Theor. Appl. Climatol. 77, 229–249 (2004)
DOI 10.1007/s00704-004-0035-x

Theoretical
and Applied
Climatology

Printed in Austria

[1] Mendel University of Agriculture and Forestry Brno, Czech Republic
[2] Institute of Atmospheric Physics, AS CR, Praha, Czech Republic

# Projections of uncertainties in climate change scenarios into expected winter wheat yields

**M. Trnka**[1], **M. Dubrovský**[2], **D. Semerádová**[1], and **Z. Žalud**[1]

With 7 Figures

Received August 15, 2003; revised November 3, 2003; accepted December 18, 2003

## Summary

The crop model CERES-Wheat in combination with the stochastic weather generator were used to quantify the effect of uncertainties in selected climate change scenarios on the yields of winter wheat, which is the most important European cereal crop. Seven experimental sites with the high quality experimental data were selected in order to evaluate the crop model and to carry out the climate change impact analysis. The analysis was based on the multi-year crop model simulations run with the daily weather series prepared by the stochastic weather generator. Seven global circulation models (GCMs) were used to derive the climate change scenarios. In addition, seven GCM-based scenarios were averaged in order to derive the average scenario (AVG). The scenarios were constructed for three time periods (2025, 2050 and 2100) and two SRES emission scenarios (A2 and B1). The simulated results showed that: (1) Wheat yields tend to increase (40 out of 42 applied scenarios) in most locations in the range of 7.5–25.3% in all three time periods. In case of the CCSR scenario that predicts the most severe increase of air temperature, the yields would be reduced by 9.6% in 2050 and by 25.8% in 2100 if the A2 emission scenario would become reality. Differences between individual scenarios are large and statistically significant. Particularly for the time periods 2050 and 2100 there are doubts about the trend of the yield shifts. (2) The site effect was caused by the site-specific soil and climatic conditions. Importance of the site influence increases with increasing severity of imposed climatic changes and culminates for the emission scenario A2 and the time period 2100. The sustained tendency benefiting two warmest sites has been found as well as more positive response to the changed climatic conditions of the sites with deeper soil profiles. (3) Temperature variability proved to be an important factor and influenced both mean and standard deviation of the yields. Change of temperature variability by more than 25% leads to statistically significant changes in yield distribution. The effect of temperature variability decreases with increased values of mean temperature. (4) The study proved that the application of the AVG scenarios – despite possible objections of physical inconsistency – might be justifiable and convenient in some cases. It might bring results comparable to those derived from averaging outputs based on number of scenarios and provide more robust estimate than the application of only one selected GCM scenario.

## 1. Introduction

Earth's atmospheric $CO_2$ concentration increased by about 30% during past 200 years, from nearly 280 to more than 360 ppm (Houghton et al., 2001; Amthor, 1998). This ongoing change is of concern because increase of greenhouse gasses may be warming the Earth's surface and could alter temporal and spatial patterns of precipitation and evaporation (e.g. Houghton et al., 2001) as well as other climatic characteristics. In fact most of Europe has already experienced increases in the surface air temperature during the 20th century, which amounts to 0.8 °C in annual mean temperature over the entire continent (Beniston and Tol, 1998). The atmospheric $CO_2$, which is the primary source of carbon for the plants, is in its present concentration suboptimal for $C_3$ type plants (Hall, 1979) and therefore the increased content of $CO_2$ in the air would stimulate photosynthesis even though some experiments seem to suggest that the increase of the photosynthesis intensity vary during individual phenological phases (e.g. Mitchell et al., 1999). In the same time, higher ambient $CO_2$ allows to reduce the transpiration intensity through decreased stomatal conductance especially under higher temperatures (Bunce, 2000). This should lead to the improved water use efficiency (WUE) and thereby to a lower probability of the water stress occurrence (Kimbal, 1983). These physiological responses are known as the $CO_2$-*fertilisation effect* (Dhakhwa et al., 1997) or the *direct effect* of increased $CO_2$. The experiments made in controlled environment indicate that the winter wheat growth and biomass production might increase up to $33 \pm 6\%$ (e.g. Cure and Ackock, 1986) at doubled ambient $CO_2$. Some studies also showed that the variability in these wheat responses to $CO_2$ enrichment is very high (e.g. Wolf et al., 2002; Bender et al., 1999). Recent review of 156 experiments with winter wheat (Amthor, 2001) that were carried out during 1976–2001 supports these results. Those experiments that were undertaken in controlled environment (laboratories or greenhouses) show 12–14% yield increase per 100 ppm of additional ambient $CO_2$ concentration while for the field experiments the reported increase is only 8.0–8.6% per 100 ppm of $CO_2$.

Majority of the recent climate change impact assessments have come to the conclusion that there is a chance of over 20% winter wheat yield increase by 2050 in some parts of Europe. This is mostly due to the fertilizing effect of $CO_2$ (e.g. Alexandrov and Hoogenboom, 2000; Harisson et al., 2000; Tubiello et al., 2000). As the counterbalance to the fertilizing effect of $CO_2$ comes the impact of the changed weather regime brought about by $CO_2$ concentration increase. This phenomenon is frequently called as an indirect (or weather) effect of the $CO_2$ increase and it might reduce cereals the yields significantly especially in the southern regions (e.g. Olesen and Bindi, 2002; Smith and Lazo, 2001). If no management responses are applied, winter wheat yields typically decrease with increasing temperature due to the shortening of phenological phases (Batts et al., 1997; Brown and Rosenberg, 1997). However the crop response to higher temperatures clearly depends on the character of temperature increase as well as on the developmental stage of the crop (Porter and Gawith, 1999). Besides changes of temperature mean also changes in the temperature variability might have large impact on the winter wheat yields. High variability of winter temperatures might cause frost damage in the temperate climatic conditions. On the contrary brief heat waves during anthesis period might lead to the severe yield reduction due to pollen sterilization (Wheeler et al., 2000; Ferris et al., 1998). Increasing solar radiation stimulates leaf assimilation (Wolf and van Diepen, 1995), thereby increasing yields (Hall, 2001; Brown and Rosenberg, 1997). On the other hand, as both increased temperature and solar radiation stimulate evapotranspiration, the yields may decrease due to deepened water stress if the water supply is under its critical level (Trnka et al., 2001). The effect of precipitation may be either positive if precipitation reduces the existing water stress, or negative, which may be related, e.g. to the intensified nitrogen leaching by excessive precipitation or by the soil oxygen concentration decrease under the critical threshold (e.g. Saarikko, 2000) etc. Naturally under the conditions of the future climate both indirect and direct effects will influence crop growth and for this situation term "combined effect" is commonly used. Experimental assessment of climate change impacts requires expensive equipment and sufficient time prior representative results are available (e.g. Wolf et al., 1998). The spatial variability in growing conditions within one field and uncertainty in the yield measurements might also lead to very large variations in the observed crop responses (Wolf et al., 2002) in some cases. Owing to these facts, crop models were employed in the majority of impact studies to assess the simultaneous effects on crop growth and yield of future elevated $CO_2$, regional climate change, and crop management despite some of their shortcomings highlighted by Tubiello and Ewert (2002).

Most of the widely used crop models require daily weather series to run simulations. This lead to the development of several methods of their preparation either by the direct modification of the measured data (e.g. Alexandrov and Hoogenboom, 2000), by applying so called analog historical weather series (e.g. Easterling et al., 1992) or by modifying stochastic weather generator parameters (e.g. Žalud and Dubrovský, 2002; Dubrovský et al., 2000; Semenov and Porter, 1995) according to given climate change scenario. Climate change scenario represents the difference between some presumable future climate and the current climate usually represented by the climate model (Houghton et al., 2001). Availability of a relatively high number of Global Climate Models (GCMs) in combination with a variety of emission scenarios, which are based on various assumptions on future socio-economical development of human society and environment (Houghton et al., 2001), results in a wide spectrum of possible climate change scenarios that differ significantly in some key parameters. The differences between the individual climate change scenarios are then projected into results of climate change assessments on different levels (local, regional or continental), e.g. in the form of uncertainty in the yields of particular crop at given time period. The uncertainties in the future development of the greenhouse gasses emissions and in the response of the climatic system are only two out of many sources of the uncertainty in the climate change impact studies. The reliability of such studies is also affected by the uncertainties in the experimental practice and observed data, in the applied models and finally in the spatial scale (Downing et al., 2000). Each of the sources of the uncertainty should be dealt with in detail as the contemporary climate change impact studies are becoming more and more complex by introducing either highly sophisticated modeling systems that are focused on the spatial analysis of climate change impacts (e.g. Harrison et al., 2000; Alexandrov and Hoogenboom, 2000; Izaurralde et al., 2003) or on the land use and crop composition change (e.g. Rounsevell, 2003). In these systems crop models are only one of the subsystems integrated in the framework but still the quality of their outputs are the key to the system reliability. It is often impossible to study all levels of uncertainty in all grids e.g. due to lack of the experimental data or lack of the required computer time. In this case, the site approach seems to be much more sensible as there is usually sufficient amount of experimental data on the site level and the required computer resources are no limit in this simulation exercise. Providing sufficient number of such sites it is then possible to carry out assessment of particular source of uncertainty over wider area and under various soil and climatic conditions.

As it is extremely difficult to foresee long-term trends in the development of agriculture technology the majority of the climate change impact studies uses either assumption of no change in the agricultural practices or only modifications in the operational management e.g. an adaptation through earlier/later sowing date or assumptions on introduction of later maturing cultivars (e.g. Izaurralde et al., 2003). The main benefits of these studies is to assess sustainability of present agricultural practices in the future climatic conditions, to help define priority of agricultural research in order to mitigate negative impacts and also to provide information to decision makers on the national and global level.

In this paper the effect of different climate change scenarios for three reference periods (2025, 2050 and 2100) on simulated winter wheat crop yields is evaluated with the special attention paid to the assessment of projections of the uncertainty in the climate change scenarios to the future winter wheat yields. The climate change scenarios used in this study had been developed using the pattern scaling technique and details maybe found in Dubrovský et al. (2003).

