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Drought Impact on Variability Crop Yields in Central Bohemia

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This paper presents the results of a study on the estimation of drought impact on fluctuation yield cereal crops in Central Bohemia. Historical climate and crop yields data for the period of 47 years (1961–2007) have been integrated into an agrometeorological database. The objective of this paper was to determine the drought impact on yield of winter and spring cereals crops on an example for the Central Bohemian region. According to crops variability models the most of low yielding years (from 3 to 5 cases) were noticed at the beginning of the 1960s and 1970s, reaching their highest points in the decade of 1991–2000 (from 3 and 8 cases). In the case of the most serious crop failures in grain production in the Central Bohemian region (1964, 1976, 2000, 2003), droughts were responsible. In agreement with the developed model, the drought impact was associated with cereals detrended yield being smaller than $y_i^{(T)} \leq -0.5\sigma$. A year has the following types of drought impact: yield detrended of $-0.5\sigma \geq y_i^{(T)} > -\sigma$ is a low drought effect; $-\sigma \geq y_i^{(T)} > -1.5\sigma$ is a middle drought effect and $y_i^{(T)} \leq -1.5\sigma$ means a high drought effect.

Keywords: drought, variability, yield, cereal crop models, impact

Introduction

In the present global situation, agriculture plays a major role in the interaction between socio-economic and climate processes and/or extreme weather events. In the 50s the introduction of inorganic fertilizers was the major topic, in the 60s the use of synthetic compounds for plant protection, in the 70s industrial crops, in the 80s organic farming and the environmental impact of agronomic practices, and in the 90s genetically modified crops. According to the European Society for Agronomy (Bologna 2008), currently, the themes are: land and water degradation, production of agricultural biomass for bio-energy and monitoring and evaluation of the effects of climate extremes (frost, showers and droughts) on the crop production. The agricultural production of many countries of the Europe suffers from droughts. Drought is a natural phenomenon that can occur in any region and cause economic, social, and environmental losses. Increasing frequencies and magnitudes

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of drought events are the focus of current research on both the local and global scales. This tendency has been recorded in the 20th century, particularly in the last decade of 1990–2000, which was the warmest decade of the last century. The recent wave of drought episodes was experienced not only in Southern Europe but also throughout Central Europe during 2000, 2003, 2006 and 2007 (Ciais et al. 2005; Potop and Turkott 2007; Potop and Koznarova 2008c). Over the past decade, significant progress has been made in drought studies worldwide. While the drought events have been studied extensively, there is limited discussion of the effects of drought on the variation in individual crop's yields. Yields of crops in the long term are a result of the interaction of a farmer's skill and technical equipment with rather conservative environmental conditions of sites (altitude, soil and climate). The actual yield and quality are affected by the occurrence of biotic and abiotic stresses within a year governed by the course of the weather. The scales at which the studied factors affect yields differ greatly, range from a plot to a continental scale. Besides the yields, a year-to-year yield variability is also a vitally important attribute as it has a negative effect on the farm's budget (Claassen and Shaw 1970; Craufurd and Oeacock 1993; Calderini and Slafer 1998; Dubrovsky et al. 2000; Chloupek et al. 2004; Konstantinov and Potop 2005).

Methods and Materials

The agrometeorological database of this paper has integrated historical climate and historical yield data. Meteorological data were used in order to study the physical processes of droughts, however, it is desirable to use drought indices based on meteorological conditions. The assessment has been based on 47 years (1961–2007) of meteorological information from 7 weather stations recorded at the Czech Hydrometeorological Institute (CHMI). Thus, most agricultural areas in Central Bohemia are situated in the altitude 168–486 m. The agrodatabases contain yearly region-level logs of winter and spring cultures of cereal yields as reported by the Czech Statistical Office. The regions are displayed in Figure 1. The original yields dataset available for 46 years (1961–2006) is included: spring wheat, winter wheat, spring barley, winter barley, winter rye, oats and maize.

