

Climate Change in the Southwest

Introduction

The overall climate of the Southwest—its weather patterns over a long period of time—tends to be warm and dry. But records of past climate show that southwestern climate is also highly variable, both across the landscape and over time. Annual temperatures and precipitation tend to be very different from one year to the next, and the Southwest has also seen major climate shifts that have lasted for centuries; for example the Southwest dried out significantly over the entire period between AD 1000 and 1450 in a series of epic droughts known as the medieval megadroughts.

Now another shift in climate is happening, but this time most climate scientists think that people, not natural processes, are driving the shift. Human activity, such as the burning of fossil fuels, is releasing greenhouse gases like carbon dioxide and methane into the atmosphere. The build-up of these gases over time is leading to a rapid global rise in temperature. Using past and present climate records, scientists have been modeling how increases in greenhouse gases will affect the earth's climate in the future and how a climate shift might affect ecosystems and human society.

Current climate

The climate of the Southwest is most influenced by its geographic location between the mid-latitude and subtropical atmospheric circulation regimes. This positioning leads to year-round warm temperatures, low annual precipitation, and clear skies. However, because of its location near two major moisture sources—the Pacific Ocean and the Gulf of Mexico—the Southwest has two noticeable peaks in precipitation every year. July through September, precipitation comes from monsoonal storms that derive their moisture from both the Pacific Ocean and the Gulf of Mexico, and November through March, the precipitation comes from winter storms originating in the Pacific Ocean (Sheppard et al. 2002). During the months between these peaks, very little precipitation falls.

The influence of the monsoon on total annual precipitation depends upon the location. The monsoon tends to be strongest in northwestern Mexico and weakest towards northern Arizona and New Mexico (Adams and Comrie 1997). Areas south of

