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Description of Meteorological Indices Presented Based on Long-Term Yields of Winter Wheat in Southern Germany

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Abstract: This study had three main objectives. First, weather indices were listed and their derivations were described to show which weather parameters could be used to describe the influence on agricultural yields. Second, farmers and agricultural scientists should be given the opportunity to evaluate the weather of the observation years in the study region. Furthermore, significant fluctuations in winter wheat yields were compared with weather events. As weather variables, 45 meteorological indices were used, such as precipitation-, temperature-, precipitation-temperature-, growing-period-, and radiation-related indices. In the case of winter wheat, heat waves and dry periods were the most important factors that affected the yields. For the past 20 years, in particular, there have been recurrent spring and summer months with low precipitation and, in some cases, significantly too warm periods, such as in 2003 and 2018 (April to October 2003: +16% °C, 2018: +27% °C, 2003: −38% mm, 2018: −12% mm in relation to 1978 to 2020), which were associated with particularly high yield losses. The qualitative assessments illustrate that in the observation period, years with reduced yield compared with the multiannual trend were frequently well explainable by extreme weather events.

Keywords: climate indices; crop production; long-term yield; plant growth; fertile site; weather anomaly

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1. Introduction

1.1. Background

Approximately 80% of the yield variability of crops can be explained by prevailing weather conditions [1]. Extreme weather events, such as heatwaves, dry periods, heavy precipitation, or unusual frost events, have a particularly significant impact on agricultural yields. These can occur either as individual events, in combination with each other, or with a time lag and result in a wide variety of effects depending on the preceding weather. Thus, weather extremes relevant to agriculture can trigger damage within a few hours, days, or weeks [1]. The temporal occurrence of extreme weather conditions plays a decisive role, as crops react differently to weather extremes during the various stages of development. Depending on the duration, extent, and geographical coverage, damage can ultimately be observed in local, narrowly defined areas or on a supra-regional scale.

Wittchen et al. [2] and Bernhofer et al. [3] provided important parameters for measuring, classifying, and evaluating extreme agrometeorological events and showed which indices are of particular relevance for arable farming.

In recent decades, extreme weather events have mainly been discussed in combination with climate change (Table 1). A selection of research works to better understand the fluctuations of yield in experimental areas show that approaches to the evaluation of certain weather anomalies, such as heat, drought, waterlogging, and frosts, are widely available. However, the combination of several successive extreme events and their concrete impact on agriculture that occur in reality has not yet been adequately investigated.

Table 1. Literature overview of various studies that investigated the effect of climate on barley, wheat, and maize grain yields.

Author	Year	Location	Crop	Factors and Effects
Weigand [4]	2014			Agricultural meteorology and the significance of certain weather anomalies for arable farming
Gömann et al. [1]	2015			Thresholds for agrometeorological extreme weather events and impacts on different agricultural crops
Barlow et al. [5]	2015	Germany	Wheat	Effects of extreme heat and frost events on wheat
Kristensen et al. [6]	2011	Denmark	Wheat	Summer temperature has the strongest effect, resulting in lower yields with increasing temperature, while yields increase with increasing radiation in summer and spring
Gobin [7]	2012		Cereals	Effects of heat stress and drought on cereal development
Ontel, Vladut [8]	2014		Maize	Correlation between drought indices and yield in maize
Wu et al. [9]	2014		Wheat	Influence of late frosts on the development of wheat
Seidel [10]	2016		Wheat, barley, maize	Extreme weather events and their role in the development of pests in wheat, barley, and maize
Ren et al. [11]	2014		Maize	Effects of heavy precipitation and waterlogging on maize cultivation
Wollmer [12]	2016	Germany	Wheat	Temporary waterlogging causes reduced growth, nutrient concentration, and yield of wheat
Heil et al. [13], Heil et al. [14]	2020, 2021	Germany	Wheat	In more fertile locations, the yield is determined, to a considerable extent, by climatic conditions in winter and the transition periods from winter to the warmer season and vice versa, and less by climatic conditions during the main growing season

Barnabas et al. [15] and Gobin [7] investigated the effects of drought and heat stress on the productivity of cereals. They pointed out that the consequences of this combination of extreme events are still insufficiently known. Seidel [10] addressed extreme weather events and their role in the development of pests in wheat, barley, and maize. According to this study, we can expect more frequent unusual weather anomalies and increased pest pressure to have a negative impact on yields.

Several authors, such as Sivakumar et al. [16], Rippel [17], and Frühauf [18], already highlighted the consequences of climate change for agriculture, also in connection with extreme weather events. They investigated the extent to which unusual weather anomalies, such as heatwaves and drought, will continue to develop in terms of their frequency and intensity. In addition, the opportunities and risks for arable farming in the wake of rising temperatures and increased precipitation variability as a result of climate change are being researched. Weigand [4] presented basic points on agricultural meteorology and the significance of certain weather anomalies, such as drought, waterlogging, and heat, with possible adaptation strategies. However, the interaction between extreme weather conditions relevant to agriculture and, ultimately, their impact on agricultural production still poses a particular scientific challenge [19].

Osborne and Wheeler [20] analyzed changes in the variability of wheat, maize, and rice in major producing countries by calculating 23 years of deviations of yield residuals from the average trend. They concluded that yield variability has decreased rather than increased since 1961, particularly for wheat and rice.

Last but not least, the Thünen Report 30 by Gömann et al. [1] on the effects of extreme weather conditions relevant to agriculture, which was commissioned by the Federal Ministry of Food and Agriculture, shows the importance of such meteorological anomalies for arable farming and the need for further research into the interactions between the extremes. They provided an overview of general extreme weather events with corresponding threshold values for them depending on their relevance for various agricultural crops during the different stages of development. Accordingly, weather situations that deviate particularly strongly from the long-term reference period and those with economic damage that exceed a certain threshold value are classified as extreme.

1.2. Objectives of This Study

This study aimed to (i) identify years with significant yield reductions; (ii) describe the relationships between these years and weather events, as well as (iii) which periods are essential for yields; and (iv) identify indices that indicate the severity of a reducing impact on yield.

2. Materials and Methods

These relationships were derived and classified based on weather indices of the climate station Freising Weihenstephan-Dürnast of the German Weather Service [21] and winter wheat yield data from the district of Freising. For this purpose, the period from 1978 to 2020 was considered and comparative values from the 30-year reference period 1950 to 1979 were used to compare the climatic indicators.

2.1. General Description, Soil, and Physiography of the Freising District

The district of Freising is divided into two main parts in terms of geology, pedology, and landscape.

The northern part is partly covered with Pleistocene loess, partly waterlogged brown earth (Cambisol), and pseudogleys (Planosol and Luvisol). The other soil types are pelosols (Vertisol) in clay lenses and para-brown earth (Luvisol) in small loess areas. On eroded hills, regosols (Leptosols, Arenosols) are often accompanied by kolluvisols (Anthrosol) in the valleys. At the bottoms of valleys, waterlogged soils dominate (Gleysol) [22,23]. Holocene deposits with small-scale changes of partly very different soil types (Phaeozem, Chernozem partly gleyic, Leptosol, and Histosol) are further observed [23]. In contrast with the northern part, the area in the south consists of Holocene deposits (dominated by flat accumulated gravel material).

The climate of the Tertiärhügelland (Tertiary Hill Country) is characterized by an annual average precipitation of 765 mm (1990–2019). The average annual temperature is 8.7 °C (1990–2019).

The location of the weather station is latitude 48.4022° N and longitude 11.6944° E, and has an elevation a.s.l. of 477 m (Figure 1 [13,14]).

Cool, humid, and, therefore, good growing conditions for agricultural plants usually prevail during the year.

Winter wheat is the cereal with the highest soil requirements. Potential evaporation from emergence to harvest is about 500 mm in the main growing season. From the beginning of May to mid-July, it is 300 to 350 mm, with high evaporation demands (radiation, temperature) up to 400 mm, with correspondingly higher yields (approx. 70–100 dt/ha grain) if this water requirement can be met. Due to its early root penetration and high root formation, winter wheat is better able than many other crops to exploit the moisture reserves of deeper soil layers (up to approx. 1.8 m on deep loamy soils, approx. 120 mm soil water). Therefore, it has deep soils with good storage capacity, even in areas with low precipitation (<600 mm annual precipitation), and has high yield stability (Bavarian State Office for Statistics, 2020). For winter wheat, the increasingly dry early summer periods present particular challenges. Shortly before flowering in May, wheat is particularly sensitive to high solar radiation, which can lead to the sterilization of pollen and prevent fruit sprouting; just before maturity in July, on the other hand, wheat is particularly sensitive to precipitation, as it can prevent the main ear from maturing by forming smaller spikelets.

