Research Report 127

# Long-Term Variations in Seasonal Weather Conditions and Their Impacts on Crop Production and Water Resources in Illinois

by
Stanley A. Changnon and Derek Winstanley

ILLINOIS STATE WATER SURVEY
DEPARTMENT OF NATURAL RESOURCES

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**Abstract:** This study reports the results of an analysis of long-term records of corn yields, water resource conditions, and seasonal weather conditions in Illinois and found major temporal shifts and important spatial variations in the types of seasonal weather conditions that have positive and negative impacts on yields and water conditions. Nineteen different types of corn-weather seasons (May–August) occurred during 1901–1997, of which nine types accounted for most of the high corn yields (highest 20 of the 97 values) and eight types produced most low yields (lowest 20 values).

An assessment of the years with either high or low yields revealed three findings about the distributions of the corn-weather seasons creating these extremes: 1) some types were uniformly distributed throughout the century; 2) others were unevenly distributed over time, some occurring only in the century's early decades and others only in the last few decades; and 3) certain types varied greatly regionally. Yield responses to certain seasonal types varied over time. The findings helped establish that changes in farming practices, corn varieties, and agricultural technology all affect how a given type of growing season affects corn yields. Sizable regional differences in yield outcomes from a given set of weather conditions, a result of varying soil and climate differences across Illinois, further revealed how impacts of similar seasonal weather conditions can vary spatially. These two conclusions revealed the importance of using weather effects in defining seasonal extremes. Seasons harmful to corn yields and the state's water resources were prevalent in three decades: 1911–1920, 1931–1940, and 1950–1960. Seasons with the best weather effects were prevalent in 1901–1910 and 1961–1967. The last 37 years have had the best seasonal conditions of the century as a result of slightly cooler temperatures and higher precipitation. Results reveal the difficulties in projecting impacts of future climate conditions.

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**Indexing Terms:** Climatic data, weather data, networks, instrumentation, monitoring, water quality, ground water, surface water, water resources, climate change, impacts of weather.

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# LONG-TERM VARIATIONS IN SEASONAL WEATHER CONDITIONS AND THEIR IMPACTS ON CROP PRODUCTION AND WATER RESOURCES IN ILLINOIS

by Stanley A. Changnon and Derek Winstanley

## ABSTRACT

An analysis of long-term records of corn yields, water resource conditions, and seasonal weather con-ditions in Illinois found major temporal shifts and important spatial variations in the types of seasonal weather conditions that have positive and negative impacts on yields and water conditions. Nineteen different types of corn-weather seasons (May–August) occurred during 1901–1997, of which nine types accounted for most high corn yields (highest 20 of the 97 values) and eight types produced most low yields (lowest 20 values).

An assessment of the years with either high or low yields revealed three findings about the distributions of the corn-weather seasons creating these extremes: 1) some types were uniformly distributed throughout the century; 2) others were unevenly distributed over time, some occurring only in the century's early decades and others only in the last few decades; and 3) certain types varied greatly regionally. Yield responses to certain sea-sonal types varied over time. The findings helped establish that changes in farming practices, corn varieties, and agricultural technology all affect how a given type of growing season affects corn yields. Sizable regional differences in yield outcomes from a given set of weather conditions, a result of varying soil and climate differences across Illinois, further revealed how impacts of similar seasonal weather conditions can vary spa-tially. These two conclusions revealed the importance of using weather effects in defining seasonal extremes. In general, the statewide results showed that the types of seasons creating high yields predominated during 1901–1910 and 1961–1997, and most seasons creating low yields were concentrated in 1911–1920, 1931–1940, and 1951–1960.

Major seasonal weather effects on Illinois' water resources (surface water supplies, ground-water sup-plies, and water quality) were found to occur in the spring and summer seasons. Two conditions caused these effects in each season: either above normal temperatures and below normal precipitation, or above normal tem-peratures and precipitation. Spring impacts on water resources were typically mixed, some negative and some positive, whereas impacts from summer season extremes had largely negative impacts on water supplies and water quality. More impacts, positive and negative, occurred in southern Illinois than elsewhere, and most of the seasons having negative impacts on water resources occurred in Illinois during 1911–1960.

Comparison of the 1901–1997 temporal distributions of yield extremes (high and low) and the nega-tive summer water resource impacts with the temporal distributions of cyclone passages and the incidence of El Niño Southern Oscillation conditions that affect spring and summer weather conditions revealed a generally good relationship. Periods with many seasons creating numerous negative impacts on corn yields and water resources occurred in several decades (1911–1920, 1931–1940, and 1951–1960) when the number of cyclones was low and most incidences of La Niña conditions that create warm temperatures and negative impacts pre-vailed. Conversely, when seasonal weather conditions were generally beneficial (1901–1910, 1961–1970, and 1981–1997), Illinois had relatively large numbers of cyclone passages and most El Niño-related cool and wet summers occurred.

Consideration needs to be given to the shifting temporal responses to various kinds of seasonal weather conditions during the 20th century to determine how future climatic conditions may affect Illinois' agriculture and water resources. Furthermore, some influential seasonal weather types appeared sporadically, some only during the early decades of the century and others only in the latter decades. Thus, data from the past 97 years reveal that efforts to project impacts of future climate conditions on agriculture and water resources may be difficult and subject to considerable error.

# INTRODUCTION

Temporal fluctuations in seasonal climatic conditions are a key issue in assessing the impacts of past and future climate conditions. Weather events combine to form seasonal climate conditions, and these have an enormous influence on agriculture and the water resources of Illinois and the Midwest. Most atmospheric impacts are caused by the climatic conditions during the growing season (May–August) for crops and those in the warm season (April–September) for water resources.

Numerous studies have investigated historical trends and fluctuations of temperatures and precipitation in the four climate seasons (spring, summer, fall, and winter). For example, after identifying 12 small community weather stations with the highest quality long-term (1901–1997) records in Illinois, the 97-year trends in seasonal temperature and precipitation values were determined, revealing slight downward shifts in temperatures in the spring and summer and upward trends in summer precipitation amounts (Changnon et al., 1997). Karl and Riebsame (1984) assessed sharp fluctuations in seasonal temperature and precipitation conditions under the assumption that abrupt changes (defined statistically) over 10- to 20-year periods would create some form of regional impacts. However, such studies have not addressed a key question: do such seasonal shifts have any impacts of significance to society? Does a decrease in summer temperatures of two degrees (Fahrenheit) over 50 to 100 years create more or fewer impacts than a decrease of one degree Fahrenheit? Does a 15 percent increase in precipitation during 20 years in eastern Illinois have minor or major impacts on the region's water resources?

Weather and climate impact analyses often focus largely either on the frequency and magnitude of weather extremes resulting from short-term events such as hurricanes, or from seasons or runs of years with climate extremes such as droughts or cold winters (Pielke, 1997). For example, an impact-based view of Midwestern summer weather recognizes that hot, dry summers reduce crop yields. Studies related to effects of changing climate conditions on crop yields have typically examined historical data and, after normalizing the values to accommodate changing technological practices, have examined the temporal behavior of crop yields as an indirect measure of shifting weather conditions (Offutt et al., 1987; Hollinger, 1988). However, this approach does not identify the changes in the various growing season weather conditions, such as in the amount of July rainfall, that could still produce similar crop yields, either high or low. Thus, yield-based temporal analyses do not allow a climatological assessment of the temporal fluctuations in various types of growing season weather conditions that have occurred over time. That is, are there more or fewer seasons in recent (or past) years with weather conditions good or bad for crop yields? Do weather conditions that produced good crop yields in 1910 still produce comparably high (or higher) yields in 1997? Weather impacts on various natural processes and on society also change over time and must be accounted for in assessing extremes that vary over time. Historical variations in these climate-impact interactions also challenge meaningful efforts to forecast the impact of future climatic conditions on agriculture, water supplies, or other currently weather-sensitive endeavors (Carter et al., 1994). This study provides some interesting results applicable to interpreting future prognostications of impacts from a more variable climate or one shifting to warmer and wetter or drier conditions.

This study approached the analysis of historical long-term fluctuations in seasonal weather conditions based on those identified as highly important from an impacts perspective, while retaining the weather conditions as the form of seasonal typing associated with pronounced impacts. In this manner one can examine the temporal variability of critical weather conditions and their impacts when a long record exists.

Two seasonal assessments were made, one based on corn growing seasons in Illinois and the other based on seasonal conditions when the most significant water resources impacts occur in Illinois. Both assessments were for 1901–1997, the longest period of good data. The results from Illinois are considered to be representative of other parts of the Midwest with similar soils, physiography, and climate, and illustrate an approach involving shifting climate-impact relationships.

Data from 41 Illinois weather stations, selected based on length of record (1901–1997) and high-quality data, were used to define the seasonal conditions. Station locations encompass the 640 kilometers (km) north-south length and 480 km width of Illinois (figure 1). This considerable areal extent in a continental type climate results in significant regional differences in average temperatures and precipitation, and Illinois has wide differences in soil types that also greatly affect crop yields and the hydrologic cycle (Wascher et al., 1950). These factors reveal the importance of a regional-temporal analysis of the seasons that create major crop and water resources impacts. This study required an approach for defining the weather-yield relationship that allowed classification of the growing season conditions each year from 1901 to 1997 into a uniform class comparable to that of all other seasons.

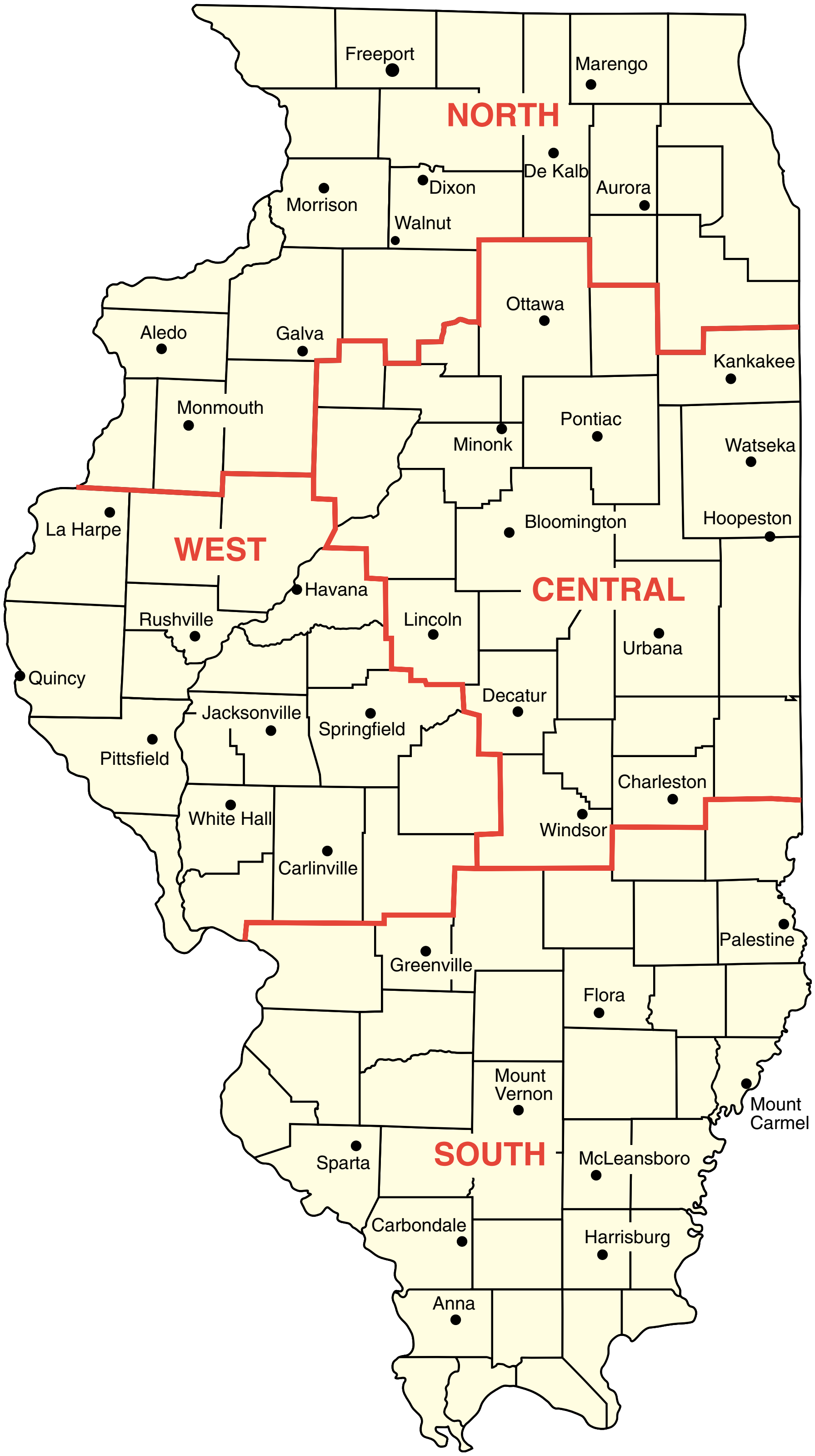



Figure 1. Corn-weather regions in Illinois and the weather stations used to define seasonal values, 1901–1997.

