Climate Effects on Corn Yield in Missouri*

QI HU

Climate and Bio-Atmospheric Sciences Group, School of Natural Resource Sciences, University of Nebraska—Lincoln, Lincoln, Nebraska

GREGORY BUYANOVSKY

School of Natural Resources, University of Missouri—Columbia, Columbia, Missouri

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ABSTRACT

Understanding climate effects on crop yield has been a continuous endeavor aiming at improving farming technology and management strategy, minimizing negative climate effects, and maximizing positive climate effects on yield. Many studies have examined climate effects on corn yield in different regions of the United States. However, most of those studies used yield and climate records that were shorter than 10 years and were for different years and localities. Although results of those studies showed various influences of climate on corn yield, they could be time specific and have been difficult to use for deriving a comprehensive understanding of climate effects on corn yield. In this study, climate effects on corn yield in central Missouri are examined using unique long-term (1895–1998) datasets of both corn yield and climate. Major results show that the climate effects on corn yield can only be explained by within-season variations in rainfall and temperature and cannot be distinguished by average growing-season conditions. Moreover, the growing-season distributions of rainfall and temperature for high-yield years are characterized by less rainfall and warmer temperature in the planting period, a rapid increase in rainfall, and more rainfall and warmer temperatures during germination and emergence. More rainfall and cooler-than-average temperatures are key features in the anthesis and kernel-filling periods from June through August, followed by less rainfall and warmer temperatures during the September and early October ripening time. Opposite variations in rainfall and temperature in the growing season correspond to low yield. Potential applications of these results in understanding how climate change may affect corn yield in the region also are discussed.

1. Introduction

Growing-season climate conditions (e.g., rainfall and temperature) affect the growth and yield of corn (*Zea mays* L.) and cause yield variations. Understanding the climate effect has been a continuous endeavor toward improving farming technology and management strategy to reduce the negative impacts of climate and to increase corn yield (Smith 1903, 1914; Davis and Pallesen 1940; Runge and Odell 1958; Runge 1968; Allmaras et al. 1964; Voss et al. 1970; Hill et al. 1979; Chang 1981; Hazell 1984; Garcia et al. 1987; among others). The early studies of Smith (1903, 1914) used short-term records ($<$10 yr) of corn yield and climate and showed that corn yield in some areas of Illinois was particularly sensitive to rainfall shortly before anthesis and the maximum temperature during anthesis. A study by Coelho and Dale (1980), using 1972–74 data from West Lafayette, Indiana, found that corn growth and yield were favored by warmer temperatures from emergence to silking, a result somewhat different from that of Smith. Although depicting some climate influences on corn yield, these studies are primarily ''case studies,'' and their results are difficult to use to gain a comprehensive understanding of climate effects on corn yield because of the short-term records for different years and localities. Additional studies using long-term data of climate and corn yield from a location or a region are needed to establish such an understanding.

Corn yield is affected by weather and climate, whereas corn yield potential is, to a high degree, determined by corn genetics and nutrient availability during growth. Introduction of genetically improved varieties and effective fertilizers since the late 1940s has boosted corn yield, which has increased significantly after 1960 (Huff and Neill 1982; Offutt et al. 1985). The increased corn yield potential also raised issues of whether the advance in technology has lessened or strengthened the sensitivity of yield variation to climate conditions. Garcia et

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* Agricultural Research Division, University of Nebraska—Lincoln, Contribution Number 13797.

Corresponding author address: Dr. Qi Hu, 237 L. W. Chase Hall, School of Natural Resource Sciences, University of Nebraska—Lincoln, Lincoln, NE 68583-0728.
E-mail: qhu2@unl.edu

al. (1987) examined these issues by contrasting the yield variations between two periods, 1931–60 and 1961–82, with very different farming technologies. They found that ‘‘when (corn) yield behavior is adjusted for the impact of weather, variances (of yield) were more likely to be equal between the two periods’’ (Garcia et al. 1987, p. 1101). The similar yield variance in the two periods of very different technology led them to conclude that the growing-season climate condition remained the primary factor affecting corn yield. This conclusion also was reached in a study by Hollinger and Hoeft (1986), who showed that the effect of nitrogen fertilizers relied heavily on weather conditions; hot and dry conditions could reverse the effect of fertilizer on corn growth and, thus, could amplify the adverse effect of weather and climate on yield. These results demonstrate persistent climate effects on corn growth and yield.

Climate effects on corn yield and the yield differences caused by different within-season distributions of rainfall, temperature, and daily temperature range are examined in this study for central Missouri using unique corn yield and climate data from 1895 to 1998 (104 yr). The yield dataset also includes records of seed variety (genetics), fertilizer usage, and irrigation, allowing us to disclose climate effects on corn yield after assessing and removing technology influences. A detailed description of the study site and experiment plots and their data is presented in the next section. In section 3, we examine the climate effects on corn yield. Because we use long-term records of yield and climate, the climate effects identified in this study will not be biased by short-term climate fluctuations; in other words, extreme climate events in individual years will have minimal influence on the long-term average effects of climate. A conclusion and some implications of the results for local agriculture in a changing climate environment are presented in section 4.

