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The impact of climate variability and change on crop yield in Bulgaria

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Abstract

During the recent decade, the problem of climate variability and change, due to natural processes as well as factors of anthropogenetic origin, has come to the forefront of scientific problems. The objective of this study was to investigate climate variability in Bulgaria during the 20th century and to determine the overall impact on agriculture. There was no significant change in the mean annual air temperature. In general, there was a decrease in total precipitation amount during the warm-half of the year, starting at the end of the 1970s. Statistical multiple regression models, describing the relationship between crop yield, precipitation, and air temperature were also developed. Several transient climate change scenarios, using global climate model (GCM) outputs, were created. The Decision Support System for Agrotechnology Transfer (DSSAT) Version 3.5 was used to assess the influence of projected climate change on grain yield of maize and winter wheat in Bulgaria. Under a current level of CO_2 (330 ppm), the GCM scenarios projected a decrease in yield of winter wheat and especially maize, caused by a shorter crop growing season due to higher temperatures and a precipitation deficit. When the direct effects of CO_2 were included in the study, all GCM scenarios resulted in an increase in winter wheat yield. Adaptation measures to mitigate the potential impact of climate change on maize crop production in Bulgaria included possible changes in sowing date and hybrid selection.

Keywords: Climate; Maize; Wheat; DSSAT; Vulnerability; Adaptation

1. Introduction

During the recent decade, the issues of climate variability and climate change have been at the center of many scientific studies (Hulme et al., 1999). Global climate variability and change caused by natural processes as well as anthropogenetic factors, are major and important environmental issues that will affect the world at the beginning of the 21st century. The earth's climate has exhibited marked 'natural' variations and changes, with time scales varying from many millions of years down to a few years. Over periods of 1 or 2 years, fluctuations in global surface temperatures of a few tenths of a degree have been recorded. Some of these are related to the El Niño-Southern Oscillation (ENSO) phenomenon; major volcanic eruptions have also had some impacts. The concentration of greenhouse gases in the atmosphere continues to increase. This is largely due to human activities, mostly fossil fuel use, land use change, and agriculture. In some regions, there is also an increase in the concentration of aerosols, which has an opposite effect on the radia-

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tive balances and tend to cool the atmosphere. About 64% of the warming effect due to greenhouse gas increase during the last 200 years, is caused by carbon dioxide. These changes in concentration of greenhouse gases and aerosols are projected to lead to regional and global changes in temperature, precipitation and other climate variables. This can ultimately result in global changes in soil moisture, an increase in global mean sea level, and prospects for more severe extreme high-temperature events, floods and droughts in many locations (Houghton et al., 1996).

Global climate change will affect all economic sectors to some degree, but the agricultural sector is perhaps the most sensitive and vulnerable. World agriculture, whether in developing or developed countries, remains very dependent on climate resources (Downing, 1996; Watson et al., 1996). The impact of climate variability on agricultural production is important at local, regional, national, as well as global scales (Kaufmann and Snell, 1997; Freckleton et al., 1999; Gadgil et al., 1999). Crop yields are affected by variations in climatic factors such as air temperature and precipitation, and the frequency and severity of extreme events like droughts, floods, hurricanes, windstorms, and hail.

Recent research has focused on assessments of the potential impacts of climate change on agriculture at different scales. For example, regional and global estimates of potential climate change on agricultural production were conducted by Harrison et al. (1995), Wolf and Van Diepen (1995), Easterling et al. (1996), Watson et al. (1996) and Adams et al. (1998). The effects of global climate change and possible adaptation measures have been described by Easterling (1996), Smith (1997), and Adams et al. (1999). Also several national assessments have been conducted by Rosenzweig et al. (1995), Peiris et al. (1996), Elmaayar et al. (1997), Davies et al. (1998), and Lal et al. (1999). Some of the climate change impact studies in eastern Europe were supported through the US Country Studies Program (Smith et al., 1996). Studies on the impact of expected changes in climate on agricultural production in Bulgaria have also been initiated by Alexandrov (1997).

The main goal of this project was to study climate variability during the 20th century and the impact on agriculture, and to determine the potential impact of climate change on agriculture in the 21st century in Bulgaria. Specific objectives included: to create new climate change scenarios for the 21st century in Bulgaria, to simulate the impact of climate variability and change for the major crops, including maize and winter wheat, and to assess possible adaptation measures for Bulgarian agriculture under an expected climate change.

2. Materials and methods

2.1. Geographic location

Bulgaria is located on the Balkan Peninsula in southeastern Europe. The country includes 31% lowlands (0–200 m), 41% hills (200–600 m), 25% highlands (600–1600 m), and 3% mountains (>1600 m). The Balkan Mountains split the country into northern and southern Bulgaria, and they have a strong effect on the temperature regime. The annual mean air temperatures in Bulgaria vary from −3.0 to 14.0°C, depending on the location and elevation. Air temperature normally reaches a minimum in January, and a maximum in July. The monthly mean temperature varies from −10.9 to 3.2°C in January and from 5.0 to 25.0°C in July. Total precipitation depends on the circulation patterns, site elevation, and the specificity of local orographic features. Annual mean total precipitation is approximately 500–650 mm, with an annual variation ranging from 440 to 1020 mm. The highest monthly values are measured in June, and at some places in May, with the mean total varying between 55 and 85 mm. February, and sometimes March and September, are the driest months, with mean totals varying between 30 and 45 mm. Mean precipitation during the warm months, e.g. April through September, is 333 mm, with a standard deviation of 72 mm. Mean precipitation varies from a maximum of 573 mm in the Balkan Mountains to a minimum of 211 mm in southeastern Bulgaria.

