Atmosphere **2014**, *5*, 1020-1041; doi:10.3390/atmos5041020

OPEN ACCESS

atmosphere

ISSN 2073-4433

www.mdpi.com/journal/atmosphere

Article

Can Agrometeorological Indices of Adverse Weather Conditions Help to Improve Yield Prediction by Crop Models?

Branislava Lalić [1,*], Josef Eitzinger [2], Sabina Thaler [2], Višnjica Vučetić [3], Pavol Nejedlik [4], Henrik Eckersten [5], Goran Jaćimović [1] and Emilija Nikolić-Djorić [1]

[1] Department of Field and Vegetable Crops, Faculty of Agriculture, University of Novi Sad, Sq. Dositej Obradovic 8, Novi Sad 21000, Serbia; E-Mails: jgoran@polj.uns.ac.rs (G.J.); emily@polj.uns.ac.rs (E.N.-D.)

[2] Institute of Meteorology, University of Natural Resources and Life Sciences, Gregor Mendel Straße 33, Vienna 1180, Austria; E-Mails: josef.eitzinger@boku.ac.at (J.E.); sabina.thaler@boku.ac.at (S.T.)

[3] Meteorological and Hydrological Service, Gric 3, Zagreb 10000, Croatia; E-Mail: visnja.vucetic@cirus.dhz.hr

[4] Slovak Hydrometeorological Institute, Jeseniova 17, Bratislava 83315, Slovak Republic; E-Mail: pavol.nejedlik@shmu.sk

[5] Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Almas Allé 10, Uppsala 750 07, Sweden; E-Mail: Henrik.Eckersten@slu.se

* Author to whom correspondence should be addressed; E-Mail: branka@polj.uns.ac.rs; Tel.: +381-21-485-3290; Fax: +381-21-635-0552.

External Editor: Timothy J. Griffis

Received: 11 September 2014; in revised form: 17 November 2014 / Accepted: 17 November 2014 / Published: 15 December 2014

Abstract: The impact of adverse weather conditions (AWCs) on crop production is random in both time and space and depends on factors such as severity, previous agrometeorological conditions, and plant vulnerability at a specific crop development stage. Any exclusion or improper treatment of any of these factors can cause crop models to produce significant under- or overestimates of yield. The analysis presented in this paper focuses on a range of agrometeorological indices (AMI) related to AWCs that might affect real yield as well as simulated yield. For this purpose, the analysis addressed four indicators of extreme temperatures and three indicators of dry conditions during the growth period of maize and winter wheat in Austria, Croatia, Serbia, Slovakia, and Sweden. It is shown that increases in the number and intensity of AWCs cannot be unambiguously associated with increased deviations in simulated yields. The identified correlations indicate an increase in modeling uncertainty. This finding represents important information for the crop modeling community. Additionally, it opens a window of opportunity for a statistical ("event scenario") approach based on correlations between agrometeorological indices of AWCs and crop yield data series. This approach can provide scenarios for certain locations, crop types, and AWC patterns and, therefore, improve yield forecasting in the presence of AWCs.

Keywords: adverse weather conditions; crop models; climate-yield correlations; yield prediction; yield simulations

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1. Introduction

Adverse weather conditions (AWCs) pose major risks to actual and future agricultural production. According to the results of observations furnished by the Global Climate Observation System (GCOS), the magnitude and frequency of AWCs are increasing worldwide. Ongoing warming has a remarkable impact on temperature variability on different scales (annual, seasonal, or monthly), shifts of temperature zones, and changes in global precipitation patterns [1–4]. On the global level, average temperatures have increased since the beginning of the twentieth century, and a significant increasing trend in terms of specific AWCs has been observed in certain areas of the world [5–9]. Under ongoing climate change conditions, a greater frequency of extremely hot days [10] and a greater frequency and severity of other AWCs [11–13] is expected.

Specifically, climate variability and changes in the intensity and frequency of AWCs are of great importance for crop growth conditions and yield formation [14–17]. An increase in the variability of temperatures and precipitation can, therefore, result in a significant increase in inter-annual yield variability and crop failures [15,18–27]. The AWCs for crops such as floods, droughts, and heat waves, could also dominate future climates in Central European regions, significantly affecting agricultural production [28–30].

The most important agrometeorological factors limiting crop growth and yield over large scales are heat and drought stress [31]. At temperatures above the lower threshold for actual growing stages, the start of active growth is advanced, plants develop faster, and the crop growth period is reduced for most annual crops [26]. Adversely high temperatures decrease the grain set, increase the grain filling rate (to a certain extent), and decrease the duration of grain filling, causing lower yields when temperatures exceed a critical level [32,33]. In the case of maize, heat stress at the stages of silking or tasseling results in a significant decrease in yield [19]. In general, a critical leaf temperature above approximately 45 °C causes heat damage to crops, an effect that is strongly dependent on the heat balance of crop tissues. Weather conditions and transpirative cooling strongly influence leaf temperatures. As a result, heat damage and water stress often coincide with periods of water scarcity. Drought stress alone reduces yield through lower photosynthesis (due to closure of stomata) and yield response to nitrogen (N) supply under ambient and elevated CO_2 [34]. Through these complex interactions, crops can respond nonlinearly to changes in their growing conditions and further exhibit threshold responses. A combination of stress factors often affects crop growth, development, and yield [15]. It can be demonstrated that, due to the complexity of the problem, it is very difficult to identify unambiguous responses of crops to AWCs, especially if the crop responses to stress levels and relevant interactions are not precisely known.

From the farm to the regional level, AWCs are the greatest cause of damage to agricultural production each year [35–38]. To improve yield forecasts or recommendations for farmers, it is of the utmost importance to have information about the appearance and effects of AWCs on crops within the specific agroecosystem and local climate conditions. For this purpose, it is necessary to have available: (a) a reliable source of meteorological information (short-term and/or seasonal weather forecasts) and (b) locally tested models and methods able to predict the effects of AWCs on crop growth and production conditions.

Because the accuracy and availability of monthly and seasonal weather forecasts is steadily increasing, one can assume that useful weather information is already available. However, the question remains: Can crop modeling tools use this information and simulate adequate responses under the influence of AWCs, or is there a need for additional information that can be provided by agrometeorological indices (AMI)?

At present, a high level of agreement among the scientific community has been achieved in terms of the development and application of crop models [39]. However, due to the complexity of the soil-plant-atmosphere system, many of the relationships incorporated in the models are partially or entirely unable to reflect extreme weather impacts properly, e.g., heat or drought [40,41]. It is extremely difficult to analyze the uncertainties in a process-based model [42], and this difficulty is not simply a consequence of multiple sources of uncertainty. Additionally, parameterization processes introduce further uncertainties [43].