# DATA AND ANALYSIS

## Crop-Based Seasonal Weather Types

Several approaches for establishing the relationship between crop yields and weather conditions have been used over the past 70 years. The approaches fall into three general classes, each with strengths and weaknesses for a given application. Typically the approach is chosen on the basis of the purpose of the given study and the availability of data. No matter which approach is selected, however, modeling of crop yield-weather relationships represents a simplification of the actual physical processes that occur.

The most definitive approach uses physiological models that can define in detail how daily or even hourly weather conditions, farming practices, and known technological shifts determine crop yields (Hollinger, 1988). Unfortunately, this approach is not suitable for this long-term historical study because the detailed historical data needed do not exist (for example, a century of solar radiation and pan evaporation data for many sites scattered across large areas). This modeling approach is often used where localized detailed data exist such as on an experimental farm.

Another crop-weather modeling approach involves definition of crop and weather relationships through assessments by crop experts who identify the periods and type of weather conditions affecting yields, such as dry July and August periods. Their assessments are then integrated with climate records in a region to assess the temporal and spatial variability of crop important conditions (Richman and Easterling, 1987). The expert systems modeling approach could not be used because it does not furnish precise quantitative measures of the effects of varying climate conditions, particularly across large areas with different soils and climate conditions.

The most commonly used approach involves regression modeling of yields, weather, and technology. It is best adapted to large area and long-term assessments of weather effects. For example, the Erosion-Productivity Impact Calculator (EPIC) regression modeling of crop-weather relations was used in a recent study of the yield increases and income shifts related to use of the El Niño Southern Oscillation (ENSO) forecasts and effects in the growth of various crops (Solow et al., 1998). The technique relies on statistical determinations of how each weather variable affects plant production or crop yields and how the effects of agricultural technology have shifted over time. The “technological” effect is generally based on the assumption that the time trend of the yields is a proxy for changes in farming practices, new plant varieties, and agricultural technological advances over many decades (Thompson, 1975). This trend may also include a trend in crop relevant climate conditions, but Thompson (1986) has shown that this was not the case for corn yields in the Midwest.

The limitations associated with this modeling approach are that it typically uses monthly or seasonal weather variables or both, which can mask identification of key shorter term, time-varying weather conditions within a month (for example, five days of high temperatures at a critical growth stage). Furthermore, because of its statistical nature, the interactions between farm technology and weather, as well as temperature-rainfall interactions, mask some of the effect of individual weather elements on yields (Offutt et al., 1987). However, this approach was considered the best for defining quantitatively the most important weather variables for this study of multi-decadal variations in weather conditions extending across areas of thousands of square kilometers and over the longest possible period (Thompson, 1969).

The regression approach was used to identify critical monthly weather variables affecting corn yields, and these served as the basis for identifying the different types of corn-weather seasons in Illinois during 1901–1997. The seasons so identified, and their relative effect on corn yields, became the input for examining the temporal fluctuations in 1901–1997 corn-weather seasons.

Past research assessing the relationship between corn yields and weather conditions across Illinois for design of irrigation water needs had identified types of growing season weather conditions for each region determined on the basis of varying rainfall effects on yields (Changnon, 1969). That research used multiple curvilinear regression relationships for 1931–1965 with yield-weather-technology equations developed for several regions in Illinois.

In a similar approach, long-term 1901–1997 climate records were used to classify each corn-weather season into one of several types defined using the key weather variables identified from a multiple regression analysis of the weather and yields during 1931–1997. An analysis was conducted for each of four regions of Illinois as described below. These regional regressions used technological variables based on statistical fittings to the long-term regional distributions of corn yields, as done in prior studies and as shown for Illinois on figure 2 (Thompson, 1975; Offutt et al., 1987).

The regression results indicated that seven weather variables explained most of the Illinois corn yield variations: May rainfall, June temperature, June rainfall, July temperature, July rainfall, August temperature, and August rainfall. This agrees well with findings from numerous past crop-weather relationship studies for Illinois (Changnon and Neill, 1967; Thompson, 1969, 1975; Richman and Easterling, 1987; Offutt et al., 1987).

Sufficient regional differences in soils and climate exist across Illinois to require delineation of regions, each with its own weather-yield-soil relationship. Four regions were identified (figure 1) based on the relationship of yields and weather previously defined for each Illinois county (Chang-non and Neill, 1967). As described above, regional equations were derived for the four regions for 1931–1997 by multiple regression analysis of corn yields, seven weather conditions, and agricultural technology. Weather conditions, when regressed alone with yields, explained 57 percent of the yield variability in the north region; 65 percent in the central region; 78 percent in the west; and 89 percent in the south (where the state's poorest soils exist). When technology and weather factors were included, the regression equations explained more than 90 percent of the yield variability in all four regions. The unexplained variability is considered to be due to random factors and to weather conditions not included in the equation.

These four regions correlate well with the corn yield-weather regions defined based on expert systems analyses (Richman and Easterling, 1987) and on the weather-yield results based on the state's nine crop reporting districts (Offutt et al., 1987). The regions also match the distribution of soils across the state. Southern Illinois has light-colored shallow soils developed under forest vegetation; western Illi-nois has a mix of light and dark soils developed under prairie grasses and forests; central Illinois has dark soils developed under grass; and northern Illinois has soils similar to those in central Illinois but with considerable amounts of sandy loams and glacial tills (Fehrenbacher et al., 1967).

To determine corn-weather-season types in each region, data from 9–12 quality long-term weather stations in each region were chosen for analysis (figure 1). The stations' monthly values for each year during 1901–1997 were combined to form regional average weather values for each year and for each of the seven monthly conditions. The 97 values for each weather condition were ranked and classified as above normal (upper third of all values), near normal (middle third), and below normal (lower third). Each growing season was then assigned a set of normality values, as shown for the three years listed in table 1. Earlier research has shown that relationships between Midwestern crop yields and summer weather conditions expressed in these three normality classes could be meaningfully interpreted (Changnon, 1982; Sonka et al., 1988).

The next step involved comparison of the 97 yearly classes and sorting them into types. Conceivably there could be 2,100 seasonal types based on all combinations of seven weather variables, each with three levels, but a much more limited number was sought based on those weather conditions most critical to corn production. Regression results of this study and all past corn weather research have shown that July temperature and rainfall values have the greatest effect on corn yields, and hence seasonal typing began by categorizing the two July variables. For example, there were nine July combinations including: 1) above normal temperature and above normal rainfall (AA), 2) above normal temperature and normal rainfall (AN), 3) above normal temperature and below normal rainfall (AB), 4) normal temperature and above normal rainfall (NA), 5) normal temperature and normal rain-fall (NN), 6) normal temperature and below normal rainfall (NB), 7) below normal temperature and above normal rain-fall (BA), 8) below normal temperature and normal rainfall (BN), and 9) below normal temperature and below normal rainfall (BB). All combinations occurred in the 97-year records in all four regions.

Then for each July class, August and May rainfall levels were compared because these two conditions ranked as the third and fourth most important weather variables in all four regions. A region was considered to have a type of corn-weather season 1) if three or more years in the 97-year sample

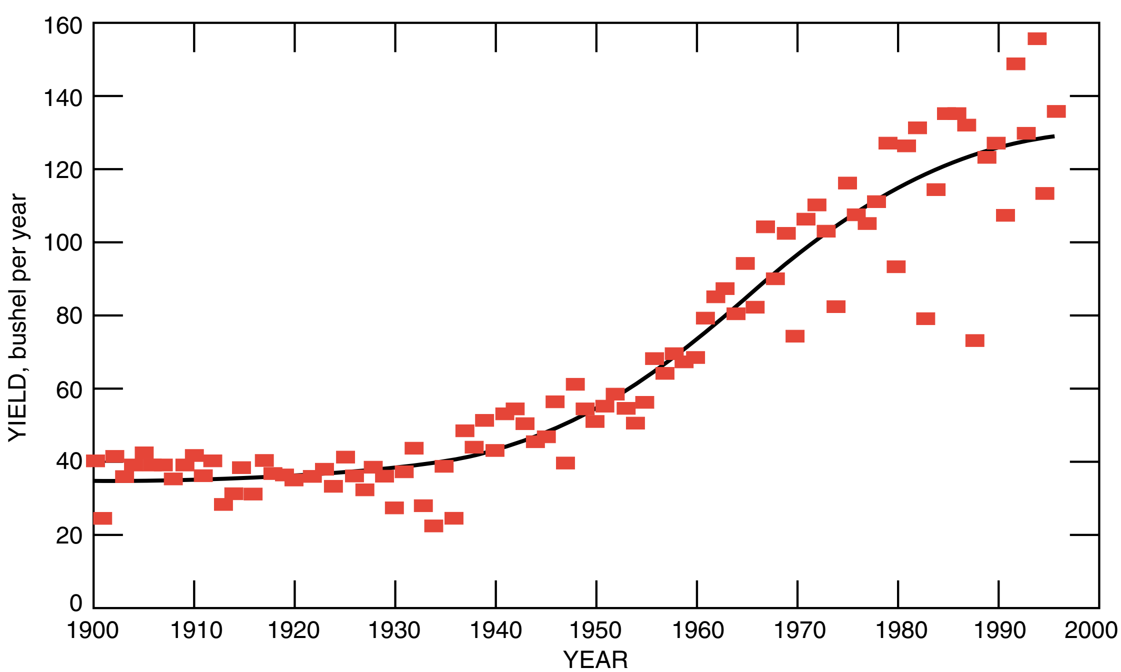



Figure 2. Annual corn yields in Illinois, 1900–1997. Curve was fit to the values and represents temporal changes resulting from shifting farm practices and changing agricultural technologies including seed varieties.

**Table 1. Total Rainfall (inches) and Average Temperature (°F) during Three Years Qualifying for Corn-Weather Type 17 (A–BN–BN–BA) in Southern Illinois, 1901–1997**

| | *May* | *June* | | *July* | | *August* | |
|---|---|---|---|---|---|---|---|
| *Year* | *Rain* | *Temp* | *Rain* | *Temp* | *Rain* | *Temp* | *Rain* |
| 1915 | A | B | N | B | N | B | A |
| Average | 5.3 | 71.0 | 4.5 | 75.6 | 2.7 | 71.5 | 9.1 |
| 1950 | N | N | N | B | N | B | A |
| Average | 3.9 | 75.2 | 5.3 | 76.2 | 3.1 | 74.8 | 8.0 |
| 1992 | A | B | B | B | N | B | A |
| Average | 5.4 | 69.5 | 0.5 | 76.8 | 3.5 | 70.7 | 4.4 |
| Most common | A | B | N | B | N | B | A |
| Average | 4.9 | 71.9 | 3.4 | 76.2 | 3.1 | 72.3 | 7.2 |

**Notes:** A = above normal, N = normal, and B = below normal.

**Table 2. Corn-Weather Season Types Identified in Illinois, 1901–1997**

| | *May* | *June* | | *July* | | *August* | |
|---|---|---|---|---|---|---|---|
| *Type* | *Rain* | *Temp* | *Rain* | *Temp* | *Rain* | *Temp* | *Rain* |
| 1 | B | N | N | B | A | B | A |
| 2 | B | B | N | N | A | B | N |
| 2 | N | N | N | A | A | N | N |
| 3 | N | N | B | N | N | N | N |
| 4 | B | A | B | A | N | N | A |
| 6 | B | A | N | N | N | N | B |
| 7 | N | N | N | B | N | N | N |
| 8 | A | A | A | B | N | A | N |
| 9 | B | N | B | A | B | A | A |
| 10 | N | A | B | A | B | A | B |
| 11 | A | N | A | A | B | N | N |
| 12 | A | B | A | N | B | B | B |
| 13 | N | N | N | B | B | B | N |
| 14 | A | B | A | B | B | A | B |
| 15 | N | B | A | B | A | B | B |
| 16 | N | N | B | A | N | A | N |
| 17 | A | B | N | B | N | B | A |
| 18 | A | B | A | N | B | B | A |
| 19 | B | A | A | A | A | A | A |
| Totals | | | | | | | |
| Above | 6 | 5 | 6 | 7 | 5 | 6 | 6 |
| Near | 7 | 7 | 8 | 5 | 7 | 6 | 7 |
| Below | 6 | 7 | 5 | 7 | 7 | 7 | 6 |

**Notes:** A = above normal, N = normal, and B = below normal.

had identical July conditions, and 2) when the associated May and August rainfall conditions each had clear preferences for being above normal, normal, or below normal. For example, as shown in table 1, in southern Illinois there were three seasons (during 1901–1997) with below normal July temperatures, normal July rainfall, and above normal rainfall in May and August. Note that if one of the May or August rainfall values for a given year was one level away from the predominant class found in all other years, as illustrated by 1950 May rainfall being normal and not above normal as found for the other two years, this year was still included in the seasonal type. Two other corn-weather seasons identified in this region had the same below normal temperatures and normal rainfall sequence for July, but one had normal May and August rainfall (found in six years), and the other had above normal May rainfall and normal August rainfall (found in four years).

June conditions and August temperature levels were not used to further subdivide the seasonal types since their effect on corn yields was relatively small, explaining less than 10 percent of the yield variability. However, the two June values and the August temperatures were used along with the other four conditions to determine the most prevalent weather conditions in each corn-weather season (as illustrated in table 1).

