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Climate Variation at Flagstaff, Arizona—1950 to 2007

By Richard Hereford

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Conversion Factors

Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer

Temperature in degrees Fahrenheit (^{o}F) may be converted to degrees Celsius (^{o}C) as follows:

$$^{o}C = (^{o}F - 32)/1.8$$

Aerial view of Northern Arizona University, Flagstaff, and San Francisco Mountain (Image courtesy of Northern Arizona University, Cline Library).

CONTENTS

INTRODUCTION

Much scientific research demonstrates the existence of recent climate variation, particularly global warming. Climate prediction models forecast that climate will change; it will become warmer, droughts will increase in number and severity, and extreme climate events will recur often—desiccating aridity, extremely wet, unusually warm, or even frigid at times. However, the global models apply to average conditions in large grids approximately 150 miles on an edge (Thorpe, 2005), and how or whether specific areas within a grid are affected is unclear. Flagstaff's climate is mentioned in the context of global change, but information is lacking on the amount and trend of changes in precipitation, snowfall, and temperature. The purpose of this report is to understand what may be happening to Flagstaff's climate by reviewing local climate history.

Flagstaff is in north-central Arizona south of San Francisco Mountain, which reaches 12,633 feet, the highest in Arizona (fig. 1). At 6,900 feet, surrounded by ponderosa pine forest, Flagstaff enjoys a four-season climate; winter-daytime temperatures are cool, averaging 45 degrees (Fahrenheit). Summer-daytime temperatures are comfortable, averaging 80 degrees, which is pleasant compared with nearby low-elevation deserts. Flagstaff's precipitation averages 22-inches per year with a range of 9 to 39 inches. Snowfall occurs each season, averaging 97 inches annually.

This report, written for the non-technical reader, interprets climate variation at Flagstaff as observed at the National

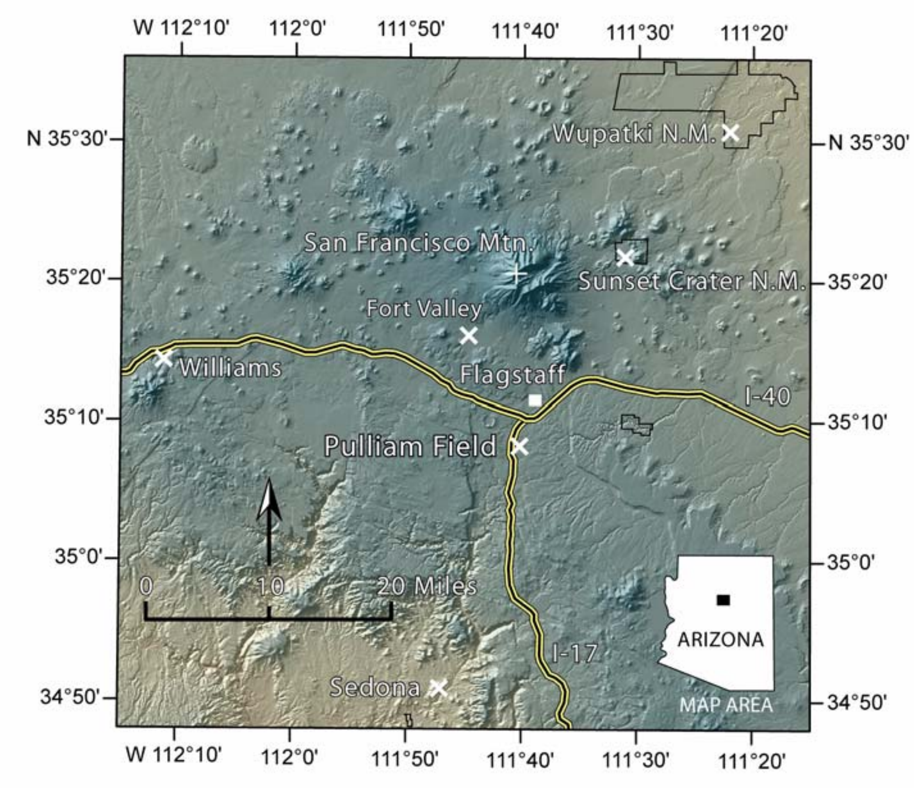

Figure 1. Shaded relief map showing Pulliam Field and other weather stations in the Flagstaff area. Dark shading corresponds to higher elevations.

Weather Service (NWS) station at Pulliam Field (or Airport), a first-order weather station staffed by meteorologists (Staudenmaier and others, 2007). The station is on a flat-topped ridge surrounded by forest 5-miles south of Flagstaff at an elevation of 7,003 feet. Data used in this analysis are daily measurements of precipitation (including snowfall) and temperature (maximum and minimum) covering the period from 1950, when the station began operation, through spring 2007. Conversations with Byron Peterson and Michael Staudenmaier of the NWS helped us understand the difficulties of collecting consistent weather data, operation of the station, and Flagstaff's climate.

Weather is the daily or even instantaneous state of temperature and precipitation. Climate is the average or accumulation of these parameters over longer time scales such as a week, month, or year. Seasonal (winter, spring, summer, and fall) and annual averages of temperature and accumulated precipitation describe the temporal variation of Flagstaff's climate, which is shown graphically with time series (figs. 2, 4, 6, 8-15). These plots show precipitation or temperature on the ordinate plotted against time on the abscissa, which is a year for annually repeating data or the year of a particular season. The plots reveal changing patterns of precipitation and temperature related to droughts, wet episodes, and rising temperatures.

PRECIPITATION

As shown in figure 2, the four driest years since 1951, arranged by amount of precipitation, were 1996, 2000, 2002, and 1956. Except for 1973, 1951 to 1977 was dry with 18 of 27 years having moisture below the long-term average. The period 1996 to the present is the driest on record with average-annual precipitation that was only two-thirds of the preceding wet episode. The wettest year was 1993 when total precipitation was slightly above 39 inches, or 1.8 times the long-term average of 21.6 inches, which is the average-annual precipitation from 1951 to 2006. Other wet years were 1986, 1983 and 1973. Late 1972 and 1973 are remarkable for having an extremely wet fall, record snowfall, and very little summer rainfall. Generally, precipitation above about 25 inches resulted from El Niño events, whereas La Niña activity produced less than around 15 inches. The definition and general effects of El Niño and La Niña on climate are in Trenberth (1997) and Ropelewski (1999).

Although a trend to either wetter or drier climate is absent in the precipitation series, the series reveals alternating wet and dry patterns within three distinctive precipitation episodes. Precipitation was substantially above the long-term average during an unusual wet period from 1978 to 1995 that is sandwiched between two dry intervals (fig. 2). These climate episodes are recognized in most of the Southwest. The first is the Mid-20th Century Drought (Swetnam and Betancourt, 1998) that began in the early 1940s, followed by the Late-20th Century Wet Episode beginning in the late 1970s, and, beginning in 1996, the ongoing Early 21st Century Drought (Hereford and others, 2002 and 2004).

