Theor. Appl. Climatol. 72, 85–102 (2002)

Theoretical and Applied Climatology

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# Modelling climate change impacts on maize growth and development in the Czech Republic

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With 11 Figures

Received March 9, 2001
Revised September 25, 2001

## Summary

The crop growth model CERES-Maize is used to estimate the direct (through enhanced fertilisation effect of ambient $CO_2$) and indirect (through changed climate conditions) effects of increased concentration of atmospheric $CO_2$ on maize yields. The analysis is based on multi-year crop model simulations run with daily weather series obtained alternatively by a direct modification of observed weather series and by a stochastic weather generator. The crop model is run in two settings: stressed yields are simulated in water and nutrient limited conditions, potential yields in water and nutrient unlimited conditions. The climate change scenario was constructed using the output from the ECHAM3/T42 model (temperature), regression relationships between temperature and solar radiation, and an expert judgement (precipitation).

Results: (i) After omitting the two most extreme misfits, the standard error between the observed and modelled yields is 11%. (ii) The direct effect of doubled $CO_2$: The stressed yields would increase by 36–41% in the present climate and by 61–66% in the $2 \times CO_2$ climate. The potential yields would increase only by 9–10% as the improved water use efficiency does not apply. (iii) The indirect effect of doubled $CO_2$: The stressed yields would decrease by 27–29% (14–16%) at present (doubled) ambient $CO_2$ concentration. The increased temperature shortens the phenological phases and does not allow for the optimal development of the crop. The simultaneous decrease of precipitation and increase of temperature and solar radiation deepen the water stress, thereby reducing the yields. The reduction of the potential yields is significantly smaller as the effect of the increased water stress does not apply. (iv) If both direct and indirect effects of doubled $CO_2$ are considered, the stressed yields should increase by 17–18%, and the potential yields by 5–14%. (v) The decrease of the stressed yields due to the indirect effect may be reduced by applying earlier planting dates.

## 1. Introduction

It is expected that the increasing concentration of greenhouse gases in the atmosphere will affect the climate in the forthcoming decades. The globally averaged surface air temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100 (IPCC, 2001). Regional temperature changes could, however, differ substantially from the global mean. Further, it is assumed that the global warming will intensify the hydrological cycle, and the frequency of droughts, floods, and hot and cold spells will be increased (Watson et al., 1996). The question stands what the effect of the climate change on various terrestrial ecosystems, e.g. agriculture, forestry, grasslands and water resources, will be.

Increased $CO_2$ concentration can affect crop growth in two ways.

Firstly, the crop is directly affected by the presence of $CO_2$ in the ambient air. As atmospheric $CO_2$ is the primary source of carbon for the plants and its present concentration is suboptimal (Nonhebel, 1996), the increased content of $CO_2$ in the air stimulates photosynthesis.

Simultaneously, the transpiration intensity is reduced by partially closing the stomata, which leads to the improved water use efficiency (WUE) and thereby to a lower probability of the water stress occurrence. 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 a controlled environment indicate that the crop growth should increase by about $14 \pm 11\%$ for $C_4$ plants (e.g., maize) at doubled ambient $CO_2$ (Kimball et al., 1988; Porter, 1992; Dhakhwa et al., 1997). If the water is a limiting factor, the yields may increase much more due to the additional effect of improved WUE.

The second effect of increased $CO_2$ relates to the response of a crop to a changed weather regime brought about by the $CO_2$ increase, and is referred to as the *indirect effect* or the *weather effect*. The most important weather variables that directly determine the crop yield are solar radiation, precipitation and temperature. If no management response (e.g., other cultivar or shift of the planting date) is applied, the maize yields typically decrease with increasing temperature due to a shortening of phenological phases (Maytín et al., 1995; Brown and Rosenberg, 1997). Increasing solar radiation stimulates the leaf assimilation (Wolf and van Diepen, 1995), thereby increasing the yields (Maytín et al., 1995; Brown and Rosenberg, 1997). However, as the increased solar radiation stimulates evapotranspiration, the yields may decrease due to a deepened water stress if the water supply is at its critical level. 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 the excessive water. The relationships between crop yields and changes in climatic characteristics may differ at individual sites depending on the present climate conditions. The situation is more complicated if the changes in individual climatic characteristics act simultaneously.

Impacts of climate change on crop growth and development may be estimated by two different methods. In experimental methods, the crop is grown under controlled conditions (greenhouse with controlled atmosphere, open top chambers, etc.). An advantage of these methods is that all required characteristics, such as the development of individual parts of the plant, may be measured directly. On the other hand, it may be too difficult to ensure that the future weather conditions are well represented. Moreover, these experiments are usually very time and money consuming. In light of these problems and due to ever increasing capacity of computer technology and improvements in mathematical modelling of physiological processes, the numerical simulation methods become more and more frequently used in climate change impact studies. The crop models used to simulate the growth and development of the maize include CERES-Maize [Jones and Kiniry (1986); used, e.g., by Iglesias (1995a, 1995b), Alexandrov and Hoogenboom (1999); Bacsi and Hunkár (1994); Dhakhwa et al. (1997); Makadho (1996); Maytín et al. (1995); Mearns et al. (1992, 1996, 1997), Cuculeanu et al. (1999)], WOFOST [Hijmans et al. (1994); used, e.g., by Wolf and van Diepen (1995)], MACROS (Penning de Vries et al., 1989), and EPIC [used, e.g., by Easterling et al. (1993, 1998), Dhakhwa et al. (1997), Brown and Rosenberg (1997)]. The crop models simulate the development of individual parts of the plants, commonly in daily steps. The input to the model incorporates the parameters of the cultivar (genetic coefficients), the field and soil characteristics, the agrotechnological management details (the most important are planting, fertilisation and irrigation), and environmental conditions (concentration of $CO_2$ and time series of daily weather characteristics). The effect of the climate change is estimated by comparing model crop yields simulated with use of weather series representing the present climate and the changed climate (Fig. 1). The weather series for the changed climate

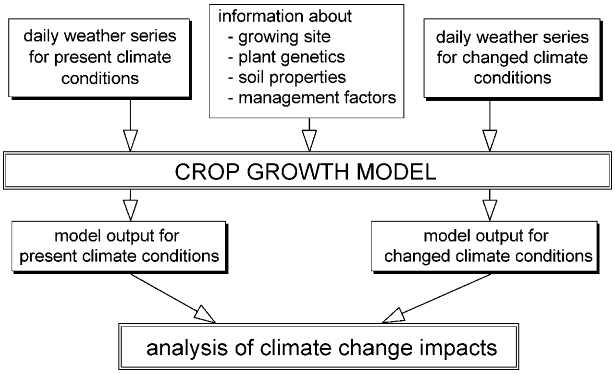

**Fig. 1.** The scheme of the crop model experiments used in climate change impact studies

conditions are obtained either by a direct modification of observed weather series (Bacsi and Hunkár, 1994; Dhakhwa et al., 1997; Maytín et al., 1995; Mearns et al., 1992; Wolf and van Diepen, 1995; Nonhebel, 1993, 1996) or with a stochastic weather generator whose parameters were derived from the observed weather series and then modified according to the climate change scenario (Cuculeanu et al., 1999; Dubrovský et al., 2000; Riha et al., 1996; Semenov and Porter, 1995; Semenov and Barrow, 1997). The model simulations are performed under two sets of conditions. In unlimiting conditions, the plant is given as much water and nutrients as it needs. In this case, no water stress and nitrogen stress may occur, and the resultant yields are referred to as the *potential yields*. In limiting conditions, water and nutrients supplies are limited and the *stressed yields* are simulated. The climate change impact studies focus on (i) impacts of an increased $CO_2$ concentration on the crop growth and (ii) possible adaptations through changes of the cultivar and sowing dates. The latter issue is addressed, e.g., by Bacsi and Hunkár (1994), Cuculeanu et al. (1999), Wolf and van Diepen (1995), Easterling et al. (1993).

Maize is one of the most important agricultural crops in the Czech Republic. It is grown both for silage and food. The arable area is about 270 000 ha for the silage and 30 000 ha for the grain maize, the average yields of the grain maize were 4.6 t/ha in 1986–1997. Recently, the MACROS crop growth model was successfully validated and used to estimate potential and water limited yields in various climatic conditions (Žalud and Rožnovský, 1998). The sensitivity of maize yields simulated by both CERES-Maize and MACROS models to selected hydrological parameters was analysed by Šťastná and Žalud (1999). Parameterisation and validation of the CERES-Maize crop model was treated in detail by Šťastná (1998).