## 2. Materials and methods

### 2.1 Description of the study area

The test sites used in the study lay within the area of the Czech Republic, located in the Central Europe between 48°33′–51°03′N and 12°05′–18°51E (Fig. 1). The climate of the Czech Republic is influenced by mutual penetration and mingling of the ocean and continental effects. It is characterized by the prevailing western winds, intensive cyclonal activities causing frequent alternating of air masses and comparatively ample precipitation (Petrovič, 1969). The climate of the area is influenced by the altitude and geographical relief to a large extend however more than 92% of land lays lower than 700 m and most of the agricultural production is situated under this altitude while above 1000 m lays only 1.0% of the total area

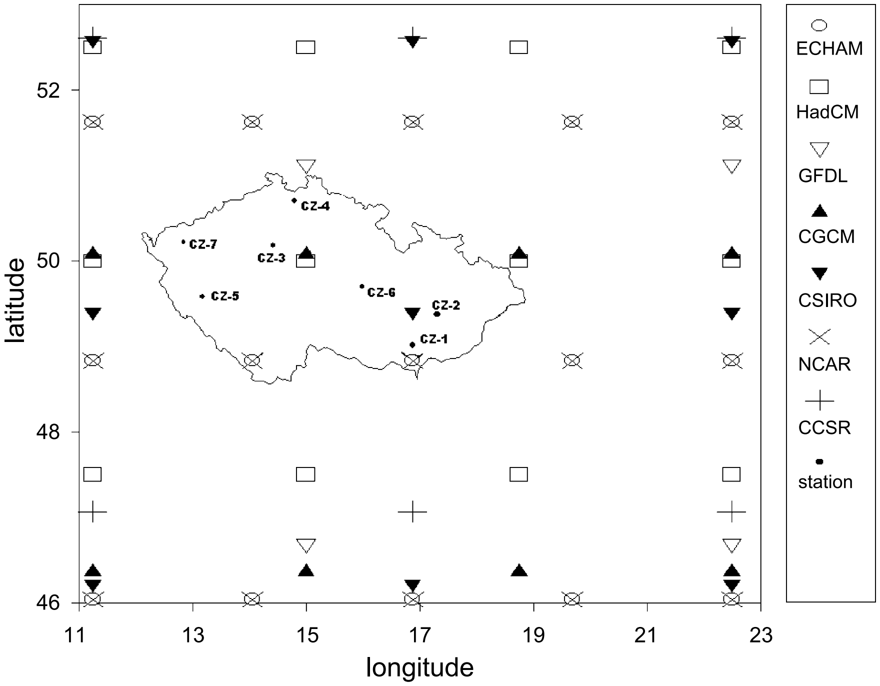

**Fig. 1.** Position of the GCM grid points lying within or close to the Czech Republic. The symbols related to the seven GCMs coincide with the centers of the grid boxes. The black points (CZ-1 to CZ-7) represent the target experimental sites used for validation of the crop model and climate change impact assessment

(www.czso.cz, 2002). The agricultural land that covers over 54% of the country area by and large composes of the arable land (72%). The most important crops grown in the Czech Republic as well as in whole Europe are cereals that cover 54% of arable land (or 21% of the total country area). The single most important crop in this region is winter wheat that accounts for 54% of the cereal acreage. These numbers document importance of the cereals and especially of wheat (mainly grown as winter crop) for the present agricultural production and prove its suitability as the model crop for climate change impact studies.

In order to carry out the crop modeling part of the study it was necessary to gather sufficiently large sample of the experimental data. The database was based on the results of the long-term experiments at seven test sites that were carefully selected out of thirty available. These sites (Table 1) were chosen according to their climatic and soil representatives of the study area. There-

**Table 1.** Selected characteristics of seven experimental sites in the Czech Republic; climatic characteristics relate to 1961–1990 period

| Site | CZ-1 | CZ-2 | CZ-3 | CZ-4 | CZ-5 | CZ-6 | CZ-7 |
|---|---|---|---|---|---|---|---|
| Name of the site | Lednice | Kroměříž | Sedlec | Chrastava | Staňkov | Domanínek | Kr. Údolí |
| Elevation (m a.s.l.) | 170 | 204 | 300 | 345 | 370 | 565 | 647 |
| Primary crop of the production region | maize | sugar-beet | sugar-beet | cereals | cereals | potatoes | forage |
| Soil type | Chernozem | Chernozem | Chernozem | Luvisol | Luvisol | Cambisol | Cambisol |
| Effective soil depth (cm) | 140 | 155 | 150 | 150 | 180 | 130 | 135 |
| Mean annual temperature (°C) | 9.5 | 9.1 | 8.2 | 7.6 | 8.2 | 6.8 | 6.4 |
| Mean annual precipitation (mm) | 488 | 571 | 510 | 816 | 526 | 591 | 604 |
| Mean accumulated global radiation per year (MJ m$^{-2}$) | 3955 | 3914 | 3706 | 3487 | 3790 | 3787 | 3634 |

fore they lay within the altitude range of 170–647 m with majority of the station placed between 200–400 m. The spatial distribution of the sites was also taken into account so they cover evenly whole area of the country (Fig. 1). Also three principal soil types used for majority of winter wheat production are represented. Average annual rainfall at the test sites ranges between 488–816 mm with the maximum reached during summer months. Mean annual temperature of the sites lays within 6.4–9.5 °C interval with maximum values reached during July 15.7–19.1 °C. In general the area represents a range of land types fairly typical for the intensively cultivated landscape of the Central Europe.

### *2.2 Climate change scenarios*

The climate change scenarios applied in this paper are based on the transient simulations made by seven GCMs (Table 2), which were available from the IPCC-DDC database (http://ipcc-ddc.cru.uea.ac.uk) in the beginning of 2001. These GCM simulations were run at IS92a (or similar) emission scenario and were made within the frame of the Coupled Model Intercomparison Project (Covey et al., 2003). All GCMs included in the analysis are coupled models with ocean circulation. The horizontal resolution of the atmospheric part of the model ranges from 2.8 to 7.5° in zonal direction and from 2.5 to 5.6° in meridional direction. The grid points lying within and close to the territory of Czech Republic are displayed in Fig. 1.

The climate change scenarios were constructed by Dubrovský et al. (2003) using the pattern scaling technique Santer et al. (1990): the scenario is defined by a product of the standardized scenario and the change of the global mean temperature. The standardized scenarios, which relate responses of climatic characteristics to 1 K rise in global mean temperature ($\Delta T_G$), were determined from a 2010–99 period of the above mentioned GCM runs. Changes in $\Delta T_G$ for three periods (2025, 2050 and 2100) were calculated by a simple climate model MAGICC (Harvey et al., 1997; Hulme et al., 2000) assuming two combinations of an emission scenario and climate sensitivity (equilibrium change in global mean surface temperature following a doubling of the atmospheric equivalent $CO_2$ concentration, $\Delta T_{G,2\times CO_2}$) and are presented in the Table 3. Finally the standardized scenario from each GCM as well as the AVG scenario was scaled by two values of $\Delta T_G$, which represent lower and upper estimates of the global mean temperature rise. The lower estimate is based on low climate sensitivity ($\Delta T_{G,2\times CO_2} = 1.5$ K) and SRES-B1 emission scenario, which is a rather optimistic scenario assuming "convergent world" with putting an emphasis on global solutions to economic, social and environmental sustainability. The upper estimate is based on high climate sensitivity ($\Delta T_{G,2\times CO_2} = 4.5$ K) and SRES-A2 emission scenario, which assumes very heterogeneous world and primarily regionally oriented economic development. The two emission scenarios will be referred to as B1 and A2 in next. More details on the SRES (The Special Report on Emission Scenarios) scenarios may be found in Houghton et al. (2001) and the details (including the model validation) on constructing GCM-based climate change scenarios for the Czech Republic are in Dubrovský et al. (2003).

**Table 2.** The list of GCMs used to construct the climate change scenarios

| Acronym | Model name | Atmospheric resolution (deg) |
|---|---|---|
| CCSR | CCSR/NIES | 5.6 × 5.6 |
| CGCM | CGCM1 | 3.8 × 3.8 |
| CSIRO | CSIRO-Mk2 | 3.2 × 5.6 |
| ECHAM | ECHAM4/OPYC3 | 2.8 × 2.8 |
| GFDL | GFDL-R15-a | 4.5 × 7.5 |
| HadCM | HadCM2 | 2.5 × 3.75 |
| NCAR | NCAR DOE-PCM | 2.8 × 2.8 |

**Table 3.** Changes in the global mean temperature for two emission scenarios and three time periods. The changes are with respect to the baseline period (1961–1990) and were calculated by MAGICC with only effect of greenhouse gasses considered (no effect of atmospheric aerosols is taken into account)

| Emission scenario/ Climate sensitivity | | 2025 | 2050 | 2100 |
|---|---|---|---|---|
| SRES-B1/low | $CO_2$ (ppm) | 420 | 467 | 548 |
| | $\Delta T_G$ (°C) | +0.49 | +0.76 | +1.17 |
| SRES-A2/high | $CO_2$ (ppm) | 438 | 535 | 826 |
| | $\Delta T_G$ (°C) | +1.10 | +2.08 | +4.29 |

The climate change scenarios used in this study do not consider changes in weather variability, because the applied outputs of GCM models included only monthly series which did not allow to reliably estimate changes in daily weather variability. As this might be considered as a serious limitation regarding the concerns being raised that changes in climatic variability might have a greater impact on crop yields than changes in means of climatic variables (e.g. Mearns et al., 1997; Semenov and Porter, 1995) sensitivity analysis was performed as a part of the study. In order to demonstrate potential effect of temperature variability on crop yields, scenarios based on four GCMs were selected (AVG, CCSR, HadCM and NCAR) for 2025 and 2100 time periods and B1 and A2 emission scenarios. Whilst mean values of individual weather elements were modified according to the appropriate GCM-based scenario the standard deviation parameters of Met&Roll were modified in such a way that it would reproduce weather series with temperature variability 12.5%, 25% and 50% lower than under present climatic conditions and also series with variability 12.5%, 25%, 50% and 100% higher than nowadays.

### *2.3 Crop model*

Despite the fact that the study concentrates on the assessment of the uncertainties in the future wheat yields originating from using number of the GCM based scenarios the crop model calibration and evaluation was an important part of the methodology. Process of selection of the appropriate and well performing crop model was part of the preceding study (Eitzinger et al., 2003). Based on the multiple criteria analysis including experimental evaluation of the soil water and evapotranspiration routines using lysimeter data the model CERES-Wheat (Ritchie and Otter-Nacke, 1985) was selected. The model algorithm for incorporation $CO_2$ effect was also thoroughly tested (e.g. Tubiello et al., 1999). This particular crop model belongs to the most frequently used tools in recent years in the climate change studies (Tubiello and Ewert, 2002). Results of the study might therefore help in interpretation of the previously conducted climate change impact studies using this model as well as in proposing methodologies for further undertakings on this field of research. Previously conducted studies also proved that the model performs well in various environments (e.g. Wolf et al., 1998; Travasso and Magrin, 1998). The used model is of the mechanistic/dynamic variety and operates within the Decision Support System for Agrotechnology Transfer 'DSSAT' (Tsuji et al., 1994). Experimental data used for the model evaluation were derived from seven experimental sites where the field trials of the State Institute for Agricultural Supervision and Testing (SIAST) are located (Fig. 1). For each of these sites all necessary input data i.e. results of the field experiments, detail description of the field operations and soil conditions as well as weather data were collected. Basic characteristics of each site are provided in Table 1. The field experiments of the SIAST are conducted strictly according to the prescribed methodology that is applied at all sites and vigorously checked. In the same time proper nutrient supply and pest protection of the trials is provided. These data thus provide excellent base for model calibration and evaluation.

Out of seven sites available two of them (CZ-3 and CZ-4) were selected to calibrate the cultivar parameters of the CERES-Wheat model (number of experiments: $n = 27$). These parameters in the model are represented by genetic coefficients and are necessary in order to simulate the differences in performance among varieties. They include thermal time, or accumulated temperature (°C) required by a crop cultivar to reach a particular growth stage, its sensitivity to the vernalisation and photoperiod and also the grain filling duration. The winter wheat (*Triticum aestivum L.*) cultivar Hana used in the study was chosen because it has been widely grown since 1985 and therefore available data series are sufficiently long. In the same time Hana still belongs to the most popular cultivars in the Czech Republic (Jurečka and Beneš, 2000). The calibration data set consisted of the date of sowing, emergence, anthesis and maturity, grain yield and biomass weight at maturity, grain number per unit area, grain number per spike and 1000 grain weight. Table 4 shows the initial values used for further simulations computed by DSSAT subroutine GENCALC (Hunt et al., 1993).