By this process, 19 corn-weather season types were defined (table 2). Also shown is the frequency of above normal, normal, and below normal conditions for each of the seven weather conditions. These numbers show rather uniform distributions among the three classes, indicating a representative sampling of various growing season conditions.

## Regional Variations in Corn-Weather-Season Types

The seasonal classification process led to the identification of corn-weather-season types in each region, most of which were found in the other regions. As shown in figure 3, 14 of the 19 season types occurred in northern Illinois during 1901–1997. All 14 types also occurred in the other three regions; central Illinois had 16 types; western Illinois had 17 types; and southern Illinois had 19 types. This southward increase reflects the more diverse summer weather conditions that occur in the state's southern sections (Changnon and Huff, 1980).

Table 3 shows the frequency of each season type in each region, revealing spatial differences. Type 1 was more prevalent in the north (17 occurrences in 97 years), whereas type 2 was more prevalent in the central and southern regions than else-where in Illinois. Type 11 was nearly twice as frequent across central Illinois (west and central regions) as in the north or south, reflecting the climatic differences that can occur across an area 640 km long. Types 4 and 6 were more common in the northern and central regions. More than half of the 14 weather types (5, 7, 8, 9, 10, 12, 13, and 14) had approximately the same frequency of occurrence in all four regions. Many of these types were not associated with years of high corn yields, but types 9 and 10 with hot, dry July conditions often produced very low yields.

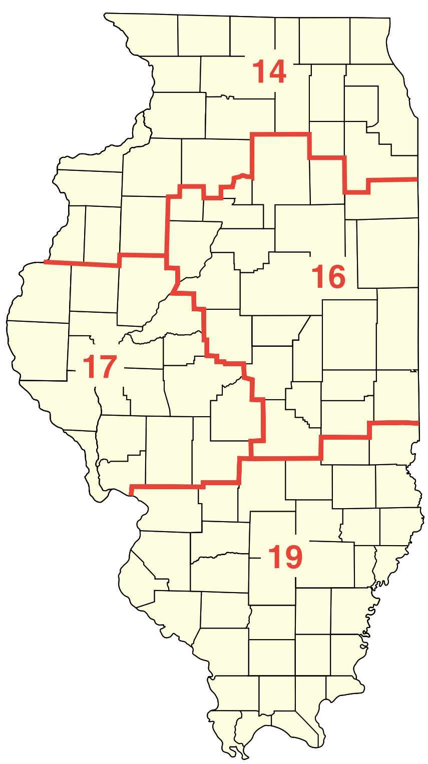
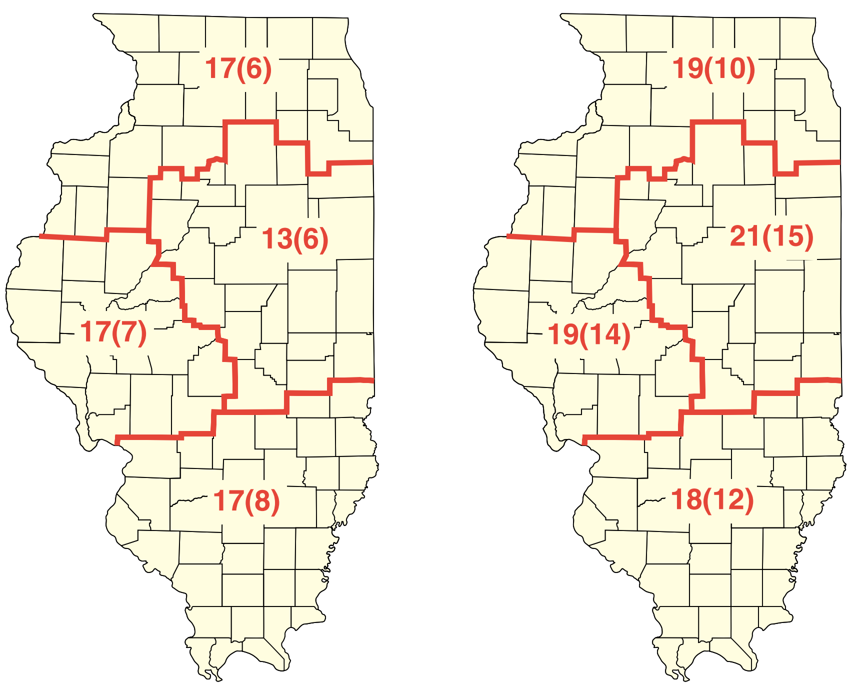



Figure 3. Number of corn-weather-season types found in each region, 1901–1997.

**Table 3. Frequency of Corn-Weather Season Types in Each Region of Illinois, 1901–1997**

| *Region* | *Frequency of season types* | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* | *16* | *17* | *18* | *19* |
| North | 17 | 6 | 7 | 9 | 4 | 9 | 5 | 5 | 6 | 9 | 4 | 9 | 4 | 3 | 0 | 0 | 0 | 0 | 0 |
| Central | 9 | 11 | 7 | 12 | 3 | 5 | 6 | 5 | 7 | 4 | 10 | 5 | 3 | 3 | 4 | 0 | 0 | 0 | 3 |
| West | 5 | 7 | 8 | 7 | 7 | 3 | 6 | 3 | 5 | 6 | 8 | 7 | 3 | 3 | 12 | 0 | 3 | 0 | 4 |
| South | 9 | 12 | 4 | 5 | 4 | 3 | 6 | 4 | 6 | 7 | 5 | 4 | 3 | 4 | 5 | 6 | 3 | 4 | 3 |

The varying regional frequencies of several seasonal types illustrate the importance of treating the crop-seasons on a regional basis, reflecting the important climate and soil differences across Illinois. Although types 1–14 occurred in all four regions, types 15–19 occurred only in portions of Illinois. For example, type 15, a cool summer with wet June and July conditions (normal May rainfall, below normal June temperatures, above normal June rainfall, below normal July temperatures, above normal July rainfall, and below normal August temperatures and rainfall), occurred in all regions except northern Illinois, while types 16 and 18 occurred only in southern Illinois, reflecting the greater number of seasonal types there. Figure 4a depicts the regional frequencies of types based on a cool, wet July, commonly recognized as good for corn production. These values vary from a low of 13 such seasons during 1901–1997 in central Illinois to 17 seasons in western and northern Illinois. Also depicted in figure 4a are the frequencies with which these weather seasons were associated with one of the top 20 corn yields during 1901–1997. For example, central Illinois had a high corn yield in 6 of the 13 years when a cool, wet July occurred.




a. July temperatures below normal and rainfall above normal (types 1 and 15). Values in parentheses show the number of cool-wet Julys associated with high corn yields.

b. July temperatures above normal and rainfall below normal (types 9, 10, and 11). Values in parentheses show the number of hot-dry Julys associated with low corn yields.

Figure 4. Number of corn-weather seasons, 1901–1997: a) with July temperatures below normal and July rainfall above normal: (types 1 and 15) and b) with July temperatures above normal and July rainfall below normal: (types 9, 10, and 11).

Figure 4b depicts the regional frequencies of years when July conditions were hot and dry, recognized as harmful to corn production. These values range from a high of 21 years in central Illinois to a low of 18 years in southern Illinois, revealing little spatial variability in these July conditions. Also shown, in parentheses, are the frequencies with which a hot, dry July was associated with a year when quite low yields occurred, with low defined as the lowest 20 yields during the 1901–1997 period. These conditions exhibit greater spatial variability but do reveal that hot, dry July conditions were responsible for many regional low corn yields, accounting for 10 of the 20 low yields in northern Illinois and 15 of the 20 in central Illinois.

## High and Low Corn Yields

Corn yield data were obtained for each region by averaging the county yields for the 1931–1997 period, but a two-step process was required to estimate regional yields for 1901–1930. First, regional weather values for each year (1901–1930) were inserted in 1931–1960 regression equations developed for each region to calculate their yield values based on a period when farming technologies were relatively similar. These regional yield values were expressed as a percent of the technological mean yield for 1931–1960, and then the departures (from the mean) of the estimated 1901–1930 yields for each region were compared with the departures of the actual state yields, which were available for 1901–1930 (figure 2). This was done to determine if any major differences existed, such as two or three regions with estimated yields below the mean when the statewide departure was above the mean. No such differences were found.

The technological mean values for 1901-1930 were determined using the curve fit to the 1901–1930 state yields shown in figure 2. This had a slight linear increase from 35 bushels per acre (bu/acre) in 1901 to 38 bu/acre in 1930. The percentage departures of the calculated yields for each region and year were then applied to this mean yield value for the year, as based on the statewide mean technology curve for 1901–1930, resulting in annual yield values estimated for each region. For example, the yield calculated for 1913 in southern Illinois was 30 percent below the 1931–1960 mean, and its adjusted value (based on 1913 with a mean value of 36 bu/acre) was 25 bu/acre (36 minus 11). In summary, the estimated yields for each region for 1901–1930 were dependent on the weather-yield relationships for another period (1931-1960) when agricultural practices were somewhat different than in 1901–1930, which has some effect on the magnitude of the estimated yields. However, since the ensuing analysis of 1901–1997 yields was based on only the 20 highest and 20 lowest yields, which are extreme values (1 or 2 per decade), the effect of any yield estimation errors on the findings about high and low yields is considered to be minimal.

High and low corn yields during the 97-year period were determined based on departures from the long-term curve fit to the historical yields in each region, which included the 1901–1930 estimated yields. To ensure selection of only the most critical yield seasons, the 20 highest and 20 lowest yield years were identified within each region.

Table 4 presents the weather types that were associated with two or more high yield years for each region, and there are considerable regional differences. For example, type 15 (below average July temperatures and above average July rainfall) was related to more high yields in the western and southern regions of the state than any other weather type (table 4), but type 15 was less frequently associated with high yields in northern and central Illinois where soils are deeper and weather effects on yields are less. Types 1 (below average July temperatures and above average July rainfall) and 2 (normal July temperatures and above average July rainfall) were often associated with high yields in northern and central Illinois, as shown in figure 5. Types 1 and 15 had identical July conditions

**Table 4. Regional and State Frequencies of High Corn Yields Associated with Corn-Weather Seasons Producing High Yields in Two or More Years, 1901-1997**

| *North* | *Central* | *West* | *South* | *State totals* |
|---|---|---|---|---|
| 1 (5) | 1 (4) | 15 (5) | 15 (5) | 1 (14) |
| 7 (4) | 2 (3) | 2 (3) | 1 (3) | 15 (12) |
| 2 (3) | 4 (2) | 12 (3) | 2 (3) | 2 (12) |
| 6 (2) | 6 (2) | 4 (2) | 4 (3) | 12 (8) |
| 12 (2) | 7, 12, 15 (2) | 1, 17, 19 (2) | 17 (2) | 4 (8) |

**Notes:**
First number = type, and number in parentheses = number of years that a particular type occurre

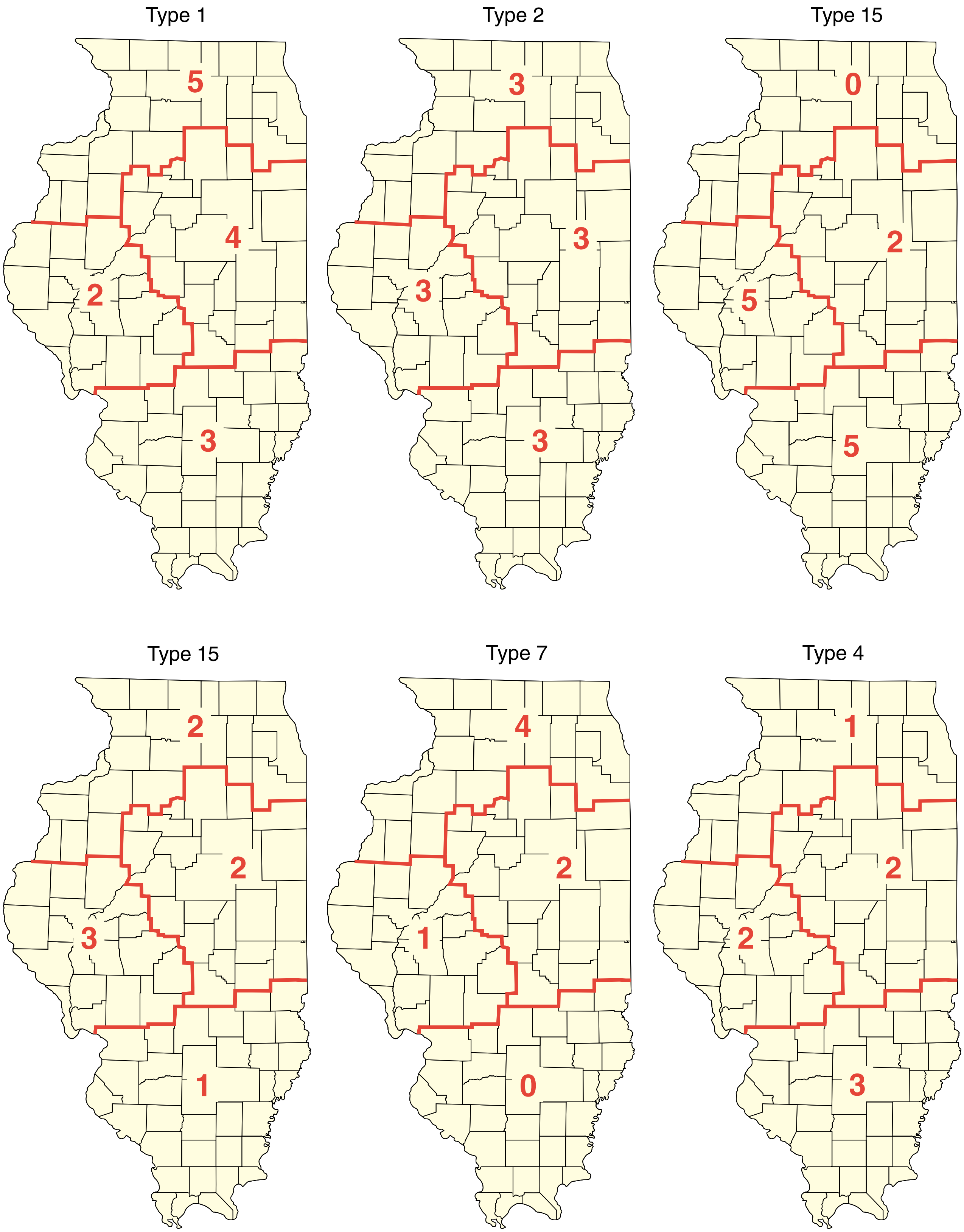



Figure 5. Patterns based on the frequency of the six corn-weather season types associated with the greatest number of high corn yields, 1901–1997. Values in each region represent the number of times the type identified produced a high yield in that region.

