sonorensis

Arizona-Sonora Desert Museum

Climate Change

Winter 2004

sonorensis
Arizona-Sonora Desert Museum

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The Arizona-Sonora Desert Museum
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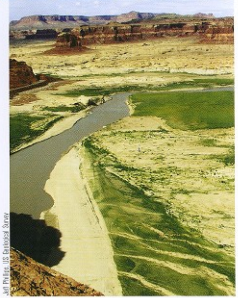


Jeff Phillips, US Geological Survey

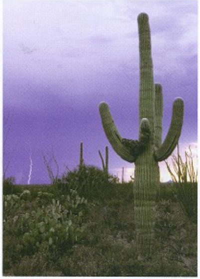
Introduction

In the movie ***The Day After Tomorrow,*** a sudden climate change into another ice age causes a tidal wave to inundate New York and freeze instantly. Once again, Hollywood ruined an interesting theme by its ignorance of science. The laws of physics preclude the "flash glacier" and most of the other disasters in the movie. But the theme is a good one because equally horrific climatic disasters are possible; they just wouldn't happen quite as fast.

Consider current reality. A drought began in 1998. Events in the Atlantic and Pacific Oceans suggest the possibility of a megadrought that could last another 15 to 20 years. In the Southwest, many of our most common plants – bursage, jojoba, palo verde trees – died during the nearly rainless year of 2001. Because of poor snowfall in the Rocky Mountains and consequently low flow in the Colorado River, Lake Powell and Lake Mead are now at all-time low water levels and are less than half full.

Uncertainty is at the core of current climate modeling; the drought could end next year. But if it continues our future could be a nightmare. According to Colorado River water managers, the reservoirs could fall below the level of the aqueduct intakes by 2007. A widespread drought would produce similar results on the other rivers that supply water for cities and agriculture. The Salt and Verde rivers would go dry. Phoenix and Tucson would have to increase use of CAP water, but Arizona takes the first hit if Colorado River water deliveries are below 7.5 million acre feet. Then Phoenix and Tucson would have to rely on ground water, which would increase land subsidence that could result in massive damage to buildings. ▶

Josh Schachter



Jim Honcoop

Jeff Phillips

In a prolonged drought the Sonoran Desert would change dramatically. Most of the palo verde trees, jojoba, bursage, and saguaros would die; most of the montane forests would burn to the ground. (There is precedence for this – it actually happened during past droughts in the 12th and 16th centuries. The Hohokam culture vanished during such a period.) Cities would enact draconian water rationing. The landscapes in parks, resorts, and home gardens would die (including most xeriscapes). Tourism would crash. Industries that use water would lay off much of their work force. The economies of the desert states could collapse.

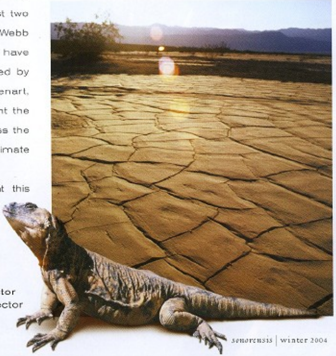
Isn't this just as scary as the events in ***The Day After Tomorrow?*** Can we predict and plan for such a crisis and avoid the fate of the Hohokam if the worst really happens? Even a modest climate change will have major effects on our lives. It bears directly on such issues as our flood and fire insurance rates, our water and electrical bills, and the probability of a good wildflower bloom or pleasant weather on the day of the family picnic.

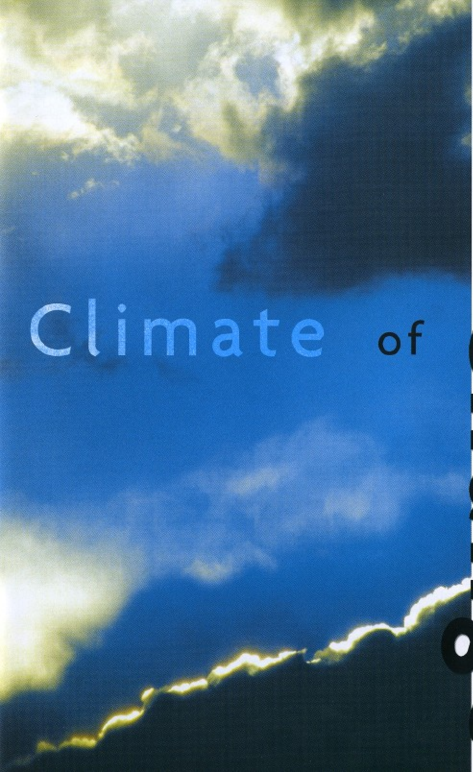
Has a long-term climate change begun? Consider this. In the summer 2003 European heat wave 15,000 people died in France alone, and even Britain recorded over 2,000 heat-related "excess deaths" during the month of August. A group of German scientists calculated that the statistical probability of such an event was 0.0001 – in other words, a heat wave on the magnitude of 2003 should only happen once ever 10,000 years! Every year the number of deaths due to "tropical diseases" climbs (e.g., malaria, dengue, pathogen-based diarrhea) as warm climes and tropical pathogens extend their ranges northward. Dengue has pushed itself nearly to the Arizona-Sonora border, and this year thousands of cases are expected to be reported in Hermosillo. In Alaska, spruce bark beetles have killed 2.3 million acres of trees since 1992, the worse insect outbreak ever to hit North American forests, and it is directly related to higher temperatures. The threshold of thermal tolerance is already being crossed for tropical coral reefs, which suffer "coral bleaching" when sea surface temperatures get too high. Bleaching reached epidemic proportions in the 1998 El Niño event, when a sixth of the world's coral reefs were destroyed. And, as the permafrost melts in Alaska and northern Canada, more and more buildings are collapsing into the softening soil. A recent paper in the prestigious science journal ***Nature*** (by Chris Thomas and his colleagues) concluded that 20-30 percent of the earth's species could be wiped out by global warming as soon as 2050. Even if all greenhouse gas emissions stopped tomorrow, most models predict that the climate would continue warming for decades into the future – probably by double that experienced over the last century. This would make the planet hotter than at any time since the end of the last ice age. In fact, the upper range of global warming estimates is higher than anything experienced in the last 40 million years, and well outside the temperature range ever experienced by humanity or the other species with whom we share this planet. Unlike past warming episodes that ended ice ages, our current situation would take us from an already warm inter-glacial period to an ever hotter world, where temperatures could be outside the evolutionary experience of most living species. It would be short-sighted to ignore these trends.

This issue of ***sonorensis*** summarizes what we know about weather and climate in the Southwest, and what the future may hold for us. Paul Huttner defines the terms weather and climate, and he explains how meteorologists and climatologists measure them. He goes on to describe some of the astronomical phenomena that cause the climate cycles that in turn influence our weather. Tom Van Devender uses the fossil record to describe the tremendous changes in vegetation of the Southwest that have occurred in the past two million years due to climate changes. Robert Webb and Ray Turner document changes that have happened during the past century as revealed by same-site repeat photography. Melanie Lenart, Jonathan Overpeck, and Gregg Garfin present the latest evidence for global warming and discuss the environmental and social consequences of climate change in the Southwest.

The Desert Museum is proud to present this contemporary overview of climate in our region. We hope our readers find this issue both engaging and informative.

Mark A. Dimmitt, Director of Natural History
Richard C. Brusca, Executive Program Director
Robert Edison, Executive Administrative Director





Climate of Change

Paul Huttner | Chief Meteorologist, KGUN-TV

The phone rings in the weather office at KGUN9 TV. "9-Weather. This is Paul. May I help you?" "Hi Paul, this is Mary. We're going on a trip to France next month and I wanted to know how we should pack? What is the weather like in Paris in September?"

I get these calls frequently. It may appear the answer to Mary's question is a simple one, but we all know appearances can be deceiving. You see, Mary isn't really asking about the *weather* in Paris in September. Even if she was, I couldn't forecast with any hope of accuracy beyond 10 days. What Mary really wants to know is; what is the *climate* of Paris in September?

"Climate Is What You Expect, **Weather Is What You Get."**

Robert A. Heinlein had it right. For Mary we might say; "*Climate* tells you how to pack, *Weather* tells you what to wear!"

Weather is what I do every day. What's the current temperature? Is it going to rain today? How strong will the wind blow tomorrow? I'm a *meteorologist*. I work with current and predicted weather conditions for the next few days.