The experimental database originally included 83 seasons, which were certified as acceptable

**Table 4.** Estimated genetic coefficients of winter wheat (cultivar Hana) used in the crop model simulation

| Genetic coefficients | P1V | P1D | P5 | G1 | G2 | G3 | PHINT |
|---|---|---|---|---|---|---|---|
| Values | 5.8 | 1.1 | 3.6 | 4.3 | 2.4 | 3.9 | 95.0 |

Legend: P1V, vernalisation sensitivity, in days (0–9; P1D, photoperiod sensitivity, number of days with less than 20 h (1–5); P5, grain filling duration in days (1–5); G1, kernel number per unit weight of stem (1–5); G2, kernel growth rate, $g \cdot m^{-2} \cdot day^{-1}$; G3, standard stem weight in grams (1–5); PHINT, phylochron interval in degree days, which is the interval in thermal time between successive leaf tip appearances. The original values are de-dimensionalised by placing them on a scale of values (in parentheses)

for further processing by the internal procedures of the SIAST. However the authors discarded 4 seasons with recorded significant infestation of the trial because the CERES-Wheat model as most other crop models does not take the yield reduction due to occurrence of pests or diseases into account. The infestation was treated as significant when its intensity reached point 5 and lower (on the 9-1 scale) that equals approximately to 30% infestation of whole plants or particular plant organ area. In the experiments occurrence of all economically important pests and diseases was taken into account i.e. *Erysiphe graminis, Ustilago spp., Septoria spp., Septoria nodoria, Puccinia striformis, Puccinia graminis, Fusarium spp., Tiletia nanifica, Tiletia triticum, Lema spp.* and *Cephus pygmaeus*. Finally all grain yields and grain weight were reduced from standard 14% water content to dry matter weight.

The minimum set of weather data needed for the CERES-Wheat model includes coordinates of the weather station, incoming solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$), daily maximum and minimum temperature (°C) and daily rainfall (mm). Forty years series of suitable weather data (1961–2001) were supplied from the meteorological stations of the Czech Hydrometeorological Institute located in the vicinity of the experimental sites. As the provided data did not include solar radiation, it had to be calculated using Angstrom's formula (Angström, 1924) using coefficients derived from the available Czech historical observations.

Model calibration was followed by the evaluation of the model performance with the extensive independent data sets ($n = 52$) originating from the remaining 5 stations with wide range of environmental conditions. Calibration and evaluation were focused both on the phenological development (anthesis and maturity dates) as well as on the production parameters (yield, weight of 1000 seeds and number of grains per sq. m). All evaluated parameters were examined with help of descriptive statistics and also by using Pearson correlation coefficient ($r$), root mean square error ($RMSE$) and modeling efficiency index ($d$) according to Wilmot (1982). The index results lay between 0 and 1. The closer it is to 1 the better the fit between the model and the field observations. The $d$ index refers to the accuracy of prediction, where the accuracy is regarded as the degree to which model predictions approach the magnitude of their observed counterparts. Values of the $RMSE$ and $d$ are widely used and considered to be one of the suitable statistical tools for assessing model effectiveness (e.g. Wegehenkel, 2000 or Diekkrüger et al., 1995). For the final overview results from all 7 sites were pooled together.

### *2.4 Simulations*

In order to carry out the climate change impact assessment the authors applied the method originally developed by Porter and Semenov (1995), which was recently adapted by Žalud and Dubrovský (2002) for the conditions of the Czech Republic. The method is based on the comparison of the outputs from the multiple crop growth model runs with weather series representing the present vs. changed climates. The inputs to the crop model consist of the pedological, physiological and cultivation data taken from a single "representative" year and from the 99-year synthetic weather series created by the stochastic weather generator Met&Roll (Dubrovský, 1997). The representative year is defined by the set of site-typical values of all non-meteorological parameters (including the planting date, soil profile description and details on the fertilization regime) needed to run the model (Table 5). While the model input data based on the representative year remain the same, the new weather series is generated for each run. The parameters of the weather generator derived from the observed series (1961–2001) are used to generate weather series representing present climate.

**Table 5.** Characteristics of the representative years applied at the test sites

| Site | CZ-1 | CZ-2 | CZ-3 | CZ-4 | CZ-5 | CZ-6 | CZ-7 |
|---|---|---|---|---|---|---|---|
| Representative year | 1989 | 1996 | 1994 | 1992 | 1996 | 1993 | 1988 |
| Sowing date | SEP 29 | OCT 4 | OCT 5 | OCT 1 | OCT 1 | OCT 7 | OCT 1 |
| Harvest date | JUL 9 | AUG 8 | AUG 3 | JUL 28 | AUG 1 | AUG 17 | AUG 19 |
| Dose of N fertilizer (kg · ha$^{-1}$) | 90/3* | 60/2* | 75/2* | 85/3* | 100/3* | 90/3* | 60/2* |
| Initial available soil water in the soil profile (mm) | 318** | 274** | 205** | 210** | 234** | 174** | 162** |
| Sowing density (seeds · m$^{-2}$) | 500 | 400 | 400 | 400 | 400 | 500 | 500 |

* Number of applications

** Soil water content in the potential rooting depth on the sowing day

The parameters of the generator are modified in accordance with the climate change scenario (Fig. 2; Table 3) to generate series representing the changed climate. These weather data series were then used as inputs to the crop model and 99-year simulation runs were performed for each combination of GCM scenario and the time period and also the temperature variability alteration. In case of the analysis of the temperature variability influence on the winter wheat yields,

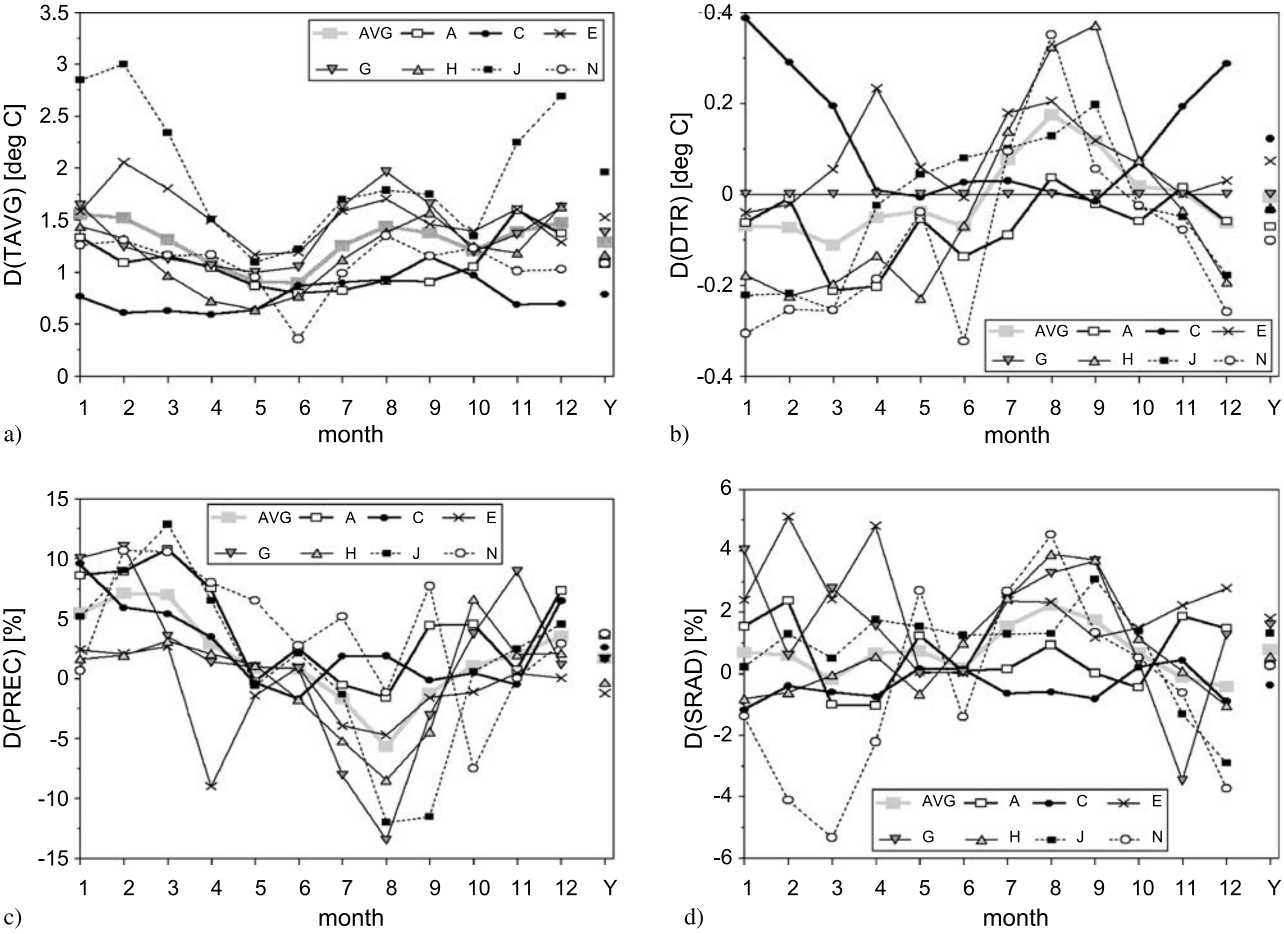

**Fig. 2.** The standardized GCM-based climate change scenarios for the Czech Republic: **a**) daily mean temperature, **b**) daily temperature range, **c**) precipitation, **d**) solar radiation (the changes of *SRAD* are based on changes in cloudiness in case of HadCM model). The GCMs are: A = CSIRO, C = CGCM, E = ECHAM, G = GFDL, H = HadCM, J = CCSR, N = NCAR. AVG represents a scenario averaged over all seven models, Y relates to the changes in the annual means (taken from Dubrovský et al., 2003). The changes are with respect to the baseline period (1961–1990)

the modeled yields were statistically evaluated using standardized Wilcoxon statistic. The hypothesis stating that the distribution of grain yields under a given temperature variability scenario does not differ from the reference distribution related to particular GCM-based scenario and unmodified temperature variability was tested.

## 3. Results and discussion

### *3.1 Evaluation of CERES-Wheat model*

The calibration of the model focused on the determination of the parameters of the used cultivar (Table 4) and it was followed by evaluation of the model performance using independent data set. When the simulated values of the anthesis and maturity dates were compared with the observed ones it was found that the mean deviation was less than 3% i.e. 8 days whilst majority of the deviations lays within ±5% (i.e. ±15 days) range. Two important yield components i.e. weight of thousand seeds and number of grains per $m^2$ were simulated with deviation smaller than 20% at all seven test sites in 85% resp. 73% cases. Despite the large variability of the experimental data only small number of simulations resulted in the difference larger than 40%. Inaccuracies in simulated values of phenological and production parameters influenced the precision of the simulated grain yield values (Fig. 3). However in the most seasons the difference between simulated and observed grain yields was smaller than 20%.