OVERVIEW

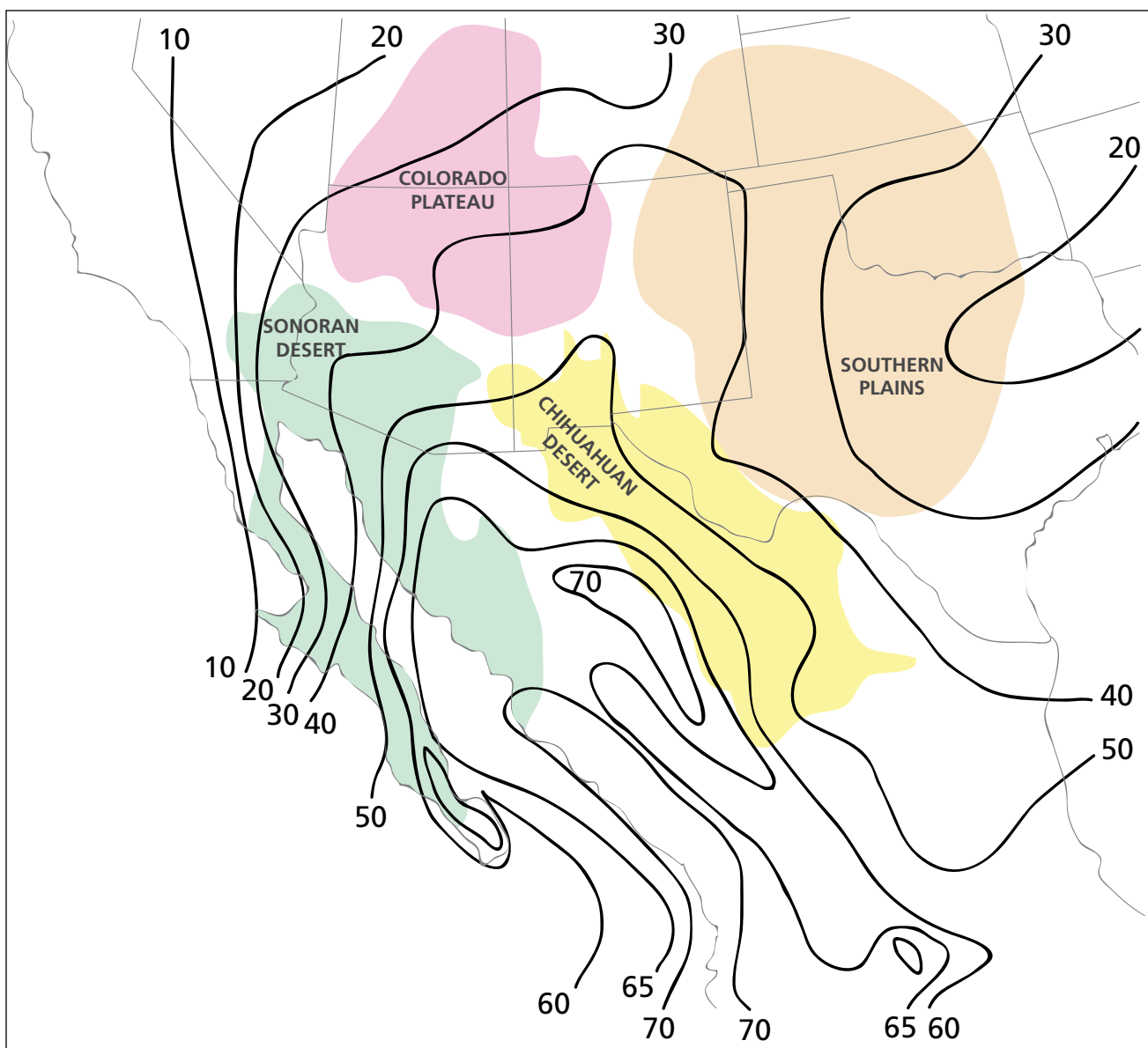


Even small changes in temperature and precipitation can significantly affect the sensitive plants and animals of desert ecosystems.

an imaginary line that runs just north of Tucson and east into New Mexico receive more than 50% of their annual precipitation during July, August, and September (Douglas et al. 1993). The mean northern extent of the monsoon forms a diagonal line through far northwestern Arizona up into Utah and Colorado (Mitchell 1976). Between this line and the line just north of Tucson, precipitation peaks in both the winter and the summer. North of this line, precipitation is spread evenly over the year (Comrie and Glenn 1998). The strength of the monsoon varies from year to year, but researchers are currently unsure why (Adams and Comrie 1997).

Winter storms, in contrast to monsoonal storms, cause widespread precipitation over a large geographical area, affecting distinct locations similarly. The amount of winter precipitation that the Southwest receives in a given year strongly depends on the sea surface temperatures in the Pacific Ocean. During El Niño years (periods when the sea surface temperatures of the eastern Pacific Ocean near the equator are warmer than normal), the Southwest experiences wetter winters. The opposite is true of La Niña years (when the sea surface temperatures of the eastern Pacific Ocean near the equator are cooler than normal). Winter precipitation is also influenced by the Pacific Decadal Oscillation (PDO), a climate pattern that can last for several decades when the temperatures in the north-eastern Pacific Ocean are warmer or cooler than usual. When





The influence of the monsoon on summer precipitation decreases from south to northwest (after Douglas et al. 1993). The dark lines show the percentage of annual precipitation that falls during July, August, and September.

the temperatures are warmer, known as the positive phase of the PDO, the Southwest experiences wetter winters. The effects of El Niño tend to be even stronger during the positive phase of the PDO, and the effects of La Niña tend to be even stronger during the negative phase of the PDO (Sheppard et al. 2002).

Regional climates

Because of the extremes in topography in the Southwest and its position between two major atmospheric circulation regimes, the climates of particular locations in the Southwest can be quite distinct from one another. The Sonoran and Chi-

huahuan Deserts experience milder winters and hotter summers than the Colorado Plateau since the Colorado Plateau is on average several thousand feet higher in elevation than the Sonoran and Chihuahuan Deserts. The Southern Plains, which are at about 7,000 feet in elevation in the northwest and about 1,000 feet in elevation in the southeast, likewise show a gradient in winter temperatures from colder in the northwest to warmer in the southeast. Summer temperatures do not show this gradient and are on average only slightly cooler than the adjacent deserts.

The average precipitation that falls on the deserts, the plateau, and the plains differs as well. The Sonoran Desert receives 3

to 20 inches annually, and the Chihuahuan Desert receives 6 to 20 inches annually, while the Colorado Plateau receives 10 to 35 inches in a year. The ranges for average precipitation are so wide because each region features mountain ranges that are colder and wetter than the surrounding areas. The two deserts receive their precipitation at different times of the year: summer and winter for the Sonoran Desert, but only during the summer for the Chihuahuan Desert. The western edge of the Southern Plains is also dry, but the plains become wetter towards the east. Precipitation in the Southern Plains averages 12 to 39 inches, mostly falling from April through September.