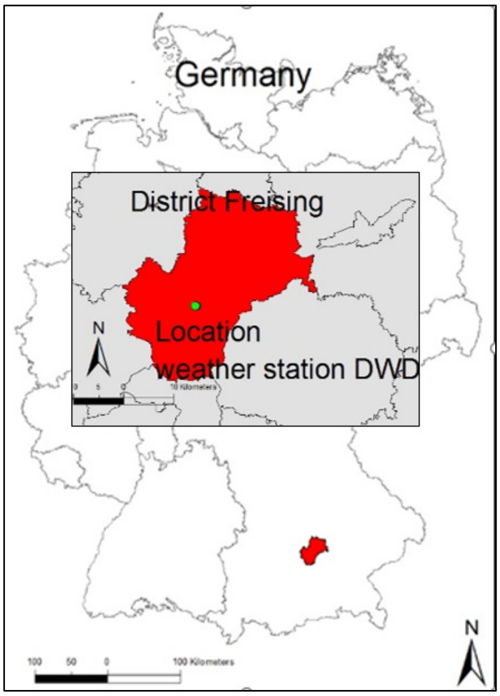


Figure 1. Location of Freising district and the weather station "Weihenstephan-Dürnast".

In a Bavarian comparison, the district has slightly above-average yields for winter wheat and winter barley and slightly below-average yields for grain maize (Bavarian State Office for Statistics, 2020).

2.2. *Description and Classification of the Weather Indices*

The basic data set contained daily data of the following:

- Maximum temperature (°C);
- Minimum temperature (°C);
- Temperature amplitude;
- Average air temperature (°C);
- Precipitation (mm);
- Relative humidity (%);
- Sunshine duration (h);
- Global radiation (Wh/m^2).

From these data, the indices were calculated and are presented in Table 2.

In the first step, it is important to define what an extreme event is. This term is not based on a precise definition. An extreme event describes an "extraordinary" event, i.e., an event that deviates from certain average values compared with other events of its kind and has a very long, irregular return period. This means for the place where the event occurs, it is rather a rarity. By definition, the characteristics of so-called "extreme weather" can vary in absolute terms from place to place. If a pattern of extreme weather persists over a period, e.g., a season, it can be classified as an "extreme climate event", especially if it has a mean or sum that is itself extreme (e.g., drought or heavy rainfall over an entire season) [25].

Table 2. Overview of the climate variables used in this study (compiled according to Bernhofer et al. [3], Wilhite [24], and Heil et al. [13,14]).

	Variable	Definition/Time Range		The Formula for the Derivation of Indices
Precipitation-related indices	Precipitation sum (Pm)	The sum of precipitation (yearly, April–October, monthly, and daily)		$P_m = \sum_{i=1}^{n} P_d$ where P_d is the precipitation per day
	Precipitation intensity (PI)	Sum of days on which a certain amount of precipitation occurred	PI1: >0–1 mm per day	$PI1 = \sum_{i=1}^{n} P > 0\ \text{mm} + P \leq 1\ \text{mm}$
			PI2: >1–10 mm per day	$PI2 = \sum_{i=1}^{n} P > 1\ \text{mm} + P < 10\ \text{mm}$
			PI3: ≥10 mm per day	$PI3 = \sum_{i=1}^{n} P \geq 10\ \text{mm}$
			Heavy precipitation, number of days	$PI4 = \sum_{i=1}^{n} P \geq 30\ \text{mm}$
			Vegetation-favorable precipitation, number of days with 2–4.9 mm	$PI5 = \sum_{i=1}^{n} P \geq 2\ \text{mm} + \leq 4.9\ \text{mm}$
			Daily, where P is the precipitation (mm) and n denotes the number of days	
	Rain-free days (P0)	Sum of days without precipitation (P0); monthly		$P0 = \sum_{i=1}^{n} N = 0\ \text{mm}$ where N is the height of the precipitation
	Number of precipitation-free pentads (P0_5 days)	The sum of the number of pentads (moving 5-day period) without precipitation		$P0\_5\ \text{days} = \sum_{i=5}^{n} N = 0\ \text{mm}$ where N is the height of the precipitation
	Meteorological dry periods (PD)	At least 11 consecutive days with daily precipitation less than or equal to 1 mm during the growing season		$PD = \sum_{i=11}^{n} N =< 1\ \text{mm}$ where N is the height of the precipitation
	Percent-from-normal ($P_y\% - \text{normal}$) ($P_m\% - \text{normal}$)	Current annual/monthly precipitation in relation to the 30-year mean from 1950 to 1979		$P_y\% - \text{normal} = \frac{P_y}{P_{(1950\text{to}1979)-\text{year}}}$ $P_m\% - \text{normal} = \frac{P_m}{P_{(1950\text{to}\ -1979)-\text{month}}}$ where P_y, P_m: precipitation per year, per month, respectively
	Cumulative precipitation deficits/surpluses (CPD)	Summation of precipitation anomalies annually/over the growing season/monthly		$CPD = \sum(P_{1950–1979} - P_{\text{actual}})$
	Precipitation (rainfall) anomaly index ($RAI_{\text{positive/negative}}$)	Relation of precipitation to extreme precipitation events from 1950 to 1979		$RAI_{\text{positive}} = 3 \times \frac{P_{\text{actual}} - P_{1950–1979}}{E_{1950–1979} - P_{1950–1979}}$ $RAI_{\text{negative}} = -3 \times \frac{P_{\text{actual}} - P_{1950–1979}}{E_{1950–1979} - P_{1950–1979}}$ P_{actual}: current precipitation per month; $P_{1950–1979}$: mean per month; $E_{1950–1979}$: mean of the 10% most extreme precipitation sums (10% percentile for positive/negative anomalies) of the validation period 1950 to 1979 for the observed month (e.g., January, then E is the mean of the 10% most extreme January precipitation sums of the years 1950 to 1979)

Table 2. *Cont.*

	Variable	Definition/Time Range	The Formula for the Derivation of Indices
Temperature- and precipitation-related indices	de Martonne aridity/humidity index (M-AI)	Evaluates the effect of precipitation and temperature on plant physiology per year	$\mathrm{M-AI} = \frac{P_y}{T_y+10}$ where P_y is the annual precipitation and T_y is the average annual temperature
	de Martonne–Reichel dryness index (MR-DI)	Evaluates the effect of precipitation and temperature on plant physiology and precipitation distribution per year	$\mathrm{MR-DI} = \frac{P_y}{T_y+10} \times \frac{K}{120}$ where P_y is the precipitation, T_y is the temperature, K is the number of days with precipitation in the observed period with $\geq$1 mm; 120 is the annual average number of days with precipitation $\geq$1 mm in Germany; 10 indicates that negative values in the denominator should be avoided
	Hydrothermal Selyaninov coefficient (HTC)	The ratio of the sum of precipitation and the sum of temperature (mean of the day) for all days above 10 °C per year	$\mathrm{HTC} = 10 \times \sum P_y / \sum T_d > 10\ ^\circ\mathrm{C}$ P_y is the precipitation per observed period and T_d is the mean temperature per day
	Rain factor (RF) after Lang	Relationship between precipitation and temperature per year (calculated for every year)	$\mathrm{RF} = \frac{P_y}{T_y}$ where P_y is the annual precipitation and T_y is the average annual temperature
Temperature-related indices	Mean temperature	Mean temperature per year, vegetation period (April to October), month (T_y, T_{veg}, T_m, respectively)	$T_y, T_{veg}, T_m = \frac{(\sum_{i=1}^{n} Td)}{n}$ where T_d is the diurnal mean air temperature of the day and n is the number of days
	Temperature threshold (TT)	Sum of the days on which the threshold values of 5 or 10 °C are exceeded; monthly values	$\mathrm{TT1} = \sum_{i=1}^{n} T_{max} \geq 5\ ^\circ\mathrm{C}$, $\mathrm{TT2} = \sum_{i=1}^{n} T_{max} \geq 10\ ^\circ\mathrm{C}$, where n is the number of days and T_{max} is the daily maximum temperature
	Frost-alternating days ($\mathrm{FAD}_{(\mathrm{Oct–Jul})}$)	Sum of days (October to July) with a change in temperatures above and below 0 °C within a day, between consecutive days	$\mathrm{FAD} = \sum_{i=1}^{n} T_{max} > 0 + \sum_{i=1}^{n} T_{min} < 0$ where n is the number of days, T_{max} is the daily maximum temperature, and T_{min} is the daily minimum temperature
	Frost index per Liu (FI_Liu)	Sum of the days on which the minimum air temperature is below −3 °C and the temperature difference is at least 8 °C from the mean value of the last 20 days; from September to May	$\mathrm{FI\_Liu} = \sum_{i=1}^{n} T_{min} <= -3\ ^\circ\mathrm{C} + \sum_{i=1}^{n=20} Td < 8\ ^\circ\mathrm{C}$ where n is the number of days, T_{min} is the daily minimum temperature, and T_d is the daily mean temperature
	Summer cold per Liu (SC_Liu)	Sum of the days on which the minimum air temperature is below −3 °C and the temperature difference is at least 8 °C from the mean value of the last 20 days; from April to August	$\mathrm{SC\_Liu} = \sum_{i=1}^{n} T_{min} <= -3\ ^\circ\mathrm{C} + \sum_{i=1}^{n=20} Td < 8\ ^\circ\mathrm{C}$ where n is the number of days, T_{min} is the daily minimum temperature, and T_d is the daily mean temperature
	Late frost index 1 (LFI 1)	Sum of the days on which the minimum air temperature falls below 0 °C; from April to June	$\mathrm{LFI1} = \sum_{i=1}^{n} T_{min} < 0\ ^\circ\mathrm{C}$ where n is the number of days and T_{min} is the daily minimum temperature

