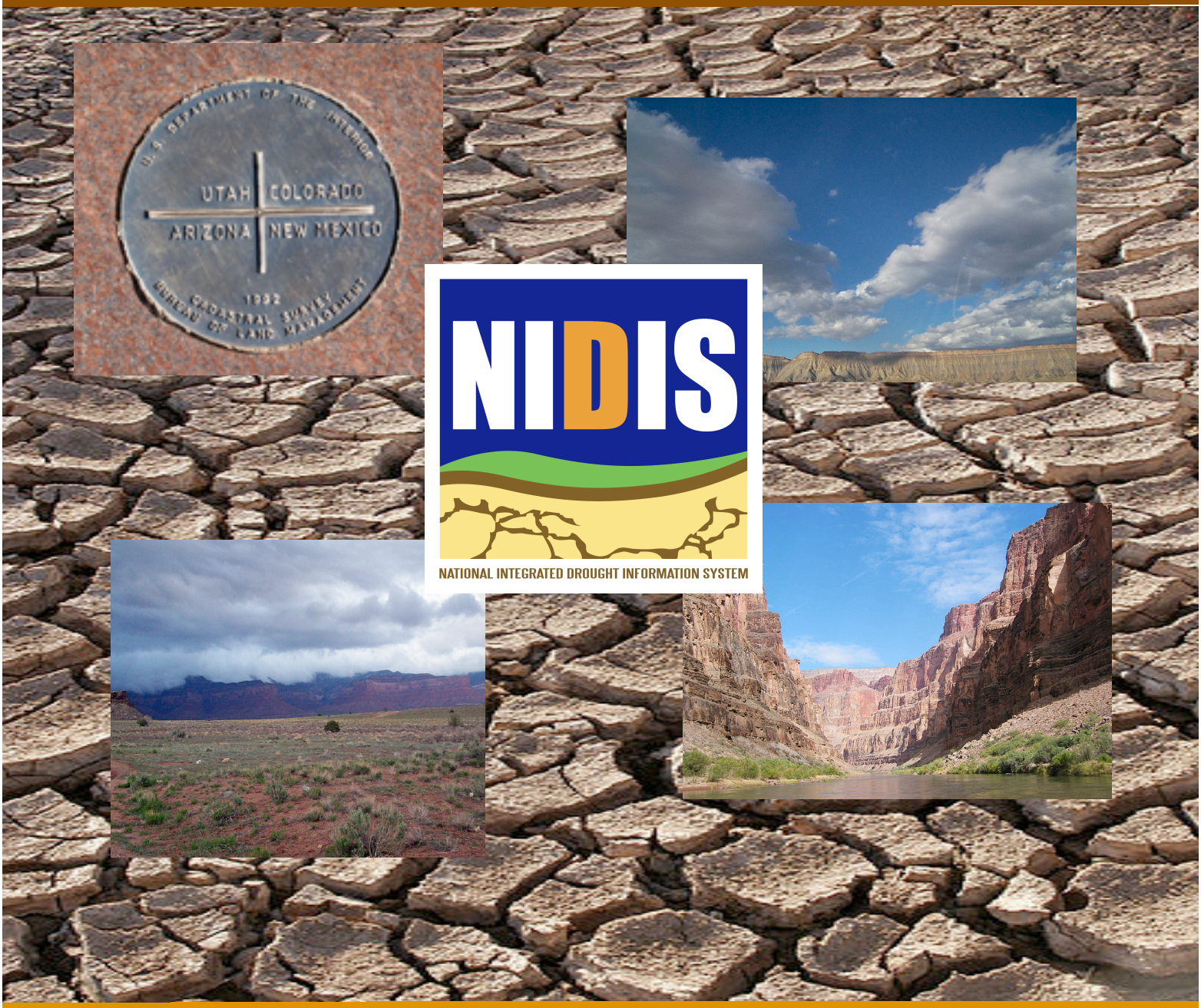
Drought Preparedness for Tribes in the Four Corners Region Workshop



Flagstaff, AZ: April 8-9, 2010

Sponsored By:
National Integrated Drought Information System (NIDIS)
Climate Assessment for the Southwest (CLIMAS)
The Western Water Assessment (NOAA-CIRES)
The National Drought Mitigation Center (NDMC)
United States Geological Survey (USGS)

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NOTE: This guide contains background information on drought monitoring, planning, and the influence of climate variability and change on the frequency, intensity, and duration of drought in the U.S. Southwest.

