Aspects on results and uncertainties of climate change impact simulation studies for agricultural crop production in Europe

J. Eitzinger, H. Formayer, S. Thaler, M. Trnka, Z. Zdenek and V. Alexandrov

Aspekte von Ergebnissen und Unsicherheiten aus Simulationsstudien zu den Auswirkungen des Klimawandels auf die landwirtschaftliche Pflanzenproduktion in Europa

Zusammenfassung

Die Erforschung der Auswirkungen einer Klimaänderung auf die Landwirtschaft muss die komplexen Interaktionen des natürlichen Systems Boden-Pflanze-Atmosphäre und gleichzeitig die vom Menschen beeinflussten Systeme, wie die sozio-ökonomischen Rahmenbedingungen berücksichtigen. Weiters basieren diese Analysen auf Klimaszenarien, welche mit verschiedenen Klimamodellen und Methoden erstellt wurden und ihrerseits auf Annahmen künftiger Emissionsszenarien beruhen. All diese modellierten Systeme und deren Interaktionen beinhalten daher eine Reihe unterschiedlicher Unsicherheiten und limitierender Annahmen, wie Trends in der technologischen Entwicklung oder menschlicher Aktivitäten, die vereinfachte Repräsentation der Realität in Modellen, Lücken im Systemwissen oder Mängel bei Kalibrierdaten. Diese Unsicherheiten werden in den jeweiligen Studien oft nur ungenügend beschrieben oder vorausgesetzt und sind daher eine Quelle von Fehlinterpretationen von Ergebnissen. Diese Arbeit versucht daher die wichtigsten Quellen von Unsicherheiten in Simulationsstudien zu den Auswirkungen des Klimawandels auf die landwirtschaftliche Pflanzenproduktion aufzuzeigen.

Schlüsselwörter: Klimaszenarien, Auswirkungen des Klimawandels, Landwirtschaft, Pflanzenproduktion, Unsicherheiten.

Summary

Climate change impact research in agriculture involves the complex soil-crop-atmosphere interactions and human determined systems such as socio-economic conditions. Furthermore it is based on climate scenarios, which were developed from various climate models and methods based on underlying assumptions of future emission scenarios. All these modeled systems and their interactions include therefore many different kind of uncertainties and limitations, such as trends in technology and human activities, models representation of reality, lack of knowledge on system responses or lack of calibration data. However, these uncertainties and limitations often are not clearly described and a potential source of misinterpretations. This paper will provide therefore an overview on the main sources of uncertainties in recent modeling studies on climate change impacts on agricultural crop production.

Key words: Climate scenarios, climate change impacts, agriculture, crop production, uncertainties.

1 Introduction

The potential impacts of climate change on agricultural crop production are manyfold and complex in general, and contain many uncertainties. Process oriented simulation models (also called mechanistic or dynamical models) are frequently used to assess the complex interactions of the soil-crop-atmosphere system at different scales. However, they still represent only a simplification of the different involved processes and rely to defined boundary conditions. Therefore simulation studies are limited in the validity of their results. In agriculture mostly specific aspects such as crop yields or yield risks under defined boundary conditions such as various climate scenarios, land use and management scenarios were investigated using simulation models (e.g. AUDSLEY et al., 2006; DOWNING et al., 2000;

EITZINGER et al., 2003; FUHRER, 2007; KERSEBAUM et al., 2005; PARRY, 2000).

Results indicate, for example, that in many Central European regions an increasing number and duration of summer drought periods under most climate change scenarios could affect crop yields through a decrease of available soil water reserves, especially under poor soil conditions (such as low soil water storage capacity). On the other hand, negative yield impacts through higher temperatures and shortening of the growing period in many locations could be compensated by the effect of increasing CO_2 levels in the atmosphere due to an increase of photosynthesis rate and water use efficiency. In regions with increasing precipitation or no water limitation for crops the higher temperatures will increase the production potential for many crops (e.g. by longer vegetation period for permanent crops or by removing temperature limiting growing conditions).

To assess the effects of adaptation options in agriculture is even more complex because of the impact of the human factor. However, there are also simple and effective adaptation measures which can be easily simulated by crop models. For example, crop production potential could be maintained under a warmer climate by a change to cultivars which are adapted to higher air temperatures or an earlier seeding for spring crops. The introduction of new cultivars, resistant to climate change related stresses (e.g. drought and heat stress, ozone, pests, diseases, etc.) is another option. Future options include not only measures in crop management, but also medium and long term adaptation for land use and farming systems. Additionally the socio-economic environment and other boundary conditions beyond the farm level can play a significant role for future expected impacts on crop production and for adaptation options. Several studies, for example, indicate that the impact of management and socio-economic conditions can outrange the pure climate change impact (e.g. HOLMAN et al., 2005).

It is quite impossible to consider all potential important influential environmental factors, crop managements or socio-economic feedbacks because of a lack of data, methods and information, which is a source of uncertainty for assessments of future climate change impacts. Sources of uncertainties can be detected also at all scales of model application, including uncertainties based on a) model representation of involved processes as well as on b) model inputs. An example for the first type of uncertainties at the crop production level is the potential effect of increasing atmospheric carbon dioxide concentration on crop growth processes and yield (e.g. EWERT et al., 2002). Uncertainties in crop model inputs can be based on measurement errors or uncertain inputs based on other model outputs such as climate change scenarios from global climate models. Basically, model application is always a compromise between model simplification (uncertainty in simulation results increases with increasing simplification of simulated processes) and input data demand (in more complex models uncertainty of simulated results increases because of increasing number of input parameters, which are not always available or have a high degree of uncertainty in the data itself).

Many uncertainties in general are related to the scaling problem such as significant differences between the model inputs and their regionalization at the farmers field level, for example soil input data from a low resolution soil map or weather input data from distant stations or from General Circulation Models (GCM's). Another problem is that from climate scenarios changes only of the mean in weather parameters (e.g. of temperature and precipitation) are considered and used in impact simulation models, neglecting a change in climate variability. Also many extreme weather events such as hail, which can have additional negative impacts on crop yields, are not represented by modeled climate scenarios directly. Regional climate scenarios can differ from GCM's on a regional basis considerably and can represent local conditions much better (e.g. seasonal variations of temperature and precipitation), however, often with a higher degree of uncertainty. Therefore downscaling methods should be used for regional crop yield simulations, if reliable and available.

2 Overview on climate change impact simulation studies for agriculture in Central Europe

The approach of analysing the effects of climate change on agro-ecosystems using dynamic crop models has the advantage to include all relevant impact factors of the soil-crop-atmosphere system over short time periods. Complex effects on crop growth and yield can be simulated directly, where most crop yield models use daily time steps. In the past decades a number of studies on potential impacts of climate change in agricultural crop production were carried out using process oriented crop or ecosystem models. A survey of applied process oriented models in Europe was recently carried out (EITZINGER et al., 2008) within COST Action 734, which was showing the main fields and problems of these model applications. Most model applications are related to climate change impact research studies, covering to a great extent the economically most important crops such as maize and wheat. There is also a focus on a small number of "crop modelling schools" manifested by different software packages or model groups. The three most important "schools of development" from Australia, the Netherlands and the United States include APSIM models (ASSENG et al., 2000), models from the "School of De Wit" (VAN ITTERSUM et al., 2003; PENNING DE VRIES, 1989) and the DSSAT family of crop models (JONES et al., 2001, 2003), respectively. However, a number of different other models (often related however to one of the "modelling schools") are applied as well in climate change impact studies, for different crops, environments and scales. In Germany, for example, AGROSIM (MIRSCHEL et al., 2001, 2005) was applied for effects on field based yield and water balance, APSIM (WESSOLEK and ASSENG, 2006) for regional effects on yield and water balance, DAYCENT (SCHALDACH and ALCAMO, 2006; WZU, 2005) for regional effects on yield and carbon balance, HERMES (KERSEBAUM et al., 2005; KERSEBAUM, 2007) for effects on yield, nitrogen leaching, adaptation, fertilization, SWIM (EPIC) (KRYSANOVA et al., 1999; GERSTENGABE et al., 2003; STOCK, 2005) for regional effects on yield and water balance. Another example from France is the STICS model which is widely used at INRA and other organizations for several crops (BRISSON et al., 2003, 2006). New developments reported are mainly the application of crop models within whole farm system models and spatial applications in combination with GIS and remote sensing methods. At the Macaulay Institute in Scotland, for example, the LADSS (Land Allocation Decision Support System) farm-scale integrated modelling framework consists of a core of biophysical simulation models overlaid by financial, social and environmental accounting modules (MATTHEWS et al., 1999). The crop module is a version of the CROPSYST model developed at Washington State University (STOCKLE et al., 1994).