As can be seen from the Table 6 the model on average slightly underestimated the length of winter wheat development (sowing-anthesis, sowing-maturity) but reproduced well the values of standard deviation. It is also apparent that the model slightly overestimated the minimum and maximum values. The relationship between the observed dates and the simulated outputs can be, based on *r*-value, classified as highly significant. These results are better than those reported e.g. by Diekkrüger et al. (1995), Landau et al. (1998) or Iglesias et al. (2000) and comparable with the results of Otter-Nacke et al. (1986) or recently Alexandrov and Eitzinger (2002). The model could be improved further e.g. by introduction of the crop stress caused by poor soil aeration under wet conditions (Saarikko, 2001), which is the case in some years during late fall and early spring. There is general tendency of the model to overestimated yields and number of grains per $m^2$ and in the same time to underestimate weight of thousand seeds. The last parameter showed poor fit expressed in terms of the Pearson correlation coefficient. This particular parameter caused problems in other studies as well, despite the fact that the values are simulated with an acceptable deviation from the observed ones but frequently with poor results in the sense of the correlation coefficient (Travasso and Magrin, 1998; Alexandrov and Eitzinger, 2002). Still the *d* and *RMSE* are comparable with other parameters examined in this study and the results are the same or better than those reported in the previously cited papers.

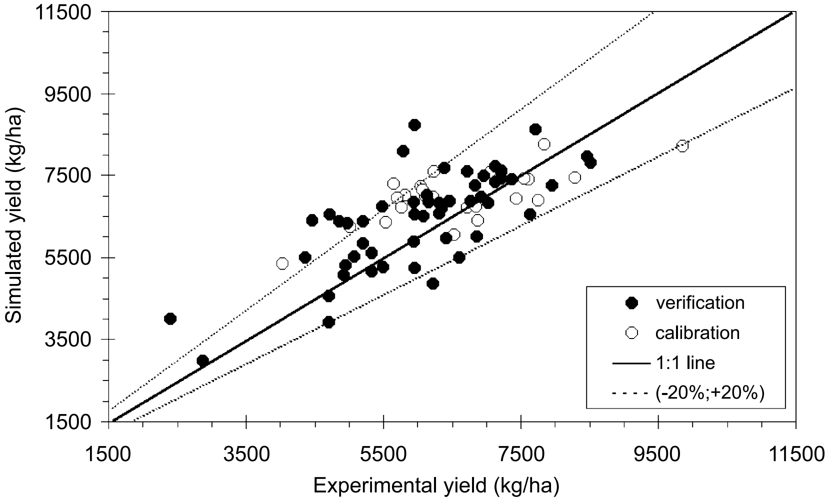

**Fig. 3.** Evaluation of the grain yields of winter wheat; the straight line represents the 1:1 line relating observed and simulated grain yields. Empty circles stand for results of calibration at Sedlec and Chrastava; black circles represent verification results; verification was based on the input data from remaining 5 localities

**Table 6.** Values of the basic statistics of the main crop parameters; Pearson correlation coefficient *r*; root mean square error *RMSE* and index of modeling efficiency *d*; according "Wilmott" (1982) for all seven experimental sites

| Parameter | | mean | std | min. | max. | *r* | *RMSE* | *d* |
|---|---|---|---|---|---|---|---|---|
| anthesis | experimental | 254 | 10.6 | 232 | 280 | 0.75** | 8.4 | 1.00 |
| (days) | simulated | 251 | 11.8 | 225 | 279 | | | |
| maturity | experimental | 302 | 12 | 277 | 330 | 0.86** | 7.5 | 1.00 |
| (days) | simulated | 299 | 14 | 272 | 339 | | | |
| Yield | experimental | 6250 | 1224 | 2399 | 9862 | 0.73** | 928 | 0.98 |
| (kg/ha) | simulated | 6636 | 1063 | 2980 | 8720 | | | |
| WTS* | experimental | 40.9 | 4.8 | 27.7 | 52.4 | 0.06 | 7.5 | 0.96 |
| (g) | simulated | 38.7 | 5.1 | 20.0 | 52.6 | | | |
| # grains/$m^2$ | experimental | 15794 | 3004 | 7364 | 21429 | 0.68** | 2845 | 0.97 |
| | simulated | 17406 | 2925 | 10475 | 23670 | | | |

* Weight of thousand seeds

** Statistically highly significant correlation

### *3.2 Climate change impacts on the winter wheat production*

Increase of the air temperature that is predicted by all scenarios would lead to the shortening of the vegetation duration of winter wheat (interval from sowing till physiological maturity) by 4–71 days (Table 7). This is in accordance with the results reported by number of other studies (e.g. Harrison et al., 2000; Tubiello et al., 2000 or Alexandrov and Eitzinger, 2002). The magnitude of the change clearly depends to a large extend on the scenario used and the reference time period because the differences in the predicted temperature increase between the individual scenarios are great (Fig. 2a). The study confirmed (Table 7) that a significant shift in the duration of the vegetation season is to be expected by 2050–2100 (depending on the emission scenario used). The length of the winter wheat vegetation duration in the production areas with altitude over 600 m will equal to the present values in the lowlands (300 m and less). The changes of the annual mean temperature expected according scenarios the HadCM-B1-2050 and the ECHAM-B1-2050 lie within interval 0.9–1.12 °C. Such changes would then lead to shortening of the vegetation period by 2.3–3.5%. These findings correspond with the results of several field experiments (e.g. Wolf et al., 1998) with winter wheat cultivar Minaret at Clermont Ferrand (France) and Rothamsted (England) in the temperature gradient tunnels. Increase of temperature during the grain filling period by 1.0 °C lead to 2.6% shorter vegetation duration at Clermont Ferrand. The same temperature increment from sowing till maturity at Rothamsted caused the shortening of vegetation duration by 2.8%. With respect to the different parameters of the used cultivar, its different vernalization requirements and also differences in the day length between these two sites and Czech conditions it can be stated that the simulated results correspond well with these field trials.

Impact of the changed weather conditions on the winter wheat yields (not including $CO_2$ fertilization effect) would lead to the yield depression, which would be the most severe in the lowland and midland sites. Applying the ECHAM-A2-2050 and the HadCM-A2-2050 resulted in yield reduction reaching up to 25% (not shown). Generally the sites in the regions with presently low air temperatures would be the ones least affected by the indirect effect of climatic change. The main reason for the yield reduction lays in temperature increase that besides shortening of the vegetation duration through speeding up the developmental processes also influences the respiration rates as well as assimilate partitioning. Generally lower amount of precipitation during some months is not sufficient to cover the increased evapotranspiration demand caused not only by the higher temperatures but in some GCMs also by increased solar radiation sums. The results correspond with the overview of 17 experimental studies (Amthor, 2001) that were aimed on the investigation of

**Table 7.** Deviations of the vegetation duration (period from sowing till maturity) and yield characteristics for individual scenarios with respect to the present conditions (climate 1961–2000). The values of all characteristics in the table represent mean deviation of each parameter averaged over all seven sites for all applied scenarios

| Emission scenario-Time period | Global circulation models | | | | | | |
|---|---|---|---|---|---|---|---|
| | CCSR | CGCM | CSIRO | ECHAM | GFDL | HADCM | NCAR |
| Deviation of the vegetation duration [days] | | | | | | | |
| B1-2025 | −10 | −4 | −6 | −8 | −7 | −6 | −6 |
| A2-2025 | −22 | −8 | −12 | −16 | −13 | −11 | −11 |
| B1-2050 | −15 | −6 | −9 | −11 | −10 | −8 | −8 |
| A2-2050 | −42 | −13 | −22 | −29 | −24 | −20 | −21 |
| B1-2100 | −23 | −8 | −13 | −17 | −14 | −12 | −12 |
| A2-2100 | −71 | −25 | −41 | −56 | −48 | −41 | −41 |
| Deviation of the yield mean [%] | | | | | | | |
| B1-2025 | +8 | +8 | +9 | +7 | +8 | +9 | +9 |
| A2-2025 | +4 | +8 | +9 | +5 | +7 | +9 | +10 |
| B1-2050 | +11 | +12 | +12 | +10 | +11 | +13 | +13 |
| A2-2050 | −10 | +14 | +14 | +6 | +11 | +14 | +14 |
| B1-2100 | +14 | +17 | +18 | +15 | +17 | +19 | +20 |
| A2-2100 | −26 | +25 | +15 | +4 | +10 | +15 | +7 |
| Deviation of the yield std [%] | | | | | | | |
| B1-2025 | −1 | −20 | −9 | −5 | −8 | −6 | −10 |
| A2-2025 | +22 | −12 | −11 | −3 | −10 | −5 | −10 |
| B1-2050 | +1 | −10 | −13 | −7 | −11 | −9 | −13 |
| A2-2050 | +75 | −17 | −2 | +5 | +4 | +7 | 0 |
| B1-2100 | +20 | −15 | −14 | −9 | −14 | −9 | −13 |
| A2-2100 | +85 | −13 | +29 | +25 | +42 | +50 | +72 |
| Deviation of the minimum yield [$\times 1000\,\mathrm{kg \cdot ha^{-1}}$] | | | | | | | |
| B1-2025 | +0.8 | +1.2 | +1.0 | +0.8 | +0.9 | +0.9 | +1.1 |
| A2-2025 | −0.2 | +1.1 | +1.3 | +0.6 | +1.1 | +1.0 | +1.3 |
| B1-2050 | +0.9 | +1.3 | +1.5 | +1.2 | +1.3 | +1.3 | +1.5 |
| A2-2050 | −1.4 | +1.9 | +1.0 | +0.3 | +0.6 | +0.8 | +1.0 |
| B1-2100 | +2.4 | +2.7 | +2.8 | +2.1 | +2.6 | +2.5 | +2.7 |
| A2-2100 | −0.9 | +3.9 | +2.7 | +0.3 | +0.9 | +2.4 | +1.8 |
| Deviation of the maximum yield [$\times 1000\,\mathrm{kg \cdot ha^{-1}}$] | | | | | | | |
| B1-2025 | +0.7 | +0.6 | +0.6 | +0.5 | +0.6 | +0.7 | +0.7 |
| A2-2025 | +0.7 | +0.6 | +0.7 | +0.5 | +0.6 | +0.7 | +0.7 |
| B1-2050 | +1.0 | +1.0 | +0.9 | +0.8 | +0.8 | +0.9 | +1.0 |
| A2-2050 | +0.6 | +1.0 | +1.1 | +0.7 | +1.0 | +1.2 | +1.2 |
| B1-2100 | +1.4 | +1.3 | +1.2 | +1.2 | +1.1 | +1.3 | +1.3 |
| A2-2100 | −0.3 | +1.6 | +1.4 | +0.9 | +1.3 | +1.5 | +1.4 |

the relationship of increased temperature and grain yield. Winter wheat reacted to the increased temperature sums (in range +1.1–4.0 °C) with yield reduction of 0.5–48% in 16 (out of 17) cases. Already mentioned study with Minaret cultivar (Wolf et al., 1998) reported 11% yield depression per 1 °C of increased temperature with only 3% standard deviation. Simulated results presented in this study show the yield reduction in interval 0–17% when scenarios the HadCM-B1-2050 and the ECHAM-B1-2050 were applied (estimated increase of annual mean temperature 0.9–1.2 °C).

