IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 121, No. 4, October – December, 2017, pp. 437–452

Application of RCM results to hydrological analysis

Anna Kis[1]*, **Rita Pongrácz**[1,2], **Judit Bartholy**[1,2], and **János Adolf Szabó** [3]

[1]*Department of Meteorology, Eötvös Loránd University,*
Pázmány Péter st. 1/A, H-1117, Budapest, Hungary

[2]*Faculty of Science, Excellence Center, Eötvös Loránd University,*
Brunszvik u. 2., H-2462, Martonvásár, Hungary

[3:]*HYDROInform Ltd., Hűvösvölgyi út 54., H-1021, Budapest, Hungary*

E-mails: kisanna@nimbus.elte.hu, prita@nimbus.elte.hu, bartholy@caesar.elte.hu,
janos.szabo@hydroinform.hu

* *Corresponding author*

(Manuscript received in final form August 29, 2017)

Abstract—It is a well-known fact that the characteristics and frequency of different hydrological processes (particularly the extremes – both droughts and floods) are definitely sensitive to climate change. Since extreme hydrological conditions often result in severe socio-economic impacts, it is essential to estimate reliable future tendencies, for which cooperation of experts in hydrology and climate modeling is a key step. In this study, the DIWA hydrological model is applied for the Upper Tisza Basin; the necessary meteorological time series are provided by the RegCM4 regional climate model simulation and the CARPATCLIM dataset. The calibrated DIWA model is run for the past and two future time periods. The comparison of the runoff characteristics concludes that an increase in winter and a decrease in summer are projected in the target watershed area.

Key-words: Upper Tisza Basin, RegCM4, DIWA hydrological model, climate change

1. Introduction

There is a recent growing need not only for climate change analyses, but more complex, detailed, and reliable impact studies as well. Therefore, more and more investigations focus on the relation between climate change and different socio-economic sectors. These assessments with particular focuses are important, as they can provide a useful basis for decision makers in order to build adaptation strategies in time and to mitigate climate change induced potential hazards.

Due to the rapid population growth, more than 7 billion people are currently living in the world (http://www.worldometers.info/world-population/); hence food-security – which is certainly determined by the climatic conditions – is a key issue. Therefore, several agricultural studies linked to climate change are published in the recent years (e.g., *Trnka et al.,* 2014; *Dobor,* 2016). According to *Betts* (2005), a complex, integrated approach is necessary for these studies to consider anthropogenic land cover changes besides the modified climatic conditions and the direct response of crops to CO_2 concentration, which also plays an important role in yield production. *Long et al.* (2005) found that rising CO_2 concentration results in a smaller surplus of yields in those areas, where a warming-induced increase of yield is projected; moreover, higher tropospheric O_3 concentration level causes a 20% yield loss generally. Among the complex impact-focused studies, some take into account not only climate change, but food production, trade, and consumption (*Fischer et al.,* 2002) or the issue of food quality (*Porter* and *Semenov,* 2005), as well. All in all, using different models and considering different aspects, most of the studies conclude that yield loss is likely to occur in the future (*Rosenzweig et al.,* 2013; *Mall et al.,* 2017).

Besides agriculture, other impact studies related to socio-economical and ecological aspects are completed for various regions using regional climate model (RCM) outputs. For instance, tourism is definitely affected by climate change (*Kovács et al.,* 2017), both in warmer regions where the beach can be considered as the main attraction (*Amengual et al.,* 2014) and in colder areas where snow and winter sports are the key sectors (*Damm et al.,* 2014). Climate change plays an important role in the energy performance of buildings too, which was addressed by *Nik* (2016) for specific buildings in Geneva and Stockholm. In addition to these economical sectors, ecological aspects are also studied in relation to the climate change. The detected and possible future shifts of natural vegetation (*Szelepcsényi et al.,* 2016) and species (*Morin* and *Thuiller,* 2009) are clearly determined by climate and its variations as abiotic factors. Moreover, the entire biogeochemical cycle and the involved processes are also closely built-up into the complex climate system of the Earth, thus, they are interrelated to climatic conditions and their changes (*Blenckner et al.,* 2002; *Meier et al.,* 2012).

Connection between climate change and hydrological processes is quite a widespread research topic, as both the lack and the excess of water may result in severe hazards. On the one hand, climate change impact on floods is analyzed by *Hirabayashi et al.* (2013) for the world: they found that flood frequency will increase in the future in southeast Asia, southern India, eastern Africa, and in the northern parts of the Andes; nevertheless, there are also other regions where flood frequency is projected to decrease. Investigating

Europe, *Madsen et al.* (2014) concluded that snowmelt peak flows will occur earlier during spring because of regional and global warming; moreover, flood water levels will decrease in the areas where snow-melting is the dominant factor in forming floods. Extreme precipitation also plays a key role in flood hazard: in the future it is projected to increase in the British Isles, western Europe (*Dankers* and *Feyen,* 2008), and northern Italy, while in some parts of Germany, Sweden, and the Baltic countries, a decrease in 100-year return values of discharge is estimated (*Rojas et al*., 2012). In addition, there are many flood analyses focusing on different smaller regions (e.g., *Cameron et al.,* 2000; *Kay* and *Jones,* 2012; *Falter et al.,* 2015). A special type of floods, the so-called flash flood is especially dangerous: it appears very suddenly (therefore, it is extremely difficult to predict when it occurs) and concentrates to a relatively small area, where it can cause severe problems. In order to be more prepared for these events and to better understand their processes, several investigations focus on this topic (e.g., *Reed et al.,* 2007; *Velasco et al.,* 2013; *Garambois et al.,* 2014; *Hejazi et al.,* 2014; *Hofierka* and *Knutová,* 2015). On the other hand, the lack of water also has negative effects, e.g., on drinking water supplement, shipping, or agricultural production. Hence, analyses concerning water scarcity (e.g., *Gosling* and *Arnell,* 2013; *Gleick,* 2014; *Schewe et al.,* 2014) are as important as flood related studies. The study of *Lehner et al.* (2006) takes into account not only climate change, but other factors, such as demographic, socio-economic, and technological trends; according to the results, flood frequencies are likely to increase in the future in northern Europe, while in the southern parts of the continent, drought frequencies are projected to increase.

