### CONTENTS

**INTRODUCTION** 1

**UPDATE OF CLIMATE VARIATION, 1950 to 2012, A SUMMARY** 1

**ANNUAL PRECIPITATION AND TEMPERATURE CYCLES** 3

**PRECIPITATION VARIABILITY** 4
  - Annual and seasonal precipitation including snowfall 4
  - Monthly precipitation 7

**VARIABILITY OF AVERAGE TEMPERATURE** 8
  - Annual and seasonal minimum temperatures 8
  - Minimum monthly temperatures 9
  - Annual and seasonal maximum temperatures 9
  - Maximum monthly temperatures 11

**DATA AND METHODS** 12
INTRODUCTION

This report is an update of an earlier study of climate variation at Flagstaff, Arizona that was published in 2007—U.S. Geological Survey Open-File Report 2007-1410 — that is available free of charge (http://pubs.usgs.gov/of/2007/1410). Five years of additional climate data are included in the present study, allowing further evaluation of temperature and precipitation trends at Flagstaff. Data and computational methods used in this analysis are discussed in the final section of the report. The second section interprets and summarizes the update and three subsequent sections illustrate the details of climate variation. Readers are also referred to a comprehensive, authoritative review of Flagstaff’s climate by the National Weather Service—NOAA Technical Memorandum NWS WR-273 (2009).

UPDATE OF CLIMATE VARIATION, 1950 to 2012, A SUMMARY

Flagstaff’s climate swings widely from year to year. A wet year follows a dry year, a cool year precedes a warm one, and vice versa. However, since the 1970s, annual long-term precipitation has decreased while temperature increased on a time scale of several decades. Briefly, precipitation declined 30 percent beginning in 1996 (figs. 1 and 2), and mean annual temperature (MAT) increased 1.4 degrees Celsius (2.5 degrees Fahrenheit) after the early 1970s (fig. 3). However, since 2007 MAT has declined during a recent cooling episode.

Figure 1 illustrates the wide range of seasonal precipitation typical of Flagstaff and much of the Southwest. For example, at Flagstaff, three remarkably dry seasons are evident: winter 1972, spring 1996, and fall 1999. Precipitation amounts were 0.5, 1.8, and 0 millimeters, respectively. Fall 1999 currently holds the record for consecutive days without precipitation. Measurable rain did not fall for 99 days from September 24 to December 31. In contrast, large, record breaking amounts of precipitation fell in fall 1972, winters 1980 and 1993, and summer 1986. Amounts were 415, 470, 537, and 495 millimeters (16.3, 18.5, 21.1, and 19.5 inches), respectively. These single season totals range from 80 to 103 percent of the average annual precipitation of 519.8 millimeters (20.5 inches).

Figure 1. Seasonal variation of precipitation from winter 1950 through winter 2012. Winter is January–March, spring is April–June, summer is July–September, and fall is October–December. Note that four symbols beginning with winter are plotted sequentially within each year.
In terms of water resources, the most important aspect of precipitation variability is the decline of fall, winter, and spring moisture beginning in fall 1995 (fig. 1; also see fig. 8), a pattern that persists into 2012. The period from about 1996 to the present is the regional and ongoing Early 21st Century Drought. Since it began, the drought has reduced accumulated precipitation by 30 percent, compared with the preceding Wet Episode of the late 1970s to mid-1990s (fig. 2). This unusual wet period from winter 1978 to fall 1995 is the wettest in Flagstaff’s recorded climate history, and regionally it is one of the wettest of the 20th century. The notable exception to the aridity after 1996 is fall 2004 and winter 2005 when moisture temporarily increased during a relatively strong El Niño event (fig. 1). Interestingly, summer monsoon-related rainfall is mostly unaffected by the drought, although the second (2009) and eighth (2000) driest summers occurred during this time (also see fig. 8). Flagstaff underwent the Mid-20th Century Drought (fig. 1), but the

![Figure 2](image2.png)

Figure 2. Accumulated precipitation by season in four 15-year intervals from 1951 through 2010; rectangles color-coded by season as in figure 1. Height of a rectangle is proportional to the seasonal total; black line at top of bars is the 15-year accumulation.

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![Figure 3](image3.png)

Figure 3. Average annual temperature (calculated from January through December) from 1950 to 2011. This is the average of the monthly minimum and maximum temperatures plotted annually. The red line is the smoothed average, which subdues the year-to-year variation.
present drought is drier in terms of 15-year accumulated moisture (fig. 2). In addition, population is now substantially larger, and MAT is higher, further exacerbating the already dry conditions.