The CERES-Maize crop model is used in this study to assess the effect of the expected climate change (induced by an increase of greenhouse gases concentration) on grain maize yields in the most fertile area of the Czech Republic. The paper follows the previous work by Dubrovský et al. (2000), which was focused on the validation of the weather generator, validation of the variability of the CERES-Maize model yields simulated with the use of synthetic weather series, and the sensitivity analysis of the model yields to changes in statistical structure of the input weather series. However, since the crop yield prediction was not the main aim of that paper, some input parameters related to the cultivar, soil and agrotechnical management were somewhat simplified. On the contrary, in this paper, these parameters are specified with the greatest accuracy available. The paper consists of the following parts: Methodology, the models (crop growth model and weather generator) and data (input parameters for the crop growth model, daily weather series, and the climate change scenarios) are described in section 2, where the validation of the crop model is also presented. The direct and indirect effects of the projected increase of the $CO_2$ concentration on the stressed and potential yields are discussed in section 3. The impact on other characteristics of the growth and development are dealt with in section 4. Of the possible adaptation responses to changed climate conditions, the effect of shifted planting date on the crop yields is studied in section 5.

## 2. Methods and data

### 2.1 Methodology

The climate change impacts on crop yields were assessed with use of the crop growth model run with weather series representing both the present and changed climates (Fig. 1). In order that the findings obtained by a comparison of model yields for the different climates have a statistical significance, multi-annual crop model simulations were run for each scenario. The descriptive statistics, such as means, standard deviations, and quantile characteristics, were determined and used for the impact assessment. This approach is considered more decisive (in a statistical sense) than the use of single values related to individual years. Since the distribution of the yields may be asymmetric and far from normal, the use of quantiles might be more appropriate because of their robustness. On the other hand, as the sample estimates of the quantiles are loaded by greater error, the means and standard deviations may be more suitable in case the time series is not long enough. Two approaches to the multi-annual crop model simulations are used in this study:

### 2.1.1 Direct modification approach

The crop model simulations are run with observed pedological, physiological and cultivation data specific for each individual year. Observed weather series is used in the present climate simulations. The weather series for simulations in the changed climate is obtained by a direct modification of observed series according to the climate change scenario (Dubrovský et al., 2000). This method will be referred to as the direct modification (DM) approach.

### 2.1.2 Weather generator approach

The input to the crop model consists of pedological, physiological and cultivation data taken from a single "representative" year and the 99-year synthetic weather series created by the stochastic weather generator Met&Roll (Dubrovský, 1997). The representative year is defined by the site-typical values of all non-meteorological parameters (including the planting date, soil profile and details on the fertilisation regime) needed to run the model. The parameters of the weather generator derived from the observed series are used to generate weather series representing the present climate. The parameters of the generator are modified in accordance with the climate change scenario to generate series representing the changed climate (Dubrovský et al., 2000). This method will be referred to as the weather generator (WG) approach.

In either approach, the stressed and potential yields were calculated, and both direct and indirect effects of increased $CO_2$ were assessed. In the adaptation analysis (section 5), only the WG approach was employed.

## *2.2 Crop model*

Crop growth model CERES-Maize version 3.0 (Jones and Kiniry, 1986) is used in this study. The model was developed within the frame of IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project and was run within the DSSAT [Decision Support System for Agrotechnology Transfer, Hoogenboom et al. (1994)] environment. The model was chosen because of its ability to simulate both the stressed yield, which is limited by the genetic potential of the crop, temperature, solar radiation and available water and nutrients, and the potential yield, which is limited only by the genetic potential of the crop, temperature and solar radiation. Moreover, the crop models from the CERES series are among the crop growth models, which allow one to modify the ambient concentration of $CO_2$.

The CERES-Maize model is a mechanistic process-based model, which increments crop growth in daily steps. Modelled processes include (i) phenological development, (ii) extension of leaves, stems and roots, (iii) biomass accumulation and partitioning, (iv) soil water balance and water use by crop, (v) soil nitrogen transformation, uptake by the crop, and partitioning among plant parts (Hunkár, 1994). The input data required for the simulations include: (i) cultivar characteristics (given in terms of genetic coefficients), (ii) field attributes (slope, drains, longitude, latitude), (iii) soil characteristics (texture, bulk density), (iv) planting details (date of seeding, seeding population, row spacing, planting depth), (v) management factors (tillage, irrigation, fertilisation), (vi) series of daily weather characteristics (sum of global solar radiation, maximum and minimum air temperatures and precipitation amount). More details may be obtained, e.g., in Jones and Kiniry (1986), Hunkár (1994), Iglesias (1995a), and Maytín et al. (1995).

## *2.3 Input data to the CERES-Maize model*

The model input data are based on the field experiments made during 1980–1996 at the Žabčice experimental station operated by the Mendel University of Agriculture and Forestry. The station is situated in the southeast of the Czech Republic (49°01′N, 16°37′E, 179 m above sea level), which is one of the warmest and driest regions of the country. The 1961–1990 mean annual temperature is 9.3 °C, and the mean annual precipitation during the same normal period is 480 mm (Rožnovský and Svoboda, 1995). Most of the parameters required as an input to the crop model simulation were measured and archived at this site. The model simulations are run at three ambient $CO_2$ levels: $1 \times CO_2$, $1.5 \times CO_2$ and $2 \times CO_2$ levels relate to present

$CO_2$ concentration (330 ppm) and concentrations increased by 50% and 100%, respectively.

### 2.3.1 Crop variety

The genetic characteristics of the crop variety are expressed in terms of five genetic coefficients, which describe the physiological processes (photosynthesis, respiration, and others) for an individual crop (Maytín et al., 1995): P1 – duration of the juvenile phase [accumulated degree-days (base 8 °C) during the non-reproductive phase of the cultivar]; P2 – sensitivity of photoperiod [coefficient (in $\text{hour}^{-1}$) to represent changes in development rate as a function of day-length]; P5 – duration of the kernel filling period [accumulated degree-days (base 8 °C) in the linear phase of filling]; G2 – maximum number of kernels per plant (obtained at optimum temperature with no water or nutrient stress); G3 – maximum rate of kernel filling (in mg $\text{day}^{-1}$ per kernel, also obtained at optimum temperature with no water or nutrient stress). The cultivar used in this study is Dea (origin PIONEER 3839, licensed from 1982), which is a middle early, two line hybrid with a FAO number of 300. Its advantages include higher resistance against diseases (especially against *Ustilago maydis*) and drought. The average number of cobs per plant is 1.00, located at 96–107 cm above a soil surface, their average length being 16–20 cm. The cobs contain 14 rows of grains, each of them having 24–38 grains. The average weight of a single grain is approximately 0.31 g. The plant develops 12–15 leaves, their mean length and width being 69 cm and 8.6 cm, respectively. The stem creates practically no offshoots and its height reaches 230–260 cm. The recommended number of plants per hectare ranges from 80 000 to 85 000.

### 2.3.2 Soil parameters

The soil type of the experimental field is described as Oxyaquic Cryofluvents according to the classification of the US Department of Agriculture (Soil Survey Staff, 1975). The soil parameters were determined by Karpíšek and Prax (1989). The upper 0–28 cm soil layer is classified as Ap, coarse subangular blocky, clay loam texture, dark brown colour and abrupt boundary. The soil layer at 28–35 cm is Ao, medium granular, silty clay texture, dark brown colour and clear boundary. The 35–61 cm layer is C1, coarse angular, up to 50 cm silty clay, below 50 cm clay loam texture, brown colour and gradual boundary. The 61–80 cm layer is C2, no observable aggregation, up to 70 cm loam, below 70 cm clay loam texture, greyish brown colour and gradual boundary. The last layer below 80 cm is classified as Cg, coarse angular and grey colour.

### 2.3.3 Weather and climate data

Observational daily series of *TMAX*, *TMIN* and *PREC* were measured at the Žabčice meteorological station, located approximately 1 km from the experimental field. Daily sums of global solar radiation (*SRAD*) were taken from the nearby (40 km apart) station at Kuchařovice. Time-parallel measurements at Žabčice and Kuchařovice during one year (1993) have shown that the mean and the standard deviation of the difference between the daily solar radiation sums measured at the two stations are 0% and 10%, respectively. This is considered to be a sufficient accuracy for using the Kuchařovice radiation data. Annual cycles of selected climatological characteristics of the Žabčice station are shown in Fig. 2; a more detailed table is presented in Dubrovský et al. (2000).

