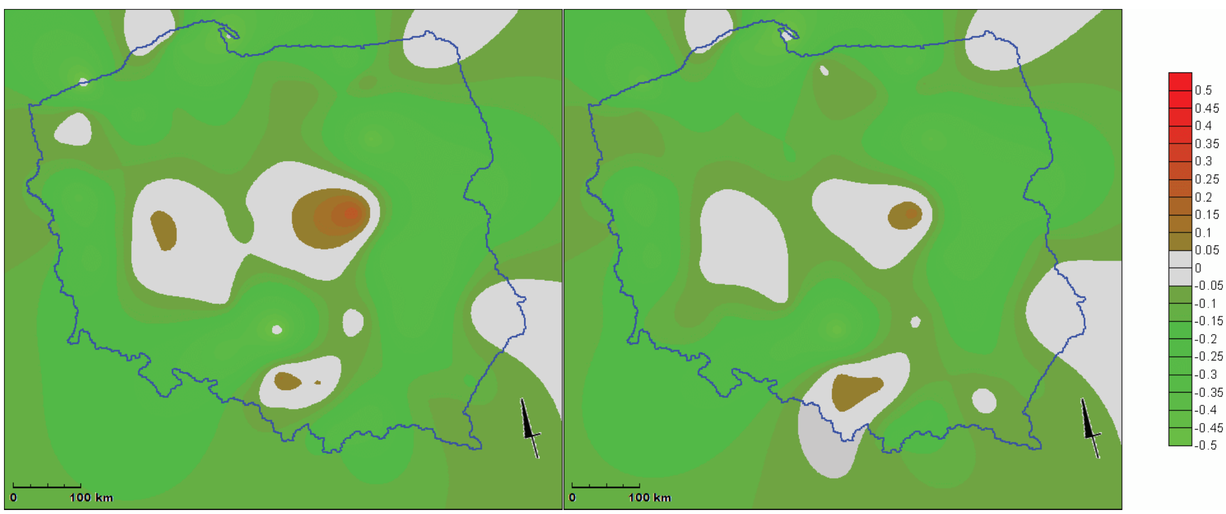

Figure 14. The worst results for COSMO model forecasts for dew point temperatures at 2 m AGL. Monthly average of 00 UTC runs for September 2013 (left) and of 12 UTC runs for September 2013 (right). Values for α coefficient: 4.74 for sandy loam; 2.79 for sand; 5.25 for loam; 8.17 for clay loam; 11.0 for clay. Results presented on a model domain covering Poland, with a spatial resolution 2.8 km x 2.8 km

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

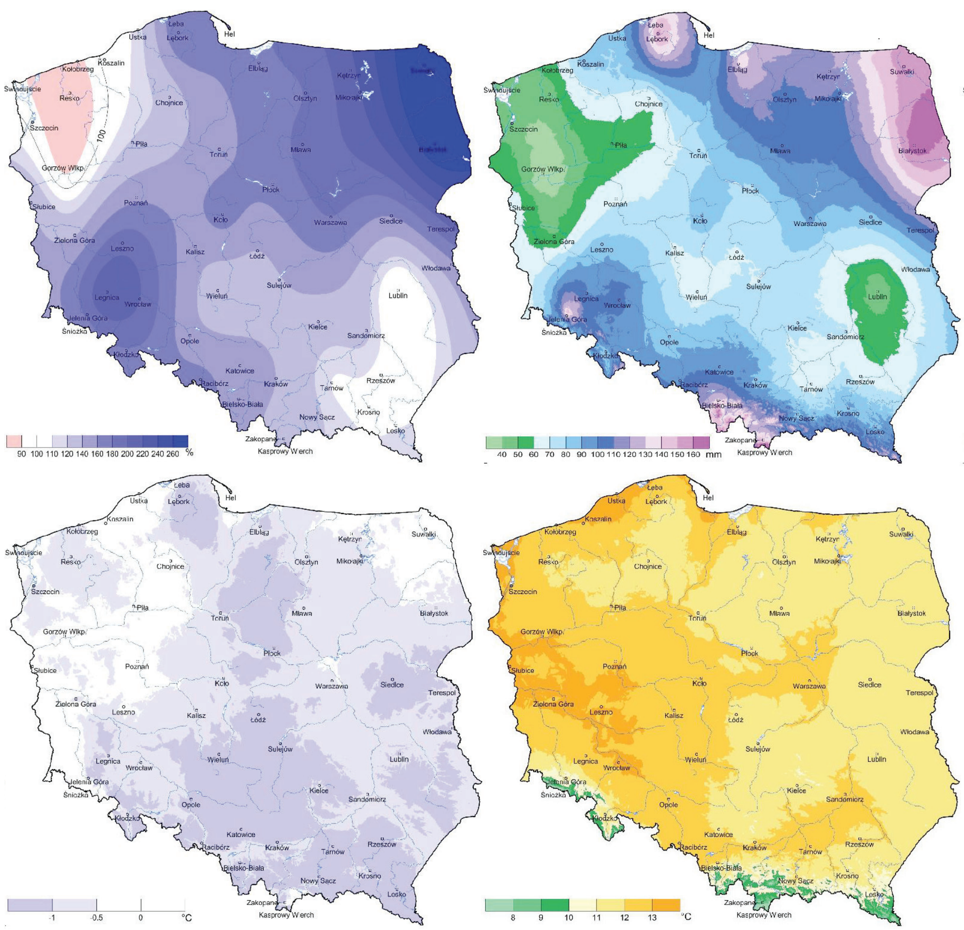

Figure 15. September 2013, from left to right: deviation of the monthly precipitation compared to the 1971–2000 long-term average; monthly total precipitation; deviation of the mean monthly air temperature compared to the 1971–2000 long-term average; and the average monthly air temperature. Source: Monthly Bulletin of the National Hydrological and Meteorological Service, changed