One of the most important factors affecting Flagstaff’s environment is the increased MAT (fig. 3; also see figs. 11 and 13). Average temperatures increased by about 1.4 degrees Celsius (2.5 degrees Fahrenheit) after 1971. Most of the increase is from warmer nighttime temperatures in winter and fall, increased daytime temperatures in winter, and an increase annually in the number of unusually warm days (Open-File Report 2007-1410). Although MAT has declined about 0.5 degrees Celsius (0.9 degrees Fahrenheit) since 2007, one-year longer than other multi-year declines in 1959–61 and 1967–69, it is much too soon to declare the recent decrease a trend.

At least two methods can be used to estimate when and how much MAT increased. In figure 3 (red line), the smoothed MAT is used to infer the year of temperature increase. The oscillating cooling trend of the 1950s reversed in 1971, and temperature increased sporadically to a plateau in the late 1980s that is approximately 1.4 degrees Celsius (2.5 degrees Fahrenheit) warmer than the low point of 1971. Another method is to again choose 1971 as the critical date and then compare straight-line MAT of the two periods, 1950–71 and 1972–2011. This yields an increase of 0.56 degrees Celsius (1 degree Fahrenheit). This estimate is probably too conservative, but the increase is significant, meaning there is less than one chance in a hundred (greater than 99 percent confidence) that MAT after 1971 is the same as it was from 1950–71.

The increased temperature at Flagstaff since the early 1970s is consistent with and closely parallels a similar change of global marine and land-surface temperatures in the same period (Journal of Geophysical Research, 2006, v. 111, D12106 and Open-File Report 2007-1410). Likewise, the decreased precipitation since 1996 supports climate modeling that predicts an imminent transition to drier climate in the Southwest (Science, 2007, v. 316, p. 1181-1184). Flagstaff, therefore, is not a high elevation climatic outlier isolated from ongoing global climate change. Warmer and drier conditions are expected to continue into at least the near future, and this will affect community planning and development. These conditions will increasingly stress water resources and promote hazardous forest-fire situations. Moreover, decreased precipitation and increased temperature affect plant and animal assemblages, effectively slowing the recovery rates from forest fire and other disturbances. Finally, water-resource studies using data that include the recent Wet Episode (fig. 1) will overestimate the availability of surface water and recharge of local aquifers for the increasingly arid conditions.

ANNUAL PRECIPITATION AND TEMPERATURE CYCLES

In this section, summaries of monthly precipitation and temperature are used to illustrate how each of them varies over the calendar year. Regarding precipitation, figure 4 shows that on average the wettest months are July and August, although other months are occasionally as wet; the driest are May and June when no rainfall is typical more than 25 percent of the time. Precipitation has not occurred at least once for each month except August.

The main feature of the annual precipitation cycle is the late spring to early summer (May to June) dry period that separates the wet monsoonal and winter precipitation patterns. Annual precipitation computed from January to December (fig. 4) does not track well with the precipitation cycle, which extends from October through September of the following year. This sequence is the water or hydrological year. Another sequence, used by dendrochronologists, is the dendroclimatic year of July to June. Each of these accounting methods yields somewhat different annual averages and years of record-breaking precipitation.

Regarding snow, 77 percent of the average annual accumulation falls from December to March (fig. 5). The rare occurrences of snow in August and September are actually hail. The single largest monthly snowfall accumulation occurred in December; it resulted from the record storm of late fall.
1967 (snowfall cycle or water year 1968) in which 2,186 millimeters (86 inches) fell in only eight days from December 13 to 20. Rapidly accumulating snow during this storm caused an unusual early dismissal for winter break at Northern Arizona University. Drifting snow and snow-clogged roads eventually paralyzed Flagstaff, and impassable roads immobilized the Flagstaff Police Department. Patrols resumed after four-wheel drive vehicles (uncommon at that time) were borrowed from the U.S. Geological Survey.

The pattern shown in figures 6 and 7 is the familiar annual cycle of air temperature. January is the coldest month followed closely by December and February with average nighttime temperatures of -9.3, -8.5, and -7.8 degrees Celsius (15.3, 16.7, and 18 degrees Fahrenheit), respectively. Average minimum temperatures are below freezing from October through March. Nights are warmest in July and August and are typically 5 degrees Celsius (8 degrees Fahrenheit) warmer than June and September. Temperature variability (indicated by taller boxes and longer whiskers) is largest from November through February largely due to the frequent passage of cold fronts during fall and winter.