The impact of climate change on crop production in Europe using process oriented crop models was investigated in several studies at different spatial scales and for different climate and management scenarios (e.g. AUDSLEY et al., 2006; DOWNING et al., 2000; HOLDEN et al., 2003). As mentioned, many studies in Europe are investigating maize and wheat production because of its economic relevance. In most of the simulation studies only climate effects without extreme weather events (except drought and heat) are considered under current production technology. Also the effect of increasing CO_2 levels on crop growth is not always considered. For example, the effect of water balance parameters and water stress on winter wheat production in north-east Austria under different climate change scenarios (without downscaling) was investigated by EITZINGER et al. (2003) using the CERES-Wheat model (including the direct CO_2 effect on crop growth). Despite higher yield levels, crop transpiration dropped compared with current conditions through the simulated increase in water-use efficiency and reduced total potential evapotranspiration (related to the shortened growing period) under the applied $2 \times CO_2$ climate scenarios (no change in climate variability assumed). This caused also less water stress for the crop. Other studies on winter wheat (EITZINGER et al., 2001) and barley (ALEXANDROV et al., 2002) also show increasing yields under future climate scenarios in Austria, which can deviate from each other considerably (Figure 1). Despite expected higher air temperatures till the 2080s, the projected increases in wheat yield were between 3 and 20 % due to the fertilization impact of the increased CO_2 level as shown in Figure 2 for a site with medium soil. Sensitivity analyses show that soil water storage capacity can have a strong impact on the yield potential, especially on sites where water is a limiting factor during the growing period such as in north-eastern Austria (Figure 3). Figure 4 demonstrates for the same region latest simulation results for winter wheat, showing the range of potential yield reactions by considering different climate scenarios, soil types and the direct CO_2 effect. It shows that negative yield trends are simulated only on soils with low soil water storage capacity, but also that negative yield trends would increase with higher rise in temperatures or a lower CO_2 effect considerably. Spring barley yields showed lower positive yield effects compared to winter wheat or even slightly decreasing yield trends for the next decades, especially in the dry regions and at soils with low soil water storage capacity.

Similar findings of mainly (except on sandy soils and dry regions) positive yield effects are reported by other studies on cereals for Europe, mainly due to the simulated effect of enhanced atmospheric carbon dioxide levels (e.g. WOLF, 1993; SEMENOV et al., 1993; TRNKA et al., 2004; WZU, 2005). Comparable results are also described for non cereal crops e.g. for potato (HOLDEN and BRERETON, 2006; WOLF and VAN OIJEN, 2002).

A slightly different picture is shown for maize, which is a C4 crop with expected low direct CO_2 fertilization effect. Most of the studies for maize indicate an increasing yield

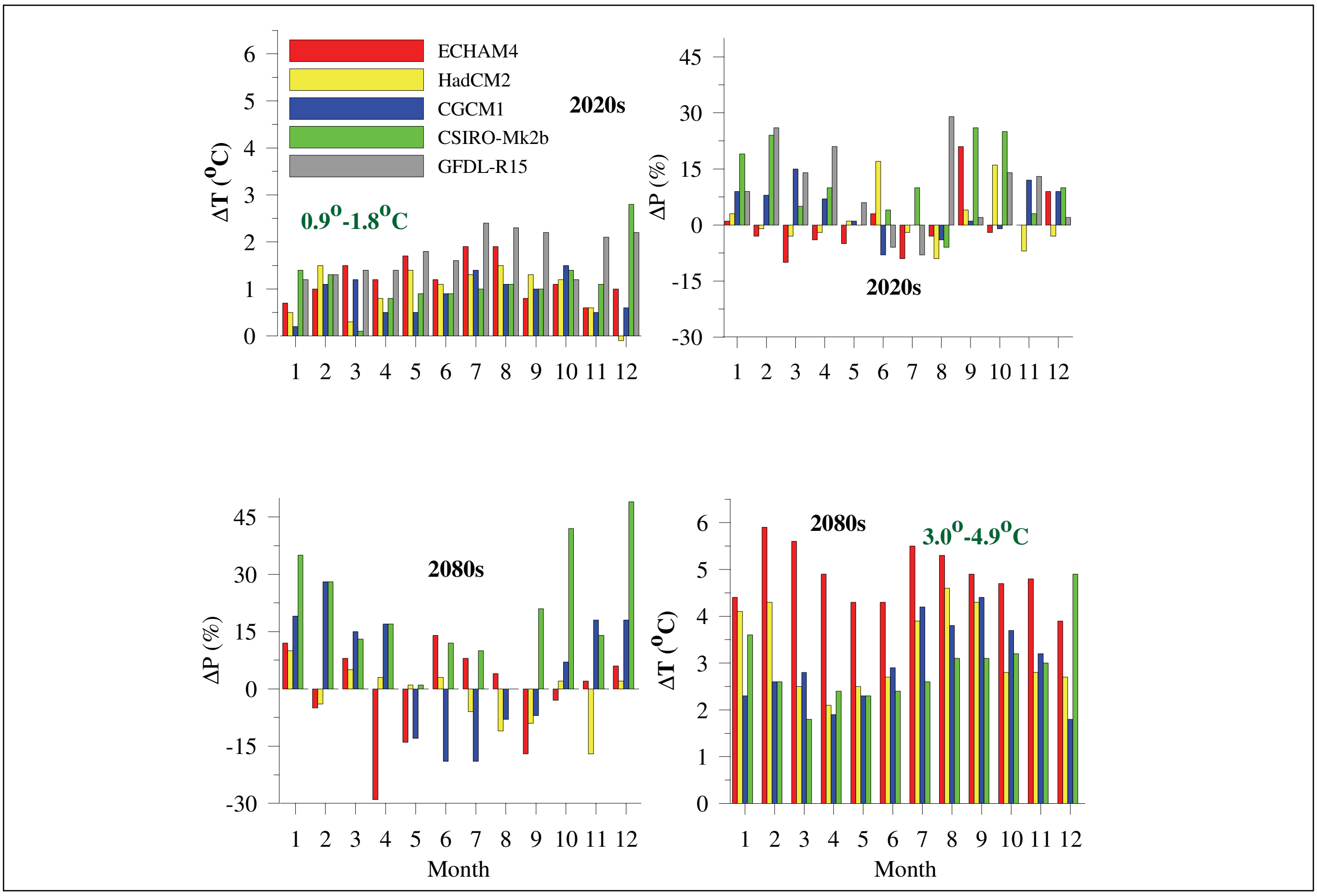

Figure 1: Transient GCM climate change scenarios for air temperature (ΔT) and precipitation (ΔP) for the 2020s and 2080s for northern Austria.
Abbildung 1: Zeitläufe von Klimaszenarien globaler Klimamodelle für Lufttemperatur (ΔT) und Niederschlag (ΔP) für 2020er und 2080er Jahre für das nördliche Österreich.

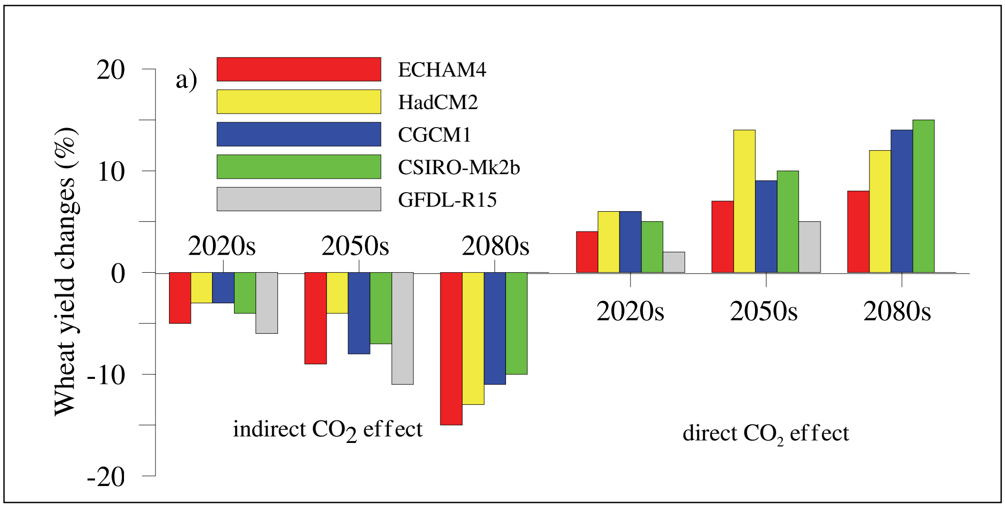

Figure 2: Winter wheat yield changes, relative to the current yields, under GCM scenarios for the 2020s (Figure 1), 2050s and 2080s (Figure 1) at a specific site (medium soil water storage capacity) in northern Austria, assuming indirect and direct CO_2 effects; CERES-Wheat model
Abbildung 2: Änderung der Winterweizenerträge im Vergleich zu gegenwärtigen Erträgen unter den Klimaszenarien der 2020er, 2050er und 2080er Jahre an einem bestimmten Standort (mittlere Bodenwasserspeicherfähigkeit) im Norden Österreichs unter Berücksichtigung des direkten und indirekten CO_2-Effektes; CERES-Wheat-Modell

potential in northern Europe and decreasing production in southern European regions, mainly due to increasing summer drought stress conditions (Wolf and Van Diepen, 1994, 1995; Žalud and Dubrovský, 2002). Significant negative yield effects for several crops and additional water demand for irrigation might be expected in southern Europe in general (e.g. Marrachi et al., 2005) or regions with low soil water availability (Tubiello et al., 2000). Rainfed summer crops are, as many simulation studies show, in general at higher yield risk because of increasing summer droughts under most climate scenarios.