Past climate

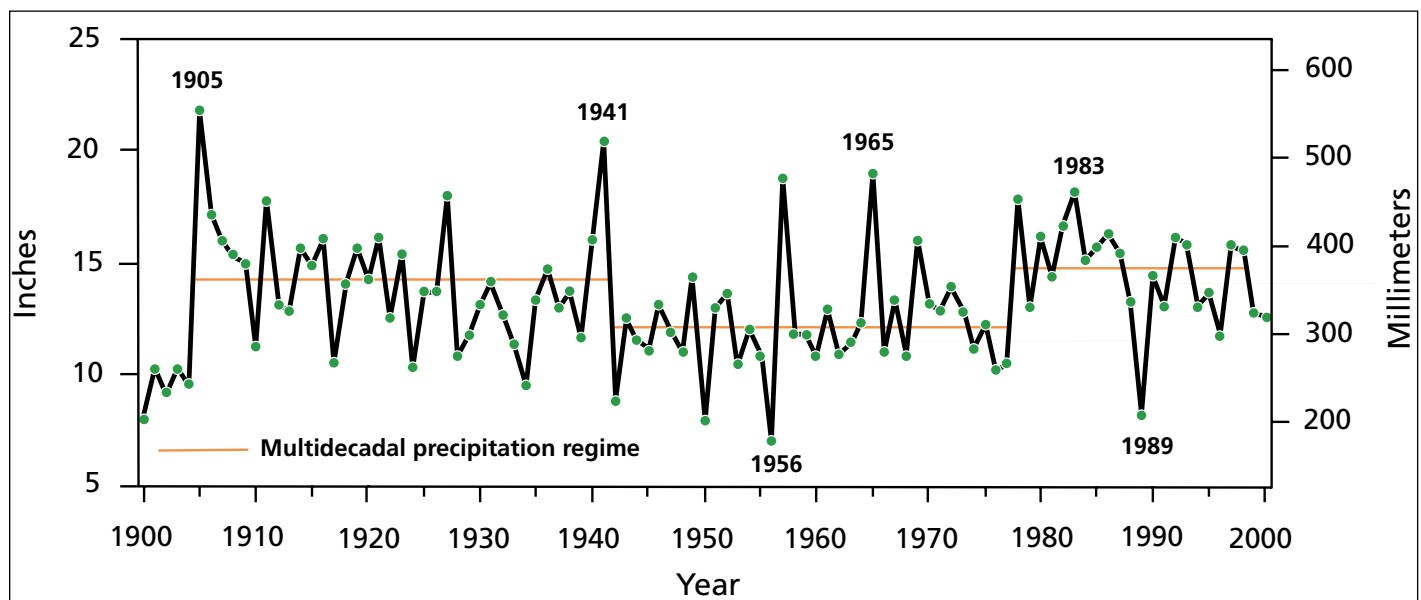
Not only is the climate of the Southwest variable across the landscape, but it has varied substantially across years, decades, and centuries, as well. The instrumental record, which covers about the past 100 years, shows that average temperatures and precipitation amounts have swung back and forth between years. For example, in 1941 the Colorado Plateau received over 20 inches of rain, but the next year it received less than 10. The instrumental record also shows that during the 20th Century, the Southwest experienced extended dry and wet periods. For example, while the period between 1905 and 1930 was unprecedently wet (Sheppard et al. 2002), the period between 1942 and 1956 was very dry.

To understand the full range of natural climate variability in the Southwest, scientists use several types of proxy records—mainly tree-ring records—to extend the climate record back thousands of years. Annual tree-rings grow in proportion to the

amount of summer precipitation, so tree-ring records are used throughout the Southwest to reconstruct past dry and wet periods. The tree-ring records show that although past droughts were of about the same severity and affected the same amount of land area as droughts in the instrumental record, these past droughts lasted for much longer (Herweijer et al. 2007). One of these droughts was centered around AD 1150 (Cook et al. 2004, Ni et al. 2002, Salzer and Kipfmüller 2005). Another widely recorded drought occurred in the late 1200s and lasted for several decades (Grissino-Mayer 1996, Ni et al. 2002). Scientists have speculated that this drought was responsible for the collapse of the Ancient Puebloan culture in the region, but this hypothesis is now hotly debated (Woodhouse 2004).

Global climate change

The Intergovernmental Panel on Climate Change (IPCC), the group of scientists who issue comprehensive assessments on climate science and were awarded the 2007 Nobel Peace Prize for their work, reports that warming of the earth is unequivocal and that most of the increase in global temperature since the mid-twentieth century is very likely due to an increase in greenhouse gas concentrations (IPCC 2007). Using a range of scenarios for future greenhouse gas emissions and concentrations in the atmosphere, the IPCC has predicted a global temperature rise of 2 to 11.5 degrees by 2099 (Jansen et al. 2007). Although the earth has been warmer in the geological past than its current temperature, global temperatures are currently rising at an exceptionally rapid rate relative to the rate that global temperatures have risen during other times in the geological record (Jansen et al. 2007). Over the next 90 years,



The instrumental record of precipitation on the Colorado Plateau over the past 100 years shows how variable annual precipitation is in the Southwest (from Hereford et al. 2002).

temperatures are projected to rise by the same amount that they rose over a 5,000 year period coming out of the last Ice Age (Jansen et al. 2007). In addition, the current concentration of carbon dioxide (a major greenhouse gas) in the atmosphere is at a record high for the past half-million years (Jansen et al. 2007).