January, February, and December have the coolest daytime temperatures (fig. 7) averaging 5.6, 7.1, and 6.3 degrees Celsius (42.1, 44.8, and 43.3 degrees Fahrenheit), respectively. Average monthly temperatures during even the coldest months have not been below freezing (except for December 1905 and January 1937; also see fig. 14). July is the warmest followed by June and August with average daytime temperatures of 27.6, 26.1, and 25.5 degrees Celsius (81.7, 79.0, and 77.9 degrees Fahrenheit), respectively.

**PRECIPITATION VARIABILITY**

Annual and seasonal precipitation including snowfall

As figure 8 shows, the early part of the precipitation record before 1950 is fragmentary and incomplete, as indicated by breaks or gaps in the symbols of the five time series comprising the figure. Similar gaps are present in the temperature data record. Because so much of the data in the early period is missing, it is not meaningful to compare pre-1950 unusual precipitation or temperature events with those of the 1950 to 2012 record nor is it possible to identify long-term trends.

Annual precipitation amounts (fig. 8) clearly show the Wet Episode of the late 1900s (fig. 1) and the ongoing Early 21st Century Drought beginning in 1996. Viewed on a seasonal basis, this drought began when winter and spring moisture decreased in 1996 along with decreased fall precipitation in 1995. Winter, spring, summer, and fall accumulated precipitation decreased since 1996 by 43, 37, 14,
Figure 5. Box and whisker plots of the annual snowfall cycle plotted from October to September based on the 1950 to 2012 data. The snowfall cycle follows the water year accounting period, although October and June to September contribute little or no snow to the annual total.

Figure 6. Box and whisker plots of monthly minimum temperatures based on the full data record. Minimum temperatures usually occur during nighttime, particularly in the early morning hours.

Figure 7. Box and whisker plots of maximum temperatures based on the full data record. Maximum temperatures generally occur during daytime hours of the mid- to late afternoon.
and 25 percent, respectively (fig. 2) compared with the preceding Wet Episode. Summer rainfall was least affected by drought. On average, the contribution to the annual total by winter through fall precipitation is 29, 11, 35, and 25 percent. Drought has substantially decreased winter and fall moisture, which are two of the three most productive seasons. These dry conditions combined with warmer temperatures are linked with bark beetle outbreaks in pine and pinyon-juniper woodlands in northern Arizona and the Colorado Plateau (fhm.fs.fed.us/mtns/wg/04/pinemortality.pdf and Proceedings of the National Academy of Sciences 102: 15144-15148, 2005).
The three wettest years of the post-1950 record are 1965, 1992, and 1993 (fig. 8). Excessive moisture was in each case related to El Niño activity. Wet conditions in 1965 resulted from slightly above average winter moisture, an unusually wet spring, average summer rainfall, and a wet fall. In 1992, winter moisture was above average, spring was well above average, and fall was unusually wet. In Flagstaff, February 1993 is remembered for extensive flooding of the Continental Country Club area related to rain on snow conditions. On February 19, the largest single daily rainfall of 99.8 millimeters (3.93 inches) was recorded.

The driest year is 1956 with 264 millimeters (10.4 inches). Regionally, 1956 was unusually dry, if not the driest on record, and 1956 marks the low point of the Mid-20th Century Drought (fig. 1) that severely damaged pinyon-juniper woodlands in the Southwest (Journal of Climate, 1998, v. 11, p. 3128-3147). Annual precipitation in 1956 is only slightly less than 1950, 1996, and 2009 that had 269, 285, and 297 millimeters (10.6, 11.2, and 11.7 inches), respectively. These extreme drought conditions were related to recurrent La Niña activity that produced below normal precipitation in three to four seasons each year.

Snowfall in Flagstaff varies widely from year-to-year (fig. 9). The maximum annual snowfall was 5,357 millimeters (211 inches) in 1973. Only 725 millimeters (28.5 inches) fell in 1996. The record snowfall of 1973 occurred during El Niño activity, whereas the paucity of snow in 1996 was during La Niña conditions. Snowfall apparently does not have a long-term trend, although the 1950s were typically below average. Snowfall amounts have been close to or above average since 2007, which is likely related to the cooling after 2007 (fig. 3).