Most impact studies conclude that there is a strong evidence that, especially for soils with low soil water storage capacity (Figure 3–4) or no groundwater impact to the rooting zone, irrigation or water-saving production techniques (e.g. by introducing mulching systems, adapting crop rota-

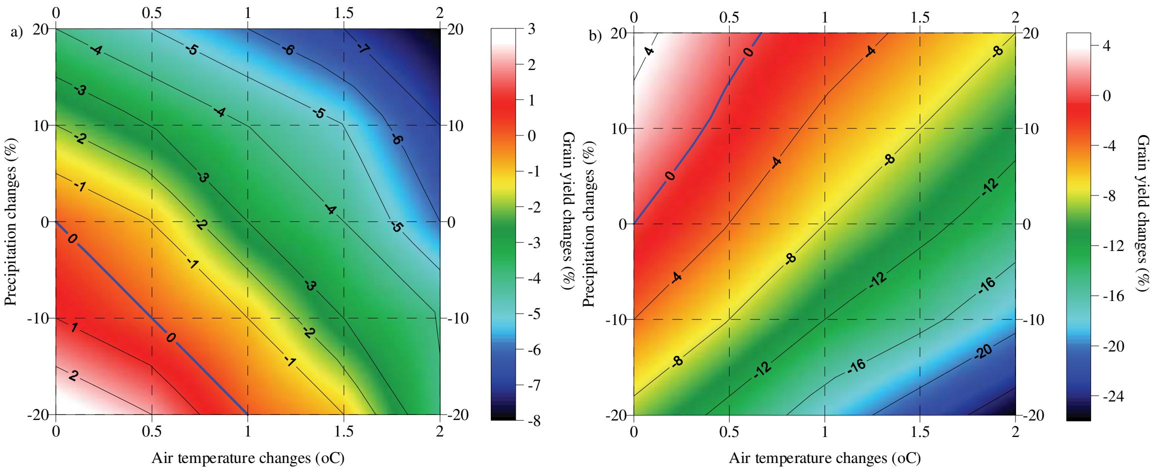

Figure 3: Changes in grain yield of winter wheat under incremental changes of air temperature and precipitation in Austria (left: soil with high available water storage capacity (300mm), right: soil with low water storage capacity (100 mm)), CERES-Wheat model

Abbildung 3: Änderung des Kornertrages bei Winterweizen bei stufenweiser Änderung von Temperatur und Niederschlag (links: Boden mit hoher verfügbarer Wasserspeicherfähigkeit (300mm), rechts: Boden mit geringer Wasserspeicherfähigkeit (100 mm)), CERES-Wheat-Modell

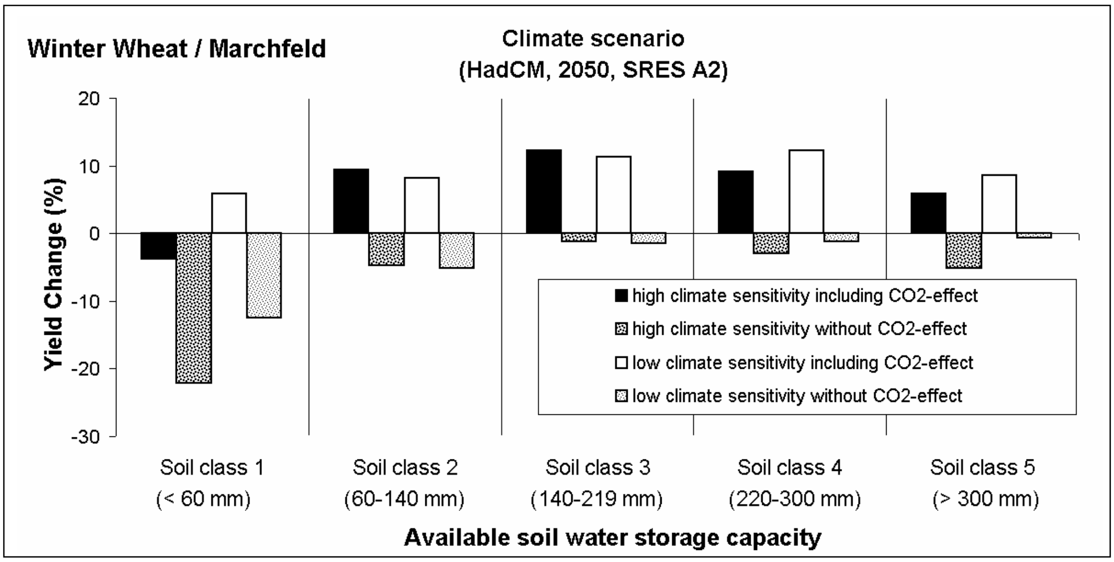

Figure 4: Changes in grain yield of winter wheat under the HadCM SRES A2 scenario (with high and low climate sensitivity/change) for the 2050s (SRES A2) for the 5 main soil classes in the Marchfeld region (north-east Austria), CERES-Wheat model

Abbildung 4: Änderung des Kornertrages bei Winterweizen unter dem HadCM Klimaszenario (mit hoher und niedriger Klimasensitivität/-änderung) für die 2050er Jahre (Emissionsszenario A2) für die 5 wichtigsten Bodenklassen im Marchfeld (Nord-Ost-Österreich), CERES-Wheat Modell tion), will remain important requirements under future climates in Central European agricultural regions for the attainment of the yield potential of crops. Summer crops will be more vulnerable and dependent on soil water reserves, as the soil water or higher ground water tables during the winter period cannot be utilized as much as by winter crops. Evapotranspiration losses during summer due to higher temperatures would increase significantly. Further many studies conclude that if the frequency and duration of droughts will increase as recent studies indicate (Pal et al., 2004; Calanca, 2007) or soil- and groundwater reserves decrease (e.g. by decreasing summer river flow from Alpine region) water shortages during summer would become more common, which could regionally also limit water availability for crop irrigation. An example of potential increase of drought risk in the region adjacent Austria (Figure 5) shows marked increase of drought risk with time (assuming realization of the given SRES and GCM scenarios). Apparently the most productive agricultural regions (i.e. typically lowlands) and semi-arid regions with poor soils are especially at risk.

Farmers and agricultural systems will, in fact, try to adjust to changing environmental conditions. Results of some simulation studies therefore include effects of adaptation measures, mostly by changing farm production methods or techniques, which can be simulated by the models. Results from these studies suggest for example that possible changes in sowing date (e.g. earlier sowing dates for summer crops) and cultivar selection can outrange negative effects of climate warming on crops (e.g. Alexandrov et al., 2002; Olesen and Bindi, 2004), especially in warmer regions with low soil water availability (e.g. Tubiello et al., 2000). Potential adaptation measures for agriculture, however, involve not only technical measures at the farm level, but a number of higher level measures such as adaptations in infrastructure, socio-economic, environmental and mitigation aspects (trends, scenarios, regulative frameworks), and all kind of options for production risk management. The overall assess-

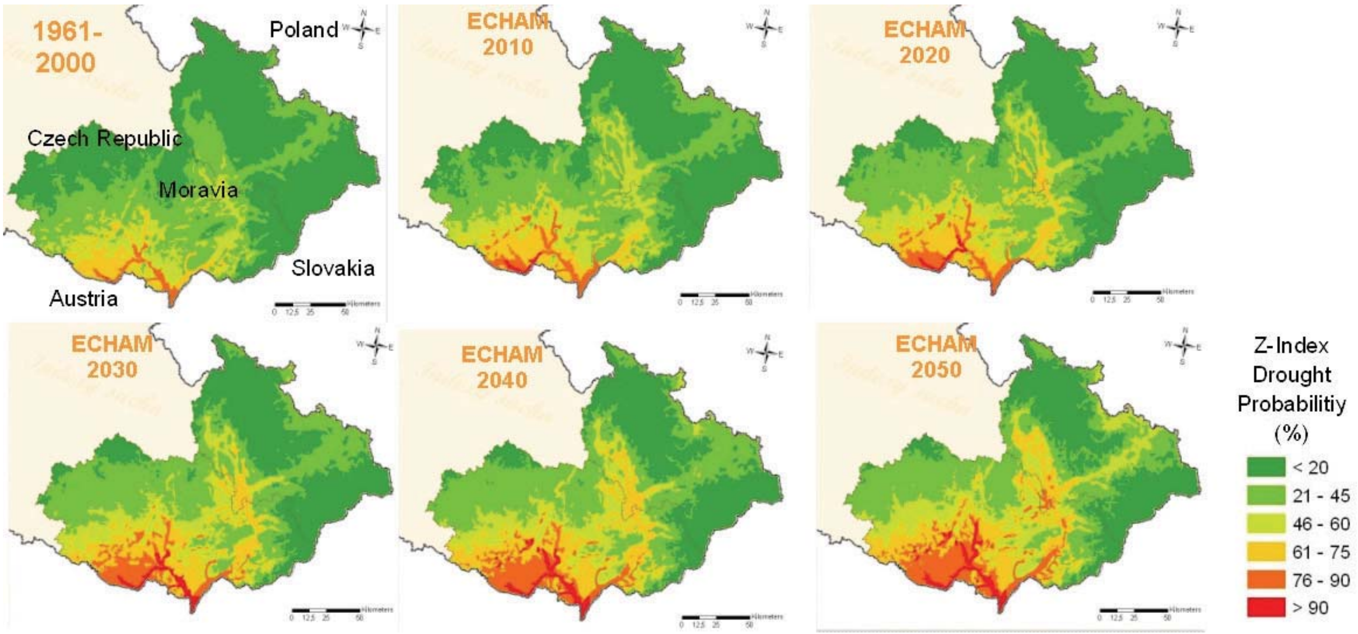

Figure 5: Spatial analysis of the percentage of dry months during the whole year (based on Palmer's relative Z-index) for the 1961–2000 baseline and expected climatic conditions in Moravia/Czech Republic. The climate change scenario is based on the ECHAM GCM model outputs driven by the average of A1 and B1 SRES scenarios and medium sensitivity of climate system to the greenhouse gas concentration increase. The relative Z-index (Dubrovský et al., 2005) calculation used 1961–2000 baseline data as the reference. The area with drought probability < 20 % is considered as "low risk" (> 60 % as "high risk" and > 90 % as "extremely high risk")

Abbildung 5: Räumliche Analyse des Anteils trockener Monate pro Jahr (basierend auf den Palmers relativen Z-index) für die Periode 1961–2000 und unter Klimaszenarien in Mähren. Das Klimaszenario basiert auf dem globalen Klimamodell ECHAM simuliert für ein Mittel aus A1 und B1 Emissionsszenarien und mittlerer Sensitivität des Klimasystems bei einer Zunahme der Treibhausgase. Der relative Z-index (Dubrovský et al., 2005) wurde unter Verwendung der Periode 1961–2000 als Referenz berechnet. Die Regionen mit einer Trockenheitswahrscheinlichkeit < 20 % werden mit „geringem Risiko", jene mit > 60 % mit „hohem Risiko" und jene mit > 90 % mit „sehr hohem Risiko" bewertet ment of adaptation options in agriculture is therefore even more complex and related to additional uncertainties by the human impact, where crop or ecosystem simulation models can only contribute a part of it. New developments such as whole farm system models try to include these additional aspects to a certain degree as mentioned above.