The indicator of agricultural drought risk may be represented by the residuals of the detrended yield. In this study, the fluctuations in crop yields over time were calculated on the basis of two components. The first one is determined by the agricultural technology level and/or the climatic conditions and the second one is based on the agro-meteorological conditions during the growing season from one year to the next:

$$Cm = y_i^{(\tau)} + y_i^{(T)} \tag{1}$$

where $y_i^{(\tau)}$ – yield is presented by a dynamically mean value (influenced by long-term factors such as cultivation technique and standard management), $y_i^{(T)}$ – anomaly of yield was represented by the residuals of the detrended yield, because the residual variation reflects the best effects of the weather on the yield (FAO 2006). Thus, the response of yield is dependent on the meteorological conditions during the growing season as well as during the

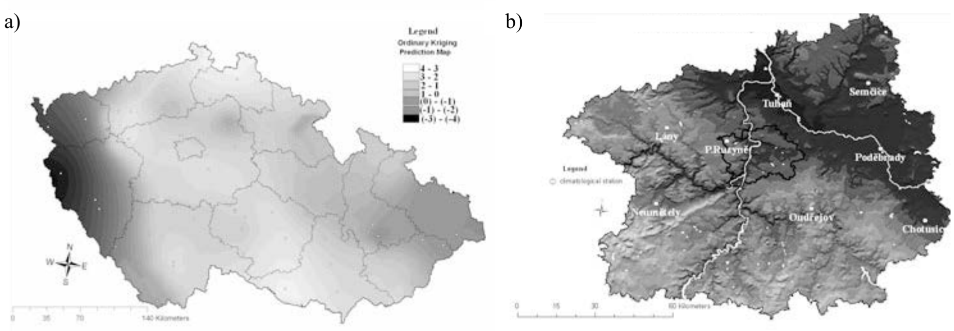

Figure 1. Location of the weather station in Central Bohemia

a) Delimitation of region in the Czech Republic affected by drought according to Si index in April 2007 (ArcMap 9.2); b) the map of Central Bohemia

antecedent periods. Using the weather-yield model as a measure of the fluctuations in crop yields, it is possible to reflect changes in the favourable and unfavourable agro-meteorological conditions and their impacts on the crop production every year. The assumption that in years when the real yield y_i^O was bigger than the mean dynamical value, agrometeorological condition was favourable during the growing season $y_i^O > y_i^{(\tau)}$. The years in which the real yield y_i^O was smaller the mean dynamical value $y_i^O < y_i^{(\tau)}$, agro-meteorological condition was considered unfavourable. Thus, the interannual departures of the regional detrended yield $y_i^{(\tau)}$ of individual cereal plants can be expressed:

$$y_i^{(T)} = y_i^O - y_i^\tau / y_i^\tau, \qquad (2)$$

where y_i^O – observed crop yield, $y_i^{(\tau)}$ – value of the trend in a separate year. The significant negative departures were assumed to be primarily an effect of a drought event.

In agreement with the developed model, the drought effect associated with the yield detrended is smaller than $y_i^{(T)} \le -0.5\sigma$. The year with a drought risk was identified by the cereals of yield detrended: low drought risk $-0.5\sigma \ge y_i^{(T)} > -\sigma$, a middle drought risk was $-\sigma \ge y_i^{(T)} > -1.5\sigma$ and $y_i^{(T)} \le -1.5\sigma$ a high drought risk (Table 1).

Crop models will presumably capture the effect of such drought. The technological trend was defined to be a quadratic function of the year (Table 2). Thus, to eliminate the bias due to the technological trend, the yield was detrended by regressing it against the quadratic time trend variable. Table 2 describes the quality of crop models. For the majority of cereals crop models are highly statistical significant. This fact is demonstrated by statistical values of a dynamic model where p values and confidence levels are significant. The magnitude error of models is shown by RMSE values. In this case RMSE is based on the one-ahead forecast errors, which are the differences between the data value at time *n* and the forecast of that value made at time *n–1*.