Table 2. *Cont.*

	Variable	Definition/Time Range	The Formula for the Derivation of Indices
	Late frost index 2 (LFI 2)	Sum of days on which the temperature is <0 °C; from April to June	$\mathrm{LFI2} = \sum_{i=1}^{n} T_{min} < 0\ ^\circ\mathrm{C}$ where n is the number of days with a temperature <0 °C and T_{min} is the daily minimum temperature <0 °C
	Early frost index 1 (EFI 1)	Sum of days on which the minimum air temperature falls below 0 °C; from July to October	$\mathrm{EFI1} = \sum_{i=1}^{n} T_{min} < 0\ ^\circ\mathrm{C}$ where n is the number of days with a temperature <0 °C and T_{min} is the daily minimum temperature <0 °C
	Early frost index 2 (EFI 2)	Sum of days on which the minimum air temperature falls below 0 °C; from July to October	$\mathrm{EFI2} = \sum_{i=1}^{n} T_{min} < 0\ ^\circ\mathrm{C}$ where n is the number of days and T_{min} is the daily minimum temperature
	Frost days (FT)	Sum of days on which the air temperature falls below 0 °C; monthly values; from October to July	$\mathrm{FT} = \sum_{i=1}^{n} T_{min} \leq 0\ ^\circ\mathrm{C}$ where T_{min} is the daily minimum temperature (°C)
	Ice days (ID)	Sum of days with a maximum temperature of <0 °C over the entire year	$\mathrm{ID} = \sum_{i=1}^{n} T_{min} \leq 0\ ^\circ\mathrm{C}$ where T_{min} is the daily minimum temperature
	Frost severity (FSev)	Annual minimum temperature	$\mathrm{FSev} = T_{min} \leq 0\ ^\circ\mathrm{C}$, where T_{min} is the daily minimum temperature
	Frost shock (FSh)	Sum of days on which the air temperature drops by 15 °C within 24 h and the minimum air temperature falls below −3 °C; annual values	$\mathrm{FSh} = \sum_{i=1}^{n} T_{max} – T_{min} = 15\ ^\circ\mathrm{C} + \sum_{i=1}^{n} T_{min} < -3$
	Summer days (SD)	Sum of days on which the air temperature exceeds 25 °C; monthly values per year	$\mathrm{SD} = \sum_{i=1}^{n} T_{max} \geq 25\ ^\circ\mathrm{C}$
	Hot days (HD)	Sum of days on which the air temperature exceeds 30 °C; monthly values per year	$\mathrm{HD} = \sum_{i=1}^{n} T_{max} \geq 30\ ^\circ\mathrm{C}$
	Maximum values (MVa)	Absolute maxima per year in °C	$\mathrm{MVa} = T_{max}$
	Summer index ($\mathrm{SI_y}$)	Sum of days with a daily maximum air temperature above 5 °C; yearly	$\mathrm{SI_y} = \sum_{i=1}^{n} T_{max} \geq 5\ ^\circ\mathrm{C}$
	Summer index ($\mathrm{SI_{veg}}$)	Sum of days with a daily maximum air temperature above 5 °C; from April to October	$\mathrm{SI_{veg}} = \sum_{i=1}^{n} T_{max} \geq 5\ ^\circ\mathrm{C}$
	Winter index (WI)	Sum of days with a daily maximum air temperature below 5 °C; from November to April	$\mathrm{WI} = \sum_{i=1}^{n} T_{max} \leq 5\ ^\circ\mathrm{C}$ where n is the number of days
	Sum of the active temperatures (SAT)	Sum of temperatures above 5 °C during the growing season	$\mathrm{SAT} = \sum_{i=1}^{n} T_{veg} \geq 5\ ^\circ\mathrm{C}$ where n is the number of days

Table 2. *Cont.*

	Variable	Definition/Time Range	The Formula for the Derivation of Indices
Growing-period-related indices	Beginning/end of the main vegetation period	The first week of the year on which the threshold value of 5 °C is permanently exceeded (at least 5 days)	
	Climatic vegetation time duration 1 (CD1)	Number of 5-day periods with a mean daily air temperature above 5 °C; values per year	
	Climatic main vegetation time duration 2 (CD2)	Number of days with the diurnal mean daily air temperature above 5 °C; values per year	
	Grassland temperature sum (GT-1)	Sum of the mean daily temperature until the value of 200 °C	
	Grassland temperature sum (GT-2)	Sum of the mean daily temperature until day 105	
Radiation-related index	Global radiation $GR_{(Oct–Jul)}$	Sum of radiation	$GR = \sum_{i=1}^{n} GR$ where n refers to the months

Additional explanations and interpretations of different levels are given in the Supplementary Materials.

Leser et al. [26] explained weather extremes as events that deviate in their occurrence from average values, trends, and experience and are characterized by extraordinary dimensions, special intensities, and a longer-term recurrence. The German Weather Service specifically describes an extreme weather event as a rare event that is rarer than the 10th or 90th percentile of the observed probability distribution. However, it should be taken into account that not only the severity but also the duration of an event is important. For example, the frequent occurrence of certain anomalies can only be classified as extreme by the sum of the deviations in a period, although the individual events are less unusual in themselves.

Using the example of the 2013 Elbe Flood, Gömann et al. [1] showed that at that time, as a result of recurring precipitation at the beginning of June and the preceding high soil moisture, the soil was no longer able to store precipitation, although the quantities that fell were not extremely high. Rather, the weather period, which in meteorology cannot be statistically classified as an extreme event, resulted in critical threshold values in ecological, physical, and social systems being exceeded, causing considerable damage. Thus, in addition to the duration, extent, and intensity, the preceding weather is also decisive.

However, it is possible that at the same time, extreme events are compensated for by favorable weather before and after the event and that damage is only slight or does not occur at all.

In this evaluation, only agriculturally relevant weather extremes that were accompanied by significant crop losses were considered. No distinction was made here as to whether the extreme events that occurred were regional events, such as droughts and heatwaves, or very local anomalies, such as heavy precipitation events, hailstorms, or topographically induced temperature extremes. Precipitation and temperature anomalies are primarily decisive for agriculture. The main focus is on the so-called drought indices. Dry periods or droughts as negative precipitation anomalies in combination with very high temperatures are some of the most important limiting factors in agriculture and, depending on their duration and severity, can lead to considerable yield losses [3].

The preceding explanations allow for a classification of weather events according to the following structure (compiled according to Bernhofer et al. [3] and Wilhite [24]).

2.3. Yield Data and Extreme Value Analysis

The yield data of winter wheat has been registered yearly by the Bavarian State Office for Statistics from all farmers and was provided by the Bavarian Office of Agriculture (Institut für Betriebswirtschaft und Agrarstruktur). The lowest level of the area of this recording is the district.

In the first step, the time series of the yield values were exponentially smoothed (with the trend after Holt). In the next step, the residuals between the measured yields and the smoothed yields were used as response variables to evaluate the weather influence.