2. Study site, data, and methods

a. *Study site and experiment plots*

The study site is Sanborn Field, which was established in 1888 as a field research laboratory on the University of Missouri—Columbia campus. Before cultivation, the area was part of a tall-grass prairie (Kucera 1991). After cultivation in 1888, the field was arranged into 39 experimental plots, each 30 m × 10 m, separated by 1.5-m-wide grass hedges. Since 1895, operation on Sanborn Field has been managed under strict guidelines; yield and residue amounts of crops from each plot were collected, weighed, and recorded each year. These data were archived with management information, including planting method, cultivars, amount of fertilizer used, residue treatment, and dates of some of these practices (Upchurch et al. 1985).

The soil in Sanborn Field is Mexico silt loam (fine montmorillonitic, mesic, Udollic Ochraqualf) developed in thin loess deposits overlying glacial till. Because the soil profile has an argillic horizon (Bt), which favors perching and lateral flow of water above it, surface runoff is enhanced, and available water in the soil profile is limited. The top layer of the soil profile contains 2.5%–2.9% organic matter.

In this study, we used corn yields from 4 of the 39 plots in Sanborn Field. None of these four plots were irrigated. One of the four has been used for continuous corn growth with a fixed annual amount of manure fertilizer equivalent to 13.4×10^3 kg ha^{-1} yr^{-1} applied at the beginning of each growing season. This plot was originally designated to preserve the corn growth in a traditionally operated environment. The other three study plots have been used to grow corn in 3-yr rotations with winter wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.) or sweet clover (*Melilotus albus* Desf.). These rotation plots were given a ‘‘full fertilizer treatment’’ that involved use of limestone, potassium (K), and phosphorus (P) to upgrade and then to maintain levels of K, P, calcium, and magnesium at appropriate soil-test values and to use chemical nitrogen (N) in accordance with then current recommendations to maintain a steady level of soil fertility each year (Upchurch et al. 1985). Such recommendations were based on the Missouri Extension Service guidelines (Buchholz 1982). In the last soil-test period of 1993–98, this full fertilizer treatment was equivalent to an annual amount of N of 220 kg ha^{-1}, phosphorous pentoxide (P_2O_5) of 17 kg ha^{-1}, and potassium monoxide (K_2O) of 60 kg ha^{-1}. Corn yields of these three rotational plots represented yield from soils with sufficient soil fertility. The other plots in Sanborn Field that were not part of this study were used to grow other crops (e.g., soybean).

Because the ‘‘farming operation’’ in the four plots has been fixed and corn was planted as the sole crop in the same way for each corn year in the plots, the bilinearity of yield dependence on human decision (Garcia et al. 1987) was minimized. The bilinearity effect on yield is significant only in farming operations in which human decision on the fraction of land planted for different crops and the amount of fertilizer used for different parts of each crop area affect the *total yield* from the land (Houck and Gallagher 1976; Cooke and Sundquist 1989; Kauffman and Snell 1997).

b. *Corn yield data*

Yield data from the continuous plot were used directly in our analysis, and data from the three rotation plots were combined to form one time series. The following method was used in developing this time series. When corn was grown in only one of the three rotation plots, yield from that plot was used as the yield for that year in the time series. When corn was grown in two or all three rotation plots in the same year (a rare situation, occurring in only 5 of the 104 yr on record), corn yields from those plots were averaged, and the average yield was used for that year in the time series. This averaging method was justified because each plot was reset to have the same soil condition according to the Missouri Extension Service guidelines whenever corn was planted so that each corn year in a plot would be an independent sample year. Thus, the average yield from the independent sample years would not create yield biases caused by plot differences. Our evaluations of yields for the same year from different rotation plots confirmed that the yields were very close. A caveat in the rotation plots was that there also were a few years in which corn was not planted in any of three plots. Thus, the yield time series for the rotation plots has gaps. However, those few missing values would have had little effect on the trend and average of a centennial series. We refer to this composite dataset from the three rotation plots as ‘‘rotation treatment’’ and use ‘‘continuous treatment’’ for the yield time series from the continuous corn plot.

Scatterplots of time series from these two treatments are shown in Fig. 1. A yield increase is shown beginning at the same time in both treatments in the late 1940s when genetically improved hybrids were introduced. The seed genetic improvement explains most of the yield increase in the continuous treatment because, except for the use of new hybrids, the management practices have been similar over the years. The steeper yield increase in the rotation treatment can be attributed to both the genetic improvement and sufficient soil fertility.

In Fig. 1, the time series also suggests an increase in variability (variance) of corn yield in the recent decades. The yield fluctuated in both treatments within a smaller range before 1945 than after. Furthermore, because of the same increase of yield variability in both the treatments, the increase in variability would have to have originated from factors shared by these treatments, that is, genetically improved hybrids and climate. We believe that the large yield variability in the recent decades shows an increased sensitivity of yield to weather and climate. The increased sensitivity could have resulted from a combination of rising yield potential following improvements in genetics and the climate effect on corn yield. With a high yield potential, the corn yield can be much higher in years with favorable climate conditions. However, in unfavorable climate conditions when the yield potential cannot be realized, yield can be low, creating the observed large fluctuations.

c. Climate data

Climate data used in this study are from the U.S. National Weather Service station in Columbia, Missouri, which is located 16 km south of Sanborn Field and is the station closest to the study site. The station’s data include daily total precipitation and daily maximum, minimum, and average temperatures from 1895 to 1998. These data have been subject to quality controls described in Reek et al. (1992) and were used in a few regional climate studies (e.g., Woodruff and Hu 1997; Hu et al. 1998).