Combination of the changed climatic conditions and increased CO$_2$ concentration on crop yields would lead to the inverse trend in the grain yields. If the fertilizing effect is not included the yields would reach 25–98% of the present values

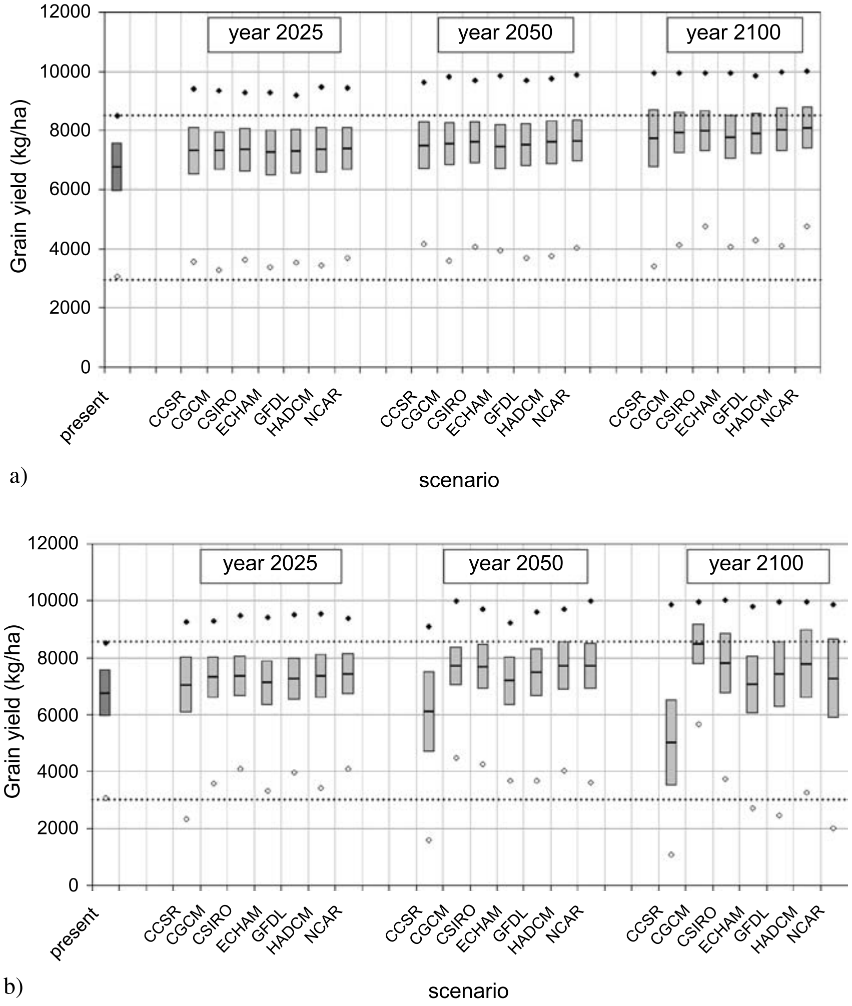

**Fig. 4.** Summary of the winter wheat yields simulated for (**a**) the B1 emission scenario, and (**b**) the A2 emission scenario. The simulations were made with 7 GCM-based scenarios and for three time periods; "present" relates to the yields simulated with present climate conditions. Each bar represents mean ± std from 693 simulated yields (the results from 99-year simulations for 7 test sites were pooled together). Empty/black circles represent the lowest/highest simulated yield for each particular scenario. Dotted lines parallel with x-axis represent the lowest and highest yields level under present climatic conditions

while when the stimulating effect is accounted for yields might increase by as much as 25% by 2100 in comparison with the present conditions. The range of the change is few percents lower than the expected changes under similar climatic conditions reported e.g. by Izaurralde et al. (2003) or Olesen and Bindi (2002). The deviation could be easily explained by applying slightly different version of the GCMs and emission scenarios as well as by the specific conditions of the region. However the presented results contradict the former findings made within the framework of US country studies program that concluded that the winter wheat yield would decrease in the Czech Republic (Smith and Lazo, 2001). The difference was most likely caused by improper calibration of the CERES-Wheat model due to limited data and imperfect data sets. This finding demonstrates the necessity for critical overview of already reported results using better-calibrated models and state of the art methodology over the same study area.

Change of the grain yield depends on the used scenario and also on the locality (Figs. 4 and 5). Increase of grain yields under the increased $CO_2$ level is influenced by the built in function of CERES-Wheat model that shows on average 9.5% yield increase per 100 ppm increase of $CO_2$ concentration under unchanged climatic conditions. This value is within the range derived from numerous experiments overviewed by Amthor (2001). Under the changed climatic conditions accompanied by increased $CO_2$ concentration it is reasonable to expect in the Czech Republic yield increase in the range of 4–10.0% by 2025, 6–14% by 2050 and 4–25% by 2100. However as it is apparent from Fig. 5b and also Table 7 under the emission scenario A2 the CCSR scenario predicts mean yield decrease equaling to 10% and 26% by 2050 and 2100

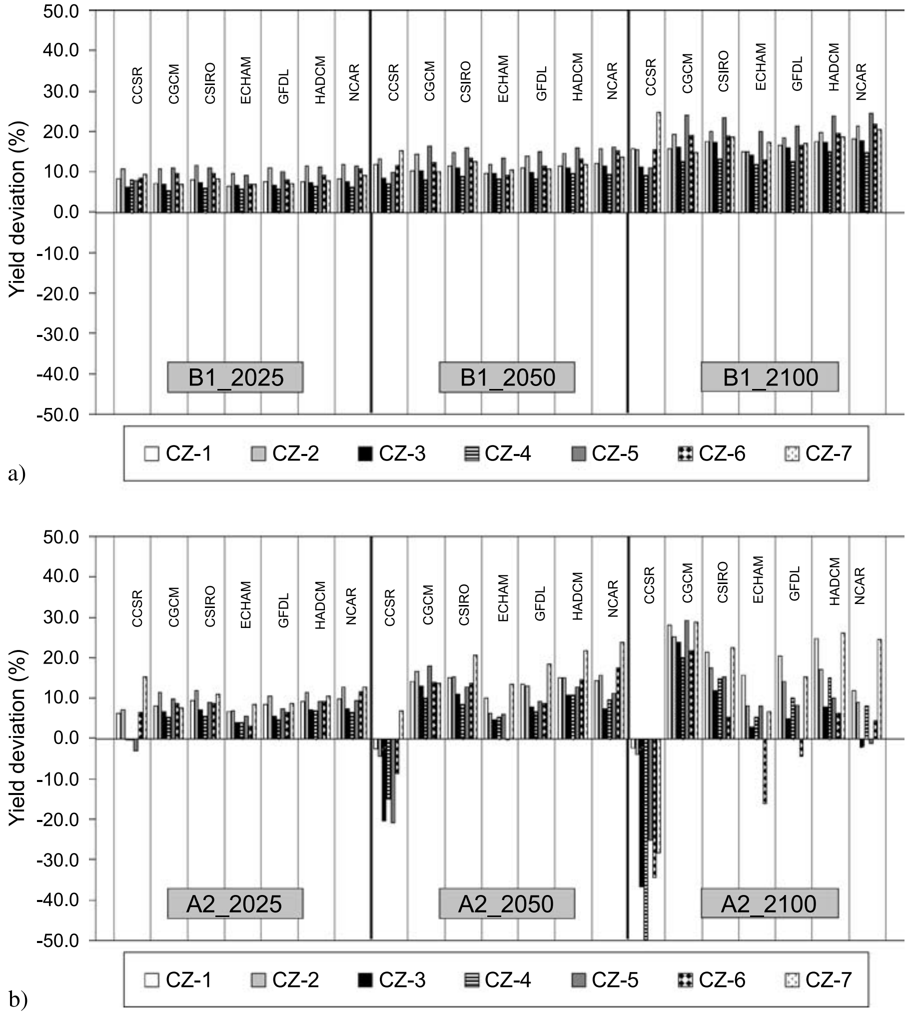

**Fig. 5.** Deviation of the mean yields (based on 99-year simulations) expected under the changed climatic conditions in comparison with the present (i.e. 1961–1990 climate) yields for (**a**) the B1, and (**b**) the A2 emission scenarios, three time periods, seven GCM and seven sites

respectively. It is necessary to add that besides the changes in climatic conditions and carbon dioxide concentration, change of no other parameters was considered in the presented study. Also eventual yield reductions due to weeds, pest, diseases or improper fertilization and soil management were not taken into account.

## *3.3 Differences between individual climate change scenarios*

### 3.3.1 B1 emission scenario

There are no large differences between the results related to seven GCMs in climate change impacts on vegetation season duration during individual time periods (Table 7). However the differences between individual scenarios and therefore uncertainty in the predicted yield change increases for later time periods. For the period 2025 shortening of the vegetation season duration by 7 ± 2 days (based on averaged results of 7 GCMs over 7 sites) is to be expected. The scenario CGCM predicts only 4 days deviation while the application of the scenario CCSR leads to shortening of the vegetation season duration by 10 days. The remaining five scenarios predict changes in range of 6–8 days. The winter wheat vegetation season by 2050 might be 10 ± 3 days shorter than under present climate. This trend continues also for 2100 time period when duration of the vegetation season could be 14 ± 5 days shorter than nowadays. For this time period differences in the predictions according to various GCMs showed the highest increase with shortening of the vegetation duration from 8 to 23 days. These variations in the predicted vegetation duration under different GCM based scenarios are primarily caused by the differences in the predicted temperature increase from September to June (winter wheat growing season). Figure 2a indicates that the highest temperature increase within this period is predicted by the CCSR scenario i.e. scenario that predicts the most significant reduction of the vegetation season. On the contrary the length of vegetation was much less affected when the CGCM scenario predicting the smallest temperature increase was applied.

Shortening of the vegetation season will clearly have profound effect on the winter wheat yields. However the decrease of the yield caused by shorter vegetation season duration will be more than offset by the positive fertilizing effect of $CO_2$ (Fig. 4a; Table 7). The yields in 2025 would increase approximately by 8% according to the applied scenario. Difference between the highest and lowest estimate for this time period equals only to 2%. As the uncertainty in prediction of climate development increase with the time also the differences between yield predictions under individual GCM based scenario increase. In case of the B1 emission scenario the predicted differences are relatively small 3% by 2050 and 5% by 2100. In general all 7 GCM based scenarios lead to the similar mean yield increase for all considered time periods and sites (Fig. 5a) under this emission scenario.

The results of the simulations presented in the Table 7 and Fig. 5 also showed that according to six GCMs there is a tendency towards decreasing of the yield variability under changed climatic conditions. But according to the CCSR model the variability of yield will increase in the time periods 2050 and 2100. The variability (when the CCSR scenario is excluded) decreases by 5–20% in 2025 and by 9–15% in 2100. The CCSR scenario indicates increase of the yield variability by the time period 2050 (0.7%) and 20% by 2100. The main cause of the decreased variability is the positive fertilizing effect of $CO_2$ in combination with the relatively mild changes in the weather patterns during vegetation season that benefits almost all experimental sites. The improvement of the climatic conditions for the production of winter wheat might be clearly demonstrated on the changes of the lowest and the highest yields that should be expected under the changed climate. Both Fig. 4a and Table 7 clearly show that the sustained increase of the minimum and maximum attained yields might be expected with the time under B1 emission scenario.

