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Weather and Crops

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The key atmospheric variables that impact crops are solar radiation, air temperature, humidity, and precipitation. The day-to-day variability of these across the landscape can be described as *weather*. Weather extremes at critical periods of a crop's development can have dramatic influences on productivity and yields. The long-term average temperature and humidity and the total solar radiation and precipitation over a crop's growing season can be described as the climate. It is the climate that, in the absence of any weather extremes, determines the realized yields for a given region.

This chapter addresses how plants respond to these atmospheric variables, how they vary over the season and across Illinois, and to what extent they can be predicted, from several weeks to several seasons into the future.

Crop Response to Weather Variables

The response of crops to the different weather variables is quite complex and difficult to describe. If one of the variables is limiting (for example, temperatures that are too hot or too cold), then the effects of solar radiation or precipitation do not greatly affect the crop. When none of the variables is limiting, the crop will respond to the variable that is farthest from the optimum for that variable. Describing the physiological response of crops at the field level introduces additional uncertainty in predicting crop yield. Predicting the exact response of crops to the weather is, as a result, an inexact science, and one that contains great uncertainty.

The information presented in this chapter is based on "normal" weather conditions. Normal is defined by the World Meteorological Organization as a 30-year period updated every decade. The current period is 1971 to 2000. New 30-year climate normals will be computed in 2011 using the 1981 to 2010 period. A "normal" year seldom occurs, if ever, because there is always variability of the weather from normal across years and within the year, with some periods being wetter/drier, hotter/cooler, sunnier/cloudier than normal.

Temperature

Other than planting, temperature is the main variable that determines when a crop will grow. It also determines, along with precipitation and solar radiation, how well a crop will grow and how fast it will develop. There are four temperature thresholds, called the cardinal temperatures, that define the growth of a crop: the absolute minimum, the optimum minimum, the optimum maximum, and the absolute maximum. The absolute minimum and maximum temperatures define the coldest and hottest temperatures at which a crop will grow. Temperatures between the optimum minimum and maximum define the range of temperature where the crop performs the best. Corn (*Zea mays* L.), for example, has an absolute minimum temperature of 50 °F (10 °C), an optimum minimum of 64 °F (18 °C), an optimum maximum of 91 °F (33 °C), and an absolute maximum of 117 °F (47 °C). Corn is an example of a C4 crop, which originates from a tropical

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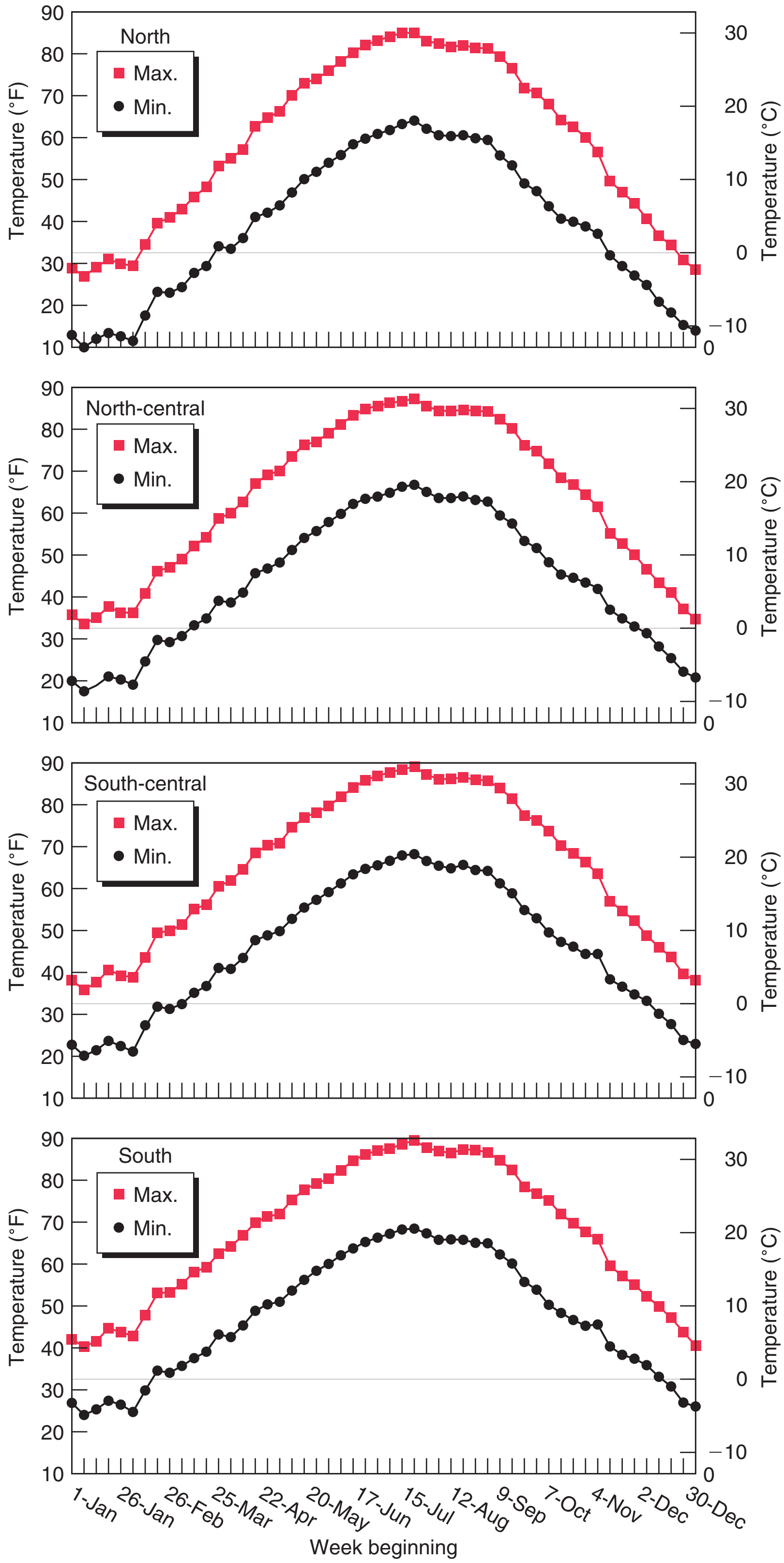