Climate is essentially the sum of all those weather variations over time. Climate is the average of all weather conditions occurring in a given area over many years. Climate can tell you what crops to plant, and when. There are many ways to define climate. Renowned climatologist Helmut Landsberg's climate definition seems to cover all the bases:

> "The sum total of the meteorological elements that characterize the average and extreme condition of the atmosphere over a long period of time at any one place or region of the earth's surface."

So where meteorologists are focused on weather over a period of days or weeks, *climatologists* study weather variations over long periods of time. The science of climatology is focused on historic records of climate over decades, centuries, even millions of years.

Many people's closest contact with climate information is in daily weather reports on TV. The daily "average" high and low temperatures we show in weathercasts are usually a 30-year average for your city.

The daily "record" high and low temperatures represent a longer time period. This is the record of "official" weather data in your area. In most areas of the U.S. this is over a hundred years. The National Weather Service in Tucson uses records that date back to 1895.

What Makes a **Climate?**

Many factors go into determining the climate of an area. Latitude determines the amount of solar energy. Oceans have a moderating effect on climate. Mid-continent locations create great annual ranges in temperature. Elevation and proximity to mountain ranges also dramatically affect climate.

> There are five different climatic zones ranging from Sonoran Desert at 2,500 feet to the fir-pine forest at 9,000 feet.

Tucsonans are fortunate to be able to experience a wide variety of climatic zones in one hour simply by driving up Mt. Lemmon. There are five different climatic zones ranging from Sonoran Desert at 2,500 feet to the fir-pine forest at 9,000 feet. It's like driving from Arizona to southern Canada in an hour. This is a great example of how elevation affects temperature and precipitation. Generally speaking the air temperature cools 5 degrees for every thousand feet you go up the mountain. That means the climate of Mt. Lemmon is about 30 degrees cooler than Tucson. It also means more than twice as much precipitation in an average year. This climatic difference is why we have beautiful saguaros at the base of the mountain and Douglas firs on top!

Another way Tucsonans see different climatic zones is to drive to San Diego. Both cities share roughly the same latitude and get the same amount of energy from the sun. But San Diego sits on the cool blue waters of the Pacific Ocean. The water temperature much of the year hovers around 60 degrees. That means that while Tucson's average high is a sizzling 101 in June, San Diegans enjoy an average high of just 72 degrees! That's a pretty stark example of how an ocean moderates climate. And it's a big reason why we "Zonies" like to frequent San Diego in summer.

Climates **Change**

In the past 20 years climate researchers have identified some of the mechanisms that cause short-term climate shifts. These shifts may last from several months to 20 or 30 years. Here are two of the best-known mechanisms for short-term climate change.

ENSO (El Niño-Southern Oscillation)

Flood in California? Blame it on El Niño. Mild winter in the Midwest? Thanks El Niño! It's probably the most used term by media when it comes time to explain why the weather's gone wacky in some part of the world. El Niño, and his sister La Niña are very real, and they do affect weather patterns across wide areas of the globe. But they are not technically weather patterns themselves. Instead they describe a warming (El Niño) or a cooling (La Niña) of ocean temperatures in the tropical Pacific Ocean. In an ENSO neutral phase ocean temperatures are said to be "near normal."

El Niño comes along on average every 3 to 5 years. This tends to produce wetter winters for the southern U.S., including Arizona. The opposite phase, La Niña tends to keep us warmer and drier in the winter.

PDO (Pacific Decadal Oscillation)

It turns out El Niño has a big brother in the North Pacific. It's called the PDO, and it lasts a lot longer than ENSO periods do. ENSO phases usually last 6 to 18 months. PDO phases stick around 20 to 30 years. Evidence suggests the PDO affects climate in the Pacific Northwest and other areas of the U.S.

Fisheries scientist Steven Hare from the University of Washington coined the term "Pacific Decadal Oscillation" in 1996 while researching connections between Alaska salmon production cycles and Pacific climate.

Like ENSO, the PDO has two phases, warm and cool. There is evidence to suggest that the PDO flipped from the warm phase to a cool phase in 1998. As you will see elsewhere in this issue, this change

Jim Honcoop

has climatologists in the Southwest concerned about the possibility of long-term drought.

Researchers do not understand the causes of ENSO and the PDO. Are they really just symptoms of other mechanisms at work? Could geothermal activity on the ocean floor play a role in changes in ocean temperatures? In science each new answer usually brings new questions. Even if we don't understand the causes, identifying the cycles has value. If we know what the effects are likely to be, we can plan accordingly.

The Long Haul

When we look back many thousands or millions of years we see that climate change is normal, and often follows irregular cycles. But some of these changes are dramatic, shockingly sudden, and last for thousands of years.

As the World Turns

We all know the earth orbits around our sun. But scientists have discovered key variations in the orbital geometry of our planet that may cause dramatic climate shifts.

In the 1920s Yugoslavian engineer Milutin Milankovitch developed a mathematical theory of climate change based on changes in the earth's orbit. Three different elements of the earth's spatial relationship with the sun change in regular cycles.

The Precession of the Equinoxes

Every 23,000 years the earth completes a wobble around its axis called the precession of the equinoxes. This means that *every 23,000 years polar regions of Earth see reduced solar energy.*

◂ *El Nino, which comes along about every three to five years, tends to produce wetter winters in the Sonoran Desert.*

The Earth's Tilt Axis Changes

You may have learned in school that Earth's axis is tilted relative to the sun at 23.5 degrees. But the amount of tilt in Earth's axis changes from 22 degrees to 24.5 degrees every 41,000 years. This means that *every 41,000 years Polar Regions of Earth see reduced solar energy.*

Elliptical Changes in Earth's Orbit

Earth's orbital path changes too. We know that Earth's orbit is shaped like an ellipse. But every 93,000 years our orbit around the sun becomes less elliptical and more circular. When the orbital "stretch" is greatest, we're about 11 million miles farther from the sun. Guess what this means? Yep! This means that *every 93,000 years Earth sees reduced solar energy during parts of our orbit.*

This is complicated stuff and a lot to keep track of, but here's the important part.

These cyclical changes in solar energy appear to be enough to cause Earth's climate to alternate between ice ages and warmer periods.

These warmer times are called "interglacial periods" or "climatic optimums." We're living in one right now.

By most accounts, the last ice age ended about 13,000 years ago. Back then global temperatures were about 10 degrees Fahrenheit colder in summer than today. A sheet of ice nearly a mile thick covered Canada and the northern United States. Imagine the number of "snow birds" that would have flocked to Tucson in those days!

But there have also been times when the earth was much warmer than today. During the Cretaceous period 100 million years ago it's believed the earth was a full 18 degrees Fahrenheit warmer than today! Ocean levels rose hundreds of feet, splitting North America into two continents.

These past climate changes were obviously caused by natural mechanisms, before humans began to change the composition of our atmosphere. There

▲ *During the Cretaceous, the climate in what is now southeastern Arizona was wet and humid; open forest of mixed non-flowering trees covered a large flat river delta. Broad, meandering streams served as highways for large, browsing dinosaurs, while carnivorous forms prowled the water edges for prey. (Artwork by Gary Dixon. Reproduced from ASDMs "Ancient Arizona" exhibit.)*

is evidence that the amount of greenhouse gases have changed naturally in the past. It is also generally accepted as fact that we humans are changing Earth's atmosphere today. The big question is, what effect are the changes we're producing having on climate?

Earth's Climate 2004: Life's a Beach

Our civilization has developed over the years in a relatively warm period between ice ages. Earth's average global temperature these days is about 59 degrees Fahrenheit, pretty comfy by human standards.

There's a lot of talk about "global warming." The discussion gets politically charged very quickly. Let's skip the politics and look at what are generally accepted facts within the scientific community.

The Earth IS Getting Warmer

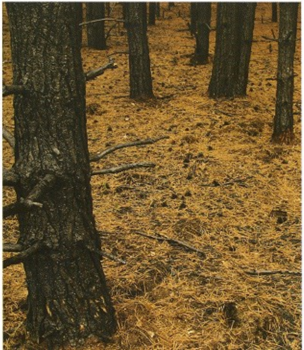
Measurements and best estimates do indicate our planet has warmed about one degree Fahrenheit in the last 100 years.

The year 2003 is expected to go down in history as the third warmest on record, according to the World Meteorological Organination (WMO). The warmest year ever was 1998, and the second warmest was 2002.

Since 1990 we've seen the 10 warmest years on record.

Since 1980 we've seen 19 of the 20 warmest.