Many agroclimatic and agrometeorological indices are in use for monitoring or forecasting crop growing conditions. A relevant survey for Europe was conducted under the COST734 action [38,44]. The majority of the descriptive conclusions, related to the impact of AWCs on crops using crop model outputs, represented attempts to explain the deviation of simulations from observations. These deviations were partly explained by the inability of models to consider or reflect certain adverse weather impacts on crop growth and yield.

The main goals of this study, therefore, are to demonstrate and quantify: (a) the level of uncertainty in observed crop production (measured yield) and crop model simulations (simulated yield) related to selected AWCs demonstrated for different climatic conditions in Europe, (b) the ability/inability of crop models to reproduce the impact of these AWCs on yield, and (c) AMI as a complementary data source for crop yield prediction under the influence of AWCs.

2. Material and Methods

The crop response to AWCs was estimated on the basis of a correlation between measured crop yield and AMI describing AWC intensity and frequency. If increases in the intensity and frequency of AWCs reduce yield, then negative correlations between measured yield and AMI should be obtained and *vice versa*. The magnitude of the correlation coefficient indicates the level of impact of certain AWCs. According to the approach that was used in an analysis of impact of air temperature on tree-ring thickness [45], the correlation coefficient may offer a way to quantify the response of crop yields to AWCs.

In this study, the assessment of the ability of crop models to simulate the impact of AWCs on plant development and yield was based on an analysis of the correlation coefficients between AMI and the relative deviation of the simulated from the observed yield. Note that the Relative Deviation of Simulated Yield (RDSY) was calculated using the relationship:

$$\mathrm{RDSY} = \frac{\text{simulated yield} - \text{measured yield}}{\text{measured yield}} \times 100\% \tag{1}$$

If AWCs do not lead to a bias of crop model-simulated yield against measured yield, then RDSY does not depend on AWC, and the correlation coefficients between RDSY and AMI should be low. Such an outcome implies that a crop model is able to retain its accuracy when crop yield is affected by AWCs. If there is a systematic impact of AWCs on simulated yield (leading to systematically lower or higher yields in comparison with the measured yield), then the correlation coefficient should be highly negative or positive. Such an outcome implies that the presence of AWCs reduces crop model accuracy but, at the same time, makes it possible to calculate this reduction. Additionally, AMI can be used as a complementary data source for crop yield prediction under AWCs. If the value of the correlation coefficient is neither low nor high, it implies a high level of crop model uncertainty related to a specific AWC. In the text below, AMI with an absolute value of the correlation coefficient greater than 0.50 (high) are shown in bold, those with an absolute value of the coefficient of correlation below 0.3 (low) are shown in italics, and those with an absolute value of the correlation coefficient in an intermediate range (between 0.3 and 0.5) are shown in normal font.

To estimate the statistical significance of the correlation coefficients, STATISTICA 12 software package (StatSoft, Inc., Tulsa, OK, USA, 2013) was used. In general, a correlation coefficient with a probability (p-value) smaller than 0.05 can be considered as statistically significant at the 0.05 level, while for $p < 0.01$ a correlation coefficient is highly statistically significant at the 0.01 level. If $p \geq 0.05$ the null hypothesis of no linear relationship between observed yield/RDSY and selected AMI cannot be rejected.

The procedure consisted of the following steps: (a) An assessment of the effect of AWCs on crop yield, analyzing the correlation coefficient between AMI and measured yield, and (b) an assessment of the ability of the crop model to simulate the impact of AWCs on yield by analyzing the correlation coefficient between AMI and RDSY.

Indices describing the number of days with extreme temperatures and drought stress (dry days) during the growing season were used as indicators of AWC presence and intensity [29]. Winter wheat (WW) and grain maize (MZ) yields were simulated using DSSAT crop models, which were run with meteorological data observed at meteorological stations in Austria, Croatia, Serbia, Slovakia, and Sweden for the periods shown in Table 1.

2.1. Locations and Data Base

The current study was based on daily weather data and WW and MZ yield data provided by members of the COST734 network. The data set to be used was defined according to the following requirements: (a) Weather data should represent the location where crop yield was measured, and (b) the time series of weather data should be sufficiently long (not less than 15 years). After a detailed inspection of the obtained data sets, seven sites situated in Austria (1), Croatia (1), Serbia (1), Slovakia (3), and Sweden (2) were included in the study (Table 1) for crop simulation and analysis of the effect of AWCs on observed yields.

Table 1. List of countries, stations, and time periods of weather data used in the study.

Country	No.	Station Name	Latitude	Longitude	Altitude (m)	Winter Wheat	Maize
						Time Period	
Austria	1	Gross-Enzersdorf	48°12′N	16°34′E	153	1991–2009	-
Croatia	2	Zagreb-Maksimir	45°49′N	16°2′E	128	-	1991–2005
Serbia	3	RimskiSancevi	45°15′N	19°50′E	84	1981–2004	-
Slovakia	4	Ziharec	48°04′N	17°53′E	112	1991–2007	1991–2007
	5	Podhajska	48°06′N	18°20′E	140	1991–2007	1991–2007
	6	Belusa	49°04′N	18°19′E	254	1991–2007	-
Sweden	7	Lund/Borgeby	55°44′N	13°04′E	<10	1980–1998 2003–2009	-
	8	Uppsala/Ultuna	59°49′N	17°40′E	<10	1961–2000 2002–2008	-

2.2. Characteristics of Locations and Data Base

The meteorological data for 1971–2000 from the selected weather stations with WMO standards represent the key agricultural regions of the given countries (Table 2). The sites in Croatia and Serbia are located in the warmest regions (annual temperatures above 10 °C) and the sites in Sweden are located in the coldest region. The sites with lowest annual precipitation considered in the study (annual precipitation < 600 mm) are located in Austria, Slovakia, Serbia, and Sweden.

Austria: Gross-Enzersdorf is located in the northeastern part of Austria and is influenced by the Pannonian climate, a transition zone between the semi-humid Western European climate and the continental Eastern European climate. The climate in this region is characterized by frequent hard frosts and limited snow cover in winter, and hot and periodically dry conditions in summer [46]. The WW yield (cultivar "CAPO") and meteorological data used for crop model calibration and simulation were measured at the same location [47]. The soils in the Marchfeld region, where Gross-Enzersdorf is located, are primarily Parachernozems, Chernozems, and Fluvisols, which are characterized as loamy sand or sandy loam soils without groundwater impact.

Table 2. Climate characteristics of the selected locations for 1971–2000 (T_a = mean annual temperature, H_a = annual precipitation sum, $T_{A\text{-}S}$ =April–September mean temperature, and $H_{A\text{-}S}$ = April–September precipitation sum).