An earlier drought from 1894 to 1904, known from weather records elsewhere in the Southwest (Gatewood, 1962; Gatewood and others, 1964), was noted for its serious effects on Arizona's cattle industry. Following that, from 1905 to around 1940, an extremely wet period prevailed, perhaps the wettest of the past 1,500 years in the West (Woodhouse and others, 2005). The effects of the early drought and wet episode on Flagstaff's climate are poorly known because

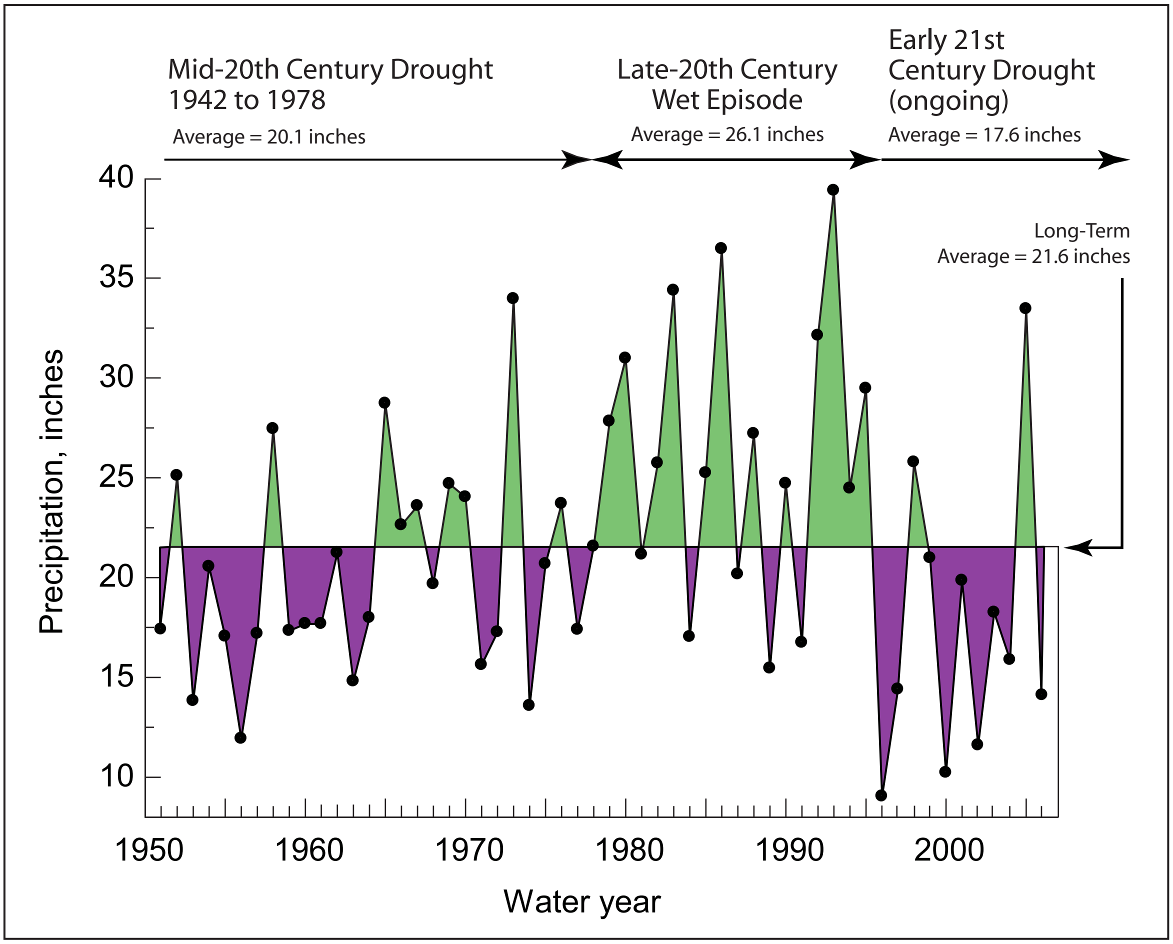

Figure 2. Water-year precipitation from 1951 to 2006. The water year (or hydrologic year), extending from October 1 to September 30 of the following year, is the annual accounting period used by hydrologists for recording accumulated precipitation.

they preceded systematic weather observations at Pulliam Field.

Although Flagstaff experienced the Mid-20th Century Drought, the much smaller population and overall cooler temperatures (temperature has increased in the late 1900s, as shown in a following section) curtailed the potential adverse effects of the drought. The problems brought on by the Early-21st Century Drought (fig. 2; Schmidt and Webb, 2001), however, are potentially severe because the present population of Flagstaff is more than five times larger than it was in 1950, average-daily temperatures are higher, and the precipitation deficiency is larger.

The ongoing drought is partly related to the interaction between the atmosphere and increased surface temperature of the Eastern Pacific Ocean (Hoerling and Komar, 2003). Certain climate indices suggest the drought may persist for another 10 to 20 years, if not substantially longer (Hereford and others, 2002; Mantua and Hare, 2002). Moreover, most climate models predict that the Southwest will become increasingly drier in the 21st century (Seager and others, 2007).

The population of Flagstaff more than doubled during the Late-20th Century Wet Episode, growing from 26,000 in 1970 to 53,000 in 2000. The large precipitation amounts of the late 1970s to mid-1990s (fig.

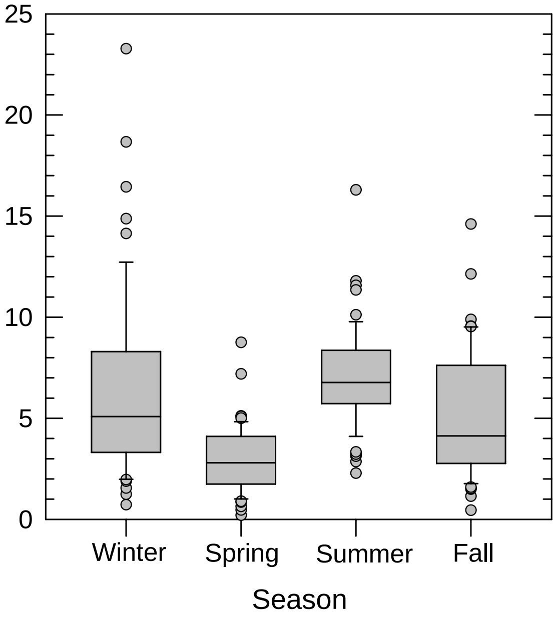

Figure 3. Box and whisker plots summarizing the statistics of seasonal precipitation from 1950 to 2007. Rectangles show the range of the 25th to 75th percentiles, which is the central 50 percent of seasonal variability; solid horizontal line is the median precipitation (may differ from the average values discussed below and those shown on figure 4); stem and whiskers extending above and below the boxes show the range of the 5th to 95th percentiles; and open circles show the largest and smallest values, those in the lower and upper five percent. For example, the uppermost circle above fall denotes 14.6 inches, most of which fell in October 1972. The lowest circle above winter is 0.7 inches from the remarkably dry winter of 2002.

2) are not typical; if used by resource managers for planning and modeling purposes, they will overestimate groundwater recharge and hydrologic balances. In addition, the success rates of urban and forest restoration projects undertaken during the wet episode were probably unusually high. Restoration will be more difficult in the present dry climate.

Seasonal Precipitation

The annual precipitation cycle runs from winter through fall (fig. 3) with distinctive winter and summer maxima, a characteristic pattern of precipitation in the Southwest. On average, 28, 14, 34, and 24 percent of the annual total occurs in winter, spring, summer, and fall, respectively. Summer rainfall, which stems mainly from the Mexican monsoon (Douglas and others, 1993), is more abundant than winter—averaging 7 inches in summer compared with six in winter. Generally, summer rainfall is less variable and more reliable than winter and spring precipitation. However, because most of the rainfall is soon lost to evaporation and surface runoff, it is much less important hydrologically than winter and spring moisture. Spring includes a fore-summer drought in May and June, another characteristic of the Southwest-precipitation cycle in which most of the spring precipitation accumulates by mid-April or early May. The lowest totals in winter and spring occurred during the last two drought episodes, particularly the Early 21st Century Drought.