Figure 1.1. Average weekly minimum and maximum temperatures for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

environment. C4 crops, which also include Miscanthus (*Miscanthus* x *giganteus*) and sorghum (*Sorghum bicolor*), have absolute minimum temperatures ranging from 45 to 50 °F (7 to 10 °C), optimum minimums from 59 to 81 °F (15 to 27 °C), optimum maximums from 91 to 104 °F (33 to 40 °C), and absolute maximums from 104 to 117 °F (40 to 47 °C). C3 crops, including wheat (*Triticum aestivum*), soybean (*Glycine max*, Merrill), and alfalfa (*Medicago sativa*), have absolute minimum temperatures ranging from 36 to 41 °F (2 to 5 °C), optimum minimums from 59 to 68 °F (15 to 20 °C), optimum maximums from 73 to 91 °F (23 to 33 °C), and absolute maximums from 81 to 100 °F (27 to 38 °C).

These temperature thresholds can be used with **Figure 1.1** to identify the weeks when the weekly mean maximum and minimum temperatures are within the absolute and optimum temperature ranges. Using corn as an example, the weekly mean minimum temperature is at or above the minimum optimum temperature from April 1 through September 16 in the northern two crop reporting districts (CRDs 1 and 2) and from March 5 through September 23 in the southern two crop reporting districts (CRDs 8 and 9). The north-central region, represented by crop reporting districts 3, 4, and 5, experiences weekly mean minimum temperatures within the optimum temperature range approximately one week earlier in the spring and one week later in the fall than the north region and one week later in the spring and one week earlier in the fall than the south-central region, represented by crop reporting districts 6 and 7. During these periods, the temperature conditions are generally considered to be optimum for corn growth and development.

Growing degree units. Research has shown that crop development—the time from planting to flowering and/or maturity—is more closely correlated with temperature than with the number of days after planting. Growing degree units (GDU), also known as growing degree days (GDD), are used to relate temperature to crop development. GDUs are accumulated when the mean daily temperature exceeds a threshold identified for a crop. For example, wheat has a threshold temperature of 45 °F. If the mean daily temperature for a day is 46 °F (8 °C), one GDU will accumulate in that day. If the next day's mean temperature is equal to 50 °F (10 °C), then 5 GDUs will accumulate for the day and 6 GDUs will have accumulated for the two-day period. The basic equation for computing accumulated GDUs is

$$GDU = \sum_{Day=1}^{n} \frac{T_{mx} - T_{mn}}{2} - T_b$$

where T_{mx} is the maximum daily temperature, T_{mn} is the minimum daily temperature, and T_b is the threshold temperature. If the daily average temperature, computed as the sum of the maximum and minimum temperatures divided by 2 minus the base temperature, is less than zero, the GDU accumulation for that day is zero.

For cool-season crops, such as cereal crops, and most C3 crops, the base temperature is 45 °F (7 °C). For warm-season and most C4 crops, a modified GDU method is used. The basic equation is the same as the one at the left, but if the minimum temperature is lower than the base temperature, then the day's minimum temperature is set equal to the base temperature, usually 50 °F (10 °C). The maximum daily temperature is also modified if the daily maximum temperature exceeds 86 °F (30 °C), in which case the maximum temperature is set equal to 86 °F.

The annual accumulated GDUs are greatest in the southern region of Illinois **(Figure 1.2).** The annual accumulation of GDUs is 1,260 F (700 C) more in the south than in the north for a base 45 °F (7 °C). For the modified 50 °F (10 °C) accumulation, the north accumulates 1,080 F (600 C). This greater accumulation in the south compared to the more northerly regions of Illinois is the result of an earlier start to accumulation in the spring, a later end in the fall, and a pace slightly faster during the summer, when the south accumulates approximately 35 F (21 C) more GDUs per week. The greater accumulation in the

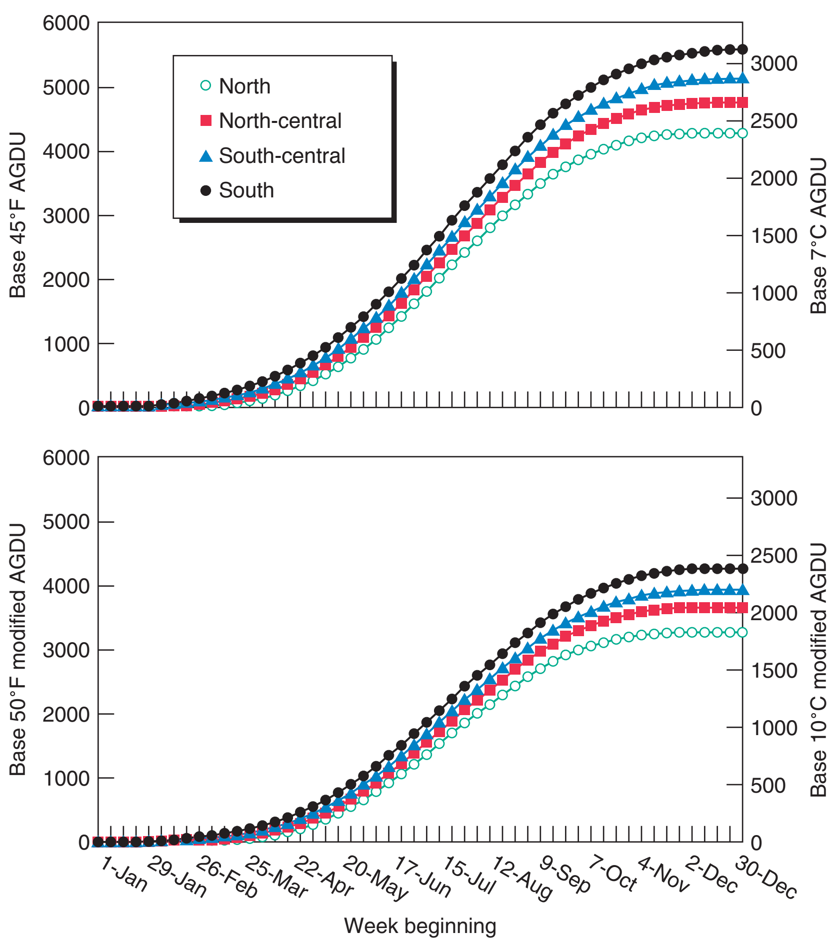

Figure 1.2. Average accumulated growing degree temperatures for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