▼ *Recent devastating forest fires in Arizona are visible signs of climate change.*



This late 20th century warming is also unprecedented for at least the past millennium. In the Northern Hemisphere, the 1990s were the warmest decade and 1998 the warmest year in the past 1,000 years. Some of the most compelling evidence of this warming comes from data at the University of Arizona Laboratory of Tree-Ring Research.

> During the Cretaceous period 100 million years ago it's believed the earth was a full 18 degrees Fahrenheit warmer than today! Ocean levels rose hundreds of feet, splitting North America into two continents.

While one degree of warming in the past century may not seem like much to you and me, it is significant enough to cause changes around the globe. Some changes may be occurring right in front

▲ *Mountain glaciers world-wide are rapidly retreating. The first photograph shows Montana's Sperry Glacier in 1907. The second shows Sperry Glacier in 2001. (1907 photo by Elrod, USGS. 2001 photo by Lisa McKeon, Glacier National Park Archives.)*

of our eyes. Huge forest fires like the Rodeo-Chedeski and Aspen fires may not just be billowing plumes of smoke in Arizona's mountains. They may be visible signs of climate change in action.

Here are some examples of observed effects of recent climate change around the world. Although some evidence comes through anecdotal observation, other effects can be directly measured.

Large coral reefs in the Pacific are dying off. This appears to be due to increasing ocean temperatures, changes in sea level, and increased sediment runoff as a result of deforestation of some Pacific islands.

Permafrost in Alaska is thawing. Satellite measurements show sea ice is dramatically thinning in the Arctic Ocean. Researchers at the University of Alaska Fairbanks report declining salmon stocks, new diseases and increased forest fires. The Alaska Climate Research Center reports that average annual temperatures in Alaska have increased 2.7 degrees Fahrenheit between 1971 and 2000.

In Venice rising sea levels are causing an increase in the number and severity of floods in the city. In response, the city is planning to spend 3 billion dollars to install 79 huge "sea gates" under the ocean floor that can be raised to hold back the Adriatic in times of flooding.

Mountain glaciers all over the world are retreating (melting) rapidly. The U.S. Geological Survey says South Cascade Glacier in Washington has receded 1.2 miles in the last century. It's lost nearly half its ice in the last 100 years. The Rhone Glacier in Switzerland has retreated 1.5 miles and 1,500 feet higher into the Alps since 1859.

Antarctica's ice shelves have lost 5,000 square miles since 1974 according to the National Snow and Ice Data Center.

◂ *Homes and other structures built in Alaska over permafrost are usually designed to minimize the heat transfer to underlying frozen ground. Although the damage to this structure was probably caused by disturbance and improper protection of the ground ice, this image does convey the potential implications of a warmer climate to infrastructure in permafrost regions. (Photo by Larry Hinzman, Water and Environmental Research Center, University of Alaska Fairbanks.)*

Future Climate: What Happens Next?

So Paul, all this climate stuff is really cool. But what happens now?

This is where things get really interesting. Recently a number of scenarios are racing through the climate world faster than an Arizona wildfire.

Forecast: Toasty Through 2100

Various computer models predict global temperatures will rise anywhere from three to nine degrees Fahrenheit over the next 100 years. In 2000 a team of experts concluded in the report "Climate Change Impacts on the United States" that temperatures in the U.S. could be on the higher end of that average. Most climate researchers agree that continued warming of some magnitude is likely through the year 2100.

As you'll see in this issue, this scenario would have wide ranging impacts on the Southwest. One possibility is a so-called "megadrought" that lasts for more than 10 years. This kind of drought has happened before and some, including U of A's Jonathan Overpeck, believe it may be happening again.

The May/June 2004 issue of *Weatherwise* highlights a study that says the climate of Iowa may change dramatically as soon as the year 2035. By 2095 the summertime climate of Iowa could be 9 to 22 degrees Fahrenheit warmer that today. Imagine taking Des Moines and putting it in northern Mississippi! That kind of warming, and increased possibility of summer drought, could have dramatic impacts on food production.

▾ *Ironwood trees are almost as drought tolerant as the champion creosotebush, but severe droughts can kill even them. Most of the ironwoods in this view are dead or dying. Chuckwalla Valley, CA.*

Mark Dimmitt

Forecast #2:

Instant Climate Change?

Recently, a very interesting and shocking theory has been proposed in climate circles. This theory is called "rapid climate change." Some researchers are suggesting that there are certain climatic thresholds that, when crossed, rapidly trigger sudden and dramatic changes in climate.

Here's how one theory goes. As our planet gets warmer, polar ice continues to melt, injecting fresh water into our oceans. Increased precipitation over land areas and fresh water runoff adds to the effect. The rapid inflow of fresh water reduces the saltiness, or salinity, of our oceans. That changes the density of major ocean currents, like the Gulf Stream, and slows them down abruptly.

The Gulf Stream is a warm ocean current that flows from the Gulf of Mexico, along the East Coast of the U.S., past Canada, Greenland, Iceland, and all the way to Northern Europe. This brings warm water and a tremendous amount of climate warming heat energy to these areas. If the Gulf Stream was to slow down considerably, some believe the effects would be swift and wide ranging.

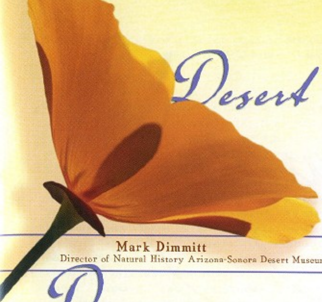
Some believe our current warming is a sign these changes are already underway. In fact a Pentagon report, *An Abrupt Climate Change Scenario* and *Its Implications for United States National Security,* issued in October 2003, urges our government to consider this scenario as a serious national security issue!

Of course Hollywood can't resist this dramatic doomsday scenario. This summer's big catastrophic blockbuster movie *The Day After Tomorrow* brought the "instant ice age" scenario to the big screen. The movie is largely based on the book *The Coming Global Superstorm* written by Whitley Strieber and late night radio host Art Bell. Though the movie is likely overblown in its effects, it may serve to highlight the very real concerns over rapid climate change.

Many climate researchers believe this "instant ice age" scenario is unrealistic. Still, U of A's Julie Cole has found evidence that abrupt changes in the Atlantic during the last ice age did affect Arizona. There is also ice core data from Greenland that shows ice ages in the past have started with shocking suddenness. Some began within a human lifetime. One in as little as 3 years!

Continued rapid warming can also have potentially dire consequences. Another global impact would cause dramatically higher sea levels. This would inundate some coastal areas where millions of people live. It could also result in "mass extinctions," where many plants and animals are not able to adapt to the sudden environmental changes.

The reality is we are all now part of a big climate experiment. Earth is our laboratory. We're changing the atmosphere, and we don't know exactly what the consequences will be. Who knows what kind of weather, or climate, I'll be forecasting in 30 years? S



Desert Wildflowers & PDO— A Connection?

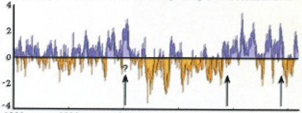
Mark Dimmitt
Director of Natural History Arizona-Sonora Desert Museum

Desert wildflower displays are stunning spectacles that attract tourists from all over the world. But residents know these events are rare: they depend on unusually wet winters. A good bloom of desert annuals happens about once per decade in a given location. In most years one must search to find scattered patches where the rains were above average. In the driest years there are almost no annuals. For more information, see our website's "desert in bloom" section or refer to *A Natural History of the Sonoran Desert*, published by the Desert Museum and The University of California Press.

There have been a few times when the entire desert Southwest from Palm Springs, California to Tucson, Arizona and from Death Valley to central Baja California supported huge carpets of wildflowers. The two most recent massive displays were in 1978 and 1998. (1977 and 1979 were also great years in the western and eastern part of the Southwest, respectively, but less spectacular on the other side.) There was an incredible display in southern Arizona in 1941, but I've been unable to find images that document whether the same thing happened elsewhere in the Southwest.

All four "banner" years occurred at about the time that the Pacific Decadal Oscillation shifted phases (see figure and discussion). 1941 was also close to a shift. Is there a real correlation here?

Monthly values for the POD index: January 1900-December 2003



Arrows indicate desert-wide wildflowers blooms

The graph shows surface temperatures in the northeastern Pacific Ocean, where the PDO is centered. Purple lines above the baseline indicate a positive phase or warmer than average sea temperature and orange lines the negative or cooler phase. During the warm phase the Southwest tends to have wetter winters, which are further reinforced by El Niño events. The arrows indicate massive, widespread displays of desert annual wildflowers.