Precipitation Variability by Season

The plots in figure 4 reveal the seasonal components of the water-year precipitation variability illustrated in figure 2. The underlying cause of the Early 21st Century Drought is the continuing failure to attain even average winter precipitation (except winter of 2005) and the substantially reduced spring precipitation. Winter precipitation was below average for 11 years from 1996 to 2007 and spring precipitation was below normal for eight of 11 years from 1996 to 2006. The drought includes the driest winter (2002) since 1951 and the driest spring (1996) since 1950. In addition, fall precipitation has been below normal since 1995 and nine years of the past 12 were below average. Figure 5 shows that combined fall, winter, and spring precipitation since 1996 (1995 in fall) is the lowest on record. The effects of this low precipitation are amplified in the hydrologic system because, on average, the three seasons account for two-thirds of the total annual moisture.

The only relief from the Early 21st Century Drought is the winter of 2005, which is the third wettest of the 57-year record. The relief, however, was short-lived as shown by the near record low-winter precipitation of 2006 and 2007 (fig. 4). The drought is evidently continuing unabated.

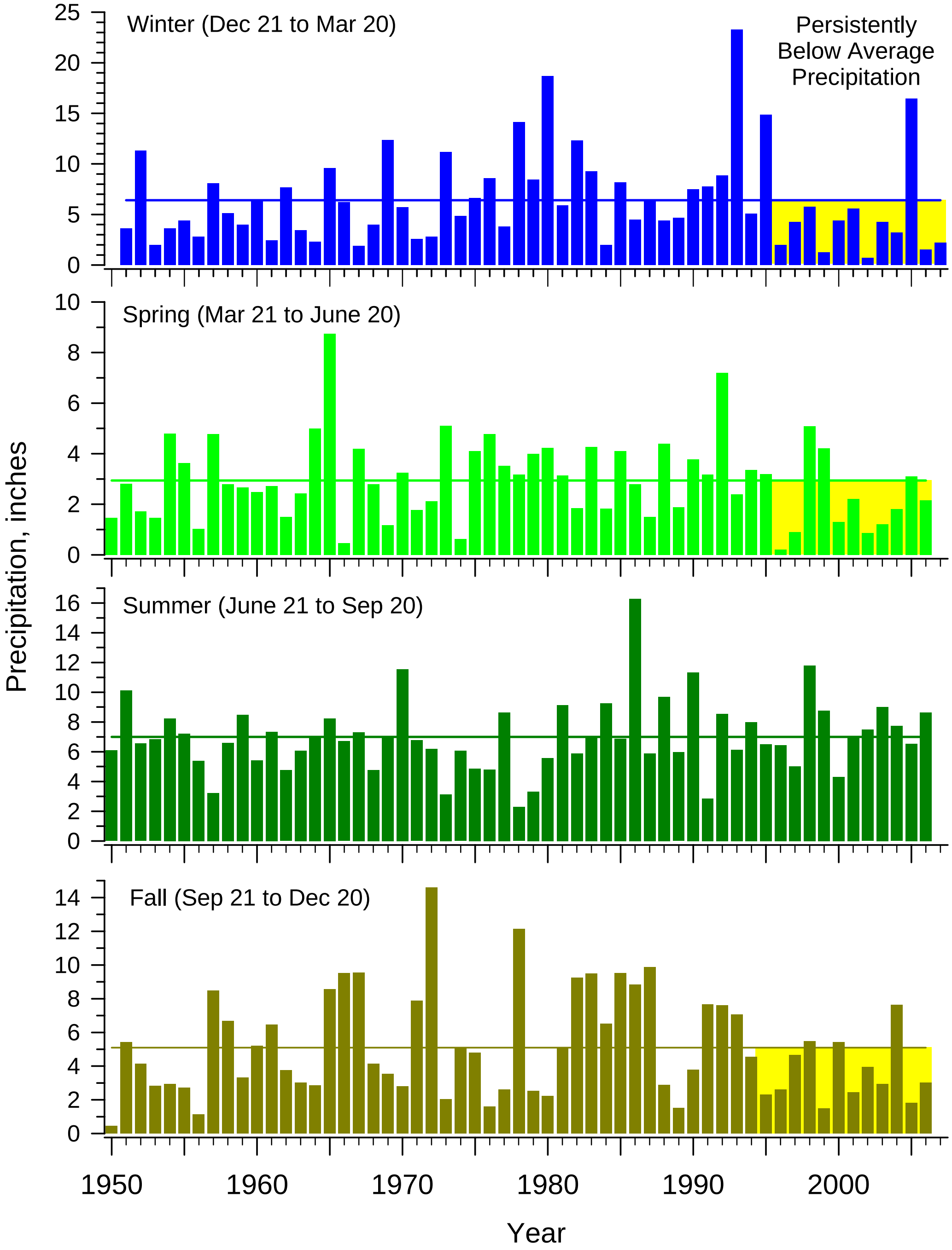

Figure 4. Annual variation of seasonal precipitation. Bars show seasonal totals and horizontal lines are the average-total seasonal precipitation. The solid color highlights the reduced fall, winter, and spring precipitation of the Early 21st Century Drought.

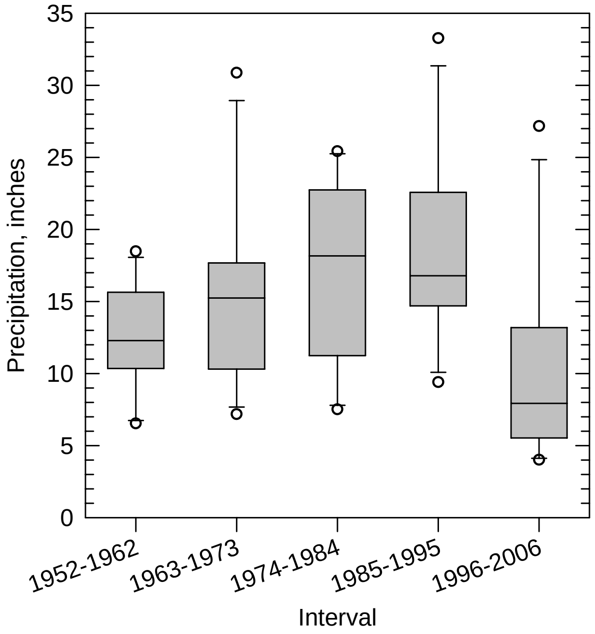

Figure 5 (left). Box and whisker plots summarizing the statistics of combined fall, winter, and spring precipitation of five 11-year intervals beginning in 1952. See detailed explanation of box and whisker plots on figure 3. Median fall through spring precipitation of 1996 to 2006 is the lowest overall of the preceding four intervals. Tabulated below is the total precipitation and percent change of each interval. Note the 44 percent decrease of the 1996–2006 interval.

Interval total (inches)		*Percent change*
1952–1962	137	–
1963–1973	169	24
1974–1984	187	10
1985–1995	203	9
1996–2006	113	- 44

Winter 1993 is impressive because it produced almost 24 inches of moisture, which by itself was close to the entire water-year average (26.1 inches) of the Late-20th Century Wet Episode (fig. 2). The largest observed daily rainfall of 3.93 inches occurred February 19, 1993. This storm caused widespread flooding from February 7 to March 1 throughout Arizona (Smith and others, 1998), including Continental Country Club in east Flagstaff.

Summer rainfall has oscillated around average conditions and is little affected by the ongoing drought. The driest summer was 1978 with only 2 inches while the wettest was 1986 with almost 17 inches, slightly less than the average water year-total of the Early 21st Century Drought (fig. 2). Between these extremes, summer rainfall averages 7 inches.