(below average temperatures and above average July rainfall), but differed in four other monthly conditions (May rainfall, June temperatures and rainfall, and August rainfall), as shown in table 2. Four types (9, 10, 11, and 14) were not associated with any high yields.

High corn yields are expected with cool, wet July conditions (types 1 and 15) and with normal temperature–wet July conditions (type 2), and these three types accounted for 38 of the 80 top yields (4 regions times 20 values) during 1901–1997. However, there were 97 seasons with types 1, 2, and 15 during 1901–1997, indicating that only 40 percent (38) of the time did such conditions produce high yields. Thus, several other weather types resulted in high yields.

Type 6 with normal July conditions was twice related to high yields in both northern and central Illinois but did not produce high yields in southern and western Illinois where the weather stress is much greater due to poorer soil conditions (Wascher et al., 1950). Above or near normal July rainfall accompanied most high yields, as expected. However, type 12 with below normal July rainfall occurred with high yields in up to three years in each region (figure 5). Type 12 had above normal rainfall in May and June, and near normal July temperatures, all acting to reduce crop stress and to provide adequate soil moisture when most needed in July. Most years in which type 12 was associated with high yields occurred in early to mid-century including 1910 (north), 1925 (south and central), 1937 (central), 1946 (west and north), and 1972 (west). Type 12 occurred in eight years after 1972, but none were associated with the top 20 yields.

Values in table 5 show the number of seasons associated with two or more low corn yields (20 lowest yields in 1901–1997 for each region). These values for all four regions reveal three seasons frequently produced low yields (types 9, 10, and 11). All three types had a hot, dry July, but they differed in the conditions that existed in May, June, and August. Type 11 created added problems with a wet May and June, conditions that can delay planting, lead to shallow root development, and leach nitrogen fertilizer, all acting to reduce yields as in 1974, a type 11 year with low yields (Changnon, 1975). Figure 6 shows the regional patterns of types 9, 10, and 11 reveal interesting spatial differences. For example, type 9 occurred most often in the southern half of the state, whereas type 10 was most common in the west and north. These types accounted for 10 low yields in northern Illinois (half of the 20 lowest yields), 14 low yields in the west, 15 low yields in central Illinois, and 12 low yields in southern Illinois. Collectively, they accounted for 51 of the 80 possible (64 percent) regional low yield seasons during 1901–1997. These three types occurred in 77 years during 1901–1997, and 51 of these, or 67 percent, created low yields. The results also reveal that 29 years of low yields were related to other weather types.

Regional differences were found for certain other weather types associated with low corn yields. Type 5 (figure 6) produced two low yield years in central Illinois, three in western Illinois, but none in northern and southern Illinois. Type 16 created three low yield years in southern Illinois but none elsewhere in the state. Above normal July and August temperatures with near normal rainfall found in type 16 are conditions more limiting to crop growth in the clay pan soils of southern Illinois than elsewhere in Illinois (Wascher et al., 1950). Five seasonal types (1, 2, 7, 15, and 17) were not associated with a low yield in any region during the 97-year period. All but type 2, which had normal July temperatures, had below normal July temperatures, and all five types had normal or above normal July rainfall (see table 2).

**Table 5. Regional and State Frequencies of Low Corn Yields Associated with Corn-Weather Seasons Producing Low Yields in Two or More Years, 1901-1997**

| *North* | *Central* | *West* | *South* | *State totals* |
|---|---|---|---|---|
| 10 (6) | 9 (5) | 10 (6) | 10 (5) | 10 (20) |
| 4 (4) | 11 (7) | 9 (4) | 9 (4) | 11 (16) |
| 3 (3) | 10 (3) | 11 (4) | 11 (3) | 9 (15) |
| 11 (2) | 19 (2) | 5 (3) | 16 (3) | 5 (5) |
| 9 (2) | 5 (2) | 12 (2) | 8 (2) | 3 (4) |

**Notes:**
First number = type, and number in parentheses = number of years that a particular type occurred.

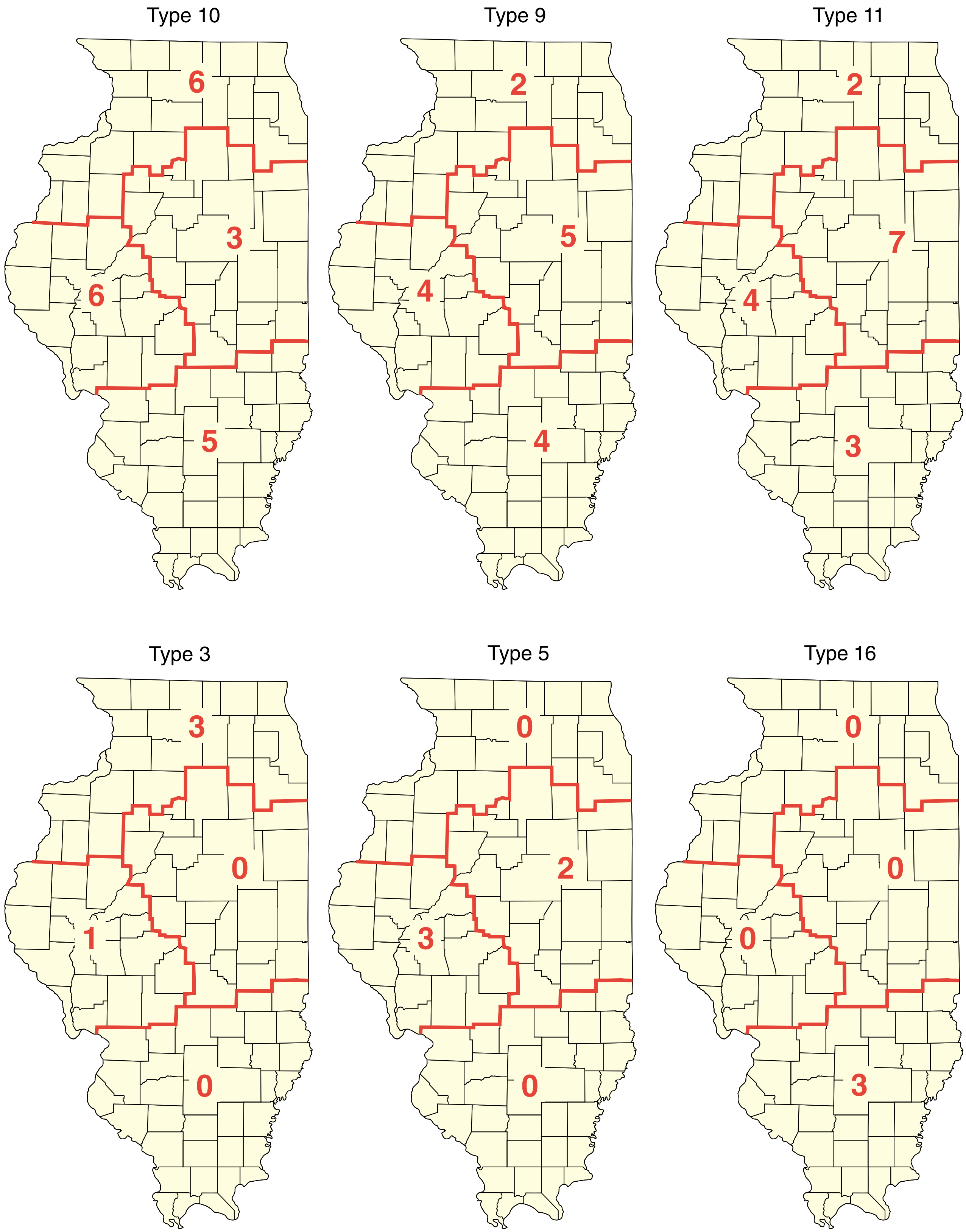



Figure 6. Patterns based on the frequency of the six corn-weather season types associated with the greatest number of low corn yields, 1901–1997. Values in each region represent the number of times the type identified produced a low yield in that region.

## Water Resource-Weather Seasons

The effect of seasonal weather conditions on Illinois' water resources was defined based on consideration of three factors: surface water conditions, including streamflow and reservoir supplies; ground-water supplies; and the quality of both surface water and ground-water supplies. Structured interviews using pre-set questions about these three water conditions were conducted with 15 hydrologists very familiar with water issues in Illinois, and this was the primary technique used to define the most critical water issues for all seasons (Changnon and Easterling, 1988).

Each hydrologist was asked to consider the three water conditions (surface water, ground water, and water quality) and to identify whether above normal, normal, or below normal temperature and precipitation conditions, or both, were weakly or strongly beneficial or harmful to each water condition for each of the four climatological seasons and for varying regions of Illinois. Their responses were the primary basis for defining the most important weather-water seasons and which temperature and precipitation conditions were most critical. Interview results were compared with published results (Lins et al., 1990) to ensure the critical seasons had been defined accurately and that other seasons or conditions of importance were not omitted.

Analysis of the responses revealed that all three water resource conditions were most frequently sensitive to weather conditions in spring (March–May) and summer (June–August). Furthermore, the results showed no major impacts when temperature or precipitation values were in the near normal class (middle third of the values). Major effects of seasonal weather conditions on water resources in Illinois come from extremes, not near normal conditions. This outcome was further verified after comparison with results from studies of Illinois floods (Singh, 1987; Changnon and Huff, 1987), droughts (Easterling and Changnon, 1987; Changnon and Easterling, 1989), surface water supplies (Singh et al., 1992), ground-water supplies (Changnon et al., 1988), and water quality (Bhowmik, 1988; Barcelona et al., 1989).

Table 6 shows the combinations of seasonal weather conditions and their impacts in the spring and summer. The conditions listed as having positive (beneficial) or negative (harmful) effects were based on consistent responses from the water experts sampled. In cases where there were uncertainties over the magnitude of the impacts, or the identification of only minor effects, or major differences in the experts' views about the type of effects (positive or negative) from a specific type of seasonal weather condition, the condition was not identified as creating a major impact. Only those effects defined by two-thirds or more of the sampled experts as producing major impacts were chosen for study. This ensured assessment of critically important outcomes, as with the crop assessment based on only the 20 highest and 20 lowest corn yields.

**Table 6. Major Impacts to Water Resources in Illinois Associated with Above and Below Normal Temperatures and Precipitation Amounts in Spring and Summer**

**Spring**

| | *Precipitation* | | *Temperature* | |
|---|---|---|---|---|
| *Resources* | *Above normal* | *Below normal* | *Above normal* | *Below normal* |
| Surface water | ± | - | - | — |
| Ground water | + | - | — | — |
| Water quality | - | ± | + | — |

**Summer**

| | *Precipitation* | | *Temperature* | |
|---|---|---|---|---|
| *Resources* | *Above normal* | *Below normal* | *Above normal* | *Below normal* |
| Surface water | 0 | - | - | — |
| Ground water | — | - | — | — |
| Water quality | - | ± | - | — |

**Notes:** - = major negative effects, + = major positive effects, — = small or neutral effects.
Water quality refers to both surface and ground water conditions.