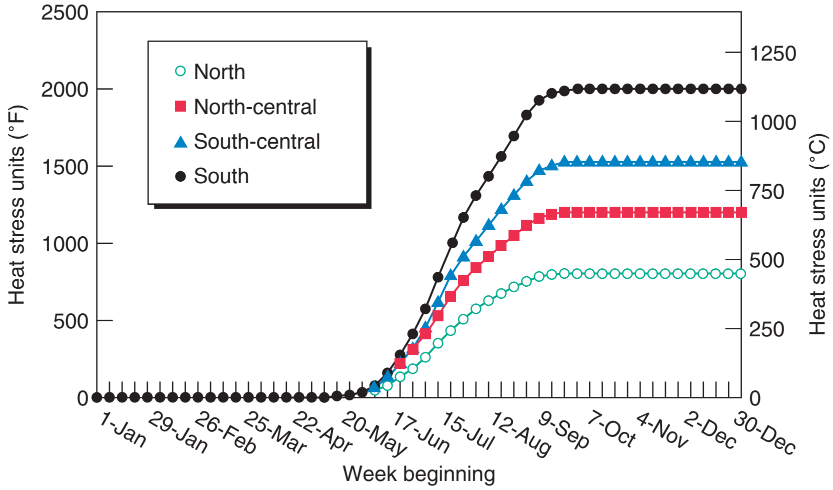

Figure 1.3. Average heat stress unit accumulations for a temperature stress base of 90 °F (32 °C) for four regions in Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

south provides the potential for growing crops that require a longer growing season to mature than in the north.

Temperature stress. Crops experience stress from both heat and cold. Heat stress mostly occurs in the summer, while cold stress occurs in the spring and fall, usually when crops are being established or maturing. Cold stress is not a serious problem for most agronomic crops in Illinois; heat stress is more likely, especially in summers when temperatures approach or exceed 90 °F (32 °C).

When temperature exceeds a crop's optimum maximum, the crop experiences heat stress. A heat stress unit (HSU) is defined as the number of degrees the maximum daily air temperature is above the heat stress threshold times the number of days. For example, if the heat stress threshold is 90 °F (32 °C), and the maximum temperature is 94 °F (34 °C), then the number of heat stress units equals 4 F (2 C) HSU. Each day the maximum temperature reaches 94 °F (34 °C), an additional 4 F (2 C) HSUs are accumulated.

Heat stress affects plants because as temperature increases, respiratory reaction rates speed up, using more of the photosynthetic compounds manufactured in a day. Also, with elevated maximum temperature, especially temperatures that exceed 100 °F (38 °C), plants require more water to maintain optimum water content in their tissues. If the soil cannot meet the additional water requirement, heat stress is compounded by an added water stress.

On average, the southern part of Illinois accumulates approximately 2,000 F HSUs (1,111 C HSUs) with a stress threshold of 90 °F (32 °C), compared to 805 F HSUs (447 C HSUs) in the northern regions. Heat stress units generally begin accumulating around the first of June and continue to accumulate until mid- to late September **(Figure 1.3).** HSUs accumulated using a stress threshold of 86 °F (30 °C) are approximately double the HSUs accumulated using a stress threshold of 90 °F (32 °C). Using a stress threshold of 95 °F (35 °C), the accumulation is approximately 20% of HSUs accumulated using a 90 °F (32 °C) stress threshold. Most crops in Illinois can withstand temperatures below 95 °F (35 °C) unless they are accompanied with drought stress, so heat stress usually results in only minor yield losses.

Soil temperature. Soil temperatures in the autumn determine when ammonium nitrogen fertilizer may be applied without excessive nitrification occurring during the autumn and winter. With soil temperatures at a depth of 4 inches (10 cm) below 50 °F (10 °C), the rate of nitrification is reduced, but the process becomes negligible only when soil temperatures are below 32 °F (0 °C). The maps in **Figure 1.4** show the last day in the fall that 4-inch (10-cm) soil temperatures are above 50 °F (10 °C) and 60 °F (16 °C). Normally, soil temperatures throughout the state are consistently below 50 °F (10 °C) by the end of November. Maps showing the dates when soil temperatures fall below 60 °F (16 °C) are included as a guide for estimating when anhydrous ammonia application with a nitrification inhibitor may begin. Soil temperature can be estimated by computing the average of the mean air temperature for the preceding 7 days. These estimates tend to overestimate soil temperatures by 1 to 2 °F (0.5 to 1.0 °C) in the autumn. The error creates a conservative estimate of the soil temperature—so, for example, when the 7-day mean temperature is 50 °F (10 °C), the soil temperature may be 48 to 49 °F (9 °C).

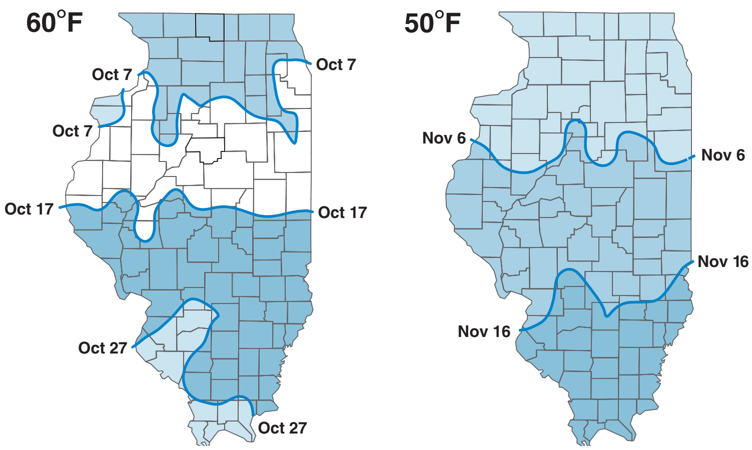

Figure 1.4. The average last dates in autumn when Illinois 4-inch soil temperatures were above 60 °F (15.6 °C) and 50 °F (10 °C), 1971 to 2000.