Climate, drought and early warning on Western Native Lands 9-11 June, 2009 Jackson Lodge Grand Teton National Park WY

Early warnings of climate events and threshold points that affect cultural, economic, and environmental resources are becoming increasingly important for preparedness and adaptation as climate changes. In this context the issues of severe sustained drought and increasing rates of environmental change are critical to the future of the Western U.S. in the near and longer terms. The multi-agency National Integrated Drought Information System (NIDIS, in partnership with…Sinte Gleska, Haskell, IWN etc) is therefore convening a workshop on assessing and responding to drought and climate impacts on western Native Lands. This workshop will be held at the Jackson Lodge in Grand Teton National Park on 9-11 June 2009. We propose to use a watershed approach with key participants from Native communities and organizations, from major river basins west of the Mississippi River, involved in developing and protecting water and energy resources, wildlife and the environment. Invited participants will also include people from internationally shared water systems such as the Columbia, the Great Lakes and the Rio Grande and from national level organizations such as the NCAI and CERT. Lodging and travel support will be provided to invitees. Climate change impacts will be different from region to region. If, as predicted, climate change results in increased water scarcity in some areas, and stresses on other natural resources, tribal use and protection of resources could face significant challenges. For example projections show that tribes in the Pacific Northwest will face warming streams and changes to the hydrologic cycle that further threaten the survival of salmon populations; likewise higher temperatures and increasing aridity in the Southwest might exacerbate tensions between tribal and nontribal interests and rights over the region's limited water resources. t the same time a number of tribal lessons are available to address climate change. Tribes have great physical and cultural resources that can help the US deal with climate risks through renewable energy development and wilderness protection in the face of climate change.

The NIDIS Act of 2006 (Public Law 109-430) mandates a multi-agency approach that focuses on, (i) communication and awareness of drought and drought impacts, (ii) improving and integrating information from monitoring and forecasting networks into drought planning, (iii) engaging communities to ensure that the needed indicators and triggers for proactive drought risk management are identified and addressed, and, (iv) the development of regionally-specific information sites that act as clearinghouses for information at different scales. The NIDIS provides a prototype for climate information services to support preparedness and adaptation climate varies and changes.

Key Recommendations to Address Early Warning Drought Monitoring on Western Tribal Lands

The Federal Trust Responsibility

Communication and Translation of Federal Trust Responsibility
Assess the Current Status of Federal Trust Responsibility Among Tribes
Assessment of What is Working: i.e. Tribal Relations with the EPA

Data Collection & Monitoring Gaps

Expand Remote Sensing Capabilities
Improve Streamflow Monitoring on Tribal Lands
Tribal Engagement & Inclusion in Data Collection

Interdisciplinary Research Needs

Impacts & Risk Assessment

Assessment of Current and Projected Drought Risk, Impacts & Vulnerabilities
Energy Impact Assessment
Drought Product/Index Development

Water Supply Assessment & Improved Management and Control of Water and Natural Resources

Water Supply Assessment: Ground and Surface Supplies
Adjudication and/or Solidification of Water Rights
Increased Interaction with Federal Agencies and the Bureau of Indian Affairs (BIA)

Development of Knowledge Systems: Staging Multi-Road Collaborations

Communicating Drought Monitoring Technologies/Datasets/Products
Climate and Water Workshops
Expand Grant Writing & Related Resources
Development of Esteemed Elder Program

Renewable Energy Scoping & Development

Renewable Energy Scoping and Development
Renewable Energy Feasibility Studies
Energy Audits
Renewable Energy Template
Renewable Energy Portal

Institutional Framework & Financial Capital

Engaging Tribal Communities & Building Awareness
Submit Proposals for Federal Funding Sources: Federal Agency and Related Collaborations
NOAA Tribal Liaison
IPCC Tribal Linkages
Partnerships with NOAA Regional Integrated Sciences and Assessments (RISA) programs and proposed Landscape Conservation Cooperatives (LCCs)
Tribal College Engagement
Partnerships with Universities

Who's paying attention to the drought on the Colorado Plateau?

By Daniel Ferguson and
Michael Crimmins

Daniel Ferguson, CLIMAS program manager, and Michael Crimmins, a climate science extension specialist for Arizona Cooperative Extension, visited staff members from the Hopi Department of Natural Resources (DNR) in May to discuss drought and climate change on the Colorado Plateau. During the day-and-a-half Ferguson and Crimmins were able to spend with the Hopi DNR, one theme continually emerged: who's monitoring the current drought on the Colorado Plateau?