Climate change in the Southwest

The global rise in temperatures will affect different locations on earth in unique ways. Scientists have identified the Southwest as a climate change hotspot—an area whose climate is particularly vulnerable to an increase in greenhouse gases in the atmosphere (Diffenbaugh et al. 2008). The models used by the US Global Change Research Program indicate that the average annual temperature in the Southwest may increase by 4 to 10 degrees, compared to temperatures between 1960 and 1979. Atmospheric circulation patterns are likely to change, causing southwestern climate to become more arid overall (Christensen et al. 2007, Seager et al. 2007). The aridity may become much worse during La Niña events, causing droughts that may be more severe than any other droughts seen in the climate record, including the medieval megadroughts (Seager et al. 2007, Dominguez et al. 2009). The Southwest may also experience more frequent and longer-lasting heat waves, and the precipitation that does fall is more likely to come from extreme precipitation events (Diffenbaugh et al. 2005). Human-caused changes in winter climate appear to be happening already: over the past 50 years, natural climate variability alone could account for only 40% of the changes observed in snow pack, winter air temperatures, and spring streams in the West (Barnett et al. 2008). These results indicate that if humans continue to emit greenhouse gases, future climate will continue to be outside the normal range of variability.

The seasonality and variability of the precipitation is likely to shift, too. Because of the effect of greenhouse gas emissions on climate, spring has been arriving earlier over the past 50 years, and this trend is likely to continue (Bonfils et al. 2008, Cayan et al. 2001, Stewart et al. 2004). The dry spring season is expected to begin earlier in the year because models predict that the late-winter storm track over the western United States may weaken and shift northward (McAfee and Russell 2008, Seager et al. 2007). If the dry-season is lengthened, severe droughts may occur more often. Drought effects could be amplified by increased variation in year-to-year winter precipitation. Although this variability has not yet been modeled for the future, it has been analyzed for the past forty years. The analysis found that extreme reversals in winter precipitation from year to year have increased since 1960 (Goodrich and Ellis 2008). For example, the winter of 2004/2005 was the wettest winter on record, but the winter the following year was

the driest winter on record. Winter precipitation is far easier to predict than monsoon precipitation because winter storms are large and follow storm tracks, but the monsoon storms are localized and their occurrence is influenced by topography. Therefore, current climate models cannot accurately predict the effect of climate change on the monsoon (Lenart 2007).

Potential climate change impacts

Water

Snowpack is a critical source of water in the Southwest, slowly releasing melted snow to streams and rivers over the dry spring and summer. The impact of climate change on snowpack and spring streamflow in the Southwest appears to be distinct from the rest of the western United States. While the rest of the West has been experiencing reduced snowpack, more winter precipitation in the form of rain, and earlier spring stream flows over the past 50 years, the Southwest has been experiencing the opposite (Knowles et al. 2006, Mote et al. 2005, Regonda et al. 2005). And while models using climate data from the past 50 years predict that spring snow melt in the West will occur even earlier than it does at present, they also predict that some streams in the Southwest will run later in the season than they currently do (Stewart et al. 2004). However, the climate over the past 50 years was influenced by a shift to a positive phase of the Pacific Decadal Oscillation in 1977. This shift would have enhanced winter precipitation over the Southwest relative to the drought years of the 1950s, especially during El Niño years, and reduced winter precipitation over the rest of the West. The clear delineation in climate patterns in recent decades between the northern half of the West



Changes in the timing and amount of precipitation could eliminate the ephemeral lakes and spring pools that are often the only source of water in the desert, like this spring-fed marsh at Tuzigoot National Monument.

and the Southwest is an indication of an El Niño influenced climate (Regonda et al. 2005). Because other models predict drier winters and earlier springs for the Southwest (McAfee and Russell 2008, Seager et al. 2007), the current trends in winter climate might reverse.