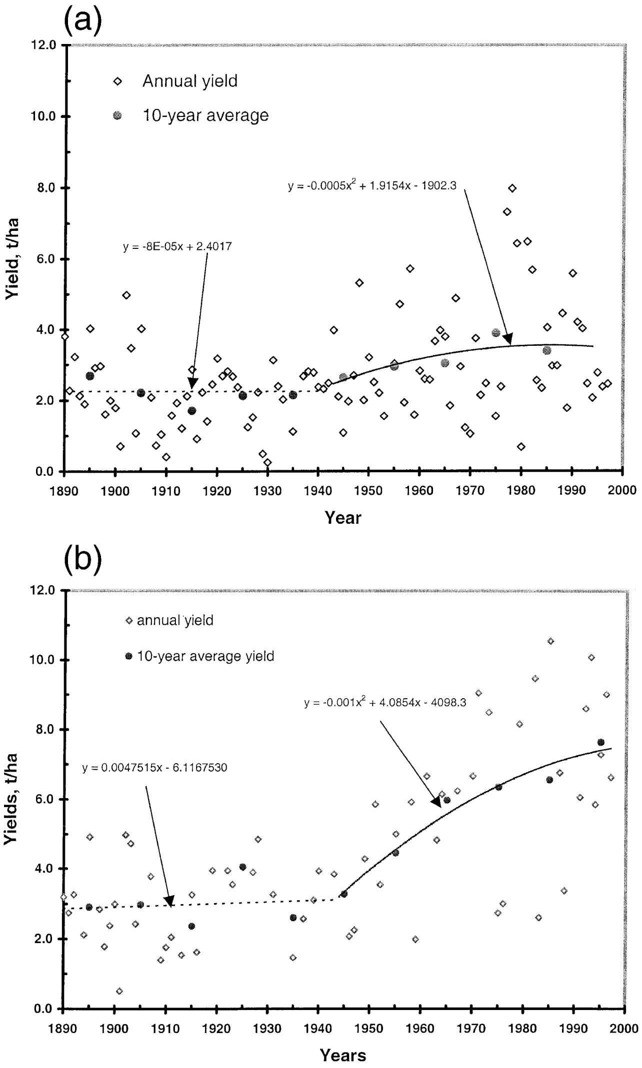

FIG. 1. Variations in corn yield for two treatments: (a) continuous corn with fixed annual manure fertilizer and (b) corn in rotation plus application of mineral fertilizers. The dashed lines show the trends of yield. The 10-yr-average yields are shown with dots (see text for details).

The average annual surface air temperature derived from the station data for the period 1895–1998 is 13°C, with a maximum monthly mean temperature of 26°C in July and a minimum monthly mean temperature of -1.5°C in January. Mean annual precipitation is 973 mm, and potential evapotranspiration is 790 mm. Variations in the station’s rainfall and temperature for spring (March–May) and summer (June–August) are shown in Fig. 2. It is important to note that these variations indicate that the average climate conditions at the station have changed little over the period 1895–1998 and that no trends in the variations of temperature and precipitation are detectable.