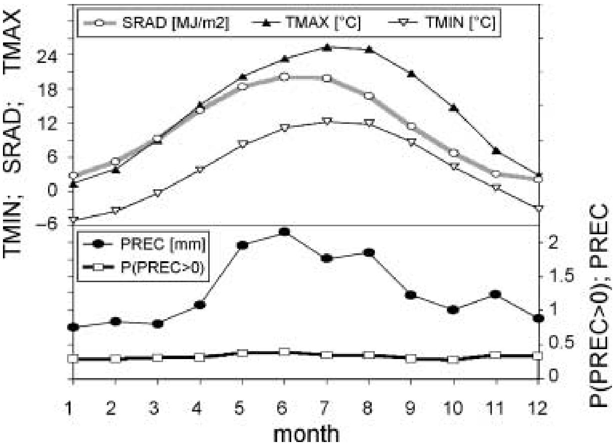

**Fig. 2.** The mean annual cycle of monthly climatic characteristics measured at Žabčice (except for the solar radiation, which was taken from the neighbouring station, 40 km apart) in 1961–1996. *SRAD*, *TMAX*, *TMIN*, *PREC* are monthly means of daily sum of global solar radiation [$\text{MJ m}^{-2}$], daily maximum and daily minimum temperature [°C], and daily sum of precipitation [mm]; P(*PREC* > 0) is the mean probability of wet day occurrence

### 2.3.4 Other input data

The planting details, management factors and fertilisation regime were set a) individually for each year in the validation experiment (sec. 2.4) and in the experiments made in the DM approach, b) constant for all simulation years in case of the experiments made in the WG approach. In both approaches, all these input data (except for the planting date in experiments made in section 5) were the same for all the climate change and $CO_2$ scenarios. In the DM approach, the planting date varied between April 24 and May 18, and three to four fertilisation dosages were applied (the total amount of nitrogen varied between 70 and 175 kg/ha) during the vegetation period. In the WG approach, the planting date was May 6, and four fertilisation dosages were applied (total amount of nitrogen was 110 kg/ ha). Details on the previous crop, residue, tillage, rotation and chemical application were set according to the historical records. No irrigation was applied.

## *2.4 Validation of CERES-Maize model*

In order that the crop growth model may be used in a climate change impact study, a proper validation must precede.

The grain yields simulated by the crop growth model with use of measured pedological, physiological, cultivation and meteorological data are compared with the observed grain yields in Fig. 3. Observational data from 17 years were available. The figure shows that the model yields fit the observed yields well for most of the years. On average, the model yields overestimate the observed yields by 17% and the standard deviation of the ratio of model to observed yield is 32%. The systematic overestimation could be caused by the occurrence of the non-simulated factors, such as harvest losses, pest and diseases, or by the occurrence of extreme weather events. The greatest departures of the model yields from those observed appear in 1981 and 1991, and are most probably related to the occurrence of extreme floods. After omitting these two years, we find that the model yields overestimate those observed by 12% on average and the standard deviation of the ratio of model to observed yield drops to an acceptable level of 11%. After omitting years 1981 and 1991, the difference between the model and observation is less than 20% (15%, 10%) in 87% (60%, 40%) of cases. If the model yields are corrected for the systematic error (i.e., the model yields are lowered by 12%) the fraction of the cases with deviations less than 20% (15%, 10%) increases to 100% (73%, 67%). Overall, the fit between the simulated and observed yields is considered satisfactory and corresponds to studies by other authors (Hunkár, 1994; Koestl, 1995; Weiss and Piper, 1992; Dhakhwa et al., 1997; Iglesias, 1995a; Guevara et al., 1999).

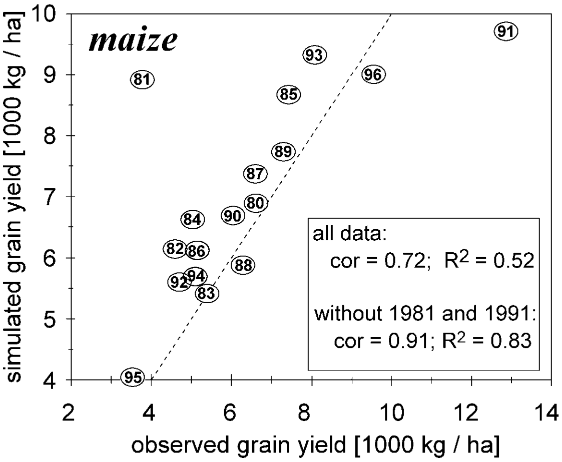

**Fig. 3.** Validation of the model yields simulated by CERES-Maize. The numbers inside the circles indicate the years. The fit between the observed and modelled yields is expressed in terms of the correlation coefficient (cor) and the coefficient of determination ($R^2$)

## *2.5 Climate change scenario*

Regarding the limited availability and reliability of GCM data, the climate change scenario was constructed in a mixed way (Nemešová et al., 1999). The $2 \times CO_2$ scenario (Fig. 4) consists of coefficients, which prescribe changes in the means of *SRAD*, *TMAX*, *TMIN* and *PREC*, and changes in standard deviations of *TMAX* and *TMIN*. The coefficients relate to individual months. The changes in the means of daily extreme temperatures are defined as the differences between the means of respective characteristics derived from GCM [model ECHAM, version 3/T42, described in DKRZ (1993)] simulations of $2 \times CO_2$ and $1 \times CO_2$ climates. The changes in the standard deviations of *TMAX*

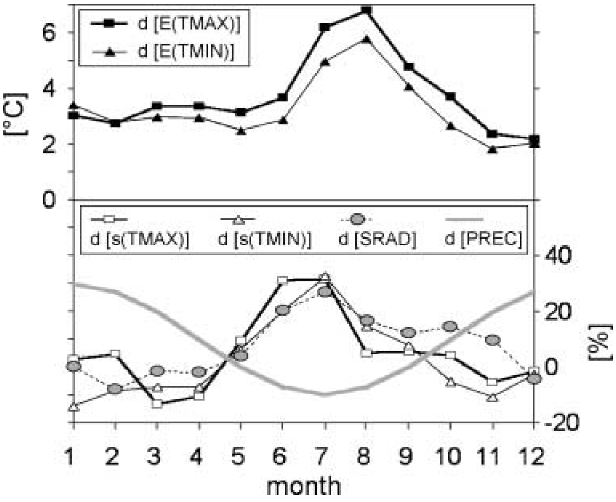

**Fig. 4.** The climate change scenario for 2 × $CO_2$ conditions (adopted from Nemešová et al., 1999). d[E(*TMAX*)] and d[E(*TMIN*)] are additive changes of monthly means of daily maximum and daily minimum temperature, d[s(*TMAX*)] and d[s(*TMIN*)] are percentage increments to the standard deviations of *TMAX* and *TMIN*, d[*SRAD*] is a percentage increment to daily sum of global solar radiation, and d[*PREC*] is a percentage increment to the daily precipitation sum

and *TMIN* are defined as the ratios of the standard deviations of the respective characteristics derived from the two GCM simulations. The data from the nearest GCM grid point (48°50′N, 16°52′E), which nearly coincides with the Žabčice station, were used to define the changes in temperature characteristics. Since the GCM output for *SRAD* was not available, the changes in global solar radiation were determined with use of statistical relations among monthly means of *SRAD*, *TMAX* and *TMIN*. Because of a significant misfit between the observed and GCM-simulated precipitation data, the scenario of changes in precipitation sums is based on both findings of the IPCC (IPCC, 1996) and the results of ECHAM validation tests (Nemešová et al., 1998). The 1.5 × $CO_2$ scenario was derived from the 2 × $CO_2$ scenario by multiplying the increments displayed in Fig. 4 by 0.5.

### *2.6 Daily weather series*

The daily weather series for the two methods outlined in section 2.1 are produced in two different ways. In the DM approach, the weather series representing changed climate conditions is derived from the observed series by modifying the four weather variables by increments taken from the climate change scenario. Maximum and minimum temperatures are modified additively, daily sums of precipitation and solar radiation are modified multiplicatively. In this approach, variability of temperature for a given day of the year, frequency of wet day occurrence, and lag-1 correlations and cross-correlations among the four daily weather characteristics remain unchanged. In using the multiplicative modification, daily variabilities of solar radiation and precipitation are implicitly modified by the same coefficient as the mean daily values.

In the WG approach, weather generator Met&Roll (Dubrovský, 1997) was used. Its parameters are derived from the observed weather series in the first step. The parameters include (i) the means and standard deviations of *SRAD*, *TMAX* and *TMIN,* determined separately for wet and dry days for each day of the year, (ii) lag-0 and lag-1 correlations among the standardised (conditionally on a wet day occurrence) values of *SRAD*, *TMAX* and *TMIN* (annual cycle of the correlations is not considered), (iii) the probability of a wet day occurrence and the probability of a wet day following a dry day (monthly), (iv) the parameters of the Gamma distribution for modelling daily precipitation amount (monthly). The set of unmodified parameters is then used to generate series for present climate conditions. To generate series representing changed climate conditions, the parameters of the generator are modified according to the climate change scenario.