Table 1. Departure of the regional detrended yield ($y_i^{(\tau)}$) of individual cereal crops

Cereal's crop		Three degree of departures, $y_i^{(\tau)}$		
		$-0.5\sigma \geq y_i^{(T)} - \sigma$	$-\sigma \geq y_i^{(T)} > -1.5\sigma$	$y_i^{(T)} \leq -1.5\sigma$
Triticum aestivum L.	Winter wheat	–0.06 to –0.11	–0.12 to –0.17	≤–0.18
Triticum aestivum L.	Spring wheat	–0.06 to –0.11	–0.12 to –0.17	≤–0.18
Hordeum vulgare L.	Winter barley	–0.09 to –0.17	–0.18 to – 0.26	≤–0.27
Hordeum vulgare L.	Spring barley	–0.09 to –0.17	–0.18 to – 0.26	≤–0.27
Secale cereale L.	Winter rye	–0.06 to –0.11	–0.12 to –0.17	≤–0.18
Avena sativa L.	Oats	–0.08 to –0.15	–0.16 to –0.23	≤–0.24
Zea mays L.	Maize	–0.09 to –0.17	–0.18 to – 0.26	≤–0.27

Table 2. The dynamic quadratic model and tendency of modification of crop yield in Central Bohemia

	Constant	Slope	Quadratic	p value	RMSE	Confidence (%)	y_i^O (t/ha)	y_i^O (t/ha)
Spring wheat	–7695.2	7.736	–0.002	0.001	0.442	95.0*	2.3	3.5
Winter wheat	–5130.9	5.127	–0.001	0.004	0.463	99.9	2.6	4.9
Spring barley	–12054.3	12.109	–0.003	0.001	0.650	95.0*	1.7	3.9
Winter barley	1.500	0.193	–0.003	0.001	0.678	99.9	1.7	3.9
Winter rye	1.791	0.105	–0.001	0.001	0.417	99.9	1.9	3.7
Oats	1.781	0.118	–0.002	0.001	0.475	99.9	1.9	2.6
Maize	2.448	0.055	0.001	0.053	0.686	95.0*	2.5	7.1

Note: RMSE is the root mean squared error. Y1 is a starting period of trend and Y2 – ending period of trend. 95.0%* – since no test are statistically significant at the higher confidence level, the models has probably adequate for the data. If $p \geq 0.05$ is not significant; $0.01 < p \leq 0.05$ is marginally significant; $0.001 < p \leq 0.01$ is significant; $p \leq 0.001$ is highly significant.

The effect of drought on cereal crops production depends on the duration, time of occurrence and severity (as expressed by the ***Si*** drought index). ***Si*** presents a difference of monthly anomalies of temperature ($\Delta T = t - t_n$) and precipitation ($\Delta R = r - r_n$) with their standard deviations (σT and σR), where i, τ are a selected climatological station and period, respectively. ***Si*** is expressed by the following equation:

$$Si(\tau) = \frac{\Delta T}{\sigma T} - \frac{\Delta R}{\sigma R} \tag{3}$$

For the *Si*, the categories range from extreme drought ($Si \geq 3$) to extreme wet ($Si = -3$), with normal falling within (–1, +1). Thus, in our analysis, the $0 \leq Si < 1$ one observes a mild drought; while $1 \leq Si < 2$ is moderate; $2 \leq Si < 3$ severe; and $Si \geq 3$ is extreme (Potop and Soukup 2008a; Potop et al. 2008b, 2008d). This index describes the intensity of drought as compared to the long-term average drought condition at different stations or a single station and different periods.

Using the drought indices in the evaluation of the drought requires an analysis of the dry condition for a sufficiently long interval (month, season, vegetation period). But for the crops it is more useful to evaluate the climatic conditions for a shorter interval (a few days). A month can be also considered dry even if the rain has produced more water than the standard, but was not distributed at the correct time, i.e. when needed by the plants, or if the whole amount was concentrated into 2–3 days and there was no other precipitation for the rest of the month. In such cases we cannot deny the need of considering the duration of the period without effective precipitations (PWP) as one of the criteria of evaluation of the dry spells. Effective precipitations are those that are useful for the plant. In the given case we can, in essence, consider a condition under which, during at least 10 consecutive days there are no precipitations or their daily amounts do not exceed 0.1 mm.

