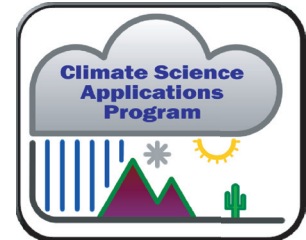


# ARIZONA AND THE NORTH AMERICAN MONSOON SYSTEM



## Introduction

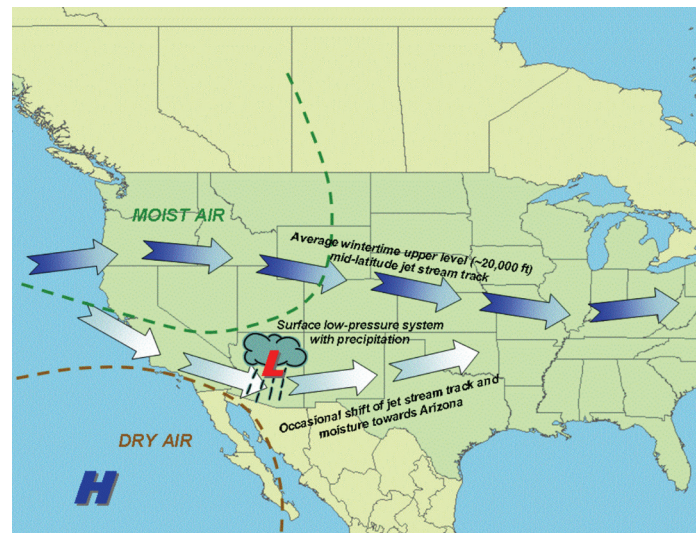
Arizona receives most of its annual precipitation in two distinct seasons, winter and summer. Winter precipitation is produced by large-scale surface low pressure systems that traverse the Southwest, drawing in moisture from the Pacific Ocean and producing widespread rain and snow (Figure 1a). Energy to fuel these large-scale low pressure systems comes from the upper-level (~20,000 ft.) mid-latitude and subtropical jet streams that are typically active in proximity to the southwest U.S. during the winter (Woodhouse 1997). Occasionally, energy will break away from these main jet streams and move slowly across the Southwest as circulation features called "cutoff" low pressure systems.

Summer precipitation in Arizona is the result of very different atmospheric features. The mid-latitude jet stream retreats far north during the summer and the subtropical jet stream is replaced by a large high pressure system anchored over the eastern Pacific Ocean (Figure 1b). The mechanism that produces summer precipitation is not associated with large-scale jet streams or strong low pressure systems, but from convective thunderstorms that arise through the combination of solar heating and moisture. Sunshine and solar heating are plentiful across Arizona during the spring and summer, but moisture levels adequate for thunderstorm development are not always present. A subtle change in circulation patterns during the summer opens up a flow of moisture from the south that dramatically increases convective thunderstorm activity across the state. That subtle change in circulation patterns is the North American Monsoon.

## How does the monsoon work

The official definition for the word 'monsoon' is a persistent surface windflow pattern caused by differential heating that shifts direction from one season to another (Greer 1996). The most intensively studied monsoon on Earth is the Indian, or South Asian, monsoon where surface heating of the Tibetan plateau during the summer causes warm, moist air and thunderstorms from the Indian Ocean to stream inland across south Asia. Winds shift direction during the winter as the Indian Ocean is warmer than the continent, bringing an end to the rains. This shift in winds, from onshore to offshore and then back again, happens each year with the changing seasons.

a)



b)



Figure 1. Average flow patterns and moisture airmass boundaries for (a) winter and (b) summer.

North America has a similar seasonal wind shift that controls summer precipitation in Mexico and the desert Southwest called the North American Monsoon System (NAMS). Mid-level winds (~ 10,000 ft.) shift from southwesterly to southeasterly as the large Bermuda high pressure system centered over the east Atlantic expands and builds northwestward across Mexico and into the southwest U.S. from June into July (Figure 2). Complex interactions between surface heating, topography, and larger-scale circulation patterns modulate the position and strength of the high pressure system. This shift in circulation transports moisture primarily from the tropical Pacific Ocean up through western Mexico, initiating the summer wet season (Bryson and Lowry 1955, Hales 1974, Carleton 1986, Douglas et al. 1993, Adams and Comrie 1997). There is considerable debate over how much moisture the Gulf of Mexico contributes to monsoon season precipitation due to large mountains in Mexico serving as a barrier to this moisture transport (Hales 1974, Douglas et al. 1993). Modeling experiments have shown that moisture at upper levels (above 10,000 ft) can flow into the southwest U.S. from the Gulf of Mexico during the summer monsoon season (Schmitz and Mullen 1996).