Radvánszky and *Jacob* (2008, 2009) analyzed the projected hydrological changes of the entire catchment of the river Tisza. Their analysis is based on the REMO (*Jacob* and *Podzun,* 1997) regional climate model, the HD (*Hagemann* and *Dümenil,* 1998) hydrological model, and the A1B (*Nakicenovic* and *Swart,* 2000) emission scenario. They concluded that by the end of the 21st century river discharge will decrease in February, March, summer, and autumn months, while in April and May, an increasing trend is estimated. In this paper, we focus on a smaller subcatchment of the Tisza, near the river source, namely, the Upper Tisza catchment using a hydrological model driven by regional climate model outputs. The main goal of our study is to evaluate the possible future climatic and hydrological changes, which are essential to adapt to the regional environmental changes and to prepare adequate strategies for optimal water management at regional/local level. In the next section, the applied data, models, and methods are presented, and then, our results are shown. Finally, we summarize the investigation and the main conclusions.

2. Data and methods

Hydrological processes are clearly determined by the main characteristics of the catchment, i.e., climate, topography, soil type and thickness, land use, vegetation type, and coverage. The physically-based DIWA (Distributed Watershed; *Szabó,* 2007) hydrological model, which is used in this study, takes into account all these parameters for each grid cell. DIWA separates constant and seasonally variable parameters. Furthermore, DIWA considers all the essential processes of the hydrological budget equation, i.e., precipitation, interception, evaporation and transpiration, infiltration, snow accumulation, and snow melting, as well as surface, subsurface, and channel runoff (*Fig. 1*).

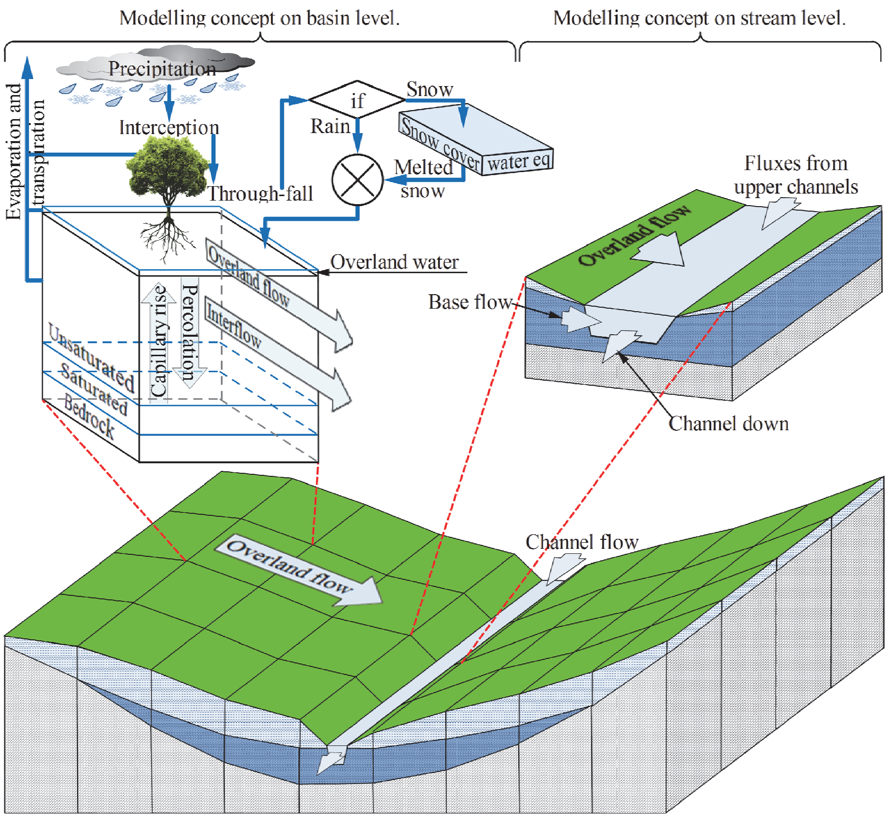

Fig.1. Schematic description of the DIWA hydrological model.

The present study focuses on the Upper Tisza catchment, which is located in Central Eastern Europe, covering parts of Ukraine, Romania, and Hungary. The target area has a quite complex topography: its highest point exceeds 2000 m, while the lowland parts of the catchment in the south and east lie below 400 m; the overall average height is 800–900 m (*Fig. 2a*). The climatic conditions of the target catchment changes with topography are: temperature is lower and precipitation is greater in the higher elevations than in the lowland areas. The annual mean temperature is 3–10 °C and the annual mean precipitation total varies between 600 mm and 1400 mm. The dominant soil type of the region is sandy loam (*Fig. 2b*), which contains 50–80% larger sand particles (with size > 63 μm) and 20–50% smaller (silt or mostly clay) particles, hence somewhat more nutrients than pure sand soils resulting in improved fertility. As a consequence, sandy loam soil drainages water quickly, as it cannot hold a larger amount of water. Other soil types, i.e., clay loam, loam, and sand can be found in the southern parts of the catchment. The Upper Tisza catchment is covered by broad-leaved and coniferous forests mainly (*Fig. 2c*). In the lower parts of the area, non-irrigated arable lands, pastures, natural grasslands, woodland, scrubs, and agricultural fields can be found – that is why the urban area is relatively small in the catchment.