Results

Comparing the regional yield of crops and the national yield of crops, one can state that the yields were comparable or higher, particularly in maize and winter wheat. The year 2006 provided a relative low yield of cereals. The departure of detrended yields of the individual cereal crops were $\mathbf{y}_i^{(T)} = -0.06$. The exception was winter wheat and winter barley. Winter wheat proved a very high yield stability in contrast to winter rye. As for spring cereals, there were high fluctuations in the period 2000–2006 (Fig. 2). The difference between spring and winter cereals was 23% in favour of winter cereals. In 2000, spring cereals reached the lowest yield because of the drought during the vegetation period. In 2003, winter barley achieved historically the lowest yield in the Czech Republic and Central Bohemia, which was around 22% lower in comparison to spring barley due to an extensive winter kill.

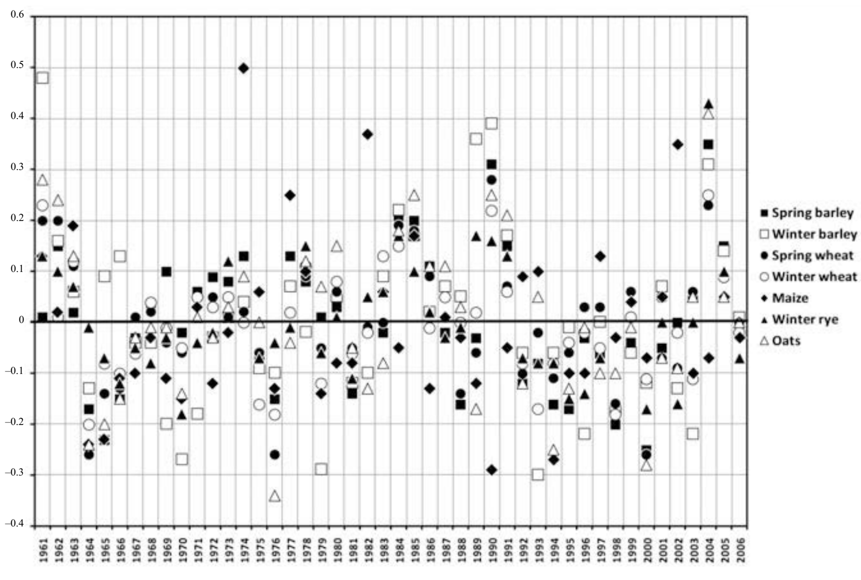

Figure 2. Departures of the regional detrended yield $\mathbf{y}_i^{(T)}$ of individual cereal plants: $\mathbf{y}_i^{(T)}$ positive values denote increases in crops yields due to favourable climatic conditions, and negative values indicate a reduction in the crop yield due to drought conditions

For a period over 46 years, the fastest yield growth was found in maize and wheat (4.6 and 2.3 t/ha), spring barley and winter barley (2.2 t/ha), while slower growth was found for oats and winter rye (0.7 and 1.8 t/ha). A severe drought limits the crop yield by causing the plant's water use to be restricted compared with a well-watered crop. According to the obtained results, the low yielding years occurred in 13 cases for these crops: winter wheat, spring wheat, winter barley and oats (Table 3). A low yielding year influenced by drought is likely to occur once in about 3.5 years, as shown by spring barley and maize – 12 cases (once in 3.8 years) and winter rye recorded 14 cases (3.2 years).

Taking into consideration the nonhomogeneity of demand by cereal crops on the hydrothermic conditions during the vegetation period, different responses by the crops in the low yielding years were observed. For example, in the year 1976 summer drought occurred and, as a result, the yield was reduced in the crops with $-0.5\ \sigma$ for spring barley, winter barley and maize, $-1.5\ \sigma$ for winter wheat, spring wheat and oat (Fig. 2). By contrast, winter rye in this year was not affected by the summer drought.