Arizona is on the northern border of the core region of the NAMS. Its location on the northern periphery of this main area of monsoon activity can lead to substantial variability in thunderstorm activity as moisture from the core region advances north or retreats south. Monsoon-related thunderstorm activity across Arizona is primarily tied to the availability of atmospheric moisture. Several regional-scale circulation features can help or hinder the flow of monsoonal moisture into Arizona (Figure 3). A low pressure area can develop from the intense surface heating over the Colorado River Valley during the summer and help steer moisture up into Arizona from the warm, moist waters of the Gulf of California. A mid-level (~15,000 ft.) high pressure system forms over northeastern Arizona ('Four-corners' High) and can help guide mid-level moisture in around the high from the northeast and east that may be in place from thunderstorm activity over the New Mexico or the Rocky Mountains in Colorado. This high pressure system can also help to move in mid to upper level (above ~15,000 ft.) moisture from the Gulf of Mexico depending on its geographic position. Southeast Arizona typically will experience a south to southeast flow between these two circulation features, which is ideal for pulling moisture north from the core region of monsoon activity in Mexico. The interplay between the strength and position of these circulation features helps guide the deep moisture into Arizona necessary for monsoon thunderstorm development.

These circulation features can also effectively shut down monsoon activity across Arizona by inhibiting the flow of moisture into the region. Subtle shifts in the location of the 'Four-corners' high pressure system can shift mid-level winds from east-southeasterly (moist) to northerly (dry). If the high moves too far west (e.g. southern Nevada) then mid-level winds are northerly and typically dry across Arizona. Any combination of circulation features that promotes flow with a westerly component can move very dry air inland from the east Pacific Ocean. This intrusion of dry air into Arizona during the summer season can shut down monsoon thunderstorm activity.

