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CLIMATE CHANGE AND AGRICULTURE PAPER

Is rainfed crop production in central Europe at risk? Using a regional climate model to produce high resolution agroclimatic information for decision makers

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SUMMARY

The reality of climate change has rarely been questioned in Europe in the last few years as a consensus has emerged amongst a wide range of national to local environmental and resource policy makers and stakeholders that climate change has been sufficiently demonstrated in a number of sectors. A number of site-based studies evaluating change of attainable yields of various crops have been conducted in Central Europe, but studies that evaluate agroclimatic potential across more countries in the region are rare. Therefore, the main aim of the present study was to develop and test a technique for a comprehensive evaluation of agroclimatic conditions under expected climate conditions over all of Central Europe with a high spatial resolution in order to answer the question posed in the title of the paper 'Is rainfed crop production in central Europe at risk?' The domain covers the entire area of Central Europe between latitudes 45° and 51·5°N and longitudes 8° and 27°E, including at least part of the territories of Austria, the Czech Republic, Germany, Hungary, Poland, Romania, Slovakia, Switzerland and Ukraine. The study is based on a range of agroclimatic indices that are designed to capture complex relations existing between climate and crops (their development and/or production) as well as the agrosystems as a whole. They provide information about various aspects of crop production, but they are not meant to compete with other and sometimes more suitable tools (e.g. process-based crop models, soil workability models, etc.). Instead, the selected indices can be seen as complementary to crop modelling tools that describe aspects not fully addressed or covered by crop models for an overall assessment of crop production conditions. The set of indices includes: sum of effective global radiation, number of effective growing days, Huglin index, water balance during the period from April to June (AMJ) and during the summer (JJA), proportion of days suitable for harvesting of field crops in June and July, and proportion of days suitable for sowing in early spring as well as during the autumn. The study concluded that while the uncertainties about future climate change impacts remain, the increase in the mean production potential of the domain as a whole (expressed in terms of effective global radiation and number of effective growing days) is likely a result

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of climate change, while inter-annual yield variability and risk may also increase. However, this is not true for the Pannonian (the lowlands between the Alps, the Carpathian Mountains and the Dinaric Alps) and Mediterranean parts of the domain, where increases in the water deficit will further limit rainfed agriculture but will probably lead to an increase in irrigation agriculture if local water resources are dwindling. Increases in the severity of the 20-year drought deficit and more substantial water deficits during the critical part of the growing season are very likely over the central and western part of the domain. Similarly, the inter-annual variability of water balance is likely to increase over the domain. There is also a chance of conditions for sowing during spring deteriorating due to unfavourable weather, which might increase the preference given to winter crops. This is already likely due to their ability to withstand spring drought stress events. Harvesting conditions in June (when harvest of some crops might take place in the future) are not improving beyond the present level, making the planning of the effective harvest time more challenging. Based on the evidence provided by the present study, it could be concluded that rainfed agriculture might indeed face more climate-related risks, but the overall conditions will probably allow for acceptable yield levels in most seasons. However, the evidence also suggests that the risk of extremely unfavourable years, resulting in poor economic returns, is likely to increase.

INTRODUCTION

For some time now, the reality of climate change has rarely been questioned in Europe as a consensus has emerged amongst a wide range of national to local environmental and resource policy makers and stakeholders that climate change has been sufficiently demonstrated in a number of sectors. The warming trend (+0·90 °C for 1901–2005) throughout Europe (e.g. Richardson *et al.* 2009) is well established, with similar values reported for Central Europe (e.g. Brázdil *et al.* 2009*a*,*b*), and it has been accelerating in the last 30 years (Alcamo *et al.* 2007). Compared to temperature, the precipitation trends are more variable spatially, with the mean winter precipitation increasing in most parts of western and northern Europe (Klein Tank 2004). In contrast, precipitation trends are negative in the eastern Mediterranean area, with no significant change in the west (Norrant & Douguédroit 2006) or in Central Europe, namely the Czech Republic (e.g. Brázdil *et al.* 2009*a*). In the case of Central Europe, the distribution of precipitation over the course of the year has become more regular in terms of the Markham seasonality index (Brázdil *et al.* 2009*a*), with a drop in precipitation reported in the early growing season (April–June). These findings were recently summarized in a report by Richardson *et al.* (2009), which concluded that greenhouse gas emissions and many aspects of the climate are changing and are near the upper boundary of the International Panel on Climate Change (IPCC) range of projections. Many key climate indicators are already moving beyond the patterns of the known natural variability within which contemporary society and the economy have developed and thrived. These indicators also include extreme climatic events, and it is clear that with unabated emissions, many trends in climate will probably accelerate, leading to an increasing risk of abrupt or irreversible climatic shifts (e.g. Richardson *et al.* 2009).

The ensemble of global circulation models (GCMs) agrees on the overall drying trend in mostly semi-arid and arid Mediterranean regions, while the trend towards a more humid climate is generally expected in northern Europe (IPCC 2007). The GCM projections do not agree on the likely water balance patterns in Central Europe (with ensemble mean indicating no change). However, recent studies based on previously unavailable data have shown that major and unprecedented drought event(s) in Central Europe are more likely to occur in the near future than at any time in the past 130 years (e.g. Brázdil *et al.* 2009*a*,*b*; Dubrovský *et al.* 2009; Trnka *et al.* 2009*a*,*b*). At the same time, several projections of water availability (e.g. the WaterGAP project at the University of Kassel (see http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/WaterGAP/index.html or CEC 2007) indicate that Central Europe is likely to face significant increases in water deficits. This is a critical issue for a region where the agriculture sector relies to a large degree on sufficient and evenly distributed precipitation (Table 1), while having an infrastructure adapted to what now appears to be the relatively benign climate of the 20th century. It is not a coincidence that Central Europe was classified as a climate change 'hot-spot' by Giorgi (2006), as the recent evidence of Seneviratne *et al.* (2006) suggests that climatic regimes in Europe are shifting northwards in response to increasing greenhouse gas concentrations, creating a new transitional climate zone with strong land–atmosphere coupling in central and eastern Europe. This might lead not only to increased variability in temperature, but probably also in the precipitation.

The overall effect of climate change on crop production is likely to be mixed and dependent on

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Table 1. *Overview of the agriculture and irrigated area in the represented countries within the ALADIN domain during the period from 2003 to 2007*

Country	Country area (1000 ha)	Agricultural area (1000 ha)	Arable land area (1000 ha)	Area equipped for irrigation: total (1000 ha)	Proportion of area actually irrigated from area equipped for irrigation	Agricultural water withdrawal as proportion of total renewable water resources
Austria	8387	3240	1382	119	0·335	0·00025
Czech Republic	7887	4249	3032	47	0·368	0·00456
Hungary	9303	5807	4592	153	0·492	0·0236
Slovakia	4903	1930	1377	180	0·249	ND
Slovenia	2027	500	177	4	0·506	ND

Data obtained from AQUASTAT and FAOSTAT statistical databases (FAO 2009).
ND, no data available.

the local environmental as well as on socio-economic factors (e.g. Eitzinger *et al.* 2009*b*). Due to increasing temperatures, some crops that are currently grown mostly in Southern Europe (e.g. maize, sunflower and soybeans) will become viable further north or at higher-altitude areas in the south (Audsley *et al.* 2006), and the length of the growing season might increase. At the same time, the projected increase in extreme weather events, e.g. spells of high temperatures and droughts, can enhance inter-annual yield variability (Jones *et al.* 2003) and reduce average yield (Trnka *et al.* 2004). In the case of crop production, the key uncertainty lies within eventual increases in the frequency of unfavourable weather or even extreme events during sensitive crop development stages. These include, for example, heat stress (especially when combined with drought) during the flowering period or rainy days during sowing and harvest time. The latter could force sowing to occur outside of the optimum range, while rainy days during harvest could ruin the product quality. While a number of site-based studies evaluating the change of attainable yields of various crops have been conducted in the region, studies aimed at evaluating agroclimatic potential across more countries in the region are rare. One of the main reasons for this is limited national and transnational availability or quality of both climatic and of soil and crop management data. This shortage of data can significantly increase uncertainties in the results of, for example, crop modelling studies (Eitzinger *et al.* 2008; Orlandini *et al.* 2008). The main aim of the present study was to develop and test a technique for a comprehensive evaluation of agroclimatic conditions under expected climate conditions over all of Central Europe with a high spatial resolution and to answer the question posed in the title of the paper, *viz* ‘Is the rainfed crop production in Central Europe at risk?’