2.2. Experimental data

Daily data for mean air temperature and precipitation from 16 weather stations were gathered for the period 1901–1997. Monthly mean air temperature and precipitation from 114 stations across the country with elevations below 800 m were also obtained for

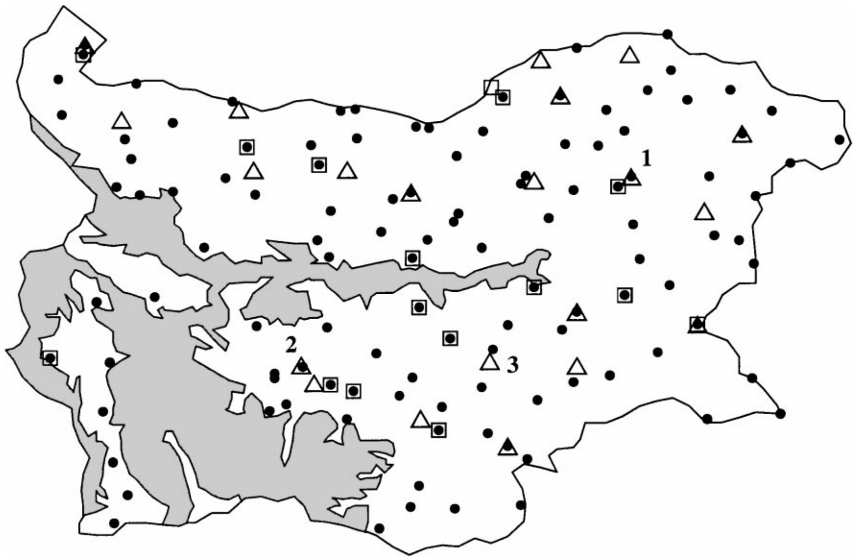

Fig. 1. Spatial distribution of weather and experimental stations in Bulgaria, used in the study: (●) weather stations with available data during 1961–1990; (□) weather stations with available data during 1901–1997; (△) experimental stations (1 — Carev brod, 2 — Ognjanovo, 3 — Radnevo).

the period 1961–1990 (Fig. 1). Weather data had been previously evaluated for erroneous and missing values. All observed meteorological data that were used in this study were provided by the weather network of the Bulgarian National Institute of Meteorology and Hydrology.

The Data Distribution Center (DDC) of the Intergovernmental Panel on Climate Change (IPCC) provided the 30-year averaged transient GCM monthly meteorological outputs for the periods: 1961–1990, 2010–2039, 2040–2069, and 2070–2099 (the latter three periods are referred to as 2020s, 2050s, and 2080s) of the next century. The GCMs used in this study, include the models from the Max-Planck Institute for Meteorology (ECHAM4), UK Hadley Center for Climate Prediction and Research (HadCM2), Canadian Center for Climate Modeling and Analysis (CGCM1), Australian Commonwealth Scientific and Industrial Research Organization (CSIRO-Mk2b), and Geophysical Fluid Dynamics Laboratory (GFDL-R15) (IPCC DDC, 1999). The simulated results from the 'business as usual' scenario (IS92a), greenhouse gas and sulfate aerosol forced GCM experiments were used. The outputs for air temperature, precipitation, and solar radiation of the GFDL-R15 model for the 2080s, were not available.

In general, the GCMs do not simulate the present climate perfectly. It is normally assumed that the model changes predicted from the present to the future climate are more reliable than the present or the future climate predicted alone (Carter et al., 1994). Regional scenarios can be created by combining average monthly output, obtained by taking the difference between transient GCM runs with observed climate data from the 30-year baseline climate period — adding the change in temperature to the observed temperatures, and multiplying ratio changes in precipitation and solar radiation by their observed daily values during the period 1961–1990 (ANL, 1994).

We used GCM data from the four nearest grid points to interpolate observed data, simulated climatic data, or transient data for the 2020s, 2050s, and 2080s to a specific point, e.g. weather station. The actual value was calculated using linear average or inverse distance techniques between the specific point and the GCM grid points (ANL, 1994). Without interpolation, sudden changes in climate can occur at the boundaries of the GCM grid boxes.

2.3. Method of investigation

The generic grain cereal model CERES v.3.5 (Ritchie et al., 1998), included in the computerized Decision Support System for Agrotechnology Transfer DSSAT v.3.5 (Tsuji et al., 1994) was used to determine the vulnerability of current agricultural management scenarios in Bulgaria. The DSSAT crop models are designed to use a minimum set of soil, weather, genetic, and management information. The models integrate at daily time steps, and therefore, require daily weather data, consisting of maximum and minimum temperature, solar radiation and precipitation, as input. The models calculate crop phase and morphological development as a function of temperature, day length, and genetic characteristics. Leaf development, growth, and expansion determine the amount of light intercepted, which is assumed to be proportional to biomass production. The biomass is partitioned to various growing organs in the plant, using a priority system. Water and nitrogen submodels provide feedback that influences the development and growth processes. All crop models are sensitive to carbon dioxide concentrations (Tsuji et al., 1998). The DSSAT seasonal analysis program (Thornton and Hoogenboom, 1994) was used to simulate possible adaptation measures, and to determine those management scenarios that can decrease the potential agricultural crop vulnerability under expected climate change conditions.

The CERES v.3.5 models of maize and wheat were previously calibrated and verified at 21 experimental variety stations across the country during the period 1980–1993 (Alexandrov and Hoogenboom, 1999). In this study, we used the Bulgarian maize hybrid ‘Knezha 611’ and winter wheat bread variety ‘Sadovo 1’. The phenological and yield data were obtained from the Bulgarian National Variety Commission of the Ministry of Agriculture. Daily weather data, including precipitation, maximum and minimum temperature, and simulated solar radiation (Slavov and Georgiev, 1985), were obtained for the same period for the nearest weather station. Simulated phenological stages and grain yields of maize and winter wheat were generally very similar to the measured data (Fig. 2).