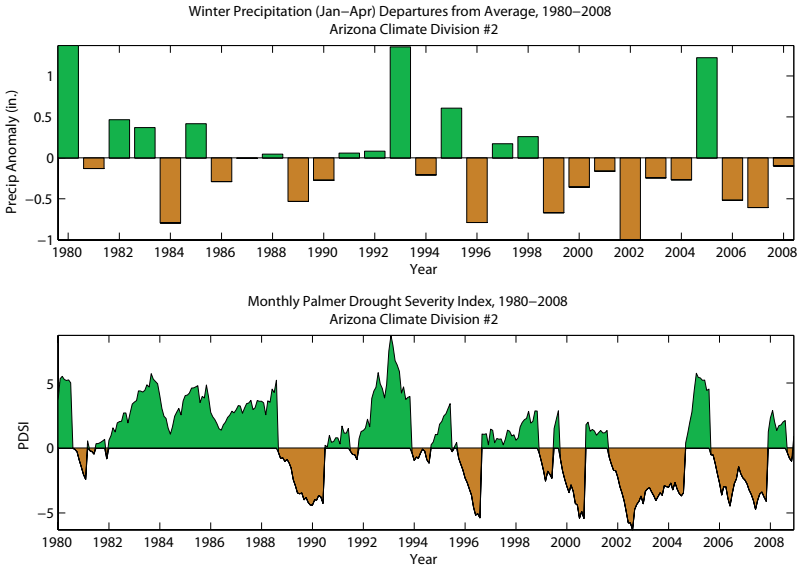

Figure 1. Precipitation and Palmer Drought Severity Index data from Arizona Climate Division 2, 1980–2008.

Driving along Arizona Highway 264 toward the Hopi mesas in May 2009, our conversation kept circling back to the unusual thunderstorms that had been forming across the southern Colorado Plateau all week. These climatologically uncommon rains were a welcome relief from an otherwise dry 2009, but they certainly did not signal the end of the long-term drought plaguing the region. At the behest of Arnold Taylor, manager of the Hopi Department of Natural Resources (DNR), we were headed to Kykotsmovi, Ariz., to meet with staff members from the Hopi DNR to discuss drought and climate change on the Colorado Plateau and begin assessing the DNR's small weather monitoring network.

Prior to our visit, we were well aware that monitoring in this part of the Southwest was spotty at best, even though several federal agencies, including the National Weather Service (NWS), the US Geological Survey (USGS), and the US Department of Agriculture (USDA), and both the Hopi Nation and Navajo Nation have weather stations and stream gages across this part of the plateau. We also knew the ongoing drought was creating a variety of impacts, but our day-and-a-half visit with our Hopi colleagues made clear that natural resource managers and climate scientists alike were all facing the same fundamental question: Is anyone actually capturing the current drought on the Colorado Plateau?

Mr. Taylor had invited us to the Hopi Nation to brief his staff about current science, but perhaps more important, he wanted to make us aware of drought conditions on the reservation and Hopi efforts to monitor it.

The string of very dry years has Mr. Taylor concerned about present conditions as well as anticipated changes in climate that are expected to bring even more intense droughts. In the midst of this current drought, it is clear the somewhat ad hoc climate monitoring network across the region is having difficulties resolving and tracking these conditions.

Hopi people have been living on or near the mesas at the heart of the current Hopi reservation for more than a millennium. Located on the Colorado Plateau, in the Little Colorado River watershed, the Hopi landscape encompasses high mesas, deep canyons, and an arid climate.

As dryland farmers and ranchers, the Hopi have a long and deep cultural relationship with the climate of the Southwest. Drought is neither uncommon nor unexpected in Hopiland, but current drought conditions and recent science about a future warmer, dryer Southwest has decision makers across the desert Southwest, including Hopi resource managers like Mr. Taylor, asking a common question: how do we best proceed into a climatologically uncertain future?

One clear component of any answer to this question is effective monitoring of weather, climate, and drought impacts. Our Hopi hosts made clear throughout our visit that monitoring on the Hopi Nation and across the Colorado Plateau is inadequate for the climate adaptation task at hand. Recent work led by CLIMAS investigator Dr. Gregg Garfin and a team of researchers from The University of Arizona, Arizona State University, and Northern Arizona University, in partnership with the Navajo Nation, resulted in a detailed assessment of monitoring issues on the Navajo Nation

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Who's paying attention, continued

that also indicated a large climate monitoring gap on the Colorado Plateau.