Snowfall

Flagstaff is a winter sports area and substantial economic activity depends on adequate snowfall. A successful season is determined by the quality and quantity of snowfall, the timing of seasonal precipitation, its amount, and the temperature.

As shown in figure 6, the least snowfall was 25 inches in 1972. In 1973, nearly 200 inches fell, the largest of the 60-year record. Few living now in Flagstaff can recall 1949 with 161 inches, most of which fell from January 9 to 25, 1949. In most of the West, that season was severe, known for cold temperatures and abundant snow. Snow fell in Los Angeles and blew into drifts 6-feet deep in Lanfair Valley in the Mojave Desert. Livestock suffered in the region and many died from exposure and starvation. Another remarkable season was 1968. Although the amount of snow (148 inches) was not particularly unusual, 84-inches fell in only eight days from December 13 to 20, 1967 (fig. 7). Drifting snow effectively paralyzed Flagstaff, leading to early Christmas-break dismissal at Northern Arizona University. Impassable, snow-clogged roads immobilized the Flagstaff Police Department. Patrols resumed after the department borrowed four-wheel drive vehicles, which were uncommon at that time, from the U.S. Geological Survey.

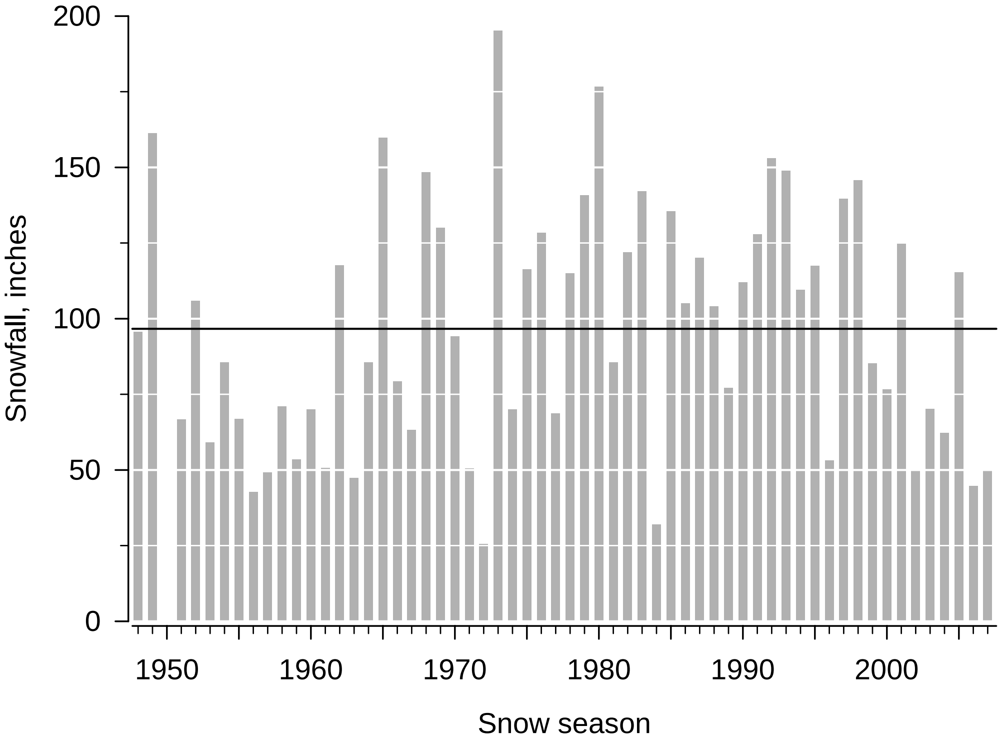

Figure 6. Snowfall from 1948 to 2007 during the snow season of November 1 to April 30. Note that data for 1950 are unavailable. Bars show seasonal accumulation. Average snowfall (horizontal line) is 97 inches. The calculated average differs depending on the length of the season and how missing data are interpolated.

Figure 7. NWS Pulliam Field station following 7 feet of snow in December 1967 (Image Courtesy of Northern Arizona University, Cline Library).

A long-term trend to more or less accumulated snowfall is not evident. For example, snowfall amounts of two 12-year periods, 1953 to 1964 and 1996 to 2007, differ little from each other. However, snowfall was generally above average from 1973 to 1998. Statistical modeling shows that the amount of snowfall is dependent on the average seasonal temperature and the amount of precipitation. Dry conditions and warm temperatures reduce the snow pack, a pattern that is already well developed.

TEMPERATURE

Average temperatures increased from 45.3 to 47 degrees from 1951 to 2006 at a rate of 0.3-degrees per decade (fig. 8, sloping line). The sloping line is the line of best fit (or regression line) that comes closest to passing through the temperature data points. This estimated 1.7-degree increase seems small, but it is 25 percent of the range between the highest and lowest average-daily temperatures of the water year, which were 1981 and 1973, respectively.

The coldest year was 1973, which was almost 3 degrees below average; it was also a year of record snowfall, as mentioned previously. Nineteen seventy-nine was almost as cold; municipal reservoirs froze over during cold spells in early December 1978 and late January 1979. On December 8, a record minimum of -23 was recorded and on January 30, it was -19. The warmest year was 1981 when the annual temperature was 4 degrees above average.