In agreement with all models for the majority of cereal crops, most of the low yielding years were noticed at the beginning of the 1960s and 1970s and in the decade of 1991–2000 (Fig. 3). Similarly, during the last 20 years, based on the *Si* drought index, in 9 cases of drought, 4 were registered as being both a severe intensity degree and an extreme intensity degree (Fig. 4). Among the cereal crops, winter rye is the one with more frequent low yields per decade. The negative values of the cereal crops yields fluctuation indicate potential adverse impacts of the agro-meteorological risk. This suggests that the more extensive the drought in the areas, the greater the fluctuation and reduction in the cereal

Table 3. Register of low yielding years reduced by droughts of various intensities

Year	Winter wheat	Spring wheat	Spring barley	Winter barley	Winter rye	Oats	Maize	Year	Winter wheat	Spring wheat	Spring barley	Winter barley	Winter rye	Oats	Maize
1964	-1.5σ	-1.5σ	-0.5σ	-0.5σ	G	$-\sigma$	$-\sigma$	1988		$-\sigma$					
1965	-0.5σ	$-\sigma$			-0.5σ	$-\sigma$	$-\sigma$	1989		-0.5σ				$-\sigma$	-0.5σ
1966	-0.5σ	$-\sigma$			$-\sigma$	-0.5σ	-0.5σ	1990							-1.5σ
1967	-0.5σ						-0.5σ	1992	-0.5σ	-0.5σ			-0.5σ	-0.5σ	
1968					-0.5σ			1993	$-\sigma$		-1.5σ	-1.5σ	-0.5σ		
1969			$-\sigma$	$-\sigma$			-0.5σ	1994	-0.5σ	-0.5σ			-0.5σ	-1.5σ	-1.5σ
1970		-0.5σ	-1.5σ	-1.5σ	$-\sigma$	-0.5σ	-0.5σ	1995		-0.5σ			$-\sigma$	-0.5σ	-0.5σ
1971			$-\sigma$	$-\sigma$				1996			$-\sigma$	$-\sigma$	$-\sigma$		-0.5σ
1972							-0.5σ	1997					-0.5σ	-0.5σ	
1975	$-\sigma$	-0.5σ		-0.5σ	-0.5σ			1998	-1.5σ	$-\sigma$	$-\sigma$	-0.5σ	-0.5σ	-0.5σ	
1976	-1.5σ	-1.5σ	-0.5σ	-0.5σ		-1.5σ	-0.5σ	2000	-0.5σ	-1.5σ	-0.5σ	-0.5σ	$-\sigma$	-0.5σ	
1979	$-\sigma$		-1.5σ	-1.5σ	-0.5σ		-0.5σ	2001		-0.5σ					
1981			-0.5σ	-0.5σ	-0.5σ			2002		-0.5σ				-0.5σ	
1982			-0.5σ	-0.5σ		-0.5σ		2003	-0.5σ						-0.5σ
1983						-0.5σ		2006					-0.5σ		
1986							-0.5σ	Cases	13	13	12	13	14	13	12

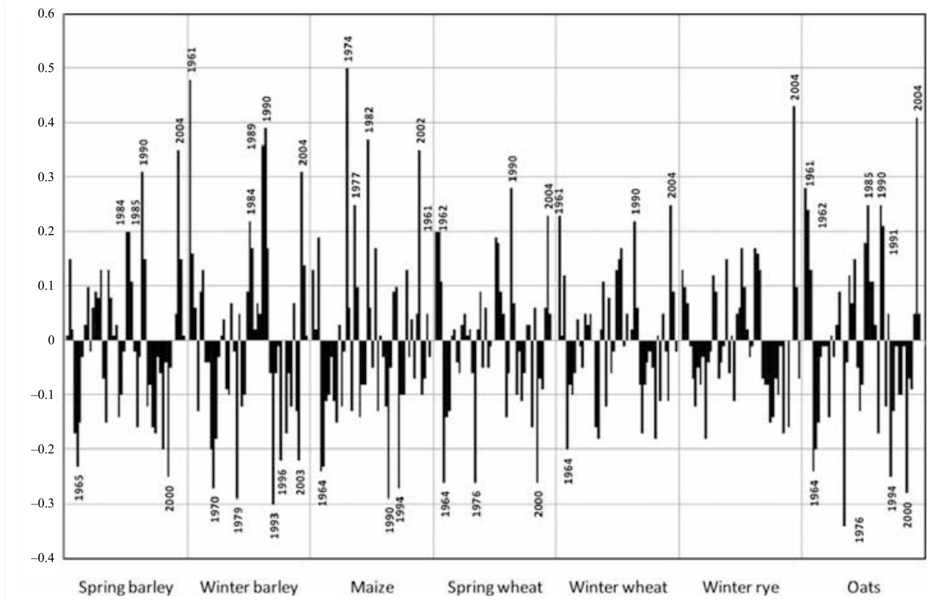

Figure 3. The evident annual challenge to yield of crops influenced by climatic factors