This procedure is needed to remove any development trends in the time series. This smoothing filters out the effects of new varieties, herbicides, insecticides, fertilizers, technical equipment, crop rotation, tillage, and climate change. According to Sterzel [27], all quantifiable factors can thus be systematically removed from the yield. Weather effects remain implicitly embedded in detrended crop yield values (Table 3).

Table 3. Overview of the effects on the temporal yield development and the effects eliminated by calculating residuals (Sterzel [27]).

Effects	Effects Eliminated by Residuals	Effects Remaining in Residuals
Biological and chemical	New varieties Herbicides Insecticides Fertilizer and fertilization level	Diseases and pest infestation
Mechanical management	Technical equipment processing	
Management advancement	Crop rotation	
Atmospheric	Climate change	Weather deviations and extreme weather events

In the second step, the residual percentile levels were calculated. These levels were then the limits for the assessment where the yield was extreme. Statistical analysis was performed using SPSS v24.0. To carry out an extreme value analysis, and thus, clarify in which years extremely low or high yields could be observed, the 10th and 90th percentiles were considered. The 50th percentile was the average of the calculated residuals, and thus, the average deviation of the measured values from the predicted values. Furthermore, the 25th and 75th percentiles were calculated for the yield residuals to be able to identify further significant deviations in the yield patterns of individual years.

3. Results

3.1. Temporal Course of the Yields

From 1978 to 2019, the yields of winter wheat in the Freising district indicated a continuous increase, albeit with considerable fluctuations at times, from approximately 50 to approximately 80 dt ha^{-1}. This means nearly 0.5 dt ha^{-1} per year (Figure 2). The reason here was mainly the progress in breeding, but biological, chemical, mechanical, and management advancements were also influential.

An additional reason was indicated by the time course of the deviations. During the observation period, positive values predominated. Negative developments were observable in the years 1979, 1980, 1982, 1993, 2003, 2009, 2010, and 2018.

It is important to note that the weather is not a directly quantifiable factor but is nevertheless very relevant to yield.

In general, the more intensive and specialized the land management, the higher the risk. This is especially true for modern high-yielding varieties, which produce top yields under favorable conditions but offer less yield security under extreme conditions [28].

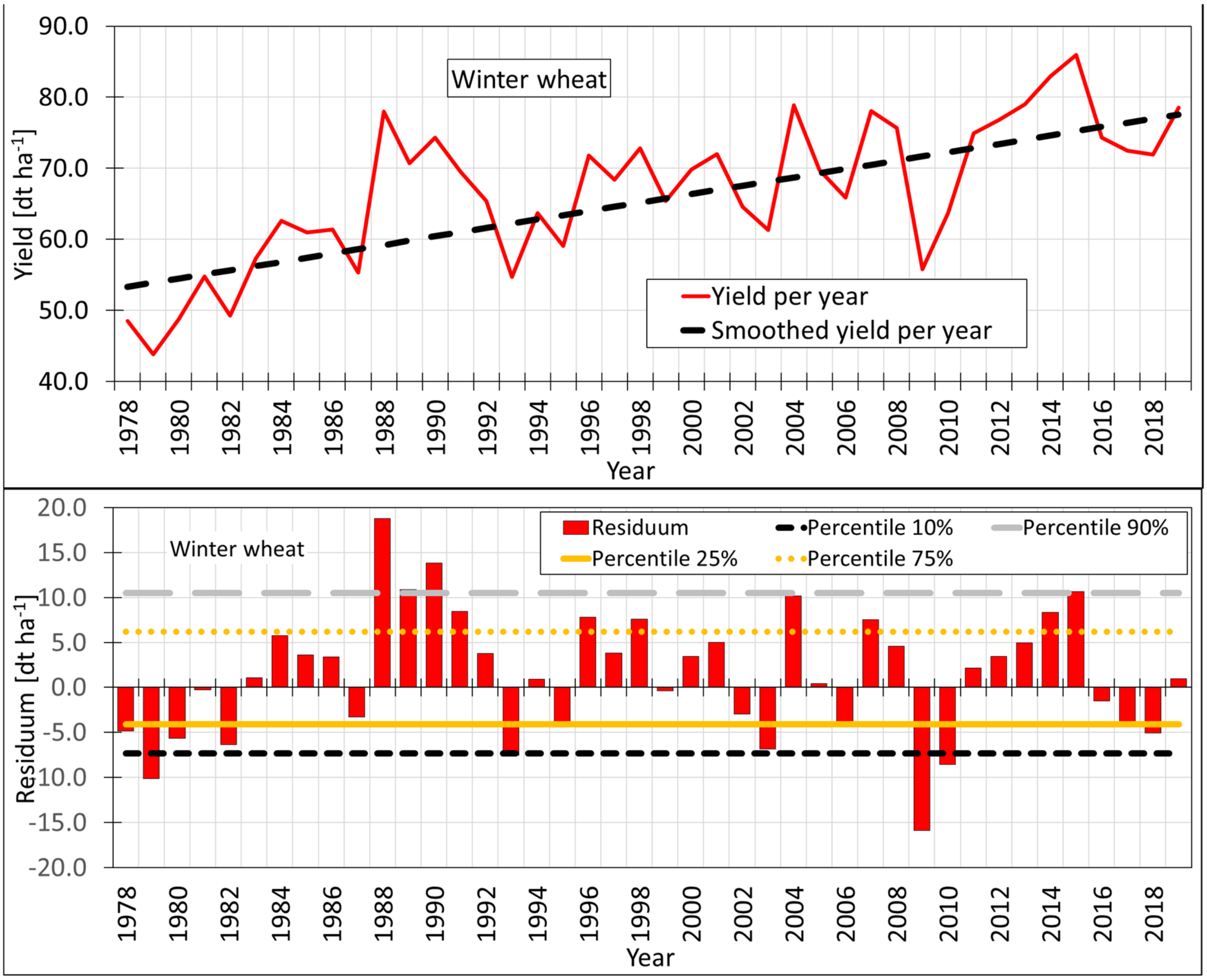


Figure 2. Annual yields of winter wheat between 1978 and 2019 in the district of Freising with the smoothing line (above) and the deviations from the smoothing line and the percentile levels (10%, 25%, 75%, and 90%).

3.2. Comparison of the Annual Variation of Yields with Weather Patterns

During the evaluation, the residuals were compared with the weather indices, and explanations for the low yields were worked out.

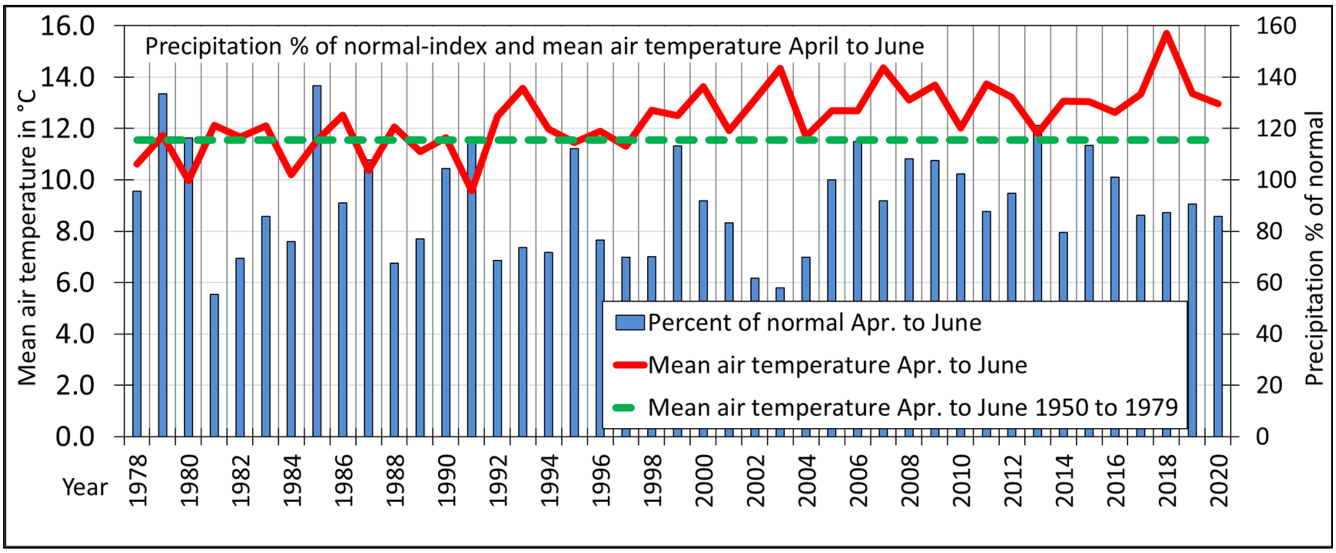
These comparisons were divided into the following stages: stock establishment, stock build-up, and production. The first stage began at sowing (October) and lasted until the beginning of shooting (May). During this period, the yield-bearing shoots/tillers were formed. The second phase began when the first node was visible and lasted until flowering (June). The production phase began after flowering and lasted until grain filling/ripening (June/August) and harvest (August).