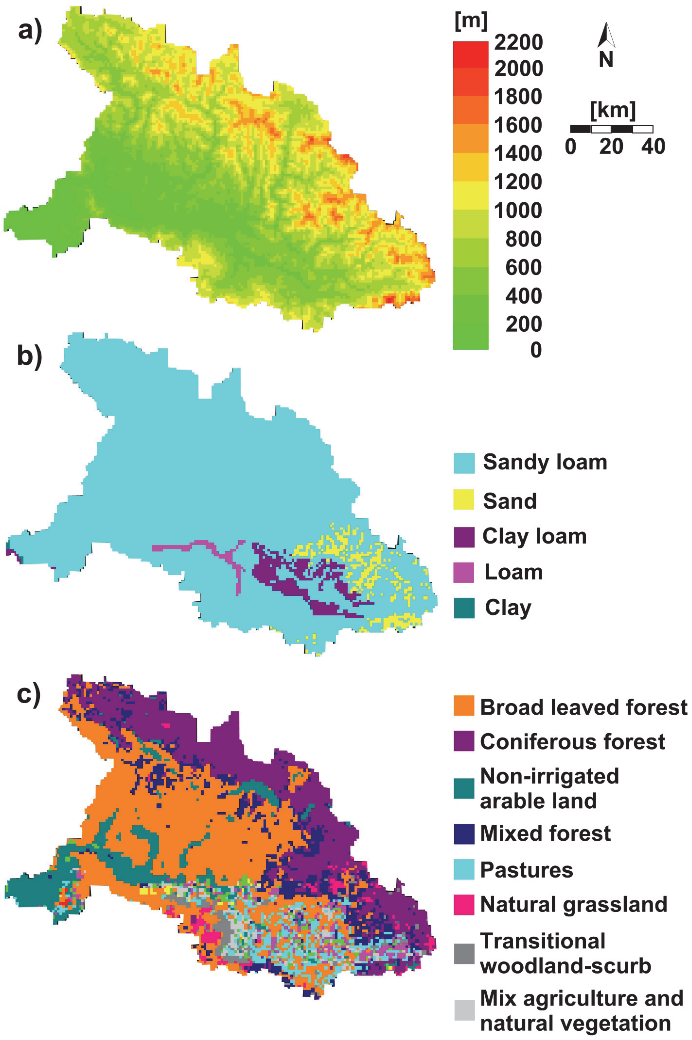

Fig. 2. Topography (a), soil types (b), and land cover (c) distributions in the Upper Tisza Basin.

Vegetation plays an important role in the hydrological cycle by transpiration and interception (which serves as the basis for evaporation from plant surfaces). These processes show a substantial seasonality because of the annual cycle of vegetation; therefore, DIWA takes into account the leaf area index (LAI) on a monthly basis. In the case of higher LAI, transpiration and interception are higher as well. It can clearly be seen that LAI values above 4 occur only in the northeastern – higher elevated – parts of the domain in January (*Fig. 3a*), while LAI is above 6 in more than the half of the entire area in July (*Fig. 3b*). Furthermore, LAI values in July exceed even 18 in some regions (mainly in the coniferous forest areas).

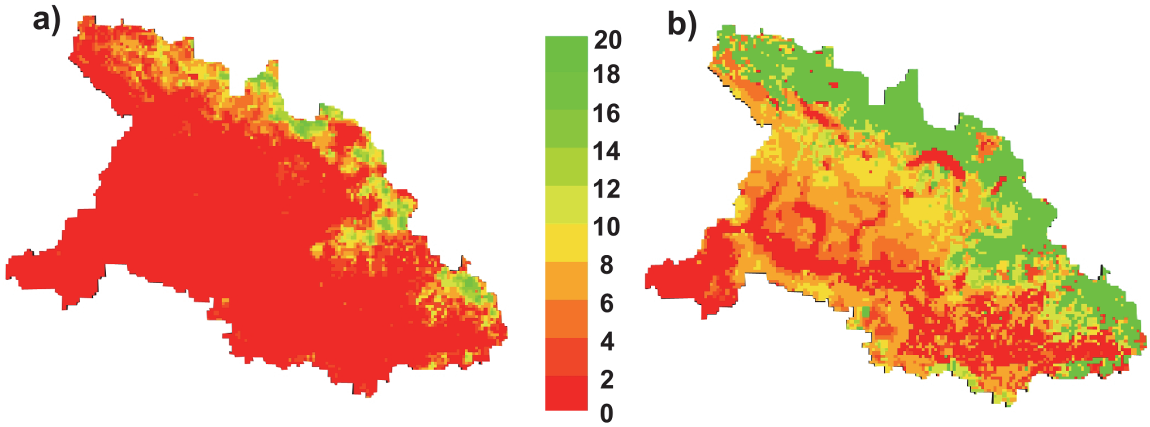

Fig.3. Distribution of the leaf area index in January (a) and July (b) in the Upper Tisza Basin.

Beside the main characteristics of the catchment, DIWA also needs meteorological input data for the simulation. In this study, the necessary time series (precipitation, mean and minimum temperatures) are provided by the CARPATCLIM database (*Spinoni et al.,* 2015) and the RegCM4 (*Elguindi et al.,* 2011) regional climate model. Currently, CARPATCLIM is considered as a reference, hence it is based on station measurements – which are interpolated to a regular grid (0.1°) using the MISH algorithm (*Bihari* and *Szentimrey,* 2013). The time series are available for 50 years (1961–2010) with a daily time step. The homogenization was solved by the MASH software (*Bihari* and *Szentimrey,* 2013). To assess the projected future changes, RegCM4 simulations with 10 km horizontal resolution (*Pieczka et al.*, 2017b) are used, nested into the 50 km resolution run, which is driven by the HadGEM global climate model (*Collins et al.,* 2011). The transient simulation encompasses 130 years (1970–2099) with a daily time step. In our investigation, RegCM4 takes into account a high anthropogenic impact via the RCP8.5 scenario (i.e., the estimated change of radiative forcing is 8.5 W/m^2 compared to the pre-industrial conditions). According to this scenario, population and GHG emission will grow in the future with high energy consumption and moderate technical development. Considering land use changes, pastures and agricultural areas will increase, while natural vegetation will decrease by the end of the 21st century (*van Vuuren et al.,* 2011).

The applied methodology is summarized in *Fig. 4.* First of all, the calibration of the DIWA hydrological model is completed for the Upper Tisza catchment. Then, DIWA simulation using CARPATCLIM data is validated for a two-year-long time period (containing both extreme high and persistent low runoff periods) using observations. The RegCM4 climate model is run for the Central European region (i.e., 43.8–50.6°N; 6–29°E). In order to assess how well the RegCM4 simulation performs, the RCM-outputs are compared to the CARPATCLIM dataset for a 30-year-long historical time period (1971–2000). If the agreement is not fully satisfactory, a bias correction method can be applied to the raw RCM-outputs, and the bias-corrected time series can be validated again to the CARPATCLIM data. Projected future climate conditions can be analyzed on the basis of both the raw and bias-corrected RCM-outputs. As a next step, simulations with DIWA are completed for the past, using meteorological data provided by the CARPATCLIM and the historical run of RegCM4. The simulated runoff values are then used for hydrological validation. If the simulation is successful for the past (i.e., the reconstruction of hydrological conditions is satisfactory), experiments can proceed for the future using simulated meteorological time series of RegCM4. Finally, a detailed statistical analysis and comparison of runoff outputs for different time periods and/or input meteorological parameters are completed. Note, that in this study we analyze only the climatic impacts on runoff; other factors (i.e., topography, land use, soil type, vegetation coverage) are considered to remain constant during the 21st century.