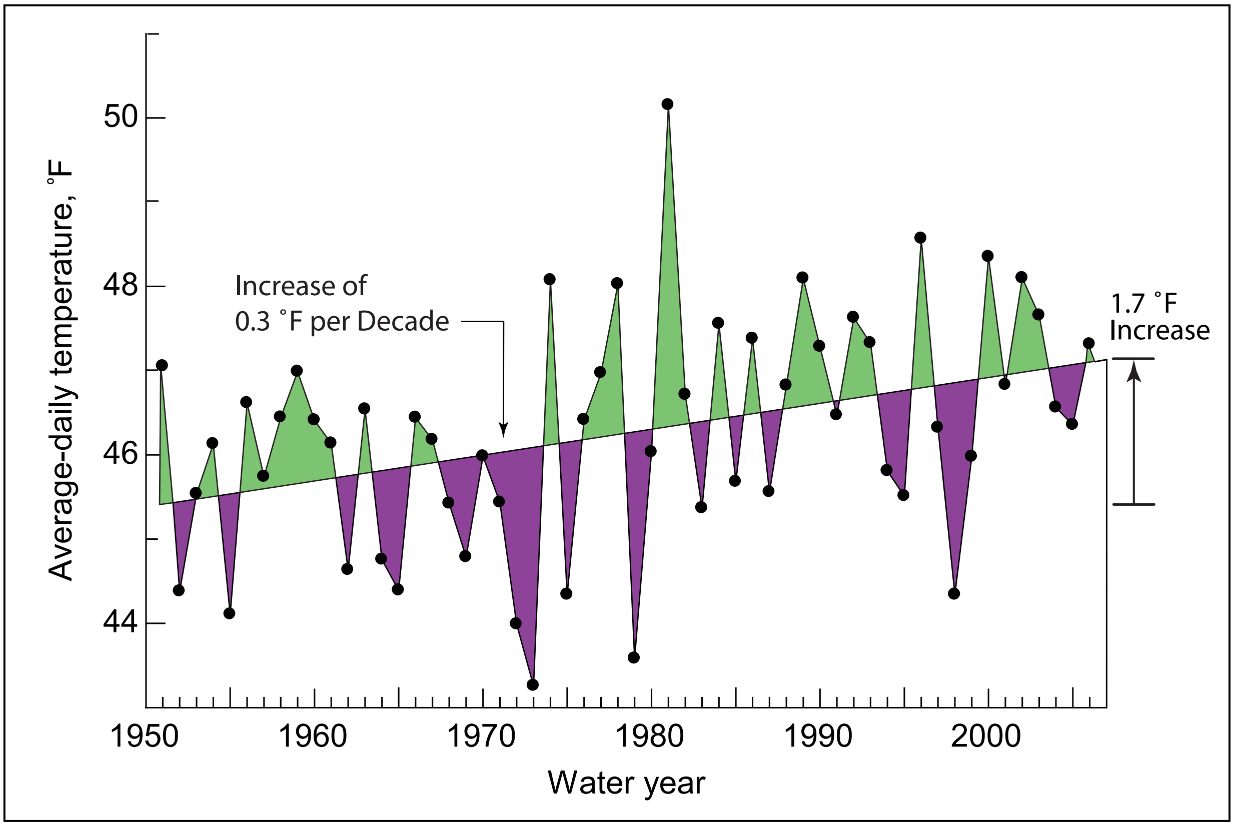

Figure 8. Average-daily temperature series from 1951 to 2006. Maximum (T_{max}) and minimum (T_{min}) temperatures are recorded daily, and the arithmetic mean of these is the average-daily temperature. The average-daily temperature of the water year is the mean of the 365 (366 in leap years) daily averages.

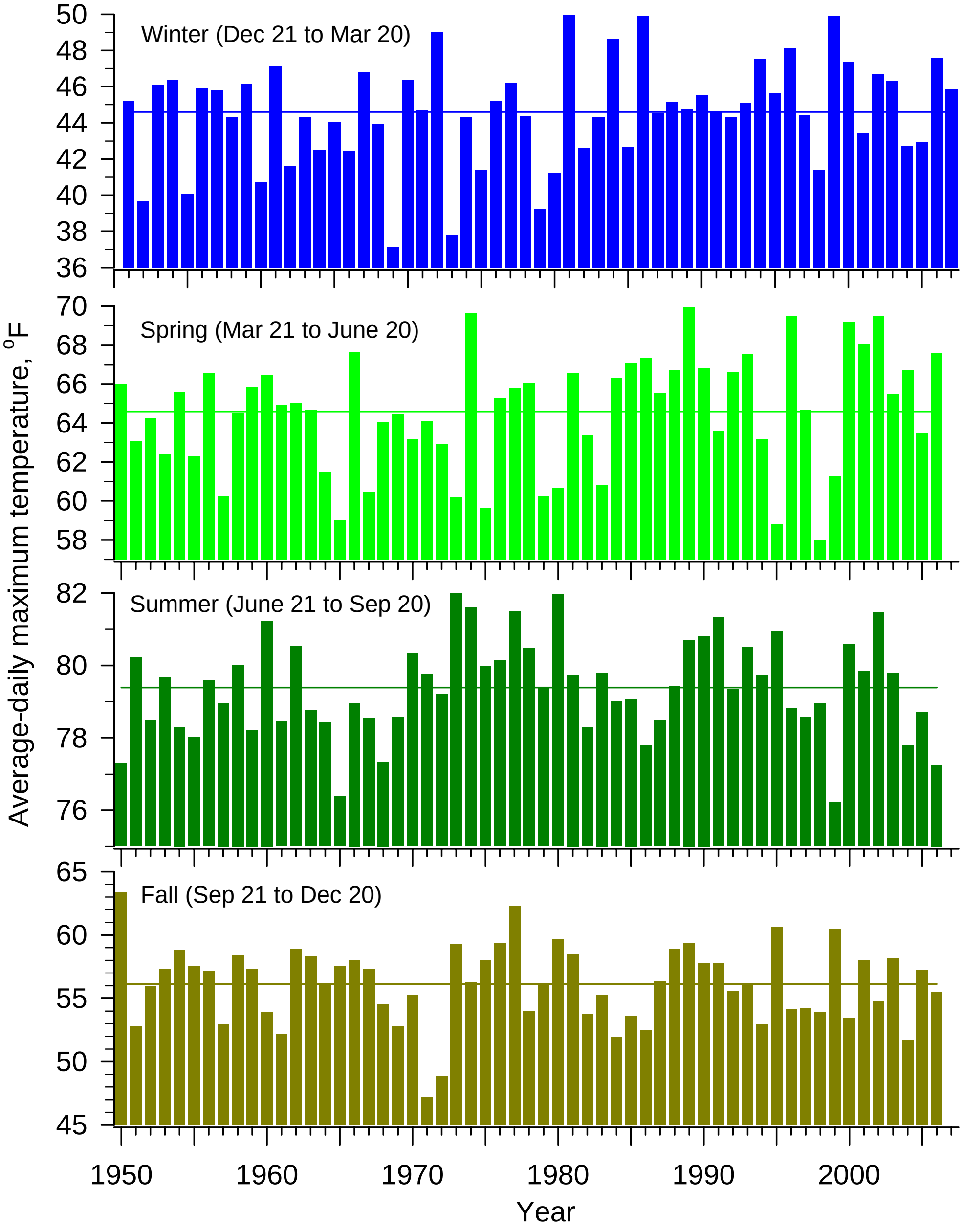

Figure 9. Seasonal variation of average-maximum (T_{max}) daily temperatures. Bars show the average temperatures of the season. The horizontal lines are the average-seasonal temperatures.

Interpretation of the gradually increasing average-daily temperatures is not straight forward, although it stems primarily from an increase in minimum-daily temperatures and from an increase in the number of unusually warm days. The former increases average-daily temperatures because overnight temperatures tend to be warmer while the latter inflates maximum temperatures when unusually warm days occur frequently.

The straight line trend toward increasing temperatures from 1951 to the present (fig. 8) is a generalization. It permits a workable statistical analysis, otherwise, it is an oversimplification that underestimates the rate and amount of temperature increase. A more complex pattern of increasing temperature based on the temperature histories of five Flagstaff area weather stations is shown in figure 14 of the *Appendix*. In that interpretation, temperatures actually decreased from the 1950s to 1970 and then rose rapidly at 0.6-degrees per decade. This resulted in an increase of 2.3 degrees from 1970 to 2006 that parallels the rise of global-surface temperatures (Brohan and others, 2006).

Maximum-Daily Temperature by Season

Average-daytime seasonal temperatures have not increased, as shown in figure 9. Nevertheless, in most cases, the warmest-average temperatures of each season occurred after 1970.

An unusually high (or extreme) daytime temperature is defined as a temperature above the 90th percentile (or those in the upper 10th percentile) of all daily maximum temperatures (T_{max}) for the period 1951 to 2006. Figure 10 shows the number of consecutive days (two or more days) of the water year in which the maximum temperature was above the 90th percentile; these are remembered as hot spells or heat waves. The solid horizontal line is the average or expected number of days annually, which is slightly more than 29. Inspection of figure 10 shows that the number of hot spells increased after 1973.

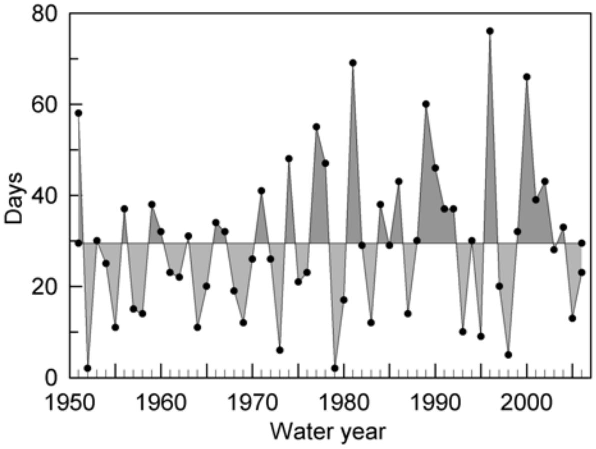

Figure 10. Consecutive days with temperatures above the 90th percentile of all recorded daytime temperatures (T_{max}) from 1951 to 2006.