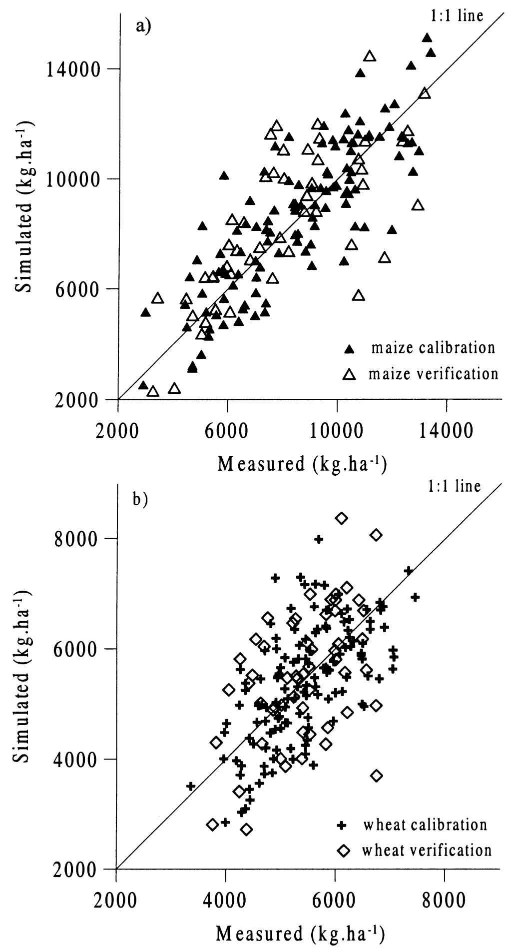

Fig. 2. Comparison between simulated and measured grain yield of maize (a) and winter wheat (b).

The modified temperature, precipitation, and solar radiation databases, corresponding to each of the climate change scenarios, were used to run the CERES v.3.5 simulation models for maize and winter wheat. Crop management and land use were assumed to be constant. The automatic irrigation option of the crop maize model was selected for irrigation applications. Planting dates were selected based on the latitude and information provided by Hershkovich and Stefanov (1982). At planting, 50 kg ha^{-1} of nitrogen fertilizer was applied for maize and winter wheat. Simulations were run with and without the direct effects of increased atmospheric CO_2 levels. In these cases, the CO_2 atmospheric concentrations were assumed to be 330 ppm for the current climate (1961–1990), 447 ppm for the 2020s, 554 ppm for the 2050s, and 697 ppm for the 2080s (Houghton et al., 1996; IPCC DDC, 1999).

3. Results and discussion

3.1. Climate variability and its effect on maize and winter wheat yield

3.1.1. Climate variability

In the initial analysis, long-term variations of air temperature in Bulgaria were investigated. In Fig. 3, anomalies of mean annual air temperature in Bulgaria, relative to the current climatic conditions are presented. Generally, there did not seem to be a significant change in mean annual air temperature in Bulgaria during the 20th century.

The period from the 1920s to 1950s was characterized as a warmer period during the warm-half of the year, i.e. April–September. There has been an obvious increase in air temperature during April–September since the end of the 1970s, despite lower air temperatures in 1991 and 1997. A slight increase in air temperature during the cold-half of the year, i.e. October–March was observed. This trend is most obvious during the winter, i.e. January–March, due to a significant warming in January and February. Spring, i.e. April–June, also tends to be warmer at the end of the 20th century. However, summer air temperatures, i.e. July–August, tended to be a little bit lower. The average air temperature for June showed a slight increase, while air temperatures in July and August showed an overall decrease, mainly due to a significant cool spell during the 1970s. Air temperature in autumn, i.e. October–December, varied around the current climatic values without any definite changes.

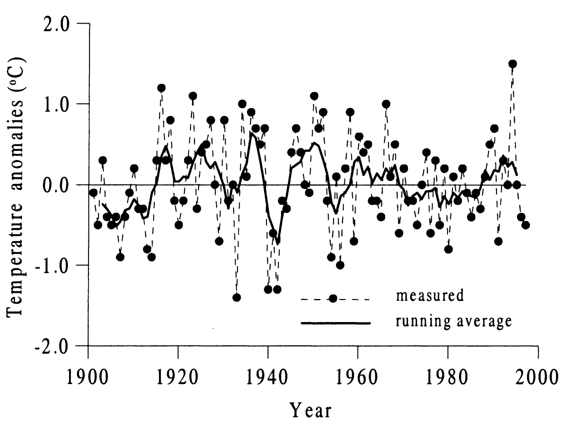

Fig. 3. Anomalies of annual mean air temperature in Bulgaria, relative to the period 1961–1990.

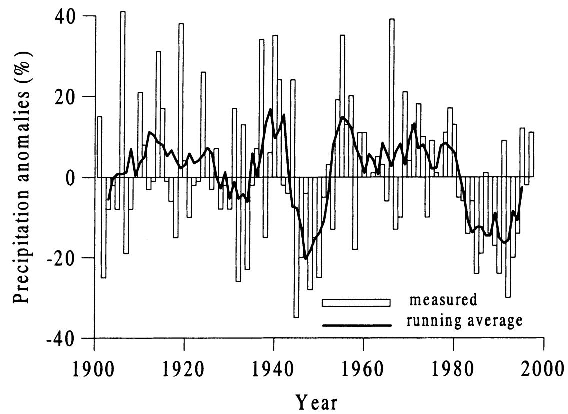

Fig. 4. Anomalies of annual precipitation in Bulgaria, relative to the period 1961–1990.

Annual precipitation in Bulgaria varied considerably from year to year during the study period. In some years, very low annual precipitation ushered in droughts of different intensities. Bulgaria experienced several drought episodes during the 20th century, most notably in the 1940s and 1980s (Fig. 4), which were observed everywhere across the country. Generally, mean annual precipitation in Bulgaria showed an overall decrease for the period from 1901 to present.