1979: Especially from mid-June 1979 onward, there were repeated heavy rainfalls, as well as continuous rainfall events. The total June precipitation was 243 mm, which could be classified as extremely wet, with an $RAI_{positive}$ of 4.32 (Figure 3). Other indices also confirmed this evaluation (CPD, P_m%-normal, precipitation summed, and M-AI). The highest individual precipitation was just under 80 mm per day. During other times of this month, the precipitation was more or less evenly distributed over the entire period. There were no other heavy precipitation events (Figure S4); it can thus be assumed that conditions of waterlogging prevailed in certain areas. Wollmer et al. [12] showed that temporary waterlogging in winter cereals, especially during grain filling, shortens this phase through premature leaf senescence, and smaller grains form as a result. According to Marti et al. [29], waterlogging during the generative development phase is associated with impairments in flower formation and fertility, and thus, ultimately with a decline in grain number. In the case of increased silt content in the soils, as is the case in the district of Freising, persistent precipitation also leads to silting. The rainwater infiltrates insufficiently and a large part runs off superficially, which can lead to erosion damage [30]. Between the months of April and June, 134% of the normal amount of precipitation according to the climatological mean fell (Figure 2). For winter wheat, this was the second largest in the study period. It can be assumed that the wet weather also favored fungal infections, which could also have been responsible for the high crop losses. However, it must be taken into account that the data on the event are insufficient and there are hardly any reports on the 1979 harvest year.

1980: The mean yield decline in 1980 ranged between the 10th and 25th percentiles. Until April, the precipitation was higher than the 30-year average, but in May and June, the percent-of-normal reached only 0.67 and 0.93 (Figure S8). Since most of the sites have a high water storage capacity or are connected to groundwater, drought cannot be assumed. Moreover, the combined indices do not indicate plant stress (RAI April to June, 0.94; CPD May and June, −28.8 and −8.1; M-AI May and June, 34.0 and 50.0; MR-DI April and June, 37.4 and 80.1) (Figure 3). This also applies to the temperature indices. Additionally, the winter season delivered no indication of less favorable growing conditions (frost days, frost-alternating days, and frost shock).

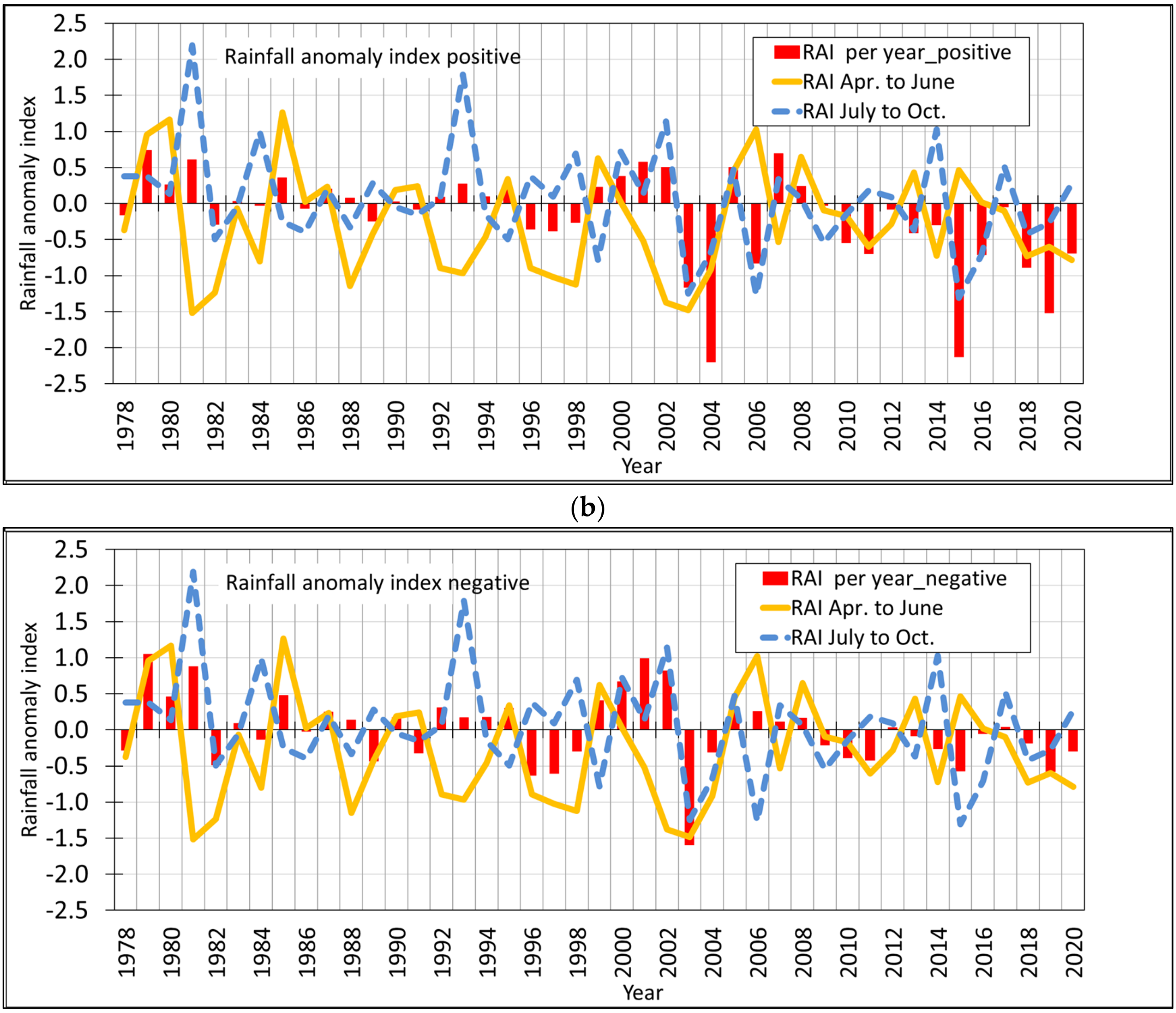
Therefore, no cause for this reduction in yield can be inferred from the available data.

1982: This year was characterized by lower precipitation from February to May, in July, and from September to November compared with the 30-year average (Pm%-normal: April, 0.45; May, 0.33; July, 0.71). The reduction was particularly pronounced in July, with only 74 mm (107 mm in the long-term mean). This was particularly evident in the CPD values (April, −28.9; May, −58.2; July, −30.4), HTC (whole year, 2.7), MR-DI (April to June, July to October, and April to October, approximately 22), and M-AI (April, 17.8; May, 15.2; July, 30.9).



(**a**)

Figure 3. *Cont.*



(**b**)

(**c**)

Figure 3. (**a**) Time course of the mean air temperature of the years 1978 to 2020, multi-annual mean temperature of 1950 to 1979, and yearly precipitation about the multi-annual precipitation (1950 to 1979). (**b**,**c**) Rainfall anomaly indices per year from 1978 to 2020 and for April to June and July to October.

The fact that the decline in yield was not even more pronounced was most likely due to June. In this month, the precipitation level reached the level of the long-term average (1982, 121 mm; 30-year average, 112 mm). This is also evident from the other indices (CPD value, 10.3; MR-DI, 60.3; M-AI, 54.9).

In addition to insufficient rainfall, plant stress may have occurred due to higher temperatures. The described year indicated 38 summer days (with 25 days in June and July) and two hot days with elevated values (Figures 4 and 5).

1987: The moderate yield reduction was caused by severe fluctuations in the winter temperatures. From November, the minimum values oscillated around 0 °C, and on 13°C, the temperature dropped to −26.3 °C. This was the lowest temperature during the whole observation period; plant damage likely occurred here. The prolonged frost meant that the number of frost change days in early 1987 was comparatively low (Figure S17).