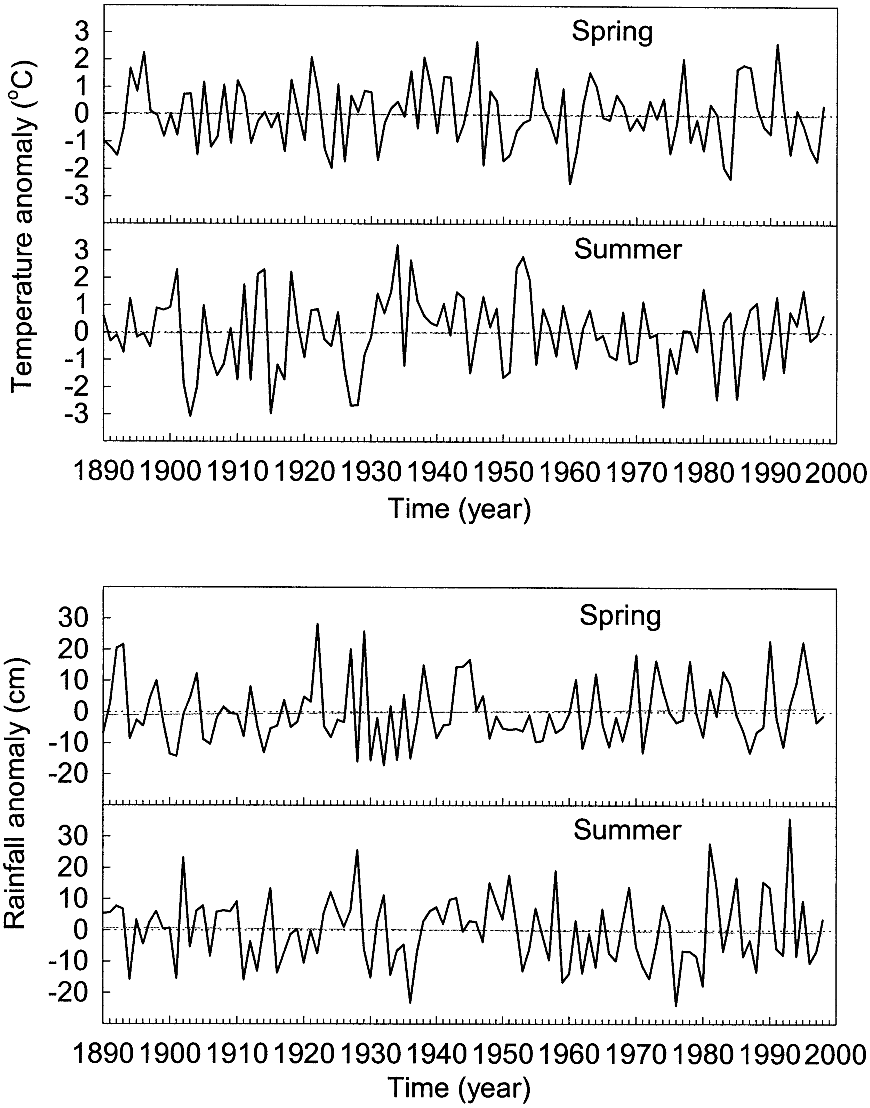

FIG. 2. Temporal variations of spring (Mar, Apr, May) and summer (Jun, Jul, Aug) (top) temperatures and (bottom) rainfall anomalies at Columbia, MO. The dashed lines show trend of the variations, and the dotted line is the zero line.

d. Data processing

Because the average climate conditions in the area have remained nearly unchanged (Fig. 2), the trend of rising corn yield since the late 1940s (Fig. 1) would have had to result from the effects of technology advancement, including seed genetics and fertilizer, as previously discussed. On the other hand, because each treatment started its growing season with a similar land condition and proceeded with the same management routine *every year*, technology effects on the interannual variation in yield are minimal in these treatments. Thus, the interannual variation, superimposed on the trend, of the yield shown in Fig. 1 had to originate from the varying year-to-year growing-season weather and climate conditions.

This particular situation at the site allows us to evaluate the climate effect on corn yield after minimizing the technology influence by eliminating the trend from the yield series. Because the yield increased substantially after 1945 (Fig. 1), we divided each yield series into two segments, one from 1895 to 1945 and the other from 1945 to 1998. As shown in Fig. 1, the average yield of 1895–1945 was nearly steady for the continuous treatment and increased a little for the rotation treatment. The average yield of 1945–1998 increased in both treatments, and the increase was particularly large in the rotation treatment.

Because of the large yield fluctuations, especially in the recent decades, identifying the trend of the yield is not an easy task. To guide our search of the trends representing the yield changes, we also plotted 10-yr-average yields at the middle year of each 10-yr period in Fig. 1 (dots). These average 10-yr yields suggest little trend in the continuous plot from 1895 to 1945 and a linear trend of slight increase of yield in the rotation treatment over the same time. This increase-of-yield trend in the rotation plot could have resulted from fertilizer effect. From 1945 to 1998, the variations of average 10-yr yield suggest a parabolic curve as a close description of the trends in the yield, a result similar to that found in Hazell (1984). In addition to the parabolic function for the trend in 1945–98, we examined various functional forms to fit the annual yield data, as well as the decadal data. Comparisons of the root-mean-square errors between those functional forms in their representation of the yield indicated that the parabolic function was the ‘‘best fit’’ with the smallest root-mean-square error. A statistical significance test (F test) further showed that the parabolic representation is significant at the 5% confidence level for both of the treatments.

An additional issue that must be addressed to confirm that the functional forms can be used to describe the scattered yield data in Fig. 1 is the data scedasticity, or whether the data have an equal variance in each segment. If a data series has significant heteroscedasticity, the assumption of the classical linear model is violated and the linear, as well as the quadratic, representation of the data becomes invalid. To test the scedasticity, we examined the correlation of the absolute value of yield residuals, defined as the distances between individual yield and the trend function value, and the year using Spearman’s rank correlation. Results of these tests showed no scedasticity in the yield data before 1945 for both treatments. For the segments after 1945, the correlation values are 0.18 and 0.16 for the continuous and rotation treatment, respectively. Because these values are both larger than the critical value of 0.15, they suggest no significant heteroscedasticity, or nearly equal variance, in the segment data of the recent decades. The correlation value for the rotation treatment is closer to the critical value because of the relatively large variance in the 1970s and 1980s before it decreased in the late 1980s through 1990s. Furthermore, because the yield data series are divided into only two segments, the serial correlation error, often arising from segmenting a data series into more than two segments, is minimal. These results support that the functions in Fig. 1 are reasonable descriptions of the trends of yield for the two treatments.

After the trend was determined, it was subtracted from the observed yield to produce detrended yield. The new series of detrended yield in each segment was further normalized after subtracting the mean and dividing each value by the standard deviation of the detrended segment series. This separate normalization was necessary for different segments of each treatment because of the differences in both average and yield variance in the segments. Because these fluctuations resulted primarily from the effects of genetics and fertilizer in favorable or unfavorable climate conditions, scaling these fluctuations down by the normalization would leave climate effects in the yield series (i.e., the basic ups and downs in the series) and would largely remove the effects of the genetics and fertilizer (i.e., the enlarged amplitudes of the ups and downs in the series). Thus, after normalizing the different segments, we have ‘‘scaled’’ the variations in the yield such that they would contain mostly the climate effect and would be comparable among different segments and treatments in the same standards. Last, the data series of the two normalized segments for a treatment were combined into one from 1895 to 1998 for further analysis.