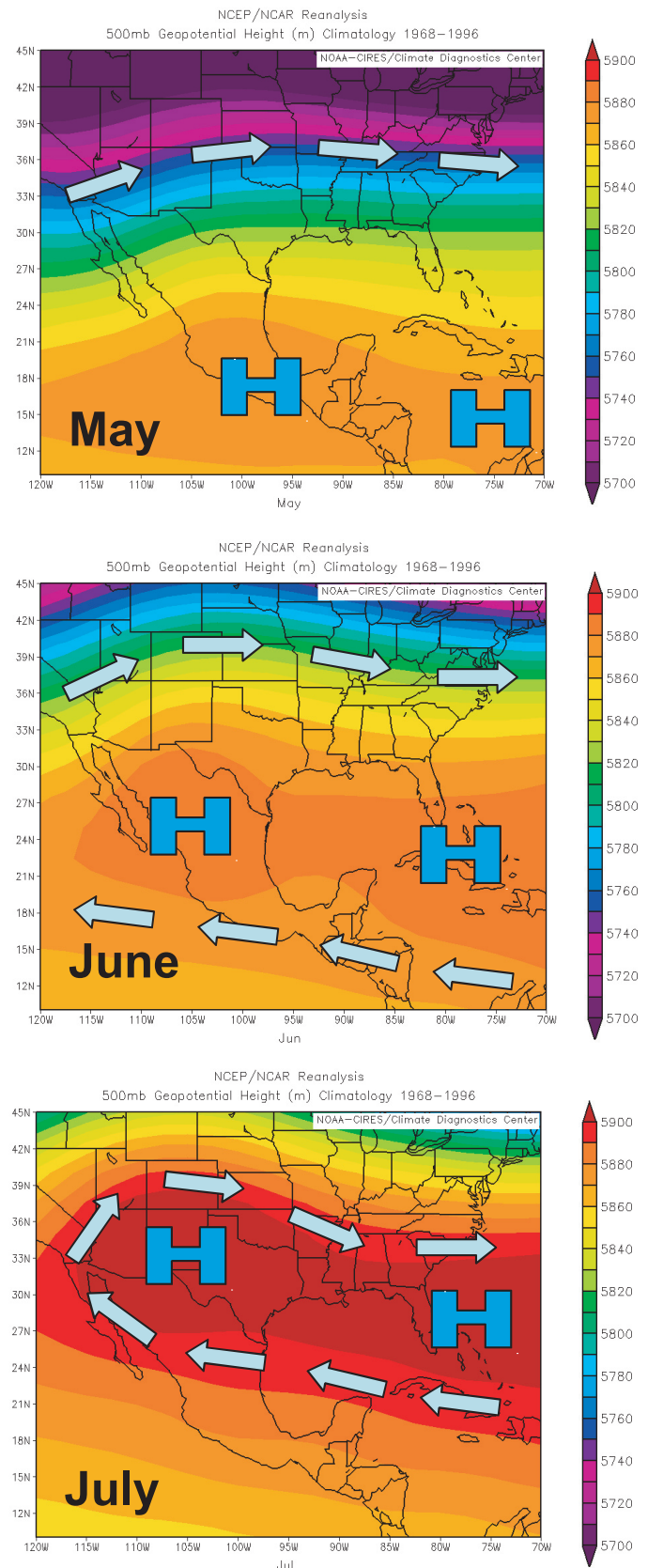


Figure 2. North and westward expansion of the Bermuda High in mid-levels of the atmosphere. Arrows indicate general flow at ~15,000 feet. (Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado from their Web site at <http://www.cdc.noaa.gov>, arrows added to show general wind flow directions)