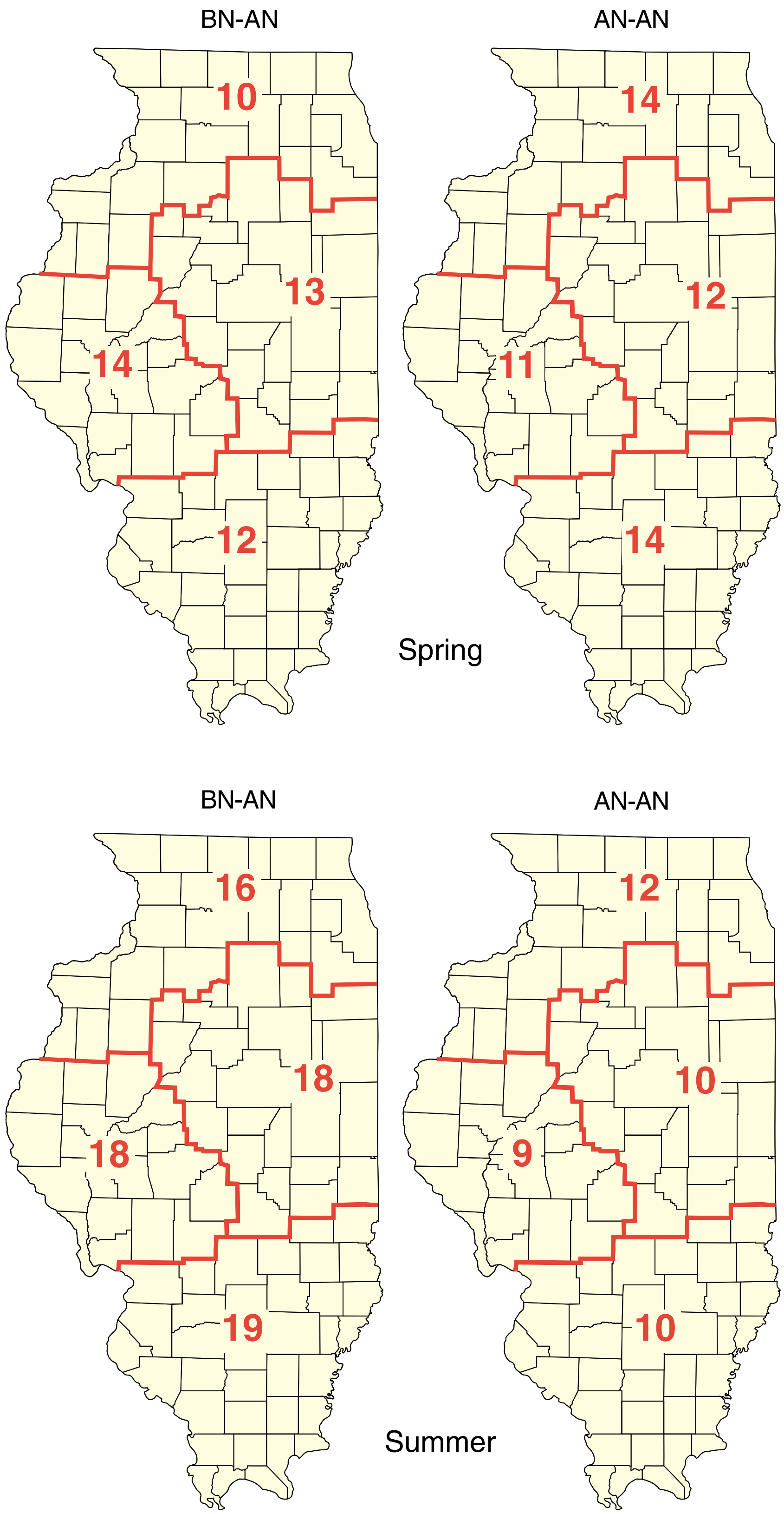



Figure 7. The number of weather-water seasons of two types, below normal precipitation and above normal temperature (BN–AN) and above normal precipitation and above normal temperature (AN–AN), occurring in each region during spring and summer seasons, 1901–1997.

The analysis of those weather-water seasons producing major impacts on the state's water resources was accomplished by examining the same four regions defined for the corn yield analysis for possible regional climatic differences. Water resource conditions vary somewhat across the state due to varying climatic conditions and to moderately different physiographic conditions. Southern Illinois is classified by geomorphologists as hill country, western Illinois as a mixture of flat and rolling topography, and central and northern Illinois as flat land with many poorly developed natural drainage systems (Leighton et al., 1948). However, the experts sampled did not indicate any significant regional differences in the occurrence of major impacts resulting from the spring and summer weather conditions. That is, a summer of above normal precipitation and above normal temperatures was as bad for the water resources in northern Illinois as for those in southern Illinois.

Analysis of the spring conditions revealed the major impacts came with two sequences of conditions defined by both precipitation and temperature conditions:

- Warm and wet spring (above normal temperatures and above normal precipitation) is deemed as both good and bad for surface water conditions, has mixed effects on water quality, and has positive effects on ground-water conditions.
- Below normal precipitation and above normal temperatures (a dry and warm spring) were defined as having negative effects for suface water conditions with mixed outcomes, positive and negative, for water quality conditions.

Analysis of the summer conditions and their major impacts showed the following outcomes for two sequences of conditions when abnormal precipitation and temperature conditions jointly acted to create impacts in at least one of the three water resource conditions assessed.

- Above normal precipitation and temperature conditions (wet and warm) have mixed effects on surface water conditions and negative effects on water quality.
- Below normal precipitation and above normal temperatures (dry and warm) produce negative effects for all three water conditions.

Results reveal that various combinations of spring and summer conditions cause some form of beneficial or negative effects on water resources, but most results in summer are negative as shown in table 6. Mixed impacts, good and bad, occur with most spring conditions. For example, above normal precipitation in the spring helps sustain surface water supplies, but it also can help create spring floods (Singh, 1987, Singh et al.,1992). Heavy spring rainfall also helps enhance shallow ground-water supplies (Changnon et al., 1988), but it erodes soil and leaches fertilizer, creating water quality problems (Bhowmik, 1988).

Comparison of the spring and summer results reveals that in both seasons the combinations of a) below normal precipitation and above normal temperature, and b) above normal precipitation and temperatures produced the most pervasive effects in all three water conditions. Other seasonal combinations, such as below normal precipitation and temperatures, produce effects limited to one or two of the three water conditions and to only one weather condition. Hence, the temporal analysis of seasonal conditions producing the major water resources impacts in Illinois was based on spring and summer conditions, which were either above normal precipitation and temperature or below normal precipitation and above normal temperatures.

The regional frequencies of each type of weather-water season occurring in the spring and summer are shown in figure 7. The below normal precipitation and above normal temperature conditions occurred more often across central Illinois, whereas above normal precipitation and temperature conditions in spring were less prevalent across the state's midsection. Southern Illinois with a total of 26 weather-water seasons during 1901–1997 had slightly more such seasons than occurred in western and central Illinois (25 seasons each) and in northern Illinois (24 seasons).

The regional frequencies in summer (figure 7), which are largely negative impacts to water resources, show that below normal precipitation and above normal temperature seasons (dry and hot) had a north-south distribution across the state with the maximum of incidences in southern Illinois and the minimum in northern Illinois. In contrast, the above normal precipitation and temperature (wet and hot) seasons were most frequent in northern Illinois. Summation of the two summer season frequencies shown in figure 7 reveals that southern Illinois had 29 weather-water seasons in 1901-1997, slightly more than in the other three regions. Recall also that the summer season impacts on water resources are negative.

# TEMPORAL TRENDS IN CORN-WEATHER SEASONS

The temporal frequencies of the various types of corn-weather seasons in northern Illinois appear in table 7. Inspection reveals several weather types (1, 3, 4, 11, and 12) were evenly distributed throughout the century. Some types were common in the early decades of the century (types 8 and 9); others were prevalent in mid-century (5, 6, and 10); and still others occurred largely in later decades (2, 7 and 13). These temporal differences in seasonal types, as based on the climatological structure of weather conditions from May–August, indicate that some growing season atmospheric conditions were repetitious over time, whereas others were shifting on longer time scales. For example, weather type 2 did not appear in the first 40 years of the century, and type 9 did not occur again after 1960. Such mixes of even and uneven temporal distributions were found for corn-weather types in the three other regions. In southern Illinois (table 8), weather type 6 occurred three times but only during 1951–1960, and type 13 occurred only three times and only during 1981–1990. Such anomalous variations have interesting implications for climate modeling and reflect wide changes in atmospheric circulation patterns during the 20th century. Tables 9 and 10 present the corn-weather type distributions for central and western Illinois.

Comparison of the seasonal distributions for the four regions revealed certain weather types with similar distributions in three or more regions. For example, weather types 1–5, 11–12, and 18 exhibited rather uniform temporal distributions in all four regions. Weather types 9–10, 14, and 17 primarily occurred early in the century. Weather types 6–7, 16, and 19 occurred mainly during mid-century, and weather types 8, 13, and 15 occurred mainly in the most recent decades. The temporal fluctuations in the corn-weather seasons that produced most of the high and low yields in each region appear in tables 11–13. Recall that most of the high and low yields in each region occurred with only five weather types, as illustrated in tables 4 and 5. The top five weather types in each region accounting for the greatest number of high corn yields are listed in table 4, and the distributions reveal that the five weather types were associated with 15 or 16 of the 20 highest yields in each region. Similarly, the five weather types accounting for most of the 20 lowest yields in each region were associated with from 17 to 19 of the 20 lowest yield years.

The temporal distributions of the five weather types producing the greatest number of high yields were determined for each region. Table 11 shows the incidence of types with high corn yields, whether high or not, and all four regions show comparable values in many decades. Seasons capable of producing high yields were quite frequent everywhere in Illinois during five decades: 1901–1910, 1961–1970, 1971–1980, 1981–1990, and 1991–1997. A preponderance of these seasons came during the last 37 years of the century. In 1921–1930, several potentially high corn yield seasons occurred in central and northern Illinois, but few occurred in southern Illinois. The northern region had more good seasons in 1961–1970 and 1991–1997 than did the other three regions. Three decades (1911–1920, 1931–1940, and 1951–1960) had very few seasons with the potential for high corn yields in all four regions.

The regional findings on high and low corn yield seasons revealed two other interesting results. First, a given weather type that was often associated with high (or low) yields sometimes was also occasionally associated with a low (or high) yield, as revealed by the southern Illinois example in table 12. Corn-weather types 1 and 2 were often associated with high corn yields, but type 2 had one year with low yields during 1981–1990. A second important result, as illustrated in table 12, is that not all occurrences of a given weather type produced an outstanding high or low yield. For example, type 2 was associated with high yields during 1901–1970, but the five such seasons that occurred after 1970 were not associated with any of the region's 20 highest yields. This may reflect varying weather-yield relationships due to shifting farm practices, technology, and corn varieties, or sampling vagaries due to the 20 yield limit set on defining high and low yields. Yields during the five years were all near to above average.

Table 13 shows the temporal distributions of weather types most often producing low corn yields, based on the five seasons with the greatest frequency of low yields (table 5). Regional values are comparable in many decades, but considerable regional differences in frequencies appear in 1921–1930 (values ranging from 1 to 4) and in 1941–1950 (values ranging from 2 to 5). Inspection of all regional distributions shows high frequencies of potentially low-yield years in 1911–1920 and 1931–1940. State totals (table 13) reveal that most seasons capable of producing very low corn yields occurred during the 50-year period, 1911–1960, with 83 of the 123 total values.

Comparison of the state decadal totals of high and low yields (tables 11 and 13) reveals that high- and low-yield seasons occurred in all ten decades (including 1991-1997, a seven-year period). The decadal ratios of low to high frequencies of seasons reveal that relatively small ratios (more high- than low-yield seasons) occurred in 1901–1910 (0.4), 1961–1970 (0.16), 1981–1990 (0.43), and 1991–1997 (0.35). Quite high ratios, indicating decades with predominately low-yield seasons, occurred in 1911–1920 (1.6), 1931–1940 (3.8), and 1951–1960 (1.4). This agrees well with findings from a study of dry summers during 1901–1990 (Changnon et al., 1996), which showed the state's higher frequencies of dry summers occurred in 1911–1920 and again in 1931–1940.

Figure 8 depicts the temporal variations in the statewide values of high- and low-yield seasons based on the sum of all regional values. This illustrates that decades with more evenly distributed incidences of high- and low-yield seasons included 1921–1930, 1941–1950, and 1951–1960. The figure illustrates the dramatic differences between values in 1911–1920 and 1931–1940, and those in the four periods after 1960.