3 Uncertainties in climate change impact simulation studies

3.1 Uncertainties based on models representation of simulated processes

A significant source of uncertainty remains from the applied methods and models, as different crop models, can have various sensitivities and levels of representation of certain soil-crop-atmosphere processes (JANSSEN, 1994; JAMIESON et al., 1998). These differences origin from various sources of knowledge on specific processes (which are changing over time, leading normally to an increasing number of model versions) but also from the way of implementation into a model driven by the requirements of planned model application. The planned model application determines also the simulated time step (e.g. hourly, daily, monthly) and the model design for a certain spatial scale (e.g. single plant, field, region). Most crop models are designed for daily time steps and the field level scale, which is the most appropriate approach also for climate change impact studies.

A well known process related problem is for example the direct CO_2-effect, which is mostly considered as a fixed value in crop models, often only distinguishing between C3 and C4 crops. FACE (Free Air Carbon Experiments) experiments show a more complex picture and strong variability between cultivars and environmental conditions of which many processes are still not known and therefore difficult to simulate (FUHRER, 2003; KARTSCHALL et al., 1995; KERSEBAUM et al., 2008; WOLF et al., 2002).

The simulation of soil and crop water balance is another crucial point in dynamic crop growth models (e.g. STENITZER et al., 2007; KROES and ROELSMA, 2007). For example, there are different approaches for soil water balance simulation applied, reaching from the simple "cascade" approach (e.g. in DSSAT models) to complex soil water flow simulations based on soil water potentials, including e.g. the Richard's equation (e.g. SWAP model; KROES and VAN DAM, 2003). It means that the more simple approaches are not always applicable in any soils (e.g. STENITZER and MURER, 2003), however, they show mostly acceptable results for crop yield simulation in free draining soils (EITZINGER et al., 2003), without significant capillary rise from groundwater tables. Another problem of simulating correctly field and soil-crop water balance is the difficult parameterization of interception (which can reach in agricultural crop stands in average 20 % of a precipitation event) and surface runoff, which is determined by infiltration capacity of the soil and surface slope. These parameters can change soil water balance and crop available soil water considerably if not correctly described, and are often a source for deviation to measured soil water contents (beside the problem of site representative precipitation inputs).

Another to the soil-crop water balance related problem is the still highly empirical simulated process of root growth, which has a strong feedback to soil water availability and use. For example, the interactions of root growth with certain soil properties (such as strong inhomogeneities, soil temperature, chemical properties or compacted layers) are mainly not considered as a dynamical process. Several studies compare different crop models in these aspects, for example by EITZINGER et al. (2004) and WOLF et al. (1996). It is shown that the representation of root growth can have a strong feedback on simulated soil water contents with soil depth. The models should therefore be calibrated well in this aspect, which is of course often not possible or carried out under different soil conditions. In climate change impact studies for large areas, e.g. the European scale, often simplified models or empirical procedures within complex models are used, where these aspects are not considered at all due to lack of data and resources.

Due to the different representations of dynamic processes crop models (and other ecosystem models) often show different sensitivities to input parameters or different responses when input parameters, such as weather or climatic conditions, are changing over time. In several studies crop model sensitivities to different model inputs are compared and estimated (NONHEBEL, 1993; DUBROVSKÝ et al., 2000). The model sensitivities should however reflect crop responses well to avoid biases in simulated model outputs, especially when input parameters vary over the simulated period.

3.2 Uncertainties based on models inputs

The requirements for model inputs (e.g. the number of input parameters and for in-time changing inputs such as weather data, the time step) are determined by the way how processes are simulated in models. Also the model design for a certain spatial scale plays an important role. Scaling problems can therefore be related to the spatial as well as time scale (e.g. if model inputs for soil or climate/weather characteristics do not represent spatial variability or if weather data of certain time steps do not reflect extremes or short term variability). These scaling problems lead to certain uncertainties, which are inherent to the applied modelling methods (OLESEN et al., 2000).

An important source of uncertainty, related to the scaling problem, is the spatial representation of the weather and soil model input data, which is one of the main problems of spatial model applications.

Soil input data need to be considered critically, because of the importance for soil water storage and availability for crops. Often spatial data on field capacity or wilting point are not directly available and need to be assessed by e.g. pedotransfer functions. In the paper of GIJSMAN et al. (2002) it is shown that the use of different pedotransfer functions can lead to significant deviations in simulated crop yields.

The weather input data for crop models are in general very important in climate change impact studies (TSVETSINSKAYA et al., 2003). Especially the spatial representation of historical temperature, precipitation and solar radiation are critical for any model application. For model applications at the field level and for short time steps (such as the mostly used daily time step), the weather input data have to represent the local variation correctly, especially for precipitation because of the high spatial variability. For spatial model applications, several authors apply interpolation methods on these weather parameters, which should be chosen carefully (TRNKA et al., 2005). Figure 6 shows that the use of different methods for estimating global solar radiation from other meteorological parameters can cause an error in the calculated crop model yields of more than 20%, when long-term production potential (i.e. mean yield over extensive period of time) is considered.

This figure illustrates that uncertainties in the weather data (if not taken into account) may seriously affect the outcome of the climate change impact studies, depending on the most limiting factor for growth (NONHEBEL, 1993). In case of solar radiation both the climate change impact and the error in solar global radiation estimates can cause a yield response of the same magnitude.

In climate change impact simulation studies the weather input data representing conditions under climate scenarios strongly determine outputs and related uncertainties, e.g. for crop growth and yield (e.g. OLESEN et al., 2007). The obvious differences in the various GCM's for a given site urge for a probabilistic approach to deal with these uncertainties as GIORGI et al. (2004a,b) showed for climate change predictions in response to anthropogenic forcing at multi-decadal time scales. He argued that the non-linear and stochastic aspects of the climate system causing variations in climate models capability to represent climate variability. Therefore, and because of uncertainties in the climate models representation of the anthropogenic and natural forcing (e.g. a realistic representation of land surface heterogeneity and interactions), climate change scenarios contain an intrinsic level of uncertainty. One of the most common approaches is to compare different climate model scenarios (related to different emission scenarios as well as different climate models) for the same site and study to indicate the potential range of uncertainty (see Figure 2, 4). Ensembles of climate model simulations are, however, needed for a more robust assessment of the model's capability to simulate climatic trends. Therefore climate change prediction as well as climate change impact descriptions needs to be approached in a probabilistic way (e.g. JASPER et al., 2004; TRNKA et al., 2004). This requires a characterization and quantification of the uncertainties associated with the sequence of steps involved in a climate change prediction study.

Finally, it has to be considered that many measured model input data can potentially contain measurement errors because of several reasons. Long time weather data series often contain inhomogeneities if they were not corrected (e.g. PETERSON et al., 1998) before (which is still often the case, especially for daily data). These inhomogeneities can easily produce wrong trends in simulated model outputs, especially for long term trends in climate change impact studies. For all input data potential errors from measurements have to be evaluated carefully. The fact that a model can not compensate for errors caused by incorrect input data is obvious.

4 Strategies to improve local representation of climate change impact simulation studies

4.1 Improvements in the representation of model input data

Recent studies on climate change impacts on crop production often include climate downscaling methods in order to improve results of crop simulation studies by a better rep-