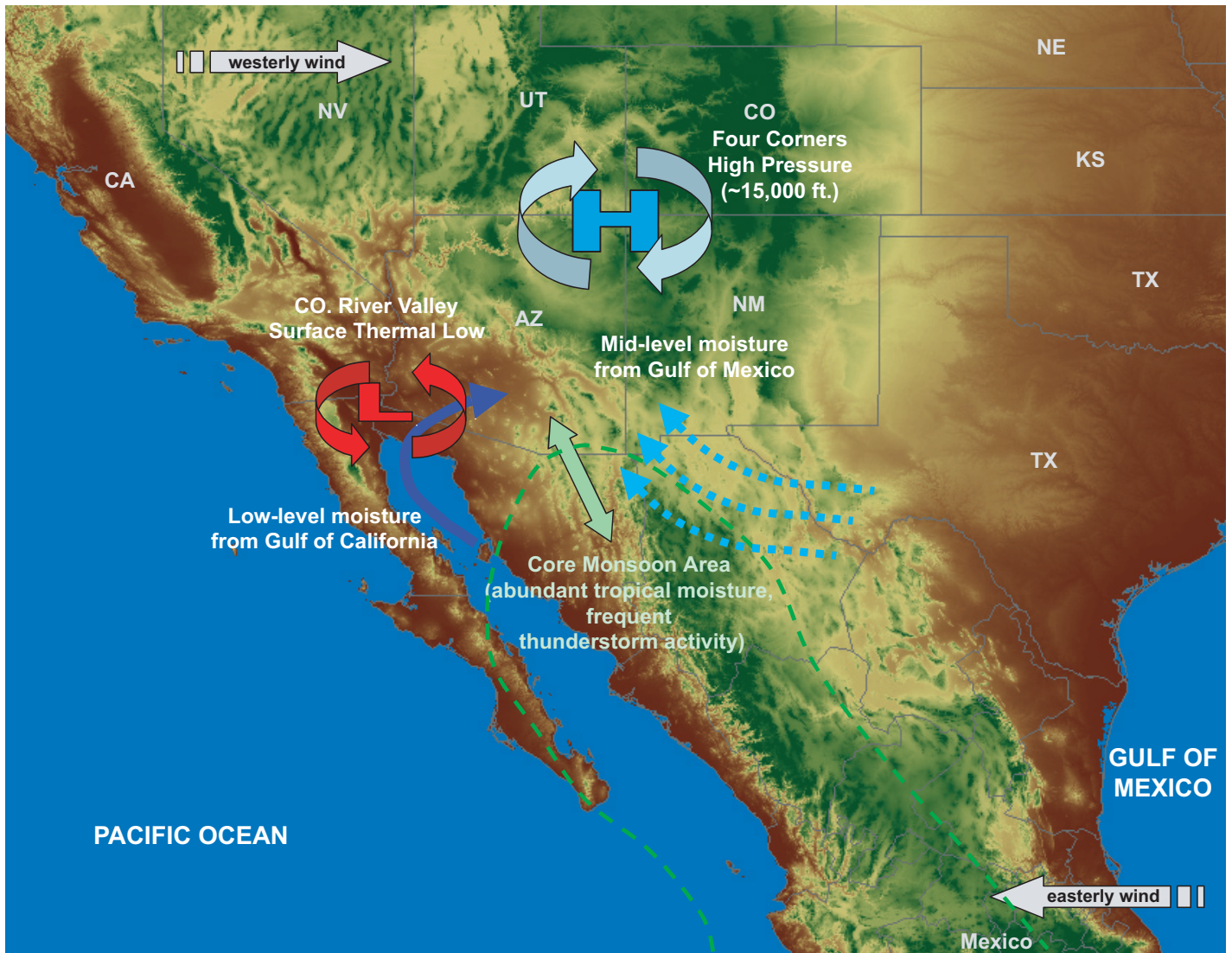


Figure 3. Conceptual diagram of key circulation features of the North American Monsoon System.

The overall circulation patterns across the southwest U.S. are very weak during the summer relative to the high and low pressure systems associated with the westerly jet stream during the winter time. Wind speeds at 10-20,000 ft. in the atmosphere are typically between 10 to 20 miles per hour during the summertime versus greater than 50 miles per hour during the wintertime. When wind flow patterns are weak, monsoon thunderstorms are often unorganized and slow moving. Storms under these conditions can produce large amounts of precipitation in localized areas. Wind flow patterns can strengthen for brief periods during the monsoon and intensify thunderstorm activity. When coupled with upper level disturbances that increase atmospheric instability, thunderstorms can organize into lines or into much larger individual storms. These types of events can produce widespread heavy rainfall amounts, hail, and damaging winds.

Monsoon activity can also increase in response to deep flows of moisture from the Gulf of California that are initiated by large-scale thunderstorm or tropical storm activity located at the southern end of the Gulf. These events are called 'gulf surges' and are pressure induced flows that bring deep moisture into

the low deserts of Arizona. Large-scale thunderstorm activity at the southern end of the Gulf of California can produce cool and wet conditions that are drawn up the Gulf towards the Colorado River thermal low pressure system. Dew point temperatures and winds from the south will often increase dramatically over the lower Colorado River Basin during gulf surge events.

Tropical storm activity in the east Pacific can also directly impact summertime rainfall amounts across Arizona. Tropical storms and hurricanes can trigger gulf surges as discussed above or make landfall in Mexico and continue northeast across the southwest U.S. bringing heavy and widespread rains. The movement of tropical storm activity across Arizona is infrequent, but does occasionally occur later in the summer season and into the early fall. Tropical storms possess both copious amounts of moisture and energy and can create widespread flooding events (Smith 1986).

## The Monsoon Season in Arizona

The circulation features that bring monsoonal moisture into Arizona are typically in place by late June or early July and persist

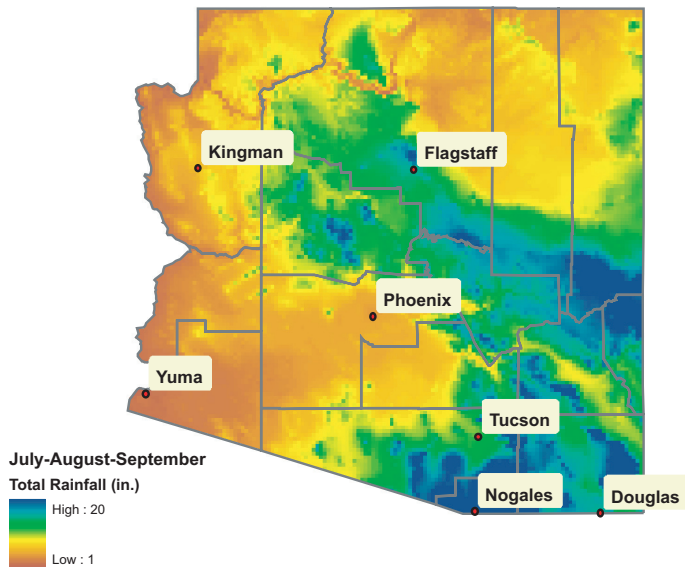


Figure 4. Long-term (1971-2000) average total July, August, and September precipitation. This was map created by interpolating climate data at point locations to a 4 km grid. Values in each grid cell represent precipitation estimates based on the interpolation model. Refer to Table 1 for actual long-term monthly average precipitation amounts measured at observation stations across Arizona. (map created with PRISM climate data from the Spatial Climate Analysis Service, <http://www.ocs.orst.edu/prism/>)