**Table 7. Decadal Distribution of Corn-Weather Types 1-14 in Northern Illinois, 1901-1997**

| | *Frequency per decade or weather types* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Decade* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* |
| 1901-1910 | 3 | 0 | 1 | 2 | 0 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1911-1920 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 | 3 | 0 | 1 | 0 | 1 |
| 1921-1930 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 1 | 2 | 1 | 1 | 0 | 0 |
| 1931-1940 | 1 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 0 |
| 1941-1950 | 0 | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 1 |
| 1951-1960 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 1 | 0 |
| 1961-1970 | 3 | 2 | 0 | 0 | 0 | 3 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| 1971-1980 | 1 | 1 | 0 | 2 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 1981-1990 | 1 | 1 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 1991-1997 | 3 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |

**Table 8. Decadal Distribution of Corn-Weather Types 1-19 in Southern of Illinois, 1901-1997**

| | *Frequency per decade of weather types* | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Decade* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* | *16* | *17* | *18* | *19* |
| 1901-1910 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| 1911-1920 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 |
| 1921-1930 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 |
| 1931-1940 | 0 | 0 | 1 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 2 |
| 1941-1950 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 0 |
| 1951-1960 | 2 | 0 | 0 | 0 | 0 | 3 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 1961-1970 | 1 | 3 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1971-1980 | 2 | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1981-1990 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1991-1997 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |

**Table 9. Decadal Distribution of Corn-Weather Types 1-15 and 19 in Central Illinois, 1901-1997**

| | *Frequency per decade of weather types* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Decade* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* | *19* |
| 1901-1910 | 0 | 3 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 0 |
| 1911-1920 | 1 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |
| 1921-1930 | 1 | 1 | 0 | 4 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 1931-1940 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 3 | 2 | 0 | 0 | 0 | 0 |
| 1941-1950 | 0 | 1 | 1 | 2 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 1951-1960 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 2 |
| 1961-1970 | 1 | 3 | 0 | 2 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| 1971-1980 | 3 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1981-1990 | 2 | 2 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| 1991-1997 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |

**Table 10. Decadal Distribution of Corn-Weather Types 1–15, 17, and 19 in Western Illinois, 1901–1997**

| | *Frequency per decade of weather types* | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Decade* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* | *17* | *19* |
| 1901-1910 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 3 | 1 | 0 |
| 1911-1920 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 1 | 0 | 1 | 0 | 1 | 0 |
| 1921-1930 | 0 | 1 | 1 | 1 | 1 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1931-1940 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| 1941-1950 | 0 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 2 |
| 1951-1960 | 1 | 0 | 2 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 1961-1970 | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 1971-1980 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 2 | 1 | 0 | 3 | 0 | 0 |
| 1981-1990 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| 1991-1997 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |

**Table 11. Temporal Frequency of Five Corn-Weather Types Most Often Associated with High Yields in Each Region, 1901-1997**

| *Decade* | *South* | *West* | *Central* | *North* | *State total* |
|---|---|---|---|---|---|
| 1901-1910 | 5 | 5 | 5 | 5 | 20 |
| 1911-1920 | 3 | 3 | 5 | 2 | 13 |
| 1921-1930 | 3 | 2 | 7 | 5 | 17 |
| 1931-1940 | 1 | 4 | 0 | 1 | 6 |
| 1941-1950 | 1 | 4 | 5 | 4 | 14 |
| 1951-1960 | 3 | 1 | 3 | 3 | 10 |
| 1961-1970 | 7 | 3 | 6 | 9 | 25 |
| 1971-1980 | 6 | 5 | 4 | 6 | 21 |
| 1981-1990 | 5 | 6 | 5 | 5 | 21 |
| 1991-1997 | 3 | 5 | 3 | 6 | 17 |

**Notes:**
The totals include all occurrences including those years when high yields did not occur. The following weather types produced high yields: south (1, 2, 4, 15, and 17), west (1, 2, 4, 12, and 15), central (1, 2, 4, 6, and 7), and north (1, 2, 6, 7, and 12).

**Table 12. Temporal Distributions of Two Corn-Weather Types in Southern Illinois and their Occurrences with High and Low Corn Yields (Upper and Lower 20 Percent or All Yields), 1901-1997**

| *Decades* | *Type 1* | | | *Type 2* | | |
|---|---|---|---|---|---|---|
| | *All events* | *High yield* | *Low yield* | *All events* | *High yield* | *Low yield* |
| 1901-1910 | 1 | | | 2 | 1 | |
| 1911-1920 | | | | | | |
| 1921-1930 | 1 | | | 1 | | |
| 1931-1940 | | | | | | |
| 1941-1950 | | | | 1 | 1 | |
| 1951-1960 | 2 | | | | | |
| 1961-1970 | 1 | | | 3 | 1 | |
| 1971-1980 | 2 | 2 | | 3 | | |
| 1981-1990 | 2 | 1 | | 2 | | 1 |
| 1991-1997 | | | | | | |

**Table 13. Temporal Frequency of Five Weather Types Most Often Associated with Low Yields in Each Region, 1901-1997**

| *Decade* | *South* | *West* | *Central* | *North* | *State total* |
|---|---|---|---|---|---|
| 1901-1910 | 2 | 2 | 1 | 3 | 8 |
| 1911-1920 | 4 | 6 | 5 | 6 | 21 |
| 1921-1930 | 4 | 3 | 1 | 4 | 12 |
| 1931-1940 | 4 | 7 | 5 | 7 | 23 |
| 1941-1950 | 5 | 2 | 2 | 4 | 13 |
| 1951-1960 | 3 | 3 | 4 | 4 | 14 |
| 1961-1970 | 1 | 1 | 2 | 0 | 4 |
| 1971-1980 | 3 | 4 | 3 | 3 | 13 |
| 1981-1990 | 1 | 3 | 2 | 3 | 9 |
| 1991-1997 | 1 | 2 | 2 | 1 | 6 |

**Notes:**
The totals include all occurrences including those years when low yields did not occur. The following weather types produced low yields: south (8, 9, 10, 11, and 16), west (5, 9, 10, 11, and 12), central (5, 9, 10, 11, and 19), and north (3, 4, 9, 10, and 11).

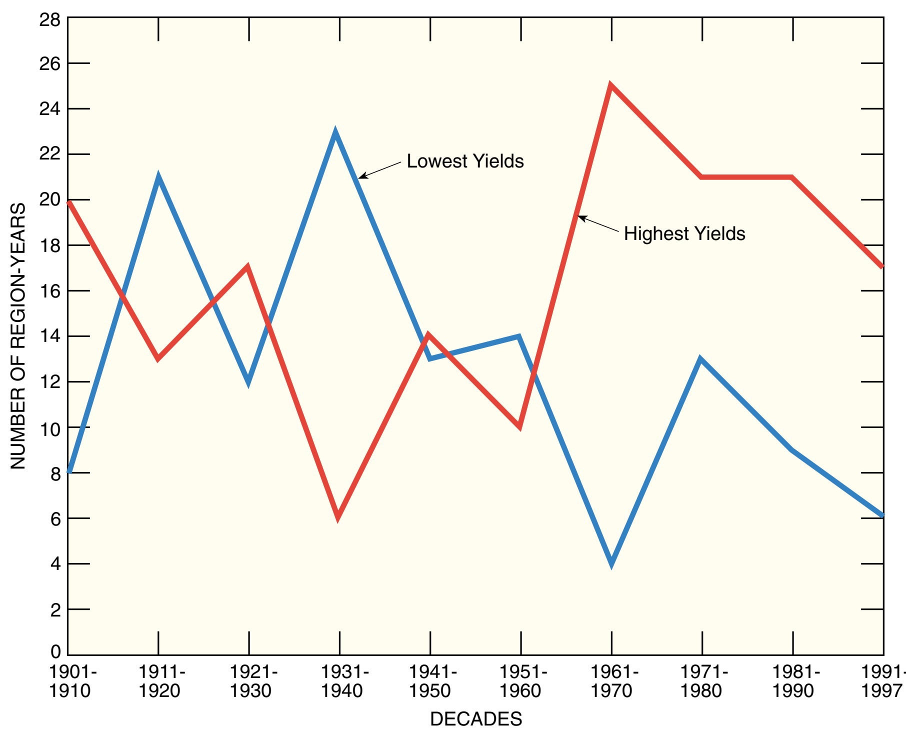



Figure 8. Number of years (sum of four regions) per decade with corn-weather seasons producing either high or low corn yields in the four regions of Illinois, based on five weather types that produced the greatest number of high and low yields. Values are sums of the decadal regional frequencies.

# TEMPORAL TRENDS IN WEATHER-WATER SEASONS

Table 14 shows temporal distributions of the weather-water seasons for central Illinois sorted according to two key conditions in spring and summer: above normal precipitation and temperatures, and below normal precipitation and above normal temperatures. The combined seasonal incidences in spring resulted in peaks of occurrences in 1921–1930 (five such seasons), and 1981–1990 (four such seasons). Only one spring weather season created major water resource impacts in 1961–1970 and 1991–1997. The combined summer distribution, based on the sum of the two weather-water seasons' frequencies, shows that a majority occurred during 1911–1960 with many fewer impact seasons since 1960. Recall that the negative impacts predominate in the summer. Weather-water seasons based on above normal precipitation and above normal temperatures in summer were rather uniformly distributed over time in central Illinois, whereas below normal precipitation and above normal temperatures in summer were most common in early to mid-century (table 14).

Table 15 presents time distributions of the weather-water seasons occurring in the four regions. Spring distributions for 1901–1997 reveal important regional differences. The spring frequencies of impact-creating seasonal weather conditions in central and northern Illinois both peaked in 1921–1930, but the highest frequencies occurred in western Illinois in 1901–1910 and 1981–1990. The spring peak of weather seasons causing major impacts on water resources in southern Illinois occurred in 1931–1940. However, all regions experienced low seasonal incidences in the springs of 1951–1960, 1961–1970, and 1991–1997. The central and west regions had high incidences of impact-creating weather-water seasons in both spring and summer during 1981–1990 when the other regions had few such conditions. Some regional uniformity exists across Illinois because similar weather conditions persisted throughout Illinois in several years. For example, above normal spring precipitation and temperatures (wet and warm) occurred statewide in 1922, 1938, 1945, and 1964, and below normal spring precipitation and above normal temperatures occurred statewide in 1910, 1911, 1930, 1936, and 1987.

Figure 9 shows the 1901–1997 distribution of all the impact-significant weather-water seasons in spring, based on the sum of the values from all four state regions per decade. This statewide distribution peaked in 1921–1930, and was

**Table 14. Frequencies of Weather-Water Seasonal Conditions Creating Major Impacts on Water Resources in Central Illinois, 1901-1997**

| | *AN - AN*[1] | | *BN-AN*[2] | | Sum of All Conditions | |
|---|---|---|---|---|---|---|
| Decade | Spring | Summer | Spring | Summer | Spring | Summer |
| 1901-1910 | 0 | 0 | 3 | 1 | 3 | 1 |
| 1911-1920 | 1 | 1 | 1 | 2 | 2 | 3 |
| 1921-1930 | 3 | 0 | 2 | 3 | 5 | 3 |
| 1931-1940 | 1 | 3 | 1 | 4 | 2 | 7 |
| 1941-1950 | 1 | 3 | 1 | 1 | 2 | 4 |
| 1951-1960 | 1 | 0 | 1 | 4 | 2 | 4 |
| 1961-1970 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1971-1980 | 2 | 2 | 1 | 0 | 3 | 2 |
| 1981-1990 | 1 | 2 | 3 | 1 | 4 | 3 |
| 1991-1997 | 1 | 0 | 0 | 2 | 1 | 2 |
| Totals | 12 | 11 | 13 | 18 | 25 | 29 |

**Notes:**

[1]AN-AN = above normal precipitation and above normal temperatures.

[2]BN-AN = below normal precipitation and below normal temperatures.

**Table 15. Temporal frequency of Weather-Water Seasons Causing Major Water Resources Impacts in Illinois, 1901-1997**

| | *Spring* | | | | *Summer* | | | |
|---|---|---|---|---|---|---|---|---|
| *Decade* | *North* | *Central* | *West* | *South* | *North* | *Central* | *West* | *South* |
| 1901-1910 | 4 | 3 | 4 | 3 | 1 | 1 | 1 | 2 |
| 1911-1920 | 2 | 2 | 3 | 3 | 2 | 3 | 4 | 3 |
| 1921-1930 | 5 | 5 | 3 | 4 | 4 | 3 | 4 | 4 |
| 1931-1940 | 3 | 2 | 3 | 5 | 8 | 7 | 6 | 7 |
| 1941-1950 | 3 | 2 | 2 | 4 | 2 | 4 | 1 | 3 |
| 1951-1960 | 0 | 2 | 2 | 2 | 5 | 4 | 4 | 4 |
| 1961-1970 | 2 | 1 | 2 | 1 | 1 | 0 | 1 | 1 |
| 1971-1980 | 3 | 3 | 1 | 1‘ | 2 | 2 | 1 | 3 |
| 1981-1990 | 1 | 4 | 4 | 1 | 3 | 3 | 4 | 0 |
| 1991-1997 | 1 | 1 | 1 | 1 | 0 | 2 | 0 | 0 |
| Totals | 24 | 25 | 25 | 25 | 28 | 29 | 26 | 27 |