Country	Station Name	T_a (°C)	H_a (mm)	$T_{A\text{-}S}$ (°C)	$H_{A\text{-}S}$ (mm)
Austria	Gross-Enzersdorf	9.8	520	16.2	321
Croatia	Zagreb	10.7	840	17.0	483
Serbia	RimskiSancevi	11.4	578	17.9	360
Slovakia	Ziharec	9.8	557	16.5	321
	Podhajska	9.8	527	16.6	311
	Belusa	8.8	707	15.0	422
Sweden	Lund/Borgeby	8.1	687	13.4	336
	Uppsala/Ultuna	5.6	575	11.9	325

Croatia: The MZ yield data used in this study were measured at DubrovčakLijevi, which is situated in the northwestern part of Croatia, in a flat area located on the western edge of the Pannonian lowland along the Sava River. The climate of this region is moderate continental with the maximum precipitation in the early summer (June) and the minimum in winter (January) [48]. The nearest meteorological station representative of this location is Zagreb-Maksimir, located 40 km from DubrovčakLijevi. According to the WMO Guide to Hydrological Practices [49], weather data from stations in lowland areas can be seen as representative to a maximum distance of 40 km. However, this distance can make a significant difference in terms of precipitation, in the short term, if strong convective precipitation occurs or is absent during the spring and summer. Therefore, this site will be used only for impact analysis of adverse temperatures. The Pioneer MZ cultivar "STIRA" was used for the period 1999–2001, and the MZ cultivar "PR38A24" was used for the period 2002–2009. These cultivars are hybrids with a medium-length growing season. They are adapted to dry and warm summer conditions and produce high grain yields.

Serbia: The RimskiSancevi site is located in the Vojvodina region (Northern Serbia), a generally flat area located in the southern part of the Pannonian lowland. The climate is moderate continental with tendencies toward a continental (a more extreme seasonal variation of temperature and precipitation) climate. The WW yield and meteorological data used for crop simulations were measured at the same location. Because most WW cultivars remain in production in Serbia for not more than five or six years, the high-yielding WW cultivars "Posavka 2" (for the period 1981–1985), "Jugoslavija" (1986–1990) and "Balcan" (1991–2004) were chosen for the simulation. All three varieties have very similar characteristics, as the first two citedare cultivars parent strains of "Balcan". All are medium-late, high-quality varieties with very good resistance to low temperatures. At RimskiSancevi, the dominant soil type is a calcareous chernozem on loess terraces.

Slovakia:The Ziharec and Podhajska stations are located in the northwestern Pannonian lowland, and the Belusa station is located at the bottom of a valley in the northwestern Carpathian Mountains, all characterized by a continental climate. Ziharec and Podhajska are in a region with relatively warm and dry summers, whereas Belusa has a more continental climate with typically cold winters. In Ziharec shallow groundwater tables influence rooting zone of crops. The minimum precipitation occurs in March at all stations, increasing to a maximum at the beginning of summer; snow cover is present each winter. However, dry spells are quite frequent in the spring and early summer periods. Meteorological stations are located at the same spots or very close (within 3 km) to the phenological and yield observation sites. All the stations are run by Slovak Hydrometeorological Institute.

Sweden: The Lund network weather station (Swedish Meteorological and Hydrological Institute [50]) is located approximately 10 km from the field experimental site (Borgeby). The whole area is a flat lowland, although Lund is located a few kilometers farther inland than Borgeby. The central Swedish site, Uppsala/Ultuna, is also located in a flat area, and data were taken from the nearby (<1 km) Ultuna climate station operated by the Swedish University of Agricultural Sciences [51]. The WW data originate from rain-fed long-term agronomic field trials at Borgeby, near Lund, in southernmost Sweden, and Ultuna near Uppsala in central Sweden. The soil organic and clay content in Borgeby [52] were lower than those in Ultuna. The clayey soils in Ultuna serve to buffer the effects of early summer drought on crops. The Swedish WW yield data were selected from long-term trials in which the crop rotation was the same for the whole period and the WW achieved the same fertilization rate. For the Swedish WW, only the years in which peas were the preceding crop were selected.

2.3. Agrometeorological Indices (AMI)

AWCs are commonly related to weather events such as strong wind, extreme temperatures, excessive rain, or drought that have extremely negative effects on society (e.g., agriculture, health, traffic, and the environment). Obviously, the definition of AWCs depends on their impact and/or the objects affected. In the case of crop production, it is a challenge to isolate and define the impact of a specific AWC on crops, because the vulnerability of crops depends on their phenology, on other present stress factors, and on the previous weather conditions.

The aim of this study was to assess the impact of AWCs on observed (measured) crop yield and the ability of crop models to simulate the effects of AWCs under various agrometeorological conditions. For these reasons, we chose those AWCs that could be defined unambiguously by AMI in terms of the presence and intensity of such events. Because the crops of interest were WW and MZ, appropriate indices were chosen to indicate the AWCs. These indices served to describe the number of days with extreme temperatures and deficits of plant available water during different periods of the growing season, based on the conditions that were supposed to have the most severe impact on yield [29]. Based on these conditions, the following AMI were selected.

AMI describing number of days with extreme temperatures:

- arctic day—day with minimum daily temperature below −20 °C;
- freeze day (FreezD)—day with maximum daily temperature below 0 °C;
- frost day (FrostD)—day with minimum daily temperature below 0 °C;
- summer day (SumD)—day with maximum daily temperature above 25 °C;
- tropical day (TropD)—day with maximum daily temperature above 30 °C.

AMI describing number of dry days:

- dry start (Dstart)—actual/reference evapotranspiration < 0.5;
- dry intensive (Dintensive)—actual/reference evapotranspiration < 0.4;
- dry extreme (Dextreme)—actual/reference evapotranspiration < 0.3;
- dry very extreme (Dvextreme)—actual/reference evapotranspiration < 0.2.

The AGRICLIM model [53] was used to calculate the AMI specified above. Using daily values of meteorological elements (maximum and minimum air temperature, precipitation, solar radiation, water vapor pressure or relative air humidity, wind speed), AGRICLIM calculates: (a) Snow cover characteristics (presence, duration, start-end), (b) water balance components (actual and reference evapotranspiration, soil water content), (c) temperature sums and extremes (number of days with temperature above or below a certain threshold, sum of temperatures), (d) “combined” indices (drought probability and duration, frost risk) and (e) crop management-related indices (e.g., the number of days with suitable conditions for sowing and harvest, growing period duration).

Table 3. Average number of days with extreme temperatures at the selected locations for the periods shown in Table 1.