through mid to late September. There is a great deal of variability from year to year regarding when substantial monsoon moisture arrives. This is due to interannual variability in large-scale circulation patterns (e.g. strength and position of the expanded Bermuda high pressure system). Atmospheric moisture values are typically high enough to support thunderstorm activity across southeast Arizona in late June or early July and gradually expands northwestward through the remainder of July.

Precipitation patterns across Arizona associated with the monsoon are strongly dictated by elevation and latitude. Given that the core of the NAMS is in Mexico, the southeastern part of the state is in closer proximity to monsoon moisture and receives higher precipitation amounts during the summer. Figure 4 depicts the long-term average total precipitation for July, August, and September (JAS). Total summer precipitation amounts of ten to twenty inches are common over the southeastern part of the state. These amounts decrease toward the north and west. The amount of rain falling during JAS relative to the total annual rainfall is shown as a percent in figure 5. This shows that monsoon rainfall makes up over half (> 50%) of the total annual rainfall for portions of southern Arizona and higher elevation locations throughout the rest of the state. The maps shown in figures 4 and 5 are created by a statistical model that interpolates between point observations of rainfall using elevation as a main model input. The exact point measurements made at numerous weather observing stations across Arizona can be found in table 1.

The complex topography of Arizona exhibits a strong control on the pattern of monsoon precipitation. Monsoon season precipitation amounts are often greater at higher elevations due

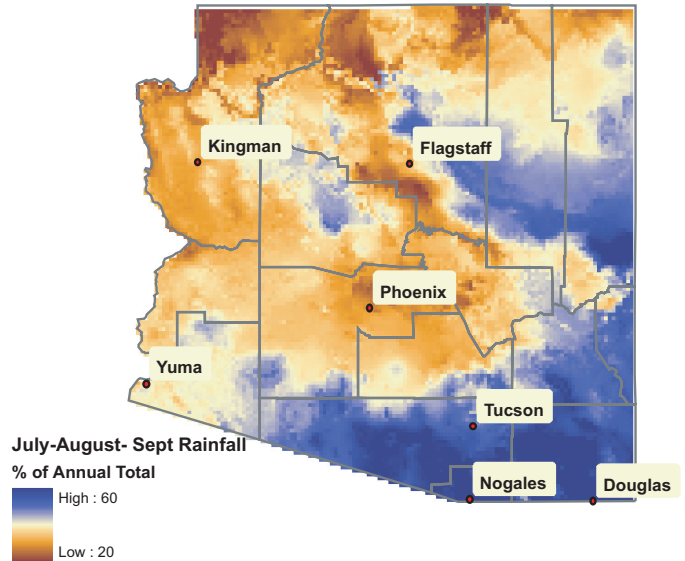


Figure 5. Percentage of annual total rainfall that occurs in July, August and September. This was map created by interpolating climate data at point locations to a 4 km grid. Values in each grid cell represent precipitation estimates based on the interpolation model. Refer to Table 1 for actual precipitation amounts measured at observation stations across Arizona. (map created with PRISM climate data from the Spatial Climate Analysis Service, <http://www.ocs.orst.edu/prism/>)

to the effectiveness of mountains at initiating and controlling thunderstorm development. Moist air flows can encounter mountains and be forced to rise and cool, initiating convection (orographic lifting). High elevation areas also heat up quickly in the high summer sun. This leads them to be much warmer than the surrounding atmosphere, which also can induce convective cloud development (elevated heating). This is often why thunderstorms form first over mountain areas and then move out into valley locations. The movement of storms off of mountain areas is controlled by mid-level winds. If the winds are too weak, the storms can remain stationary on the mountain ranges where they formed.