MATERIALS AND METHODS

Study domain and regional climate model (RCM) model set-up

One of the major restrictions of climate change studies in Central Europe has been a lack of climate data with sufficient density. In order to overcome this hurdle, outputs of the RCM ALADIN-Climate/CZ, made available through the CECILIA project (www.cecilia-eu.org), were applied using the scheme presented in Fig. 1. The present study was prepared in close collaboration with the model developers from the Czech Hydrometeorological Institute (CHMI), which is also taking part in the international consortium involved in developing and using another version of ALADIN for weather prediction. The first test running of ALADIN-Climate/CZ for a longer period was performed at the end of the 1990s and showed the capability of the model to be adapted for climate research purposes (Huth *et al.* 2004). Further work has led to the development of a regional climate model and the current version of the RCM ALADIN-Climate/CZ is derived from ALADIN NWP version CY28T3, with details as described in Farda *et al.* (2007). It should be noted that ALADIN-Climate/CZ is a different model from the RCM ALADIN-Climate model developed at Centre National de Recherches Météorologiques of Météo-France, which is employed in other countries of the ALADIN consortium.

The first step in preparing the study was to conduct a high-resolution simulation of the baseline (1961–2000) climate conditions, which was performed with ALADIN-Climate/CZ over the Central Europe domain. The area considered, the domain, covers the entire area of Central Europe between latitudes 45° and 51·5°N and longitudes 8° and 27°E, including at least part of the territories of Austria, the Czech Republic, Germany, Hungary, Poland, Romania,

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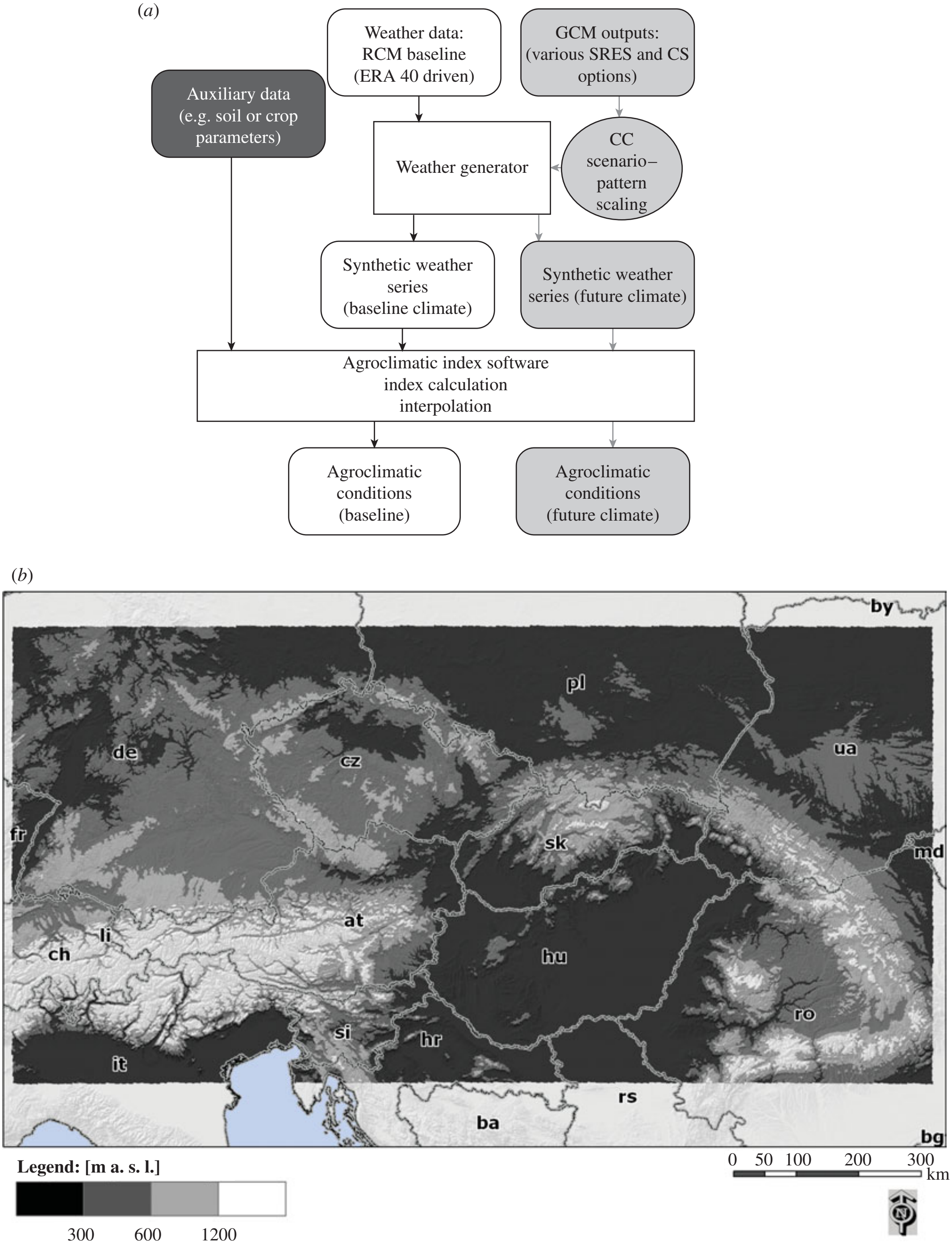

Fig. 1. (*a*) Flowchart of the study methodology. GCM, global circulation models; RCM, regional circulation models; CC, climate change; SC, scenario. (*b*) Overview of the domain considered in the study including basic map of altitude and national boundaries. Countries are indicated by internet country codes (at = Austria; ba = Bosnia and Herzegovina; by = Belarus; ch = Switzerland; cz = Czech Republic; de = Germany; fr = France; hr = Croatia; it = Italy; li = Liechenstein; md = Moldova; ro = Romania; rs = Serbia).

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Slovakia, Switzerland and Ukraine. For the present climate run, the perfect lateral boundary condition (LBC) represented by ERA-40 re-analysis (ERA-40 is a re-analysis of meteorological observations from September 1957 to August 2002 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with many institutions; Uppala *et al.* 2005) was used, and the nesting technique was applied to enable RCM ALADIN with a 10 km grid to be driven by a coarse resolution ERA-40 re-analysis. The ALADIN 50 km grid integration forced by ERA-40 re-analysis was taken to drive the model at 10 km resolution over the smaller, Central European, domain. A summary of the experimental settings and results of the run in comparison with observed data can be found in Skalák & Štěpánek (2008).

In most of the studies where the RCMs are used to produce high resolution data for the future climate conditions, the boundary conditions of RCMs are derived from a run of a GCM, and the RCM is nested within the global domain of a particular GCM. The main disadvantage of this conventional approach is that it requires run times of several months, which limits the number of GCMs that are considered. As the inter-GCM variability for the Central European region is considerable (e.g. Dubrovský *et al.* 2005), an alternative approach was proposed and applied in the present study (Fig. 1). To avoid long run times, the climate change scenarios were developed by means of combining the RCM data for the baseline climate and GCM-based scenarios. At first, the parameters of the weather generator (WG) were derived for each ALADIN-Climate/CZ grid from the ERA-40 driven ALADIN-Climate/CZ run for the period (1961–90). Then, the WG M&Rwin (a follower of Met&Roll described in Dubrovský *et al*. 2000, 2004) was applied in each grid to obtain the set of WG parameters for the present climate. These grid-specific parameters were perturbed according to the appropriate GCM-based climate change scenarios derived by the 'pattern-scaling' technique. In this approach, the climate change scenario is defined by the product of the standardized scenario and the change in global mean temperature (ΔT_G). The standardized scenarios, which relate to the increase in global mean temperature by 1 K, were derived from the outputs of three GCMs from an IPCC-AR4 database (HadCM3 (the third version of the Hadley Centre coupled model), NCAR–PCM (National Center for Atmospheric Research–Parallel Climate Model) and ECHAM5 (the fifth generation of the Max Planck Institute for Meteorology atmospheric general circulation model)). The value of ΔT_G was determined by the MAGICC model (Harvey *et al.* 1997; Hulme *et al.* 2000), assuming high climatic sensitivity (4·5 K) and emission scenario IPPC SRES-A2. The MAGICC estimate for these settings is $\Delta T_G = 2{\cdot}3$ K, which is slightly lower than the change in global mean temperature for 2100 assuming moderate climate sensitivity (2·6 K) and emission scenarios ($\Delta T_G = 2{\cdot}7$ K for SRES-B2 and $\Delta T_G = 3{\cdot}0$ K for SRES-A1b). As a result, the present impacts for 2050 (using 'high' versions of GCM-based scenarios) are about the same as those for the end of the 21st century with 'moderate' versions of the climate change scenarios. Based on the results of Dubrovský *et al*. (2005), it was assumed that ECHAM, HadCM and NCAR would provide a representative triplet, as they represent various versions of the expected climate for the region. As the outcome of the procedure (Fig. 1), the daily weather series of meteorological data (daily sum of global radiation, maximum and minimum temperatures, sum of precipitation, daily mean air humidity and windspeed) were prepared. They were then used as inputs for assessment of the agroclimatic conditions. Simulation runs of 99 years were performed routinely for each combination of GCM scenarios for the time horizon of 2050. The proposed methodology that directly applies RCM outputs raises further methodological problems and it is preferable to implement procedures for the elimination of RCM data bias. However, corrected RCM outputs are currently available only for a fraction of the studied area, where station data are available to the team. It is highly unlikely that the data necessary for the bias correction will be made available for most of the domain in the near future. While the bias correction of RCM data remains an urgent task, the authors believe that the use of presently available RCM data will improve our understanding to the possible climate change impact on crop production at the regional level.