Locations	**January**		**February**		**March**	**April**		**May**		**June**		**July**		**August**	
	FrostD	**FreezD**	**FrostD**	**FreezD**	**FrostD**	**SumD**	**FrostD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**
Gross-Enzersdorf	19.9	9.6	15.3	3.4	9.4	0.9	1.9	0.4	7.5	3.4	14.6	7.9	21.1	6.8	20.2
Zagreb	20.9	5.8	17.0	2.0	8.1	0.7	1.2	1.6	10.8	6.7	18.3	10.3	23.7	8.9	23.4
RimskiSancevi	22.2	8.5	18.4	4.9	10.3	2.0	1.8	1.0	10.8	5.1	16.7	10.2	23.4	11.0	24.6
Ziharec	21.6	8.1	19.2	2.3	14.2	1.9	3.6	2.1	10.9	5.0	17.4	10.2	22.9	10.8	23.2
Podhajska	23.0	10.3	19.6	3.5	13.9	1.9	3.6	1.9	10.8	5.5	16.5	10.9	22.3	9.3	22.1
Belusa	23.6	9.9	20.8	3.9	16.6	1.9	5.1	0.7	8.1	3.4	13.6	7.1	18.9	6.6	20.2
Lund	13.2	8.2	16.0	8.5	10.2	0.2	2.7	0.0	0.4	0.1	1.8	0.2	3.4	0.2	3.4
Uppsala	24.6	13.9	23.1	12.5	22.5	0.0	15.5	0.0	1.1	0.1	4.5	0.5	6.8	0.5	4.4

Table 4. Average number of dry days at the selected locations for the periods shown in Table 1.

Locations	**Dstart**			**Dintensive**			**Dextreme**			**Dvextreme**	
	AMJ	**JJA**	**MAM**	**AMJ**	**JJA**	**MAM**	**AMJ**	**JJA**	**MAM**	**AMJ**	**JJA**
Gross-Enzersdorf	47.4	59.8	58.5	29.9	44.1	38.3	16.2	26.5	25.8	6.5	10.7
RimskiSancevi	41.2	59.2	49.8	26.5	45.6	35.8	12.9	28.3	22.7	4.4	15.2
Ziharec	75.3	73.3	82.6	62.6	63.5	71.7	42.1	45.1	53.4	16.6	24.6
Podhajska	72.3	75.1	76.1	59.9	62.2	64.9	34.9	45.1	37.0	14.8	27.2
Belusa	36.5	35.6	42.0	23.4	19.8	30.1	15.6	10.2	22.3	6.1	2.7
Lund	46.7	36.5	50.2	33.2	23.5	35.3	20.8	8.6	23.1	9.3	3.1
Uppsala	52.0	34.9	49.3	-	36.5	10.0	33.6	-	7.5	3.7	27.2

Tables 3 and 4 show the average values of the selected indices during the simulation period for the selected locations (Table 1). In terms of the number of days with extreme temperatures, two regions can be identified: (a) Northern Europe (Sweden), with a higher probability of frost and freezing days and a lower probability of summer and tropical days (as expected), and (b) Central and Eastern Europe (all other countries), with a uniform distribution of all indices within the region. If the number of days with various levels of dryness was defined as small (<20), medium (>20 and <50), or large (>50), then Gross-Enzersdorf (33.1), RimskiSancevi (31.1), Belusa (22.2), Lund/Borgeby (26.4), and Uppsala/Ultuna (28.3) can be classified as medium, and Ziharec (55.6) and Podhajska (51.8) as locations with a high number of dry days during March–August.

2.4. Crop Yield Simulations

The crop models CERES-Wheat and CERES-Maize, a part of the Decision Support System for Agrotechnology Transfer (DSSAT), were applied. The DSSAT models were first developed in 1982 and have been constantly refined and modified. DSSAT version 4.0.2.0 was used in this study [54]. The core components of DSSAT are crop simulation models and programs to facilitate their application in different regions of the world. The models allow users to (1) input, organize, and store data on crops, soils, and weather; (2) request, analyze, and display data; (3) calibrate and validate the crop growth models; (4) simulate different crop management practices; and (5) evaluate economic risks connected with different options. DSSAT is a process-based, management-oriented model that simulates the daily time-step effects of the cultivar characteristics, crop management, weather, soil water, and N on crop growth, phenology, and yield [20]. The input data include weather and soil conditions, plant characteristics, and crop management [55].

Four soil classes were defined for the crop simulations at all locations based on the case study conditions for the Austrian region (Marchfeld, represented by weather station Gross-Enzersdorf) and applied to all other case study regions to cover a wide range of soil conditions. For each location, simulation results were used from the soils that best fit in terms of plant-available soil water storage capacity (AWC); see Table 5 for further analysis. For WW, soil 2 was used for Uppsala; soil 3 was used for Gross-Enzersdorf, Rimski Sancevi, Ziharec, Podhajska, and Belusa; and soil 4 was used for Lund. For MZ, soil 1 was used for DubrovčakLijevi and soil 3 was used for Podhajska and Ziharec (Table 5). At the Austrian reference region Marchfeld, the first two soil types are Parachernozems, which are characterized as loamy sand or sandy loam soils with an available water capacity of <140 mm for a soil depth of 100 cm. Soils 3 and 4 are Chernozems and Fluvisols, respectively, with an available water capacity of >140 mm for a soil depth of 100 cm (sandy loam and loamy silt, respectively). DSSAT was applied at all locations of this study with calibration on Austrian WW and MZ cultivars [41]. All simulations specified a rain-fed water supply, automatic planting, N-fertilizer auto application, and an atmospheric CO_2 concentration of 390 ppm, which reflects the mean value for the period of interest. For the crop simulations at all locations, the same period used for AMI calculations was applied (Table 1).

Table 5. Physical characteristics of soil types used in crop simulations for all considered locations.

Soil Depth (cm)	Texture Clay (%)	Silt (%)	Sand (%)	Bulk Density (g/cm³)	Organic Carbon (%)	Wilting Point (% vol.)	Field Capacity (% vol.)
soil type 1 (AWC*: 52 mm)							
0–20	11.3	28.4	60.3	1.32	1.90	8.3	26.3
20–40	11.3	28.4	60.3	1.94	0.80	3.1	6.5
40–100	11.3	28.4	60.3	2.05	0.25	1.4	3.0
soil type 2 (AWC*: 112 mm)							
0–20	15.6	34.2	50.2	1.29	1.70	13.3	31.4
20–40	16.4	34.4	49.2	1.43	1.78	14.8	32.8
40–100	14.8	32.7	52.5	1.81	0.50	8.3	14.9
soil type 3 (AWC*: 184 mm)							
0–20	19.7	48.2	32.1	1.27	2.25	19.3	39.2
20–40	20.8	49.6	29.6	1.39	2.29	20.3	40.4
40–100	18.2	48.3	33.5	1.60	1.05	20.6	37.9
soil type 4 (AWC*: 225 mm)							
0–20	16.5	60.4	23.1	1.24	2.00	18.1	40.0
20–40	16.9	61.8	21.3	1.35	1.78	17.9	40.6
40–100	14.5	64.4	21.1	1.48	0.65	15.8	38.5

* plant-available soil water storage capacity for soil depth 0–100 cm.