### 3.3.2 A2 emission scenario

On the contrary to the B1 emission scenario the scenario A2 predicts higher increase of the $CO_2$ ambient concentration resulting in a correspondingly higher increase of global temperature and thereby to a more significant change of the site-specific climatic conditions. These factors consequently lead to much larger differences between the individual GCMs. The uncertainty in the character of future climatic conditions projects itself also into the uncertainty about changes in the winter wheat growth and development. Realization of the A2 scenario would cause the contraction of the winter wheat growth duration by $13 \pm 5$ days by 2025 (based on average of 7 GCM scenarios and 7 sites). While the CCSR scenario predicts shortening of the vegetation duration by 22 days, application of the CGCM scenario implies that the vegetation duration will be only 8 days shorter than under the present conditions. Reduction of the vegetation duration becomes much more severe for the time period 2050 ($24 \pm 9$ days) and by 2100 the vegetation duration would be on average reduced by $46 \pm 14$ days. For the latter time period the difference in estimates of vegetation season duration between the CGCM and the CCSR equals to 46 days. Combination of the conditions predicted under A2 emission scenario applied together with the CCSR scenario would reduce the overall duration of the vegetation season by approximately one quarter i.e. by 71 days. High temperatures during winter months under such conditions would lead to poor vernalization of the present wheat cultivars and would of course mean severe reduction of the key phenological stages length (e.g. tillering and grain filling). If the wheat cultivars similar to Hana would be grown the unfavorable changes in the duration of the phenological stages would necessarily lead to significant yield reductions according to some tested scenarios (Fig. 5b).

As it is clear from Table 7 and Fig. 5b average yields would be still $7.6 \pm 2.1\%$ higher by 2025 than under the present climatic conditions. Together with the increase of the mean yield the maximum attainable yield would also increase. On the other hand there is a chance of yields lower than the presently recorded yield minimum at least according to the CCSR scenario. Difference between the highest and the lowest estimates for this time period equals to more than 5.6%. High variability in prediction of climate development leads to increased variability in latter time periods. Thanks to the CCSR scenario the trend of average yields development cannot be considered to be homogenous, as according to this scenario yield would decrease by 26% by 2100.

The yield variability values depend on the reference time period and the applied scenario. For the period 2025 the CCSR predicts increase of the variability by 22% while according to other scenarios the yield variability would decrease by 3–12%. By the year 2100 only application of the CGCM-based scenarios showed decrease of the yield variability while remaining 6 scenarios would lead to the increased yield variability by 25–85%. Such a difference in the yield variability between individual GCM scenarios within the same emission scenarios and time period clearly demonstrates great uncertainty in the yield variability especially for 2050 and 2100 reference periods under A2 emission scenario. These results point out to the relatively rapid aggravation of the suitability of the environmental conditions for the winter wheat production in the Czech Republic using the contemporary crop husbandry practices. Such increase of variability would contradict the trend toward the increased yield stability observed through out the 20th century as it was reported by Calderini and Slafer (1998). The changes in the yield variability also project themselves into the values of minimum and maximum yields. According to Table 7 in each both 2025 and 2100 time periods six GCMs provide and increase of the minimum yield. As can be also seen at Fig. 5b maximum attainable yield would reach the level close to 10,000 kg/ha by 2100 according to all GCM scenarios. Despite the fact that the maximum expected yield would increase in comparison with the present conditions, the increase in the time period 2050 is in general smaller than under appropriate B1 scenario. It might be concluded that the higher positive effect of $CO_2$ due to its higher ambient air concentration is not sufficient to offset the unfavorable weather conditions. In the same time under A2 emission scenarios differences between the individual climate change scenarios play much larger role than under the emission scenario B1.

### 3.4 *Differences between individual sites*

The Fig. 5 demonstrates that despite similar trend patterns at individual emission scenarios and time periods there is a significant influence of the site-specific conditions that plays an important role in the determination of absolute value of the climate change impact on yields. The smallest diversity between the expected yield changes (5–11%) relative to the present conditions is expected under the B1-2025 emission scenario i.e. under conditions relatively closely resembling the present state. On the contrary for the emission scenario A2-2100 the difference in the relative change of grain yield ranges from 50% decrease up to 29% increase. Differences between the sites apparently grow with the mounting severity of imposed climatic change and culminate for the emission scenario A2-2100. There is a sustained tendency benefiting two warmest sites CZ-1 and CZ-2 (year average temperature > 9 °C). Impacts of the climatic change on the mean yields at this site are positive for all time periods and combinations of the emission scenarios and GCMs with exception of the CCSR based scenario for the A2-2050 and A2-2100. However these projections of the future climate are rather extreme yielding negative climate change impacts regardless of the location. The second apparent trend visible in all simulations based on the B1 emission scenario is relatively high benefit for both sites with very deep soil profiles and optimum physical properties i.e. CZ-2 and CZ-5. These two sites seem to benefit the most from the positive fertilizing effect of $CO_2$ and in the same time the good quality soil profile helps to reduce negative effects. Increase of temperatures helps also to improve the climatic conditions for winter wheat development at CZ-7 that is on the fringe of marginal areas for agricultural production under the present climate. Especially conditions imposed under A2-2050 and A-2100 emission scenarios enhance production at this site.

### *3.5 Role of variability*

The effect of the temperature variability on the winter wheat yields proved to be a complex and highly dependent on the severity of change of the mean temperatures predicted by the individual GCMs. As it is apparent from the presented results from the site CZ-3 (Fig. 6a, b) the relative impact of the increased temperature variability decreases with the increasing severity of mean temperature changes i.e. the effect of variability is much lower under the A2 (Fig. 6b) emission scenario than under B1 (Fig. 6a). Whilst under the conditions of the emission scenario B1 and the 2100 time period effect of the increased variability would lead to the yield decrease by 35–50%, doubling the temperature variability under A2 emission scenario would cause much smaller impact. Also effects of changes in temperature variability were found to be surprisingly more pronounced for the time period 2025 than for 2100. Relatively small changes of mean temperature predicted for 2025 in combination with direct $CO_2$ effect will on general improve conditions for winter wheat production (providing unchanged temperature variability in comparison with the present climate) and therefore possible aggravation caused by increased temperature

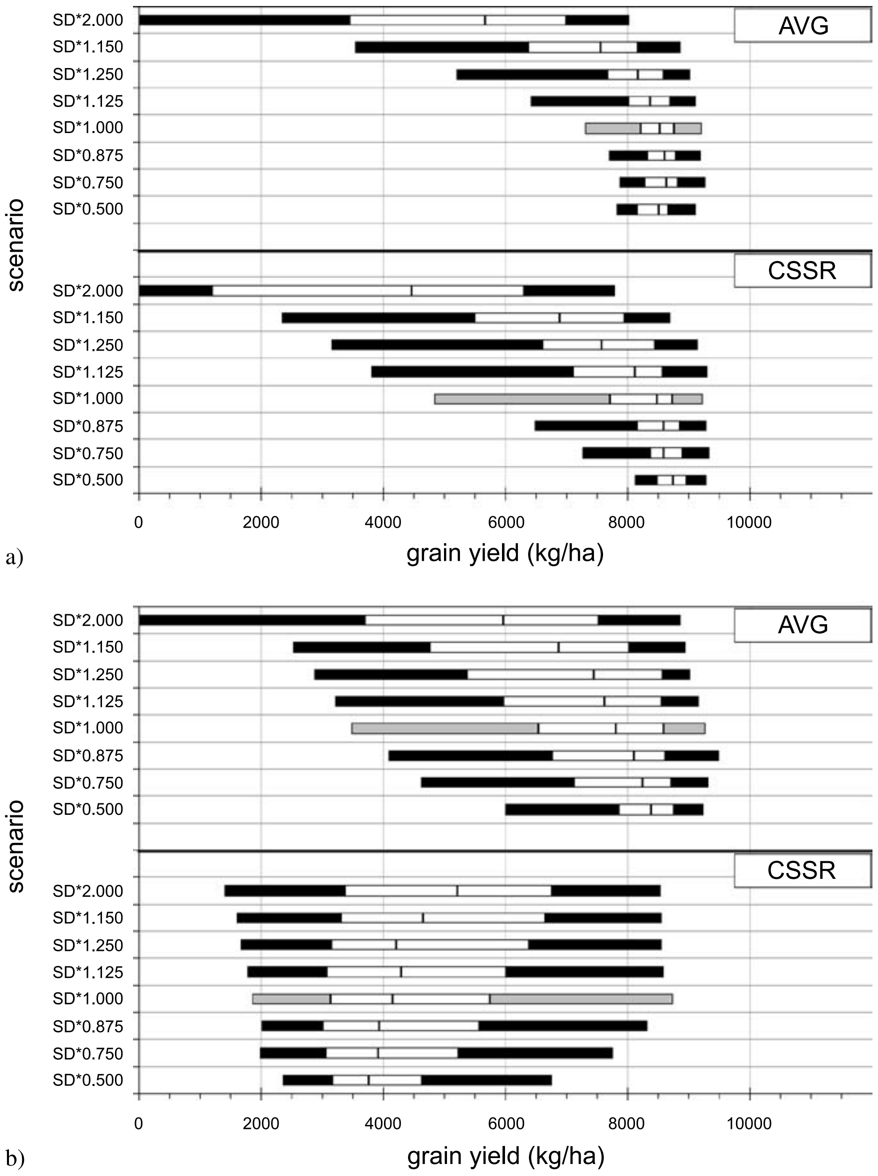

**Fig. 6.** Sensitivity of the model yields to the temperature variability. The summary statistics of the grain yields were derived from the 99-year crop growth simulation run in the WG approach and are expressed in terms of quantiles. The bars represent the 5th, 25th (lower quartile), 50th (median), 75th (upper quartile), and 95th member from the set of values arranged in an ascending order. The results of crop growth simulation at site CZ-3 for two climate change scenarios and given value of the temperature standard deviation (SD). Top panel (**a**): the B1 emission scenario is assumed, bottom panel (**b**): the A2 emission scenario. In both cases the 2100 time reference period was used. The numbers to the left of each bar represent fraction by which the present SD was changed (e.g. SD*0.750 equals to SD reduction by 25%). For the gray shaded bars no change of SD was applied

variability would be much higher than under A2 scenario 2100 climatic conditions (Fig. 6b). Results of Wilcoxon test showed that alteration of temperature variability in range of ±12.5% will not cause statistically significant alteration of yield distribution for any site or used climate change scenario. The change of temperature variability by ±25% and more would lead to a statistically significant change of the yield distributions for both emission scenarios and all tested GCMs in the time period 2025. The same finding was repeated for the B1 emission scenario and the time period 2100. Under the A2 emission scenario in some cases (CCSR, HadCM) even doubling temperature variability would not cause statistically significant change of the yield distributions. The results also proved that increased temperature variability leads to an increase in number of crop failures i.e. yields lower than $1000\,\mathrm{kg \cdot ha^{-1}}$. The yield failures were caused mostly by frost kill due to the high variability of temperature during winter months that lead on one hand to the early onset of crop development followed by period of subzero temperatures. Large difference in frost damage between the B1 and A2 emission scenarios in case of the CCSR can be explained by the fact that under the A2 emission scenario it predicts so high increase of the mean temperature values that risk of crop failure due to frost damage is almost eliminated even under doubled temperature variability.