Agroclimatic indices

Agroclimatic indices attempt to describe complex relations existing between climate and crops (their development and/or production) as well as the agrosystems as a whole (Nejedlík & Orlandini 2008). In order to describe agroclimatic conditions, a total of nine agroclimatic indicators were selected from a plethora of available options. The goal was to use as few indices as possible that would be relevant for various aspects of crop production but would not simultaneously compete with other and sometimes more suitable tools (e.g. process-based crop models, soil workability models, etc.). Instead, the selected indices can be seen as complementary to crop modelling tools, describing aspects not fully addressed or covered by crop models for an overall assessment of crop production conditions. The final list included: (a) sum of effective global radiation, (b) number of effective growing days, (c) Huglin index, (d, e) water balance during the period from April to June (AMJ) and during the summer (JJA), (f, g) proportion of days

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suitable for harvesting of field crops in June and July and (h, i) proportion of days suitable for sowing in early spring as well as during fall.

The sum of the effective global radiation was calculated as the sum of global radiation during the period with mean air temperature continuously above 5 °C (and without snow cover or frost occurrence) and with sufficient soil water available for evapotranspiration (ratio between the actual and potential evapotranspiration had to be above 0·4). Similarly, the number of growing days represents days without frost and snow presence, with a daily mean air temperature continuously above 5 °C and the same soil water requirements as in the previous case. The temperature thresholds used followed suggestions by Brown (1976), Chmielewsky & Köhn (2000), Mitchell & Hulme (2002) and Larcher (2003). The direct effect of drought stress on crop growth is often expressed as the ratio between actual and potential transpiration (van Ittersum *et al.* 2003). However, in situations where evaporation from soil is not a large component, the use of evapotranspiration values will provide reasonable results. According to a number of studies (e.g. Eliasson *et al.* 2007), growth of the crop on a given day is not considered water limited, if the ratio of daily actual and potential evapotranspiration exceeds 0·5. For the present study, a lower threshold (0·4) was chosen deliberately, thus allowing for a certain level of drought stress in order to limit over-reporting drought by the used indices.

The Huglin index is calculated from 1 April to 30 September in the Northern hemisphere. This index enables different viticultural regions to be classified in terms of the sum of temperatures required for vine development and grape ripening (Huglin 1978). The Huglin index value was calculated for the period from 1 April until 30 September using the following formula:

$$HI = \sum_{i=10}^{n} ((T_{\max} - 10) + (T_{\text{mean}} - 10) \times \mathrm{K})/2 \quad (1)$$

where $T_{\max}$ corresponds to maximum daily temperature, T_{mean} to mean daily temperature and K represents the coefficient for latitude that changes linearly from 1·02 at 40°N to 1·06 at 50°N. Different grape varieties are thus classified according to the minimal thermal requirement for grape ripening. The minimal Huglin index for vine development is defined between 1500 and 1600. However, because the Huglin index considers only thermal conditions during the growing season the results must be interpreted with caution, especially in the eastern part of the domain where continental climate is predominant as wine growing is prevented by frequent occurrence of winter temperatures below − 20 °C.

The availability of water was assessed with the help of climatological water balance (i.e. difference between reference evapotranspiration (ETr) and the precipitation) during the period April–June, which is crucial for the formation of all crops grown in the region, and also during the summer (JJA) when this deficit is usually the highest.

In order to evaluate suitability for sowing, the early spring period was defined as the period between 1 March and 25 April (55 days), while the autumn sowing window is assumed to begin on 15 September and lasts until 30 November (76 days). A given day is considered suitable for sowing when the soil water content in the top layer of soil (the top 100 mm) is between 0·10 and 0·70 of the maximum soil water-holding capacity of a given soil. In addition, a suitable day has to be without snow cover, and the mean daily air temperature during at least two consecutive days has to be above 5 °C. The day is also not considered suitable if there is precipitation above 1 mm on the date of sowing or above 5 mm the preceding day. These thresholds were tested using the reported sowing dates of spring barley, winter wheat and maize at 30 experimental stations at the State Institute for Agriculture Supervision and Testing during the period 1985–2005 in the Czech Republic. A similar approach was used by Leenhardt & Lemaire (2002) and Maton *et al.* (2007) to estimate maize sowing dates for regional water management in France.

Finally, the proportion of days suitable for harvesting in June and July were considered. Soil water content below 0·70 of the retention capacity in the top layer of soil is required, together with no precipitation above 1 mm on the given day or above 5 mm on the preceding day. Snow cover and temperature requirements were not considered because only days between June and July were evaluated in terms of harvesting suitability. The thresholds of soil moisture used to define days suitable for sowing and harvesting were stricter than those used by Rounsevell (1993) and Cooper *et al.* (1997) in order to avoid soil compaction, which is unsustainable in the long term.

All agrometeorological parameters described above were calculated with a new software package, *AgriClim,* developed and tested between 2005 and 2009 at the Institute of Agrosystems and Bioclimatology (Mendel University of Agriculture and Forestry in Brno). The experimental version of *AgriClim* is available from the authors upon request. The software uses daily inputs of global radiation, maximum and minimum temperatures, precipitation, air water vapour pressure and mean daily wind speed to calculate a whole range of indices as presented above. The software takes into account snow cover using a modified version of the model originally described by Running & Coughlan (1988) and improved by Trnka *et al.* (2010). The soil water balance model was calibrated and validated for the range of soil and climate conditions in Central Europe and the US using an extensive archive of experimental

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data (e.g. Hayes *et al.* 2007). *AgriClim* provides information on soil water content in two predefined layers, as well as values of daily reference and actual evapotranspiration, based on the work by Allen *et al.* (1998, 2005). In all cases, spring barley was used as the reference surface, as it was assumed to be a viable crop option across the whole study area, including drier regions as well as higher altitudes. Solid precipitation (i.e. snow) was taken into account only at the time of melting, and no evapotranspiration is assumed on days with snow cover present; this is replaced by the constant rate of sublimation on days without precipitation (1·0 mm/day), based on the values provided by Allen *et al.* (1998). When calculating the actual soil water content, homogenous soil conditions and a soil water-holding capacity of 20 mm in the top 0·1 m were assumed in order to estimate the number of sowing and harvest days. The soil profile necessary for calculating some of the indices (i.e. a, b, e and f) was based on the clay-loam deep Chernozem soil profile with a maximum rooting depth of 1·3 m and a soil water holding capacity of 270 mm. The soil conditions vary across the grid, but the value used is likely to be higher than that for the prevailing soils in many parts of the domain. However, to allow grid-to-grid comparability, the same soil profile was used at all sites. While calculating the evapotranspiration, an adjustment for the increased CO_2 concentration was always made using the method proposed by Kruijt *et al.* (2008), and the CO_2 ambient air concentration for the time horizon of the study (i.e. 2050) was set at 536 ppm with the baseline calculations set at 360 ppm. The reference surface had characteristics of a C_3 crop, therefore accounting for the CO_2 effect resulted in a considerable decrease in ETr rates compared to runs that did not consider increases in the CO_2 levels. The whole set of agroclimatic indicators was calculated for all 99 years in each grid for the horizon of 2050. In most cases, the median value of the parameter was analysed as well as the 5th and 95th percentile in order to determine 20-year extremes of the given agroclimatic index. To increase the spatial resolution of the interpolated outputs, the values in the 10 × 10 km grids were regridded at 1 × 1 km resolution using co-kriging techniques with altitude used as an additional parameter.