3. Results and discussion

The results of the hydrological simulations are presented in this section: after the calibration and validation, seasonal runoff is analyzed for three 30-year-long time periods (reference 1971–2000, and future 2021–2050, 2069–2098).

The calibration of DIWA is completed for the target area by fine-tuning different parameters, namely, the water-storage capacity of the surface, the saturated hydraulic conductivity of the so-called O-horizon (i.e., concentrated organic layer, which consists of decaying plant and animal tissues), the critical temperature of snowmelt, and the numerical diffusion. We used CARPATCLIM data for the calibration, which are considered as reference against RegCM4 outputs. Observations are available for a couple of years for Tiszabecs gauge (48.1°N; 22.8°E), so we could validate the runoff values from the CARPATCLIM driven DIWA simulation against them (*Fig. 5*). There is an extremely large runoff value on the 310th day of the calibration period (May 1, 2000–April 30, 2002): the DIWA simulation reproduces this peak, however, the observation is slightly underestimated. In general, an underestimation of observations can be found in the hydrological winter period (from November to March, indicated by grey background in *Fig. 5*), which is probably because of snow accumulation/melting. A longer period with low values occurs between the 150th and 192nd days of the calibration period, which is realistically simulated by DIWA. To sum up, it can be concluded that the DIWA simulation is in an acceptable agreement with observations, as its timing is adequate and there are no systematic errors. Therefore, the calibration process is considered to be successful.

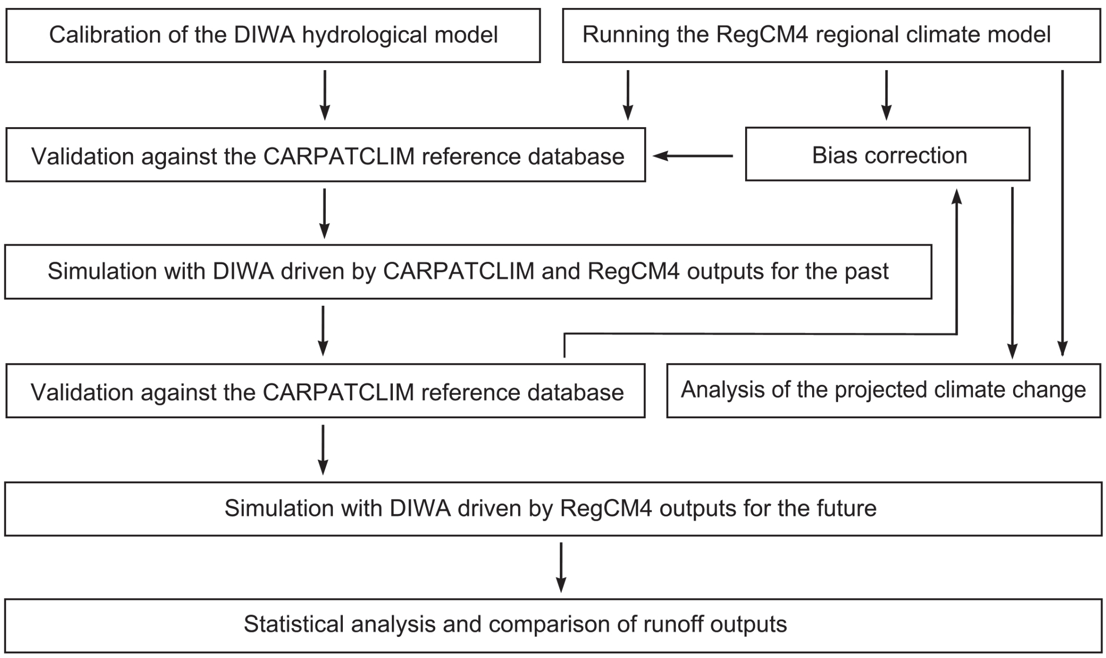

Fig.4. Main steps of the presented analysis.

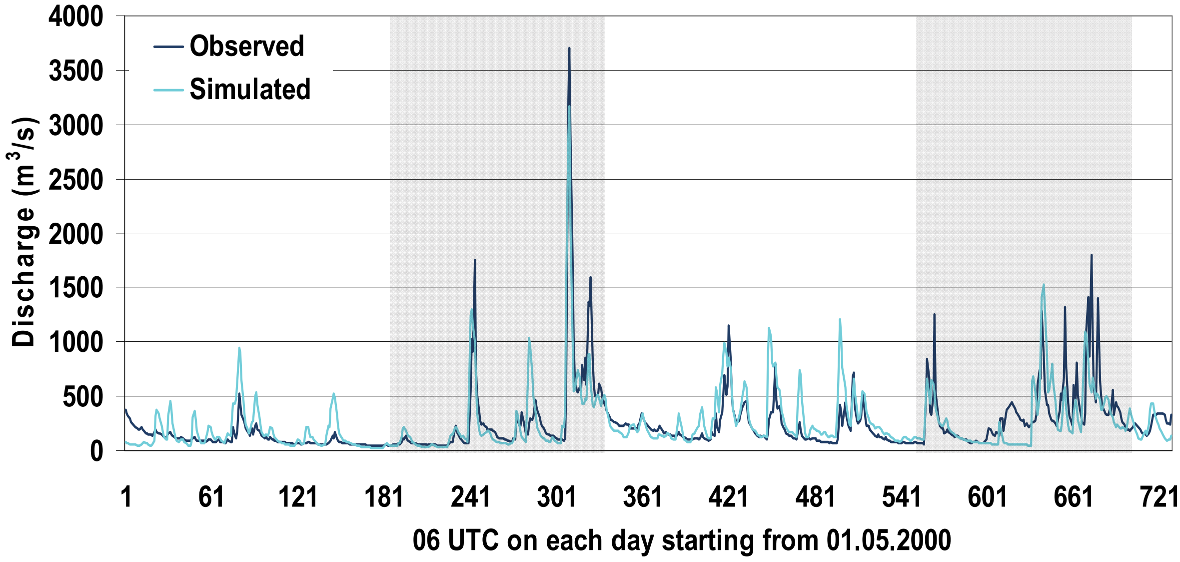

Fig. 5. Calibration of the DIWA hydrological model for Tiszabecs gauge (48.1°N; 22.8°E) using CARPATCLIM data as driving meteorological input for the May 1, 2000–Aril 30, 2002 period (reference: observations). Grey background indicates winter (from November to March).