## What does the Monsoon mean to Arizona?

The onset of the monsoon season has a different meaning to different sectors of the Arizona economy. In general the monsoon brings much needed rainfall to the state, but can inflict property damage and cause risk to human lives through thunderstorm winds, flash flooding, hail and lightning. Maricopa County reported more than \$225 million in property damage associated with monsoon thunderstorms for the period of 1996 through 1999 (National Weather Service-Phoenix 2006). The National Weather Service, emergency managers and flood control districts work together to monitor monsoon thunderstorm activity and minimize risks to lives and property.

### Electric Power Delivery

The delivery of electric power through above-ground transmission lines is especially vulnerable to damage by monsoon thunderstorms. The combination of high wind events and intense cloud-to-ground lightning activity can

Table 1. Monthly average total precipitation (inches) from National Weather Service Cooperative Observer stations from across Arizona. (Data from Western Regional Climate Center, <http://wrcc.dri.edu>)

Cooperative Observer Station	County	Period of Record	July	August	September	July-August-September Total	Year Total	July-August-September (% of Annual Total)
AGUILA	Maricopa	1924-2004	0.9	1.4	0.75	3.05	8.64	35
AJO	Pima	1914-2004	1.17	1.92	0.84	3.93	8.4	47
ALPINE	Apache	1904-2004	3.61	3.97	2.33	9.91	20.79	48
BAGDAD	Yavapai	1925-2004	1.26	2.2	1.31	4.77	14.42	33
BETATAKIN	Navajo	1948-2004	1.3	1.62	1.13	4.05	11.83	34
BOUSE	La Paz	1952-2004	0.58	0.92	0.57	2.07	5.55	37
BOWIE	Cochise	1899-2004	2.06	2.09	1.04	5.19	10.69	49
GRAND CANYON NATIONAL PARK	Coconino	1948-2004	1.91	2.58	1.67	6.16	25.09	25
CASA GRANDE	Pinal	1898-2004	1.01	1.52	0.79	3.32	8.38	40
CHIRICAHUA NATIONAL MONUMENT	Cochise	1909-2004	4.1	4.08	1.72	9.9	19.23	51
CLIFTON	Greenlee	1893-2004	2.15	2.4	1.64	6.19	13.18	47
CORDES	Yavapai	1948-2004	1.76	2.36	1.66	5.78	15.1	38
DOUGLAS	Cochise	1948-2004	3.85	3.18	1.58	8.61	14.35	60
DUNCAN	Greenlee	1901-2004	1.86	2.09	1.14	5.09	10.7	48
FLAGSTAFF	Coconino	1950-2004	2.46	2.87	1.97	7.3	21.33	34
FREDONIA	Mohave	1948-2004	0.79	1.22	0.7	2.71	9.36	29
GANADO	Apache	1948-2004	1.4	1.64	1.06	4.1	10.54	39
GILA BEND	Maricopa	1892-2004	0.73	1.02	0.52	2.27	6.15	37
GREER	Apache	1948-2004	4.13	4.33	2.24	10.7	22.98	47
HEBER	Navajo	1950-2004	2.73	2.96	1.91	7.6	17.48	43
HOLBROOK	Navajo	1893-2004	1.36	1.52	1.02	3.9	8.46	46
JEROME	Yavapai	1897-2004	2.57	3.11	1.47	7.15	18.59	38
KEAMS CANYON	Navajo	1948-2004	1.21	1.62	0.89	3.72	10.01	37
KINGMAN	Mohave	1901-2003	0.9	1.42	0.98	3.3	10.34	32
KOFA MINE	Yuma	1952-2004	0.84	1.05	0.97	2.86	6.86	42
LEES FERRY	Coconino	1916-2004	0.78	1.04	0.59	2.41	6.2	39
MESA	Maricopa	1896-2004	0.92	1.11	0.81	2.84	8.36	34
NOGALES	Santa Cruz	1952-2004	4.33	4.12	1.57	10.02	17.45	57