RESULTS

The climate forecast by the climate scenarios considered would positively affect the annual sum of effective global radiation through increases in the duration of the potential growing period (i.e. with mean air temperatures continuously above 5 °C). Additionally, the effective annual global radiation would be affected in some cases by the increase in global radiation as a result of decreased cloudiness associated with a decrease in precipitation, especially during the summer months. However, the decrease in precipitation also increases the probability of water deficit, leading to a decrease in the overall value of this key parameter. As shown in Fig. 2*a–d*, under present conditions the southern and south-eastern parts of the domain have the highest values of this parameter and thus the potential productivity of rainfed agriculture should be highest at these areas. The western and northern parts of the domain would benefit most from the changed climate conditions, with areas in Germany, Poland, parts of Austria, Slovakia and the Czech Republic showing sustained increase in the values of effective global radiation (Fig. 3). The largest decreases in effective global radiation are to be expected within the Pannonia lowland (the lowlands between the Alps, the Carpathian mountains and the Dinaric Alps), which includes almost all of Hungary, northern Serbia and Croatia as well as parts of southern Slovakia, eastern Austria and western parts of Romania. The most marked changes (both positive and negative) within the regions are predicted by the HadCM-driven scenarios, while the NCAR-based results suggest a much slower rate of change. However, the overall spatial pattern of these changes remains the same. A marked shift within the shape of the distribution of this key indicator over the whole domain is seen by plotting the distribution of the annual effective global radiation values over the whole domain, taking into account the present area of arable land (Fig. 3). All three GCM-based scenarios forecast significant increases in the indicator value over the whole domain, which is already suggested from Fig. 2*b–d*. When the changes at the national level are plotted (Fig. 3), it is clear that the Czech Republic, Slovenia and partly Slovakia and Austria would benefit from the shift of climate conditions (if the national productivity is considered only in terms of the sum of effective global radiation and disregard the soil conditions and terrain configuration). In the case of Hungary, a substantial drop in the sum of the effective global radiation is forecast. However, in many regions, the negative trends in agriculture productivity could be overturned by the use (or increased intensity) of irrigation, which are not considered in the present study, which investigates only the suitability for rainfed agriculture that currently dominates the area (Table 1). A similar pattern of change as in the case of the effective global radiation is to be expected also for the effective growing days (Fig. 2*e–h*), with the largest gains being expected in the northern and western parts of the domain with some reduction in the south-eastern parts of the domain. Still, in terms of effective growing days, there is a tendency towards more uniform distribution of effective growing days across the whole domain.

The significant increase in the Huglin index value across the whole domain (Fig. 4*a–h*) is understandable as a direct consequence of the expected temperature

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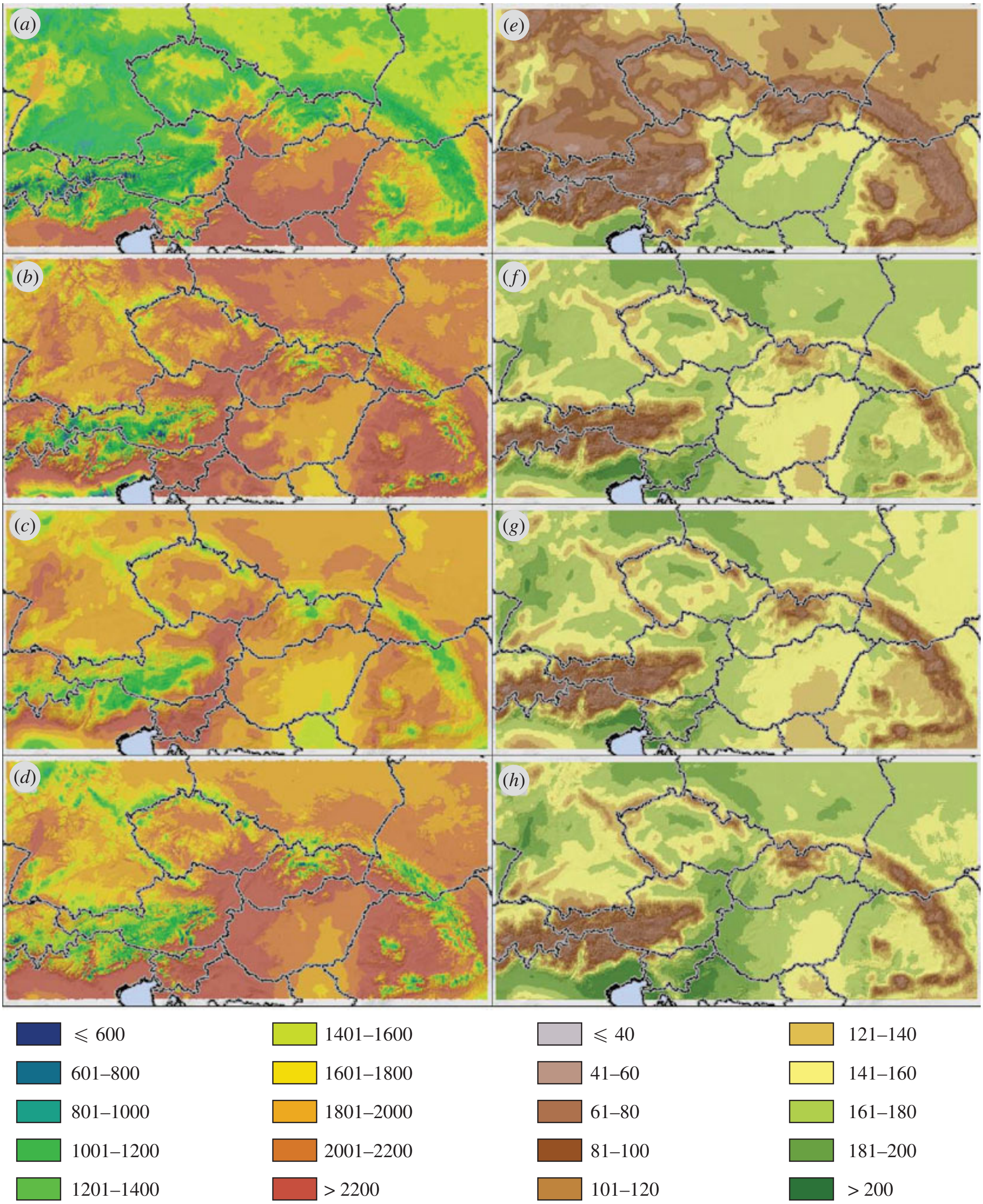

Fig. 2. Median of the annual global effective radiation (MJ/m^2/year) and number of effective growing days (days) plotted for the domain. (*a*) and (*e*): Baseline (1961–2000) conditions. (*b–d*) and (*f–h*): Projections for 2050 based on results from the following GCMs: (*b*) and (*f*): HadCM; (*c*) and (*g*): ECHAM and (*d*) and (*h*): NCAR.

increase that might take place within the next 40 years, with dramatic consequences for agriculture. Figure 4*a* shows that the present 20-year lows of the Huglin index do not allow a permanent successful harvest of the wine across most of the domain, except in areas already established as wine growing regions. Alternatively, in the warm years (i.e. 20-year return period), Fig. 4*e* shows that very good thermal