Between 1941 and 1978 there were a few local displays. This was a cold, dry PDO phase and there were few wet years. Between 1979 and 1998 the warm, wet phase predominated, reinforced by some El Niño events. During this period there were several excellent wildflower years in local areas, but no desert-wide spectacles.

The atmospheric conditions that tend to keep winter storms out of the arid Southwest seem to break down during PDO shifts, allowing storms to roll over the whole area. There isn't enough data to determine whether this is a real link. If it is, expect another super wildflower year when the next phase shift occurs. S

Top: *A small playa near the Sierra Calamajue on the northern Gulf Coast of Baja California. This is a typical spring in this part of the Sonoran Desert; no rain has fallen during the preceeding winter.* **Bottom:** *The same playa after a hurricane storm dumped several inches of rain in one day. (It was the first rain in almost two years.) The lupines are more than a foot tall and completely cover the surface.*

Spanish Version

Tropical deciduous forest near Alamos in southern Sonora.

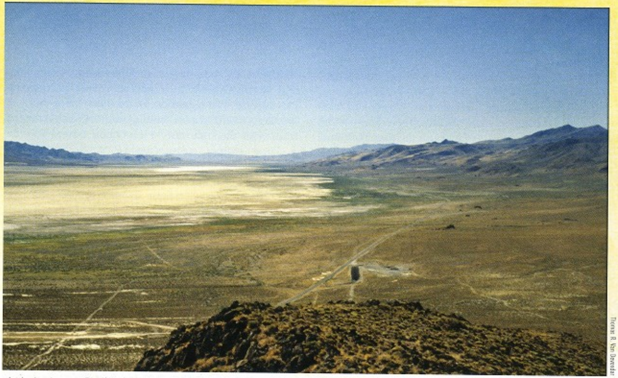
EVER-*changing* LANDSCAPES IN THE SONORAN DESERT

Thomas R. Van Devender | Senior Research Scientist
Arizona-Sonora Desert Museum

The Sonoran Desert is considered to be the most "tropical" of the North American deserts because of its climate with mild winters and summer monsoonal rainfall from the tropical oceans. The scenic foothill palo verde (*Parkinsonia microphylla*)-saguaro (*Carnegiea gigantea*) vegetation in the northeastern Arizona Upland subdivision is structurally similar to thornscrub and tropical deciduous forest to the south, and very different from the treeless shrublands of the Great Basin, Mohave, and Chihuahuan deserts. And indeed the evolutionary roots of many Sonoran Desert plants are in early Tertiary dry tropical forests.

The composition and structure of local communities and regional biotas are shaped by climate. Cold winter air, rainfall, and other features of local weather are imported from distant regions by atmospheric circulation. Extreme climatic events, especially hard freezes and severe droughts, are the most important factors in limiting geographic ranges of organisms. The remarkable transition from temperate zone oak woodlands near Nogales on the Arizona border to Neotropical dry forests near the Spanish colonial town of Alamos in southern Sonora reflects the north to south increase in minimum winter temperatures and summer rainfall. Many tropical plants and animals occur surprisingly far north in eastern Sonora because mountains in the borderlands block the frigid Arctic air masses.

As complex and fascinating as the biota and natural history of the Sonoran Desert Region are today, the fossil record provides us with stories of dynamic landscapes, wondrous beasts, and ever-changing climates that rival tales in children's or fantasy books.



In the last ice age, Pluvial Lake Lahontan filled the modern Winnemuca Lake to 500 feet deep.

Glaciers, Pluvial Lakes, and Ice Ages

On a field trip in the Swiss Alps, a young physician named Louis Agassiz realized that large boulders in an open area (erratics) and long lines of rocky debris (moraines) were dropped by a glacier at some time in the past. In 1840 he published his thoughts on the great Ice Age in an article entitled *Etude sur les Glaciers*. Evidence of montane and continental glaciers was soon discovered in many places in Europe and North America. Although Agassiz was a lifelong opponent of Charles Darwin's theory of evolution, he became a renowned systematist and paleontologist at Harvard University in Boston. The desert tortoise *(Gopherus agassizii)* was named after him.

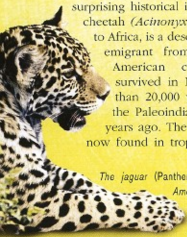
About the same time of Agassiz's discovery, botanists in Europe, and later in the United States, discovered leaves and pollen grains of plants that grow in colder climates today in sediments in seeps and bogs. Tundra once grew in modern boreal forests in Europe, and spruce *(Picea)* forest replaced temperate deciduous forest in North America. Eventually, the last 2.4 million years were recognized as the Pleistocene — the only geologic time period based on climate rather than evolutionary stages of fossil animals. At first, four ice ages were recognized based on terrestrial deposits in Europe, North America, and South America. However, later studies of isotopic climatic indicators (zooplankton) in continuous sediment cores from the ocean floors recorded 15 to 20 glacial/interglacial cycles in the Pleistocene. Ice ages were about ten times as long as the 10,000 to

20,000-yr long interglacials. The present interglacial (the Holocene) began about 13,000 years ago.

In the last glacial period (the Wisconsin), the massive Laurentide ice sheet covered most of Canada, and extended as far south as New York and Ohio. Boreal forest with spruce and pine occurred as far south as northern Louisiana, and in the modern Great Plains as far south as the Panhandle of Texas. In the western United States, glaciers covered the tops of the Rocky Mountains and the Sierra Nevada, and Pluvial Lakes Bonneville and Lahontan were over 500 feet deep. Enough water was tied up in ice on land to lower sea level about 100 meters.

Immigration and Ice Ages

During each glacial period, lower sea levels closed the Bering Strait, uniting Siberia and Alaska as a single region. At the beginning of each interglacial period, the Canadian ice sheet melted, allowing Asian animals to colonize the rest of North America. Sometimes, the fossil record of well-known animals provides surprising historical insight. For example, the cheetah *(Acinonyx jubatus),* now restricted to Africa, is a descendant of a late Pliocene emigrant from North America. The American cheetah *(A. trumani)* survived in North America until less than 20,000 years ago, possibly until the Paleoindians arrived about 13,000 years ago. The lion *(Panthera atrox)* is now found in tropical areas in Africa and southeastern Asia, but was widespread in Europe and North America in temperate forests in the late Pleistocene. The jaguar *(P. onca),* now the symbol of the New World tropics, immigrated to North America from Asia through early Pleistocene boreal forests. A large extinct subspecies *(P. o. augusta)* was widespread in temperate forests in the southeastern United States in the late Pleistocene. Today the jaguar reaches its northern limit in thornscrub and oak woodland in Sonora and Arizona. Other surprises are that camels evolved in North America and later colonized both Eurasia (dromedaries) and South America (llamas), and that hyenas and pandas briefly reached North America from Asia but did not survive. Early Pleistocene hyaena fossils are known from the 111 Ranch near Safford, Arizona, and El Golfo de Santa Clara in northwestern Sonora.

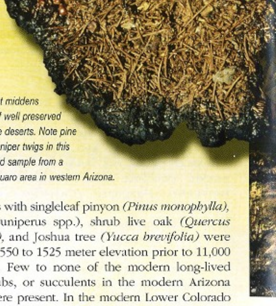


The jaguar (Panthera onca) *immigrated to North America from Asia across the Bering Strait in the early Pleistocene. Today it is the sympol of the New World tropics.*

Packrats as Desert Historians

In 1962, botanist Phil Wells and mammalogist Clive Jorgenson climbed Aysees Peak in southern Nevada in search of relictual junipers or oaks. On the way down, they found a dark, organic mass with a rich conifer aroma in a dry rockshelter — full of juniper twigs! A date of 10,100 radiocarbon years on the sample showed that these *amberrat* deposits were a new source of fossils from the driest deserts in North America. Wells dubbed them packrat (Neotoma spp.) 'middens' — an archeological term for human refuse piles.

In the next 20 years, midden fossils were used to reconstruct vegetation in all of the North American deserts for the last 45,000 years. In the Sonoran Desert in southwestern Arizona, ice age woodlands with singleleaf pinyon *(Pinus monophylla),* junipers (Juniperus spp.), shrub live oak *(Quercus turbinella),* and Joshua tree *(Yucca brevifolia)* were present at 550 to 1525 meter elevation prior to 11,000 years ago. Few to none of the modern long-lived trees, shrubs, or succulents in the modern Arizona Upland were present. In the modern Lower Colorado River Valley, California juniper *(Juniperus californica),* Joshua tree, and creosotebush *(Larrea divaricata)* grew at 240 to 550 meter elevation. Sonoran desertscrub developed in the Holocene as the last woodland plants retreated upward and northward 8000 to 9000 years ago. In the middle Holocene, saguaros and brittlebush were living with catclaw *(Acacia greggii)* and blue palo verde *(Parkinsonia florida).* About 4500 years ago, modern desertscrub formed with the arrival of foothill palo verde, organpipe cactus *(Stenocereus thurberi),* and desert ironwood *(Olneya tesota).*



Ancient packrat middens are a source of well preserved fossils from the deserts. Note pine needles and juniper twigs in this 14,000 year old sample from a palo verde-saguaro area in western Arizona.