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ORGAN PIPE CACTUS NATIONAL MONUMENT	Pima	1948-2004	1.36	1.93	0.93	4.22	9.54	44
RUCKER CANYON	Cochise	1893-2004	4.36	3.85	1.86	10.07	19.17	53
SAFFORD	Graham	1948-2004	1.62	1.62	1.01	4.25	9.05	47
SAINT JOHNS	Apache	1901-2004	2.06	2.19	1.33	5.58	11.23	50
SAN CARLOS RESERVOIR	Pinal	1948-2004	1.61	2.19	1.22	5.02	14.78	34
SAN SIMON	Cochise	1898-2004	1.7	2.06	0.88	4.64	9.56	49
SEDONA	Coconino	1948-2004	1.72	2.1	1.71	5.53	18.05	31
SELLS	Pima	1948-2004	2.69	2.59	1.17	6.45	11.91	54
SNOWFLAKE	Navajo	1897-2004	2.07	2.49	1.42	5.98	12.18	49
SPRINGERVILLE	Apache	1911-2004	2.68	3.04	1.55	7.27	11.98	61
SUPERIOR	Pinal	1920-2004	1.9	2.77	1.5	6.17	18.28	34
TOMBSTONE	Cochise	1893-2004	3.39	3.31	1.53	8.23	13.87	59
TONOPAH	Maricopa	1951-2004	0.56	1.14	0.58	2.28	7.67	30
TUBA CITY	Coconino	1900-2004	0.73	0.85	0.81	2.39	6.55	36
TUCSON (UNIVERSITY OF ARIZONA)	Pima	1894-2004	2.03	2.13	1.17	5.33	11.15	48
WICKENBURG	Maricopa	1908-2004	1.27	1.93	1.14	4.34	11.22	39
WIKIEUP	Mohave	1948-2004	0.82	1.39	0.87	3.08	9.79	31
WILLCOX	Cochise	1898-2004	2.44	2.61	1.17	6.22	12.21	51
WILLIAMS	Coconino	1897-2004	2.83	3.21	1.77	7.81	21.54	36
WINSLOW	Navajo	1898-2004	1.27	1.45	0.95	3.67	7.82	47

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cause transmission lines to fail. One particularly bad summer thunderstorm event in 1996 downed electric power lines across the Phoenix metropolitan region, knocking out power to over 250,000 customers (Haro and Green, 1996). Some customers were without power for over a week.

### Water Resources

Monsoon precipitation can, in rare cases, provide boosts to water storage in reservoirs when thunderstorms are widespread through a watershed and produce large amounts of runoff. Usually thunderstorms are localized and produce runoff that either quickly infiltrates or evaporates. High afternoon temperatures and full sunshine can quickly cause the previous day's rainfall to reenter the atmosphere through evaporation or plant transpiration. Due to these factors, monsoon precipitation typically does little to alleviate long-term drought conditions or improve groundwater or reservoir water levels.

### Agriculture

The arrival of the monsoon often impacts agricultural crop production in a negative way. Precipitation and high relative humidity values create wet conditions that are favorable for the development of insect pests and plant diseases (Olsen and Silvertooth 2001). The high relative humidity values associated with the monsoon can also cause heat stress in plants by reducing the ability of plant leaves to cool themselves through transpiration. The normal features of a thunderstorm (high winds, flooding, hail) also inflict damage directly to crops.

### Range Management

Much of the rangeland in Arizona is populated with grasses that respond to monsoon season precipitation. Summer is the growing season for these native perennial grasses. They rely on monsoon precipitation to support growth and the accumulation of biomass that can be eaten by wildlife and livestock (Cable 1975). A poor monsoon with below-normal precipitation can have significant impacts on the condition of rangelands across Arizona.

### Wildfires

The arrival of significant monsoon rains can also mean a substantial decrease in wildfire activity across the state. The average number of wildfires decreases rapidly in early July, which coincides with the arrival of the monsoon (Mohrle et al. 2003). Precipitation, higher dew points, and lower temperatures can inhibit the growth of new fires and limit the spread of actively burning fires.

## Summary

The North American Monsoon system is an important circulation feature for Arizona due to its control of summer precipitation amounts across the state. Thunderstorm activity during the summer monsoon season can contribute to over half the annual total precipitation over the southeastern and higher elevation areas of Arizona. The northern and low desert portions of the state see little monsoon thunderstorm activity except during large-scale thunderstorm outbreaks. The strongest and

most active portion of the North American Monsoon System is located in Mexico; Arizona is located on the northern periphery of this region. Complex interactions between circulation features and topography interact to guide moisture from this core region of activity into Arizona. The position and strength of these circulation features vary over time (during the summer season and from year to year), leading to high variability in precipitation amounts received across Arizona during the summer monsoon season.

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