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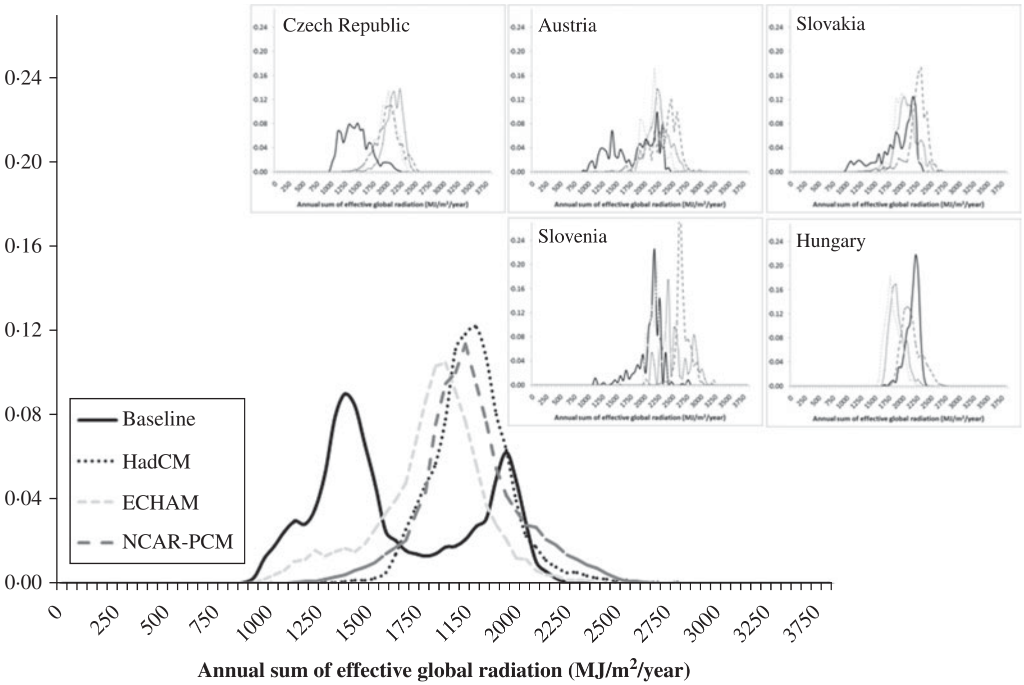

Fig. 3. Distribution of the mean sum of effective global radiation across the agriculture land over the whole domain and in five countries within the domain for the baseline (1961–2000) conditions and those expected by 2050 using three GCMs (HadCM, ECHAM and NCAR). Note: As the digital elevation model with 10 km resolution was used in the study, an overestimation of areas between 1000 and 1500 m in the Alps was obtained that partly explains the bimodal shape of the distribution curve, especially in the case of Austria under the present climate.

conditions for wine growing are to be found especially in the south-eastern part of the domain. Under the predicted changed climate, the potential wine growing area would increase substantially, with Huglin index values sufficient for wine production across much of the region with the exception of mountainous areas (however, small-scale local climatic variations based on terrain effects, such as the slope, on temperature are not considered in the present study). It must be stressed that the Huglin index takes into account only temperature requirements during the summer period, which is a sole factor affecting wine production in any case. However, the results clearly show that the present wine growing regions in Central Europe will be faced overall with much warmer conditions, requiring in some cases different cultivars than those currently planted. The predictions also suggest that there is a prospect of wine growing even in areas where the present climate prohibits this.

The spatial patterns in the intensity of a 20-year drought during the first part of the growing season (April–June) differ for the three GCMs considered (Fig. 5*b–d*). While HadCM- and ECHAM-based scenarios predict an increase in the 20-year drought intensity across the domain (despite accounting for the positive effect of CO_2), realization of NCAR-based projections would lead to only a slight deterioration in the eastern part of the domain and slight improvements in the west and north. However, when the shifts in the value of 20-year droughts are investigated only over the presently arable land (Fig. 6), it is clear that more intensive water deficits are likely to endanger the rainfed agriculture systems of Central Europe. The scale of the present study made it possible to analyse the consequences of water balance changes for several countries. Figures 5*b–c* and 6*a* show that realizations of ECHAM or HADCM projections would lead to an increased intensity in 20-year drought in all five countries considered. The magnitude of the changes has a south-eastern gradient, as the arable land in the Czech Republic would be affected least, and Hungary and Slovenia show the most marked changes. However, realization of the NCAR scenario would mean a slight easing of the 20-year drought intensity in the Czech Republic, Austria, Slovakia and Slovenia, leaving only the arable land in Hungary worse off.

The results of the study suggest that there is a probability that the wet years (with a return period of 20 years) are going to lead to higher water excess when

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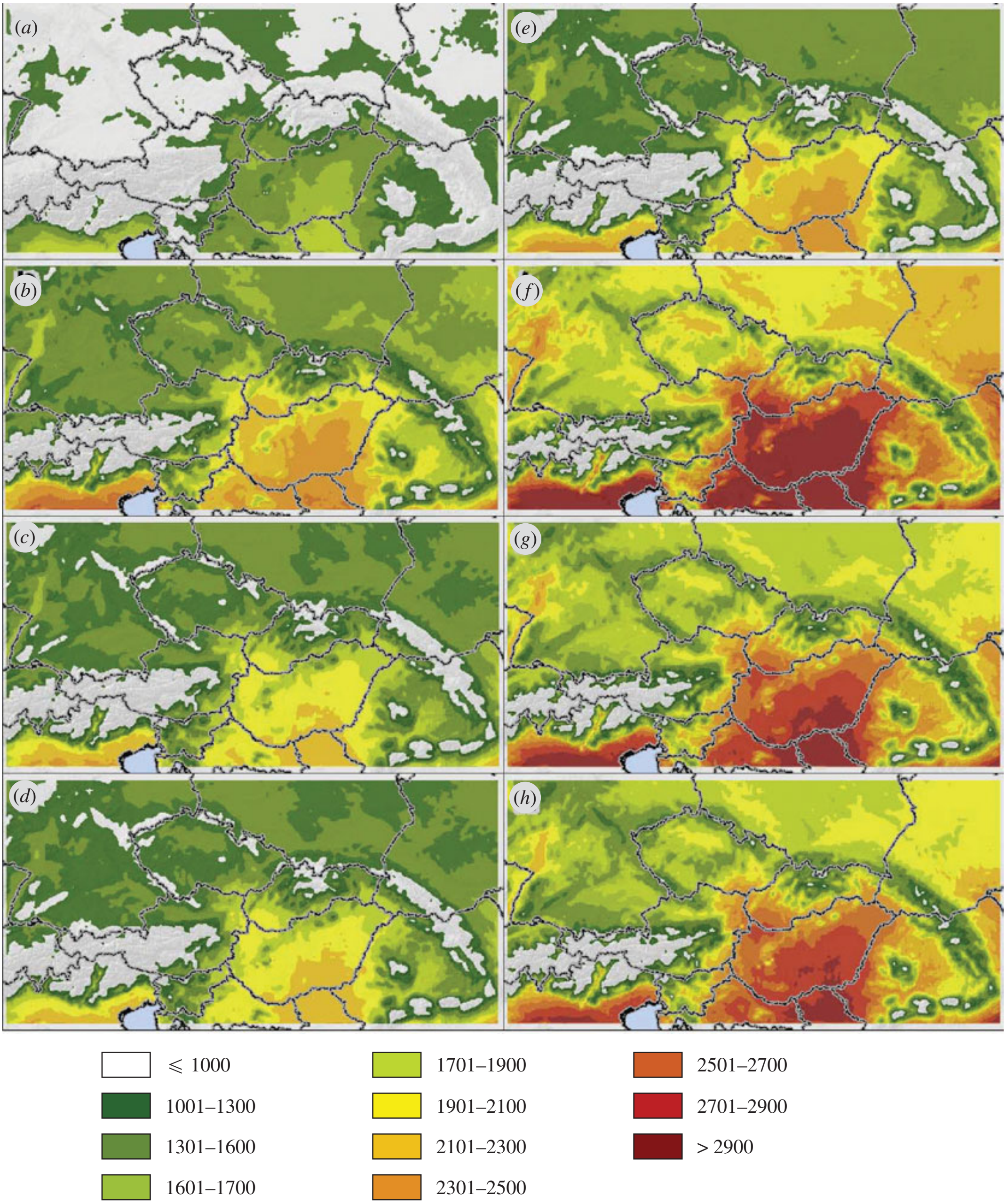

Fig. 4. Values of 20-year lows (*a*–*d*) and highs (*e*–*h*) of the Huglin Index. (*a*) and (*e*): Baseline (1961–2000) conditions. (*b*–*d*) and (*f*–*h*): Projections for 2050 based on results from the following GCMs: (*b*) and (*f*): HadCM; (*c*) and (*g*): ECHAM and (*d*) and (*h*): NCAR.

compared with the present situation (Figs 5*e*–*h* and 6*b*), especially in the north and north-eastern parts of the domain and also in the highest parts of the Alps. The highest increase in the water excess in this area is associated with the predictions from the ECHAM- and NCAR-based scenarios. It seems that in the central and northern parts of the domain (including also the Czech Republic, Austria, Slovakia and partly in Hungary), there is a predicted trend towards greater inter-annual variability of water balance between dry