There was a decrease in precipitation for the period from April to September, starting at the end of 1970s. Precipitation has been below normal or the 1961–1990 average for the 13 of the last 17 years in this study. The years 1985, 1988, and 1993 were among the driest warm-half years. There was no significant overall trend in precipitation during the cold-half of the year, despite the decreasing trend that has been observed since the end of 1960s. A deficit in winter precipitation was observed during the last decade. Both spring and summer, as well as autumn precipitation have shown a tendency to decrease during the 20th century. However, February, April, August, and December have shown an increasing trend in precipitation, while all other months have had precipitation reductions during the study period.

As part of the climate variability study, long-term variations of agroclimatic indexes were also determined. We used the starting and ending, as well as the duration periods that have a temperature above a base of 5 and 10°C; and accumulated temperatures during these periods as agroclimatic indexes. The beginning of the periods above 5 and 10°C usually occurred in March and April, while the end of these periods can be observed in November and October, respectively. Potential crop growing seasons above the two thresholds started earlier in the 1910s, and 1920s, 1940s, and during the last decade, except for 1996 and 1997. The beginning of these periods occurred later in the 1900s, 1950s, and 1970s. As a result of these variations, a slight delay of the beginning for the growing conditions above a base of 5°C was found. The variations for the end of the period above bases of 5 and 10°C occurred 2–3 days earlier. Overall, this caused a decrease in the duration of potential crop growing season above 5 or 10°C (Fig. 5a). From the middle of the 1920s until the end of 1970s, there is significant decrease in total accumulated degree days for growing season above either 5 or 10°C. Since the early 1980s, an increase in total accumulated degree days has been observed (Fig. 5b).

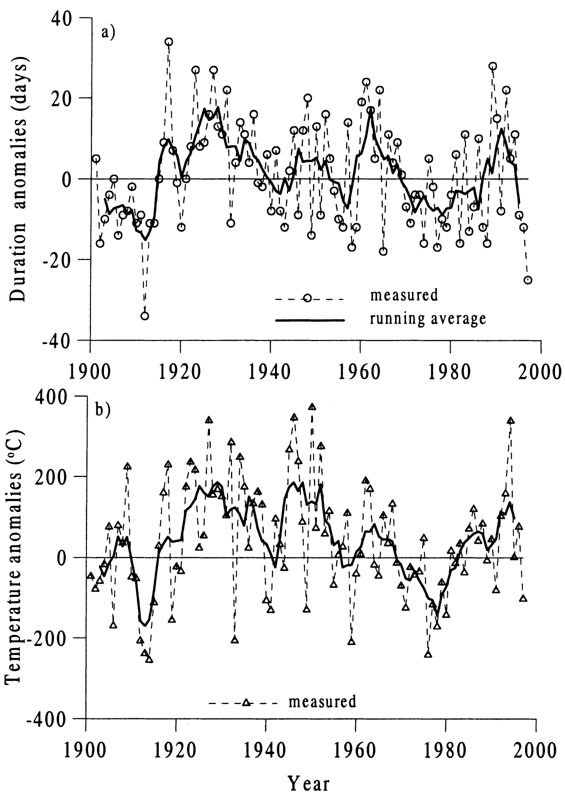

Fig. 5. Anomalies of duration of the period (a) and accumulated air temperatures (b) above a base of 10°C, relative to the period 1961–1990.

3.1.2. Crop-weather relations

Soil and climatic conditions in Bulgaria are suitable for cultivation of maize. However, sometimes a precipitation deficit and high air temperature occur during the critical period of maize development. Both factors are the ones that most limit growth, development, and final yield of maize in Bulgaria. In Fig. 6a and b, the long-term fluctuations for the period 1970–1993 and trends of mean air temperature and precipitation from April to September across the Bulgarian territory for elevations below 800 m are presented. During the period 1970–1993, the trends of these meteorological variables are opposite. The variation in air temperature, and especially in precipitation, affected the national levels of maize production.

Statistical models were developed for regional assessment of maize and winter wheat productivity in Bulgaria. For the northern part of the country (NB), the following equations were obtained:

$$Y_{\mathrm{mz}}^{\mathrm{NB}} = 18.4R_{\mathrm{MAR}}^{\mathrm{NB}} + 20.8(R_{\mathrm{JUL}}^{\mathrm{NB}} + R_{\mathrm{AUG}}^{\mathrm{NB}}) + 5908.8, \quad r = 0.77 \tag{1}$$

$$Y_{\mathrm{wh}}^{\mathrm{NB}} = -639.4\bar{T}_{\mathrm{MAY}}^{\mathrm{NB}} - 17.9R_{\mathrm{MAY}}^{\mathrm{NB}} + 17503.2, \quad r = 0.78 \tag{2}$$

where $Y_{\mathrm{mz}}^{\mathrm{NB}}$, $Y_{\mathrm{wh}}^{\mathrm{NB}}$ are the average maize and winter wheat grain yield in north Bulgaria (kg ha^{-1}), $R_{\mathrm{MAR}}^{\mathrm{NB}}$, $R_{\mathrm{MAY}}^{\mathrm{NB}}$, $R_{\mathrm{JUL}}^{\mathrm{NB}}$, $R_{\mathrm{AUG}}^{\mathrm{NB}}$ the average precipitation in north Bulgaria in March, May, July and August, respectively (mm); $\bar{T}_{\mathrm{MAY}}^{\mathrm{NB}}$ the mean air temperature in north Bulgaria in May (°C) and r is the correlation coefficient.