In this processed yield series, because the interannual yield variations resulted primarily from year-to-year changes in growing-season weather and climate, effects of climate on yield can be detected by comparing and contrasting climate conditions between the years with high and low yield. Thus, we separated the yield data into high-, average-, and low-yield groups and, based on this separation, categorized the climate conditions that correspond to the individual yield groups. A way to separate the yields was to use the deviation distribution of the yield data. Because the deviation was unity after the yield data were normalized, it was natural to define high-yield years as those with yield in the top 1/3 of the deviation distribution, low-yield years as those with yield in the bottom 1/3 of the distribution, and average-yield years as those with yield in the middle 1/3 of the distribution. After this ‘‘classification,’’ the yield data were grouped into three bins of high, average, and low yield, which correspond to average annual yields of $>5 \times 10^3$, $3–5 \times 10^3$, and $<3 \times 10^3$ kg ha^{-1}, respectively.

The elements or years in the high- and low-yield bins from 1895 to 1998 are listed in Table 1 for the two treatments. The years not listed in Table 1 had average yields. The numbers of elements in the two groups in Table 1 are different because the rotation treatment missed a few corn years. Except for this difference, the high or low yield was observed in the same year in both treatments, clear evidence that shows a significant relationship of yields between the two very different treatments and an indication of consistent climate effects on corn yield.

According to the yield groups in Table 1, monthly and pentad (5 day) average climate conditions for each yield group were developed. Because climate conditions in each growing season of the same yield group were not identical, it was necessary to composite (average over a selected subset of) the climate variables over the years in the same yield group to get a representative condition for that yield group. The following procedures were used to derive the composite climate conditions for each yield group. For monthly conditions, we averaged the monthly precipitation for years in each yield group. The same average was done for monthly temperature and daily temperature range. These averages describe the differences in variations of monthly climate

TABLE 1. Years with high and low yields. In rotation treatment, missing years (for which there was no plot growing corn) are put in parentheses.

Treatment	Low-yield years	High-yield years
Continuous corn treatment	1898, 1901, 1904, 1908, 1909, 1910, 1911, 1913, 1916, 1918, 1935, 1945, 1946, 1947, 1953, 1959, 1969, 1970, 1975, 1976, 1980, 1983, 1988, 1989, 1994, 1995, 1997	1895, 1902, 1903, 1905, 1920, 1921, 1922, 1928, 1939, 1943, 1948, 1951, 1955, 1956, 1958, 1964, 1965, 1967, 1971, 1973, 1977, 1978, 1979, 1981, 1982, 1985, 1990, 1992, 1993
Rotation treatment	1898, 1901, 1904, (1908), 1909, 1910, 1911, 1913, 1916, (1918), 1935, (1945), 1946, 1947, (1953), 1959, (1969), (1970), 1975, 1976, (1980), 1983, 1988, (1989), 1994, 1995, 1997	1895, 1902, 1903, 1905, (1920), 1921, 1922, 1928, 1939, 1943, 1948, 1951, 1955, (1956), 1958, 1964, (1965), 1967, 1971, 1973, (1977), (1978), 1979, 1981, 1982, 1985, (1990), 1992, 1993

variables between different groups. For pentad data (the pentad is grouped starting from the first day of the year), because they would be used to compare and contrast variations of climate departures (anomaly) from the mean climate conditions between different yield groups, we computed a normalized pentad composite for each yield group. In doing so, we calculated the pentad mean and standard deviation of precipitation, temperature, and daily temperature range from the data of 1895–1998 and then normalized the pentad data series and derived composites of these variables for the high-, low-, and average-yield groups. The pentad averaging could be viewed as a time filter that removes daily and fast weather fluctuations and transforms the daily data to focus on meaningful temporal scales that influence corn growth. Thus, the pentad data allow us to reveal detailed rainfall and temperature variations that could be important to corn growth and yield but are not disclosed by monthly or coarser temporal-resolution data.

3. Climate effects on corn yield

To understand how climate influenced corn yield and what growing-season climate conditions favored or disfavored corn growth and yield, we first compared and contrasted the average monthly precipitation and temperature for the growing season and average growing-season climate for the high-, low-, and average-yield groups. These monthly conditions and their differences are shown in Table 2. According to Table 2, high-yield years are characterized by lower rainfall in April and higher rainfall from May through August, from after planting through most of the growth time, with the most significant above-average rainfall in July. Rainfall in September and early October, the ripening time, is low in high-yield years. For temperature, high-yield years have warmer temperatures from April to June and cooler temperatures in July and August. The demand for cooler temperatures in July and August in high-yield years is, to a large degree, consistent with that in Lobell and Asner (2003). High-yield years also have smaller daily temperature range from May through September, particularly in July and August. These small temperature ranges, together with the below-average mean temperature in those months, indicate similar and cool daytime temperature in the high-yield years, contrasting with high and fluctuating daytime temperatures in low-yield years, as indicated by above-average mean temperature and large daily temperature ranges. Synthesizing these differences in monthly rainfall and temperature, we found that the high-yield years are warmer and dryer in the spring months (April and May) and are wetter and cooler, with stable or similar daytime temperatures, in the summer months (July and August). Opposite distributions of monthly temperature and rainfall with high-

TABLE 2. Average monthly climate conditions for high-, low-, and average-yield groups. The difference between high- and low-yield years is significant at 10% confidence level when shown in boldface and is significant at 5% confidence level when shown in boldface italics.