### *3.6 Performance of "average" scenario*

The results that have been already presented demonstrate that 7 GCMs in combination with two emission scenarios lead to a great deal of calculations especially when moving from site to multiple site or even to spatial analysis. Some of the studies solve the dilemma by applying scenarios based on one selected GCM (usually the one which performed the best during the evaluation process) or its several versions as e.g. Mavromatis and Jones (1998) or Parry et al. (1999). In some cases such selection is impossible due to the inconclusive results of GCM evaluation as e.g. in the study presented by Ittersum et al. (2003). When there is a need to limit necessary number of calculations and in the same time a robust estimate of the "mean" impact is required the average (AVG) scenario might be applied. This approach consumes much less computer resources than averaging of the model outputs after running model with number of scenarios. Applicability of the average scenario is justified by the fact that estimates of the mean yields obtained by both approaches do not differ (Fig. 7). The values of the standard deviation, the 5th and the 95th percentiles calculated by either method are also very similar. This match was verified by applying the standardized Wilcoxon statistic (which has approximately normal distribution, N(0,1)) on the data used for construction of Fig. 7. The separate tests were carried out for each of the two emission scenarios i.e. each test included 21 values for all parameters (7 sites × 3 time periods). It was found that there is no statistically significant difference between the distributions of either parameter between the pooled results of 7 GCM scenarios and AVG based outputs. The values of Wilcoxon statistics for these three parameters were less than 0.49 and therefore we can accept hypothesis on equality of the two distributions in case of all four characteristics. Whether these somewhat surprising results are going to be repeated under different environmental conditions or scenarios remains to be tested.

Authors are aware of the fact, that the climate change scenario averaged over several GCMs would not meet sympathy of all readers because of the commonly raised objection on the physical inconsistency of such scenarios and because of the need to deal with multiple scenarios (to give a notion on the uncertainty). However the results presented above document that the average of the impacts on the mean yields related to seven single-GCM-based scenarios are nearly the same as the impacts based on the single AVG scenario. This of course does not solve the argument related to the "physical consistency". If we want to assess the physical consistency of the scenario, we should have some quantitative criterion. This criterion might be related to the relationships between changes in individual climatic characteristics. These relationships should follow from the physical laws of our world and should be therefore the same in all GCMs. The fact is that these relationships are not exactly the same in all GCMs, which may be also related to effect of changes in some other climatic characteristics not included in the scenarios, for example large-scale circulation. Although the relationships between the changes

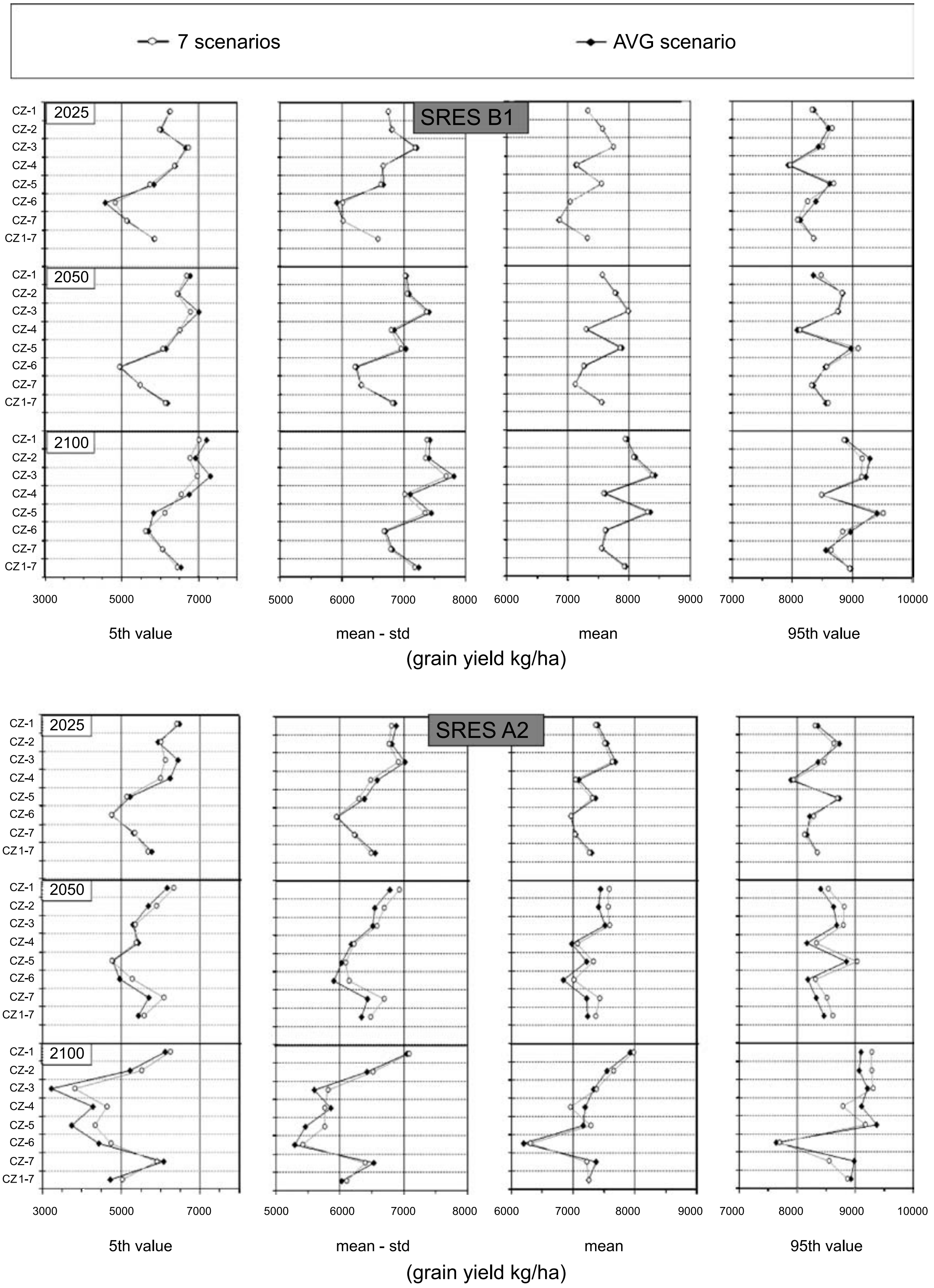

**Fig. 7.** Comparison of the yield characteristics related to the averaged scenario (AVG scenario) with those related to seven single-GCM-based scenarios (7 scenarios). In the latter case, the mean and the mean-std values were calculated from the set of grain yields obtained by pooling the 99-year CERES-Wheat simulation runs over 7 GCMs at each experimental site (i.e. 693 seasonal simulations were used for each site), while the 5th and 95th values were determined as averages of respective characteristics related to the seven GCM scenarios. In case of AVG scenario, all characteristics were determined from the set of 99 seasonal simulations at each experimental site. Value of CZ 1–7 represents pooled results from all test sites used in the study

in individual climatic characteristics are not generally linear, they may be represented by linear relationships within reasonably small intervals of the changes. In this case, if the "physical consistency" of individual GCMs would observe the same physical laws of our world, the scenario constructed by averaging outputs from several GCMs would also observe this one physics. On the contrary, if the relationships between individual climatic characteristics are different, than the scenario averaged over several GCMs would observe the "averaged physics" (i.e. averaged input parameters and assumptions), which might be a problem, if the average scenario would be related to the entire globe. However this should not be a problem if we use the average scenario for a single site or relatively small area because the differences in the relationships between individual climatic characteristics might be related to some hidden climate variable i.e. parametrized subscale processes (e.g. circulation) so that the averaging of the GCM-based scenarios only averages the effect of this hidden factor. This averaging would function on the assumption that the changes in this hidden factor are small and the effects of these changes on other climatic characteristics may be represented by linear relationships. If the above conditions are satisfied, the probability that the averaged scenario will come true is not a priori lower than the probabilities related to the single GCM-based scenarios. The results obtained in our analysis suggest that at least for conditions of the Central Europe the averaged scenario is applicable.

## 4. Conclusions

Four conclusions can be drawn from this study. Firstly, the wheat yields show an increasing tendency (40 out of 42 applied scenarios) in most locations in range between 8–25% in all three time periods. In case of the CCSR scenario, which predicts the most severe increase of air temperature, the yields would be reduced by 10% in 2050 and by 26% in 2100 if the A2 emission scenario would become reality. Differences between individual scenarios are large and statistically significant and especially for later time periods may lead to doubts about the trend of the yield shift. Secondly, the site effect on the magnitude of climate change impact on the winter wheat yield is caused by differences in the soil and climatic conditions. The site effect increases with increasing severity of imposed climatic changes and culminates for emission scenario A2 and the time period 2100. The sustained tendency benefiting two warmest sites has been found as well as better response to the changed climatic conditions of sites with deeper soil profiles than those with less suitable soil conditions. Thirdly, the temperature variability proved to be an important factor and influenced both mean and standard deviation of the yields. Change of the temperature variability by more than 25% leads to statistically significant changes in the yield distribution, but the effect of temperature variability decreases with increased values of mean temperature occurring in latter time periods or at A2 emission scenario. It is highly probable that similar effect will be found for other meteorological elements and therefore use of climate change scenarios accounting for possible changes in weather variability is highly desirable. Finally, the study proved that the application of AVG scenarios – despite possible objections on physical inconsistency – might be justifiable and might bring results comparable to those derived from averaging results related to a number of scenarios or provide more robust estimate than use of one GCM-based scenario.

### Acknowledgement

This study was conducted with the support of the Grant Agency of the Czech Republic, contract no. 521/02/0827 and the research project "Regulation of biological and technological processes for competitive agriculture" registered on Mendel University of Agriculture and Forestry Brno under No. J 08/98: 432100001. Authors would like to thank to Daniel Jurečka, M.Sc. and to Vladimíra Horáková, M.Sc. (State Institute for Agricultural Supervision and Testing) for providing necessary crop and soil input data.