A comparison between measured and calculated maize and wheat yields, based on Eqs. (1) and (2), is presented in Fig. 7. Calculated grain yield of maize was in accordance with the measured data for the calibration data (1970–1990) as well as the evaluation data (1991–1993). Differences near 20% between calculated and measured maize grain yield were observed for only 1974 and 1985, when a significant drought occurred. The deviations between measured and

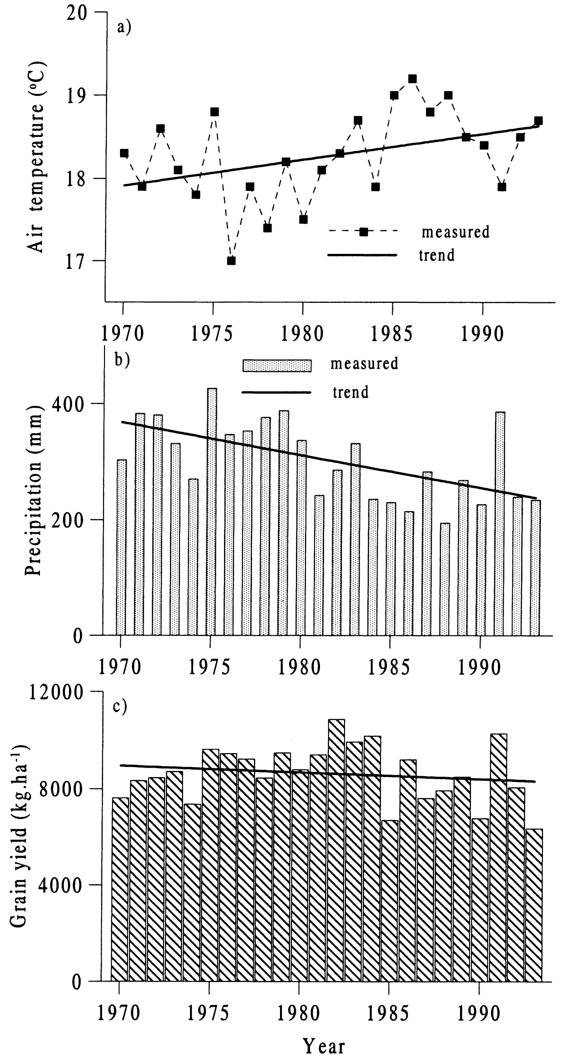

Fig. 6. Long-term fluctuations of mean air temperature (a) and precipitation (b) during the warm-half of the year (April–September) and average grain yield of maize (c) at the experimental stations.

calculated grain wheat yield during the study period did not exceed 11%, except for 1974.

3.2. Climate change scenarios

The current (1961–1990) climatic outputs from the GCMs should first be compared with averaged observed climatic data for a region, not with site-specific climate data. To expect that a large GCM grid box can represent climate for any particular point is unreasonable (ANL, 1994). Therefore, averages of observed and simulated monthly air temperature and precipitation normals from 114 locations were used.

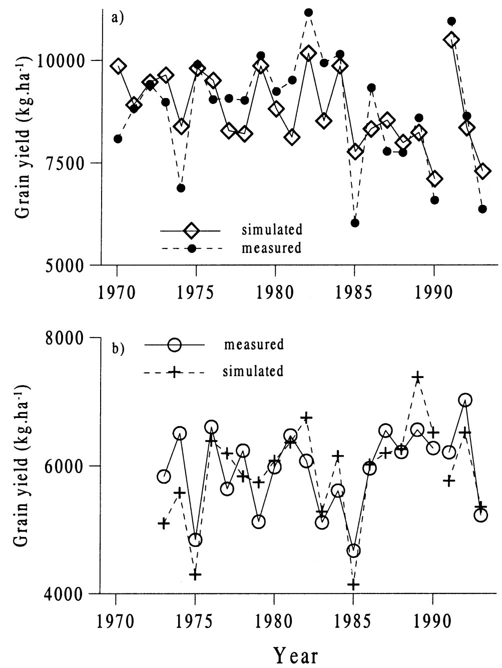

Fig. 7. Comparison between simulated and measured mean grain yield of maize (a) and winter wheat (b) at the experimental crop stations in north Bulgaria during the periods 1970–1990 for calibration and 1991–1993 for verification.

Based on the comparisons shown in Table 1, the HadCM2 model was considered to be the most appropriate transient GCM to simulate monthly air temperature in Bulgaria. The difference between simulated and observed monthly air temperature exceeded 2°C for only 3 months, i.e. April, May, and June. The GFDL-R15 model also simulated monthly air temperature well during the period from September to February (Table 1).

Most transient GCMs used in the study, except the CGCM1 model, overestimated average precipitation for Bulgaria during the cold-half of the year. However, precipitation during the summer months, e.g. July–September, was underestimated by most GCMs, especially by the CGCM1 and GFDL-R15 models. The CSIRO-Mk2b model simulated the observed precipitation well from April to September, as well as in November, with deviations ≤15%. The other GCMs

Table 1
Deviations of global climate model (GCM) monthly outputs for the period of current climate, air temperature T (°C) and precipitation P (%), relative to the observed (1961–1990) climate in Bulgaria

GCM	Element	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
ECHAM4	T	5.3	3.4	1.2	−0.9	−1.8	−1.3	−0.4	0.5	1.3	2.5	3.4	4.6
	P	88	56	89	12	−27	−40	−32	−55	−4	79	67	89
HadCM2	T	1.6	0.6	−0.7	−2.8	−3.1	−2.3	−0.3	0.5	−1.0	−0.6	0.0	0.6
	P	59	55	72	29	32	11	−25	−22	−2	18	52	34
CGCM1	T	5.1	3.7	1.7	−0.1	0	1.8	4.2	4.9	2.9	1.9	1.3	3.6
	P	19	3	21	−10	−32	−54	−70	−83	−65	−16	−25	5
CSIRO-Mk2b	T	3.4	2.3	1.2	−1.0	−1.3	−0.9	−0.4	0.3	0.2	0.8	1.6	2.5
	P	58	51	47	10	−8	−15	−4	−5	5	46	4	50
GFDL-R15	T	−0.4	−1.2	−3.1	−4.6	−4.7	−2.3	0.1	2.7	0.8	−0.8	−1.2	−1.6
	P	51	56	89	78	25	−42	−67	−78	−33	72	79	57

either considerably overestimated or underestimated precipitation for most months.