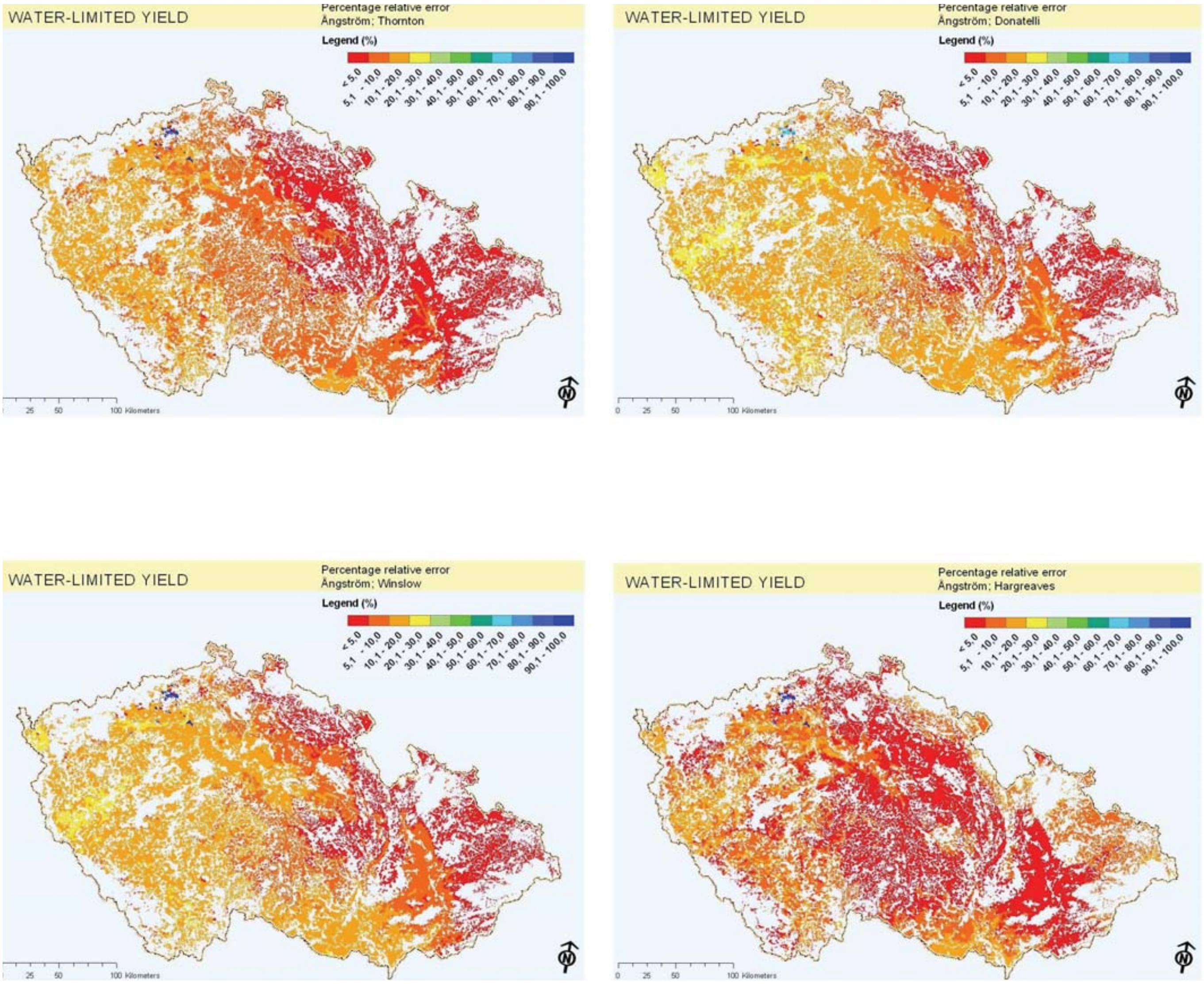

Figure 6: Relative bias in the simulated mean spring barley yield (1961–2000) caused by the different methods of estimating global solar radiation. The spatial analysis was based on crop yields calculated using WOFOST crop growth model at 50 weather stations and taking into account 25 different soil types. In this study the Angström-Prescott formula (based on the sunshine duration hours) was selected as a benchmark method in accordance with results of Trnka et al. (2005). The layer of crop yields attained using this method was then compared to those obtained when diurnal temperature range and precipitation (a–b) and diurnal temperature range only (c–d) were used as predictors of solar global radiation

Abbildung 6: Relative Abweichung des mittleren simulierten Sommergerstenertrages (1961–2000) durch unterschiedliche Methoden der Bestimmung der Globalstrahlung als Eingangsdaten für ein Wachstumsmodell. Die räumliche Analyse basiert auf Simulationen mit dem WOFOST Modell unter Berücksichtigung von 50 Wetterstationen und 25 verschiedener Bodenarten. In dieser Studie wurde die Angström-Prescott Gleichung (basiert auf Sonnenscheindauer) aufgrund der guten Ergebnisse aus Trnka et al. (2005) verwendet. Die Auswirkung auf die Erträge wird mit anderen Methoden zur Bestimmung der Globalstrahlung verglichen: (a–b) unter Verwendung der tägl. Temperaturamplitude sowie des Niederschlags und (c–d) nur die tägl. Temperaturamplitude

resentation of local climate variability and extremes. Downscaled climate scenarios can change the GCM's picture considerably especially in complex terrain which is a serious limitation of past studies without downscaled scenarios. Especially in complex terrains such as in Austria, both statistical and dynamical downscaling showed large regional differences in air temperature and precipitation characteristics (Formayer et al., 2003; Loibl et al., 2007).

For example, local-scale climate change scenarios for temperature and precipitation at about thirty stations in Austria, based on IPCC IS92a emission scenarios whose effects on the climate system, were calculated by use of the ECHAM4/OPYC3 global circulation model, were developed and presented by MATULLA et al. (2004). The study applies statistical downscaling, which is based on empirically derived relationships between the GCM scale (based on monthly NCEP/NCAR reanalysis data) and the local scale of the stations. The data sets are analysed by use of Empirical Orthogonal Functions (EOF) and brought into relation using the Canonical Correlation Analysis (CCA). Downscaling was performed for each season separately. Moreover, different climatic provinces in Austria were distinguished (because of strong influence by the Alps). The results show a complex regional pattern and differences to the large scale GCM climate scenarios. For example, the local-scale scenarios for the next four decades show no increase or even a slight decrease in precipitation during the winter period. Temperature is increasing significantly, especially in winter and stronger with increasing elevation (Figure 7). Further, an increase in the frequency of drought periods is estimated in the southern part of Austria.

Another recent study (LOIBL et al., 2007) on dynamical downscaling for Austria (using regional models but based on ECHAM5) revealed the potential spatial pattern for seasonal temperature and precipitation for the 2040's on a 10x10km grid. Compared to the above mentioned statistical downscaling results based on ECHAM4 it showed different seasonal changes with the highest temperature increase in late summer and autumn. Precipitation change shows significant spatial variability, however, with much higher uncertainty. In general, a similar slight decrease (eastern Austria) to increase (western Austria) of precipitation depending on the season is described. The study reveals also a strong increase of number of heat waves (doubling and more of heat days till the 2040s) and regional different increase of extreme precipitation.

On a seasonal and monthly time scale many climate models indicate an increase of climate variability such as the summer temperatures in Central Europe (SENIVERATNE et al., 2006) causing more frequent heat weaves. This has important consequences for assessing agricultural production potentials and risks. A problem with climate impact studies in the past was that information on a change in climate variability on a smaller time scale than seasonal or monthly (such as daily) was not included, because of high uncertainties from the climate models (e.g. SEMENOV and PORTER, 1995). TRNKA et al. (2004) showed for example that potential increasing variability of temperatures can have a strong negative yield impact on cereals in Central Europe (Figure 8). Combined with a change in the frequency of drought periods this negative effect could further increase. Recent studies therefore consider potential changes in daily climate variability by applying weather generators using information about change in climate variability from the updated climate models with better representation of land-atmosphere interactions.

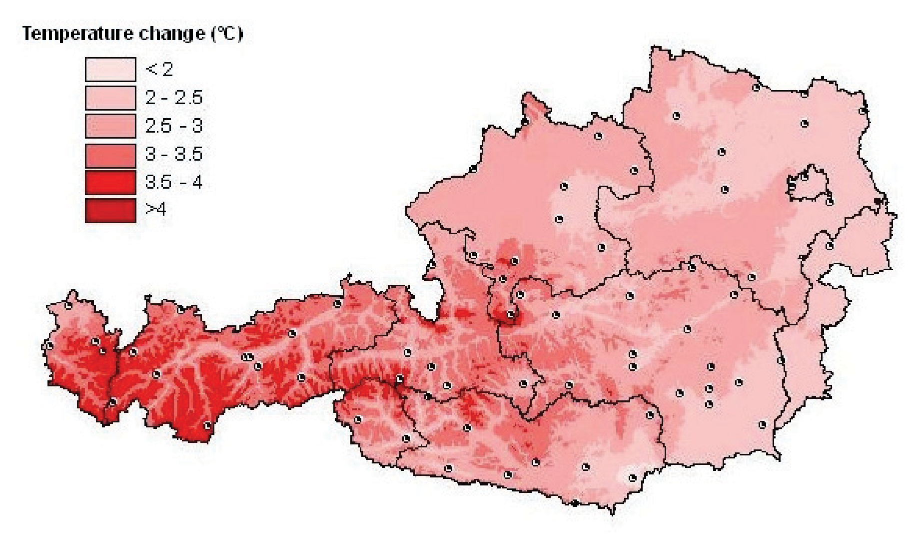

Figure 7: Change in temperatures over the Austrian terrain, depending on elevation, as calculated by statistical downscaling for the 2040's (Formayer et al., 2003)

Abbildung 7: Temperaturänderung in Österreich in Abhängigkeit von der Seehöhe, berechnet durch statistisches Downscaling für die 2040er Jahre (Formayer et al., 2003)