Weather generator Met&Roll was validated in previous studies in two ways. Firstly, the stochastic structure of the synthetic series was compared with the structure of the observed series (Dubrovský, 1996, 1997). Validation tests revealed some discrepancies in the statistical structure of synthetic weather series, the most important being: (i) The frequency of occurrence of long dry spells, extreme daily precipitation amounts and the variability of monthly means are underestimated by the generator. (ii) Correlations and lag-1 correlations among weather characteristics exhibit a significant annual cycle not assumed by the model. On the whole, the best fit between the observed and synthetic weather series is experienced in summer months. Secondly, it was tested how the discrepancies in the stochastic structure affect the variability of the model yield (Dubrovský et al., 2000). In this experiment, the variability of the model yields simulated with the observed series from 17 Czech stations was compared with the variability of the model yields simulated with use of synthetic weather series. No statistically significant difference was revealed, and it was therefore concluded that the weather generator is applicable for the CERES-Maize simulations.

## 3. Direct and indirect effects of increased $CO_2$ on crop yields

The time series of the model grain yields simulated in the DM approach at various combinations of ambient $CO_2$ levels and weather regimes are displayed in Fig. 5 (stressed yields) and Fig. 6 (potential yields). The summary statistics for the 17-year runs made in the DM approach and for the 99-year runs in the WG approach are given in Table 1 and graphically displayed in Figs. 7 and 8. The variability of the grain yields simulated in the WG approach is expressed in terms of quantiles (Fig. 8), which give better insight into the variability but cannot be used with the DM approach (Fig. 7) because of the shortness of the simulation series. The results displayed in the figures and in Table 1 show the following:

### *3.1 Indirect effect*

The indirect effect of increased $CO_2$ on stressed crop yields in individual years may be seen in Fig. 5a,b. Regarding the method of obtaining the weather data for the changed $CO_2$ level, it

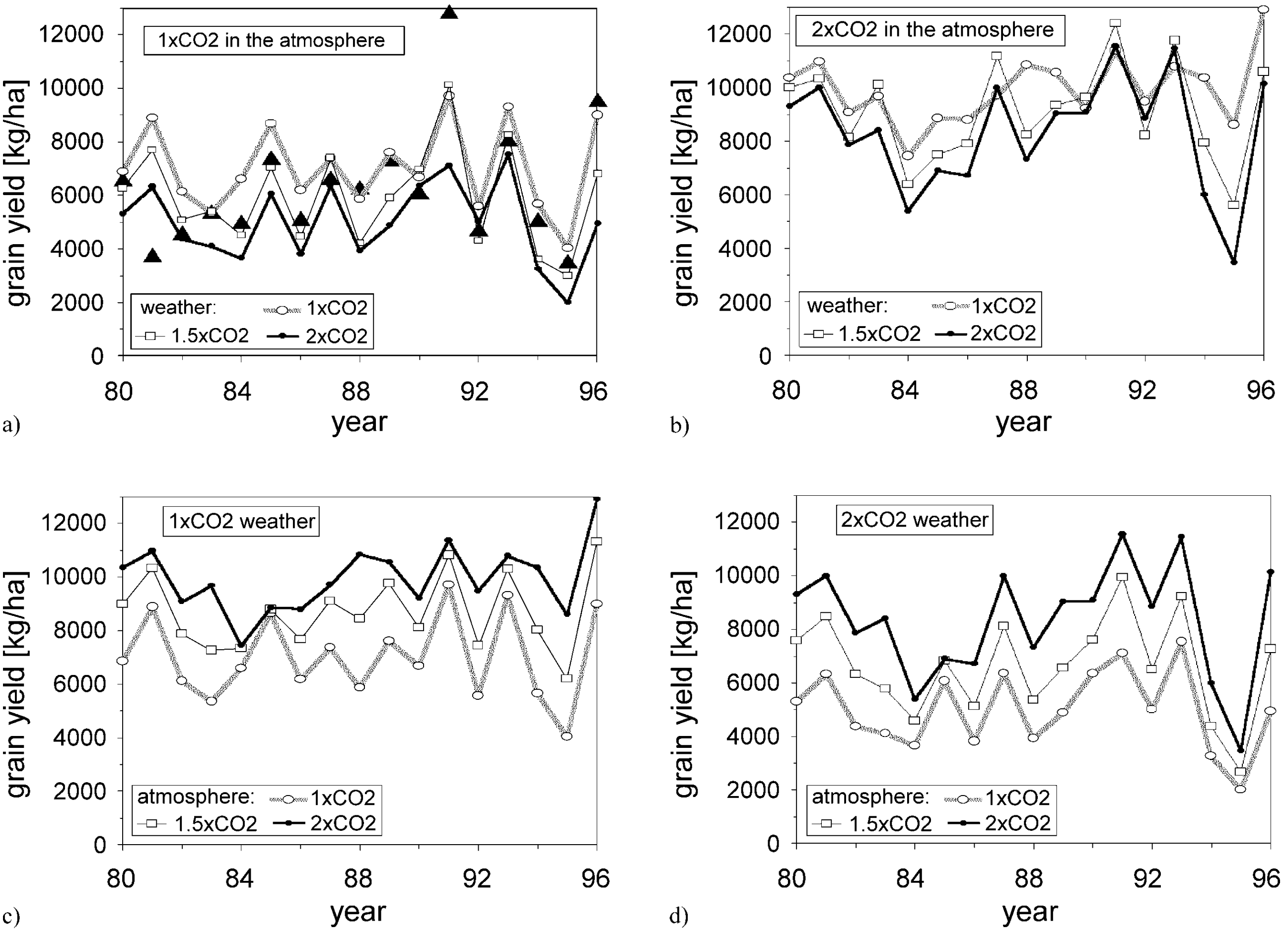

**Fig. 5.** Time series of stressed grain yields simulated at various levels of direct and indirect $CO_2$ effects. The weather series for $1.5 \times CO_2$ and $2 \times CO_2$ climates were obtained by direct modification of observed weather series (Žabčice, 1980–1996). **a**) present level of ambient $CO_2$ and weather regimes related to three $CO_2$ levels; **b**) as (a) but for doubled ambient $CO_2$; **c**) present weather regime and three levels of ambient $CO_2$; **d**) same as (c) but for $2 \times CO_2$ weather regime. The solid triangles in (a) mark the observed yields

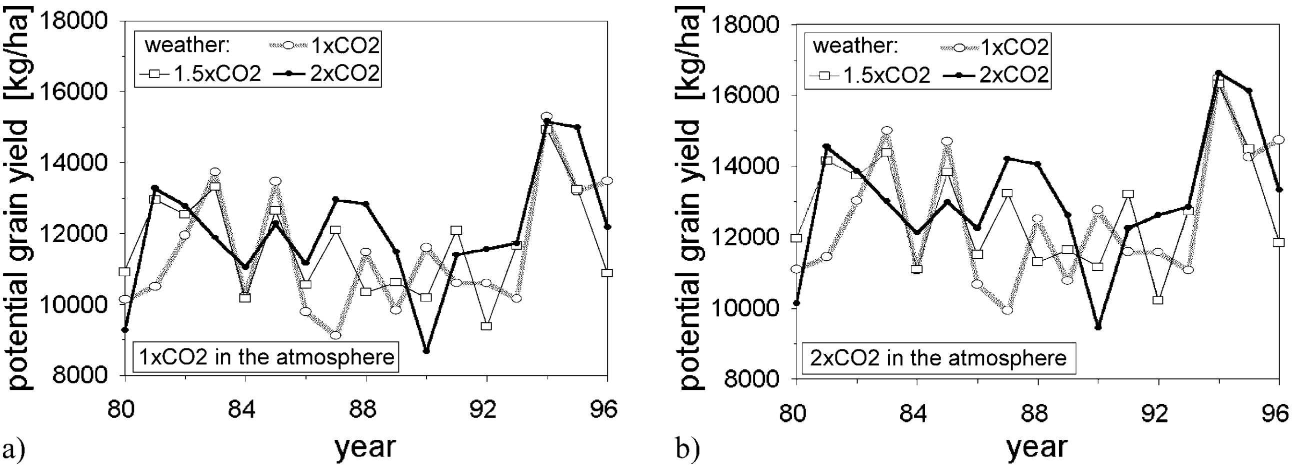

**Fig. 6.** As Fig. 5a,b but for the potential yields (note the changed scale of the ordinate)

**Table 1.** Summary statistics of the stressed and potential model yields obtained in DM and WG approaches. The "CO$_2$ for the indirect effect" indicates the concentration of CO$_2$ (with respect to the baseline concentration) used to drive the climate change scenario (sec. 2.5), the "CO$_2$ for the direct effect" indicates the concentration of ambient CO$_2$. The magnitudes of the direct/indirect/both effects are given in terms of the ratios of the means of the respective yields and the yields obtained with the zero direct/indirect/both effects. *Z*(avg) is the index of production potential (Eq. 1)