crops yields. Droughts were responsible for the most serious crop failures in grain production in Central Bohemia in these years: 1964, 1976, 2000, 2003 and 2006. Thus, higher yields of winter rye, maize and barley were found in the years with Si index drought with values of –1 and –2 (moderate humidity) during the growing period. In the years with spring drought (April to May) lower yields of winter wheat were registered. Drought spells in May caused lower yields (–1.5 σ) of spring barley, spring wheat and oats. If drought occurred during June, then 70% of the lower yield years (with –σ to –1.5 σ) were registered for maize. As an example, the 2005/2006 agrometeorological year noticed an uneven distribution of total rainfall as well as alternation in hottest and driest months with coldest and wettest months, warm and wet months with hydrothermal normal months in the Czech Republic. The drought in October and November had a negative influence on winter crops in addition to lower temperatures (σ = –2.9 °C) and with a low total precipitation (37% of normal) in January, to which the reduction of soil water reserves had contributed. Occurrence of dry periods during the warm half of the year in May, June, July and September had an episodic character. Thus, the drought spell from the first half of the warm period in 2006 year affected 70% agricultural production areas in the Czech Republic.

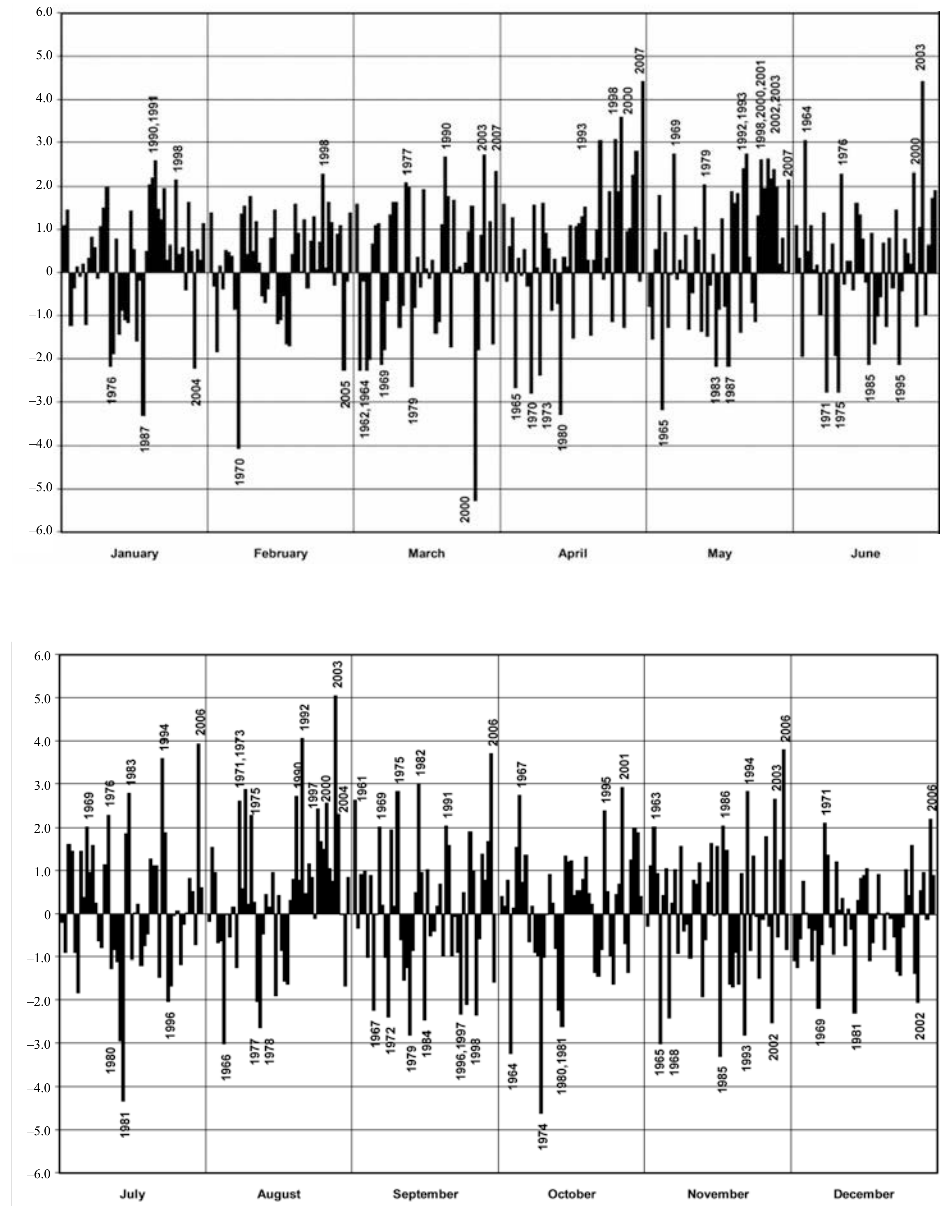

Figure 4. Drought evolution in the Central Bohemian region during last 47 years. Positive values of *Si* correspond to drought month, negative to humid ones. Another interpretation may be made as follows: positive values of *Si* correspond to a warmer thermal regime during some period, whereas the negative ones reflect a colder thermal regime

Discussions

According to the CHMI source, there are two driest areas in the Czech Republic, in which the first zone extends from the foothills of the Krušné Hory into the Labe River lowland and Central Bohemia as well as into Western and Southern Bohemia. The second driest area is in Moravia, mainly South-Moravia. Thus, the territory of the Central Bohemian region is situated in a zone, which is affected by drought. For the territory of Central Bohemia stable variability of yield winter crops is characteristic, while for spring crops it is a moderate stable variability of yields. It has an important role that determines the evident annual challenge to agricultural crops variability of yield crops.