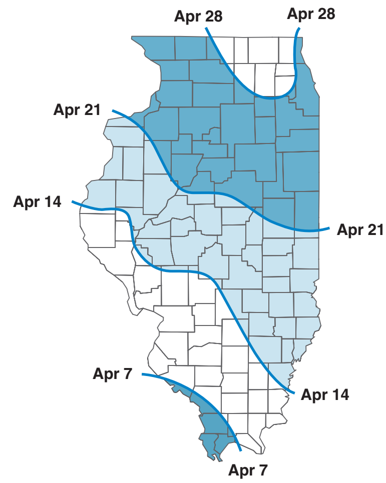

Figure 1.5. Average last occurrence in spring of 32 °F (0 °C) in Illinois, 1971 to 2000.

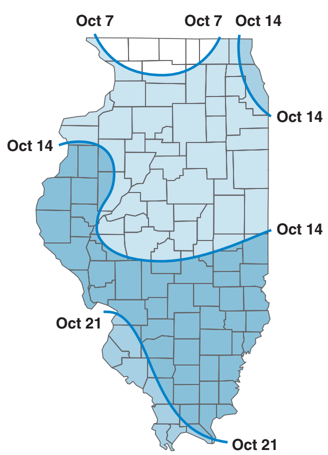

Figure 1.6. Average first occurrence in spring of 32 °F (0 °C) in Illinois, 1971 to 2000.

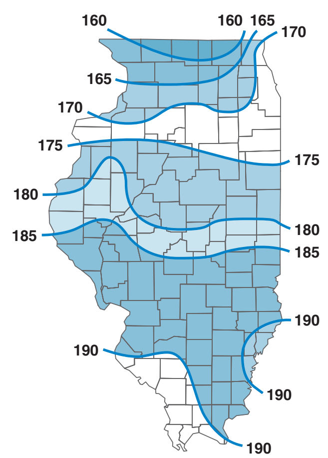

Figure 1.7. Average frost-free growing season length (days) in Illinois, 1971 to 2000.

Growing season length. The growing season is defined as the period between the last spring frost and the first fall frost. A frost will generally occur when the minimum temperature is less than or equal to 32 °F (0 °C). Most annual crops are planted after the major risk of frost or freeze has passed. However, late frosts—particularly very late frosts—can damage both annual and perennial crops during the spring. Frosts or freezes with temperatures less than 30 °F (–1 °C) result in major damage to crops in the spring. Mean dates of last spring frosts are as early as April 7 in southern Illinois and as late as April 28 in northern Illinois (**Figure 1.5**). In 1 out of every 10 years, the last spring frost can occur as early as March 27 in southern Illinois and as early as April 21 in northern Illinois. In nine years out of 10 the last spring frost occurs as late as April 24 in southern Illinois, and as late as May 14 in northern Illinois.

The average dates of first fall frosts range from October 7 in northern Illinois to October 21 in southern Illinois (**Figure 1.6**). In 1 out of 10 years, the first fall frost occurs by September 26 in northern Illinois and October 6 in southern Illinois. In 9 out of 10 years, the first frost occurs before or on October 21 in northern Illinois and November 5 in southern Illinois.

These dates mean that the normal growing season is generally less than 170 days in northern Illinois and more than 185 days in southern Illinois (**Figure 1.7**). In north-central Illinois, which includes crop reporting districts 3, 4 and 5, the growing season is approximately 180 days.

Precipitation

The type, timing, and amount of precipitation received during the year play critical roles in crop productivity. Precipitation types include unfrozen (rain) and frozen (snow, sleet, and hail). Snow and sleet occur in the winter and hail in the warmer seasons. In the winter, frozen precipitation is less efficient than unfrozen in recharging the soil profile due to its accumulating on the soil surface, which is quite often frozen. As the snow melts on a frozen soil surface, the water tends to run off rather than move down into the soil. Also, snow on the surface will sublimate (i.e., be transformed directly from snow to water vapor) and be carried away from the soil surface. Sublimation occurs even with air temperatures below freezing. Snow may also blow off fields and into ditches and fence rows, further limiting its contribution to soil moisture in the field.

Rain is generally more efficient in recharging the soil profile and thus is more available for crops. The efficiency of rain in recharging the soil depends on the rate or intensity with which the rain falls. Rain showers or storms that fall at rates greater than 0.5 inches an hour (12.7 cm/hr) are less efficient than lighter showers because the water forms ponds on the surface and runs off the fields into ditches and rivers, carrying along precious topsoil.

The timing of precipitation is critical to crop growth. In the period from harvest to planting, referred to as the fallow season, recharge of the soil profile occurs. In Illinois, there is usually enough precipitation to recharge the soil profile by January of the year following the harvest. In those years when the soil profile is not recharged by January, rainfall during February, March, and April is usually adequate to recharge the soil profile. If the soil profile is not sufficiently recharged during the fallow season, the possibility of drought during the upcoming growing season increases because of a greater likelihood of a soil water deficit during critical crop growth stages.

Timing of precipitation. The timing of rainfall while crops are growing is critical. During seed germination and stand establishment, either too much or too little rain can influence yields. Too much rain, especially with cool temperatures, can result in seed diseases, causing poor stands, or can saturate the soil, causing poor soil aeration and poor germination and stands. Dry soils during germination and stand establishment can result in either poor seed germination or weak and small plants that may not withstand dry weather during the early growth of the crop, causing smaller plant leaf area. For corn, the critical time during the early growth lasts for approximately 30 days, from planting to tassel initiation, when the corn leaves are being initiated and beginning to grow.

During the rapid vegetative growth stage, too much rain can result in a smaller shoot-to-root ratio and the establishment of shallow roots. When this happens, the crop is more susceptible to dry spells during the hot months of July and August when the crop is flowering and establishing harvestable grain on ears of corn or pods on soybean plants. A dry period after the crop stand has been established will result in a greater shoot-to-root ratio, with roots growing deeper into the soil profile and allowing the plant to use more of the water stored in the soil. After a dry spell, if adequate rain to recharge the soil is received in the 2 weeks before corn tasseling and pollination, the effect of the dry spell will be minimized. Rainfall during the week or two before the start of flowering in the soybean crop will also reduce the effect of a dry spell during the pure vegetative growth stage.