Drought on the southern Colorado Plateau: 15 years and counting

Both the Hopi Nation and Navajo Nation in northern Arizona have quietly been suffering through drought conditions for well over a decade. A quick look at coarse precipitation data for the northeastern quarter of Arizona (Climate division 2, covering all of Coconino, Apache, and Navajo counties) shows that winter precipitation from January through April has been below average 11 out of the last 15 years since 1994 (Figure 1). The years 1996 and 2002 stand out as exceptionally dry, with most of the other years just below the long-term average for winter precipitation. A plot of monthly Palmer Drought Severity Index (PDSI) values over the same period shows a clearer picture of the cumulative effect of the somewhat subtle string of below-average winters (Figure 1). A shift from very wet conditions in the winter of 1993 to very dry in 1994 marked what several Hopi natural resource managers that we met consider the beginning of the current long-term drought. Below-average precipitation has kept PDSI values negative (indicating dry conditions) in a majority of months up through the present.

An unusually wet winter spanning December 2004 through February 2005 brought widespread, heavy snow to northern Arizona and temporary drought relief. Above-average temperatures and below-average precipitation later that spring quickly melted snow and brought back short-term drought conditions, as depicted in the deep drop in PDSI values (see Figure 1).

These climate data only hint at the actual drought conditions experienced on the ground by the Hopi and Navajo people. Resource managers on the Hopi Nation report wide-ranging drought impacts to rangeland and water resources, including poor forage quality and dry stock tanks.

Figure 2. Rangeland across the Hopi Nation and Navajo Nation was heavily impacted by severe dust storms in April. Range conditions, already stressed by overgrazing and years of persistent drought, have been degrading rapidly in recent years.

During our visit to Kykotsmovi, we were presented with photographs and range reports related to extreme dust storms in April 2009. These storms buried rangelands on parts of the Hopi Nation as high winds moved loose soil from dunes and already degraded rangelands. Several inches of dust smothered vegetation across the plateau, leading to further impacts on range conditions. Such wind-driven sandstorms have plagued the Hopi Nation and Navajo Nation in recent years. Indeed, research by U.S. Geological Survey (USGS) scientist Dr. Margaret Hiza-Redsteer has indicated recent drought conditions have supported a large increase in wind erosion and sand dune mobility across northeastern Arizona. In addition, as reported in the June 2008 issue of *High Country News*, Dr. Hiza Redsteer and University of Arizona Ph.D. candidate Casey Thornbrugh observed that higher spring temperatures in recent years have negatively impacted rangeland vegetation, leading to more wind erosion and movement of sand dunes.

The sensitivity of this landscape to complex interactions between temperature and precipitation variability and its ominous slide toward desertification argue for more responsive and place-based drought monitoring strategies. These could include a combination of volunteer climate observations, new remote sensing-based tools, and investment in new, high-quality official monitoring stations tied to national networks (e.g., NOAA Climate Reference Network).

Compounding dust storms and desertification, warming temperatures and the invasion of new weed species hamper the recovery of rangelands when more favorable rains return. In addition, in an area where livestock production is an important industry, the invasive weeds are changing the composition of existing forage; many of the encroaching species are of limited palatability or are even toxic to livestock, reinforcing the stress on ranching operations. During our visit, Priscilla Pavatea, director of the Hopi Range Management Office, reported the total number of cattle on Hopi lands has fallen 60 percent since 1994 due to decreasing forage production and quality.

A challenging geography for drought monitoring

These drought impacts are particularly surprising if you look at a current map of long-term precipitation deficits for

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Who's paying attention, continued

the region or even the current National Drought Monitor (see page 8). Precipitation totals have been slightly below-average over the past couple of years, but have not signaled a deep and persistent drought. Why is it that current drought monitoring programs at state and national levels seem to be overlooking this drought situation on the Hopi Nation and Navajo Nation?

Part of the problem is explained by examining how precipitation and temperature data, key variables in tracking drought conditions, are collected across this region. The recent work by Dr. Garfin and his colleagues to assess hydroclimatic monitoring needs for the Navajo Nation found only 20 active National Weather Service Cooperative Observer (NWS-COOP) sites collecting temperature and precipitation data across the Navajo and Hopi reservations. The land area of the two reservations covers nearly 30,000 square miles, roughly the size of South Carolina, which has more than 100 NWS-COOP sites.