that makes the amount of evaporated water (assuming a "bare" soil case, i.e. the soil not covered with vegetation) related to other factors such as the drag coefficient in the boundary layer, the air humidity at the Earth's surface and the pressure of water vapour in the air and on the surface of the soil.

As suggested in numerous works, none of the developed schemas reflect reality in an ideal way. As shown by the numerical experiments carried out by many researchers, over- and underestimation of evaporation from the soil surface can be observed, and moreover, the soil dries too slowly or too quickly in comparison to actual measurements. The COSMO model with the Dickinson's parameterization implemented is also burdened with these shortcomings.

In this paper, an attempt was made to reduce these problems. The authors are aware that the complete elimination of shortcomings resulting from the parameterization of physical processes occurring in the soil on a scale smaller than the numerical grid's resolution is not fully possible, among other things, because all the physical processes that occur in the soil are not entirely understood, and secondly because there is no accurate field studies or measurements carried out on a spatial scale other than the one used in numerical weather models.

References

Chen, F & Dudhia, J 2001, 'Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity', *Mon. Wea. Rev.*, vol. 129, pp. 569–585.

Chen, F, Mitchell, K & Schaake, J 1996, 'Modeling of land surface evaporation by four schemes and comparison with FIFE observations', *J. Geophys. Res.*, vol. 101, pp. 7251–7268.

Dickinson, RE 1984, 'Modeling evapotranspiration for three-dimensional global climate models' in *Climate Processes and Climate Sensitivity*, eds JE Hansen & T Takahashi, *Geophysical Monograph 29, Maurice Ewing*, vol. 5, pp. 58–72.

Doms, G, Foerstner, J, Heise, E, Herzog, HJ, Mironow, D, Raschendorfer, M & Reinhart, T 2011, 'A description of the nonhydrostatic regional COSMO model. Part II: Physical parameterization', *Tech. Rep., DWD*. Available from <http://www.cosmo-model.org/content/model/documentation/core/default.htm> [10 September 2011].

Vol. 20 • No. 4 • 2016 • pp. 48-58 • ISSN: 2084-6118 • DOI: 10.1515/mgrsd-2016-0023

Duniec, G & Mazur, A 2015, 'Modified description of soil processes vs. quality of numerical weather forecasts – "Bare" soil case', *Ecological Chemistry and Engineering – S*, vol. 22, issue 4, pp. 659–673. DOI: 10.1515/eces-2015-0040.

Duniec, G & Mazur, A 2016, 'Influence of parameterization of soil processes on meteorological forecasts of vertical profiles', *Ecological Chemistry and Engineering – S*, vol. 23, issue 3, pp. 493-503. DOI: 10.1515/eces-2016-0036.

Ek, MB, Mitchell, KE & Lin, Y 2003, 'Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model', *J. Geophys. Res.*, vol. 108, p. 8851. DOI: 10.1029/2002JD003296.

Hillel, D 1998, *Environmental soil physics*, Academic Press, London.

Kędziora, A 1995, *Podstawy agrometeorologii* (Introduction to agrometeorology, in Polish), PWRiL, Poznań.

Mahfouf, J-F 1991, 'Analysis of soil moisture from near-surface parameters: a feasibility study', *J. Appl. Meteor.*, vol. 30, pp. 1534–1547.

Moene, AF & van Dam, JC 2014, *Transport in the atmosphere-vegetation-soil continuum,* Cambridge University Press, New York.

Noilhan, J & Planton, S 1989, 'A simple parameterization of land-surface processes for meteorological models', *Mon. Wea. Rev.*, vol. 117, pp. 536–549.

Santanello, JA & Carlson, TN 2001, 'Mesoscale simulation of rapid soil drying and its implication for predicting daytime temperature', *J. Hydrometeor.*, vol. 2, pp. 71–88.

Sellers, PJ, Mintz, Y, Sud YC & Dalcher, A 1986, 'A simple biosphere model (SiB) for use within general circulation models', *J. Atmos. Sci.*, vol. 43, pp. 505–531.

Stensrud, DJ 2007, *Parameterization schemes – keys to understanding numerical weather prediction models,* Cambridge University Press, New York.

Vila-Guerau de Arellano, J, van Heerwaarden, CC, van Stratum, BJH & van den Dries, K 2015, *Atmospheric boundary layer*, Cambridge University Press, New York.

Viterbo, P & Beljaars, ACM 1995, 'An improved land surface parameterization scheme in the ECMWF model and its validation', *J. Climate*, vol. 8, pp. 2716–2748.

IMWM-NRI 2013, *Monthly Bulletin of the National Hydrological and Meteorological Service* (in Polish). Available from IMWM-NRI [2013].