The rivers, streams, springs, wetlands, reservoirs, and lakes of the Southwest are sensitive to changes in the timing, amount, and predictability of precipitation. For the streams, a small change in average annual precipitation can greatly affect the surface flow. If late winter or spring moisture falls as rain rather than snow, catastrophic flooding could occur and the snowpack would be removed earlier, which would increase the susceptibility of these streams to extreme drying later in the year. While the aquatic communities are already disturbance prone and very resilient, larger-scale changes in the geomorphology of the stream channels, like arroyo-cutting, would have profound consequences for ecosystem structure and functioning. For the lakes, playas, and wetlands, changes in evaporation rates would alter electrolyte concentrations and chemistry. Also, decreased runoff would eliminate the ephemeral lakes and spring pools that are so important for supporting a diversity of animals and plants in the desert (Grimm et al. 1997). Warmer water temperatures and increased salinization may increase the likelihood that nonnative aquatic species will invade (Rahel and Olden 2008).

Vegetation

Vegetation shifts

Because water is the most limiting resource in arid ecosystems, even subtle changes in precipitation could lead to species migrations and re-shuffling of plant communities. For example, severe droughts can very swiftly shift the composition of a forest. During the 1950s drought, massive vegetation die-offs occurred over a variety of ecosystems in the Southwest (Swetnam and Betancourt 1998), and researchers have documented that pinyon-juniper woodlands at one site in the Jemez Mountains, New Mexico, completely converted to a ponderosa pine forest over a distance of 1.2 miles (Allen and Breshears 1998). This vegetation shift has endured for 40 years. The 2002-2003 drought, which was warmer than the 1950s drought, combined with a subsequent attack by bark beetles, caused extensive mortality of pinyon pines over 7,500 mi² across the Southwest, even on moister high-elevation sites (Breshears et al. 2005). Over the entire western United States, mortality rates of overstory trees have been increasing in 87% of unmanaged forest plots, and these mortality rates are expected to double in 29 years for forests in the interior West (van Mantgem et al. 2009). Regional warming and consequent drought stress are the most likely explanations for why the



High-elevation ecosystems, like this mixed-conifer forest, are particularly sensitive to a warming climate.

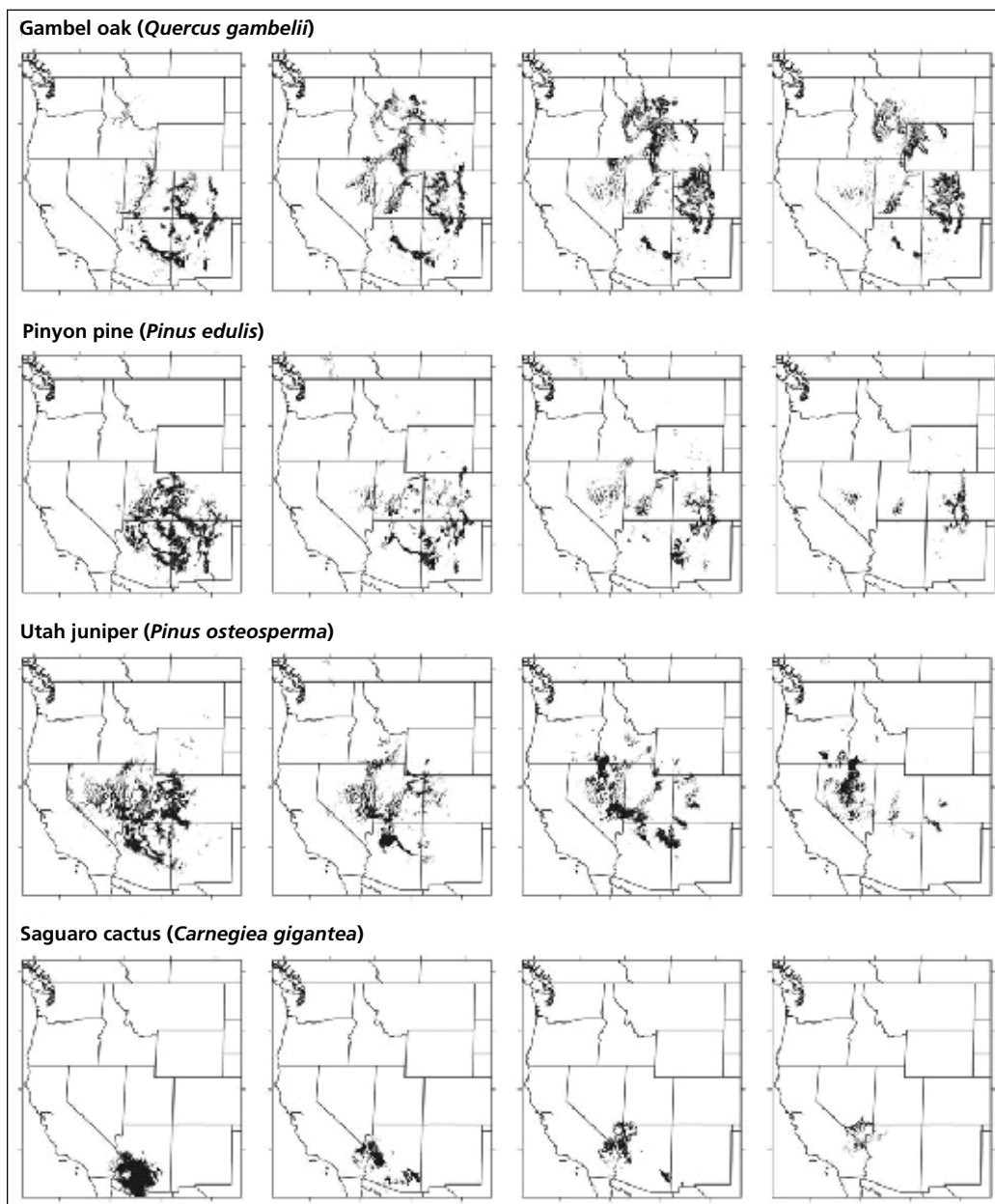
trees are dying (van Mantgem et al. 2009). However, tree mortality can also occur during wet periods: although bark beetle outbreaks occur during droughts, spruce budworm outbreaks occur during wet conditions (Swetnam and Betancourt 1998).