It was found that the crop-drought function was sensitive to short-periods (i.e. days, weeks), because the amounts of precipitation distributed at different times during the growing season, may have different effects on the crop. In the territory of Central Bohemia the records have shown that a greater probability of the 15 to 20 PWP is only during April, July and September. Furthermore, if a short episode of drought (18–25 days) occurs in the critical crop growth stages, the effects on agriculture can be severe (as it was the case during the drought years 2000 and 2007). At the same time, lack of rainfall in the Czech Republic from April–May 2000, during the critical cereal crops growing period coupled with excessive temperatures caused various degrees of cereal crops damage. A severe spring drought was registered across the Czech Republic, which started as a consequence of poor winter snowfalls and little spring rain. Then, during April 2007, the drought affected 96% of the territory of the Czech Republic (Fig. 1). Due to the fact, that the drought in the Czech Republic did not occurred during the reproductive phase of the crops, the yields were not drastically affected. It was established, that in the majority of cases the years with highest negative yield departure ($\leq -1.5\,\sigma$) corresponding with the highest values of $Si \geq 3$ and PWP > 20 suffered a severe drought. The presented results clearly indicate that droughts have become one the decisive factors determining a significant portion of the variability in the cereal crops in the Central Bohemian region. Also, the effect of drought on the crop yields during May–June remains a significant factor, which influences the seasonal soil water supply.

A drought risk is considered to have potentially adverse effects on the regional production level of cereal crops yields. The major aspects of drought that increase or decrease its adverse effects are the frequency, severity and the spatial extent. A risk assessment framework utilizes the historical climate and crop yield data to characterize and quantify the impact of drought. The methods have certain advantages, such as having simple processes and easily available data, and providing quantitative and comparative analysis results. The methodology employed in this paper can be applied to the study of other agro-meteorological risks. Information from this study provides a potentially useful reference in the decision making concerning the drought disaster prevention and agricultural sustainable development planning.

In this context, the methodology of the paper will be very timely and, hopefully, will be welcomed by all those interested in knowing more about the detection of drought from the agrometeorological point of view.

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