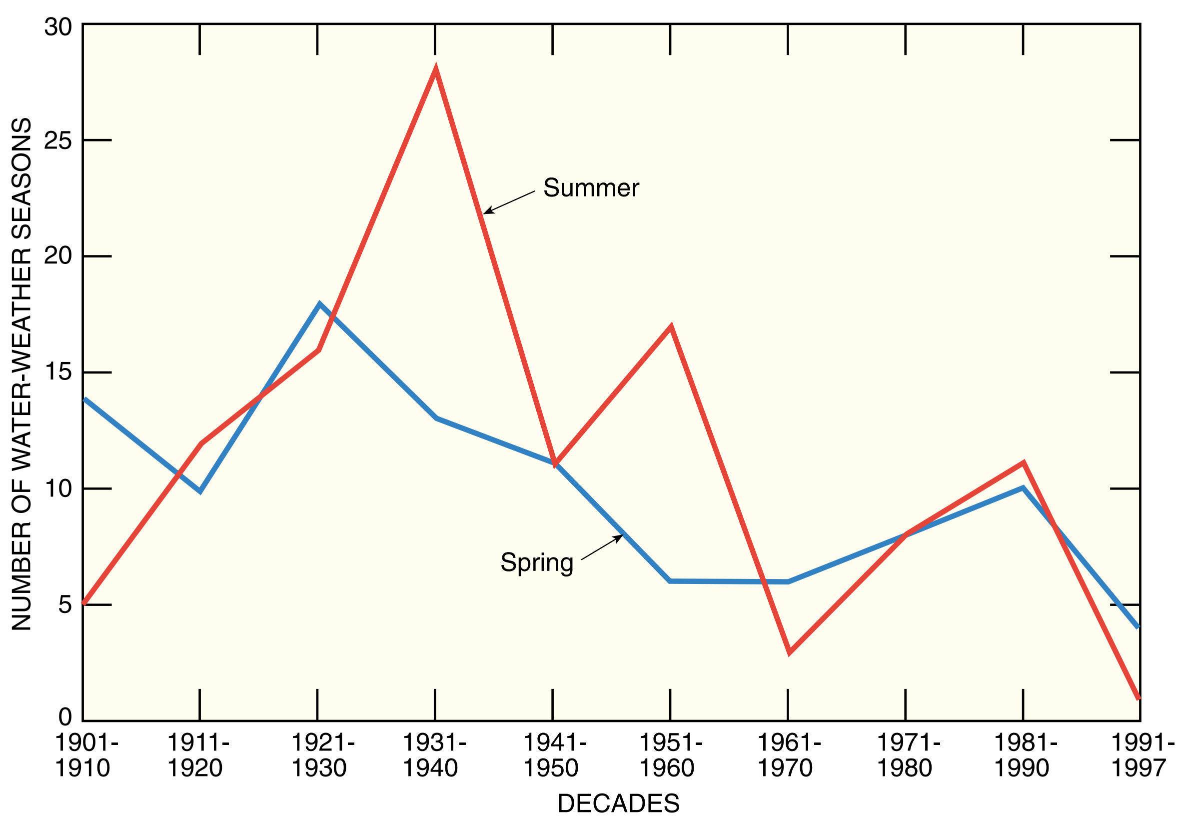



Figure 9. Number of weather-water seasons per decade in the spring and summer seasons based on the sum of the regional frequencies.

followed by a decline in incidences until a secondary peak occurred during 1981–1990. The first 50 years of the century had many more weather-water seasons (65 in the four regions) in spring than occurred in the last 47 years (only 34 events). Thus, the kinds of spring weather conditions that seriously affect water resources in Illinois have declined markedly over time.

Summer distributions of the weather-water seasons in all four regions (table 15) are similar to those in spring. All summer distributions maximized in the 1931-1940 decade with a state total of 28 seasons of negative effects on the state's water resources. Regional values ranged from 6 to 8 during this decade, revealing that most summers during the 1930s experienced negative effects on water resources. Figure 9 shows the 1901–1997 frequencies based on the sum of the four regional values of weather-water seasons in summer. This reveals a steady increase in incidences from 1901 to a peak in 1931–1940, followed by a low value in 1941–1950, higher values again in 1951–1960, very low frequencies in 1961–1970, and a third lesser peak again in 1981–1990.

Regional values for summer (table 15) reveal that all parts of Illinois had few impact-creating weather-water seasons in the summers during 1901–1910, 1961–1970, and 1991–1997. Dry and hot summer weather conditions (below normal rainfall and above normal temperatures) existed across the entire state in 1901, 1913, 1922, 1933, 1936, and 1952. The 50-year-period (1911–1960) included 84 of the four regions' water-weather seasons, whereas the other 47 years of the century included 28 such seasons, only one-third of the 1911–1960 total. As in spring, the kinds of summer weather conditions having major impacts on water resources have declined significantly since 1960.

# TEMPORAL FLUCTUATIONS OF CYCLONES AND ENSO CONDITIONS

The goal of this phase of the research was to find and analyze measures of fluctuations in atmospheric conditions during 1901–1997 that could help explain the distributions of the seasonal variations found for corn yields and water resources. Two available sets of long-term atmospheric data that help define the atmospheric conditions over Illinois affecting seasonal temperatures and precipitation were analyzed: 1) the number of cyclones crossing Illinois, and 2) the years when El Niño and La Niña events occurred**.** El Niño (warm tropical Pacific Ocean) and La Niña (cool tropical Pacific Ocean) are the opposite phases of ENSO conditions, and each produces effects on the weather conditions in the Midwest**.**

Cyclone frequency helps explain the incidence and amount of seasonal precipitation in Illinois (Hiser, 1956; Changnon and Huff, 1980). For example, during 1951–1960, southern Illi-nois had only one good corn yield year and three low-yield years, as compared to three good yield years in northern Illinois. During summers of this decade, 38 cyclones crossed northern Illinois, but only 19 cyclones crossed southern Illinois. Angel (1996), in a study of cyclonic activity over the Great Lakes basin, defined the passages of all cyclones and those with a strong central pressure (<992 millibars or mb) during 1900–1990. These data, supplemented with cyclonic data for 1991–1997, became the source for measuring seasonal cyclone passages across Illinois. Cyclone frequencies were summed per decade for comparison with seasonal weather types.

A recent analysis of the ENSO conditions in the tropical Pacific defined the effects of the intermittent El Niño and La Niña events on the seasonal weather conditions in the Midwest for the 1895–1997 period **(**Mauget and Upchurch, 1998). These data provided the basis for examining the potential effect of these two conditions on the seasonal precipitation and temperature conditions in Illinois. The aforementioned study found that the 11 El Niño years during 1901–1997 resulted in summer conditions in Illinois with below normal temperatures and above normal precipitation (1902, 1905, 1918, 1941, 1951, 1957, 1965, 1972, 1982, 1987, 1987, and 1997). The study further found that these 11 El Niño events correlated highly with above normal corn yields in Illinois.

Mauget and Upchurch (1998) also found a statistically significant relationship between seven strong La Niña events and above normal summer temperatures in Illinois and below normal corn yields (1916, 1954, 1955, 1970, 1973, 1975, and 1988). A third effect defined was between El Niño conditions and below normal early spring (February–April) precipitation in Illinois. This condition would negatively affect spring season water resources and could negatively influence corn yields if the ensuing summer rainfall was low. The years with this effect included 1905, 1906, 1914, 1915, 1919, 1926, 1931, 1940, 1941, 1958, 1983, 1987, and 1992.

Summer values of the high and low yields and summer weather-water seasons (negative impacts) for each decade were compared with 1) the cyclone incidences (all events and only the stronger cyclones), and 2) with the incidences of the El Niño and La Niña events. Summer values determined for each decade were: 1) the ratio of number of low-yield years per decade to number of high-yield years, and 2) the rank of the decade based on the statewide incidences of negative weather-water seasons (based on the sum of the summer values in table 15).

Examination of these two measures led to a sorting of the ten decades into three highly different classes: 1) decades with very good weather conditions (many high yields and few bad water resources seasons), 2) decades with very bad weather conditions (many low corn yields and many water resource seasons producing negative impacts), and 3) decades with mixed conditions, some positive and some negative impact years. Table 16 lists the decades qualifying in each class, revealing that four decades had good weather conditions (beneficial impacts) for corn yields and water resources, three decades had mixed good and bad impacts, and three decades had largely bad weather seasons. As shown in table 16, the four decades classified as good all had notably low yield ratios, 0.42 or less, indicating many more years with high yields than low yields. The ranks based on the number of water resource impacts were all classified as high and included decades ranking 1 (fewest negative impacts), 2, 3, and 5. In general, what was good for corn was good for water resource conditions in Illinois.

For comparative purposes, the frequency of cyclone passages per decade was ranked high (most) to low (1=highest number), and these rankings are listed in table16 along with the number of El Niño and La Niña years per decade. The 1991–1997 frequencies of cyclones were adjusted (actual 7-year value divided by 0.7) to estimate a decade equivalent value.

Comparison of the yield and water resource rank values for the four decades with good weather seasons revealed large numbers (high ranks) of cyclones (ranks 1, 2, 3, and 4) and of strong cyclones (ranks 1, 3, 4 , and 5). The good weather decades also included 7 of the 11 El Niño summers when good yields occurred with only one La Niña season and only two of the El Niño-driven dry springs. In contrast, the three bad weather decades with large numbers of negative seasonal conditions (1911–1920, 1931-1940, and 1951–1960) had relatively low numbers of cyclone passages. The frequency of all cyclone passages for the three bad decades had ranks of 7, 9, and 10 (lowest number), and the three strong cyclone values ranked 6, 8, and 9. These 30 years also included 4 of the 7 bad La Niña years and 6 of the 11 El Niño years that produced dry springs.

Rankings for the decades with a mix of good and bad weather seasons for corn yields and water resources were in the middle range (4, 5, 6, and 8). These decades included 1921–1930, 1941–1950, and 1971–1980. Rankings for the incidence of cyclones was similar and in the middle range (5, 6, and 8) for all cyclones. Clearly, a mixture of atmospheric conditions producing seasons capable of good and bad impacts on corn yields and water resources existed during these decades. Thompson (1986) noted that a large number of extremely high and low corn yields occurred in the Corn Belt after 1972, following a decade (the 1960s) with consistently good weather and high yields. The comparative analysis indicated that the degree of seasonal weather impacts per decade was reasonably well related to decadal cyclone frequencies and to the type and number of ENSO events.

## Table 16. Decadal Values Based on Ratios of Bad-to-Good Corn Yield Years, Frequencies of Summer Season Negative Impacts on Water Resources, Summer Frequencies of All Cyclones and Strong Cyclones, and the Incidence of ENSO Conditions Affecting Illinois' Summer and Spring Weather

| | | *Rank* | | | *Number of years* | | |
|---|---|---|---|---|---|---|---|
| | *Ratio*[1] | *Water resource impacts*[2] | *All cyclone passages*[3] | *Strong cyclone passages*[3] | *El Niño summer effects* | *La Niña summer effects* | *El Niño spring effects* |
| *Positive impacts* | | | | | | | |
| 1901-1910 | 0.42 | 3 | 5 | 3 | 2 | 0 | 1 |
| 1961-1970 | 0.16 | 2 | 2 | 5 | 1 | 0 | 0 |
| 1981-1990 | 0.40 | 5-6 | 3-4 | 4 | 2 | 1 | 1 |
| 1991-1997 | 0.35 | 1 (fewest) | 1 (most) | 1 | 2 | 0 | 0 |
| *Mixed impacts* | | | | | | | |
| 1921-1930 | 0.72 | 8 | 8 | 2 | 0 | 0 | 1 |
| 1941-1950 | 0.90 | 5-6 | 3-4 | 7 | 1 | 0 | 1 |
| 1971-1980 | 0.63 | 4 | 6 | 10 | 1 | 3 | 1 |
| *Negative impacts* | | | | | | | |
| 1911-1920 | 1.6 | 7 | 7 | 6 | 1 | 1 | 3 |
| 1931-1940 | 3.9 | 10 (most) | 10 (fewest) | 9 | 0 | 0 | 1 |
| 1951-1960 | 1.4 | 9 | 9 | 8 | 2 | 2 | 2 |

**Notes:**
[1] Values less than 1.0 mean more good yield seasons than bad yield seasons
[2] Rank 1 = fewest negative, 10 = most negative impacts
[3] Rank 1 = most cyclones, 10 = fewest

# SUMMARY AND CONCLUSIONS

During 1901–1997, 19 distinctly different corn-weather seasons were identified in Illinois. These seasons were defined using weather-corn yield technology regression analyses, and identified seven monthly weather variables, beginning the season with May rainfall and ending with August temperatures and rainfall, as important for explaining yields. Combinations of these weather variables were used to identify types of corn-weather seasons. The number of these corn-weather types during 1901–1997 decreased from south to north (19 types in southern Illinois versus 14 in the north), reflecting known geographical differences in the warm season climate of Illinois.

Regional analysis of the 19 types showed that 14 types were prevalent throughout the state, whereas five types occurred in only certain parts of the state. Corn-weather type 1 (with a cool, wet July) occurred 17 times in northern Illinois but only 9 times in southern Illinois. The number of cool, wet Julys during 1901–1997 ranged from 13 (central Illinois) to 17 (northern and western Illinois). Hot, dry July conditions occurred in 18 years in southern Illinois with a regional maximum of 21 such years in central Illinois.

Analysis of the seasonal conditions associated with the 20 years with the highest corn yields during the 97-year period revealed that weather type 15 (normal May precipitation, below normal June temperatures, above normal June precipitation, below normal July temperatures, above normal July rainfall, and below normal August temperatures and precipitation) occurred most often with high yields in southern and western Illinois. Types 1 and 2, which had normal July temperatures and above normal precipitation, were the most common seasons when high corn yields occurred in the central and northern regions. As expected, most high yield years came with July conditions that had normal or above normal rainfall, but weather type 12, which had below normal July rainfall, also came with high yields in all regions. Type 12 had above normal precipitation in May and June and below normal June and July temperatures, conditions that minimized crop moisture stress in July.