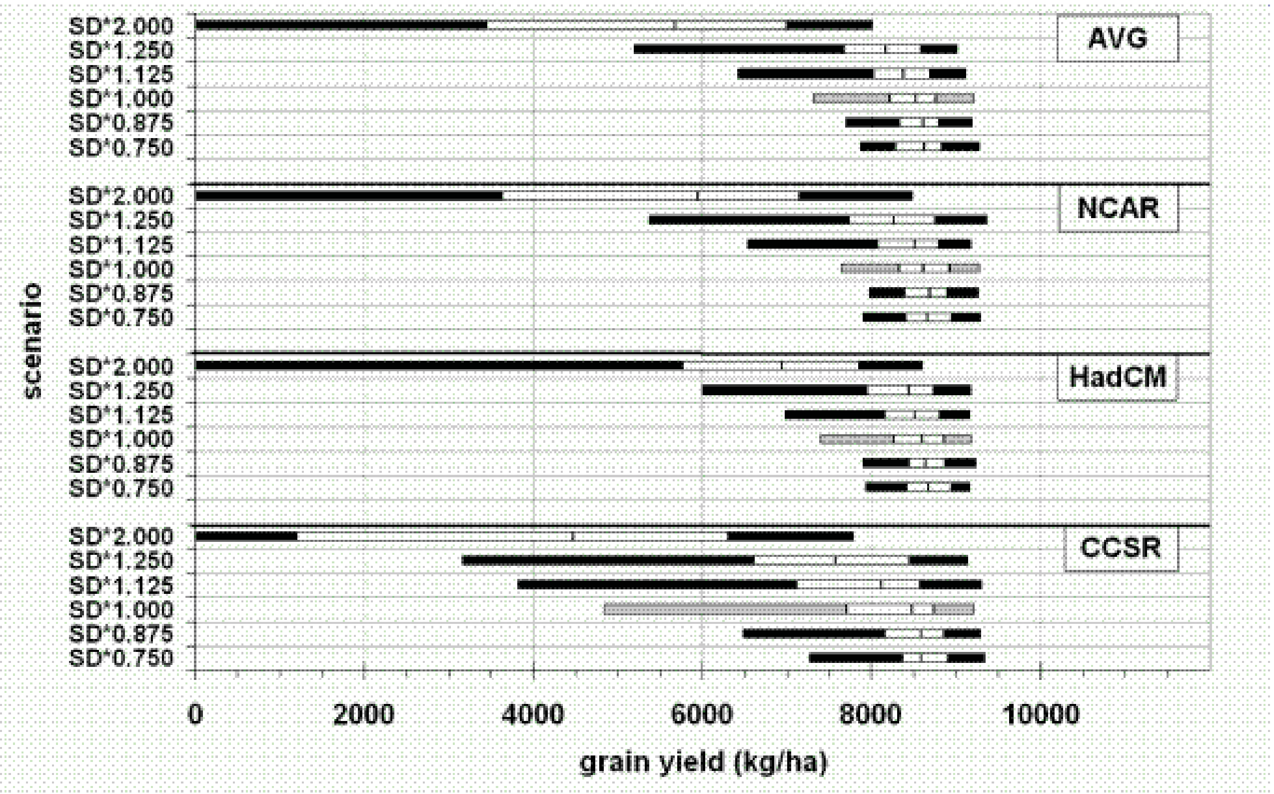

Figure 8: Impact of increasing temperature variability on simulated crop yields (SD=standard deviation) and different GCM's (AVG = average of 7 GCM's); (Trnka et al., 2004)

Abbildung 8: Einfluss zunehmender Temperaturvariabilität auf simulierte Getreideerträge (SD = Standardabweichung) bei unterschiedlichen Klimaszenarien (AVG = Mittelwert von 7 Klimaszenarien); (Trnka et al., 2004)

The other three main groups of model inputs are soil, plant and management characteristics, which are needed for any kind of model application (not only for climate change impact studies). For all three groups technical developments allow better representative input data for future applications, especially for spatial applications in combination with GIS such as Crop Growth Monitoring Systems (CGMs). For soil data, for example, digital soil maps with improved spatial resolution (e.g. NACHTERGAELE, 2008) are already available. For actual land use information remote sensing data can be used (e.g. DELECOLLE et al., 1992; BOUMAN, 1995; MOULIN et al., 1998). Also information on management input data could be gathered from remote sensing, especially for spatial model applications. Examples for that are sowing, harvest or cutting dates. Parameters derived from remote sensing can be used also for model calibration and validation (such as LAI or NDVI, duration of snow cover, surface temperatures, etc.). One example of application is the Crop Growth Monitoring System of MARS (Monitoring Agriculture with Remote Sensing) (http://mars.jrc.it/) for yield prediction at the European scale. Here, databases of meteorological data, soil characteristics from the European soil map (KING et al. 1995) and crop specific parameters from remote sensing (BOONS-PRINS et al., 1993) available for the whole EU are applied.

For point applications of crop models (e.g. on farm scale) many new and increasingly cheap measurement techniques are available even for operational applications (e.g. irrigation scheduling), such as agrometeorological field stations for gathering actual weather input data or soil water content sensors for crop irrigation scheduling. Field stations are also recommended for crop pest and disease models as well as warning systems.

4.2 Improving results by considering the human factor

Recent publications on climate change impacts on agriculture and potential adaptation measures include crop management, socio-economic scenarios and feedbacks from other boundary conditions such as regulatives or large scale infrastructure (REIDSMA, 2007; REIDSMA and EWERT, 2008). In several cases it turned out that socio-economic changes could outrange the pure climate change impact in Europe as described for example in the paper of HOLMAN et al. (2005). He investigated climate and socio-economic impacts, adaptation options as well as cross-sectoral interactions between four major sectors driving landscape change (agriculture, biodiversity, coastal zones and water resources) in England. Despite yield changes, cropping in that region is shown generally insensitive to climate, but very sensitive to socio-economic change. Similar findings for Central Europe from the EU-project ACCELERATES are described by AUDSLEY et al. (2005). They found that areas of agricultural land use in Central Europe may not change significantly, however significant shifts of cropping pattern were simulated. Socio-economic scenarios generated larger changes than climate scenarios, although the climatic conditions are a basic driving factor. Purely differences in climate scenarios had marginal effects on agricultural land use in many regions. This study however shows that there are still severe limitations for interpreting the results of such studies in general. These includes the often large spatial scale of soil data, which is much more heterogeneous in reality or the simplifications of applied crop models for specific crops. Also not considered or unknown potential production risks or stresses on crop production such as weather extremes or pest and diseases as well as the uncertainties in socio-economic scenarios are important limitations. Often hydrological aspects of river basins are neglected as well, although they could have a significant impact on groundwater resources, water availability for crops, soil erosion and others under changed climate (e.g. JASPER et al., 2004; PRUDHOMME, 2003). Additional often not considered aspects, which are especially important for the assessment of adaptation measures, are effects for mitigation, sustainability of production and long term effects such as changes in soil conditions and fertility. Current site specific agricultural conditions like cost related technological aspects of farm management, including the field size or the terrain, also should be considered, which opens a wide area for future research.

5 Conclusions

Simulation of climate change effects on crops using process oriented models is a promising method for the assessment of potential impacts of climate change and adaptation options in agriculture. Many studies carried out in Europe and in general are limited however by defined boundary conditions and model limitations. These, and problems of model applications for various scales can produce a number of uncertainties in the model outputs and related study results.

Past simulation studies on climate change impacts on crop yield in Central Europe show a mixed picture of results, depending on model complexity, the applied spatial scales, input data availability and applied scenarios. In general, the simulation studies show under climate scenarios in Central Europe decreasing yields at locations with water limitation and increasing yields at locations where water is no limiting factor for crops. Also there are simulated strong positive potential yield effects of increasing atmospheric carbon dioxide on C3 crops, which is also one of the most discussed uncertainties: New results from FACE and other field experiments often limit this effect considerably, depending on environmental interactions. Results on actual yields under the same climate change scenario can also differ considerably between regions as represented by soil and current climate conditions, crops and management options as well as and socio-economic assumptions.

Although large scale studies can detect basic trends the question arises if they are able at all to characterize reliable the impact of climate change on agricultural production for local decision conditions and decision makers. A better approach might be a synthesis of a pattern of small scale studies with locally calibrated models and methods, a high spatial soil data resolution and "downscaled" climate and socio-economic scenarios. A number of new methods and techniques is available and will be used for future studies, especially in order to improve the representation of spatial model input data. However, also other impacting factors have to be considered such as potential changes in climatic variability or impact of extremes not considered so far. Other boundary conditions like socio-economic developments and long term effects of climate change on natural resources should be considered by combination of data sources and methods. This is especially true for the assessment of adaptation measures, especially in Central Europe with large differences of farming systems and conditions between regions such as the farm size or the increasing number of organic farms.

Acknowledgement

The study was partly supported by COST 734 activities (www.cost734.eu), the ADAGIO project (www.adagio-eu.org) and by Grant Agency of the Czech Republic (project no. 521/08/1682) which is greatly appreciated.

Literature

Alexandrov, V., Eitzinger, J., Cajic, V. and M. Oberforster (2002): Potential impact of climate change on selected agricultural crops in north-eastern Austria. Global Change Biology 8 (4), 372–389.

Asseng, S., H. VAN Keulen, W. Stol (2000): Performance and application of the APSIM Nwheat model in the Netherlands, European Journal of Agronomy, Volume 12, P: 37–54, 2000.

Audsley, E., K.R. Pearn, C. Simota, G. Cojocaru, E. Koutsidou, M.D.A. Rounsevell, M. Trnka and V. Alexandrov (2006): What can scenario modelling tell us about future European scale land use, and what not? Environmental Science and Policy 9(2): 148–162.

Boons-Prins E.R, De Koning G.H.J., Van Diepen C.A., Penning De Vries F.W.T. (1993): Crop Specific Simulation Parameters for Yield Forecasting across the European Community. Simulation Reports No 32. CABO-DLO, The Netherlands.

Bouman, B.A.M. (1995): Crop modelling and remote sensing for yield prediction. Netherlands J. Agric. Sci. 43, 143–161.

Brisson, N., Corre-Hellou, G., Dibet, A., Launay, M., Crozat, Y. (2006): Evaluation of the STICS crop model within the EU INTERCROP project. Grain Legumes, 45: 10–12.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussiere, F., Cabidoche, Y.M., Cellier, P., Debake, P., Gaudillere, J.P., Henault, C., Maraux, F., Seguin, B., Sinoquet, H. (2003): An overview of the crop model STICS. Eur. J. Agron.,18, 309–332.