Time series from RCM simulations are used for estimating future tendencies. In order to test how reliable the RegCM4 outputs are, DIWA simulations for 1971–2000 are compared using (i) CARPATCLIM and (ii) RCM meteorological data as input on a Q-Q plot comparing the empirical distributions of simulated hydrological time series (*Fig. 6*). On the one hand, the winter runoff values are overestimated when DIWA uses RCM outputs. The largest difference occurs above the 65th percentile, when RegCM4-driven DIWA simulates one and a half times higher runoff values than CARPATCLIM-driven DIWA. On the other hand, a slight underestimation can be found in summer. This discrepancy probably appears, because the RegCM4 historical simulation overestimates precipitation throughout the year, except in summer (*Pieczka et al.,* 2017a). In order to eliminate these systematic errors, applying a bias correction to the raw RCM outputs is advisable. However, the bias correction might distort the physical consistency of climate simulations, which becomes an important issue when more than one meteorological variable are used in the subsequent impact study. Therefore, we used only raw RCM data here to analyze the likely hydrological trends in the future. (Note that the projected discharge values might not be realistic due to the general overestimation of precipitation.)

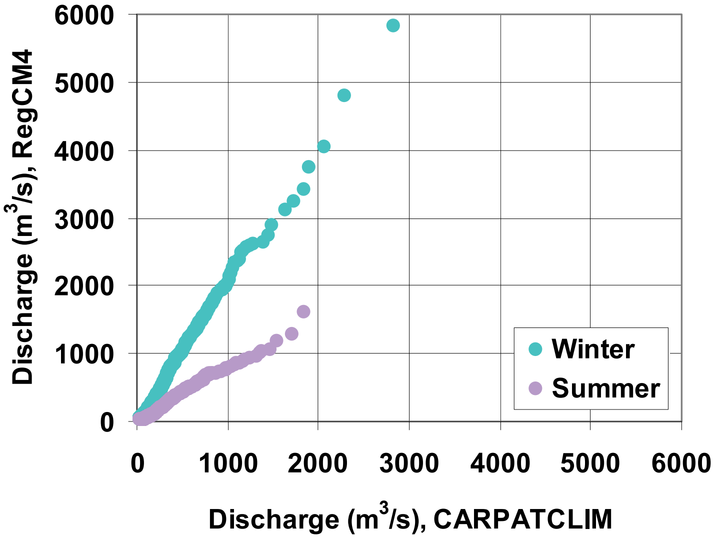

Fig. 6. Seasonal Q-Q plots of the hydrological simulations using the RegCM4 and CARPATCLIM time series for the 1971–2000 period.

Considering the annual distribution of daily runoff values at Tiszabecs gauge, substantial changes are estimated by the end of the 21st century (*Fig. 7*). The most pronounced decrease is projected for April: the 90th percentile of calculated daily runoff values is likely to decrease by 55%; furthermore, the upper quartile, the median, and the lower quartile are also estimated to become lower by 48%, 49%, and 30%, respectively. In 1971–2000, snowmelt dominantly occurred in spring; less snow is likely to accumulate in the future winters because of the overall warming. Therefore, discharge peaks – induced by melting in spring – will not be as high in the future as they were in the past reference period. Moreover, the decrease of discharge is also projected for summer, especially August, which is in line with the RegCM4-simulated drying projection in the Carpathian Basin, including the Upper Tisza catchment. The results show that mainly the difference between the lower and upper quartiles are likely to decrease from June to September. In July and August, the 90th percentiles are also projected to decrease, so the variation of runoff values in these two months will probably become smaller. The simulated changes of the median are –42%, –53%, and –65% in June, July, and August, respectively. On the contrary, from November to February, an increase of the runoff values is estimated. In January and February, both the upper quartile and the 90th percentile are projected to become much higher by 2069–2098, presumably because of the estimated increase of precipitation totals in these months. The median is also likely to increase by 188% in January and 125% in February. In the case of the 10th percentile, no substantial change is likely to occur in any month of the year. Considering the annual distribution of runoff, the highest values of the 75th and 90th percentiles occurred in March and April in the late 20th century, while the lowest percentile values were detected in January, July, and August. This temporal distribution is likely to be somewhat restructured by the late 21st century: the highest runoff is shifted towards the winter months and the lowest values are still likely to occur in late summer (i.e., August).

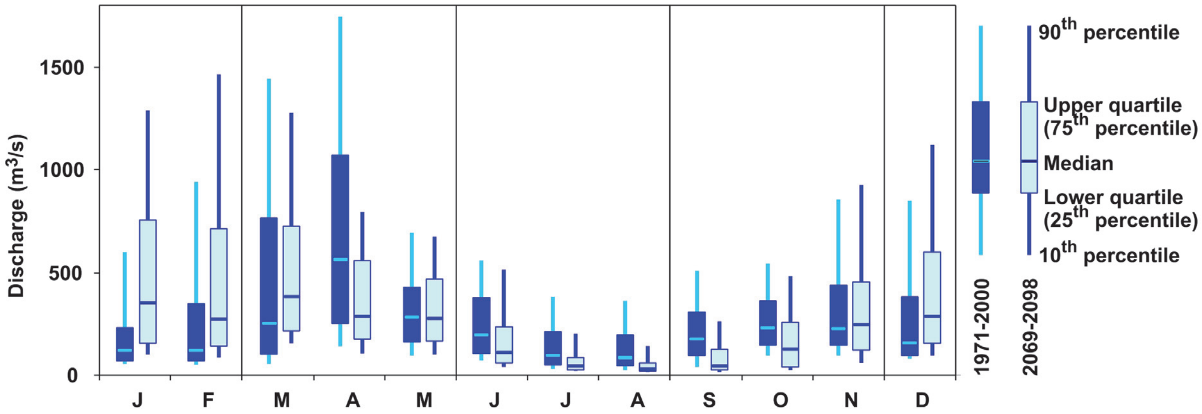

Fig. 7. Annual distribution of the 10th, 25th, 50th, 75th, and 90th percentiles of runoff values calculated for each month at Tiszabecs gauge (48.1°N; 22.8°E), based on the daily averages of the 30-year-long time periods (1971–2000 and 2069–2098).