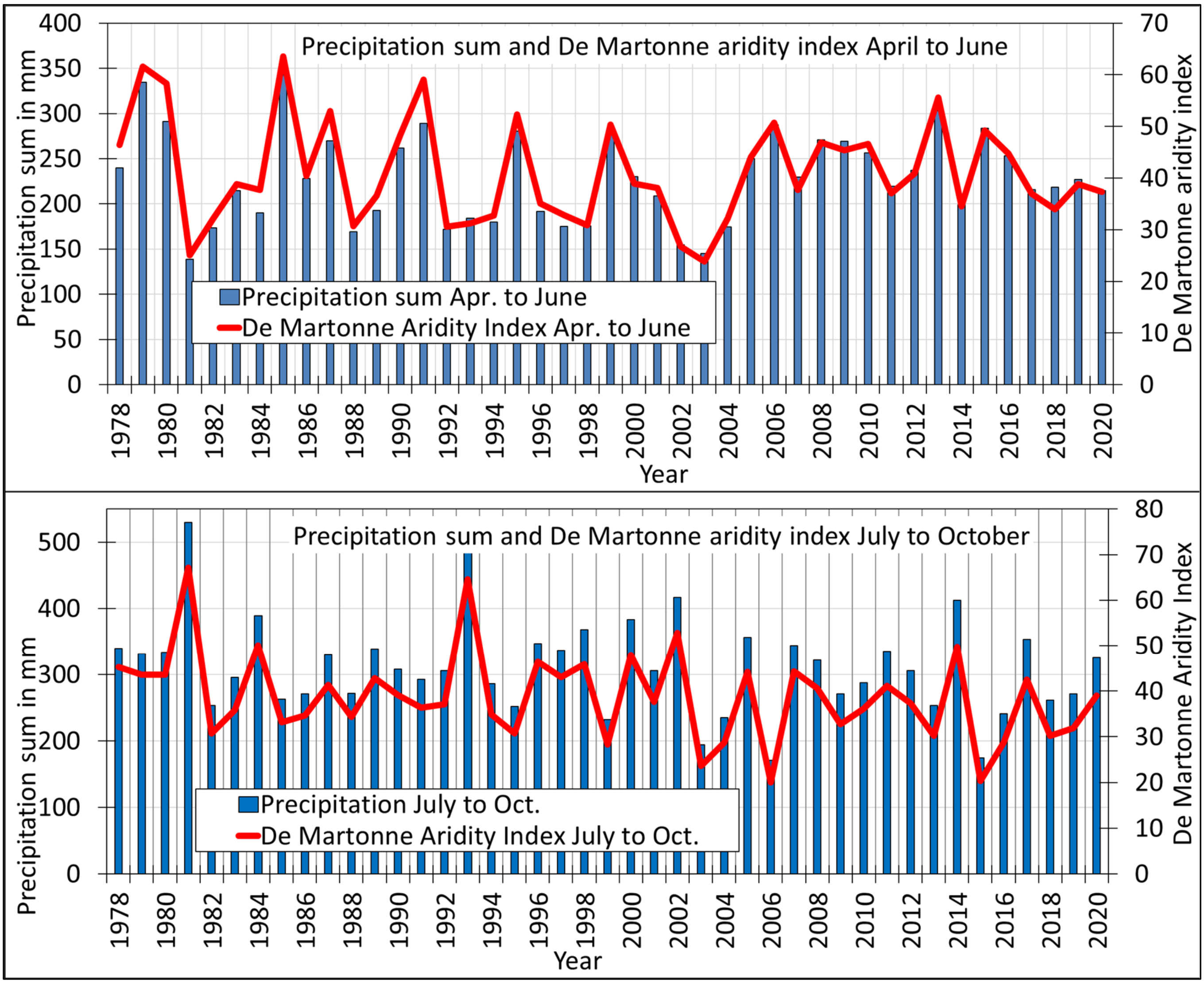


Figure 4. Time course of the precipitation sum and the de Martonne aridity index.

1993: The yield loss was ultimately considerable, with over 12%, thus belonging to the 10% of the worst yield years from 1978 to 2019.

Based on the meteorological data, two main observations were responsible for this decline.

The first five days of this year were characterized by a temperature of >5 °C in the second week. In the whole measurement period, this was the earliest beginning of the vegetation period. However, until April, 66 frost days, 44 frost-alternating days, and two frost shock days followed.

Severe drought-related crop failures had already occurred previously in 1993 when the entire first half of the year was characterized by precipitation deficits (January–May, 112 mm; January–June, 193 mm; 30-year average January–May, 268 mm; 30-year average January–June, 379 mm). The percent-of-normal precipitation indicated values from January to June of 0.9, 0.22, 0.5, 0.59, 0.83, and 0.73. These observations correspond with the number of rain-free days (January–May, 86 days; January–June, 102 days).

This is also evident from other indices from April to June (CPD values, −21.4, −14.5, and −30.3; MR-DI, 20.2, 7.0, and 61.0; M-AI, 18.4, 34.8, and 38.1) (Figures 4, 5 and S9).

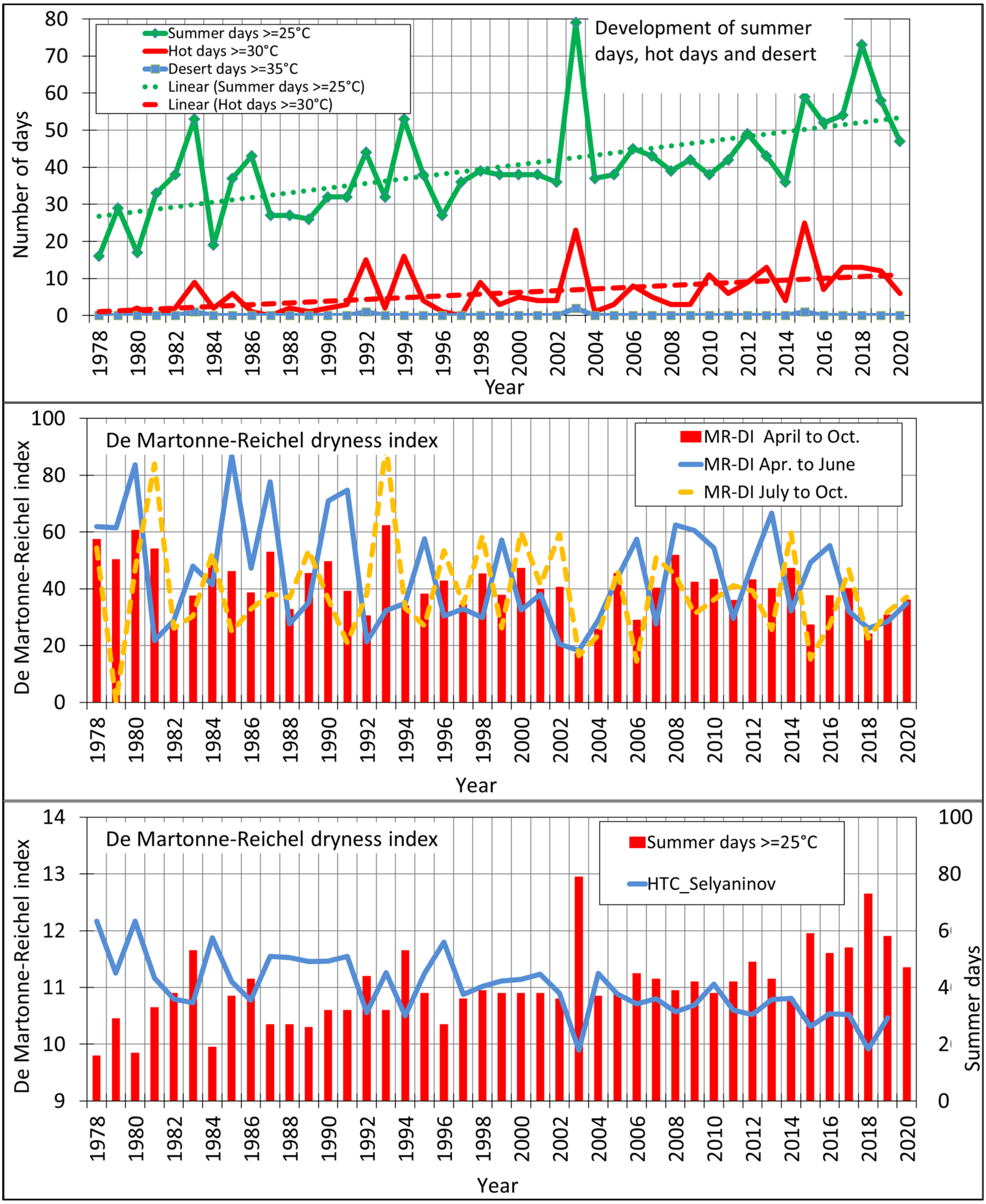


Figure 5. Time course of the de Martonne–Reichel dryness index, summer days, hot days, desert days, and HTC.