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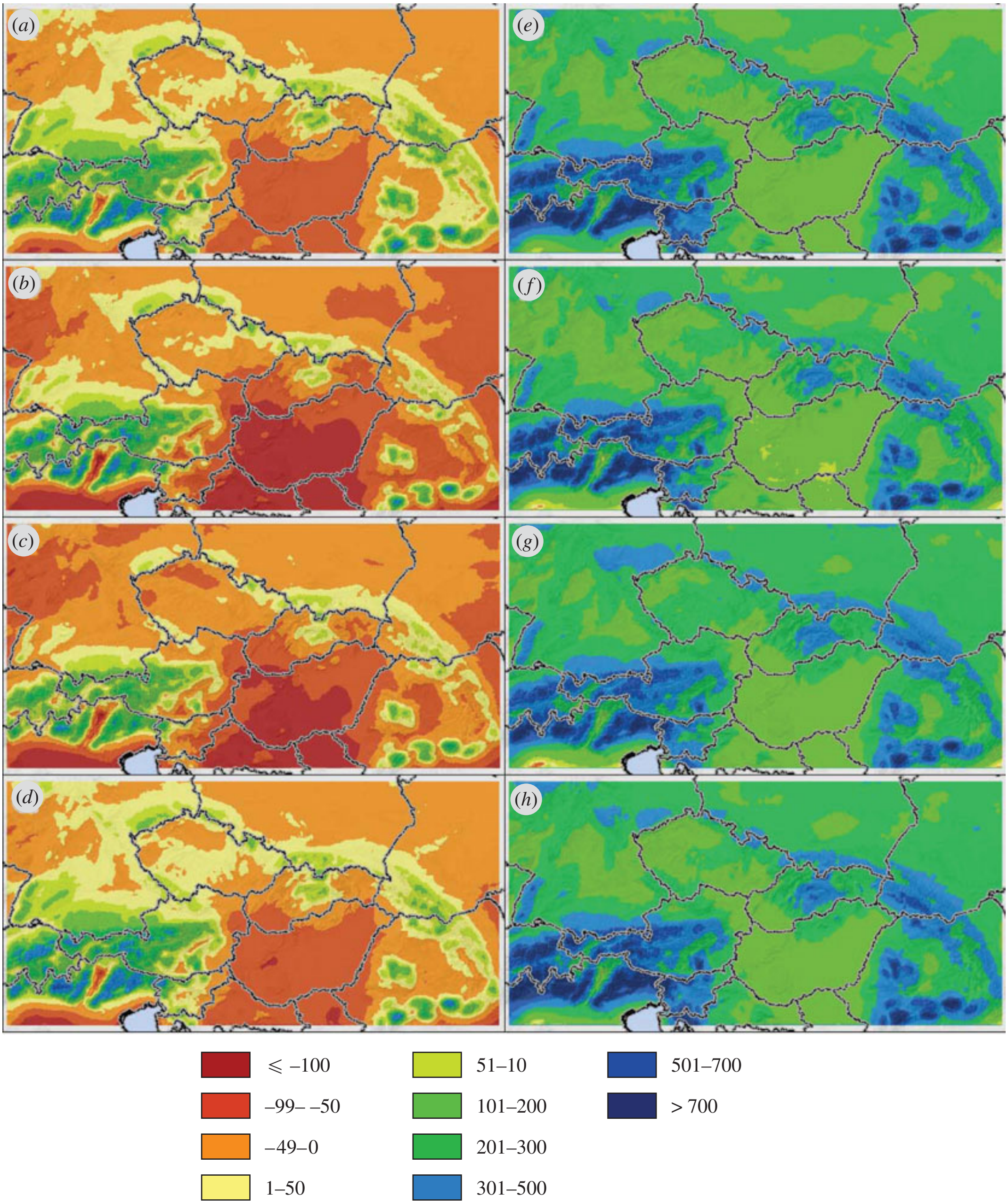

Fig. 5. Values of 20-year lows (*a–d*) and highs (*e–h*) of April to June water balance (mm), i.e. difference between sum of precipitation and reference evapotranspiration. (*a*) and (*e*): Baseline (1961–2000) conditions. (*b–d*) and (*f–h*): Projections for 2050 based on results from the following GCMs: (*b*) and (*f*): HadCM; (*c*) and (*g*): ECHAM and (*d*) and (*h*): NCAR.

and wet seasons with a 20-year return probability (i.e. more severe dry and wet episodes are likely).

The earlier start to the growing season will be accompanied by changes in the proportion of days suitable for sowing. However, the three GCM-based predictions show little agreement in terms of the proportion of suitable sowing days during early spring (Fig. 7*a–d*). While the NCAR-based projections would lead to a slight decrease in suitable days in the central and north and increases in the south of the

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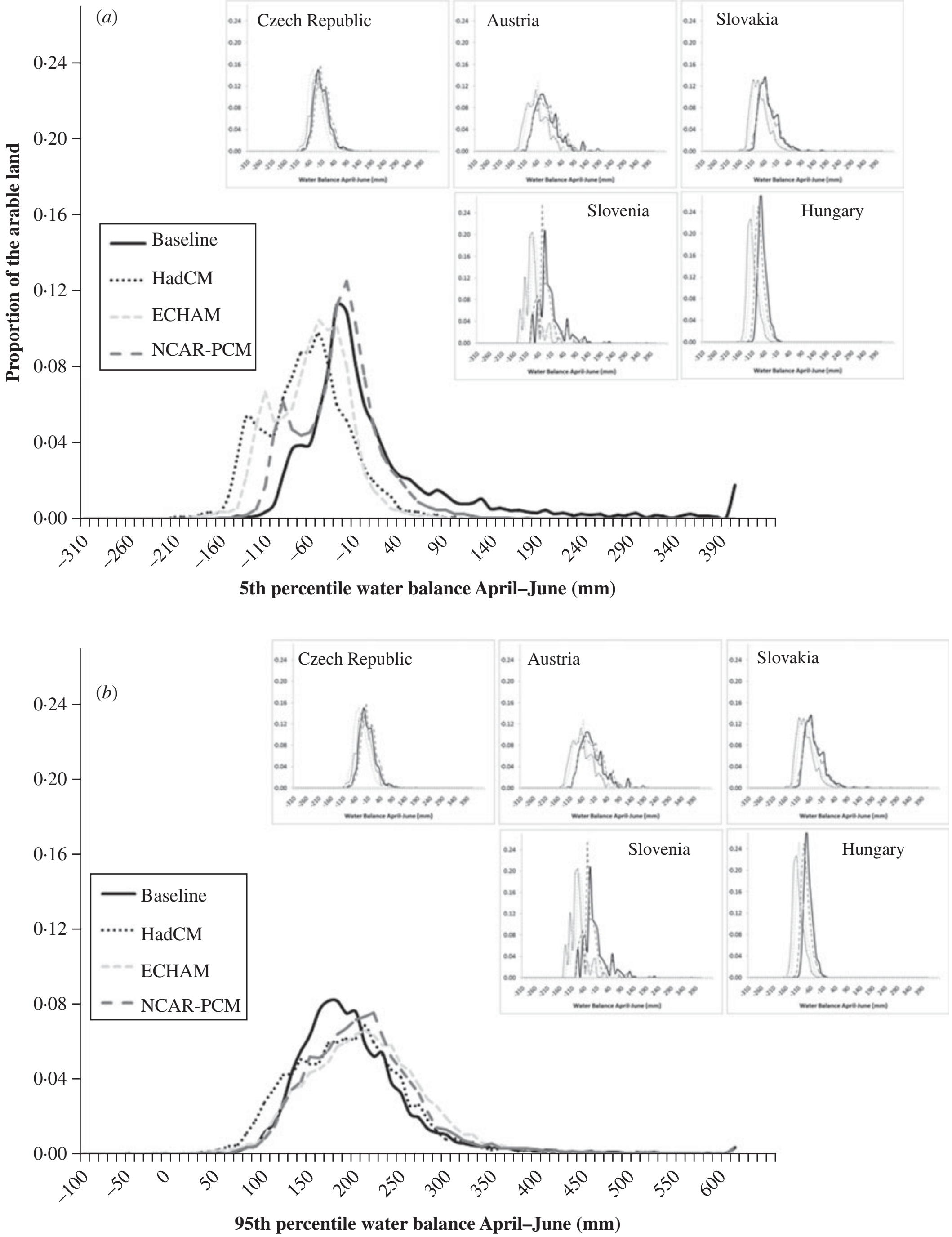

Fig. 6. Distribution of the water balance (April–June) values (*a*) during the 'dry' season with a 20-year return period and (*b*) the wet season (the same return period i.e. 20 years) over the agriculture land within the whole domain and in five countries. The baseline conditions represent values valid for the period from 1961 to 2000, while projections are based on those expected by 2050 using three GCMs (HadCM, ECHAM and NCAR).