Minimum-Daily Temperature by Season

The four-temperature series in figure 11 show the seasonal components of increasing water-year average-daily temperatures. Winter and spring minimum temperatures increased at rates (after extrapolation from a decade to a century) of 8- and 5-degrees per century, respectively, while fall temperatures increased at 2-degrees per century. For readers requiring additional information, an informal analysis shows these trends are statistically significant, meaning there is less than one chance in 20 that the long-term averages did not change. Summer-minimum daily temperatures have not increased, although the warmest summers occurred after the early 1970s.

Factors other than climate variation could cause these pervasive, rising temperatures (Jones and others, 1990). Temperatures could increase independently of natural causes by the urbanization of Flagstaff and by local climate conditions at the Pulliam Field station. However, evidence presented in the *Appendix*, which the interested reader is encouraged to review, indicates these factors had minimal influence and that warming is also typical of nearby rural weather stations (fig. 1). This means that the rising temperatures at Flagstaff are, for the most part, climate related.

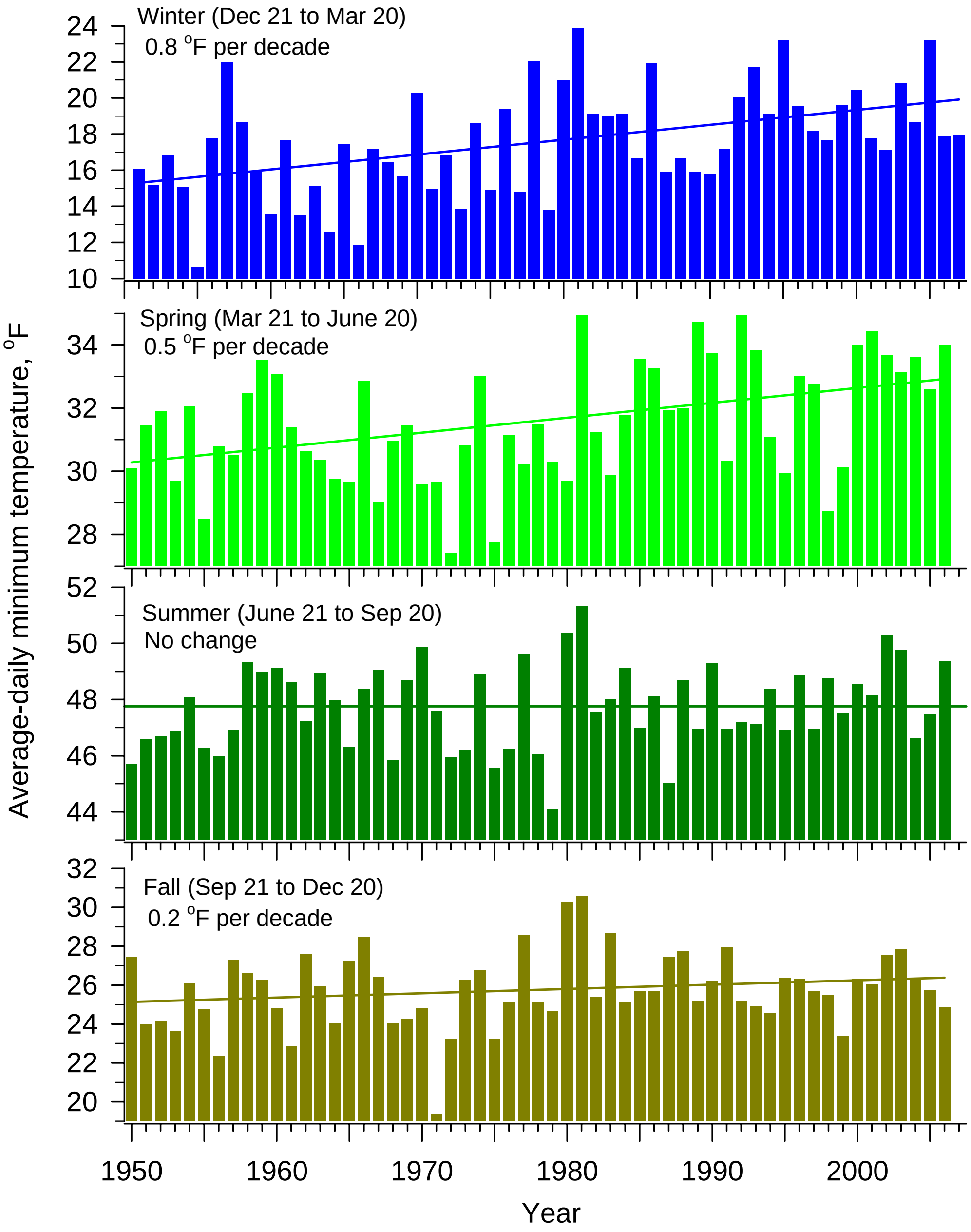

Figure 11. Seasonal variation of average-minimum (T_{min}) daily temperatures. The lines are the average-seasonal temperatures, which increased in winter, spring, and fall.

WHAT IS HAPPENING TO FLAGSTAFF'S CLIMATE?

Flagstaff is becoming warmer and drier. Estimated average-daily temperatures of the Flagstaff area are 2.3-degrees warmer since 1970 and annual precipitation at Flagstaff has been below average for nine of 11 years since 1996. The causes of rising temperatures are (1) an increase in nighttime-minimum temperatures and (2) more days having unusually warm-daytime temperatures, particularly heat waves lasting two or more days. This increase is probably unrelated to local conditions because increasing temperatures prevail at four of five nearby rural weather stations. Rising temperatures in the Flagstaff area, moreover, parallel the increase of global temperatures, particularly the rapid temperature rise since the early 1970s.

Ongoing drought since 1996 is strongly affecting winter, spring, and fall precipitation. Winter moisture has been below average in 11 of the past 12 years, spring was below average in eight of the past 11 years, while fall was below normal in nine of the past 12 years. The precipitation decrease of the three seasons is 44 percent since 1996. In contrast, summer monsoon-related rainfall is unaffected by the ongoing drought. Although summer rainfall is more abundant and dependable than winter precipitation, winter moisture is more effective hydrologically. This means that aspects of Flagstaff's environment that require cool-season moisture, particularly the ponderosa pine forest, are increasingly stressed.

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APPENDIX—SOME TECHNICAL DETAILS OF RISING TEMPERATURES

Diurnal Temperature Variation

The average diurnal temperature range (DTR) of the water year decreased 1.3 degrees since 1951 at the Pulliam Field station (fig. 12). Decreasing average DTR suggests that factors other than climate-related warming might have artificially influenced the weather at the Pulliam Field station. Reduced DTR, as figure 11 shows, resulted partly from an *increase* in nighttime temperatures in winter, spring, and fall. The consequence of increased-minimum temperatures is higher average-daily temperatures (fig. 8).

A number of factors affect DTR. Among these are the urban-heat island effect (UHI), cloud cover, humidity, and soil moisture. The UHI results from urbanization, including asphalt and concrete pavement that retain heat, and urban heat generated by cooling and heating. This excess heat radiates at night, increasing nighttime temperatures. Cloud cover also increases nighttime temperatures by reducing outgoing radiation, and soil moisture and humidity limit overnight cooling by retaining heat.