3. Results

3.1. Adverse Weather Conditions (AWCs) and Observed Yield

The impact of AWCs on yield was calculated for the periods shown in Table 1 and assessed using the correlation coefficient between observed (WW and MZ) yield and the number of days with extreme temperatures and water deficit. Statistical significance of obtained correlations is quantified using *p*-values. The results of this calculation are presented in Tables 6–9, where negative values indicate yield depression and positive values yield improvements with higher value of the relevant AMI. Corresponding *p*-values are presented according to the following rules: (a) *p*-values larger than 0.01 are reported to two decimal places, (b) *p*-values between 0.01 and 0.001 to three decimal places, and (c) *p*-values smaller than 0.001 as $p < 0.001$.

Although very high values (close to 1) of the correlation coefficient between AMI and observed yield were expected, they were not obtained at all locations or for the same indices. However, several common features can be identified from the results presented in Tables 6–9:

(a) For AMI describing the effect of the number of days with extreme temperatures on observed yield, it is possible to distinguish between significant impact (a high correlation coefficient) and no impact (a low correlation coefficient) in 23 of 30 cases (all combinations of stations and AMI) with MZ and in 43 of 63 cases with WW (Tables 6 and 7).

(b) Very similar results, 18 of 22 cases for MZ and 27 of 49 cases for WW (Tables 8 and 9), were obtained for the relationship between AMI and the number of dry days. In the remaining cases, it was not possible to determine an effect.

(c) In the case of MZ, for the majority of the indices it was possible to identify either high (20% for high temperatures and 32% for drought) or low correlations (57% for high temperatures and 55% for drought). Otherwise, this percentage was generally lower for WW, but the information obtained is more precise because the percentage of low correlations was 65% for high temperatures and 55% for drought, whereas high correlations could be identified for only 3% of the indices for high temperatures and 6% for drought.

(d) A high correlation between the duration of cold periods (number of arctic days: −0.74, −0.50) and WW yield could only be identified for Sweden.

(e) The effect of dry period duration and intensity on MZ yield was much more pronounced than the effect of high temperatures.

Table 6. Correlation coefficients and *p* values (in brackets, underlined values are significant) between AMI describing number of days with extreme temperatures and observed MZ yield. No effect: *17 of 30*; with effect: **6** of **30**.

Location	**April**		**May**		**June**		**July**		**August**	
	SumD	**FrostD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**
DubrovčakLijevi	*0.03* (*0.93*)	−0.43 (0.18)	−0.31 (0.35)	−0.34 (0.30)	*−0.07* (*0.83*)	−0.37 (0.26)	*0.15* (*0.65*)	*−0.05* (*0.88*)	**−0.64** **(0.03)**	−0.42 (0.19)
Ziharec	*0.09* (*0.79*)	*0.24* *(0.47)*	**0.51** **(0.10)**	0.38 (0.24)	*−0.01* (*0.97*)	*−0.01* (*0.97*)	**−0.58** **(0.06)**	**−0.72** **(0.01)**	*−0.25* (*0.45*)	*−0.25* (*0.45*)
Podhajska	−0.47 (0.14)	*0.08* (*0.81*)	*0.00* (*1.00*)	*−0.20* (*0.55*)	*−0.19* (*0.57*)	*−0.11* (*0.74*)	*0.08* (*0.81*)	*0.06* (*0.86*)	**−0.56** **(0.07)**	**−0.56** **(0.07)**

Table 7. Correlation coefficients and p values (in brackets, underlined values are significant) between AMI describing number of days with extreme temperatures and observed WW yield. No effect: *41 of 63*; with effect: **2** of **63**.

Location	**January**		**February**		**March**	**April**	**May**	**June**	
	FrostD	**FreezD**	**FrostD**	**FreezD**	**FrostD**	**FrostD**	**SumD**	**TropD**	**SumD**
Gross-Enz.	*−0.14* (*0.59*)	*−0.14* (*0.59*)	−0.43 (0.08)	−0.43 (0.08)	*−0.27* (*0.29*)	*0.14* (*0.59*)	−0.32 (0.21)	*0.04* (*0.87*)	*−0.24* (*0.35*)
RimskiSancevi	*−0.27* (*0.20*)	*−0.10* (*0.64*)	−0.42 (0.04)	−0.44 (0.03)	*−0.03* (*0.88*)	*−0.22* (*0.30*)	*−0.02* (*0.92*)	*−0.24* (*0.25*)	*−0.30* (*0.15*)
Ziharec	−0.37 (0.21)	−0.44 (0.13)	*−0.12* (*0.69*)	−0.34 (0.25)	−0.33 (0.27)	*−0.06* (*0.84*)	*−0.22* (*0.47*)	−0.33 (0.27)	*0.07* (*0.82*)
Podhajska	*−0.23* (*0.40*)	−0.32 (0.24)	*−0.15* (*0.59*)	*0.08* (*0.77*)	*−0.02* (*0.94*)	*−0.23* (*0.40*)	**−0.64** (**0.01**)	**−0.58** (**0.02**)	*−0.29* (*0.28*)
Belusa	*0.11* *(0.68)*	*−0.23* (*0.39*)	*−0.30* (*0.25*)	*−0.28* (*0.29*)	*−0.21* (*0.43*)	*−0.03* (*0.91*)	*−0.20* (*0.45*)	−0.32 (0.22)	*−0.17* (*0.52*)
Lund	−0.40 (0.17)	−0.44 (0.13)	*−0.24* (*0.42*)	−0.31 (0.30)	*−0.15* (*0.62*)	*0.10* (*0.74*)	*0.21* (*0.49*)	-	*0.29* (*0.33*)
Uppsala	*−0.26* (*0.19*)	−0.36 (0.07)	*−0.03* (*0.88*)	−0.32 (0.11)	−0.39 (0.04)	*−0.05* (*0.80*)	*0.29* (*0.15*)	-	*−0.15* (*0.46*)

Climate differences among regions are a visible cause of the different sensitivity of WW and MZ to AWCs. Three locations used in the MZ simulation study are in the Pannonian lowland, with similar average temperatures during the growth period (from 16.5 °C to 17 °C) and a slightly greater number of dry days in Ziharec in comparison with Podhajska in Slovakia. Maize shows under these conditions mostly a negative yield reaction under higher temperatures (Table 6). At Ziharec positive yield reaction under more dry atmospheric conditions (Table 8) are probably caused by groundwater impact to the maize rooting zone.

Table 8. Correlation coefficients and p values (in brackets, underlined values are significant) between AMI describing number of dry days and observed MZ yield. No effect: *11 of 22*; with effect: **7** of **22**.

Location	**Dstart**		**Dintensive**			**Dextreme**			**Dvextreme**		
	AMJ	**JJA**	**MAM**	**AMJ**	**JJA**	**MAM**	**AMJ**	**JJA**	**MAM**	**AMJ**	**JJA**
Ziharec	**0.59**	*0.10*	**0.65**	**0.59**	*0.13*	**0.52**	**0.50**	*0.08*	*0.08*	**0.63**	*−0.12*
	(0.05)	(*0.76*)	**(0.03)**	**(0.05)**	(*0.70*)	**(0.10)**	**(0.11)**	(*0.81*)	(*0.81*)	**(0.03)**	(*0.72*)
Podhajska	*0.19*	−0.42	*0.26*	*0.23*	**−0.51**	0.49	*0.10*	−0.32	0.40	*0.12*	*−0.15*
	(*0.57*)	(0.19)	(*0.44*)	(*0.49*)	**(0.10)**	(0.12)	(*0.76*)	(0.33)	(0.22)	(*0.72*)	(*0.65*)

Table 9. Correlation coefficients and p values (in brackets, underlined values are significant) between AMI describing number of dry days and observed WW yield. No effect: *27 of 49*; with effect: **3** of **49**.