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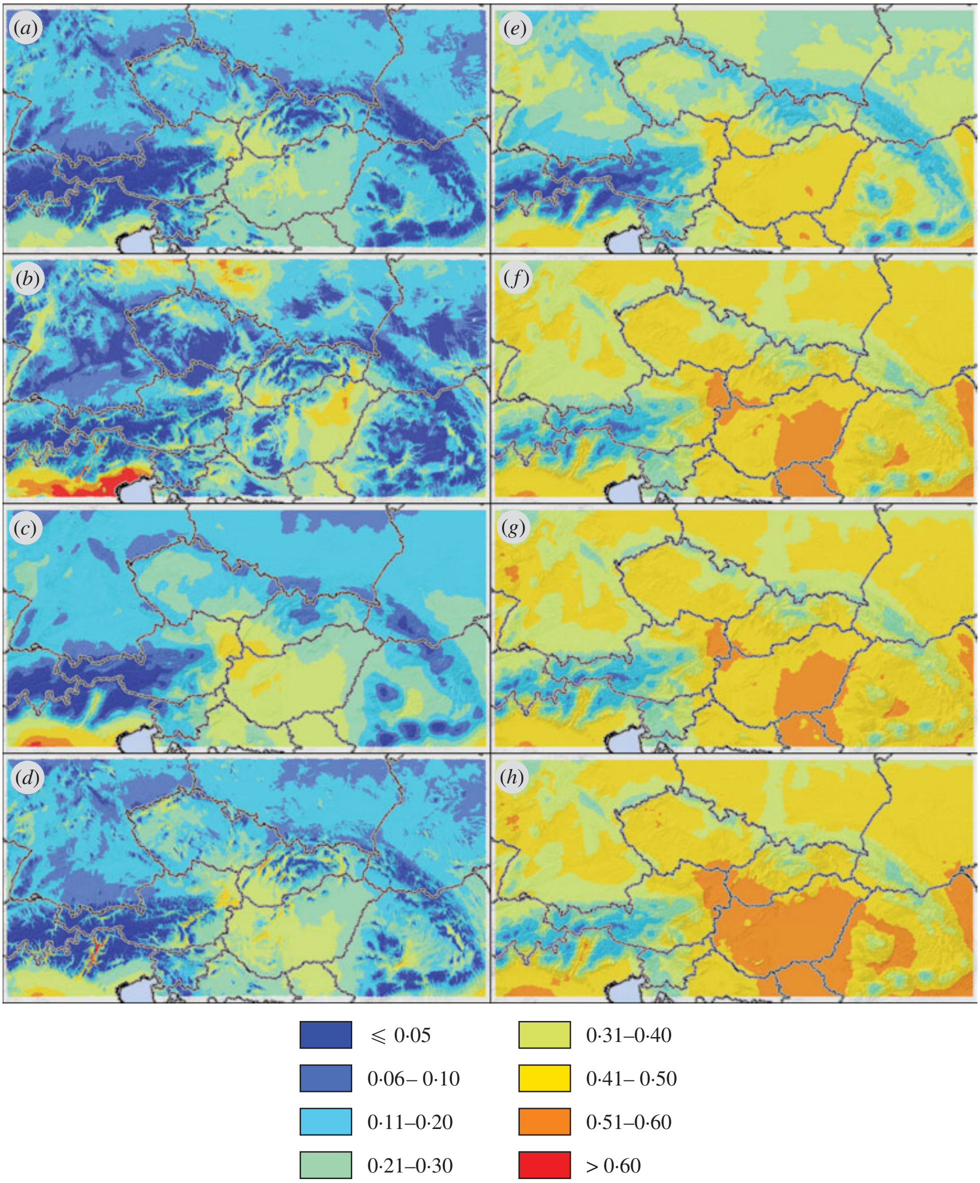

Fig. 7. Proportion of days suitable for sowing (0–1) during the early spring sowing window (*a*–*d*), defined as the period from March 1 to April 25 (55 days), and the fall sowing window (*e*–*h*), which is assumed to begin September 15 and last until the end of November (76 days). The baseline (1961–2000) conditions are captured by maps (*a*) and (*e*), while the projections for 2050 are captured by maps (*b*–*d*) and (*f*–*h*). The projections based on GCM HadCM are presented at maps (*b*) and (*f*), ECHAM at (*c*) and (*g*) and NCAR results at (*d*) and (*h*).

domain, the ECHAM-based results show an overall increase in early spring sowing suitability (except for small regions in the northeast and southwest). The HadCM (Fig. 7*b*) prediction differs from the other two predictions, in showing a substantial drop in the number of suitable days in most of the Czech Republic, Bavaria, northern and eastern Austria and in some regions of Hungary and Romania. At the same time, the number of suitable days increases sharply in northern Italy, eastern Hungary and in parts of Saxony that are within the domain. This particular result is most likely due to the predicted

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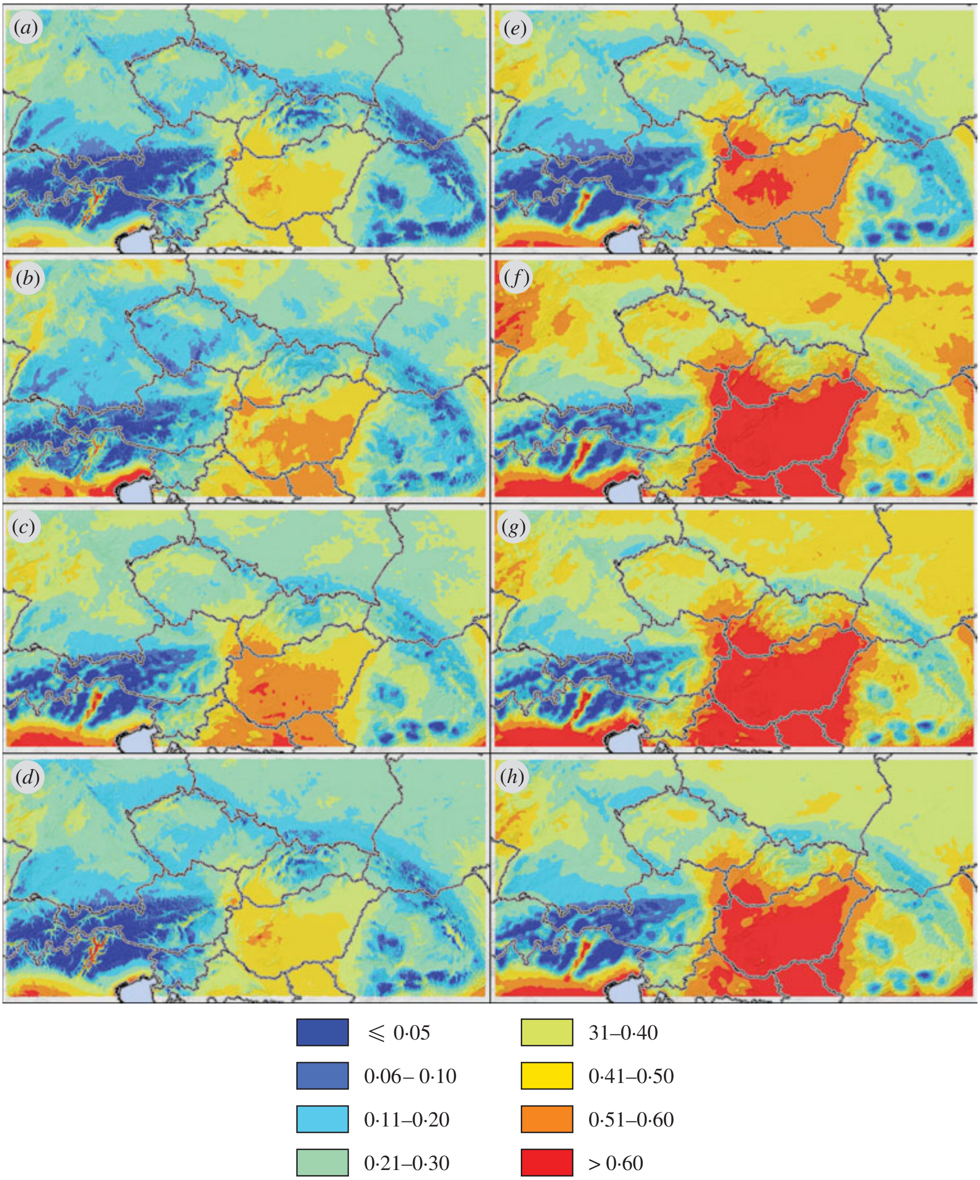

Fig. 8. Proportion of days suitable for harvest (0–1) during June (*a–d*) and July (*e–h*). The baseline (1961–2000) conditions are captured by maps (*a*) and (*e*), while the projections for 2050 are captured by maps (*b–d*) and (*f–h*). The projections based on GCM HadCM are presented at maps (*b*) and (*f*), ECHAM at (*c*) and (*g*) and NCAR results at (*d*) and (*h*).

increases in the precipitation during March and April compared to the present result according to the HadCM model. The increase in suitable days for sowing during the autumn (25 September–25 November) is very pronounced, with all three projections indicating sharp increases, due particularly to the drop in precipitation in September and partly also in October and November (Fig. 7*e–h*).