Monthly precipitation

Figure 10 is a time series of monthly precipitation totals plotted year-by-year. The 12 plots supplement the annual and seasonal figures by showing which month or months were characterized by average or unusual moisture or temperature conditions as shown in figures 12 and 14. For example, the aforementioned dry years had deficient moisture year around; whereas the extremely wet years typically have one unusually wet month with the remainder nearly normal (or average).
Annual and seasonal minimum temperatures

The five plots in figure 11 show the time-dependent variation of average annual and seasonal minimum temperatures. The annual series shows a rapid upward shift of temperature after 1979. This
corresponds well to an increase of winter nighttime temperatures. Spring temperatures began a gradual increase around 1975. Summer nighttime temperatures, in contrast, do not have a readily detectable trend. Fall temperatures increased abruptly after 1971 reaching a plateau in 1980 and then declining to near average conditions after 1983.

Minimum monthly temperatures

Monthly minimum temperatures (fig. 12) do not generally show systematic patterns or variations. However, March was unusually cool from 1962-73 after which temperatures increased to mostly average to above average. After 1979, April temperatures appeared to increase to a maximum in 1981, thereafter decreasing to mostly average temperatures. For the remaining 10 months, the annual variability overwheels any persistent deviation from average temperatures.

Annual and seasonal maximum temperatures

Annual maximum temperatures (fig. 13) show substantial variation in the post-1950 record. The year with warmest daytime temperatures is 1989; maximum daily temperatures averaged 18 degrees Celsius (64 degrees Fahrenheit). High temperatures in 1989, combined with below average to
average precipitation during a brief regional drought (fig. 8), resulted in an active fire season in the Flagstaff area. At 17.7 degrees Celsius (63.9 degrees Fahrenheit), 1977 was only slightly cooler. In both cases, seasonal temperatures were above to well above average.

Coolest daytime temperatures occurred in 1969, 1979, and 1998 with averages of 14.7, 14.8, and 14.7 degrees Celsius (58.5 and 58.6 degrees Fahrenheit), respectively. A very cool winter combined with otherwise normal seasonal temperatures reduced the average maximum temperature of 1969. A cool winter and spring along with normal summer and fall temperatures lowered the daytime
Below average winter, a very cold spring, and average summer and fall temperatures characterized 1998. Daytime temperatures rose steadily with only two downturns from 1969–77. Temperature then swung widely from 1979–82. It has since been mostly above normal. This pattern is seen in winter, spring, and summer daytime temperatures, which have tended to be above average.

**Maximum monthly temperatures**

Temporal patterns in monthly maximum temperatures (fig. 14) are not discernible in the summer months. However, average temperatures in December, January, February, March, and perhaps October were mostly normal to above average after the late 1970s to mid-1980s.
DATA AND METHODS

The data used in this analysis are monthly precipitation totals and average temperatures recorded at various localities in and near Flagstaff, specifically the downtown area and Pulliam Airport. The data are available online without charge from the National Climate Data Center (http://www.ncdc.noaa.gov/cdo-web/). The period of record is 1893 to the present (May 2012). The early part of the record from 1893 through 1949 has numerous missing entries (figs. 8–14) and is largely
incomplete. This update, therefore, mainly addresses climate variation of the 1950 to 2012 period for which the record is complete, although average annual temperature and total precipitation for the full record are shown in figures 4-14. The weather data were collected at Pulliam Airport by National Weather Service meteorologists from 1950 to 1994. Since July 1, 1994, official weather observations for Flagstaff have been recorded at the airport by an automated weather station.

Although the results of the present study and the 2007 report are comparable and consistent, they differ in detail. The earlier study used daily climate information from the airport and several surrounding weather stations. With daily data, the seasons are based on the calendar date. For example, winter, defined here as January through March, will generally not give the same total precipitation or average temperature as winter defined from December 21 to March 20. And, the earlier study used the hydrologic or water year accounting period of October 1 to September 30. Computations based on the water year will not be identical to those based on the calendar year, and patterns of climate variation and record-breaking years (for example, wettest or driest) may differ as well. Finally, precipitation and average temperatures cited here span the entire record in several cases or 1950–2012 in other cases. These values will differ from the “climatological normals” reported by the National Weather Service, calculated over a 30-year period (1971–2000), which coincidently was unusually wet and warm compared with the preceding record.

Any errors or omissions in this report are those of the author. Critical comments by B.A. Klimowski (National Weather Service, Flagstaff), L. Amoroso, L.S. Beard, and S. Priest (all with the U.S. Geological Survey) were helpful and appreciated. Additional snowfall data were supplied by B.A. Klimowski.