1995: The comparatively low yield reduction was likely caused by severe fluctuations in the temperature during the spring of this year. The temperature dropped on 15.05.1995 to a level of −1.3 °C at an altitude of 2 m after four weeks, with temperatures up to

11.3 °C. The last negative temperatures were recorded on 14 April, with −1.0 °C. This late frost event damaged the rapid plant development and caused a lower yield.

Additionally, a negative effect of the high precipitation in June during the phase of grain filling is imaginable. The total June precipitation was 153 mm, which means a CPD of 41.92 and a P_m%-normal of 1.38. Figure S5 indicates that the precipitation was more or less evenly distributed over the entire period. Wollmer et al. [12] and Marti et al. [29] described the influence of temporary waterlogging and wheat development. Especially during grain filling (June), waterlogging leads to premature leaf senescence, smaller grains, and a lower grain number.

2003: A very significant extreme weather period for the vegetation occurred in the year 2003, which, in comparison with the 30-year means, was too dry in February to April and June to September. Only the month of May showed a normal level of precipitation (Figure S2). Because the last five months of the preceding year (2002) were very rainy, the impact on vegetation was probably somewhat mitigated (Figure S5).

Low precipitation can also be seen in the corresponding indices (CPD, percent-of-normal, precipitation-free days and pentads, meteorological dry periods, number of summer days, and hot days).

In June, which is important for flowering and grain filling, approximately 19 summer days and 5 hot days were registered. With a mean air temperature of 20.26 °C, it was the warmest June since weather records began at the Weihenstephan-Dürnast site. In addition, only 38 mm of precipitation occurred. The unusual meteorological dry period could be documented using the de Martonne–Reichel aridity index, which showed a value of only 13.6. The very low $RAI_{negative}$ value of −3.06 is also an indicator that the month was too dry (Figure 3).

A cumulative precipitation deficit of −82.1 mm had already built up between February and April. From April to June, only 145 mm of precipitation occurred, which was approximately 58% of the usual amount of precipitation according to the 1950–1979 climatological mean. In the wake of high temperatures, the Martonne drought index was 23.8 during the period, lower than in any other year between 1978 and 2019 in the same time interval.

It can thus be assumed that a large proportion of the winter wheat stands suffered from water stress during June. This was reflected in the yield pattern, which was approximately 10% lower than expected. Since the decline was outside the 25th percentile and just above the 10th percentile, it can be considered a significant but not extreme loss. Because vegetative growth was almost complete at the beginning of the heatwave, the drought-related decline was thus less severe than for summer crops [31]. Nevertheless, the numerous days above 25 °C or above 30 °C from the beginning of June onward, precisely at the time of flowering and grain formation, led to a considerable proportion of the crop losses.

2006: This vegetation year showed strongly changing weather conditions. An extremely mild second half of October and the first half of November in 2005 likely promoted the development of infection.

In the long cold winter of 2005/2006, a persistent snow cover occurred, which repeatedly thawed and subsequently froze due to repeated severe frosts. In some places, the snow cover reached a record height of up to 50 cm for the northern foothills of the Alps, in early March 2006. In addition to an increasing lack of air under the hardened snow cover, the yield losses this year were likely to have been caused by increased snow mold infestation (*Gerlachia nivale* L.) in unfavorable areas [32]. This is the most important wintering disease of winter cereals, often originating from infected crop residues [33]. Particularly favorable infection opportunities are already offered by well-developed stands in the fall [31].

The growing period in 2006 started with unusually high precipitation in March and April. This filled possible deficits in the soil water reservoir.

The entire summer was characterized by very low precipitation. In particular, July was too dry, with 19.5 mm and only 19% of the long-term average of the years 1950–1979 (Figure S5). In addition, the highest temperature since records began was recorded for a July month at 21.06 °C. This combination resulted in a very low MR-DI of only 5.3. It should be noted that precipitation deficits already occurred in May and June, which ultimately added up to approximately 110 mm by the end of July [21].

Between July and October, the MR-DI fell to 20, the lowest value in the entire observation period (Figure S5), although this was mainly due to the exceptionally dry and hot July. In addition, only 170 mm of precipitation fell in these four months, which was the lowest between 1978 and 2020.

The climate indices reflect these conditions well (CPD, percent-of-normal, RAI, and HTC).

Despite the drought, which can be classified as extreme, especially in July but also in May and June, the reduction in the observed yield was only comparably weak. This could have been because the spring precipitation prevented a sharper decline.

2009: The 2009 growth period was characterized by several negative impacts. The autumn of 2008 and the following winter were already too dry overall. At 11.82 °C, April was the warmest month since weather records began. The greatest damage was caused by a violent thunderstorm in the district of Freising with hailstones up to 3 cm in size (May 26). The northern parts of the district were particularly affected, with complete crop destruction as a result of the storm [34]. At the Weihenstephan-Dürnast weather station, 26.5 mm of precipitation was measured within one hour. However, as this was a local thunderstorm cell, the amount of precipitation was likely to have been much greater in some parts of the district. The other districts surrounding Freising were less affected by this storm, but here, the yields were also lower. With only 55.8 dt/ha in the Freising district, almost 16 dt/ha less winter wheat was harvested than was expected from the smoothed forecast values. The 10th percentile was again clearly undercut with the largest negative deviation in the observation period. According to Weigand (2014), hail can not only destroy entire plant stands in a short time, but the numerous wounds also favor fungal secondary infections, even in the case of small hailstones.

2010: Significant yield losses, although not quite as high as in 2009, were also recorded for 2010. The beginning of the main vegetation period was characterized by a drought in January to April. This was followed by a very wet period from May to mid-June. Around 230 mm of precipitation occurred within these six weeks. At the same time, the temperatures rose significantly in June. According to local media, numerous fungal infections occurred during this period [35]. According to Hatfield et al. [36], very humid and warm conditions, especially in May and June, cause an increased risk of infestation by plant pathogens in wheat. According to Jahn et al. [37], the most important disease for cultivated winter wheat in Germany, namely, Septoria leaf drought, as well as brown rust, may have spread as a result of the warm and humid conditions. The fungus Septoria tritici causes oval spots on the leaves and causes, on average, the highest yield loss of 7 dt/ha and peak losses of up to 30% [35]. Brown rust (*Puccinia triticina*) shows a similar disease pattern with the formation of oval, brown summer spore deposits and an average yield loss of 2.5 dt/ha [34]. Fusarium infections, such as Fusarium graminearum, may also have been widespread. In partial dew rot, the ear spindle axes are colonized by the fungus. As a result, the water supply is interrupted and the green color of the ear fades to whitish. In the process, the fungus produces, among other things, the Fusarium toxin deoxynivalenol, for which there are strict limits in food processing [38]. If the existing limits are exceeded, the harvested crop cannot be further processed and must be disposed of. According to West et al. [38], drought from autumn to spring can increase the probability of increased pest pressure from Fusarium. Accordingly, the conditions in 2010 were optimal for the strong spread of fungal infections. Also, for this year, the yield deficit was below the 10th percentile value, and thus, extremely high.

2017: In this year, the average yield reductions were around 5 dt/ha. The month of June was the third warmest since the beginning of weather records, with 18.54 °C, and it can therefore be assumed that the high water demand of winter wheat, especially in shallow soils, could not be fully met during this period and that it partly suffered from water stress. In addition, there was an unusually high number of summer days, with

16 days, as well as 3 hot days, associated with the negative effects described above during and in the days around the flowering period (Figure 5).

2018: In this year, the drop in yields due to drought was also pronounced. Thus, already in the late winter (February and March), as well as in the following spring (April, 11.3 mm), there was significantly too low precipitation. Much of the cumulative precipitation deficits of the 2018 growing season are shown in Figures S9 and S11.

May and June again showed normal precipitation compared with the long-term mean, but July and August were again too dry.

The April of 2018 was the warmest April, with 13.1 °C, since the beginning of weather records. The DI dropped to an extremely low value of 4.1, the RAI was −3.7, and the summer mark of 25 °C was exceeded on three days. This was immediately followed by the warmest May since records began (16.25 °C). Due to the two extremely warm months and further above-average temperate weather in the following months, it was the warmest vegetation period from April to October in the entire observation period (Figure S18). This is also shown by the summer days, with 40 days from April to July. The high-temperature totals in spring in particular are likely to have caused plant growth to be too rapid, to the detriment of the grain size and number, thus ultimately leading to lower yields. Over the course of the soil moisture deficit in early summer, the plant availability of nutrients decreased, and fertilization measures were only effective to a limited extent. In addition, the weather, which was also significantly too warm in the further course, accelerated a rapid maturation of the grain, which, in some cases, led to a stunting of the ears and a significant loss of mass in the grain yield (DWD 2018, 2).