Climate variable	Yield group	Apr	May	Jun	Jul	Aug	Sep	Growing season
Precipitation (mm)	High	80	133	109	112	96	103	105
	Avg	95	125	105	96	87	103	102
	Low	110	117	101	79	78	114	100
	High − low	**−30**	16	8	***33***	18	−11	5
Mean temperature (°C)	High	13.3	18.3	23.0	25.1	24.1	20.6	20.7
	Avg	12.7	18.0	22.8	25.3	24.5	20.2	20.6
	Low	12.0	17.7	22.7	25.6	25.0	20.2	20.5
	High − low	***1.3***	**0.6**	0.3	−0.5	***−0.9***	0.4	0.2
Temperature range (°C)	High	12.0	11.4	11.1	11.2	11.8	12.3	11.7
	Avg	11.8	11.7	11.5	12.0	12.0	12.1	11.8
	Low	11.7	11.7	11.6	12.6	12.7	12.4	12.1
	High − low	0.3	−0.3	−0.5	***−1.4***	***−0.9***	−0.1	**−0.4**

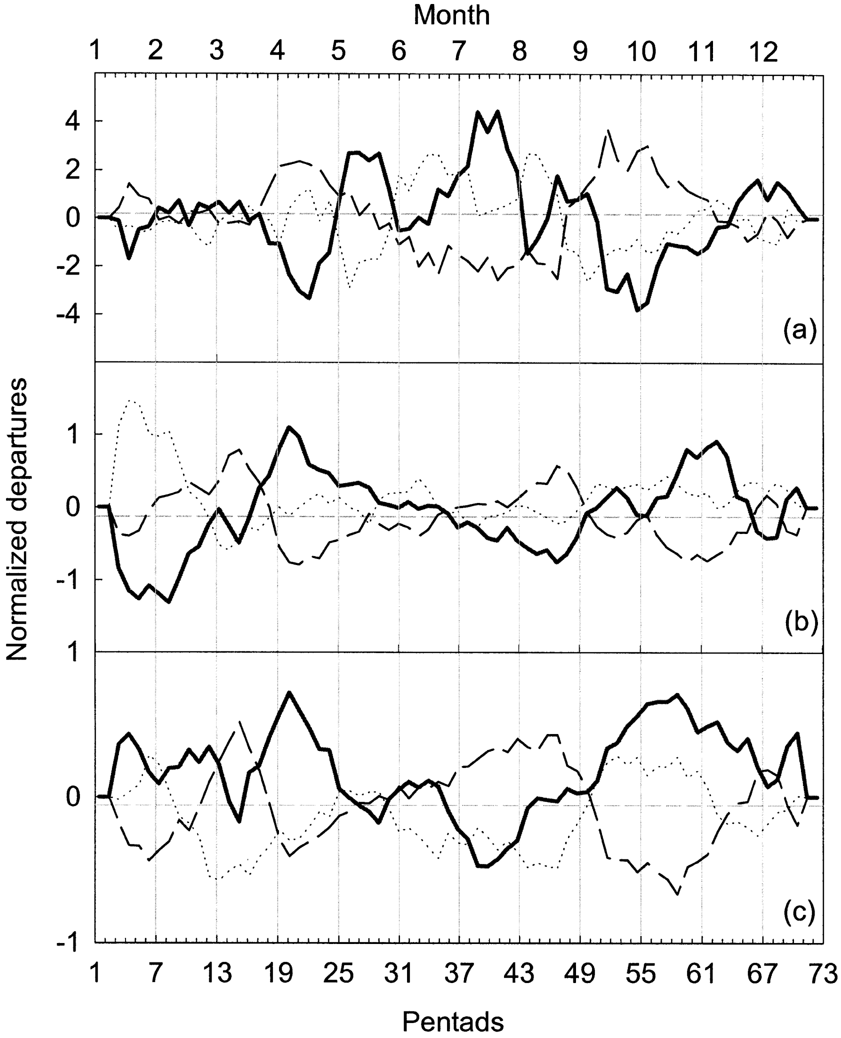

FIG. 3. Variations of composite pentad (a) rainfall and (b) mean temperature, and (c) pentad average daily temperature range. Variations for high-, average-, and low-yield years are shown by solid, dotted, and dashed lines, respectively.

er temperatures and large daily fluctuations in the summer months are associated with low corn yields.