Rainfall of 1 to 2 inches in the 2 weeks following corn pollination will generally result in the highest yields, especially if the period of pollination had adequate soil moisture. The period from corn pollination to maturity is about 60 days. If soil moisture is near normal or wetter than normal, a dry spell from day 14 to day 60 after pollination will have a small influence on final corn yield. However, if no rain were to occur during those 46 days, final yield and quality of the corn crop would be reduced.

Because the soybean crop continues to flower and fill pods from the start of flowering to almost the beginning of maturity, soybean requires adequate rainfall throughout the months of July and August for best yields. Failure to receive adequate rainfall during flowering and pod fill will result in fewer flowers and pods on the plants.

Generally, annual rainfall exceeds the water requirement of Illinois crops. Mean annual rainfall is greatest in southern Illinois **(Figure 1.8),** about 45 inches (115 cm). In the rest of the state, annual precipitation is about 37 inches. (95 cm). However, there is a south–north gradient: seasonally, there is more precipitation in the south-central region during spring and fall than in the north-central and northern regions. Conversely, summer precipitation is greater in the north (12 in./30 cm) and north-central regions than in the south. Winter is the driest season, with about 5 inches (13 cm) of precipitation in the north and 10 inches (25 cm) in the south. Spring is the wettest season in the south, with more than 13 inches (33 cm) of rain, whereas summer is the wettest season in the north, with 12 inches (30 cm) of rain.

While wetter-than-normal years usually benefit crop yields, years that are drier than normal can greatly reduce yield. The severity of the reduction is a function of the size and timing of the rainfall deficit. **Figure 1.9** shows the annual distributions of rainfall for the central CRD (CRD 4) in the dry years of 1971 to 2000. The driest year, 1988, began with below-average precipitation in January and February. Late March through early April received about 3 inches (8 cm) of rain. Following that rainy period, rainfall was evenly distributed but below normal throughout the growing season. The second-driest year was 1976. From May through July, there were 2- to 3-week periods with little or no rainfall followed by a week or two when 3 inches (8 cm) of rain fell. August through December was the driest period. In 1971, the third-driest year of the period, rainfall was below average until mid-June, when about 5 inches (12.70 cm) of rain was received from mid-

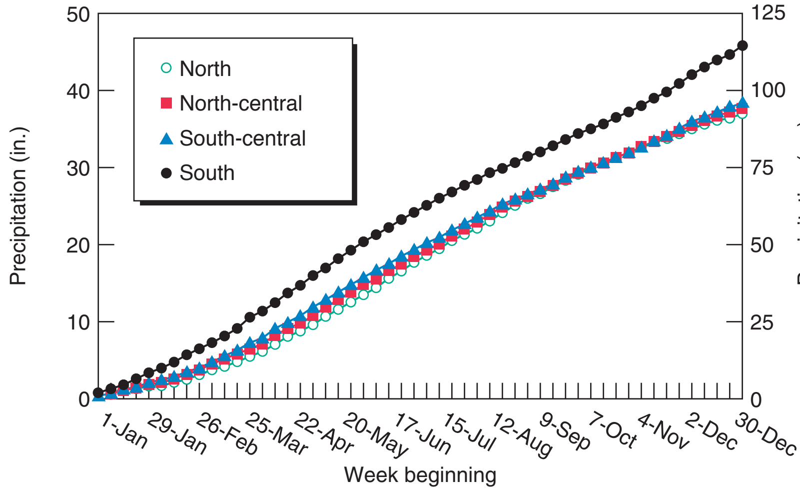

Figure 1.8. Normal accumulated rainfall from January through December for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

June through mid-July. The earlier pattern then returned, with about 4 inches (10 cm) of rain received through late November. In 1992, the first 6 months of the year were drier than normal. July was much wetter than normal. August through December received near-normal rainfall. The start of 1996 was also drier than normal, followed by above-normal rainfall in April and May. The rest of the year was drier than normal, with the exception of a wet week in July (7–14).

The corn and soybean yields for these years in Illinois' central crop reporting district demonstrate the importance of rainfall timing. To fully understand the impact, corn yields must be adjusted to remove the effect of genetic improvement on yields. Studies have shown that corn yields have increased about 1.1 bu/A/yr (69 kg/ha/yr) due to genetic improvement (A.F. Troyer, 2004, "Background of U.S. hybrid corn II: Breeding, climate and food." *Crop Science*, Vol. 44, pp. 370–380). Corn yield from one year can be adjusted to a different year by adding 1.1 bu/A/yr (69 kg/ha/yr) times the number of years separating the two years. For example, the corn yield in 1988 was 68 bu/A, giving a 1996 genetically adjusted yield of 77 bu/A (4.2 metric tons per hectare—tons/ha). Soybean yields do not increase as rapidly as corn yields, so a genetic adjustment for soybeans is not available.

Corn and soybean yields were the lowest in 1988, the year with a prolonged drought throughout the growing season. Corn yield (adjusted to approximate 1996 genetics) was 77 bu/A (4.8 tons/ha), and soybean yield was 27.5 bu/A (1.8 tons/ha). In the second-driest year, 1976, genetically adjusted corn yield was 147 bu/A (9.2 tons/ha), and soybean yield was 37.5 bu/A (2.5 tons/ha). This was the year with the wettest spring but little or no rain during 2- to 3-week stretches **(Figure 1.9).** Although 2 to 3 inches (5.08 to 7.62 cm) of rain fell during or shortly after pollination, it was not enough to offset the dry conditions during rapid vegetative growth followed by very little rain during grain fill. In 1971, when a dry spring with little rainfall until late June and early July was followed by rainfall of less than an inch each week during grain fill, the final average corn yield adjusted to 1996 genetics was only 133 bu/A (8.4 tons/ha), and the final average soybean yield was 38 bu/A (2.6 tons/ha). Rainfall in 1992 can be compared to the 1971 rainfall in that the spring and early-growth periods of corn were equally dry. However, from late June through late July, about 12 inches (30 cm) of rain was received. The average 1992 corn yield adjusted to 1996 genetics was 156 bu/A (9.8 tons/ha), and the average soybean yield was 46 bu/A (2.1 tons/ha). In 1992, the July rains were adequate to offset some of the effects of a dry early growing season and a dry grain-fill period. Even though 1992 was wetter than 1996, the average genetically adjusted 1996 corn yield was only 1 bu/A (63 kg/ha) less than in 1992, and soybean yields were 0.5 bu/A (34 kg/ha) less. The 1996 year began dry, followed by a wet planting season, a dry period of rapid vegetative growth, a wet period 1 to 2 weeks before pollination, and a relatively dry grain-fill period. The timely rains during 1992 and 1996 show the importance of adequate rainfall in the growing season.