Calanca, P. (2007): Climate Change and drought occurrence in the Alpine region : How severe are becoming the extremes? Global and Planetary Change 57, 151–160.

Delécolle, R., Maas, S.J., Guérif, M., Baret, F. (1992): Remote sensing and crop production models: present trends. ISPRS J. Photogramm. Remote Sens. 47, 145–161.

Downing, T.E., Harrison, P.A., Butterfield, R.E., and K.G. LONSDALE (eds) (2000): Climate Change, Climatic Variability and Agriculture in Europe. An Integrated Assessment, Research Report No. 21, Brussels, Belgium: Commission of the European Union, Contract ENV4-CT95-0154, 445.

Dubrovský M., Žalud Z. and M. Štastná (2000): Sensitivity of CERES-Maize yields to statistical structure of daily weather series. Climatic Change 46, 447–472.

Dubrovský, M., Trnka, M., Svoboda, M., Hayes, M., Wilhite, D., Žalud, Z. and D. Semeradova (2005): Application of three drought indices to assess impact of climate change on drought conditions. In: 5th Annual Meeting of the European Meteorological Society, 12–16 September 2005, Utrecht, The Netherlands , CD ROM. ISSN 18127053.

Eitzinger, J., Žalud, Z., Alexandrov, V., Van Diepen, C.A., Trnka, M., Dubrovský, M., Semerádová, D. and M. Oberforster (2001): A local simulation study on the impact of climate change on winter wheat production in north-eastern Austria. Die Bodenkultur (Austrian Journal of Agricultural Research), Vienna, 52 (4), 199–212.

Eitzinger, J., Štastná, M., Žalud, Z. and M. Dubrovský (2003): A simulation study of the effect of soil water balance and water stress on winter wheat production under different climate change scenarios. Agricultural Water Management, 61, 3, 163–234.

Eitzinger, J., Trnka, M., Hösch, J., Žalud, Z. and M. Dubrovský (2004): Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecological Modelling 171 (3), 223–246.

Eitzinger, J., Thaler, S., Orlandini, S., Nejedlik, P., Kazandijev, V., Vucetic, V., Sivertsen, T.H., Mihailovic, D.T., Lalic, B., Tsiros, E., Dalezios, N.R., Susnik, A., Kersebaum, CH. K., Holden, N.M., Matthews, R. (2008): Agroclimatic indices and simulation models. In: Nejedlik, P. and Orlandini, S. (Eds.), 2008: Survey of agrometeorological practices and applications in Europe regarding climate change impacts. Report, Cost Action 734 "Impact of climate change and variability on European agriculture" (available at: www.cost734.eu).

Ewert, F., Rodriguez, D., Jamieson, P., Semenov, M.A., Mitchell, R.A.C., Goudriaan, J., Porter, J.R., Kimball, B.A., Pinter, P.J., Manderscheid, R., Weigel, H.J., Fangmeier, A., Fereres, E. and F. Villalobos

(2002): Effects of elevated CO2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. Agriculture Ecosystems & Environment, 93 (1–3): 249–266.

Formayer, H., Matulla, Ch., Groll, N., Haas, P. and H. Kromp-Kolb, H. (2003): Einsatzmöglichkeiten verschiedener statistischer Downscalingmethoden für Klimaänderungsszenarien in topographisch stark gegliedertem Terrain und explizite Anwendung auf Österreich für Niederschlag und Temparatur. Endbericht, Bundesministerium für Bildung, Wissenschaft und Kultur. GZ 30.893/1-VIII/A/4a/2001.

Fuhrer, J. (2003): Agroecosystem responses to combinations of elevated CO_2, ozone and global climate change. Agr. Ecosyst. Environ. 97, 1–20.

Fuhrer, J. (2007): Sustainability of Crop Production Systems under Climate Change. In: Newton, P.C.D., Carran, R.A., Edwards, G.R., Niklaus, P.A. (Hrsg.) Agroecosystems in a Changing Climate, CRC Press, Florida, 167–185.

Ijsman, A.J., Jagtap, S.S. and J.W. Jones (2002): Wading through a swamp of complete confusion: how to choose a method for estimating soil water retention parameters for crop models. European Journal of Agronomy 18 (1–2): 75–105.

Gerstengarbe, F.-W., Badeck, F., Hattermann, F., Krysanova, V., Lahmer, W., Lasch, P., Stock, M., Suckow, F., Wechsung, F., Werner, P. C. (2003): Studie zur klimatischen Entwicklung im Land Brandenburg bis 2055 und deren Auswirkungen auf den Wasserhaushalt, die Forst- und Landwirtschaft sowie die Ableitung erster Perspektiven. PIK-Report, Nr. 83, ISSN 1436-0179.

Giorgi, F., Bi, X. and J.S. Pal (2004a): Mean, interannual variability and trends in a regional climate change experiment over Europe. I. Present-day climate (1961–1990). Climate Dynamics 22 (6–7): 733–756.

Giorgi, F., Bi, X. and J.S. Pal (2004b): Mean, interannual variability and trends in a regional climate change experiment over Europe. II. Climate change scenarios (1971–2100). Climate Dynamics 23: 839–858.

Holden, N. M, A. J., Brereton, R., Fealy, J., Sweeney (2003): Possible change in Irish climate and its impact on barley and potato yields. Agricultural and Forest Meteorology 116: 181–196.

Holden, N. M., Brereton, A.J. (2006): Adaptation of water and nitrogen management of spring barley and potato as a response to possible climate change in Ireland. Agricultural Water Management 82: 297–317.

Holman, I.P., Nicholls, R.J., Berry, P.M., Harrison, P.A., Audsley, E., Shackley, S. and M.D.A. Rounsevell (2005): A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK. Climate Change 71 (1): 43–73.

Jamieson, P.D., Porter, J.R., Goudriaan, J., Ritchie, J.T., Van Keulen, H. and W. Stol (1998): A comparison of the models AFRCWHEAT2, CERES wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. Field Crops Research 55, 23–44.

Janssen, P.H.M. (1994): Assessing sensitivities and uncertainties in models: a critical evaluation. In: Grasman, J. & G. van Straten (Eds.): Predictability and nonlinear modeling in natural sciences and economics.- Kluwer, Dordrecht, 344–361.

Jasper, K., Calanca, P., Gyalistras, D. and J. Fuhrer (2004): Differential impacts of climate change on the hydrology of two alpine river basins. Climate Research 26 (2): 113–129.

Jones, J.W., Keating, B.A., Porter, C.H. (2001): Approaches to modular model development. Agricultural System 70, 421–443.

Jones, J.W., Hoogenboom, G., Porter, CH., Boote, KJ., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T. (2003): The DSSAT cropping system model, European Journal Of Agronomy, Volume 18 (3–4), P: 235–265.

Kartschall, T.H., Grossman, S., Pinter, P. J. J.R., Garcia, R. L., Kimball, B. A., Wall, G. W., Hunsaker, D. J. and R.L. Lamorte (1995): A Simulation of Phenology, Growth, Carbon Dioxide Exchange and Yields under Ambient Atmosphere and Free-Air Carbon Dioxide Enrichment (FACE) Maricopa, AZ, for Wheat, Blackwell Science Ltd, Journal of Biogeography, 611–622.

Kersebaum, K. C., Lorenz, K., Reuter, H. I., Schwarz, J., Wegehenkel, M., WENDROTH, O. (2005): Operational use of agro-meteorological data and GIS to derive site specific nitrogen fertilizer recommendations based on the simulation of soil and crop growth processes. – Physics and Chemistry of the Earth 30 (1–3): 59–67.

Kersebaum, K.C. (2007): Modelling nitrogen dynamics in soil–crop systems with HERMES. Nutrient Cycling in Agroecosystems 77 (1), 39–52.

Kersebaum, K.C., Nendel, C., Mirschel, W., Manderscheid, R., Weigel, H.-J., Wenkel, K.-O. (2008): Testing different CO2 response algorithms against a FACE crop rotation experiment and application for climate change impact assessment at different sites in Germany. Idöjaras (im Druck).

King, D., Le Bas, C., Daroussin, A.J., Thomasson, A.J., Jones, R.J.A. (1995): The EU map of soil water available for pants. In King D., Jones R.J.A., Thomasson A.J. (Eds.): European Land Information System for Agro-environmental Monitoring. European Commission, Luxemburg, 131–141.

Kroes, J.G., Roelsma, J. (2007): Simulation of water and nitrogen flows on field scale: application of the SWAP-ANIMO model for the Müncheberg data set. In: K.C. Kersebaum, J.M. Hecker, W. Mirschel, M. Wegehenkel (eds.): Modelling water and nutrient dynamics in soil-crop systems. Springer, Dordrecht. 111–128.

Kroes, J.G., Van Dam, J.C. (eds) (2003): Reference Manual SWAP version 3.0.4. Wageningen, Alterra, Green World Research.. Alterra-Report 773. 211 pp, Wageningen, The Netherlands

Krysanova, V., Wechsung, F., Becker, A., Poschenrieder, W., Gräfe, J. (1999): Mesoscale ecohydrological modeling to analyze regional effects of climate change. Environmental Modeling & Assessment, 4, 259–271.

Loibl, W., Beck, A., Dorninger, M., Formayer, H., Gobiet, A. and W. Schöner (2007): Kwiss Program Reclip: more research for climate protection: model run evaluation. Final report, ARC Berichte, Hg. Austrian research Centers GmbH, Tech Gate Vienna; http://systems research.arcs.ac.at/projects/climate/

Maracchi, G., Sirotenko, O. and M. Bindi (2005): Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. Climate Change 70 (1–2): 117–135.