Location	**Dstart**	**Dintensive**		**Dextreme**		**Dvextreme**	
	AMJ	**MAM**	**AMJ**	**MAM**	**AMJ**	**MAM**	**AMJ**
Gross-Enz.	−0.49	−0.41	**−0.52**	*−0.16*	−0.39	*0.10*	*−0.16*
	(0.04)	(0.10)	**(0.03)**	(*0.53*)	(0.12)	(*0.70*)	(*0.53*)
RimskiSancevi	*−0.22*	*−0.13*	−0.32	−0.41	*−0.30*	−0.48	−0.34
	(*0.30*)	(*0.54*)	(0.12)	(0.04)	(*0.15*)	(0.01)	(0.10)
Ziharec	−0.37	*−0.26*	−0.31	*−0.28*	−0.43	**−0.61**	−0.39
	(0.213)	(*0.39*)	(0.30)	(*0.35*)	(0.14)	**(0.02)**	(0.18)
Podhajska	−0.34	−0.38	−0.31	*−0.17*	**−0.51**	−0.42	−0.41
	(0.21)	(0.16)	(0.26)	(*0.54*)	**(0.05)**	(0.11)	(0.12)
Belusa	*−0.24*	*0.00*	−0.38	*−0.27*	*−0.27*	*−0.18*	*−0.15*
	(*0.37*)	(*1.00*)	(0.14)	(*0.31*)	(*0.31*)	(*0.50*)	(*0.57*)
Lund	0.34	*0.16*	*0.15*	*0.02*	*0.09*	*0.19*	0.32
	(0.25)	(*0.60*)	(*0.62*)	(*0.94*)	(*0.77*)	(*0.53*)	(0.28)
Uppsala	*−0.07*	*0.03*	*−0.16*	*0.01*	*−0.11*	*0.28*	*0.23*
	(0.73)	(*0.88*)	(*0.43*)	(*0.96*)	(*0.59*)	(*0.16*)	(*0.25*)

At the WW locations in the Pannonian lowland, the temperature and precipitation regimes are quite similar, with the exception of the Serbian location (approximately 1.5 °C higher average annual temperatures) and Belusa in Slovakia (approximately 50% greater annual amount of precipitation). These characteristics can explain the consistently negative and slightly higher correlations between the observed yield and the indices describing dry conditions during the vegetation period (Table 7) and the appearance of extreme temperatures in June (Table 9). In contrast, lower sensitivity to dry conditions was observed at the Belusa location due to its more favorable precipitation.

In Sweden, at both locations, sensitivity to the dry period was low, but at Uppsala, four degrees further north than Borgeby, sensitivity to extreme low temperatures (especially during the spring) was more evident.

3.2. Adverse Weather Conditions (AWCs) and Simulated Yield

The relative deviation of simulated *vs.* measured yield depends on the quality of the input data and the accuracy of the modeling techniques applied, particularly if the response of the plant and crop model to AWCs is expected. The results shown in Tables 10–13 can be summarized as follows:

Table 10. Correlation coefficients and p values (in brackets, underlined values are significant) between AMI describing number of days with extreme temperatures and RDSY for MZ relative to observed value. No effect: *17 of 30*; with effect: **6** of **30**.

Location	**April**		**May**		**June**		**July**		**August**	
	SumD	**FrostD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**	**TropD**	**SumD**
DubrovčakLijevi	*0.25*	-	0.47	**0.61**	0.45	0.31	0.39	*−0.13*	*0.10*	*−0.06*
	(*0.45*)	-	(0.14)	**(0.04)**	(0.16)	(0.35)	(0.23)	(*0.70*)	(*0.76*)	(*0.86*)
Ziharec	*0.28*	−0.45	*−0.19*	*−0.02*	*0.10*	0.32	*0.21*	*−0.10*	*0.04*	*0.16*
	(*0.40*)	(0.16)	(*0.57*)	(*0.95*)	(*0.76*)	(0.33)	(*0.53*)	(*0.76*)	(*0.90*)	(*0.63*)
Podhajska	*−0.17*	*0.30*	**−0.52**	**−0.67**	**−0.55**	**−0.60**	*0.21*	**0.56**	*0.27*	*0.15*
	(*0.61*)	(*0.37*)	**(0.10)**	**(0.02)**	**(0.07)**	**(0.05)**	(*0.53*)	**(0.07)**	(*0.42*)	(*0.65*)

Table 11. Correlation coefficients and p values (in brackets, underlined values are significant) between AMI describing number of days with extreme temperatures and RDSY for WW relative to observed value. No effect: *46 of 63*; with effect: **4** of **63**.

Location	**January**		**February**		**March**	**April**	**May**	**June**	
	FrostD	**FreezD**	**FrostD**	**FreezD**	**FrostD**	**FrostD**	**SumD**	**TropD**	**SumD**
Gross-Enz.	*−0.18*	*−0.18*	*0.02*	*0.02*	*0.19*	*−0.12*	*−0.07*	−0.33	*00.14*
	(*0.48*)	(*0.48*)	(*0.93*)	(*0.93*)	(*0.46*)	(*0.64*)	(*0.78*)	(0.19)	(*0.59*)
RimskiSancevi	*−0.13*	*−0.23*	*−0.16*	*−0.21*	*−0.04*	*0.30*	*0.24*	*0.22*	0.34
	(*0.54*)	(*0.27*)	(*0.45*)	(*0.32*)	(*0.85*)	(*0.15*)	(*0.25*)	(*0.30*)	(0.10)
Ziharec	*0.26*	*0.17*	0.33	*−0.02*	*0.17*	0.36	*0.06*	*−0.15*	0.35
	(*0.39*)	(*0.57*)	(0.27)	(*0.94*)	(*0.57*)	(0.22)	(*0.84*)	(*0.62*)	(0.24)
Podhajska	*0.24*	*0.24*	0.41	0.38	0.48	0.48	*0.21*	−0.37	*−0.19*
	(*0.38*)	(*0.38*)	(0.12)	(0.16)	(0.07)	(0.07)	(*0.45*)	(0.17)	(*0.49*)
Belusa	*0.24*	*0.00*	*0.25*	*−0.01*	*0.06*	*−0.05*	*−0.16*	−0.36	*−0.21*
	(*0.37*)	(*1.00*)	(*0.35*)	(*0.97*)	(*0.82*)	(*0.85*)	(*0.55*)	(0.17)	(*0.43*)
Lund	**0.64**	**0.77**	0.37	**0.58**	**0.51**	*0.16*	*−0.16*	*−0.16*	*−0.06*
	(0.02)	**(0.002)**	(0.21)	**(0.03)**	**(0.07)**	(*0.60*)	(*0.60*)	(*0.60*)	(*0.84*)
Uppsala	*−0.12*	*−0.14*	*−0.28*	*−0.14*	*−0.08*	*0.14*	*−0.25*	-	*−0.10*
	(*0.55*)	(*0.49*)	(*0.16*)	(*0.49*)	(*0.69*)	(*0.49*)	(*0.21*)	-	(*0.62*)