Potential Evapotranspiration

Evapotranspiration is the removal of water from soil by a combination of evaporation from the soil surface and transpiration (loss of water vapor) from plant leaves. Surface evaporation is limited to the top 2 to 4 inches of soil, while

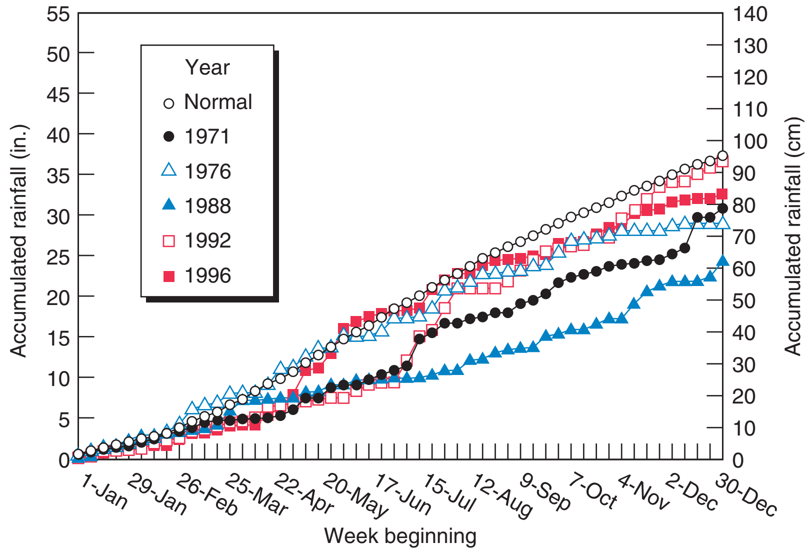

Figure 1.9. Rainfall distribution in the Illinois central crop reporting district (CRD 4) during the dry years of 1971, 1976, 1988, 1992, and 1996.

transpiration results in removal of water from the soil to a depth equal to the deepest roots.

Potential evapotranspiration is the amount of water that would evaporate from the soil surface and from plants when the soil is at field capacity. Field capacity defines the amount of water the soil holds after it has been saturated and then drained, until drainage virtually ceases. Soil that is drier than field capacity will experience actual evapotranspiration less than potential evapotranspiration. Actual evapotranspiration will also be less than potential evapotranspiration when plant canopies do not totally cover the soil.

Potential evapotranspiration is greatest in dry years with low humidity and predominantly clear skies and least in wet years with high humidity and cloudier-than-normal skies. Total potential evapotranspiration, from April though September, ranges from about 33 inches (84 cm) in dry years to about 27 inches (69 cm) in wet years. During wet years, actual evapotranspiration will approximately equal potential evapotranspiration. In dry years, actual evapotranspiration will be less than potential evapotranspiration. During the growing season, the normal total monthly evapotranspiration is least in September, approximately 3.8 inches (9.7 cm), and greatest in June and July, approximately 5.8 inches (14.7 cm). Potential evapotranspiration is highest in June and July because the sun is highest in the sky during those months, and more solar radiation is received during each day because of more daylight hours. Drought conditions occur when the potential evapotranspiration exceeds rainfall by more than the normal difference for several months in a row.

Soil Moisture

The amount of water held in the soil is determined by soil texture, soil drainage, precipitation, and evapotranspiration. During the summer months, evapotranspiration generally exceeds the rainwater absorbed by the soil, and the soil profile dries out. From October through April, evapotranspiration is usually less than precipitation, and the soil profile is recharged.

Wet soils in spring play an important role in determining how many days are suitable for field work. When soil moisture is normal or wetter than normal, even small rains will result in field work delays on all but the sandiest soils in Illinois. Rains greater than 0.10 inch (0.25 cm) often delay field work, especially in the spring and early summer, when soils are the wettest. On average, there are 7 days each month with rainfall greater than 0.10 inch (0.25 cm) during April and May, 6 days each in June and July, and 5 days each in August, September, and October.

During the spring planting season, the amount of water in the top 6 inches (15 cm) of soil controls field work activities. When the top 6 inches of soil is wet, planting is delayed, and nitrogen can be lost to either denitrification or leaching. Traffic on or tillage of fields when soil is near field capacity (80% of saturation) causes maximum compaction. During an average spring, soil moisture in April is great enough that rains of more than 0.3 inch (0.8 cm) will bring the soil water to field capacity. In the wettest years, rains greater than 0.3 inch result in significant periods of near-saturated soils in the upper 6 inches. The rainfall amounts shown in **Table 1.1** are the minimum amounts of rain needed to trigger denitrification and provide optimum compaction conditions. When the subsurface soil levels are dry, more rain than the amounts shown is needed to have this effect. Only in the driest years will soils seldom reach field capacity.

Excessive soil moisture in late spring and early summer may result in loss of nitrogen through denitrification and leaching and may lead to the development of seed, root, and crown diseases. Conversely, dry soil during planting may result in poor stand establishment and may cause plant stress when dryness occurs during the periods of flowering and seed set.

The typical arable soil in Illinois is a silt loam or silty clay loam that will, on average, hold approximately 7.5 inches (19 cm) of plant-available water in the top 40 inches (101 cm) of soil. Plant-available water is defined as the amount of water in the soil between field capacity and wilting point. The wilting point is defined as the amount of water still in the soil when plants are unable to recover at night from wilting during the day. Illinois soils hold about 6.5 inches (17 cm) of water in the upper 40 inches of soil at the wilting point. Water in the top 40 inches of soil at saturation is approximately 14 inches (36 cm). Individual soils vary significantly from the average. Coarse-textured soils, such as sands, hold less plant-available water and less water at the wilting point and field capacity than do fine-textured soils or soils with high clay content.