### References

Alexandrov V, Eitzinger J (2002) Potential climate change impact on winter wheat and spring barley in Austria. Global Change Biology (in press)

Alexandrov A, Hoogenboom G (2000) The impact of climate variability and change on crop yield in Bulgaria. Agric Forest Meteorol 104: 315–327

Amthor JS (2001) Effects of atmospheric $CO_2$ concentration on wheat yield: review of results from experiments using various approaches to control $CO_2$ concentration. Field Crops Res 73: 1–34

Amthor JS (1998) Perspective on the relative insignificance of increasing atmospheric $CO_2$ concentration to crop yield. Field Crop Res 58: 109–127

Angström A (1924) Solar and terrestrial radiation. Quart J Roy Meteor Soc 50: 121–125

Batts GR, Morison JIL, Ellis RH, Hadley P, Wheeler TR (1997) Effects of $CO_2$ and temperature on growth and yield of crops of winter wheat over four seasons. Eur J Agron 7: 43–52

Bender J, Herstein U, Black CR (1999) Growth and yield responses of spring wheat to increasing carbon dioxide, ozone and physiological stresses: a statistical analysis of "ESPACE-wheat" results. Europ J Agron 10: 185–195

Beniston M, Tol RJS (1998) Europe In: Watson RT, Zinyowera MC, Moss RH (eds) The regional impacts of climate change: an assessment of vulnerability. A Special Report of IPCC Working Group II. Cambridge: Cambridge University Press

Brown RA, Rosenberg NJ (1997) Sensitivity of crop yield and water use to change in a range of climatic factors and $CO_2$ concentrations: a simulation study applying EPIC to the central USA. Agric Forest Meteorol 83: 171–203

Bunce JA (2000) Responses of stomatal conductance to light, humidity and temperature in winter wheat and barley grown at three concentrations of carbon dioxide in the field. Global Change Biology 6: 371–382

Calderini DF, Slafer GA (1998) Changes in yield and yield stability in wheat during the 20th century. Field Crop Res 57: 335–347

Covey C, AchutaRao KM, Cubasch U, Jones P, Lambert SJ, Mann ME, Phillips TJ, Taylor KE (2003) An overview of results from the Coupled Model Intercomparison Project. Global and Planetary Change (in press)

Cure JD, Ackock B (1986) Crop responses to carbon dioxide doubling: a literature survey. Agric Forest Meteorol 38: 127–145

Diekkrüger B, Söndgerath D, Kersenbaum KC, McVoy CW (1995) Validity of agroecosystem models A comparison of results of different models applied to the same data set. Ecol Modelling 81: 3–29

Dhakhwa GB, Campbell CL, LeDuc SK, Cooter EJ (1997) Maize growth: assessing the effect of global warming and $CO_2$ fertilization with crop models. Agric Forest Meteorol 87: 253–272

Downing TE, Barrow EM, Brooks RJ, Butterfield RE, Carter TR, Harrison PA, Hulme M, Olesen JE, Porter JR, Schellberg J, Semenov MA, Vinther FP, Wheeler TR, Wolf J (2000) Quantification of uncertainty in climate change impact assessment In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and Agriculture in Europe: an integrated assessment. Environmental Change Institute, University of Oxford, pp 415–434

Dubrovský M (1997) Creating daily weather series with use of the weather generator. Environmetrics 8: 409–424

Dubrovský M, Nemešová I, Kalvová J (2003) Uncertainties in Climate Change Scenarios for the Czech Republic. Climate Research (in press)

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

Easterling WE, Rosenberg NJ, McKenney MS, Jones CA (1992) An introduction to the methodology, the region study and a historical analog of climate change. Agric Forest Meteorol 59: 3–15

Eitzinger J, Trnka M, Hösch J, Žalud Z, Dubrovský M (2003) Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecol Modeling (in press)

Ferris R, Ellis RH, Wheeler TR, Hadley P (1998) Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. Annals of Botany 82: 631–639

Hall AE (1979) A model of leaf photosynthesis and respiration for predicting carbon dioxide assimilation in different environments. Oecologia 143: 299–316

Hall AE (2001) Crop responses to environment. Boca Raton: CRC Press, p 232

Harrison PA, Porter JR, Downing TE (2000) Scaling-up the AFRCWHEAT2 model to assess phenological development for wheat in Europe. Agric Forest Meteorol 101: 167–186

Harvey LDD, Gregory J, Hoffert M, Jain A, Lal M, Leemans R, Raper SBC, Wigley TML, de Wolde J (1997) An introduction to simple climate models used in the IPCC Second Assessment Report: IPCC Technical Paper 2 (eds JT Houghton, LG Meira Filho, DJ Griggs, Noguer M), Intergovernmental Panel on Climate Change, Geneva, Switzerland, pp 50

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). UK: Cambridge University Press, pp 944

Hulme M, Wigley TML, Barrow EM, Raper SCB, Centella, Smith S, Chipanshi AC (2000) Using a climate scenario generator for vulnerability and adaptation assessments: MAGICC and SCENGEN Version 2.4 Workbook. Norwich, UK: Climatic Research Unit, 52 pp

Hunt LA, Pararajasingham S, Jones JW, Hoogenboom G, Imamura DT, Ogoshi RM (1993) GENCALC – Software to facilitate the use of crop models for analyzing field experiments. Agron J 85: 1090–1094

Iglesias A, Rosenzweig C, Pereira D (2000) Agricultural impacts of climate change in Spain: Developing tools for a spatial analysis. Global Environmental Change 10: 69–80

Ittersum van MK, Howden SM, Asseng S (2003) Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in $CO_2$, temperature and precipitation. Agriculture, Ecosystems and Environment (in press)

Izaurralde RC, Rosenberg NJ, Brown RA, Thomson AM (2003) Integrated assessment of Hadley Center (HadCM2) climate change impacts on agricultural productivity and irrigation water supply in the conterminous

United States Part II. Regional agricultural production in 2030 and 2095. Agric Forest Meteorol 117: 97–122

Jurečka D, Beneš F (2000) Přehled odrůd obilnin. Brno: UKZUZ OOZ, p 141

Kimbal BA (1983) Carbon dioxide and agricultural yield. An assemblage of analysis of 430 prior observations. Agron J 75: 779–788

Landau S, Mitschell RAC, Barnett V, Colls JJ, Craigon J, Moore KL, Payne RW (1998) Testing winter wheat simulation models' predictions against observe UK grain yields. Agric Forest Meteorol 89: 85–99

Mavromatics T, Jones PD (1998) Comparison of climate change scenario construction methodologies for impact assessment studies. Agric Forest Meteorol 91: 51–67

Mearns LO, Rosenzweig C, Goldberg R (1997) Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. Climatic Change 35: 367–396

Mitchell RAC, Black CR, Burkart S, Burke JI, Donnelly A, Temmmerman L de, Fangmeier A, Mulholland BJ, Theobald JC, van Oijen M (1999) Photosynthetic responses in spring wheat grown under elevated $CO_2$ concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'. Europ J Agron 10: 205–214

Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. Europ J Agron 16: 239–262

Otter-Nacke S, Godwin DC, Ritchie JT (1986) Testing and validation the CERES-wheat model in diverse environments agRISTARS Technical Report, YM-15-00407, JSC-20244, Johnson Space Center Houston, TX, USA

Parry M, Rosenzweig C, Iglesias A, Fischer G, Livermore M (1999) Climate change and world food security: a new assessment. Global Environmental Change 9: S51–S67

Petrovič S (ed) (1969) Podnebí Československé socialistické republiky – souborná studie. Prague: Hydrometeorological Institute, p 357

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10: 23–36

Ritchie JT, Otter-Nacke S (1985) Description and performance of CERES-Wheat: A user-oriented wheat yield model. In: Willis WO (ed) ARS Wheat Yield Project. ARS-38. U.S. Department of Agriculture-Agricultural Research Service, 159–175

Rounsvell MDA, Annetts JE, Audsley E, Mayr T, Reginster I (2003) Modelling the spatial distribution of agricultural land use at the regional scale. Agriculture, Ecosystems and Environment 95: 465–479

Saarikko RA (2000) Applying a site based crop model to estimate regional yields under current and changed climates. Ecol Modelling 131: 191–206

Santer BD, Wigley TML, Schlesinger ME, Mitchell JFB (1990) Developing climate scenarios from equilibrium GCM results. Max Planck Institute für Meteorologie, Report No. 47, Hamburg, Germany

Semenov MA, Porter JR (1995) Climatic variability and the modeling of crop yields. Agric Forest Meteorol 73: 265–283

Smith JB, Lazo JK (2001) A summary of climate change impact assessments from the U.S. country studies program. Climatic Change 50: 1–29

Travasso MI, Magrin GO (1998) Utility of CERES-Barley under Argentine conditions. Field Crops Res 57: 329–333

Trnka M, Žalud Z, Dubrovský M (2001) Role of the solar radiation in spring barley production process. In. Mezinárodní konference "Extrémy prostredia – limitujúce faktory bioklimatologických procesov", Slovenská bioklimatologická společnost SAV, Racková dolina 10.–12.9.2001, CD – ROM

Tsuji GY, Uehara G, Balas S (1994) DSSAT v3, University of Hawaii, Honolulu, Hawaii

Tubiello FN, Donatelli M, Rosenzweig C, Stockle CO (2000) Effects of climate change and elevated $CO_2$ on cropping systems: model predictions at two Italian locations. Europ J Agron 13: 179–189

Tubiello FN, Ewert F (2002) Simulating the effects of elevated $CO_2$ on crops: approaches and applications for climate change. Eur J Agron 18: 57–74

Tubiello FN, Rosenzweig C, Kimball BA, Pinter PJ Jr, Wall GW, Husanker DJ, LaMorte RL, Garcia RL (1999) Testing CERES-Wheat with free-air carbon dioxide enrichment (FACE) experiment data: $CO_2$ and water interactions. Agron J 91: 247–255

Wegehenkel M (2000) Test of a modeling system for simulating water balances and plant growth using various different complex approaches. Ecol Modelling 129: 39–64

Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Vara Prasad PV (2000) Temperature variability and the yield of annual crops. Agriculture Ecosystems and Environment 82: 159–167

Wilmott CJ (1982) Some comments on the evaluation of model performance. Bull Amer Meteor Soc 64: 1309–1313

Wolf J, van Diepen CA (1995) Effects of climate change on grain maize yield potential in the European Community. Climatic Change 29: 299–331

Wolf J et al (1998) Model evaluation of experimental variability to improve predictability of crop yields under climatic change Final report of the EU MODEXCROP project. University of Essex, UK; Royal Veterinary and Agricultural University, Copenhage, Denmark; Wageningen University Research Center, Wageningen, The Netherlands, 165 p

Wolf J, van Oijen M, Kempenaar C (2002) Analysis of the experimental variability in wheat responses to elevated $CO_2$ and temperature. Agriculture, Ecosystem and Environment 93: 227–247

Žalud Z, Dubrovský M (2002) Modelling climate change impacts on maize growth and development in the Czech Republic. Theor Appl Climatol 72(1–2): 85–102

Authors' addresses: Miroslav Trnka, Daniela Semerádová, Zdeněk Žalud (e-mail: zalud@mendelu.cz), Institute of Landscape Ecology, Mendel University of Agriculture and Forestry Brno, Zemědělská 1, 613 00 Brno, Czech Republic; Maritn Dubrovský, Institute of Atmospheric Physics, AS CR, Praha, Czech Republic.

Verleger: Springer-Verlag KG, Sachsenplatz 4–6, A-1201 Wien. – Herausgeber: Prof. Dr. H. Graßl, Max-Planck-Institut für Meteorologie, Bundesstrasse 55, D-20146 Hamburg. – Redaktion: Josef-Baumann-Gasse 1, A-1210 Wien. – Satz und Umbruch: Thomson Press (India) Ltd., Chennai. – Druck und Bindung: Grasl Druck & Neue Medien, A-2540 Bad Vöslau. – Verlagsort: Wien. – Herstellungsort: Bad Vöslau – Printed in Austria.