(a) For the AMI describing number of days with extreme temperatures, for MZ in 23 of 30 cases and for WW in 50 of 63 cases (Tables 10 and 11) it is possible to identify an effect on RDSY. In six cases for MZ and four for WW, the effect was high, whereas in 17 cases for MZ and 46 for WW the effect was low.

(b) Very similar results with the same high/low effect partitioning were obtained for the AMI related to the number of dry days: an effect was found for MZ in 16 out of 22 cases (six for high and 10 for low effect) and for WW in 38 of 49 cases (0 for high effect and 38 for low) (Tables 12 and 13).

Table 12. Correlation coefficients and *p* values (in brackets, underlined values are significant) between AMI describing number of dry days and RDSY for MZ relative to observed value. No effect: *10 of 22*; with effect: **6** of **22**.

Location	Dstart		Dintensive			Dextreme			Dvextreme		
	AMJ	JJA	MAM	AMJ	JJA	MAM	AMJ	JJA	MAM	AMJ	JJA
Ziharec	*−0.05*	*0.14*	*−0.25*	−0.37	*0.04*	*−0.10*	−0.33	*−0.03*	−0.41	−0.49	*−0.27*
	(*0.88*)	(*0.68*)	(*0.45*)	(0.26)	(*0.90*)	(*0.76*)	(0.32)	(*0.93*)	(0.21)	(0.12)	(*0.42*)
Podhajska	**−0.62**	*−0.27*	**−0.72**	**−0.77**	*−0.29*	**−0.72**	**−0.79**	−0.32	−0.48	**−0.56**	*−0.18*
	(0.04)	(*0.42*)	**(0.01)**	**(0.005)**	(*0.38*)	**(0.01)**	**(0.003)**	(0.33)	(0.13)	**(0.07)**	(*0.59*)

Table 13. Correlation coefficients and *p* values (in brackets, underlined values are significant) between AMI describing number of dry days and RDSY for WW relative to observed value. No effect: *38 of 49*; with effect: **0** out **49**.

Location	Dstart	Dintensive		Dextreme		Dvextreme	
	AMJ	MAM	AMJ	MAM	AMJ	MAM	AMJ
Gross-Enz.	*−0.09*	*−0.27*	*−0.25*	−0.46	*−0.29*	−0.36	−0.33
	(*0.73*)	(*0.29*)	(*0.33*)	(0.06)	(*0.25*)	(0.15)	(0.19)
RimskiSancevi	*0.25*	*0.10*	*0.20*	*0.05*	*0.21*	*0.06*	*0.09*
	(*0.23*)	(*0.64*)	(*0.34*)	(*0.81*)	(*0.32*)	(*0.78*)	(*0.67*)
Ziharec	*0.05*	*0.13*	*0.09*	0.40	*−0.10*	*−0.23*	*0.02*
	(*0.87*)	(*0.67*)	(*0.77*)	(0.17)	(*0.74*)	(*0.44*)	(*0.94*)
Podhajska	*−0.13*	−0.41	*−0.28*	−0.38	−0.38	*−0.28*	*−0.24*
	(*0.64*)	(0.12)	(*0.31*)	(0.16)	(0.16)	(*0.31*)	(*0.38*)
Belusa	*−0.03*	*−0.03*	*0.08*	*0.00*	*0.02*	−0.31	*−0.20*
	(*0.91*)	(*0.91*)	(*0.76*)	(*1.00*)	(*0.94*)	(0.24)	(*0.45*)
Lund	*−0.28*	*−0.29*	*−0.18*	*−0.17*	*0.01*	*−0.15*	*−0.02*
	(0.35)	*(0.33)*	(*0.55*)	(*0.57*)	(*0.97*)	(*0.62*)	(*0.94*)
Uppsala	*0.09*	*−0.27*	-	*0.06*	*0.05*	−0.38	-
	(*0.66*)	(*0.18*)	-	(*0.77*)	(*0.80*)	(0.05)	-

Particularly low correlations between both the indices describing the frequency of days with extreme temperatures and the indices related to drought suggest the robustness of the CERES—Wheat model in DSSAT. However, the almost equal frequency of high and low correlations for MZ, in the case of AMI describing the number of dry days, indicates a high level of uncertainty in the CERES—Maize model simulations under drought-related AWCs.

4. Discussion

The results obtained demonstrate significantly different responses of yield to AWCs relative to crop and region. In general, WW yield was less sensitive to the selected AWCs then MZ yield. The reason for this finding is that the periods with an increased number and intensity of AWCs (such as drought- and heat-related ones) during the year (April-September), which are important for agricultural production, coincide to a greater extent with the growth period of summer crops then with that of winter crops. An absence of highly negative correlations between the measured WW and MZ yields and the AMI describing AWC intensity and frequency is a result of nonlinearity and variability (e.g., dependent on the stage of development) in the crop response to changes in growing conditions [15].

First, the effects of AWCs on actual yields were estimated. With all locations included, this study showed that in 57% of cases with MZ and 65% of those with WW, the effect of the AMI describing the number of days with extreme temperatures on actual yield was low. Conversely, the yield effect was high (positive or negative) in 20% of cases with MZ and 3% of those with WW. In general, as expected, we see higher statistical significance with higher correlations. The key factor, however, is the size of the sample, which varied in our case between 11 and 24 years. This is a large number when dealing with observed yields, but it can negatively affect the statistical significance. Statistically significant correlations at level 0.05, in the case of MZ, were obtained for number of tropical days in August in Dubrovčak Lijevi and number of summer days in July in Ziharec. In the case of WW, the same statistical significance was obtained for number of frost and freezing days in February in Rimski Sancevi and number of summer days in May and tropical days in June in Podhajska. Very similar results with respect to correlation coefficients (low effects of 50% in the case of MZ and 55% for WW) were obtained for the AMI related to the number of dry days on actual yield. The positive or negative effect of dry days on actual yield was high: At 32% of cases for MZ and 6% for WW. Statistically significant correlations at level 0.05, in the case of MZ, were obtained for different intensities of drought in AMJ and only for very extreme drought in MAM. In Gross-Enzersdorf and Podhajska, a statistically significant drought occurred in the AMJ period, while at Rimski Sancevi and Ziharec, drought in MAM appears with higher significance. Note that in the decade following the year 2000 several extremely dry and hot years occurred in Central Europe (*i.e.*, 2003 and 2006), during which the response of yield to drought and heat extremes was, most likely, even more pronounced (*i.e.*, [56]) than in the preceding decades.