Considering the seasonal empirical distribution functions of runoff (*Fig. 8*), a clear decrease is projected for the future, except in winter (*Fig. 8a*). Only a slight shift is estimated in winter by the middle of the 21st century compared to the reference period, which is projected to be followed by a larger increase of runoff values by the end of the 21st century, especially in the case of the low (< 5th percentile) extremes (their relative change exceeds 100%). The projected change of runoff is caused by the general increase of total precipitation and the overall warming in the area: as a result of higher temperature values, snow accumulation will be substantially less than in the recent past. Moreover, a greater portion of precipitation is likely to occur in the form of rain instead of snow, which leads water to proceed faster into the runoff process. The shapes of the empirical distribution functions in winter are quite similar to each other for the different 30-year-long periods.

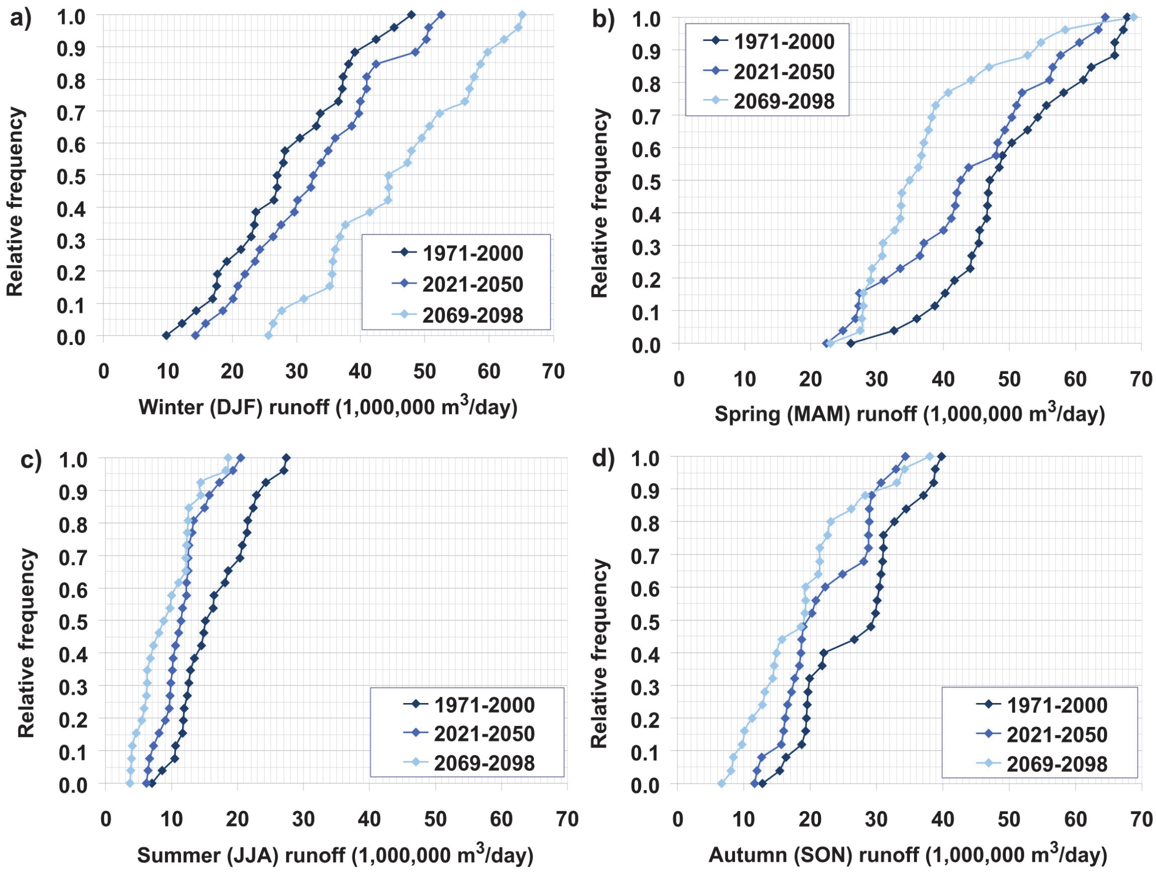

Fig. 8. Comparison of simulated seasonal average runoff distributions at Tiszabecs gauge (48.1°N; 22.8°E).

In spring, a decreasing tendency is expected (*Fig. 8b*), which can also be explained by the projected changes of snow accumulation. In the Upper Tisza catchment, snowmelt is dominant in March and April – if less snow will be accumulated in winter then less water will appear during the spring melting, thus, less water flows into the rivers as well. Furthermore, low and high extremes are not projected to change substantially; values between the 5th and 95th percentiles are likely to decrease (significantly by the end of the 21st century).

According to the RegCM4-driven DIWA simulation, the smallest runoff values occurred in summer during the late 20th century, the runoff is estimated to decrease in the future (*Fig. 8c*). Greater runoff values (above the 65th percentile) are likely to decrease already by the middle of the 21st century, and then, no further substantial change is projected by the late 21st century. The projected shift of the distribution in the smaller runoff values (below the 65th percentile) is more balanced throughout the century: the relative average changes are –26% and –49% by 2021–2050 and 2069–2098, respectively. This overall summer decrease of runoff can be explained by a general projected summer drying in the catchment.