Changing Climates in the Sonoran Desert

Fossil plants and animals can provide insights into past climates. Animals such as fish, mud turtles *(Kinosternon* spp.), and amphibians are indicators of aquatic habitats. Fossils are more useful if they can be identified to species, allowing inferences to be based on their

A young white-throated packrat (Neotoma albigula).

The ice age woodlands in the modern Sonoran Desert were dominated by singleleaf pinyon (Pinus monophylla), *various junipers, and Joshua tree* (Yucca brevifolia), *shown above. Saguaro and palo verde didn't return to the area until about 10,500 years ago.*

distribution, physiological tolerances, and natural history habitats. For example, the presence of the sabinal frog *(Leptodactylus melanonotus)* in the Rancho La Brisca Fauna in north-central Sonora 240 kilometers north of the nearest population suggests that interglacial climates 80,000 years ago were more tropical than today. However, extinct species such as horses, mammoths, and camels are less useful because they lived in a broad range of habitats. Packrat midden fossils are usually excellent for paleoclimate reconstructions because they can usually be identified to extant species and are reliably associated with radiocarbon dates.

In the Sonoran Desert, packrat middens older than 9000 year ago consistently contained perennials — now found at higher elevations in woodland or chaparral, or at higher latitudes in the present Mohave Desert — and winter rainfall annuals. These plants reflect paleoclimates with much cooler summers than today, more precipitation from Pacific winter frontal storms, and greatly reduced summer monsoons.

The interpretations of middle Holocene climates have been controversial. Ernst Antevs was a geologist who devised a sequence of climatic periods for the last 10,000 years based on varves (very fine annual layers of sediments) in Swedish lakes. In 1955, he proposed a similar climate chronology for playa lake sediments in a winter-rainfall area in Oregon that was used throughout the West. The anthropological community often invoked the hot, dry Altithermal (7500 to 4000 years ago) climate to explain erosion, population crashes, and other calamities. In 1961 however, Paul Martin concluded from his study of pollen in arroyo sediments that summer rainfall in the middle Holocene was greater than today in southeastern Arizona. In the Puerto Blanco and Tinajas Altas mountains of southwestern Arizona, catclaw and blue palo verde are restricted to desert washes. In the middle Holocene, they grew on rocky slopes, suggesting wetter climates than today in the northeastern Sonoran Desert.

ALTHOUGH SUMMERS HAVE BEEN HOT AND THE SUMMER MONSOONS WELL-DEVELOPED FOR THE LAST 4000 YEARS, CLIMATES CONTINUED TO FLUCTUATE ON VARIOUS TIME SCALES.

Although summers have been hot and the summer monsoons well-developed for the last 4000 years, climates continued to fluctuate on various time scales. Even the youngest midden assemblages the Puerto Blanco Mountains in Organ Pipe Cactus National Monument contained plants not found near the midden rockshelters today, the legacy of freezes or droughts in the last few centuries. One sample dated at 990 years ago had nearly twice the number of species at the site today, suggesting that for a short period rainfall was greater in both summer and winter. Interestingly this was the same time as the Hohokam peoples were thriving in the Phoenix and Tucson areas.

The fossil record has shown us that the Sonoran Desert biota and landscapes have been dynamic for millions of years, responding to climate changes on many different time scales. S

Fossils of the tiny sabinal frog (Leptodactylus melanonotus) *at Rancho La Brisca, 240 kilometers north of its modern range, indicates that the climate of 80,000 years ago was more tropical than today.*

Sonoran desertscrub vegetation is a complex mixture of short-lived herbs that were present in ice age woodland, and trees, shrubs, and cacti that immigrated to the area in the last 11,000 years. These dynamic communities continually respond to climate fluctuations, never reaching equilibrium.

Thomas R. Van Devender

Climate & Vegetation

Change in the Sonoran Desert

The recent drought and death of a variety of desert-adapted species reminds us that climate, and especially climatic fluctuations, are the primary forces shaping the type and density of vegetation that we see around us in the Sonoran Desert. Short-lived species—for example triangle-leaf bursage *(Ambrosia deltoidea)*—suffered widespread death in the Tucson Basin recently, and even longer-lived species, such as creosotebush *(Larrea divaricata tridentata)* and foothills palo verde *(Cercidium microphyllum)* suffered losses. Drought is widely recognized as a mechanism for resetting parts of terrestrial ecosystems, and even though the effects may be more dramatic in forests, drought can kill the hardiest of desert plants.

Drought is but one of the forces changing vegetation in the Sonoran Desert over the last century. Three major wet periods, from about 1880 through 1891, 1906 through 1920, and 1978 through 1995, spurred significant establishment and growth of desert vegetation throughout the Sonoran Desert. Deep droughts, particularly from 1891 through 1904, from the mid-1940s through 1964, and generally since 1996, checked some of this growth. Land uses, particularly fire suppression at upper elevations of the Sonoran Desert, and livestock grazing throughout our region, had significant effects as well. Finally, two on-going changes of current concern – increases in atmospheric carbon dioxide and temperatures – are likely affecting our Sonoran Desert plants.

For the last 40 years, we've used repeat photography to document vegetation change in the Sonoran Desert. After finding the camera stations for more than 500 historical photographs in the region and matching them one or more times, we have made some general conclusions about long-term changes in desert vegetation. The most striking thing we've seen is that the landscapes surrounding us continually change, in ways that are startling even to us. The Sonoran Desert is not unchanging, and we should not ascribe every change we see to the hands of humans.

Robert H. Webb, Hydrologist & Raymond M. Turner, Retired Biologist
U.S. Geological Survey

Ventana falls

February 1901

Ventana Falls provides one of the contrasts between flowing water and the upper Sonoran Desert in the Santa Catalina Mountains. Most of the dark plants above the falls are Arizona rosewood (Vauquelinia californica). No saguaros are visible above the waterfall. (S.J. Holsinger, courtesy of James Klein).

December 10, 2003

The falls are dry owing to the current drought. The amount of woody vegetation has increased throughout the view, and young saguaros are abundant. Although at least two individual rosewoods persist on the slope above the falls, many new plants are now visible. (D. Oldershaw, Stake 3741).

ca. 1935

This view north along a loop road in Saguaro National Park (East Unit) shows the charismatic namesake cactus of this park, which was established in 1932. (photographer unknown, courtesy of the National Park Service).

Desert-wide, the most important change we've documented is the increase in woody vegetation. It doesn't matter whether it is mesquite encroaching on former grassland, riparian trees coming into formerly barren river channels, or palo verdes increasing on desert hillslopes, woody plants have increased at the expense of bare ground and herbaceous species. Established plants have grown, giving "after" photographs the startling appearance of greatly increased vegetation on the landscape. Although one predicted outcome of increased carbon dioxide in the atmosphere is that woody plants will increase at the expense of perennial grasses, there is no direct evidence to suggest that changes in the Sonoran Desert are caused by this factor.

Another startling change is in the charismatic cacti of the Sonoran Desert. Some photographs portend the demise of the saguaro *(Carnegiea gigantea)*, leading to some speculation that the name of Saguaro National Park might one day be changed to Palo Verde National Park. A permanent study plot established in the area (visible in the photographs) contained 209 saguaros in 1961. By 1988, this number had fallen to 100. In 200l, the population had rebounded and there were 227 plants in this 9-acre plot. Most of these new cacti are small and will not be visible from the camera station for a quarter of a century or more. Although more plants are present today than in the 1960s, how does this new number compare with the number at the time of the 1935 photograph or even to the number of plants in the grand old forest when the photographed plants became established a century earlier? Using a model derived from studies at this plot, plant heights were converted to plant age. This allowed a look deep into the past, and a robust establishment period was seen from about 1800 to 1870. Following that period and until the late 20th century, the population rarely added enough plants to maintain numbers near 200. Thus, it was the early 19th century pulse of establishment that provided the large number of mature plants seen in photographs from the 1930s. The post 1870s decline is timed closely with the

A permanent study plot established in the area contained ***209*** *saguaros in 1961. By 1988, this number had fallen to* ***100****. In 2001, the population had rebounded and there were* ***227*** *plants in this 9-acre plot.*

beginning of livestock grazing in the area as well as with impacts from nearby charcoal kilns, for which saguaro "nurse trees" were harvested. Cattle were removed from this part of the Monument in 1958; the kilns were gone earlier. Establishment returned to this plot in the 1960s and appears robust at this time. How will this forest appear in another century? Will saguaro establishment be influenced by the drought-induced death of numerous palo verdes that can now be seen in this area?