The transient GCMs predicted that annual temperatures in Bulgaria are to rise between 0.7 (HadCM2) and 1.8°C (GFDL-R15) in the 2020s. However, the HadCM2 model simulated a slight decrease in air temperature for November in the 2020s. A warmer climate is also predicted for the 2050s and 2080s, with an annual temperature increase ranging from 1.6 (HadCM2) to 3.1°C (GFDL-R15) in the 2050s, and 2.9 (HadCM2 and CGCM1 models) to 4.1°C (ECHAM4) in the 2080s. Warming is projected to be higher during the summer in the 2080s.

The CGCM1 model predicted an increase in annual precipitation in the 2020s and 2050s. The GFDL-R15 model projected a decrease in precipitation in May, June and July in the 2020s and 2050s. The ECHAM4, HadCM2, and CSIRO-Mk2b models simulated a decrease in monthly, seasonal and annual precipitation in the 2080s. The changes in monthly solar radiation are expected to vary between −10 and 10% during the next century. An increase of solar radiation is expected during the cold-half of the year, based on the ECHAM4 model runs.

3.3. *Vulnerability assessments of maize and winter wheat*

All transient GCM climate change scenarios used in the CERES simulation model projected a shorter vegetative and reproductive growing season for maize and winter wheat during the 21st century. These changes were caused by the predicted temperature increase of the GCM scenarios. The duration of the regular crop-growing season for maize was between 5 (HadCM2) and 20 (GFDL-R15) days shorter in the 2020 s. Maturity dates for maize were expected to occur between 11 and 30 days earlier in the 2050s. The predicted changes in the crop-growing duration for maize in the 2050s were less for the HadCM2, CGCM1, and CSIRO-Mk2b climate change scenarios than the changes predicted by the ECHAM4 and GFDL-R15 models. These last two models simulated a higher increase of air temperature in Bulgaria, especially the GFDL-R15 model, during the summer months July and August. The GCM climate change scenarios for the 2080s projected a decrease in maize growing season by 17 (CSIRO-MK2b) to 39 (ECHAM4 and CGCM1) days. This will cause a shift in harvest maturity dates for maize from September to August at the end of the next century.

Winter wheat showed a decrease in growing season duration for the 2020s, varying between 3 (HadCM2) and 14 days (GFDL-R15). The projected decreases in growing season for the 2020s, 2050s, and 2080s were less for the HadCM2 model, which predicted a smaller air temperature increase during November and December. Even a slight decrease in monthly air temperature in November was projected for the 2020s under the HadCM2 climate change scenario. The transient GCM climate change scenarios predicted that harvest maturity for winter wheat would be approximately 1–2 weeks earlier in the 2050s, and between 2–3 weeks earlier in the 2080s.

The decrease in simulated maize yield for the next century was primarily caused by a shorter growing season duration and reductions in precipitation. All GCMs simulated a decrease in precipitation from March to June for the 2080s, which affected soil moisture recharge during the spring and the early developmental stages of maize. The simulated increase in maize grain yield for the HadCM2 climate change scenario for the 2020s was due to a relatively low projected increase in air temperature, as well as a predicted increase in precipitation in July. Because maize is a C_4 crop, an increased level of CO_2 alone had no significant impact on either maize crop growth, and development or final yield (Tables 2–4). Maize yield decreased by 3–8% in the 2020s for the ECHAM4, CGCM1, and CSIRO-Mk2b model scenarios. The projected decrease was highest for the GFDL-R15 model, e.g. between 8 and 14%, while the HadCM2 scenario projected an increase from 4 to 12% for the next decades. A slight increase at the most experimental stations in northeast and south Bulgaria is even projected under the HadCM2 climate change scenario for the 2050s (Table 3). The decrease in simulated maize yield for the 2050s ranged for most stations from 10 to 20% for the ECHAM4, CGCM1, CSIRO-Mk2b, and GFDL-R15 GCM scenarios. The largest decrease in maize yield is expected to occur at the end of the century.

All transient GCM climate change scenarios for the 21st century, including the adjustment for only air temperature, precipitation and solar radiation, projected a reduction in winter wheat yield across Bulgaria. Projected yield reductions at the experimental station Radnevo (south Bulgaria) varied between 0 and 7% during the 2020s and 2050s, and between 4 and 20% in the 2080s. When the direct effect of higher CO_2 levels was assumed, all GCM climate change scenarios projected an increase in winter wheat yield (Tables 2–4). The major cause for this change in impact is that many crops, such as wheat and soybean, belong to the group

Table 2
Departures of grain yield (%) for maize and winter wheat under transient global climate model scenarios for the 2020s (CO_2=447 ppm), relative to the current climate

Station	Region	ECHAM4		HadCM2		CGCM1		CSIRO-Mk2b		GFDL-R15	
		Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
Kapitanovci	NW	−7	16	4	10	−5	18	−8	17	−13	16
Medkovec	NW	−7	18	4	14	−7	22	−7	19	−11	16
Selanovci	NW	−6	18	9	16	−6	30	−6	24	−11	18
Kojnare	N	−5	15	12	9	−8	18	−8	16	−12	14
Pordim	N	−3	15	10	9	−3	20	−4	16	−8	15
Pavlikeni	N	−3	15	10	15	−4	27	−4	22	−8	14
Svetlen	N	−5	15	12	9	−8	18	−8	16	−12	14
Brashljan	N	−8	10	5	12	−6	18	−8	17	−14	8
Kubrat	N	−6	16	10	9	−6	20	−6	15	−11	15
Sitovo	NE	−5	12	5	10	−6	16	−6	13	−12	8
Carev brod	NE	−5	16	12	10	−8	20	−8	17	−12	17
Dobrich	NE	−5	12	5	10	−6	16	−6	13	−12	8
Jitnica	NE	−4	20	11	14	−6	25	−6	21	−12	21
Burgas	SE	−4	14	11	8	−6	12	−7	12	−11	13
Zimnica	S	−5	13	11	9	−7	13	−6	13	−13	15
Bojanovo	S	−6	14	12	8	−7	15	−7	14	−12	14
Radnevo	S	−6	14	11	8	−7	14	−7	12	−12	12
Ljubimec	S	−8	13	6	12	−7	17	−8	15	−14	10
Gorski izvor	S	−5	14	12	8	−6	14	−7	12	−11	12
Benkovski	S	−7	12	5	12	−6	17	−8	16	−14	9
Ognjanovo	S	−7	12	5	12	−6	17	−8	16	−14	9