Years with high yields: Evaluating years with high yields is much more difficult. These cannot be linked to individual events. Years with particularly good yields were those with adequate and well-distributed precipitation and moderately warm temperatures during the heat-sensitive development stages, such as 1988, 1989, 2012, and 2014. The site-specific water content must be included in the analysis of high-yield years.

3.3. Summary Evaluation of the Meteorological Indices

As per Döring et al. [39], there is no clear standard for evaluating such indices, and thus, several criteria are used:

- Agreement of the indices with yield data;
- Sensitivity of the indices to changes in the input values;
- Efforts to determine the indices.

When looking year-by-year, several indices could be identified that can be used as assessment variables for the annual weather. A visual assessment could, of course, only provide indications of meaningful variables, but explanatory patterns could be discerned in the temporal sequence. On the one hand, these were combined indices, such as the rain factor (RF) after Lang, precipitation (rainfall) anomaly index, de Martonne aridity/humidity index (M-AI), and the hydrothermal Selyaninov coefficient (HTC) (Figure 5). However, the precipitation indices percent-of-normal and the cumulative precipitation deficits/surpluses (CPD) also show parallels to the yield values. Additional indices that were also used as explanations were the summer index and the grassland temperature sum (GT-2).

When looking at the monthly values, the visual comparison also shows an influence of precipitation-free pentads and frost indices (early frost index 1 and late frost index 1).

According to the current state of the evaluation, the question of the most meaningful index for the investigated location cannot be answered. While it may be established that several indices together explain the yield declines, it was not possible to identify one or a few indices.

One reason for this was that none of the indices considered here adequately took into account the amount of water available to plants in the soil. This is important, however, because water stored in the soil can buffer a temporary precipitation deficit. Therefore, any drought index that does not or does not properly account for the amount of water stored in the soil is ultimately flawed.

4. Discussion

The results presented and discussed provide an important basis for the investigation of the question of which weather extremes are of particular importance for arable farming and in which context they lead to particularly high yield losses. Based on this, this overview can also contribute to finding out whether climate change will lead to increased yield variability in the future as a result of more frequent and more intensive occurrences of weather extremes relevant to agriculture. Thus, the time series from 1978 to 2020 was long enough to derive a certain trend development concerning the significance of special weather anomalies.

In general, it should be noted that no fixed percentage decrease or increase in yield could be determined as a result of certain extreme meteorological events. Weather conditions determine decisive components, such as the soil water balance, the development stage, and the degree of hardening of the arable plant at the time of the weather extreme, which is why the reactions of the plants in the respective stress situations can turn out to be completely different. In this respect, a further challenge is to clarify which extreme weather phenomena cause damage and to what extent. This was discussed and classified, but not precisely quantified, taking into account the respective development stages and their demands on climate and soil.

In addition, it should be noted that the entire analysis that was carried out was based on point-by-point weather data from the Weihenstephan-Dürnast weather station. In particular, in the case of locally occurring extreme events, such as violent thunderstorms with very high rainfall amounts in a short time or hailstorms, it must be taken into account that significant deviations could have occurred within the district of Freising.

In the case of winter wheat, heat waves and dry periods played the most important role in yields in the Freising district under consideration. In particular, for the last 20 years or so, there have been frequent spring and summer months with low precipitation and, in some cases, being significantly too warm, such as in 2003 and 2018, which were accompanied by particularly severe crop losses. The climatic conditions were also influential in the parameters of summer and hot days (Figure S5), as well as a lower de Martonne–Reichel dryness index (Figure 5). The same applies to the hydrothermal Selyaninov coefficient, which showed decreasing index values over time from 1978 to 2020, and this indicates increasing dryness (Figure 5). Over the course of climate change, an accumulation of heat and drought is thus to be expected [19,27]. It can therefore be assumed that the district will suffer more frequently from heat and water stress, and thus, be associated with an increased yield risk. According to this, a more frequent occurrence of spring and early summer drought is also to be expected. According to Semenov and Shewry [40], more hot days before and during the wheat flowering period are to be expected, which are associated with considerable yield losses. Accordingly, a greater yield risk is expected in the future, particularly from heat waves and less from dry spells.

Heavy precipitation events with large surface runoff or waterlogging during prolonged precipitation, which occur repeatedly due to the proximity to the Alps, are also of crucial importance for arable farming, especially for the moisture-sensitive maize. An increase in the observed 42 years could not be detected, but such precipitation events cause, in addition to plant damage, major erosion damage, as well as the washing away of nutrients [4]. In this context, according to Kornhuber et al. [41], a decrease in precipitation variability can be expected due to a change in circulation patterns. According to this, certain weather situations in Central Europe manifest themselves over significantly longer periods. The consequences are very wet phases with the danger of waterlogging and flooding due to persistent low-pressure influence, as well as heatwaves and dry periods lasting weeks with long-lasting high-pressure areas. These contrasting weather extremes sometimes follow one another directly, as was particularly the case in 2010. As a result, considerable yield losses are to be expected in some cases. In the district of Freising, a slight increase in the frequency of the occurrence of meteorological dry periods, during which less than 1 mm of precipitation occurred for at least 11 days (mainly 2000–2020), as well as a decrease in days with precipitation amounts to the vegetation of 2–4.9 mm, could be observed in the period under consideration (Figure S5). Instead, heavy precipitation events are likely to be more frequent. However, the connection was not tested for statistical correlation.

For winter wheat, it can also be assumed that secondary infections caused by plant damage over the course of severe weather events, such as thunderstorms or hailstorms, will occur more frequently in the future [42].

5. Conclusions

A lack of precipitation and/or the presence of high temperatures cause significantly reduced yields in agriculture. To describe and quantify these conditions, so-called meteorological indices are often used in agrometeorological descriptions. There are a variety of such indices, of which in this work, those frequently described in the literature were used.

Using Freising, which has mostly fertile soils, as an example location, the yields of winter wheat were compared with these indices.

The correlations between unusual weather anomalies and yields serve as an important basis for investigating the question of which weather extremes are of particular importance for arable farming and in which context they lead to particularly high yield losses. Based on this, the resulting overview can also contribute to determining whether climate change will lead to increased yield variability in the future as a result of more frequent and more intensive occurrences of weather extremes relevant to agriculture.

Supplementary Materials: The following supporting information can be downloaded from https://www.mdpi.com/article/10.3390/agriculture13101904/s1. Figure S1: Monthly precipitation (observation period covers 1978–2020); Figure S2: Precipitation summed up monthly with daily values (observation period covers 1978–2020, with means of 30 years from 1950 to 1979); Figure S3: Number of days with precipitation intensities of <1 mm, 1–10 mm, and >10 mm per day summarized as monthly values; Figure S4: Number of days with heavy precipitation summarized as monthly values (PI4); Figure S5: Number of days with vegetation-favorable rainfall (2–4.9 mm) summarized as monthly values (PI5); Figure S6: Number of rain-free days and meteorological dry periods summarized as monthly values; Figure S7: Number of days with precipitation-free pentads and rain-free days summarized as monthly values; Figure S8: Precipitation percentage of the normal means over the 30 years calculated for every month; Figure S9: Cumulative precipitation deficits/surpluses calculated for every month; Figure S10: Yearly values of the rain factor after Lang; Figure S11: Temperature-related indices (images are not indicated in the main text); Figure S12: Summer index and sum of the active temperature (April–October); Figure S13: Number of summer days, hot days, and desert days; Figure S14: First week with a temperature < 0 °C and number of days with a temperature <3 °C during the day; Figure S15: Yearly values of the early frost indices 1 and 2; Figure S16: Grassland temperature sum and late frost index yearly values; Figure S17: Frost shock days and frost-alternating days; Figure S18: Annual values of the frost days and ice days; Figure S19: Annual values of the frost severity and frost index per Liu; Figure S20: Beginning and end of the vegetation periods with a mean temperature for >5 days of >5 °C and $\leq$5 °C calculated for every year; Figure S21: Number of days/pentads with means with >5 °C, summarized as annual values (CD1 and CD2); Figure S22: Sum of the temperature daily mean until the value of 200 °C (GT-1) and sum of the temperature daily mean until day 105; Figure S23: Global radiation monthly values.

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