The 20 NWS-COOP sites on the reservations are distributed relatively well across the Navajo and Hopi lands but cannot even begin to adequately characterize the complex climatic patterns across the region. Only a subset of them have reports timely enough to be integrated into weekly and monthly climate maps used by state and national drought monitoring officials.

Elevations vary from over 2,500 meters in the Chuska Mountains to less than 1,200 meters along the banks of the Colorado River, so the region is home to dramatically varying mean precipitation amounts and vegetation communities that range from conifer forest to desert scrub.

The characteristics of the precipitation that falls across this region also creates a challenging environment for climate and drought monitoring. Winter storms typically bring widespread light- to moderate-intensity rain and snow, providing relative uniform coverage that can support the recharge of soil moisture and local water resources. Summer thunderstorms, on the other hand, can be very isolated, dropping large amounts of rain over small areas. This can create a patchwork of drought impacts during the summer that reflects where precipitation has or has not fallen. Only very dense rain gage networks—which the reservations lack—can capture the capricious patterns of precipitation during the summer in northern Arizona.

Furthermore, traditional precipitation-based drought metrics have missed some subtle but important interactions with other climate variables, adding to the drought monitoring hurdles in the region. Increasing temperatures over the period have been implicated in exacerbating some of the observed drought impacts by creating additional moisture stress on vegetation.

Monitoring drought and climate for the 21st century on the Colorado Plateau

On the morning of the second day of our visit to Kykotsmovi, we had the opportunity to visit two of the Hopi Water Resources Program's (WRP) weather monitoring stations with Jon Mason, the WRP Non-point Source Coordinator, and Shirley Piqosa and Avery Pavinyama, both WRP technicians.

Through the WRP, the Hopi DNR is able to gather some weather data across a handful of sites on the Hopi Nation. The small network the program is able to maintain, however, is insufficient for truly monitoring climate or drought, a fact that is abundantly clear to Mr. Taylor and the DNR staff. With extremely limited resources, the Hopi DNR, like many other natural resource management agencies throughout the region, is unable to gather enough quality data or analyze what they can collect in such a way that it is useful for decision making.

With a potential long-term drought already underway, and a strong signal that the whole Southwest is warming, it seemed clear to all of us during our visit that it is going to take a sustained effort and a number of partnerships to begin addressing the monitoring gap that exists on the Colorado Plateau.

Our visit to Kykotsmovi presented us with a question: who is monitoring drought and climate on tribal nations on the Colorado Plateau? The answer, it turns out, is many of us in the climate science and natural resource management communities are monitoring the situation, but in an incoherent and uncoordinated way that does little to support management decisions across the region. With an ad hoc network of instruments from the Hopi Nation and Navajo Nation, the National Weather Service, the USGS, and a variety of other entities, a steady stream of information exists but much of it is ill-suited for answering fundamental questions about adapting to climate.

One obvious path forward is working toward better coordination and cooperation among the many stakeholders in the region. The Hopi and Navajo reservations represent a significant portion of the Colorado Plateau and Colorado River watershed. Given the scale of this area, tribal, federal, and state land and water resource managers all have an interest in better climate monitoring across the region. Neither the tribes themselves, nor any one agency, is well positioned to solely support monitoring and data analysis activities on the Plateau.

Short-term resource management decision making and long-term climate change adaptation planning both require a high-quality regional climate monitoring network. Building creative partnerships and working together to find resources and coordinate efforts currently offers the best hope of improving our collective understanding of what is happening now across the region and how to prepare for anticipated changes in climate in the future.

Warmer means drier: comparing the 2000s drought to the 1950s drought

By Zack Guido

Jeremy Weiss wears many hats as a senior research specialist for the Environmental Studies Laboratory in the Department of Geosciences at the University of Arizona. His interests include studying past and present vegetation in western North America, worldwide changes in sea level, and visual methods for communicating science. His research, however, has one thing in common: it focuses on climate.