Not only does the total amount of precipitation over a year influence plant communities, but when the precipitation falls affects them, too. In much of the Southwest, the balance between winter and monsoonal precipitation determines whether perennial grasses or woody vegetation predominates. For example, at a site in the Chihuahuan Desert in southeastern Arizona, increases in winter precipitation correlated with shrub expansion into grasslands (Brown et al. 1997). Future changes in the seasonality of precipitation can be expected to alter the composition of plant communities.

Warming, regardless of precipitation changes, can also affect plant communities. In montane ecosystems, warming is expected to cause plant species to shift upwards in elevation. In southern California, this shift is already happening. Between 1977 and 2007, dominant plant species in the Santa Rosa Mountains shifted upwards in elevation by about 65 m (Kelly and Goulden 2008). Warming may also affect the distribution of desert plants because of their sensitivity to freezing. Since the lower boundary of the Sonoran desert may be where freezes never happen and the upper boundary may be where freezes last less than 24 hours, warming temperatures would allow thorny shrubs and scrub trees from further south to establish in the current boundaries of the Sonoran desert, and the Sonoran desert would expand northward, eastward, and upward in elevation (Weiss and Overpeck 2005). From 1960 to 2000, the number of days below freezing has already decreased (Weiss and Overpeck 2005).

Over a larger scale, these subtle impacts to plant communities may cause extensive changes, both to the distribution of whole plant communities and to individual species. One study modeled the future distributions of vegetation in the West if unmitigated climate change continues (Rehfeldt et al. 2006). The study found that over the current century, grasslands and montane forests would increase, largely at the expense of arid woodlands, and subalpine, alpine, and tundra communities. The whole plant communities would not migrate together; instead, the range shift of each species would be unique. Of the nine species studied, Gambel oak (*Quercus gambelii*) would increase in area, and the area occupied by Douglas-fir (*Pseudotsuga menziesii*) would remain constant, but the other spe-

cies, notably western larch (*Larix occidentalis*), pinyon pine (*Pinus edulis*), Engelmann spruce (*Picea engelmannii*), and Utah juniper (*Juniperus osteosperma*), would decrease drastically in area. The species' ranges would shift both in elevation and in latitude and longitude. For example, the range of the saguaro cactus (*Carnegiea gigantea*) is projected to rise in elevation by 2000 ft and to shift northward by 310 miles, so that its range will shift to southern Nevada. By the end of this century, approximately 55% of the western landscape would experience climates incompatible with the vegetation located there today. Therefore, the plant communities in these areas would have no contemporary analogue in the region, and it would be impossible to predict the exact composition and dis-



Modeled future distribution of four plant species in the years 2000, 2030, 2060, and 2090 (left to right) (from Rehfeldt et al. 2006). While Gambel oak would increase in area if unmitigated climate change continues, the area occupied by pinyon pine and Utah juniper would decrease dramatically. Saguaro cactus would shift northward into Nevada.



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The 2002 Rodeo-Chediski Fire, which followed four years of drought, was the largest fire in Arizona's recorded history. Areas of the ponderosa pine forest that had received fuel-reduction treatments or had been thinned experienced only surface fires, while the areas that had not been treated experienced crown fires, which are not typical of the fire regime in ponderosa pine forests. Future drought could lead to more frequent severe fires in unmanaged ponderosa pine forests.

tribution of future plant assemblages over the West (Rehfeldt et al. 2006).