| **CO$_2$ for the indirect effect** | 1 × | 1 × | 1 × | 1.5 × | 1.5 × | 1.5 × | 2 × | 2 × | 2 × |
|---|---|---|---|---|---|---|---|---|---|
| **CO$_2$ for the direct effect** | 1 × | 1.5 × | 2 × | 1 × | 1.5 × | 2 × | 1 × | 1.5 × | 2 × |
| **a) stressed yields, DM approach:** | | | | | | | | | |
| avg [kg/ha] | 7037 | 8706 | 9955 | 5948 | 7702 | 9143 | 5010 | 6616 | 8332 |
| std [kg/ha] | 1567 | 1380 | 1244 | 1814 | 1972 | 1809 | 1438 | 1804 | 2100 |
| std/avg [%] | 22 | 16 | 12 | 31 | 26 | 20 | 29 | 27 | 25 |
| direct effect | 1.00 | 1.24 | 1.41 | 1.00 | 1.29 | 1.54 | 1.00 | 1.32 | 1.66 |
| indirect effect | 1.00 | 1.00 | 1.00 | 0.85 | 0.88 | 0.92 | 0.71 | 0.76 | 0.84 |
| both effects | 1.00 | | | | 1.09 | | | | 1.18 |
| *Z*(avg) | 0.61 | 0.73 | 0.80 | 0.51 | 0.63 | 0.72 | 0.41 | 0.53 | 0.63 |
| **b) potential yields, DM approach:** | | | | | | | | | |
| avg [kg/ha] | 11482 | 11962 | 12515 | 11677 | 12167 | 12761 | 12044 | 12555 | 13133 |
| std [kg/ha] | 1704 | 1743 | 1836 | 1427 | 1485 | 1553 | 1608 | 1678 | 1743 |
| std/avg [%] | 15 | 15 | 15 | 12 | 12 | 12 | 13 | 13 | 13 |
| direct effect | 1.00 | 1.04 | 1.09 | 1.00 | 1.04 | 1.09 | 1.00 | 1.04 | 1.09 |
| indirect effect | 1.00 | 1.00 | 1.00 | 1.02 | 1.02 | 1.02 | 1.05 | 1.05 | 1.05 |
| both effects | 1.00 | | | | 1.06 | | | | 1.14 |
| **c) stressed yields, WG approach:** | | | | | | | | | |
| avg [kg/ha] | 7777 | 9494 | 10581 | 6665 | 8374 | 9718 | 5666 | 7439 | 9127 |
| std [kg/ha] | 1950 | 2025 | 1676 | 1814 | 1675 | 1459 | 1687 | 1795 | 1629 |
| std/avg [%] | 25 | 21 | 16 | 27 | 20 | 15 | 30 | 24 | 18 |
| direct effect | 1.00 | 1.22 | 1.36 | 1.00 | 1.26 | 1.46 | 1.00 | 1.31 | 1.61 |
| indirect effect | 1.00 | 1.00 | 1.00 | 0.86 | 0.88 | 0.92 | 0.73 | 0.78 | 0.86 |
| both effects | 1.00 | | | | 1.08 | | | | 1.17 |
| Z(avg) | 0.68 | 0.79 | 0.84 | 0.59 | 0.72 | 0.79 | 0.52 | 0.65 | 0.76 |
| **d) potential yields, WG approach:** | | | | | | | | | |
| avg [kg/ha] | 11486 | 11960 | 12546 | 11227 | 11703 | 12272 | 10999 | 11470 | 12049 |
| std [kg/ha] | 1927 | 2015 | 2120 | 1716 | 1789 | 1878 | 1673 | 1743 | 1836 |
| std/avg [%] | 17 | 17 | 17 | 15 | 15 | 15 | 15 | 15 | 15 |
| direct effect | 1.00 | 1.04 | 1.09 | 1.00 | 1.04 | 1.09 | 1.00 | 1.04 | 1.10 |
| indirect effect | 1.00 | 1.00 | 1.00 | 0.98 | 0.98 | 0.98 | 0.96 | 0.96 | 0.96 |
| both effects | 1.00 | | | | 1.02 | | | | 1.05 |

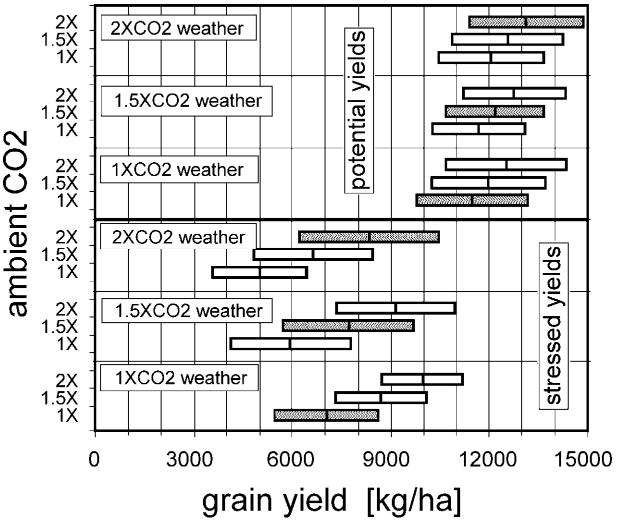

**Fig. 7.** Summary statistics (average ± standard deviation) of the stressed (bottom) and potential (top) model yields in the 17-year crop growth simulation run with weather series obtained by the direct modification of the observed weather series. The labels to the left of the vertical give the concentration of ambient $CO_2$ (with respect to the present level), the interior labels (1 × CO2 weather, 1.5 × CO2 weather, 2 × CO2 weather) indicate the climate change scenario used to create the weather series. The shaded bars indicate that both direct and indirect effects are driven by the same $CO_2$ concentration

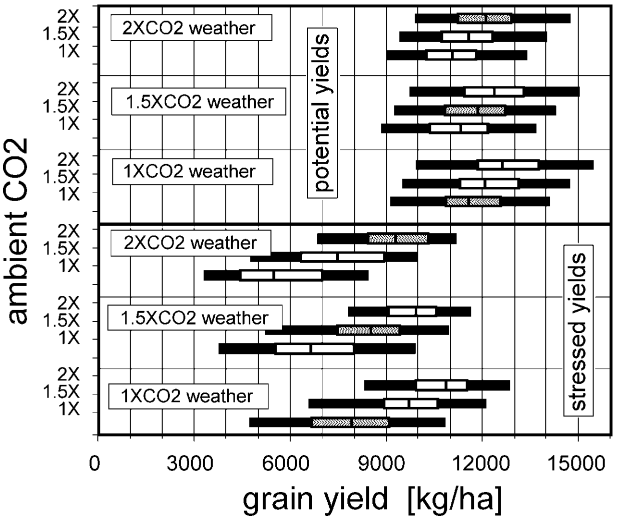

**Fig. 8.** Similar as the previous figure but the summary statistics of the grain yields were derived from the 99-year crop growth simulation run in the WG approach and are expressed in terms of quantiles. The bars represent 5th, 25th (lower quartile), 50th (median), 75th (upper quartile), and 95th member from the set of values arranged in an ascending order

is assured in the DM approach that the values of the weather characteristics for a given year in the $1.5 \times CO_2$ climate are always between the values related to the $1 \times CO_2$ and $2 \times CO_2$ climates. However, although the changes in weather characteristics related to increased $CO_2$ tend to reduce the stressed yields (Fig. 7, Fig. 8), the model yields do not follow this trend in some years (see, e.g., yields in 1987 and 1991 displayed in Fig. 5b). The analogous analysis applied to the time series of the potential yields (Fig. 6) shows that the relationship between the model potential yields and weather is even more complex. On average, the stressed yields decrease due to the indirect effect of doubled $CO_2$ by 14% ($2 \times CO_2$ in the atmosphere, WG approach) to 29% ($1 \times CO_2$ in the atmosphere, DM approach). This decrease is assumed to be due to the rise of temperature sums and a resultant shortening of individual phenological phases not allowing for an optimal development of the crop. Moreover, the simultaneous decrease of summer precipitation and increase of potential evapotranspiration (due to increased temperature and solar radiation) imply an elevated water stress (Fig. 9c) that also contributes to a reduction of the yields. Due to the lack of the effect of increased water stress, the magnitude of the indirect effect on potential yields is significantly lower: slightly negative in the WG approach (Fig. 8) and even slightly positive in the DM approach (Fig. 7).