The weather station is 5-miles south of heavily urbanized Flagstaff (fig. 1). After 1980, urban development, mainly low density single- and multi-family dwellings, spread south from Flagstaff to the northeast and north of Pulliam Field with rapid growth and infilling from 1990 to 2000.

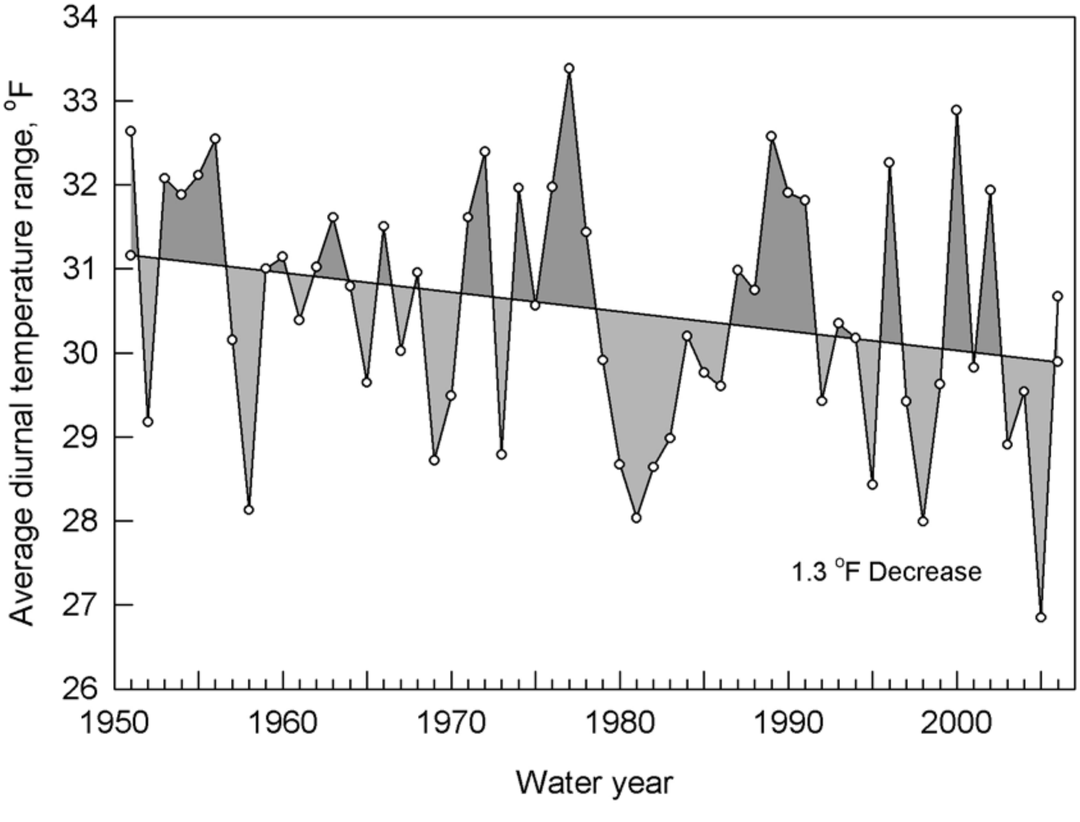

Figure 12. Average DTR from 1951 to 2006. The DTR is the difference between the daily maximum and minimum temperatures.

However, a belt of largely undeveloped forest 0.5- to more than 1-mile wide surrounds the airport, separating it from these developments (U.S. Geological Survey, 1962, and as revised in 1974 and 1983). The growth and urbanization of Flagstaff were probably too limited and too distant to alter conditions at the weather station.

Another type of UHI, however, may have developed locally at the station. The station history reveals that it was not moved and the instruments were unobstructed by trees or buildings (fig. 7) from 1950 to July 1995. Since 1995, the station moved several times and buildings and trees now provide distant obstructions and modify its exposure. The elevation of the station has not changed more than 3 feet in the several relocations, essentially eliminating the effects of elevation change on temperature. Nonetheless, the station has been located within 50 feet of asphalt at all of its locations. Because the station has been near asphalt for its entire history, minimum temperatures might be artificially elevated, although the affect should have been constant unlike the observed long-term increase. Temperature measurements, moreover, should have been affected by relocation after 1995; however, the temperature increase was ongoing by 1950 or began in the early 1970s, depending on how one interprets the trend. As explained in the following section, temperatures since 1950 quite likely decreased then increased. This down then up pattern is particularly difficult to correlate with changes in the station's history.

The decrease in DTR, therefore, resulted mainly from intrinsic climate factors, as explained generally by Parker (2004 and 2006), rather than the UHI and the microclimatology of the station. Decreasing DTR occurs in three ways: 1) a decrease in maximum temperatures, 2) unchanging maximum temperatures accompanied by rising-minimum temperatures, and 3) an increase of both in which minimum temperatures increase more rapidly than maximum temperatures. The first cause is unlikely, but two and three are plausible explanations for the decreasing DTR.

Temperature History of Nearby Weather Stations

If the observed temperature increase of the Pulliam Field station is real and not merely an artifact of the local environment, temperatures should increase at the other weather stations shown in figure 1. The mean of the average-daily temperatures at these stations (except Sunset Crater) rose 1.4 degrees (fig. 13) with a range of 1.2 to 2.4 degrees, and the trends are statistically significant. (The weather record at Sunset Crater begins in 1969. It is evidently too short to reveal a trend in either minimum or maximum temperatures and the local topography probably enhances nighttime cooling.) The details of increasing temperature are slightly different for each station; nevertheless, besides increasing temperature (except Sunset Crater), all of them show an increase in the number of unusually warm days similar to the Pulliam Field station (fig. 10). These results indicate that warming is also typical of the greater Flagstaff area, which is further evidence that the increasing average-daily temperatures at the Pulliam Field station result primarily from intrinsic climate variation.

Figure 13 shows an interesting aspect of temperature variation that is not immediately apparent in the Flagstaff series (fig. 8). The linear trend from 1951 (1950) to 2006 shown in the two temperature series (figs. 8 and 13) is probably an oversimplification. Smoothing the data reveals a more realistic interpretation—temperature *decreased* from 1950 to the early 1970s and then increased rapidly until the present.

Figure 14 is an improved interpretation of the temperature patterns in the Flagstaff