Whenever plant-available water in the top 40 inches (101 cm) of soil is less than 3.8 inches (10 cm) in June, July, or August, plants will show significant moisture stress during the day. Soil moisture is generally below this limit only during the driest months of July and August. Even in these months, soils should experience some periods above this stress threshold, especially following rains. In the wettest years, plant-available water exceeds plant needs, and periods of saturation may occur during the summer months.

Solar Radiation

Plants use the solar energy from the sun to fix carbon dioxide from the atmosphere, in combination with water from the soil, into carbohydrates that cause plants to grow, reproduce, and provide the grain and vegetation used as food by humans and animals. The solar energy available to plants is a function of sunshine intensity and duration. In southern Illinois, the intensity of sunshine is greater than in the northern regions. This greater intensity of sunshine in the south does not translate into significantly more total solar energy available in a single day compared to the north because the longer days during the summer in the north offset the lower intensity sunshine with more hours of sunshine.

Total daily solar energy received at the earth's surface has units of megajoules per square meter per day ($MJ/m^2/day$). The average solar energy received by a crop on relatively clear days around the summer solstice is approximately 31 $MJ/m^2/day$ **(Figure 1.10).** At the spring equinox, clear-day total solar energy is approximately 23 $MJ/m^2/day$, and at the autumn equinox approximately 21 $MJ/m^2/day$.

A question often asked is how cloudiness and low solar radiation affect yields. New technology allows continuous measurement of the exchange of CO_2 between the atmosphere and the earth's surface. When plants are fixing CO_2 through the process of photosynthesis, the flux of CO_2 is toward the surface. By summing the quantity of CO_2 that is being fixed by the plant over the daylight hours and simultaneously measuring the solar energy available to the crop, the efficiency of solar energy use by the crop can be estimated. The carbon fixation rates given below were obtained from data gathered over 4 years of corn and 4 years of soybean CO_2 flux monitoring in central Illinois.

A heavily overcast day in this discussion means no shadows would be seen at any time. An average day is one when light shadows would be seen, such as on a very hazy day when the sky has a blue-gray appearance or when the skies are partly cloudy and there are periods of both full sun and full shade (when no shadows are visible). A clear sunny day is characterized by deep blue skies with no clouds visible.

Table 1.1. Water content in the top 6-inch soil layer of a typical Illinois silt loam or silty clay loam during April, May, and June, and the minimum rain needed to bring soil moisture to field capacity.

	Dry		Average		Wet	
Month	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)
April	1.5	0.7	1.9	0.3	2.4	0.0
May	1.2	1.1	1.6	0.7	2.2	0.1
June	0.9	1.4	1.5	0.8	2.0	0.3

Dry conditions apply when the months of April, May, and June have less than 2 in. of rainfall each month; average conditions, between 2 and 4 in. each month; wet conditions, more than 4 in. per month.

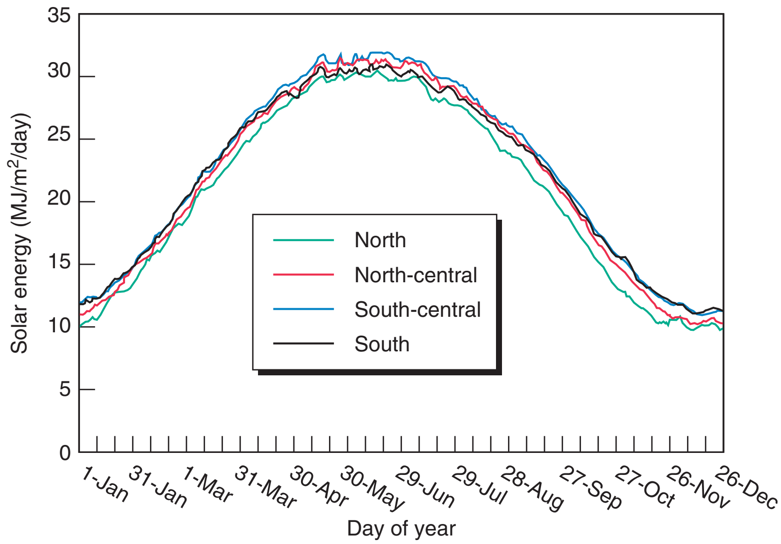

Figure 1.10. Daily solar energy received on clear days throughout the year for four regions in Illinois. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

When the crop has a full canopy, leaf area index greater than 2.7 the rate of carbon fixation by corn results in an accumulation of approximately 0.14 bushels of grain per acre per megajoule—bu/A/MJ (8.8 kg/ha/MJ). An average heavily overcast day between May and August receives about 8.2 MJ of solar energy. Thus, if all the carbon fixed by photosynthesis were to go into the grain, the yield gain on a heavily overcast day would be 1.2 bu/A/day (75.5 kg/ha/day). The average daily solar energy received during the same period is about 21.7 MJ, which translates into about 3.1 bu/A (194.9 kg/ha/day). On an average clear sunny day, the daily solar energy available to the crop is approximately 29.7 MJ, producing about 4.3 bu/A (270.4 kg/ha/day) of grain during the day. So on a heavily overcast day, approximately 1 bu/A would be lost compared to an average day, and an additional 1.2 bu/A would be gained on a clear day compared to an average day.

The average rate of carbon fixation by soybean results in an accumulation of about 0.07 bu/A/MJ (4.7 kg/ha). Thus, on a heavily overcast day, about 0.6 bu/A (40.4 kg/ha/day) would accumulate, while on an average day, 1.5 bu/A (101.1 kg/ha/day) would accumulate, and on a clear sunny day, 2.0 bu/A (134.7 kg/ha/day) would accumulate. Compared to an average summer day, the yield loss on a heavily overcast day would be approximately 0.9 bu/A (60.6 kg/ha/day), and the yield gain on a clear day would be 0.5 bu/A (33.7 kg/ha/day).