### *3.2 Direct effect*

An increased concentration of ambient $CO_2$ implies higher yields (Fig. 5c,d; Fig. 7; Fig. 8). As given in the introduction, this increase is contributed to by the intensified photosynthesis and (in the case of limited yield only) improved WUE. As the magnitude of the latter mechanism depends on water available, the increase of the yields in the years with sufficient precipitation during the vegetation period (1984, 1985, 1987, 1991) is less pronounced compared to the "dry" years (1983, 1994, 1995). Since the water availability affects only stressed yields, the magnitude of the direct effect on the potential yields (9–10% increase in the $2 \times CO_2$ atmosphere) is only due to the intensified photosynthesis, and accordingly lower than for the stressed yields. Comparing the magnitudes of the direct effect on the stressed and potential yields (Table 1), we can see that the effect of better

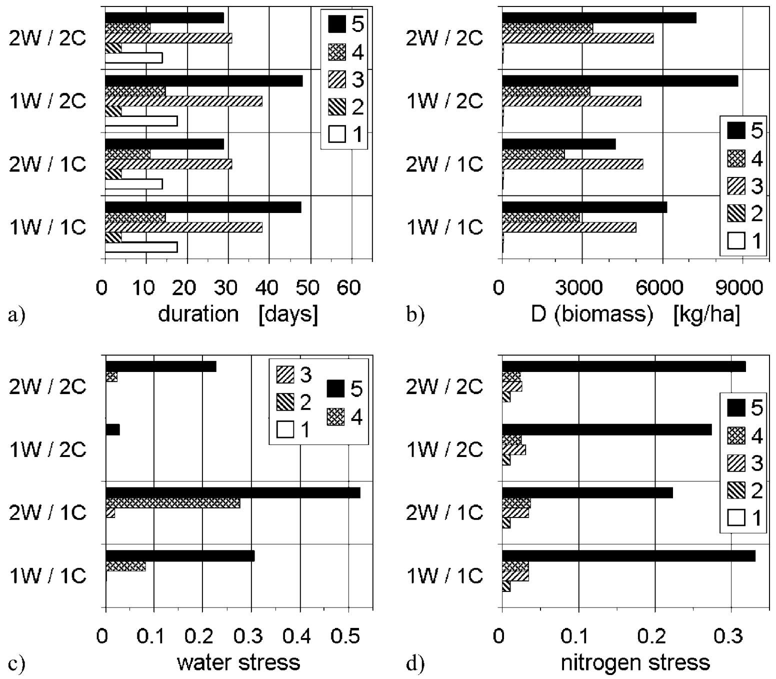

**Fig. 9.** The means of the crop growth characteristics related to the five phenological phases (indicated by numbers 1–5 in the legend box). The characteristics were calculated from the 99-year crop model simulations performed in the WG approach at two levels of ambient $CO_2$ ($1 \times CO_2$ and $2 \times CO_2$ levels are labelled by 1C and 2C on the ordinate) and present and $2 \times CO_2$ weather conditions (labelled by 1W and 2W). The four panels relate to **a**) duration of the phenological phase, **b**) an increment to the biomass, **c**) index of the water stress (value within ⟨0,1⟩ interval), and **d**) index of the nitrogen stress (value within ⟨0,1⟩ interval)

WUE is much greater than the effect of intensified photosynthesis. Contrary to the indirect effect, the changes of the yields are approximately proportional to the change in ambient $CO_2$ concentration (Fig. 5c,d).

### *3.3 Combined effects of $CO_2$ change*

It may be noted that the direct and indirect effects of increased $CO_2$ on stressed yields are not additive. The mean stressed yields simulated in the DM approach (Table 1, Fig. 7) decrease due to the indirect effect of doubled $CO_2$ by 29% (from 7037 to 5010 kg/ha) in the present ambient $CO_2$ concentration, but only by 16% (from 9955 to 8332 kg/ha) in the $2 \times CO_2$ atmosphere. The mean stressed yields increase due to the direct effect of doubled $CO_2$ by 41% (from 7037 to 9955 kg/ha) in $1 \times CO_2$ weather, but by 66% (from 5010 to 8332 kg/ha) in $2 \times CO_2$ weather conditions. Similar trends are obtained in the WG approach (Fig. 8). These results may indicate that the reduction of the yields due to the water stress (as a result of the indirect effect) will be lower in the $2 \times CO_2$ atmosphere, or, from a different point of view, the positive effect on the yields of the better WUE due to increased $CO_2$ will be greater in $2 \times CO_2$ weather conditions. The magnitude of the direct effect of increased $CO_2$ is greater than the magnitude of the indirect effect, so that the superposition of both effects implies positive change in maize yields in increased $CO_2$ conditions. The mean model stressed yields increase by 17–18% in $2 \times CO_2$ conditions and the trends are almost identical in both DM and WG approaches. The potential yields increase by 5–14% in $2 \times CO_2$ conditions, the trends obtained in WG approach are lower compared to the trends obtained in DM approach.

### *3.4 Effect of the $CO_2$ change on the variability of the model yields*

The variability of the model stressed yields (expressed in terms of the coefficient of variation, which is defined as a ratio of the standard deviation to the average) decreases due to the direct effect of increased $CO_2$ but increases due to the indirect effect of increased $CO_2$. These changes are assumed to be related to the water stress, the intensity of which is negatively (positively) correlated with the intensity of the direct (indirect) effect. The increasing intensity of the water stress reduces the mean yields but enhances the variability of the yields. If both direct and indirect effects are combined, variability tends to increase (from 22% in $1 \times CO_2$

conditions to 25% in $2 \times CO_2$ conditions) if simulated in the DM approach but tends to decrease (from 25% to 18%) if simulated in the WG approach.

### *3.5 Comparison of results obtained in DM and WG approaches*

The means of the stressed yields obtained in the WG approach are by 10% greater on average than the yields obtained in the DM approach. This corresponds to the choice of the representative year whose parameters were based on year 1989 which exhibited about 10% greater yields compared to the average yield. Importantly, the ratio of the WG mean to DM mean exhibits no significant relationship with $CO_2$ change, which implies that the trends in the mean yields due to the direct and indirect effects are similar in both approaches (paragraphs a and c of Table 1). The results of the F-test suggest that the differences between the variabilities (expressed in terms of the coefficient of variation) of the stressed yields obtained in the two approaches are statistically significant but the explanation is not apparent to the authors. It may be just noted that the number of the yields used to calculate a single statistic in the DM approach is much lower compared to the number of values available in the WG approach (17 vs. 99), so that the statistics obtained in the WG approach are loaded by a lower sampling error and thus should be given greater weight in assessing the trends. In addition, the variability of DM yields may be affected by the interannual variability of non-meteorological parameters, which are held constant in the WG approach. This should result in greater variability of DM yields, which may be observed in the $1.5 \times CO_2$ and $2 \times CO_2$ climates. As for the potential yields, the magnitude of the direct effect is about the same in both the WG and DM approaches; the indirect effect is slightly negative in the WG approach but slightly positive in the DM approach.

### *3.6 Stressed vs. potential yields*

The effects (both direct and indirect) of varying $CO_2$ on potential yields are much less pronounced than those in water and nutrient limited conditions (stressed yields). For example, the direct effect of doubled $CO_2$ on potential yields is 9–10% (compare with 36–66% in stressed conditions) and the indirect effect is $+5\%$ in the DM approach (compare with $-16$ to $-29\%$ in stressed conditions) and $-4\%$ in the WG approach (compare with $-14$ to $-27\%$ in stressed conditions). In contrast with the stressed conditions, the direct and indirect effects on potential yields are mutually additive: the magnitude of the direct effect is the same for all weather regimes, and the magnitude of the indirect effect is the same for all ambient $CO_2$ levels. This is explained by the water stress, which causes unlinearities in trends of the stressed yields but is absent in simulating the potential yields. For further interpretation, the index of production potential, $Z$, is introduced. The value of the index is defined as a ratio of stressed ($Y_S$), and potential ($Y_P$) yields under given weather conditions ($w$) and ambient $CO_2$ concentration ($c$):

$$Z(w,c) = \frac{Y_S(w,c)}{Y_P(w,c)} \times 100\% \tag{1}$$

This index may serve as a measure of impacts of limiting factors on the grain yields. In case of the field experiment the value of $Z$ is always greater than 0% and lower than 100%. The zero value of $Z$ would mean that the stress totally inhibits the growth, $Z = 100\%$ would mean that no stress affects the yields. It can be seen from Table 1 that $Z$ increases with increasing intensity of the direct effect but decreases with increasing intensity of the indirect effect. This behaviour relates to the water stress, which decreases due to the direct effect of increased $CO_2$ but increases due to the indirect effect. If both the effects are combined, the value of $Z$ slightly increases with increasing $CO_2$.