While, according to the NCAR-based scenario, the harvest suitability in June (Fig. 8*a–d*) is likely to remain the same or decrease slightly over the main producing areas if the NCAR scenario is realized, the predictions from the ECHAM-based scenario indicate increases in the harvesting window, especially in the southern parts of the domain. The HadCM-based predictions indicate a relatively sharp drop (by >10%,

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on average) in suitable harvest days in June, especially across most of the Czech Republic, parts of northern and eastern Austria as well as almost all of Bavaria with improvements over northern Italy and eastern parts of Hungary.

DISCUSSION

The changes expected in the annual sum of effective global radiation and annual sum of effective growing days support the conclusions of the expert-based study conducted by Olesen *et al.* (2008) and of another study covering 21 European countries using high quality data from representative agroclimatic stations (M. Trnka, personal communication). The results of these two studies as well as the present work suggest that there is a high probability of increase in both indicators in northern and western Europe as well as at higher altitudes (the Alps in particular) and of decrease all over the Pannonia basin and the Mediterranean. This should have a positive effect on the overall production potential of the domain. However, this increase is accompanied by an increase in water deficit over the summer months (June–August); in some parts of the domain this might result in two short growing seasons (one in spring and the second in autumn). The production in the summer, without irrigation systems, might be difficult if not impossible.

The significant increase in the Huglin index across the whole domain is understandable, but it must be stressed that the Huglin index takes into account only one aspect of wine production, namely the summer temperature requirements. Additionally, small-scale terrain effects on local climates have to be taken into consideration for a small-scale assessment of wine production potential. However, the results show clearly that the present wine growing regions in Central Europe (similar to the results of Stock *et al.* 2005 and Eitzinger *et al.* 2009*a*) will be faced with much higher values of the index. In some cases, this may require the planting of different cultivars from those planted currently. The results also indicate that it may be possible to grow wine further north than at present. The likely shift of the northern limitation of the culture of grapevines in Europe has been analysed by Moisselin *et al.* (2002), Seguin & Cortazar (2005) and Eitzinger *et al.* (2009*a*), with Moisselin *et al.* (2002) claiming that an increase of 1 °C in mean temperature would shift the boundary north by 180 km. The magnitude of such a shift is supported by the historical analyses of Legrand (1978) and Eitzinger *et al.* (2009*a*). This might eventually increase competition for the traditional viticulture regions (if that is permitted, e.g. by the Common Agricultural Policy of EU). The present study offers a new perspective as it provides the range of Huglin index values with a 20-year return probability. The analysis of the range between warm and cool years indicates a probable increase in the variability of the Huglin index values, which might in turn affect the quality of individual vintages.

The present results on the water balance changes during the period from April to June, which has been shown to be critical for the water stress sensitivity of field crops in the region (Eitzinger *et al.* 2003; Brázdil *et al.* 2009*a*,*b*; Hlavinka *et al.* 2009), indicate worrying trends for rainfed agriculture. The climate change might lead to an increase in incident global radiation, or higher ambient air temperatures, or both, which will lead to increased saturation deficits. Consequently, a higher rate of ETr is expected under future climate conditions, which may not be matched either by an adequate increase in precipitation or by increased water use efficiency, leading to a more severe water deficit across most of the domain (Fig. 5*b*–*c*). This tendency seems to have support in the studies based on the past measurements, as the whole region has shown significant drying trends since the 1940s (e.g. Dai *et al.* 2004; van der Schrier *et al.* 2006; Brázdil *et al.* 2009*b*; Trnka *et al.* 2009*b*). The results of the present study correspond well with the conclusions of Olesen *et al.* (2007) for the Mediterranean region and the results for the Alpine Region reported by Calanca (2007). The realization of ECHAM- or HadCM-based scenarios would put large areas of Austria, the Czech Republic, Slovenia, Hungary and Slovakia in need of either irrigation for drought-sensitive crops or measures for increasing agricultural water use efficiency (e.g. improved irrigation water use efficiency). This would be a challenging task to achieve given that only a fraction of the arable land has access to the irrigation (Table 1), and in some countries (e.g. Czech Republic) there is only a limited number of water reservoirs suitable for substantial increases of irrigated areas during periods of prolonged water deficits is limited.

While severe droughts during the early part of the growing season might have dire consequences for crop production, the excess of water during this period also has a negative effect on the crop production and its quality as it increases the risk of diseases, leads to root anoxia, nutrient leaching and makes tillage operation more difficult. The results of the present study suggest that the wet years (with a return probability of 20 years) will lead to higher water excess compared with the present situation (Figs 5*e*–*h* and 6*b*), especially in the north and north-eastern parts of the domain and also in the highest parts of the Alps.

The reported increase in the inter-seasonal variability in the proportion of spring days suitable for sowing as compared to the baseline conditions is in agreement with findings of Trnka *et al.* (in press). While the number of suitable days is, in general, increasing, a higher variability in sowing–limiting conditions is to be expected and can also contribute

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to higher inter-annual yield variability as postulated in recent crop simulation studies (e.g. Thaler *et al.* 2008). A study by Trnka *et al.* (2009c) estimated that the number of days suitable for harvesting in the central part of the domain (i.e. the Czech Republic and Austria) should generally increase by 12–35% by 2050 (using the same set of scenarios), accompanied by a decrease in inter-seasonal variability during August and September. This agrees well with the findings of Olesen & Bindi (2002). Also, in the case of July, Trnka *et al.* (2009c) found a positive trend regarding the number of suitable days, which agrees well with Fig. 8*e–h*. As the growing season and sowing period will tend to move to the beginning of the year, the proportion of area that will be harvestable in June is likely to increase. However, June generally has the lowest number of suitable days for harvesting in the evaluated period (Fig. 8*a–d*), primarily due to a comparatively higher probability of rainfall and, consequently, a wet soil profile. Even in the warmest part of the domain, the mean proportion of suitable days is below 0·50, compared to 0·70 in July (Fig. 8*e–h*). In addition, the results show considerable inter-seasonal variability that would put further stress on the farmers' workload during the harvesting period and decrease the availability of machinery during the requested time. Figure 8 also reflects uncertainty resulting from different GCM runs.

While uncertainties about the future climate change impact remain (and many of them were not explicitly considered in the present study), the present results seems to indicate that the mean production potential of the domain (expressed in terms of effective global radiation and number of effective growing days) is likely to increase as a result of climate change, while inter-annual yield variability and risk may increase. However, this is not true for the Pannonian and Mediterranean parts of the domain where increases in the water deficit will further limit rainfed agriculture but increasingly probably also irrigation agriculture if local water resources are diminishing.

The areas that are already warm (in the south-eastern part of the domain) and relatively dry, such as the central and western parts of the domain, would probably experience an increase in the severity of the 20-year drought deficit and a more substantial water deficit during the critical part of the growing season. Similarly, the inter-annual variability of water balance is likely to increase over the domain. There is also a chance of deteriorating conditions for sowing during spring due to unfavourable weather. This might increase the preference given to winter crops, which is already likely due to their ability to withstand spring drought stress events. Harvesting conditions in June (when harvest of some crops might take place in the future) are not improving beyond the present level, making the planning of the effective harvest time more challenging. Based on the evidence provided by the present study, it could be concluded that rainfed agriculture might indeed face more climate-related risks, but the analysed agroclimatic indicators will likely remain at the level allowing for acceptable yields in most of the seasons. However, the evidence also suggests that the risk of extremely unfavourable years resulting in poor economical returns is likely to increase. Finally, the methodology used enables the coverage of a large territory with an unusually high level of detail, allowing for an assessment of the climate change impact in local, national and regional contexts. This is crucial for tailoring appropriate adaptation responses to the expected changes.

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