Also of interest is the increase in smaller-statured cacti, particularly prickly pear, which appear to be responding to the simultaneous effects of increased precipitation in the 1980s and increased winter temperatures. You might have noticed that prickly pear, in particular, has suffered considerable mortality during the current drought.

The extended wet period between 1978 and 1995 created what probably is an unsustainable plant population in the more humid northeastern parts of the Sonoran Desert. If we are entering a sustained drought period, which some are predicting, expect to see an increasing number of dead shrubs and trees in our desert. While this may be disconcerting to some, and have others wanting to blame human land-use practices, we believe these changes are a normal part of the boom-bust cycle driven by climatic fluctuations in this desert we call home.

For more information on long-term vegetation change in the Sonoran Desert and Pima County, see R.M. Turner, R.H. Webb, J.E. Bowers, and J.R. Hastings, *The Changing Mile Revisited* (University of Arizona Press, 2003) and www.pima.gov/cmo/sdcp/reports/Wdweb.pdf ■

July 19, 1960

Although many saguaros have grown (foreground), an overall decline in the number of cacti in the view had started by the early 1960s. Woody vegetation, primarily foothill palo verde, has increased. (J.R. Hastings).

April 29, 2004

The most common plant visible is foothill palo verde, although small saguaros are abundant beneath these nurse plants. The many small saguaros have become established since the early 1970s and many will not be visible from this camera station for several decades. (D. Oldershaw, Stake 20).

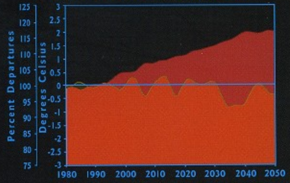
The Aspen fire burns through a desert canyon in the Santa Catalina Front Range in July 2003. The fire later wreaked havoc on Summerhaven, a community at the top of Mount Lemmon. Ecologists are concerned that a warmer climate will make severe wildfires more common in the Southwest. Photo by Ellis Margolis.

Melanie Lenart,
Gregg Garfin, and Jonathan Overpeck
Institute for the Study of Planet Earth
The University of Arizona

the Heat is on

The Southwest is in the midst of a potentially disastrous drought. At the same time its cities are growing by leaps and bounds. The implications are sobering: a Southwest with shortages of water and an overabundance of blazing wildfires in this century and beyond. Globally, average annual temperature is expected to rise by somewhere between 3 and 10 degrees Fahrenheit by 2100, according to a range of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Computer models are less adept at simulating regional climate change, but some researchers with NOAA (the National Oceanic and Atmospheric Administration) predict a rise in average annual temperature in the Southwest of 3 to 4 degrees Fahrenheit by 2050 (see chart on page 22). Their projection averages results from four different computer models, and doesn't assume the warming will stop at mid-century.

Winter Climate Projections for the Southwest US



By the year 2050, average annual temperature (top line) in the southwestern United States is projected to increase by about 2 degrees Celsius, or roughly 3½ degrees Fahrenheit, in an analysis done by researchers at the National Oceanic and Atmospheric Administration (NOAA) based on input from a variety of computer models. Meanwhile, the analysis projects that southwestern precipitation (wavy line) will follow its usual pattern of ups and downs, with perhaps an enhanced potential for longer dry spells. The straight line in the middle represents the average values for both temperature and precipitation based on instrumental records from 1971-2003. The projected departures from average, in percent, are given at the far left of the graphic. The analysis was done by Martin Hoerling, Jon Eischeid and Gary Bates of NOAA for the Western Governor's Association meeting in March 2004. Graphic produced by Jon Eischeid based on an analysis by M. Hoerling, J. Eischeid and G. Bates.

The IPCC expects the biggest temperature changes to come during winter and at night, but residents in the Southwest can also expect to feel more heat throughout the year as temperatures rise. Climate change could well usher in more of what we're experiencing now, with widespread drought in the Southwest. Higher temperatures mean the atmosphere holds more moisture, and this can aggravate drought conditions. In fact, one analysis found higher-than-usual temperatures helped create drought conditions between 1998 and 2002 in at least some of the area in the Four Corners states (Arizona, New Mexico, Colorado, and Utah).

Other studies have documented a nationwide trend toward an earlier spring, with snow melting and flowers blooming sooner than in previous

> *Buildings that collectively housed more than 3,000 people were abandoned by this civilization during a long dry spell in the second half of the 12th Century.*

decades. Dan Cayan of the Scripps Climate Research Division in California and several colleagues reported in 2001 that both lilacs and honeysuckle at long-term observation stations in the West were tending to bloom about 5-10 days earlier in recent decades compared to the first few decades of record. (Records go back to 1957 for lilacs and to 1968 for honeysuckle.) Gages measuring peak springtime river flow correlate well with blooming dates in the western United States, strengthening the argument for an earlier spring thaw.

In addition to bringing on an earlier spring, climate change will likely mean more frequent torrential rains, fewer frost days, a longer growing season, a longer fire season, and lower reservoir levels.

Specific precipitation changes are difficult to pinpoint at regional levels. Although some general circulation models predict an increase in southwestern precipitation, others project a decrease or lack of change. However, even in a best-case scenario that bequeaths the Southwest more rain and snow, any increases in annual precipitation will likely be lost to even greater increases in evaporation.

A warmer atmosphere holds roughly 4 percent more water vapor for each rise of 1 degree Fahrenheit. Already water loss exceeds gains throughout most of the Southwest. For instance, the Arizona Meteorological Network measures cumulative evaporation rates that are about 10 times higher than precipitation rates in Phoenix. An increase in evaporation rates over the landlocked Southwest guarantees an increased rate of drying, most notably during spring and summer. This is partly why climatologists expect "extreme events" like droughts and floods to become more common as the world warms.

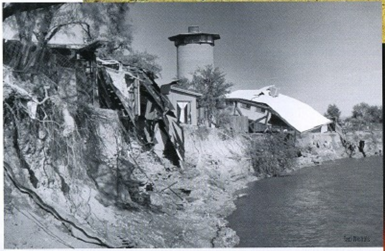
Long-term drought haunts the southwestern desert, in the past, present and future. A "megadrought" spanning more than 20 years in the 16th Century desiccated western North America from Mexico to Canada, according to tree-ring researchers such as Dave Stahle of the University of Arkansas. Scientists use the term "megadrought" to describe a widespread drought that lingers for a decade or more. The Chaco Canyon ghost town of structures built by the ancestors of the Pueblo people stands as a silent testament to how megadrought can affect society. Buildings that collectively housed more than 3,000 people were abandoned by this civilization during a long dry spell in the second half of the 12th Century.

While higher evaporation rates over land can promote drought, higher evaporation rates over the ocean contribute to the expectation of more floods. What goes up must come down, and there's reason to believe that some of the moisture in the atmosphere will come down in more frequent torrential rains. For instance, Thomas Karl and Kevin Trenberth at the National Center for Atmospheric Research analyzed daily precipitation values for a variety of climate regimes and found warmer climates were more likely to receive their moisture in large episodic doses.

The semi-arid lands of the Southwest already tend to have more than their share of extreme events compared to the rest of the country, at least when measured in terms of devastating drought and erosion from flooding. Climate change seems more likely to reinforce rather than temper the southwestern climate see-saw, which some climatologists sum up with the adage that droughts tend to end in floods.

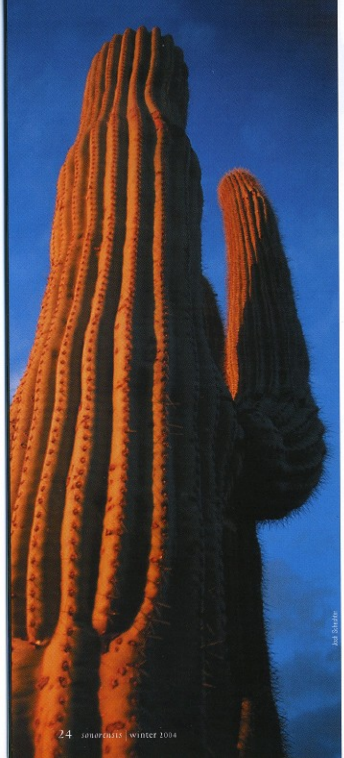
An increase in aridity brings challenges for plants in southwestern deserts and forests alike. In the desert, plants already struggling for survival will face

▲ During a "megadrought" all the vegetation in an area may die. Aguirre Valley, AZ.