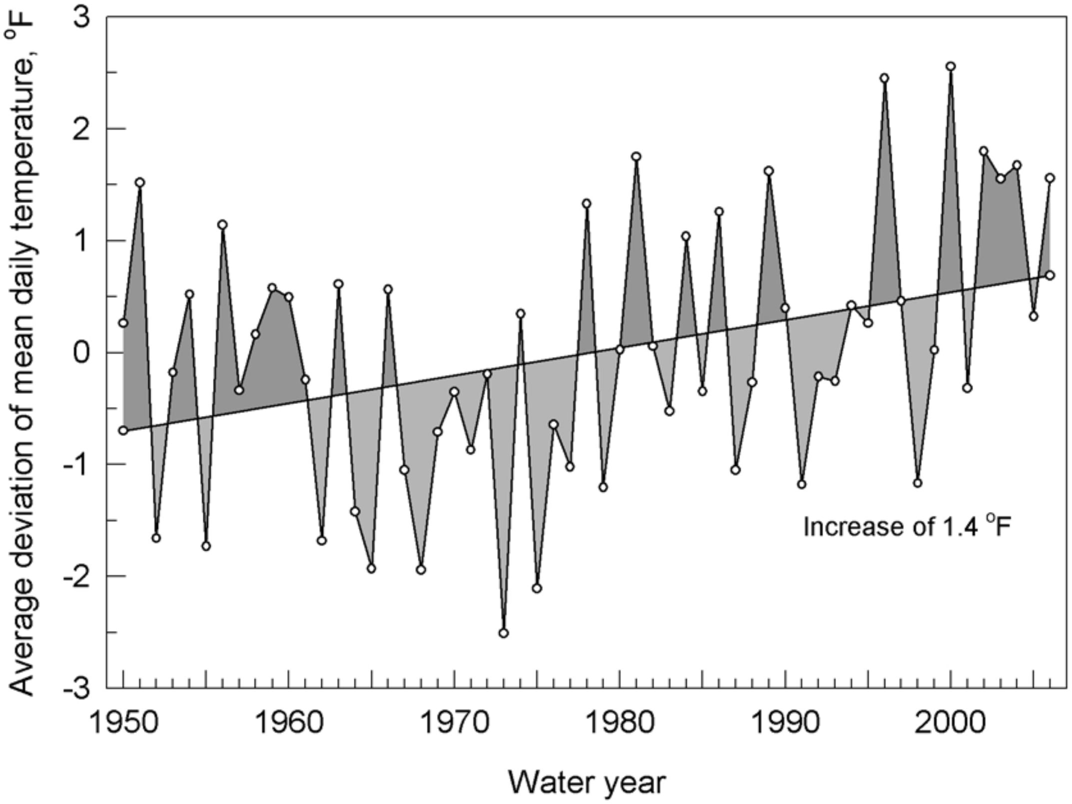

Figure 13. Average deviation from 1950 to 2006 of mean-daily temperatures at five rural weather stations in the Flagstaff area (Fort Valley, Sedona, Sunset Crater National Monument, Williams, and Wupatki National Monument in fig. 1). Volunteers in cooperation with the NWS operate these stations, and the stations cover a wide range of elevation and temperature regime. Calculation of the average deviation involves subtracting the stations long-term average temperature from each annual value and then averaging the deviations of the five stations year-by-year. Removal of the average is necessary so that each station receives equal weight in the calculation. Upward sloping line is the best fit of temperature data points with the water year.

area. In this model, average temperatures declined by 1.1 degrees from 1950 to 1970. Thereafter temperatures climbed 2.3 degrees. The rate of temperature increase in this scenario is 0.6-degrees per decade, twice the rate of the linear trend model.

Global-Surface Temperature

The global-temperature series (Brohan and others, 2006) in figure 15 shows a persistent increase from 1910 to the early 1940s. After that, global temperatures declined until the early 1950s and then oscillated with little change until 1970 when they began to rise steeply. Flagstaff area temperatures were declining in 1950, a pattern that probably began in the 1940s. In 1970, temperatures began to rise rapidly, largely in phase with the steep increase of global temperatures.

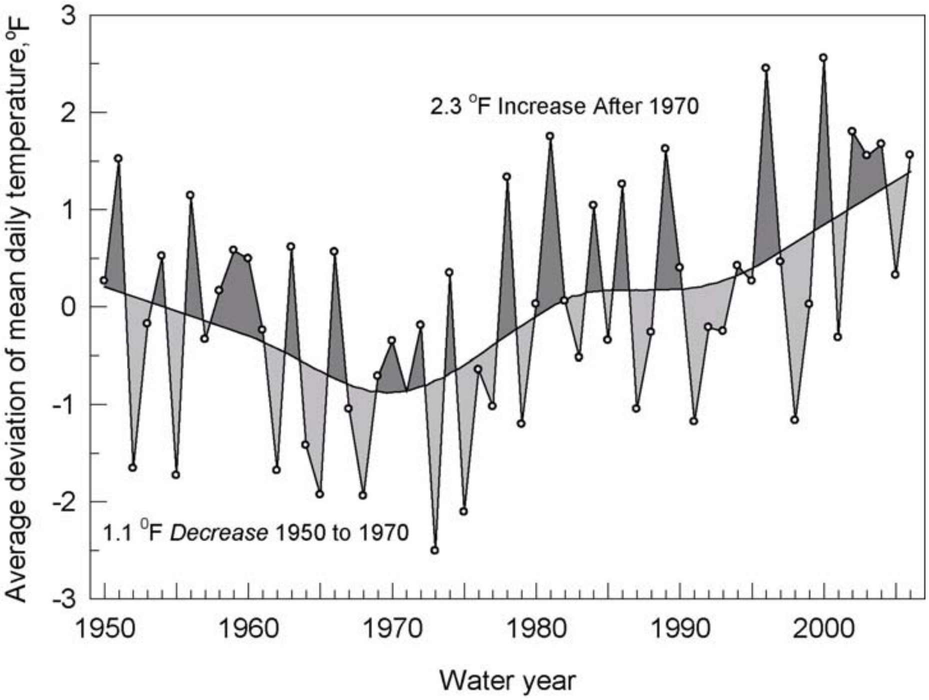

Figure 14. Data points identical to figure 13 except a smoothing function (curved line) reveals a down then up temperature pattern from 1950 to 2006.

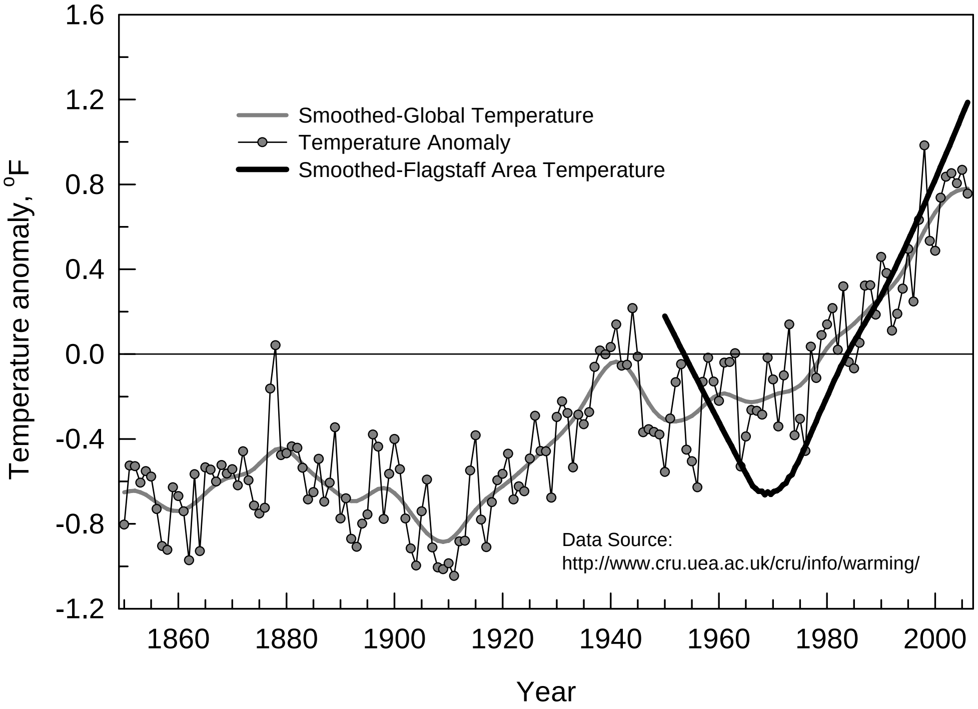

Figure 15. Observed marine and land-surface temperature series of the world from 1850 to 2006 shown with the previously explained Flagstaff area series (fig. 14). The global series is the average-temperature anomaly or deviation (average deviation is explained in the caption of figure 13) from the 1961 to 1990 global-mean temperature.