## 4. Effect of $CO_2$ change on other growth and development characteristics

The studies of climate change impact on crops are mostly concerned with yields. However, biomass growth, occurrence of the water and nitrogen stresses during individual growth phases, duration of the phases, and maximum leaf area index (LAImax), are also worth mentioning in the impact assessments. The mean values of selected characteristics related to the five growth

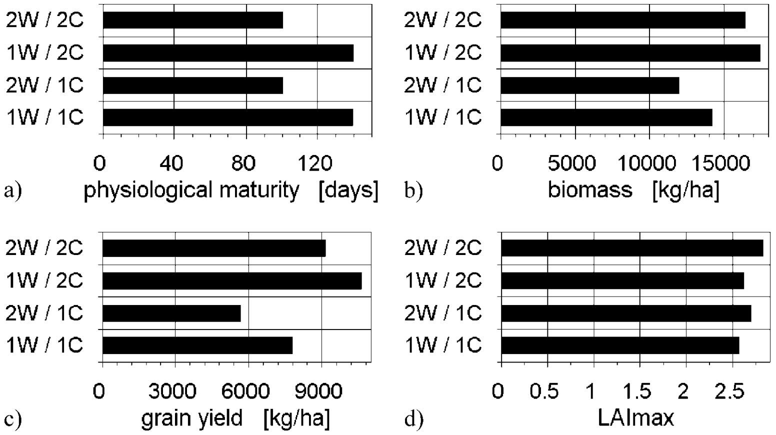

**Fig. 10.** As in Fig. 9 but for the characteristics related to the whole growing period. The four panels display **a**) the time of achievement of the physiological maturity (days after planting), **b**) the total biomass at the harvest maturity, **c**) the grain yield, and **d**) the maximum value of the leaf area index

phases (considered by the CERES-Maize model) and the whole growing period, two climate scenarios and two ambient $CO_2$ levels are shown in Figs. 9 and 10. The five phases are: (i) from emergence to the end of juvenile phase, (ii) from the end of juvenile phase to the floral initiation, (iii) from the floral initiation to the end of leaf growth, (iv) from the end of leaf growth to the beginning of grain filling, and (v) the grain filling phase. The figures indicate:

### *4.1 Direct effect*

(i) The duration of individual phenological phases (Fig. 9a) and LAImax (Fig. 10d) are nearly independent of the concentration of $CO_2$ in the atmosphere. (ii) More biomass (increases by 23% and 37% in present and $2 \times CO_2$ weather conditions, respectively; Fig. 10b) and grain yield (increases by 36% and 61% in present and $2 \times CO_2$ weather conditions, respectively; Fig. 10c) are expected if the ambient $CO_2$ concentration is doubled. The increase is mostly related to the improved WUE, which nearly eliminates the water stress in the 4th and 5th growth phases (Fig. 9c). The changes in biomass growth are expected only in these two phases (Fig. 9b).

### *4.2 Indirect effect*

(i) Increasing temperature sums will result in shortening the crop phenological development (Fig. 9a). All phenological phases (except for the second one, which lasts 4 days on average and will not be affected) will be shortened. The 5th phase is reduced most significantly, by 40%. The physiological maturity (Fig. 10a) will be achieved by 39 days sooner: it drops from 139 to 100 days. (ii) The biomass will be reduced by 15% (6%) and the grain yields by 27% (14%) in the present (doubled) ambient $CO_2$ concentrations (Fig. 10b,c). The reduction of the biomass is mainly due to a shortening of the fifth phenological phase and significant increase of the water stress in this phase (as a result of increased temperatures, increased intensity of solar radiation and decreased precipitation).

## 5. Adaptation to climate change by shifting the planting date

Up to now, it was assumed that all input parameters except for the weather series and ambient $CO_2$ concentration are constant. However, the yields may apparently be modified by various management responses, such as adjustments in fertilisation and irrigation regimes, shifting the planting date, or using other cultivar. Only the shift of the planting date (PD) is considered in the present study.

The 99-year crop model simulations were run in the WG approach for two levels of ambient $CO_2$ (present and doubled concentrations) and two climates (present and $2 \times CO_2$ climates), at water and nutrient limited conditions. The value of PD was varied within the interval ($D_0 - 60$ days, $D_0 + 30$ days), where $D_0 = 126$ (May 6) is the planting date of the "representative year". The results displayed in Fig. 11 show:

(i) The model grain yields simulated in the present climate and ambient $CO_2$ concentration (Fig. 11a) are rather insensitive to small changes in PD. Specifically, the median of

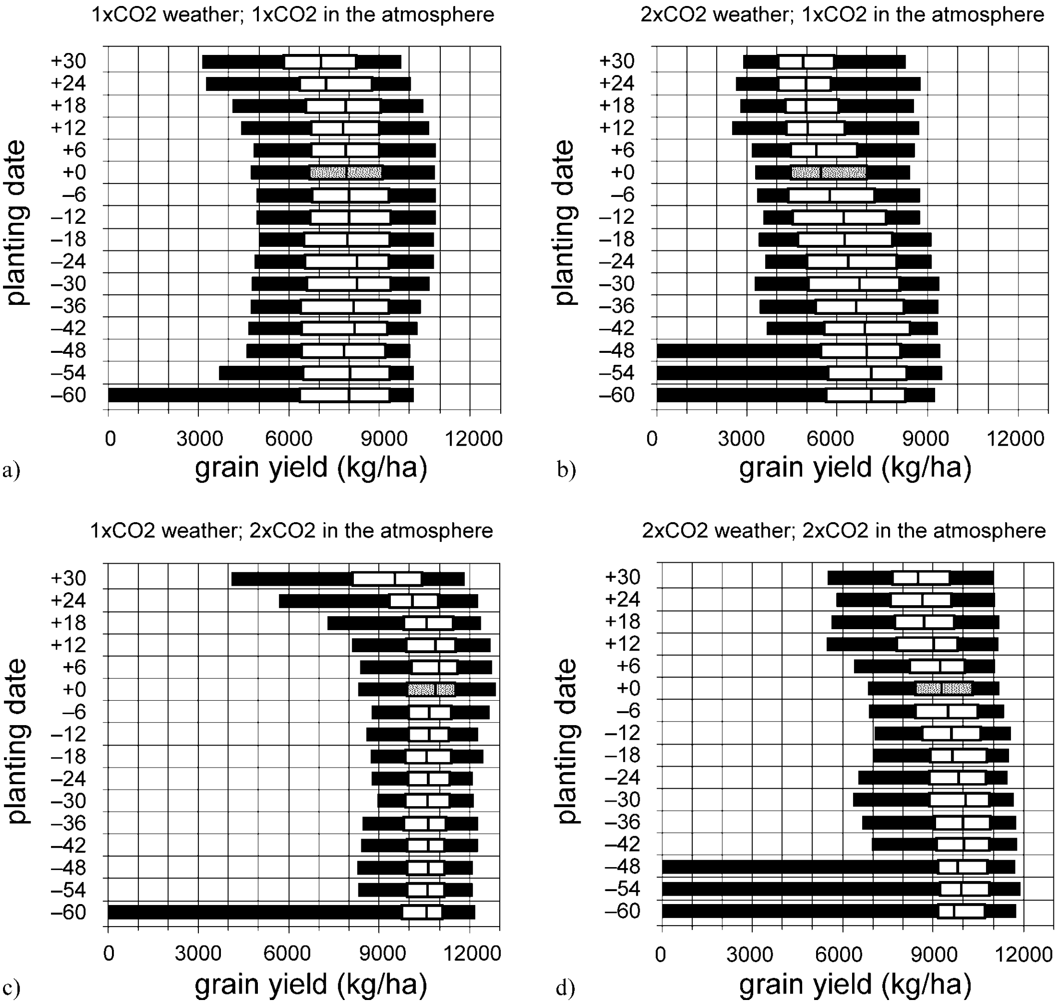

**Fig. 11.** Sensitivity of the grain yields to the planting date, which is given in terms of the deviation (in days) from the representative year's planting date (May 6, the 126th day of the year). The bars represent quantiles (5th, 25th, median, 75th, 95th) of the model yields obtained in the 99-year simulations made in the WG approach at two levels of ambient $CO_2$ and two weather regimes. The shaded bars relate to the representative year's planting date

the yields remains nearly constant if PD varies within ($D_0 - 60$ days, $D_0 + 18$ days). In case of the earlier PD, the probability that the yield is damaged by a spring frost increases: one zero yield occurs in the 99-year series if $PD = D_0$, but three (six) zero yields occur if $PD = D_0 - 36$ ($D_0 - 60$). On the other hand, if the planting date is delayed beyond $D_0$, the grain yields tend to decrease due to the occurrence of the autumn low temperatures, which precociously terminate the grain filling phase. In the case of the planting date delayed by 1 month, the average grain yield decreases by 11%.