Three types (1, 2, and 15) with below or near normal July temperatures and above normal July precipitation, conditions expected to produce high corn yields, did account for 50 percent of the 80 high yields. The temporal distributions of these three seasons showed they were concentrated in the 1901–1910 and 1961–1997 periods when 70 percent of these types occurred.

More than 63 percent of the 20 lowest corn yields in 1901–1997 occurred with weather types 9, 10, or 11. These types all had a hot, dry July but with temperature and precipitation conditions differing in the other growing season months. Certain other weather types created low yields in some regions but none in others. Type 3 was associated with low corn yields in western and northern Illinois but with none elsewhere; type 5 was associated with low corn yields in both the western (two times) and central (three times) regions but none elsewhere; and type 16 was associated with three low-yield years in southern Illinois but none elsewhere. Five of the 19 weather types (1, 2, 7, 15, and 17) were not associated with low yields, and four weather types (9, 10, 11, and 14) were never associated with high yields. More of the 80 low-yield years were concentrated around fewer seasons than were the 80 good yield seasons, which occurred with a wider diversity of seasonal weather conditions.

The temporal distributions of the corn-weather seasons revealed that two decades before mid-century (1911–1920 and 1931–1940) had many more seasons that resulted in low corn yields than did any decade of the last 50 years. Seasons with hot, dry July conditions were responsible for low corn yields throughout the century, but 66 percent of these Julys occurred in 40 percent of the years, 1911–1940 and 1951–1960. Certain other low-yield seasons were also very unevenly distributed throughout the century. For example, types 3 and 4 produced five low yields in northern Illinois between 1901 and 1934, but no low yields in their nine occurrences since 1940. Weather type 16 (hot July with near normal rainfall) occurred during six years in southern Illinois, and three of these years (1916, 1933, and 1944) had low yields. The other three type 16 seasons came in later years and did not have low corn yields. These varying temporal responses reflect differing yield responses to weather resulting from constantly changing corn varieties, farming practices, and other technological changes since 1901.

Weather extremes expected to create low corn yields, such as hot, dry July conditions, produced 63 percent of the 80 low yields (four regions with 20 lows in each), but many low yields came with seasonal conditions that would not necessarily have been selected *a priori* as a set of conditions causing very low yields. For example, weather type 3 with normal values in all non-July conditions and a hot but wet July accounted for four of the 40 low yields in western and northern Illinois. Weather type 5 with a hot July and normal July precipitation and with above normal precipitation in August and below normal precipitation in June would not be expected to cause low yields, yet this type was associated with five of the lowest 80 yields during 1901–1997.

Weather conditions vary sufficiently across Illinois in any given decade to result in seasons with high yields in some regions and other seasons with low yields in other regions. Comparable numbers of high- and low-yield seasons occurred in Illinois during 1921–1930 and 1941–1950.

The decades when good corn yield seasons were most common came early in the century, 1901–1910, and again during the 37 years since 1960. Certain seasonal weather types that occurred throughout the century (for example, types 1, 2, and 15) were often associated with high yields, but many of their occurrences did not produce high yields. For example, type 1 occurred in southern Illinois in nine years distributed throughout the century, but the type 1 years with high yields all came during the 1971–1997 period. This again reflects how temporal changes in farming practices and agricultural technology altered crop responses to a given sequence of growing season weather conditions. Weather type 12 (July with normal temperatures and below normal rainfall) occurred seven times in western Illinois and three of those years were associated with high yields, but the other four type 12 occurrences, all in years prior to 1934, did not result in high yields. Such temporal differences in weather-yield responses further reflect shifting responses to weather conditions. For example, the extremely good crop-weather seasons of the 1960s led farmers to increase planting densities and fertilizer applications (Thompson, 1986).

Another factor to consider is the long-term trends in seasonal weather conditions. Thompson noted that since the 1930s there had been a systematic trend towards cooler and wetter growing season conditions in the Corn Belt. A study of Illinois' summer maximum and minimum temperatures for 1901–1995 found an increase from 1901 to peak values in the 1930s, followed by decreasing values, becoming 1 to 2 degrees Fahreinheit lower by the 1990s (Changnon et al., 1997). Mean summer temperatures during the 1947–1996 period in much of the eastern United States (figure 10) and the Midwest have been lower than in the preceding 50-year period, 1897–1946. Summer precipitation trends in Illinois for 1901–1995 showed slight increases in western and northern Illinois with little change elsewhere in the state. In summary, it appears that summer weather conditions important to corn production and water resource conditions have improved gradually with time in Illinois and especially since the 1930s.

Major water resource impacts, some positive but most negative, occurred with two types of precipitation-temperature conditions in spring and two types in summer. These impacts to surface water, ground water, and/or water quality conditions were caused by weather-water seasons with either below normal precipitation and above normal temperatures or above normal precipitation and temperatures. Regional frequencies showed that slightly more water-weather seasons occurred during 1901–1997 in southern Illinois: 26 spring seasons and 29 summer seasons compared to 24 spring seasons and 28 summer seasons in northern Illinois.

Temporal analysis of the weather-water seasons in spring for the four regions of Illinois revealed that both seasonal types were similarly distributed. The greatest number of water-impact seasons in spring occurred during 1921–1930 with a secondary maximum in 1981–1990. In summer, the dry, hot seasons occurred primarily during 1911–1960, whereas the impact-creating wet, hot seasons were more evenly distributed throughout the century. The summer fre-quencies of both weather types, which largely caused negative impacts to water resources, had a major peak in the 1931–1940 decade, the same period when corn-weather seasons causing low yields peaked. Water- impact-producing seasons declined in 1941–1950 but increased again during 1951–1960 with a third peak in 1981–1990. Periods with the fewest summer seasons producing impacts on the states' water resources included 1901–1910, 1961–1970, and 1991–1997.

In many respects, the temporal distribution of the weather-water seasons in summer during the century is similar to that for corn-weather seasons producing low corn yields in Illinois. Both temporal distributions were low (few negative impacts) early in the century (1901–1910); both were extremely high in 1931–1940; both had a secondary peak of incidences in 1951–1960; and both had few occurrences in 1961–1970 and

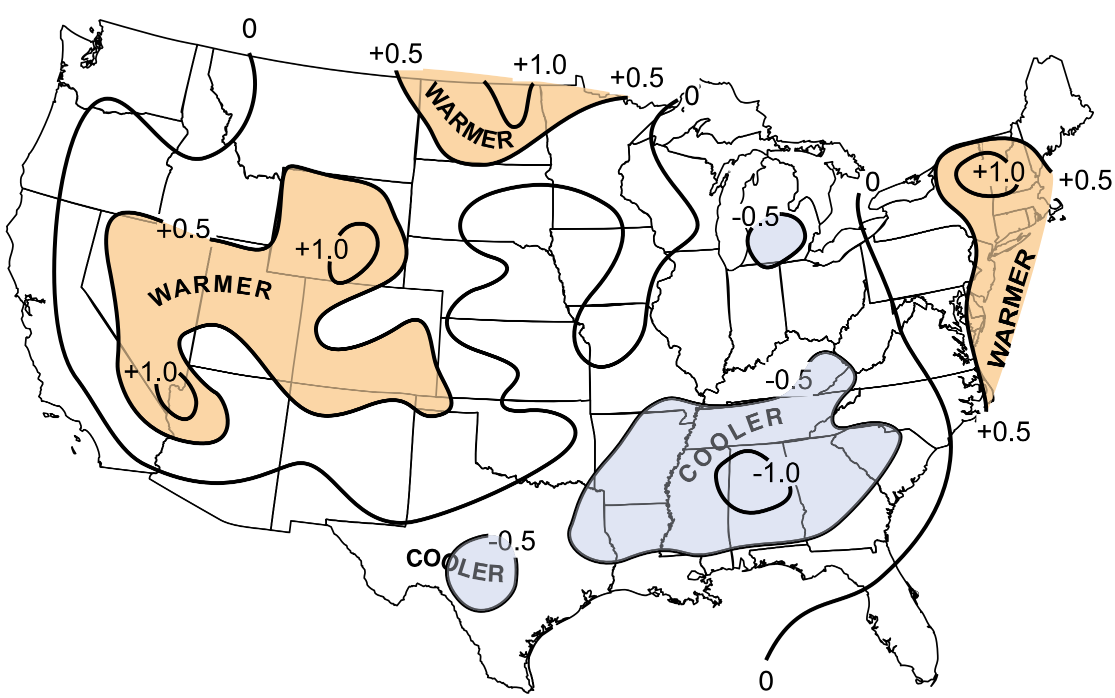



Figure 10. Pattern of the temperature difference between 1947-1996 and 1896-1946, isotherms in degrees Centigrade.

again in 1991–1997. However, they differed in 1981–1990 when several water-impact seasons occurred, but few low-yield seasons occurred.

This study of seasons causing agricultural and water resource impacts in Illinois reveals that major temporal changes in the weather-impact relationships occurred during the 20th century. The more stressful seasonal conditions were most frequent from 1911 to the late 1950s, and many fewer stress-causing seasons have occurred since 1960. Also, the effects of several corn-weather seasons causing either high or low yields shifted during the century. Certain weather conditions causing either high- (or low-) yield outcomes in the first 30 to 40 years of the century did not produce the same yield responses in later years of the century, and some seasonal conditions not related to high or low yields in early decades were related to yield extremes later in the century.Yield responses to seasonal weather conditions have shifted considerably due to altered farming practices, improved corn varieties, and technological developments.

Atmospheric measures of storm activity and precipitation in summer, as reflected by the frequency of cyclone passages over Illinois, exhibited a good relationship between the incidence of good and bad yield years and summer water resource problems. Periods with notably good weather, defined as many high-yield years and few summers with negative water resource impacts, had the century's largest number of cyclones (1901–1910, 1961–1970, and 1980–1997). The three decades with the highest incidence of bad weather (1911–1920, 1931–1940, and 1951–1960) had the fewest cyclones, indicative of less rainfall, and also had three of the century's seven La Niña years that create low yields. In general, these results reveal that fluctuations in atmospheric conditions affecting summer weather conditions in Illinois agreed with the incidence of good and bad seasonal weather conditions, as defined by impacts on corn yields and the state's water resources.

The results reveal why it is difficult to arbitrarily select seasonal weather conditions as extremes of significance without considering the impacts of the seasonal weather conditions. Many crop-weather seasons accounting for either high or low yields during 1901–1997 would likely not have been those selected *a priori*. Crop-yield responses to certain weather conditions have clearly shifted over time, and the seasonal differences in weather-yield responses found across the regions of Illinois further point to the need to assess impacts when selecting seasonal weather extremes of significance to human activities and the environment.

The shifting yield responses to various seasonal weather types found during the 20th century illustrate the complexities that must be faced in attempting to forecast yield responses to future weather and climate scenarios. Such endeavors require accounting for possible changing growing season weather types (and the frequency with which each type may occur in a given future period such as a decade), as well as defining changing crop responses due to ever-changing agricultural practices, crop varieties, and technologies. Assessment of the future impacts of a changed climate, a goal of the Intergovernmental Panel on Climate Change or IPCC (Carter et al., 1994), involves projections of societal and technological changes and how they will interact with a changed climate. In the case of crop production, Thompson (1986) illustrated the difficulties in projecting the yield trends due to shifting farm practices and agricultural technologies. For future impact assessments, the estimation of the future climate conditions used by the IPCC is based on the concept that the climate conditions will differ from existing or recent past conditions and the climate scenarios that can be defined are essentially unlimited (Carter et al., 1994). The impact assessment process advocated by IPCC rests on defining the future relationship between a different climate and a different societal-technological mix than has existed in the past (Carter et al., 1994). Most statistical modeling of relationships, as used in this Illinois study, rests on historical data relationships that are likely invalid for predicting impacts of future climate conditions. An alternative approach, estimating future relationships through use of process modeling, involves many assumptions and the predicted outcomes become highly problematic.

Regardless of the approach used for future projections of climate impacts, the results of this study of Illinois' crop-weather conditions during the 20th century are not encouraging that either approach can achieve realistic projections of future crop impacts under a changed climate. For example, if this analysis of crop-weather seasons had been based solely on the results from the 1910–1950 period, as the basis for future projections to 1997**,** it would have to anticipate: 1) occurrences of several crop-weather seasonal types that did not occur in 1901–1950, 2) a very different frequency of the types that had occurred in 1910–1950, and 3) many of the seasonal conditions during 1901–1950 that produced high (or low) yields would not result in the same extremes again in the next 50 years.

In fact, a few crop-weather seasons in 1901–1950 that led to high corn yields in turn created low yields during 1951–1997, a reflection of the effect of the major changes in farm practices after 1950. Would a 1950-based point of projection be able to correctly predict a 12-year run of continuously good crop weather (1960–1971) that led to rapid increases in planting densities and fertilizer use that forever dramatically shifted agricultural production? It seems unlikely, and keep in mind that what happened during 1901–1997 was without a major change in climate. In sum, this study of the 97years of crop-weather seasons across four regions of Illinois illus-trates the enormous difficulty of projecting realistic future impacts of climate, with or without a climate change.

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