Similarly to spring and summer, a decrease of runoff is likely to occur in autumn (*Fig. 8d*), which is mainly due to the projected decrease of precipitation totals relative to 1971–2000. Larger change compared to the reference is estimated mainly by 2069–2098. However, in the case of high extremes (> 90th percentile), a larger decrease is projected by 2021–2050 than 2069–2098.

4. Conclusions

Hydrological simulations using RCM-outputs are presented in this study for the Upper Tisza catchment. For the analysis, the physically based, distributed DIWA hydrological model driven by the RegCM4 regional climate model taking into account the RCP8.5 scenario was used. Validation shows that RegCM4 simulations usually overestimate precipitation, except in summer (compared to the CARPATCLIM reference database). This bias appears in the case of hydrological simulations as well; therefore, this paper focuses on the analysis of projected changes via distributions instead of the actual values.

The yearly average of runoff values is estimated to decrease; however, both monthly and seasonal scale analyses reveal different trends within the year. (i) Analyzing the simulated discharge values on a monthly scale, one can conclude that decreasing tendency is likely to occur in spring (especially in April) and summer, while a substantial increase is projected for the winter months, especially in the case of higher (75th and 90th) percentile values. (ii) According to our results focusing on seasonal scale, an overall decrease of runoff values is projected for spring, summer, and autumn, which can mainly be explained by the simulated decrease of precipitation totals in these seasons. On the contrary, a substantial runoff increase is estimated in winter related to the general increase of winter precipitation and the reduction of snow accumulation due to higher temperatures. It is also important to note that both the low and high extreme runoff values are likely to change (except in spring). Our results confirm a former analysis for the Upper Tisza catchment (*Pongrácz et al.,* 2013), which used a previous version of DIWA driven by bias-corrected RCM simulation (i.e., PRECIS outputs (*Bartholy et al.,* 2014) bias-corrected by the percentile-based method) with coarser (i.e., 25 km) horizontal resolution, taking into account the SRES A1B scenario. Although a quite different RCM and a different scenario were used here, the opposite hydrological trends of winter and summer are projected in our study as well. These similarities are very promising, however, it is important to note that in order to provide as valuable input as possible for decision makers in water management, more hydrological model experiments are needed using different hydrological models, different driving RCMs, and all available scenarios.

Acknowledgements: Research leading to this paper has been supported by the EEA Grant HU04 Adaptation to Climate Change Programme (EEA-C13-10), the Ministry of National Development of the Hungarian Government via the AGRÁRKLIMA2 project (VKSZ_12-1-2013-0034), the Széchenyi 2020 programme, the European Regional Development Fund, and the Hungarian Government (GINOP-2.3.2-15-2016-00028). Furthermore, we acknowledge the CARPATCLIM Database © European Commission – JRC, 2013.

References

Amengual, A., Homar, V., Romero, R., Ramis, C., and *Alonso, S.,* 2014: Projections for the 21st century of the climate potential for beach-based tourism in the Mediterranean. *Int. J. Climatol. 34*, 3481–3498.

Bartholy, J., Pongrácz, R., and *Pieczka, I.,* 2014: How the climate will change in this century? *Hun. Geograph. Bull*. 63, 55–67.

Betts, R.A., 2005: Integrated approaches to climate–crop modelling: needs and challenges. *Phil. Trans. R. Soc*. B 360(1463), 2049–2065.

Bihari, Z. and *Szentimrey, T.,* 2013: CARPATCLIM Deliverable D2.10. Annex 3 – Description of MASH and MISH algorithms.

Blenckner, T., Omstedt, A., and *Rummukainen, M.,* 2002: A Swedish case study of contemporary and possible future consequences of climate change on lake function. *Aquatic Sci. 64*, 171–184.

Cameron, D., Beven, K., and *Naden, P.,* 2000: Flood frequency estimation by continuous simulation under climate change (with uncertainty). *Hydrol. Earth Syst. Sci. 4*, 393–405.

Collins, W.J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C.D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and *Woodward, S.,* 2011: Development and evaluation of an Earth-system model – HadGEM2. *Geosci Model Dev 4*, 997–1062.

Damm, A., Köberl, J., and *Prettenthaler, F.,* 2014: Does artificial snow production pay under future climate conditions? – A case study for a vulnerable ski area in Austria. *Tourism Manage. 43*, 8–21.

Dankers, R. and *Feyen, L.,* 2008: Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *J. Geophyis. Res. 113*, D19105.

Dobor, L., 2016: Possible impacts of climate change on the productivity and carbon balance of Hungarian croplands. *PhD dissertation,* ELTE, Budapest. 147p. (in Hungarian)

Elguindi, N., Bi, X., Giorgi, F., Nagarajan, B., Pal, J., Solmon, F., Rauscher, S., Zakey, A., and *Giuliani, G.,* 2011: Regional climatic model RegCM – User manual. Version 4.3. ICTP, Trieste, Italy.

Falter, D., Schröter, K., Dung, N.V., Vorogushyn, S., Kreibich, H., Hundecha, Y., Apel, H., and *Merz, B.,* 2015: Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain. *J. Hydrology 524*, 182–193.

Fischer, G., Shah, M., and *van Velthuizen, H.,* 2002: Climate Change and Agricultural Vulnerability. A special report, prepared by the International Institute for Applied Systems Analysis under United Nations Institutional Contract Agreement No. 1113 on “Climate Change and Agricultural Vulnerability” as a contribution to the World Summit on Sustainable Development, Johannesburg 2002.

Garambois, P.A., Larnier, K., Roux, H., Labat, D., and *Dartus, D.,* 2014: Analysis of flash flood-triggering rainfall for a process-oriented hydrological model. *Atmos. Res. 137*, 14–24.

Gleick, P.H., 2014: Water, Drought, Climate Change, and Conflict in Syria. *Weather clim. Soc. 6*, 331–340.

Gosling, S.N., and *Arnell, N.W.,* 2013: A global assessment of the impact of climate change on water scarcity. *Climatic Change 134*, 371–385.

Hagemann, S. and *Dümenil, L.,* 1998: Documentation for the Hydrological Discharge Model. Max Planck Institute for Meteorology, Technical Report No. 17. ISSN 0940-9327

Hejazi, M.I., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedli, V., Wise, M., Patel, P., Eom, J., and *Calvin, K.,* 2014: Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrol. Earth Syst. Sci.* 18, 2859–2883.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and *Kanae, S.,* 2013: Global flood risk under climate change. *Nat. Climate Change 3*, 816–821.