Fire

The interaction between climate and fire may further alter vegetation communities. The effect that climate change will have on fire regimes strongly depends on the vegetation type—fires in particular vegetation types can be limited by fuel moisture or fuel availability, or both. For example, spruce-fir forests, which are relatively wet forests, naturally experience infrequent, high-severity fires, usually during drought. Therefore a shift to more arid conditions would result in more severe fires (Schoennagel et al. 2004). The fire severity in mixed conifer forests, which typically occur along a complex moisture gradient on elevations between spruce-fir forests and ponderosa pine forests, is controlled by both climate and fuel availability. Drier conditions would result in a mosaic of fire effects on the landscape, where the fire regimes of the wetter sections of the forests would be more influenced by extended drought (Schoennagel et al. 2004). Ponderosa pine forests, which are typically drier and occur at lower elevations than spruce-fir

and mixed-conifer forests, historically experienced frequent, low-intensity fires that were limited by the availability of fine fuels. However, 20th century fire suppression has resulted in increased tree density; therefore the fires that occur are high-severity, stand-replacing fires (Schoennagel et al. 2004). The fire regimes in pinyon-juniper woodlands are not as well-studied as the fire regimes in higher elevation plant communities. Large, stand-replacing fires in pinyon-juniper woodlands have been occurring more frequently since the 1980s, but not enough evidence on historical fire regimes exists to determine whether this increase in large fires is due to climate (Romme 2009). While the recent increased frequency of large wildfires across the West is associated with earlier spring snowmelts or spring or summer temperatures, this is not the case in the Southwest, likely because extended drought is not the only influence on severe fires in the major forest types of the region (Westerling et al. 2006).

The effect that climate change will have on fire regime will also depend upon the climate variability from year to year. In the past, climate variability has influenced the outbreak of fires across the Southwest. From analyzing the fire scars in

tree-ring records spread over Arizona and New Mexico, researchers have found that synchronous fires across the regions have occurred multiple times, and these fire years coincide with drought, or, in the case of open ponderosa pine forests, a wet year followed by a dry one (Swetnam and Betancourt 1998). Analyses of more recent fires have uncovered the same pattern—in ponderosa pine forests, and in dry shrublands and grasslands, wet conditions in the years prior to the fire year influence the fire severity more than drought conditions in the year of the fire (Littell et al. 2009, Westerling et al. 2003). The reason may be that during the wet years, fine fuels accumulate (Swetnam and Betancourt 1998). Unlike in spruce-fir forests, fires in ponderosa pine forests and in grasslands feed off of fine fuels, like grasses and needle litter. These studies of fire history in the Southwest indicate that a warmer and drier climate may not necessarily cause more severe fires; instead the effect that climate has on individual fire regimes will depend upon the vegetation type, the overall aridity, the interannual variability of precipitation, the seasonality of the precipitation, and how the forests are managed.

Conclusion

Records of past climate show that the Southwest's climate has been highly variable over time, but now human activity is altering that climate to an unprecedented state. Climate models project that the Southwest will become even warmer and more arid than it is today. Because water is such a limiting resource for life in desert environments, a more arid climate could profoundly impact southwestern ecosystems and human society. This overview describes only some of those potential impacts to ecosystems in the Southwest. Because any impact to a part of an ecosystem can affect the whole, climate change impacts can cascade, indirectly affecting the biological processes of many different organisms. In addition, different impacts can interact with each other and compound the effects of climate change. For example, in the Sonoran desert, the combination of grasses invading the desert and an increased frequency of fires could devastate saguaro cacti. While scientists may not be able to forecast the exact impacts of climate change, human-induced climate change will clearly have consequences for the arid Southwest.

References

- Allen, C. D., and D. D. Breshears. 1998. Drought-induced shift of a forest-woodland ecotone: rapid landscape response to climate variation. *Proceedings of the National Academy of Science* 95: 14839-14842.
- Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. *Science* 319: 1080-1083.
- Bonfils, C., B. D. Santer, D. W. Pierce, H. G. Hidalgo, G. Bala, T. Das, T. P. Barnett, D. R. Cayan, C. Doutriaux, A. W. Wood, A. Mirin, and T. Nozawa. 2008. Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate* 21: 6404-6424.
- Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Princes, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Science* 102(42): 15144-15148.
- Brown, J. H., T. J. Valone, and C. G. Curtin. 1997. Reorganization of an arid ecosystem in response to recent climate change. *Proceedings of the National Academy of Science* 94: 9729-9733.
- Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82(3): 399-415.
- Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C. G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton. 2007. Regional climate projections. Pages 847-940 in Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Comrie, A. C., and E. C. Glenn. 1998. Principal components-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability. *Climate Research* 10: 201-215.
- Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-term aridity changes in the western United States. *Science* 306: 1015-1018.
- Diffenbaugh, N. S., F. Giorgi, and J.S. Pal. 2008. Climate change hotspots in the United States. *Geophysical Research Letters* 35: L16709.
- Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, F. Giorgi, and S. H.