Another intriguing result in Table 2 is that the season-average rainfall and temperature for the entire growing season (last column in Table 2) are very similar between the high- and low-yield groups; growing-season average rainfall difference is merely 34 mm, and the mean temperature difference is 0.2°C. Our additional analysis of individual yields further showed that very high corn yields (6–10 × 10^3 kg ha^{-1}) were produced in the growing season the average rainfall and mean temperature of which were nearly the same as in years with yields of one-half to one-third. The very similar average growing-season rainfall and mean temperature between high- and low-yield years indicate that the average growing-season climate gives little indication of climate effect on corn yield. In contrast, the large differences in monthly rainfall and temperature between high- and low-yield years indicate that the monthly and shorter *within-season* differences in climate conditions have caused the yield differences. Although the within-season weather and climate conditions may have long been recognized as important to corn yield differences, this importance was not evaluated in a consistent framework as in this Sanborn Field case. In addition to showing this importance, the Sanborn Field results in Table 2 quantify the specific monthly differences in rainfall and temperature that cause the significant yield differences.

To further reveal the within-season climate effects on corn yield, we examined the composite pentad rainfall and temperature variations for the high-, low-, and average-yield years. The pentad rainfall, temperature, and average daily temperature range variations are shown in Fig. 3, depicting more details in variations than that in Table 2. The rainfall variations in Fig. 3a show that high-yield years have below-average rainfall in the preplanting period in April (pentads 19–24), followed by a rapid increase of rainfall in early May. Rainfall sustained above the average from May through August. From mid-September to the harvest the rainfall is below average. Nearly opposite anomalies in growing-season rainfall correspond to low corn yield (dashed line in Fig. 3a).

Composite pentad temperature variations (Fig. 3b) describe that in high-yield years temperature is above average from late March through May. Temperature changes to near average and slightly below average in June and remains below average from late June through August, with the largest negative anomaly occurring in late August. In September, the temperature becomes above average, and the above-average temperature lasts through the harvest. A nearly opposite anomaly pattern in temperature prevails in low corn yield (dashed line in Fig. 3b). These contrasts in temperature anomalies also are shown in the pentad average daily temperature range shown in Fig. 3c. In high-yield years, the temperature range is large in the planting and early growth period. Because the temperature during that period is warmer than average (Fig. 3b), the large temperature range suggests higher daytime temperatures in the period, favoring germination and emergence. Small daily temperature ranges are observed in July followed by large temperature ranges from early September to the harvest. Low-yield years are characterized by an opposite distribution of temperature range anomalies (dashed line in Fig. 3c).

Each panel in Fig. 3 shows opposite anomalies of rainfall or temperature between the high- and low-yield years, but Figs. 3a and 3b also show mostly opposite anomalies in rainfall and temperature in the same yield group (except for May in the high-yield years; this in-phase relationship will be discussed later in this section). For example, in high-yield years, above-average temperatures occurred simultaneously with below-average rainfall in April, and the above-average rainfall from June through August coexisted with below-average temperatures. Although such relationships may be expected from our intuition, they are not the norm of the climate in the study area (see Fig. 3 in Hu and Willson 2000, p. 1905). The continental humid climate in the study area has warmer temperatures, occurring often concurrently with above-normal rainfall. So, the opposite anomalies in temperature and rainfall in the high- and low-yield years are unique to the yield anomalies.

The effects on corn yield from these unique combinations of rainfall and temperature anomalies and their variations in the growing season are explained as follows. First, the contrasting climate conditions in the planting period affect the planting date and seed germination, both of which are important to later growth and yield (e.g., Bauder and Randall 1982). In high-yield years, the dry condition in April favors timely planting, and the warm temperatures reduce the potential of freezing damage to the seeds and encourage seed germination. Another explanation of the dry condition in the planting and early growth in high-yield years would be that the dryness and associated water stress stimulate growth of a larger and deeper root system of corn. Such a root system favors high yields because the corn plant can obtain more moisture from deeper layers during later growth than a plant could without a large root system. In low-yield years, a wet and cold condition in April affects planting negatively. (It is arguable whether the planting date should be considered to be a management decision and, thereby, differences in planting date to be a management effect on yield. First of all, planting has to happen within a ‘‘planting window.’’ When to plant in that time interval is very much dependent on the weather condition. An extended wet period prevents fieldwork from taking place and postpones planting. Extreme dryness also delays planting. If plantings were made as a result of a management decision, the dry condition would have damaged seed germination and hampered subsequent crop development. On the other hand, if planting is made according to the weather condition, the postponement of planting because of either the wet or dry condition would affect corn yield by, for example, shortening the growing season for planted variety or exposing its ripening to deep frost damage. Therefore, even though management decides the planting date, the weather condition during the planting window deciphers the date and, more important, determines the outcome of the planting. Hence, to a large extent, the influence of planting date on yield is a part of the climate effect on yield.)

After planting, the rainfall increases rapidly in early May in high-yield years (pentad 25, Fig. 3a), and the above-average rainfall remains through May. The abundant rainfall in May is accompanied by above-average temperatures (Fig. 3b), creating an in-phase relationship of rainfall and temperature, noticed earlier, and a warm and moist condition. This condition favors seed germination and emergence (Cardwell 1984). After this short warm and wet period, the rainfall remains above average from late June through most of August (pentads 35–49), but the temperature changes and stays below average. This cool and wet condition in this major growth period from silking and kernel filling is essential to corn yield. The growing season finishes by a dry and warm condition in September and October, a condition favoring ripening. In high-yield years, the diurnal temperature range is small in the entire growing season from May to early September (Fig. 3c). This small range and relatively cool daily mean temperature reflect lower and similar daytime temperatures, and, according to Duncan (1975), such ‘‘environments with lower but similar day temperatures speed (corn) development.’’ In the low-yield years, the condition in May is wet and cool, disfavoring planting and germination. After May, rainfall decreases, and insufficient rainfall is the norm in June, July, and August. In September and October, the wet and cool condition further hampers the ripening and timely harvest, affecting yield negatively. Low-yield years also have hot daytime temperatures in July and August, as indicated by both the above-average mean temperature and the large daily temperature range. Because the high daily temperature promotes plant respiration and high respiration results in large grain loss (Chang 1981), high temperatures in July and August affect corn yield negatively. These contrasting climate conditions in low-yield years as compared with that in the high-yield years cause the yield differences.