These estimates are just rules of thumb and cannot precisely specify yield loss due to cloudiness. Further, the rate of carbon fixation depends on the supply of water and minerals and the presence or absence of disease and insects. If there is an adequate supply of water and minerals without the presence of disease or insects, the rate of carbon fixation may be greater than the rates given here. Conversely, if the supply of water or minerals is not adequate, or there is disease or insect pressure on the crop, the rate of carbon fixation will be lower than the rate given here, and yields will be lower. With higher carbon fixation rates under optimum growing conditions, the effect of cloudiness will be greater. Under suboptimal growing conditions, the effect of cloudiness will be less.

Weather and Climate Forecasts and Accuracies

Forecasting the weather variables at different time scales is important to both short-term and long-term planning in agricultural production. Short-term predictions, from hours out to 2 weeks, called weather forecasts, are important for day-to-day management decisions. Long-term predictions, for seasons out to a year or two in advance, called climate forecasts, are important for successful crop selection and crop rotation planning.

Day-by-day weather forecasts up to 2 weeks out are widely used in agriculture and are readily available from the National Weather Service and private forecasters; the forecast accuracy does decrease, however, the farther the forecast is from present day. Climate predictions beyond 2 weeks cannot specify the exact weather conditions on any specific day. Rather, they identify the general conditions that will occur, whether the period will be generally warmer or cooler or wetter or drier than normal. A number of techniques have been developed for climate forecasts that can be put into two broad categories: statistical and physical.

Statistical techniques rely on historical climate data to establish relationships between different time periods. For example, an analysis of Illinois temperature data for 1895 to 2001 identified the 35 warmest winters. Following those winters, the summer temperatures were above normal in 18 summers, near normal in 10, and below normal in 7. A very simple statistical climate prediction can thus be developed for summer temperatures based on winter temperatures: if winter temperatures are above normal, the odds for a warm summer increase.

Statistical techniques have several limitations, however. They do not incorporate any knowledge of the causes of variations. In many cases, there is no consistent relationship on which to base a prediction. For example, following the 35 warmest autumns, 11 winters were drier than normal, 12 were wetter than normal, and 12 were near normal. Thus, warm autumn temperatures provide no predictive information about precipitation the following winter.

By contrast, physical prediction techniques rely on known causes of climate variations. A prominent example is the El Niño, a periodic disruption of the ocean and wind currents in the equatorial Pacific Ocean. Weather is affected not only in this region but in other parts of the world, including the United States. An El Niño event occurs about every 4 to 7 years and lasts for about a year.

Since 1995 the National Weather Service has produced climate predictions of temperature and precipitation out to a year in advance. They use both statistical and physically based techniques to develop their predictions. Their techniques include running global climate models, examining similar conditions in the historical record, and considering recent trends in temperature and precipitation.

Influence of El Niño and La Niña on Illinois Climate

The equatorial Pacific Ocean can be considered to be in one of three phases: normal, El Niño (warm), or La Niña (cold). The surface winds at the equator blow from east to west in the normal phase, which causes warm waters to collect at the western end of the basin. As the warm water is pushed westward, it is replaced by colder water upwelling from below, along the eastern edge of the basin. Heavier precipitation in the basin follows the warmer waters and is therefore found in the western half of the basin. During an El Niño event, easterly winds die down and sometime reverse. This allows warm water to return to the eastern half of the basin and effectively caps the upwelling of cold water. Heavy precipitation also shifts eastward, bringing wetter-than-normal conditions to the eastern basin and drier-than-normal conditions to the western basin.

Easterly winds found in the normal phase intensify during a La Niña. This causes even more warm water to collect in the western basin and the upwelling in the eastern basin to be stronger. As a result, waters in the eastern basin are much colder than average, and precipitation is pushed further west.

The three phases have atmospheric impacts that extend beyond the Pacific Ocean basin. El Niño and La Niña events have strong impacts on North American weather because North America is “downwind” of the Pacific Ocean. Because most North American weather patterns move from west to east, the weather systems tend to originate or pass over and are in some way influenced by the Pacific Ocean. Normal life cycles of El Niño and La Niña begin in late spring or summer, develop fully by the following fall or winter, and then weaken by the next spring. As a result, most impacts of these events occur in the colder months in Illinois.

Typical Illinois weather impacts of El Niño include these: during strong events, warmer conditions prevail from December to March with less snow, followed by wet conditions during March through May; in weaker events, the impact on temperature is minimal and drier conditions may prevail from January to March.

Typical Illinois weather impacts of La Niña include these: generally drier conditions during July and August, when La Niña events begin, and in November to January and April to June, as La Niña progresses. In weaker events, warmer conditions may occur during October to December and February to May.

General weather characteristics of both El Niño and La Niña can be identified, but each event has a unique personality based on timing of the event, intensity of sea-surface temperature changes, and area of the ocean over which these changes occur. For example, a strong storm track developed over the Midwest during the winter of the 2007–08 La Niña event. This resulted in heavy precipitation that continued into the spring and early summer—very atypical of La Niña.

The National Weather Service Climate Prediction Center monitors conditions in the Pacific Ocean and issues forecasts on any upcoming El Niño and La Niña events. This information also is used in their seasonal forecasts of temperature and precipitation. Scientific research over the past

20 years has led to breakthroughs in understanding this phenomenon. As a result, it is now possible to anticipate by several months the beginning and evolution of these events. Research also has increased knowledge about how these events affect the climate of Illinois.

Considerable research is identifying other causes of climate variations. It is likely that in the future, physically based climate predictions will gradually become more skillful for anticipating conditions a few months to a few years ahead. A primary focus of this research is the relationship of atmospheric circulation patterns to the condition of the land and ocean surface. The distribution of sea-surface temperatures affects atmospheric circulation patterns, the most prominent example being El Niño. However, anomalies of sea-surface temperatures in other parts of the oceans also have effects on the atmosphere, but they have not yet led to the dramatic improvements in predictive skill as obtained with El Niño events. Some future improvements likely will result, however. The condition of the land surface, particularly the extent of snow cover and the amount of soil moisture, also affects climate. For example, there is evidence that deficient soil moisture in the southern Plains and Midwest during early summer often leads to dry, hot conditions later in summer because of decreased evaporation.

Generally, weather and climate forecasts focus on predicting temperature and precipitation, and the amount of cloudiness and sunshine are inferred from these forecasts.