(ii) The decreases of the yields resulting from the changes in daily weather conditions in the $2 \times CO_2$ climate, especially from the increased temperature, might be mitigated by applying earlier planting terms (Fig. 11b,d). However, the mitigation is only partial, as the high temperatures occurring at the later phases of the crop development cannot be avoided by earlier planting. In the case of the one month earlier planting date, the mean duration of the growing period is prolonged from 100 days to 117 days (compare to 140 days in $1 \times CO_2$ climate) and the mean yields are increased by 775 kg/ha at present ambient $CO_2$ (Fig. 11b; note that the graphs display quantile characteristics but the magnitudes of the indirect effect are calculated from the means), and by 402 kg/ha at doubled ambient $CO_2$ (Fig. 11d). This means that the negative indirect effect of doubled

$CO_2$ manifested by a 27% decrease of the stressed yields simulated in the WG approach at present ambient $CO_2$ (Table 1) is reduced to 17%, and the 14% decrease at doubled $CO_2$ is reduced to 10%. Surprisingly in the first sight, the frequency of a frost damage is greater in the $2 \times CO_2$ climate, which exhibits warmer temperatures compared to the present climate. This paradox may be explained partly by a faster development of the plants in $2 \times CO_2$ climate, which implies that the individual phenological phases start sooner, and partly by a randomness involved in generating the synthetic weather series. The randomness affects the sample frequency of occurrence of spring frosts, but the differences in the frequencies of occurrence of zero yields between the present and $2 \times CO_2$ climates cannot be considered statistically significant.

## 6. Conclusion

The impacts of increased concentration of atmospheric $CO_2$ on grain maize yields were analysed. The analysis was based on the multi-year CERES-Maize crop model simulations run with daily weather series obtained alternatively by a direct modification of observed weather series and a stochastic weather generator. Two effects of increased $CO_2$ were distinguished. The direct effect, which is related to the functioning of $CO_2$ in the ambient air, is manifested by an increased rate of photosynthesis and an improved water use efficiency. The indirect effect is related to weather conditions, which will change due to the increase of greenhouse gases concentration. To show the role of the two $CO_2$ effects, the scenarios linking their different levels (present level, $CO_2$ increased by 50%, $CO_2$ increased by 100%) were employed in this paper. The core experiments were those, in which the $CO_2$ concentration for both direct and indirect effects of increased $CO_2$ was the same. As the model yields are affected by water and nitrogen stresses, which depend on weather conditions in a rather complex manner, and, moreover, may be mitigated by adjustments in the irrigation and fertilisation regime, the yields were simulated in two model settings. The stressed yields were modelled with water and nutrient routines switched on, and the potential yields were modelled with the water and nutrient routines switched off. In the latter settings, the crop is given as much water and nutrients as it needs.

The main results obtained in this study may be summarised in the following points:

(i) The validation tests show a very good fit between the observed and modelled yields of maize. After omitting the two most extreme misfits (probably originating from extreme floods), the accuracy expressed in terms of the standard error is 11%, which is comparable with other studies.

(ii) The magnitude of the indirect effect related to changed weather conditions is negative. The stressed yields decrease by 27–29% in the present concentration of ambient $CO_2$, and by 14–16% in the $2 \times CO_2$ atmosphere. The increased temperature will shorten the phenological phases and will not allow for an optimal development of the crop. The simultaneous decrease of precipitation and increase of temperature and solar radiation sums will further reduce the yields through deepening the water stress. Since the magnitude of the indirect effect is closely related to the site-specific climatic conditions and the climate change scenario employed, the comparison with other studies has only limited information value. Nevertheless, it may be noted that Bacsi and Hunkár (1994) report changes in maize yields from $-14$ to $+7$% using three GCM-based climate change scenarios and the DM approach. Similarly, Iglesias (1995b) used five GCM-based climate change scenarios and five locations in Spain to simulate maize yields under increased $CO_2$. Although the direct effect of increased $CO_2$ was included, the maize yields decreased (by 2 to 27%) for all scenarios and locations. The decreases were attributed mainly to shortened crop growth phases due to the increased temperatures.

(iii) The magnitude of the direct effect of increased $CO_2$ on stressed yields is a result of a superposition of two mechanisms: intensified photosynthesis and better WUE. The stressed yields increase by 36–41% (the two numbers relate to the WG and

DM approaches) due to the direct effect in the present climate and by 61–66% in the $2 \times CO_2$ climate. The values obtained in the $2 \times CO_2$ climate are higher because the water stress is higher and the positive effect on the yields of improved WUE is more pronounced. The obtained values may be compared to results by other authors. For example, Dhakhwa et al. (1997) found in their crop simulation experiments that the direct effects of elevated $CO_2$ concentration varied for different plant components; the yield increased by 18% (CERES-Maize model) and by 14% (EPIC model) in doubled ambient $CO_2$. Wolf and van Diepen (1995) report 0% (at Brindisi in Italy) to 46% (at Orleans, France) increase in maize yields due to the increase of $CO_2$ from 353 to 550 ppm. Brown and Rosenberg (1997) used EPIC to simulate maize yields in three locations under various climate sensitivity scenarios and found the yields to increase by 6–19% as the $CO_2$ increased from 350 to 550 ppm. These numbers, however, relate to stressed yields and are therefore affected by changes in water stress, which may differ for individual sites and climate scenarios used.

(iv) The positive direct effect of doubled $CO_2$ dominates over the negative effect of changed weather conditions. In result, the stressed yields would increase in $2 \times CO_2$ conditions by about 17–18% if both the direct and indirect effects were considered.

(v) The decrease of the mean yields due to the indirect effect of doubled $CO_2$ may be reduced by one third if the maize is planted 1 month sooner (compared to the planting date of the representative year). Application of the earlier planting date would result thus in an additional 4% increase of the yields in $2 \times CO_2$ conditions.

(vi) The impacts of doubled $CO_2$ on potential yields are less pronounced than the impacts on the stressed yields. The lower magnitude of the indirect effect (the yields change by $-4$ to $+5\%$) is related probably to the water stress: The stress increases in the $2 \times CO_2$ climate, thereby reducing the yields simulated under water and nutrient limited conditions, but does not affect the potential yields. The lower magnitude of the direct effect of doubled $CO_2$ (9–10% increase of the yields) is related to a missing additional effect of improved water use efficiency, which increases the stressed yields but does not apply in water and nutrient unlimited conditions. Superposition of both direct and indirect effects of doubled $CO_2$ results in the 5–14% increase of the potential yields. The increase of the potential yields found in the present study contradicts Wolf and van Diepen (1995) who used the WOFOST crop model and report no direct effect of increased $CO_2$ on the potential yields. The disagreement may be explained by the use of different methods to incorporate the direct effect of $CO_2$ in the two crop models.

(vii) The results obtained in the two approaches (DM and WG) are similar. Although the values of the mean yields differ, the percentage changes mostly exhibit the same behaviour. The differences between the results obtained in the two approaches may be attributed to the differences between the input data used: (a) The usage of the representative year in the WG approach may cause a systematic deviation of the mean yields. In addition, it implies that the non-meteorological input parameters do not vary from year to year in contrast with the DM approach and reality. On the other hand, it may be noted that the non-meteorological input data (e.g., planting date and fertilisation regime), which are varied in dependence on the weather regime in reality, need not be optimal if the weather series is modified but other settings of the crop simulation experiment are left unchanged (although different for individual years). (b) The changes in variability of daily extreme temperatures and solar radiation included in the climate change scenario were taken into account in the WG approach but not in the DM approach. This may contribute to some discrepancies regarding the effect of the variability of weather characteristics on crop yields (Dubrovský et al., 2000). (c) The number of values used to calculate a single statistic for a given scenario is limited by the length of the observational series in the DM approach. In the present study, this length is 17 years which is much lower compared to 99 years used in the WG approach. In result, the statistics obtained in the WG approach are loaded by a lower sampling error. In summary, both approaches appear to be valuable tools in assessing climate change impacts on crop yields and have their important advantages. The superiority of the DM approach is the intensive usage of all (both weather and non-weather) observed data. This (a) allows one to better account for the interannual variability of all input parameters, and (b) eliminates the necessity to approximate the statistical structure of the weather series by the model, which cannot reproduce all statistical properties of the weather series. On the other hand, the employment of the generator allows (a) running longer crop simulation experiments, thereby achieving higher accuracy of model summary statistics, and (b) making more detailed sensitivity analyses with respect to changes in a broad spectrum of climate characteristics (Dubrovský et al., 2000). Moreover, since the parameters of the generator may be interpolated in space relatively easily (Guenni, 1994), the impact analysis may be performed even if the sufficiently long observed weather series is not available for the location.

To conclude, it may be stated that the results are in good agreement with the rules governing the growth and development of the crop. Specifically, the increases or decreases of the stressed and potential yields may be logically explained by effects of a changed weather regime and changed ambient $CO_2$ concentration on the duration of growing period, water stress occurrence and photosynthesis rate.

### Acknowledgements

The authors would like to thank R. Huth for helpful suggestions leading to improvement of the paper. The study was sponsored by the Grant Agency of the Czech Republic, contracts 521/97/P089, 205/97/P159 and 205/99/1561.

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