- Schneider. 2005. Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of the United States of America* 102(44): 15774-15778.
- Dominguez, F., J. Cañon, and J. Valdes. 2009. IPCC-AR4 climate simulations for the Southwestern US: the importance of future ENSO projections. *Climatic Change*: published online October 10, 2009.
- Douglas, M. W., R. A. Maddox, and K. Howard. 1993. The Mexican monsoon. *Journal of Climate* 6: 1665-1677.
- Goodrich, G. B., and A. W. Ellis. 2008. Climatic controls and hydrologic impacts of a recent extreme seasonal precipitation reversal in Arizona. *Journal of Applied Meteorology and Climatology* 47: 498-508.
- Grimm, N. B., A. Chacon, C. N. Dahm, S. W. Hostetler, O. T. Lind, P. L. Starkweather, and W. W. Wurtsbaugh. 1997. Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the Basin and Range, American Southwest and Mexico. *Hydrological Processes* 11: 1023-1041.
- Herweijer, C., R. Seager, E. R. Cook, and J. Emile-Geay. 2007. North American droughts of the last millennium. *Journal of Climate* 20: 1353-1376.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Summary for policymakers *in* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jansen, E., J. Overpeck, K. R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba and D. Zhang. 2007. Pages 434-497 *in* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. *Global change impacts in the United States*. United States Global Change Research Program. Cambridge University Press, New York, NY, USA.
- Kelly, A. E., and M. L. Goulden. 2008. Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Science* 105(33): 11823-11826.
- Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate* 19: 4545-4559.
- Lenart, M. 2007. Global warming in the Southwest: projections, observations and impacts. *Climate Assessment for the Southwest*, Institute for the Study of Planet Earth, Tucson, AZ.
- Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. *Ecological Applications* 19(4): 1003-1021.
- McAfee, S. A., and J. L. Russell. 2008. Northern Annular Mode impact on spring climate in the western United States. *Geophysical Research Letters* 35: L17701.
- Mitchell, V. L. 1976. The regionalization of climate in the western United States. *Journal of Applied Meteorology* 15(9): 920-927.
- Mote, P. W., A. F. Hamlet, M. P. Clark, and D. Lettenmaier. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86(1): 39-49.
- Ni, F., T. Cavazos, M. K. Hughes, A. C. Comrie, and G. Funkhouser. 2002. Cool-season precipitation in the southwestern USA since A. D. 1000: comparison of linear and nonlinear techniques. *International Journal of Climatology* 22: 1645-1662.
- Pierce, D. W., T. P. Barnett, H. G. Hidalgo, T. Das, C. Bonfils, B. D. Santer, G. Bala, M. D. Dettinger, D. R. Cayan, A. Mirin, A. W. Wood, and T. Nozawa. 2008. Attribution of declining western U.S. snowpack to human effects. *Journal of Climate* 21: 6425-6444.
- Rahel, F. J., and J. D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* 22(3): 521-533.
- Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate* 18: 372-384.
- Rehfeldt, G. E., N. L. Crookston, M. V. Warwell, and J. S. Evans. 2006. Empirical analyses of plant-climate relationships for the western United States. *International Journal of Plant Sciences* 167(6): 1123-1150.
- Salzer, M. W., and K. F. Kipfmüller. 2005. Reconstructed

temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, U.S.A. *Climatic Change* 70: 465-487.

Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience* 54(7): 661-676.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. Huang, N. Harnik, A. Leetmaa, N. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316: 1181-1184.

Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21: 219-238.

Swetnam, T., and J. L. Betancourt. 1990. Fire-southern oscillation relations in the southwestern United States. *Science* 249: 1017-1020.

Swetnam, T., and J. L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* 11: 3128-3147.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* 62: 217-232.

van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fule, M. E. Harmon, A. J. Larson, J. M. Smith, A. H. Taylor, and T. T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323: 521-524.

Weiss, J. L., and J. T. Overpeck. 2005. Is the Sonoran Desert losing its cool? *Global Change Biology* 11: 2065-2077.

Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger. 2003. Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society* 595-604.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313: 940-943.