To examine the significance of the differences of within-season rainfall variations between the high- and low-yield groups shown in Fig. 3 and, hence, the climate effect on the yield discussed in the previous paragraphs, we tested the association of rainfall variations in the opposite yield years. The test used the pentad data series for the entire year. The null hypothesis was that there was no difference between their within-season variations. However, the Student's *t* test showed a large difference between the two rainfall variations with nonequal variance ($T = -2.56$, $p = 0.0116$). Thus, the null hypothesis was rejected, and the inverse relationship shown in Fig. 3a was significant at the 5% level. Similar test results with significance at the 5% level also were obtained for the inverse relationships of temperature and temperature range between the high- and low-yield years (Figs. 3b and 3c), indicating that these relationships of temperature between high- and low-yield groups were statistically significant.

4. Summary and concluding remarks

We examined climate effects on corn yield using yield and climate data from 1895 to 1998 at Sanborn Field in Columbia, Missouri. This dataset is unique for this study. First, no trends in precipitation and temperature are detectable. Thus, the observed trend of increasing corn yield at the site since the late 1940s was primarily a result of advancements of cropping technology, that is, improving seed genetics and fertilizers. Second, the yield data were from two treatments with fixed management routines. One had continuous corn with application of a fixed amount of organic (manure) fertilizer; in the other, corn was in a 3-yr rotation with different crops and was treated with chemical fertilizers in corn years to assure a constant soil fertility level. Third, no irrigation was applied in either of the treatments. Fourth, because corn was the sole crop in a corn year and management was a fixed routine, the bilinear dependence of the yield on climate and human decision addressed in Garcia et al. (1987) was minimized in these treatments, and the yield variations were dependent primarily on climate variation. These features allowed us to use the dataset, after removing the yield trend, to identify climate effects on corn yield in central Missouri.

Our analysis of the yield data showed that high or low yield was observed in the same years in both treatments regardless of the differences in soil fertility, a result clearly indicating climate influences on corn yield. To describe the climate effect, the years from 1895 to 1998 were categorized into three groups with high, average, and low yield. Daily data of precipitation and temperature in the years of each group were processed to get composite monthly and pentad (5 day) data series. The composite data were used to examine difference of the climate conditions between different yield groups and to identify climate effects on corn growth and yield. Major results showed that climate effect on yield can be explained only by within-season variations in rainfall and temperature and cannot be distinguished by average growing-season climate conditions. In fact, the growing-season average rainfall and temperature were very close between high- and low-yield years; the average rainfall and temperature were 633 mm and 20.7°C, respectively, in high-yield years vs 599 mm and 20.5°C in low-yield years. A major result of this study has been to reveal the detailed variations in rainfall, temperature, and daily temperature range from preplanting to harvest and to understand how differences in these within-season variations separate the high and low yield. This understanding also helps us to comprehend the results of previous studies of climate effect on corn yield using short-term (<10 yr) data for different areas in the central United States.

Our analysis of the within-season climate variations showed that both the monthly and pentad data captured the climate variations affecting corn yield, although the pentad data further detailed the transitions of climate conditions during the growing season. These variations show that high-yield years had a unique growing-season distribution of rainfall and temperature characterized by less rainfall and warmer temperatures in the planting period, a rapid increase in rainfall in early May, and above-average rainfall and warmer temperatures throughout May, when seed germination and emergence took place. More rainfall but cooler and stable daily temperatures were in the major growing period from June through August, followed by less rainfall and higher temperatures in the September–early October ripening period. Opposite distributions in precipitation and temperature in the growing season corresponded to low corn yield.

The within-season climate conditions corresponding to different corn yields in central Missouri can be used to evaluate potential climate-change impacts on corn yield in the area. As general circulation modeling studies have suggested, one of the possible future climate conditions in the middle latitudes of inland areas of a major continent, such as the central United States, could be dry summers following wet springs because of early melting of winter snowpack and early migration of the polar jet to its northern position in late spring and early summer (Manabe et al. 1981; Wetherald and Manabe 1995). Fluctuations of summer rainfall and temperature also would amplify in future climate conditions (Mitchell et al. 1990; Wigley 1999; Dai et al. 2001). Although uncertainties exist in these model predictions, should the increase of spring rainfall and snowmelt occur in early spring (e.g., March and April), the future climate condition could have a negative effect on corn yield in central Missouri. On the other hand, if a rainfall increase occurs in late April and early May, it would favor high yield of corn in the region. Effects of these changes in climate on the region's corn yield can be evaluated from the differences between current and future climate conditions and the identified relationship of the current climate and corn yield obtained in this study. Understanding these effects can help to address related agricultural concerns rising from the changing climate.

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