Hofierka, J., and *Knutová, M.,* 2015: Simulating spatial aspects of a flash flood using the Monte Carlo method and GRASS GIS: a case study of the Malá Svinka Basin (Slovakia). *Open Geosci. 7*, 118–125.

Jacob, D., and *Podzun, R.,* 1997. Sensitivity studies with the regional climate model REMO. *Meteorol. Atmos. Phys.* 63, 119–129.

Kay, A.L., and *Jones, R.G.,* 2012: Comparison of the use of alternative UKCP09 products for modelling the impacts of climate change on flood frequency. *Climatic Change 114*, 211–230.

Kovács, A., Németh, Á., Unger, J., and *Kántor, N.,* 2017: Tourism climatic conditions of Hungary – present situation and assessment of future changes. *Időjárás 121*, 79–99.

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., and *Kaspar, F.,* 2006: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Climatic Change 75*, 273–299.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., and *Morgan, P.B.,* 2005: Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Phil. Trans. R. Soc. B 360*(1463), 2011–2020.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., and *Kjeldsen, T.R.,* 2014: Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *J. Hydrol. 519,* 3634–3650.

Mall, R.K., Gupta, A., and *Sonkar, G.,* 2017: Effect of Climate Cahnge on Agricultural Crops. In (Eds.: *Dubey, S.K., Pandey, A., Sangwan, R.S.*) Current Developments in Biotechnology and Bioengineering Elsevier, Academic Press.

Meier, H.E., Müller-Karulis, B., Andersson, H.C., Dieterich, C., Eilola, K., Gustafsson, B.G., Höglund, A., Hordoir, R., Kuznetsov, I., Neumann, T., Ranjbar, Z., Savchuk, O.P., and *Schimanke, S.,* 2012: Impact of Climate Change on Ecological Quality Indicators and Biogeochemical Fluxes in the Baltic Sea: A Multi-Model Ensemble Study. *AMBIO 41*, 558–573.

Morin, X., and *Thuiller, W.,* 2009: Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology 90*, 1301–1313.

Nakicenovic, N. and *Swart, R.,* 2000: Emissions Scenarios. A special report of IPCC Working Group III. Cambridge University Press, UK.

Nik, V.M., 2016: Making energy simulation easier for future climate – Synthesizing typical and extreme weather data sets out of regional climate models (RCMs). *Appl. Energy 177,* 204–226.

Pieczka, I., Pongrácz, R., André, K.S., Kelemen, F.D., and *Bartholy, J.,* 2017a: Sensitivity analysis of different parameterization schemes using RegCM4.3 for the Carpathian region. *Theor. Appl. Climatol.130*, 1175–*1188.*

Pieczka, I., Pongrácz, R., Bartholy, J., and *Szabóné André, K.,* 2017b: Future temperature projections for Hungary based on RegCM4.3 simulations using new representative concentration pathways scenarios. *Int. J. Glob. Warming*, in press.

Pongrácz, R., Bartholy, J., and *Szabó, J.A.,* 2013: Distributed hydrological modelling- and stochastic weather generator-based combined estimation technique for future flood frequency using regional climate model simulation. In: *93rd Annual Meeting of the American Meteorological Society*. Austin, TX. Paper J6.1, 9p. Available online at https://ams.confex.com/ams/93Annual/webprogram/Manuscript/Paper218149/PR-BJSZJA-AMS-2013-paper-final.pdf

Porter, J.R., and *Semenov, M.A.,* 2005: Crop responses to climatic variation. *Phil. Trans. R. Soc. B. 360*(1463), 2021–2035.

Radvánszky, B. and *Jacob, D.,* 2008: Prospective climate changes in the drainage area of the River Tisza and their effects on the overlend flow. Application of the Regional Climate Model (REMO) and the Hydrological Discharge Model (HD). *Hidrológiai Közlöny* 88, 33–42. (in Hungarian)

Radvánszky, B. and *Jacob, D.,* 2009: The changing annual distribution of rainfall in the drainage area of the River Tisza during the second half of the 21st century. *Zeit. Geomorphol. 53*(Suppl. 2), 171–195.

Reed, S., Schaake, J., and *Zhang, Z.,* 2007: A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations. *J. Hydrol. 337*, 402–420.

Rojas, R., Feyen, L., Bianchi, and *A., Dosio, A.,* 2012: Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. *J. Geophys. Res. 117,* D17109.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., and *Jones, J.W.,* 2013: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Nat. Acad. Sci. USA 111*, 3268–3273.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., and *Kabatt, P.,* 2014: Multimodel assessment of water scarcity under climate change. . *Proc. Nat. Acad. Sci. USA 111*, 3245–3250.

Spinoni, J. and *the CARPATCLIM project team (39 authors),* 2015: Climate of the Carpathian Region in 1961–2010: Climatologies and Trends of Ten Variables. *Int. J. Climatol.* 35, 1322–1341.

Szabó, J.A., 2007: Decision Supporting Hydrological Model for River Basin Flood Control. In (eds.: *Peckham, R.J.* and *Jordan, Gy*.) Digital Terrain Modelling: Development and Applications in a Policy Support Environment, Springer-Verlag, Germany, 145–182.

Szelepcsényi, Z., Breuer, H., Kis, A., Pongrácz, R., and *Sümegi, P.,* 2016: Assessment of projected climate change in the Carpathian Region using the Holdridge life zone system. *Theor. Appl. Climatol.* DOI: 10.1007/s00704-016-1987-3

Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Zalud, Z., and *Semenov, M.A.,* 2014: Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Clim. Chan. 4*, 637–643.

Velasco, M., Versini, P.A., Cabello, A., and *Barrera-Escoda, A.,* 2013: Assessment of flash floods taking into account climate change scenarios in the Llobregat River basin. *Nat. Hazards Earth Syst. Sci. 13*, 3145–3156.

van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Thomson, A.M., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., and *Rose, S.,* 2011: The representative concentration pathways: an overview. *Climatic Change 109*, 5–31.