▲ Flood damage along Tucson's Rillito River, October 1983. The semi-arid lands of the Southwest tend to have more than their share of extreme events compared to other parts of the country.

Photo Right and on pg 22. ▸
Fires burning in Sabino and Bear Canyons light up the night sky over Tucson during the Aspen fire of July, 2003. Photos by Ellis Margolis.



more water stress. In the forest, catastrophic wildfires could rage more frequently during longer fire seasons in the future. It's no coincidence that the greatest fire danger occurs during the typically bone-dry southwestern late spring. What is less obvious, but well-documented by Thomas Swetnam of the University of Arizona's Laboratory of Tree-Ring Research and his colleagues, is that the see-saw of wet to dry years actually increases the potential for large wildfires in some southwestern forests.

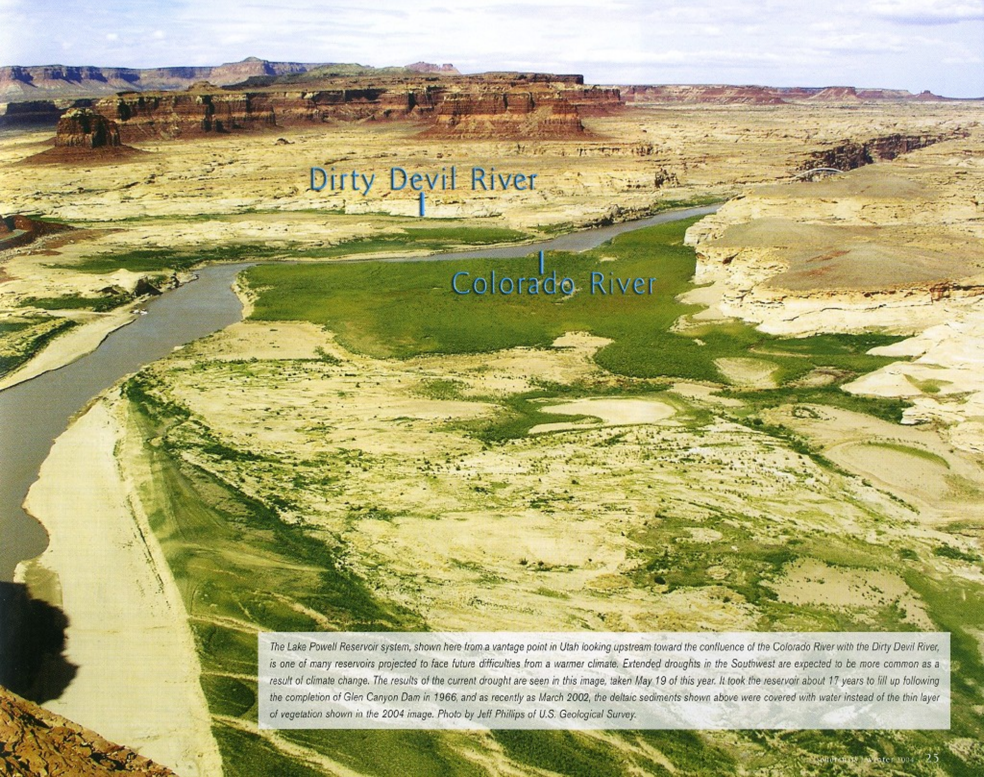
Other aspects of climate change also present challenges for natural and managed plant systems. The tendency toward earlier springs and longer growing seasons is bound to benefit some plant species, probably at the expense of others. Many species will face a change in their suitable range. The classic southwestern cactus, the saguaro, might relocate further east in Arizona, a 1997 study led by Robert S. Thompson of the U.S. Geological Survey suggested. Meanwhile, ponderosa pine populations could decline in Arizona yet increase in New Mexico. Other tree species that could decline in the Southwest include spruce, pinyon pine, Douglas fir, and Gambel oak. Species standing to gain ground from climate change in this region include other oak species, creosotebush, and Joshua trees.

A changing climate will shift the distribution of both plant and animal species. It's unlikely that things will move smoothly, synchronously or in ways that are easy to predict. (Imagine a musical chairs approach to shifting ecological niches.) The chance of seeing a smooth transition declines if climate change occurs abruptly, something that particularly concerns scientists because they've seen it before in records of prehistoric climate. Records of past climate inferred from marine sediments, for instance, indicate regional climate can make an abrupt switch in a matter of years. Of course, plant and animal communities may take longer than decades to adjust.

The giant saguaro, towering icon of the American Southwest, may relocate further east as the climate continues to warm. Earlier springs and longer growing seasons will tend to benefit some plant species, often at the expense of others.

Southwestern society may also struggle to adjust to the impacts of climate change, particularly impacts involving water supply. The many reservoirs storing Colorado River water help buffer many parts of this region in comparison to other western basins. Still, the inflow to the Colorado system accounts for only a fraction of the water allocated to various users each year. Water compacts were designed during a period of above-average stream flow in the 1920s, and the reservoirs themselves hold more water than can flow through the system even in a flood year. As a result, it takes the system many years to rebound from a regional drought. Having such a high ratio of storage capacity compared to river flow makes the Colorado reservoir system extremely sensitive to changes.

The tendency toward earlier springs and longer growing seasons is bound to benefit some plant species, probably at the expense of others.



The Lake Powell Reservoir system, shown here from a vantage point in Utah looking upstream toward the confluence of the Colorado River with the Dirty Devil River, is one of many reservoirs projected to face future difficulties from a warmer climate. Extended droughts in the Southwest are expected to be more common as a result of climate change. The results of the current drought are seen in this image, taken May 19 of this year. It took the reservoir about 17 years to fill up following the completion of Glen Canyon Dam in 1966, and as recently as March 2002, the deltaic sediments shown above were covered with water instead of the thin layer of vegetation shown in the 2004 image. Photo by Jeff Phillips of U.S. Geological Survey.

A monsoonal rain storm is seen in the distance. Monsoonal storms usually occur during the summer months of July and August in the southwestern United States, with timing dependent on location and variable by year. They bring much-needed water to the Sonoran Desert vegetation, but don't necessarily recharge declining groundwater aquifers.

For instance, an Environmental Protection Agency report published in 1993 estimated that a consistent 5 percent decrease in streamflow runoff could reduce by a full quarter (25 percent) the capacity of the Central Arizona Project to deliver its full allocation of water to Phoenix and Tucson. In a state-of-the-art modeling study, University of Washington hydrologists used projections for early snowmelt and increased temperatures to estimate that Glen Canyon Dam releases to the states in the lower Colorado River basin would be met less than 75 percent of the time between 2010 and 2098. This would challenge the basin's capacity to store water, produce hydropower, and deliver water to Mexico as promised by the compact.

An increase in monsoonal rains may look impressive, but generally the water rushes downstream without much opportunity for replenishing groundwater supplies.

Obviously an increase in drought frequency would not bode well for reservoirs and aquifers. But what of the increase in floods that is also a possible outcome of climate change? In this case, the type of water storage system matters, as does the seasonal timing of precipitation.

Floods do little for aquifers. An increase in monsoonal rains may look impressive, but generally the water rushes downstream without much of an opportunity for replenishing groundwater supplies. If winter precipitation increases, however, aquifers could benefit. Aquifers do best when moisture can sink in over many weeks of fairly cool weather, such as when it trickles down from snowpack. Of course, if the snow evaporates into thin air – a process that consumed tons of southwestern snow this past March – then local soil moisture gains nothing.

Floods can boost reservoir levels, though. Rain-on-snow events, a recipe for floods, may become more frequent given the documented earlier springs and projected increase in torrential rainfall events. Floodwater, however, carries deposits of sediment to reservoirs, reducing their capacity. Also, an increased threat of spring floods may force water managers to make difficult choices about how much water to release downstream when reservoirs are running high. Reservoirs help reduce societal risk by allowing for the storage of potential floodwaters — but only if sufficient holding capacity remains when a flood strikes.