Table 3
Departures of grain yield (%) for maize and winter wheat under transient global climate model scenarios for the 2050s (CO_2=554 ppm), relative to the current climate

Station	Region	ECHAM4		HadCM2		CGCM1		CSIRO-Mk2b		GFDL-R15	
		Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
Kapitanovci	NW	−15	28	−7	30	−9	25	−10	26	−21	24
Medkovec	NW	−14	27	−8	32	−10	29	−9	27	−19	24
Selanovci	NW	−12	42	−6	43	−11	45	−9	40	−16	36
Kojnare	N	−12	27	1	30	−11	31	−10	29	−19	29
Pordim	N	−10	28	−4	32	−7	31	−6	29	−15	29
Pavlikeni	N	−11	35	−1	40	−7	41	−7	37	−17	30
Svetlen	N	−12	27	1	30	−11	31	−10	29	−19	29
Brashljan	N	−15	26	−6	29	−11	24	−12	23	−21	17
Kubrat	N	−11	29	−4	32	−10	31	−9	30	−17	31
Sitovo	NE	−10	23	1	29	−10	23	−9	23	−18	18
Carev brod	NE	−12	29	2	32	−11	32	−10	31	−19	32
Dobrich	NE	−10	23	1	29	−10	23	−9	23	−18	18
Jitnica	NE	−11	34	5	38	−10	40	−9	37	−18	37
Burgas	SE	−8	22	6	22	−10	23	−9	22	−18	22
Zimnica	S	−10	28	4	27	−11	29	−10	28	−19	29
Bojanovo	S	−9	25	5	25	−11	26	−10	25	−18	26
Radnevo	S	−12	24	0	25	−11	25	−11	24	−19	25
Ljubimec	S	−13	20	−7	27	−11	23	−11	20	−21	14
Gorski izvor	S	−11	24	1	25	−10	25	−10	24	−19	25
Benkovski	S	−12	20	−6	28	−11	23	−11	19	−20	14
Ognjanovo	S	−12	20	−6	28	−11	23	−11	19	−20	14

of C_3 crops, which are more sensitive to changes in CO_2 concentration than the group of C_4 crop, such as maize. The CO_2 effect alone caused an increase in wheat yield 10–20% above the baseline (1961–1990) for the 2020s. The simulated deviations of wheat yield increased in the 2050 by more than 20–25% for the ECHAM4, HadCM2, CGCM1, and CSIRO-Mk2b climate change scenarios. The increase in wheat yield varied from 14 to 37% for the GFDL-R15 scenario, depending on the location. Despite expected high air temperatures and precipitation reductions during the spring in the 2080s, projected increases in wheat yield varied between 12 and 49% due to the fertilization impact of the increased CO_2 level.

3.4. Adaptation options

The sowing dates of spring crops in Bulgaria could shift under the GCM climate change scenarios in order to reduce the yield loss caused by an increase in temperature. The selection of an earlier sowing date for maize will probably be the appropriate response to offset the negative effect of a potential increase in temperature (Fig. 8). This change in planting date will allow for the crop to develop during a period of the year with lower temperatures, thereby decreasing developmental rates and increasing the growth duration, especially the grain filling period. The results depicted in Fig. 8 show that the sowing date of maize for the experimental station Carev brod (northeast Bulgaria) should occur at least 2 weeks earlier in the 2080s under the ECHAM4 scenario, relative to the current climate conditions. It should be noted, however, that although changes in sowing date are a no-cost decision that can be taken at the farm-level, a large shift in sowing dates probably would interfere with the agrotechnological management of other crops, grown during the remainder of the year.

Another option for adaptation is to use different hybrids and cultivars. There is an opportunity for cultivation of more productive, later or earlier-maturing, disease- and pest-tolerant hybrids and cultivars. Switching from maize hybrids with a long to a short or very short growing season projected an additional

Table 4
Departures of grain yield (%) for maize and winter wheat under transient global climate model scenarios for the 2080s (CO_2=697 ppm), relative to the current climate

Station	Region	ECHAM4		HadCM2		CGCM1		CSIRO-Mk2b		GFDL-R15	
		Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
Kapitanovci	NW	−19	24	−24	24	−22	27	−13	31	NA	NA
Medkovec	NW	−17	27	−28	29	−20	28	−10	34	NA	NA
Selanovci	NW	−14	39	−27	41	−18	48	−9	57	NA	NA
Kojnare	N	−19	40	−14	24	−22	40	−12	41	NA	NA
Pordim	N	−12	36	−22	27	−18	40	−7	42	NA	NA
Pavlikeni	N	−15	30	−20	39	−18	38	−8	49	NA	NA
Svetlen	N	−19	40	−14	24	−22	40	−12	41	NA	NA
Brashljan	N	−19	17	−21	29	−21	20	−14	30	NA	NA
Kubrat	N	−14	44	−23	25	−18	44	−10	46	NA	NA
Sitovo	NE	−16	23	−10	32	−18	28	−11	36	NA	NA
Carev brod	NE	−18	42	−14	24	−22	42	−12	43	NA	NA
Dobrich	NE	−16	23	−10	32	−18	28	−11	36	NA	NA
Jitnica	NE	−16	47	−12	33	−20	46	−12	49	NA	NA
Burgas	SE	−10	31	−9	16	−14	28	−10	30	NA	NA
Zimnica	S	−19	40	−14	24	−22	40	−12	41	NA	NA
Bojanovo	S	−10	35	−11	19	−15	32	−11	34	NA	NA
Radnevo	S	−13	33	−20	18	−19	32	−13	34	NA	NA
Ljubimec	S	−18	11	−21	23	−21	14	−13	21	NA	NA
Gorski izvor	S	−15	33	−15	18	−20	32	−13	34	NA	NA
Benkovski	S	−19	12	−20	23	−20	14	−14	20	NA	NA
Ognjanovo	S	−19	12	−20	23	−20	14	−14	20	NA	NA