Matthews, K.B., Sibbald, A.R. & Craw, S. (1999): Implementation of a spatial decision support system for rural land use planning: integrating geographic information system and environmental models with search and optimisation algorithms. Comput. Electron. Agric. 23 (1): 9–26.

Matulla, CH., Penlap, E.K., Haas, P. and H. Formayer (2004): Comparative Analysis of Spatial and Seasonal Variability: Austrian Precipitation during the 20th Century. International Journal of Climatology, 23, 13, 1577–1588.

Mirschel, W., Wenkel, K.O., Schultz, A., Pommerening, J., Verch, G. (2005): Dynamic phenological model for winter rye and winter barley, European Journal of Agronomy, Volume 23, P: 123–135.

Mirschel, W., Schultz, A., Wenkel, K.-O. (2001): Assesing the Impact of Land Use Intensity and Climate Change on Ontogenesis, Biomass Production, and Yield of Northeast German Agrolandscapes. In: Tenhunen, J.D., Lenz, R., Hantschel (Eds.): Ecosystem Approaches toLandscape Management in Central Europe. Ecological Studies, Vol. 147, Springer-Verlag Berlin Heidelberg, New York, 299–313.

Moulin, S., Bondeau, A., Delécolle, R. (1998): Combining agricultural crop models and satellite observations: from field to regional scales. Int. J. Remote Sens. 19 (6), 1021–1036.

Nonhebel, S. (1993): The importance of weather data in crop growth simulation models and assessment of climate change effects, Ph.D. Thesis, Wageningen Agricultural University.

Nachtergaele, F., Van Velthuizen, H., Verelst, L. (2008): FAO/IIASA/ISRIC/ISS_CAS/JRC, (2008): Harmonized World Soil Database (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria, (available at: www.iiasa.ac.at/research/luc).

Olesen, J.E., Bøcher, P.K. & Jensen, T. (2000): Comparison of scales of climate and soil data for aggregating simulated yields of winter wheat. Agriculture, Ecosystems and Environment 82, 213–228.

Olesen, J.E., Bindi, M. (2004): Agricultural impacts and adaptations to climate change in Europe. Farm Policy Journal, 1: 36–46.

Olesen, J.E., Carter, T.R., Diaz-Ambrona, C.H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikof, J., Quemada, M., Ruiz-Ramos, M., Rubæk, G., Sau, F., Smith, B. & Sykes, M. (2007): Uncertainties in projected impacts of climate change on European agriculture and ecosystems based on scenarios from regional climate models. Climatic Change 81, 123–143.

Pal, JS., Giorgi, F. and X.Q. Bi (2004): Consistency of recent European summer precipitation trends and extremes with future regional climate projections – art. no. L13202. Geophysical Res. Letters 31 (13): 13202–13202.

Parry, M. (ed) (2000): Assessment of Potential Effects and Adaptations for Climate Change in Europe. The Europe Acacia Project. Jackson Environment Institute, University of East Anglia, Norwich, UK, 320.

Penning De Vries, F.W.T, Jansen, D.M., Ten Berge, H.F.M., Bakema, A. (1989): Simulation of ecophysiological processes of growth in several annual crops. Pudoc, Wageningen, 271.

Peterson, T.C., Easterling, D.R., Karl, T.R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullet, D., Vincent, L., Heino, R., Tuomenvirta. H., Mestre, O., Szentimrey., Salinger, J., Forland, E.J., Hanssen-Bauer, I., Alexandersson, H., Jones, P., Parker. D. (1998): Homogeneity adjustments of In Situ atmospheric climate data: a review. Int J Climatol 18:1493–1517.

Prudhomme, C., Jakob, D. and C. Svensson (2003): Uncertainty and climate change impact on the flood regime of small UK catchments. Journal of Hydrology 277 (1–2): 1–23.

Reidsma, P. (2007): Adaptation to Climate Change: European Agriculture. PhD thesis Wageningen University, Wageningen, The Netherlands, ISBN: 978-90-8504-792-6.

Reidsma, P., Ewert, F. (2008): Regional Farm Diversity Can Reduce Vulnerability of Food Production to Climate Change. Ecology and Society 13 (1): 38.

Schaldach, R., Alcamo, J. (2006): Coupled simulation of regional land use change and soil carbon sequestration: A case study for the state of Hesse in Germany. Environ. Model. and Software 21, 1430–1446

Semenov, M.A., Porter, J.R. and R. Delecolle (1993): Simulation of the effects of climate change on growth and development of wheat in the U. K. and France. In: EPOCH Project: The Effects of Climate Change on Agricultural and Horticultural Potential in the EC. Final Project Report, University of Oxford-European Communities.

Semenov, M. A. and J.R. Porter (1995): Climatic variability and the modelling of crop yields. Agric. For. Meteorol. 73, 265–283.

Seneviratne, S.I., Lüthi, D., Litschi, M. and Ch. Schär (2006): Land-atmosphere coupling and climate change in Europe. Nature 443. 205–209.

Stenitzer, E., Diestel, H., Franko, U., Schwartengräber, R., Zenker, T. (2007): Performance of the model SIMWASER in two contrasting case studies on soil water movement. In: Modelling water and nutrient dynamics in soil-crop systems, Proceedings, ed.: Kersebaum, K.H., Hecher J-M., Mirschel, W., Wegehenkel, M.; Springer, 27–36.

Stenitzer, E., Murer, E. (2003): Impact of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model. Soil Till Res 73: 43–56.

Stock, M. (ed.) (2005): KLARA: Klimawandel – Auswirkungen – Risiken – Anpassung. PIK Report 99, Potsdam.

Stockle, C.O., Martin, S.A. & Campbell, G.S. (1994): CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield. *Agric. Syst.* 46(3): 335–359.

Trnka, M., Dubrovský, M., Semeradova, D. and Z. Žalud (2004): Projections of uncertainties in climate change scenarios into expected winter wheat yields. Theoretical and Applied Climatology 77 (3–4): 229–249.

Trnka, M., Žalud, Z., Eitzinger, J. and M. Dubrovský (2005): Quantification of uncertainties introduced by selected methods for daily global solar radiation estimation. Agricultural and Forest Meteorology, Volume 131, Issues 1–2: 54–76.

Tsvetsinskaya, E.A., Mearns, L.O., Mavromatis, T., Gao, W., Mcdaniel, L., and M.W. Downton (2003): The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climate Change 60 (1–2): 37–71.

Tubiello, F.N., Donatelli, M., Rosenzweig, C. and C.O. Stockle (2000): Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. Europ. J. Agronomy 13 (2–3): 179–189.

Van Ittersum, M.K., Leffelaar, P.A., Van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J. (2003): On approaches and applications of the Wageningen crop models, European Journal of Agronomy, Volume 18, P: 201–234, 2003.

Wegehenkel, M., Kersebaum, C.K. (2003): A Modelling System For Calculating Water Balance And Crop Growthat Different Spatial Scales Using Remote Sensing And GIS, Geophysical Research Abstracts, Volume 5, 2003.

Wessolek, G, Asseng, S. (2006): Trade-off between wheat yield and drainage under current and climate change conditions in Northeast Germany. Eur. Journal Agronomy 24, 333–342.

Wolf, J. (1993): Effects of climate change on wheat production potential in the European Community.- Eur. J. Agron.2, 281–292.

Wolf, J. and C.A. Van Diepen (1994): Effects of climate change on silage maize production potential in the European Community.-Agricultural and Forest Meteorology 71, Nos. 1–2, 33–60.

Wolf, J. and C.A. Van Diepen (1995): Effects of Climate Change on Grain Maize Yield Potential in the European Community.-Climatic Change 29 : 299–331.

Wolf, J., Evans, L.G., Semenov, M.A., Eckersten, H., and A. Iglesias (1996): Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. Climate Res. 7, 253–270.

WOLF, J., VAN OIJEN, M. and C. KEMPENAAR (2002): Analysis of the experimental variability in wheat responses to elevated CO_2 and temperature. Agriculture Ecosystems & Environment 93 (1–3): 227–247.

WOLF, J. and M. VAN OIJEN (2002): Modelling the dependence of European potato yields on changes in climate and CO_2. Agricultural and Forest Meteorology 112 (3–4): 217–231.

WZU – Wissenschaftliches Zentrum für Umweltsystemforschung, Universität Kassel (2005): Klimawandel und Landwirtschaft in Hessen: Mögliche Auswirkungen des Klimawandels auf landwirtschaftliche Erträge. INKLIM Final Report. http://www.hlug.de/medien/luft/inklim/dokumente/endberichte/landwirtschaft.pdf

ŽALUD, Z. and M. DUBROVSKÝ (2002): Modelling climate change impacts on maize growth and development in the Czech Republic. Theoretical and Applied Climatology 72 (1–2): 85–1.

Address of authors

Josef Eitzinger, Herbert Formayer, Sabina Thaler, Institute of Meteorology, Department of Water, Atmosphere and Environment, University of Natural Natural Resources and Applied Life Sciences, Vienna, Austria
E-Mail: josef.eitzinger@boku.ac.at
Mirek Trnka, Zalud Zdenek, Institute of Agrosystems and Bioclimatology, Mendel University of Agriculture and Forestry Brno (MUAF), Czech Republic
Vesselin Alexandrov, National Institute of Meteorology and Hydrology, Sofia, Bulgaria

Eingelangt am 24. September 2007
Angenommen am 25. November 2008