Water managers won't be alone in having to make tough decisions as a result of climate change. Society will need to make some difficult decisions. At the dawn of the 21st Century, Arizonans are lucky to have groundwater and abundant agricultural water allotments. (Agriculture accounts for more than 70 percent of Arizona water use.) These factors provide a buffer to help society get through drought. But as aquifers are depleted, and agricultural water is converted to urban use, the Southwest's ability to weather droughts will be diminished.

The most immediate climate change impacts are likely to be felt by riparian and non-irrigated areas. As society tries to cope with drier conditions via expanded infrastructure and conservation, natural areas could, quite literally, be left high and dry. Stream flow and groundwater tables could continue to drop just as temperatures raise the evaporative stress on plants and animals. There are other possible future climate scenarios, but they all likely include periods of prolonged drought on top of significantly warmer temperatures. The only way to reduce this threat is to curb anthropogenic climate change by reducing the societal input of greenhouse gases, which come mainly from burning fossil fuels in factories, power plants, and vehicles, and also from the burning and destruction of forests.

Even if society itself abruptly changed course and reduced greenhouse gas emissions, it would take time to reverse the warming that has begun. Still, there are actions individuals and society can take to reduce the impacts of climate change and the associated drought.

Even if society itself abruptly changed course and reduced greenhouse gas emissions, it would take time to reverse the warming that has begun. Still, there are actions individuals and society can take to reduce the impacts of climate change and the associated drought. Desert dwellers can plant drought tolerant species, and avoid exotic grasses or moisture-loving plants. Society can assist in groundwater recharge efforts during times of plenty. If timber managers, ecologists and environmentalists can work together, society could clear the forest of a proportion of fuels and understory trees. Defusing catastrophic wildfires is like putting carbon in the bank instead of into the atmosphere as carbon dioxide.

Here's another strategy society could adopt: Make sure each species exists in multiple reserves (or reservoirs and river systems, in the case of aquatic species). That's a logical response to the threat of climate change. As our ancestors would advise, don't put all your eggs in one basket. Finally, society would be wise to restrict development in flood plains and other riparian areas. There's no need to add more risk to life and structure to the climate change impacts. As it is, the challenges posed by climate change will be difficult enough on the Southwest. S

The only way to reduce the impacts of climate change is to curb impacts caused by humans. One way is to reduce the production of greenhouse gases, which come mainly from burning fossil fuels in factories and power plants, vehicle emissions, and the burning and destruction of forests.

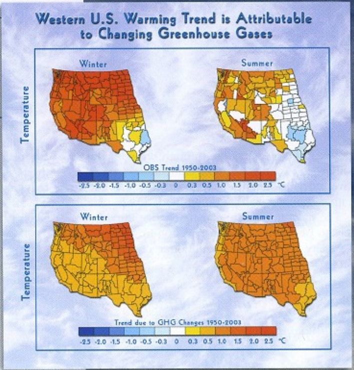
Is the Climate *Really* Changing?

The earth's atmosphere warmed in the past century, particularly at planetary and northern hemisphere scales. The evidence for this is clear. The thermometer record shows a clear rise of about one degree Fahrenheit since the beginning of the 20th Century, after the effects of urbanization have been taken into account. What's more, the warming has accelerated in the last several decades. The warming trend of the past century also shows up in longer term natural archives of climate such as tree-ring and ice-core records. Even most global warming skeptics generally acknowledge that the temperature is rising, preferring to limit their argument to whether the modern increase relates to natural climate variability or the societal input of greenhouse gases such as carbon dioxide to the atmosphere.

Although natural climatic variation certainly has an influence, most of the surface temperature increase scientists have documented for recent decades fits the warming pattern scientists have long been predicting would result from the increase input of greenhouse gases (see graphic at right). The annual input of greenhouse gases includes more than 15,000 billion pounds (about 7 petagrams) of carbon dioxide released by fossil fuel burning and deforestation worldwide, with about a quarter of these emissions coming from the United States.

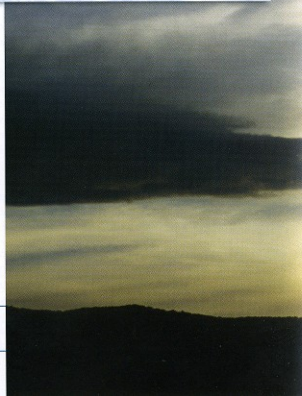
Greenhouse gases trap heat at the earth's surface by blocking the escape of infrared heat to space. In its 2001 report, the Intergovernmental Panel on Climate Change attributed "most of the observed warming over the last 50 years" to the societal input of greenhouse gases. Water vapor, methane, ozone, nitrous oxides and chlorofluorocarbons all contribute to the greenhouse effect, but carbon dioxide alone accounts for about 60 percent of the enhanced warming projected for this century. The input of all these gases continues to rise, with the exception of chlorofluorocarbons. So it's logical to expect a continuing rise in temperature in years to come.

And that's exactly what computerized climate models predict for the future. Although some climate change scenarios suggest ocean changes could actually lead to less warming over parts of Europe that are currently graced by the balmy breezes borne by the Gulf Stream, there's scant hope for a cooling influence in the Southwest. So there's plenty of cause for concern about the impacts of climate change in this region. S



The pattern of warming observed in the instrumental record in the West (top panel) is well matched by the pattern that would be expected based upon changes in greenhouse gas levels (bottom panel), based on an analysis done in 2004 by Martin Hoerling, Jon Eischeid and Gary Bates of the National Oceanic and Atmospheric Administration (NOAA). Winter (on left in both panels) refers to December through February, while summer (on right, both panels) refers to June through August. The top panel shows the observed (OBS) net change in surface temperature based on the instrumental record since 1950, with each 1 degree Celsius representing about 1.8 degrees Fahrenheit. The bottom panel shows the warming trend that would be predicted as a result of greenhouse gases (GHG) for that same time frame, based upon a combination of eight climate models that are described in the Intergovernmental Panel on Climate Change Third Assessment Report. The IPCC report is available online at http://www.grida.no/climate/ipcc_tar/wg1/ .

Graphic produced by Jon Eischeid based on an analysis by M. Hoerling, J. Eischeid and G. Bates presented to the Western Governor's Association in March 2004.



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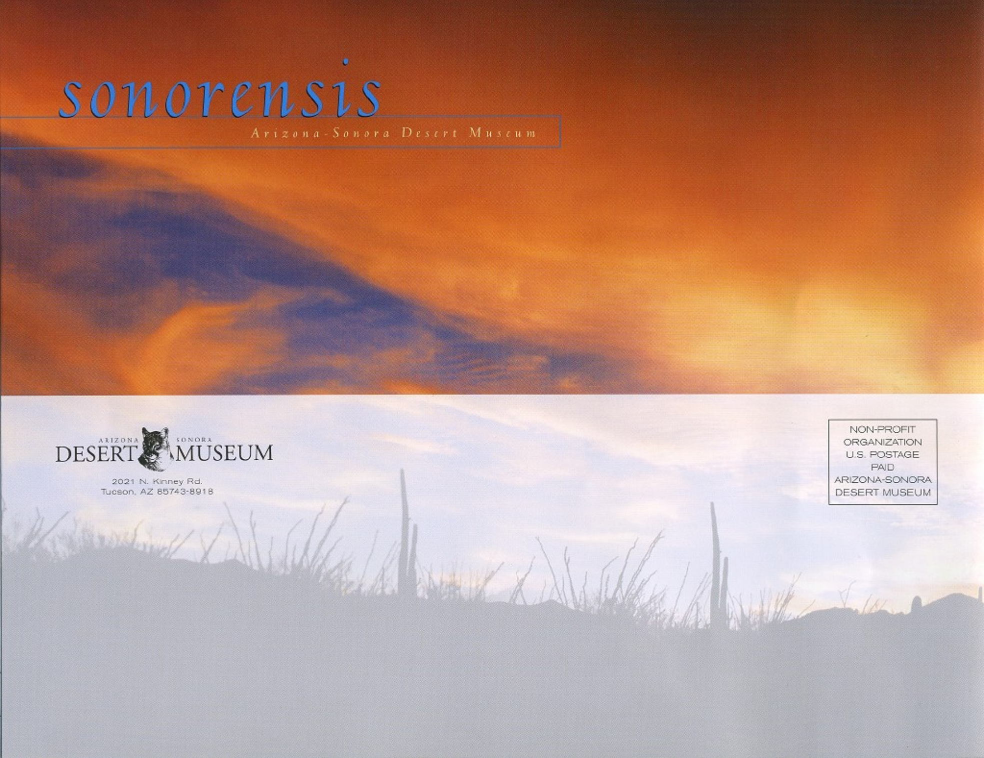
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