decrease of final yield under a potential warming in Bulgaria. However, using hybrids with a medium growing season, would be beneficial for maize productivity (Fig. 9). Technological innovations, including the development of new crop hybrids and cultivars that may be bred to better match the changing climate, are considered as a promising adaptation strategy. However, the cost of these innovations is still unclear.

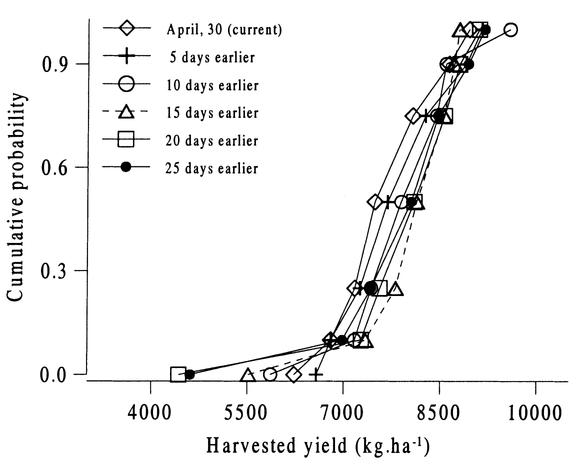

Fig. 8. Cumulative probability function of maize yield at Carev brod under the ECHAM4 climate change scenarios for the 2080s and different sowing dates (CO_2=697 ppm).

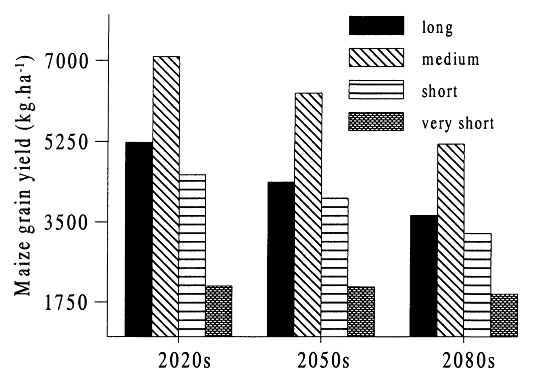

Fig. 9. Simulated maize yield in Ognjanovo under the HadCM2 transient climate change scenarios for the 2020s, 2050s, and 2080s and hybrids with different growing duration.

4. Limitations

Using the observed, e.g. 1961–1990 climate data for creating climate change scenarios, provides spatial and temporal variability. However, it assumes that there is no change in climate variability in the future, compared to current conditions. The created GCM climate change scenarios do not include changes in climate variability, which might represent a very important factor for crop production. An additional limitation of using GCMs is that, although they accurately represent global climate, their estimates of current regional climate are often inaccurate. In many regions, GCMs significantly underestimate or overestimate current temperatures and precipitation (Grotch and MacCracken, 1991). Also, the spatial scale of most GCMs is too large. A single GCM, or even several GCMs, may not represent the range of potential climate change in a region. In this study, it was considered that the selected GCMs that gave a better estimate of current (observed) climate conditions, would also give better estimates of changed climate conditions. There is no guarantee, however, that this assumption is correct.

The crop model CERES v.3.5 embodies a number of simplifications. For example, the impacts of weeds, diseases, and insect pests on crop growth, development, and final yield formation were assumed to be controlled. There was also no problem with soil conditions, e.g. salinity or acidity, and there were no extreme weather events, such as hurricanes, heavy rains, hailstorms, and dry winds, or changes in the frequency of drought occurrence. Technology and land use were assumed to be constant under the vulnerability assessments, even though it is certain that they will change in the future. Thus, the impact of climatic change on yield in farmers' fields may be different from those simulated by the crop models.

5. Concluding remarks

In this study, we did not find a significant change in the mean annual air temperature in Bulgaria during the 20th century. This is in contrast to the global mean near-surface air temperature, which has increased. Bulgaria has experienced several drought episodes during the 20th century, most notably in the 1940s and 1980s. The mean annual precipitation of Bulgaria has decreased during the 20th century. From the end of the 1970s, we also found a decrease in precipitation during the summer months from April to September.

A potential change in climate will impact agricultural production, either positively or negatively. Under the current level of CO_2, the transient GCM scenarios projected a decrease in both winter wheat and especially maize yield for the 2020s, 2050s, and 2080s. These yield reductions were mainly caused by a shortened vernalization period for winter wheat, and a shorter crop growing season duration for both crops. The simulated increase in maize grain yield for the HadCM2 climate change scenario for the 2020s was due to the relatively low projected increase in air temperature, and a predicted increase in precipitation in July. When the direct effect of CO_2 was included, all GCM scenarios resulted in an increase in winter wheat yield. As maize is a C_4 crop, an increased level of CO_2 alone had no significant impact on growth and final yield.

Results from the adaptation assessments suggest that possible changes in sowing date and hybrid selection can reduce the negative impact of potential warming on maize yield during the next century. Changes in cropping mixtures, irrigation, and agricultural land use can be additional alternative options for adaptation in agriculture. Some economic adaptation measures, such as substitution possibilities for other crops, availability, and costs of alternative production techniques, are recommended for evaluation in the future.

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