Two regions, northern Europe and central and southeastern Europe, can be distinguished in terms of crop responses to AWCs. In the northern locations, the effect of very low winter temperatures on actual and simulated yield was much more pronounced then the effect of extreme temperatures and drought conditions during the rest of the WW growing season. Only in Sweden yield was related to low temperatures. Specifically, low yields were correlated with the number of arctic days in January. A previous study [57] has found, for basically the same data set, that high yields were related to high February temperatures and were less significantly related to January temperatures, indicating that the relationship of temperature to yield depends on the way in which the effects of temperature on the crop are expressed. The apparent absence of a correlation between yield and number of days with drought in Sweden is in agreement with other studies, which have seldom found clear relationships between the precipitation in specific months from March through June and winter wheat yield in Sweden [58], Denmark [59], and Finland [60]. This lack of clear relationships may be due to prevailing frequent irregular precipitation and the ability of the soils to buffer short-term water shortage.

The analysis of the deviations between simulated and actual yields showed the following results: At 57% of cases with MZ and 73% of those with WW, the effect of the AMI describing the number of days with extreme temperatures on the deviation of simulated yield from the actual yield was weak. Statistically significant correlations at level 0.05 can be identified for number of summer days in May in Dubrovčak Lijevi and number of summer days in May and June in Podhajska for MZ, as well as number of frost and freezing days in January in Lund. Values very similar to the above, *i.e.*, 45% for MZ and 78% for WW, were obtained from the analysis of the effect of the AMI related to the number of dry days on yield simulations. In Podhajska, a statistically significant correlation (at level 0.05) can be identified between number of dry days in AMJ and MAM and RDSY in the case of MZ. For WW a similar result was obtained for number of days with very extreme drought in the MAM period in Uppsala. The deviations between the DSSAT simulated yields and observed yields at Lund in southern Sweden were correlated with the number of cold days in February. This result might be explained by the lack of considered overwintering processes in the model. The use of frost tolerance models (e.g., [61]) might improve the simulations. Surprisingly, however, for Uppsala, which is located farther north than Lund, the deviations could not be related to winter temperatures, although they are known to influence yield even more than in southern Sweden [57]. The different model performances between the locations, both for extreme temperatures and dry conditions could be caused partly also by the fact that that the same cultivar settings (calibrated on Austrian cultivars) were applied at all sites. Obtained *p*-values for the majority of calculated correlation coefficients are larger than 0.05, indicating that the null hypothesis of no linear relationship between RDSY and AMI failed to be rejected. However, it should be taken into account that a relationship can be strong and yet not significant. Conversely, a relationship can be weak but significant.

5. Conclusions

The effects of adverse weather events on crops and agricultural crop production are still poorly understood and their prediction with crop models is currently very difficult [6,41]. The conclusion of our study, based on the applied DSSAT models, is that the simulated yields show less sensitivity to AWCs, as represented by the selected AMI, than the correlation with actual yields. This means that the sensitivity of the applied crop models to AWCs is generally too weak, at least under the conditions of the study sites selected for our analysis. However, this result can also be a consequence of other strong effects on actual yields, which are not adequately represented by the crop simulation processes (*i.e.*, the effects of a combination of different stresses, different cultivar specific responses, or the time lag effects of stresses). In any case, it is very difficult to uniquely define the relationship between the selected AMI and RDSY for MZ and WW. If present, even small correlations between the AMI and RDSY for WW and MZ yields can be an indication of an AWC effect on the deviation of the simulated yield from the observed one, as the crop response may vary depending on additional factors mentioned above.

The important message of this and many other studies addressing the effects of AWCs on crops is that AWCs will affect yield but it is very hard to predict: (a) the time and magnitude of the effects, (b) the plants' vulnerability at the time of an AWC (as one of the key factors of the plant response to

AWCs), and (c) whether or not the AWC will affect the ability of a crop model to reproduce this effect. In the presence of AWCs, the response of the soil-plant-atmosphere system is so uncertain due to several factors influencing stress responses that it is only possible to talk about the probability of a scenario rather than the specific event itself. Evidently, there is much room for the improvement of crop models and their response to AWC signals in terms of meteorological data input, as well as for the use of additional information about the effect of AMI on potential crop yield risk. Accordingly, a focus on the assessment of errors and level of uncertainty in crop simulations, rather than the reduction or elimination of these errors and uncertainties, can result in a more efficient use of crop models in the presence of AWCs. From that perspective, one possible approach that can be taken in our attempts to improve the forecasting of yields in the presence of AWCs is the so-called "event scenario" approach. This is a statistical approach based on the analysis of long-term crop yield-AWC data series and AMI as AWC signals under the specific agroecosystem conditions. Such an approach can produce typical scenarios for specified location and climate, crop growing, multiple stress conditions, crop type vulnerabilities, and AWCs. However, because the severity and frequency of AWCs will be affected by climate change, regular reassessment will be necessary as increasing effects of heat and drought on yield are expected under future climate scenarios [29].

Acknowledgments

This research has been conducted as part of the COST Action 734 "Impacts of climate change and variability on European agriculture (CLIVAGRI)". Projects contributing to the study: "Climate variations and changes and response in affected system of the Croatian Ministry of Science, Education and Sport"; "Studying climate change and its influence on the environment: impacts, adaptation and mitigation" (43007) financed by the Ministry of Education and Science of the Republic of Serbia within the framework of integrated and interdisciplinary research for the period 2011–2014; and AgroDroughtAustria (ADA, 2013–2016), Project No. KR12AC5K01071 of the Austrian Climate Research Program (ACRP). VišnjicaVučetić is grateful to the Pioneer-Sjeme d.o.o. Zagreb for the crop data from the farm in Dubrovčak Lijevi.

Author Contributions

Branislava Lalić: Design of scope of research, calculation of correlation coefficients, data analysis and interpretation and paper writing;

Josef Eitzinger: Idea and design of scope of research, data supply, data analysis and interpretation and paper writing;

Sabina Thaler: Crop simulations;

Višnjica Vučetić: Data supply and description of local characteristics for Croatia;

Pavol Nejedlik: Data supply and description of local characteristics for Slovakia, critical analysis of obtained results, reading and commenting of paper;

Henrik Eckersten: Data supply and description of local characteristics for Sweden, critical analysis of obtained results, reading and commenting of paper;

Goran Jaćimović: Data supply and description of local characteristics for Serbia, critical analysis of obtained results, reading and commenting of paper;

Emilija Nikolić-Djorić: Statistical calculation and analysis.

Conflicts of Interest

The authors declare no conflict of interest.

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