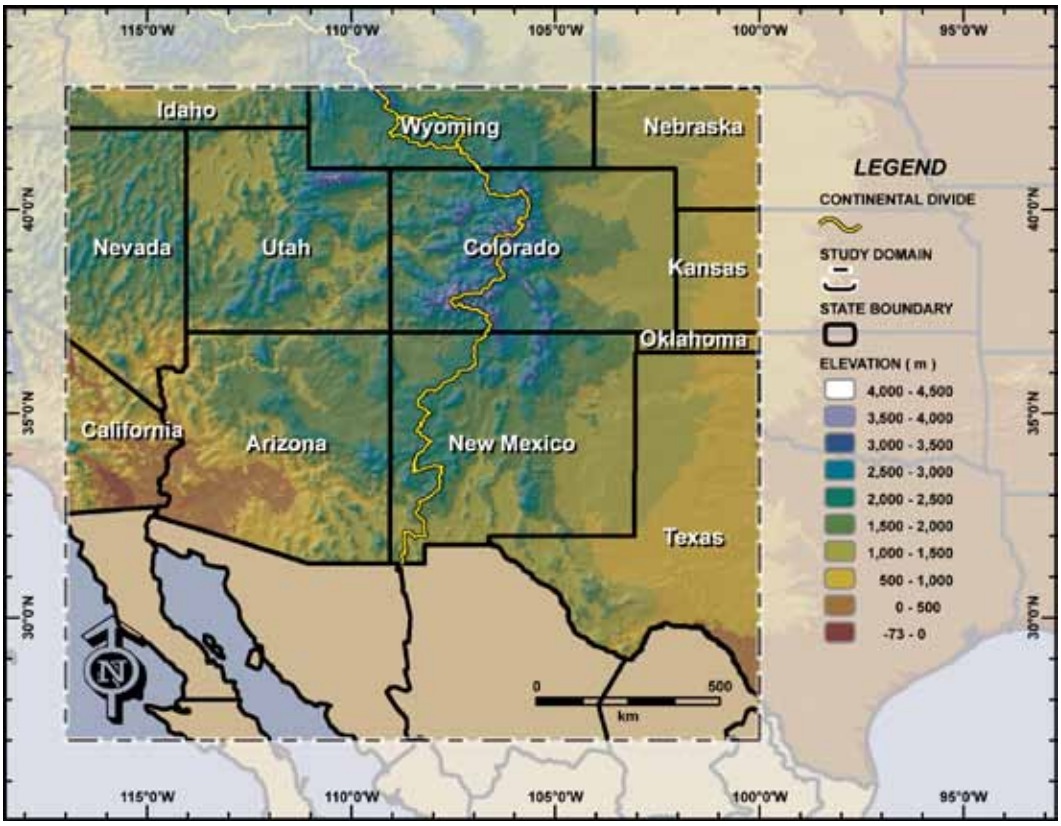

Figure 1. Area of study includes all of Arizona and New Mexico. Figure courtesy of Jeremy Weiss.

His latest research, with Christopher Castro, assistant professor of atmospheric sciences at the UA, and Jonathan Overpeck, a UA geosciences professor and lead principal investigator for the Climate Assessment for the Southwest (CLIMAS), dissected a hot topic in the Southwest—drought. Weiss and his team examined how recent drought has compared to past drought, the implications of warmer temperatures on drought severity, and how the combination of warmer temperatures and drought are mostly bad news for wildfire, air quality, and water demand.

In a February interview with Zack Guido, CLIMAS staff scientist, Weiss discussed his research results. His findings were published in the November 15 issue of the *Journal of Climate* in the paper, "Distinguishing Pronounced Droughts in the Southwestern United States: Seasonality and Effects of Warmer Temperatures."

Question: How does the title of your recent paper reflect the research?

Jeremy Weiss: The general topic of our article is drought in the Southwest. Drought is a normal part of the region's climate. We know this by looking at the last century of instrumental data, and we can identify drought periods using tree rings and other indicators stretching back hundreds of years. In this paper, we picked the two most recent droughts—the 1950s drought, which has been regarded as the most severe drought of the last 100 years, and the drought that we've experienced over the past decade.

The particular findings that came to the forefront during the research were the differences in temperatures between the droughts and the times of the year when these differences occurred. Quite convincingly, the 2000s drought was significantly warmer than the 1950s drought. Unfortunately for residents of the Southwest, these higher temperatures occurred during the warmer months of the year and were especially prevalent during the foresummer. This period right before the monsoon is exactly the time of year when you would not want hotter and drier conditions during a drought.

Q: What questions did you initially set out to answer?

JW: We wanted to detail how the most recent drought compared to the 1950s drought, get a better understanding of the relative severities of each, and look at what seasonal differences might have occurred. For example, we wanted to know which drought had less precipitation during the winter months and which had less precipitation during the summer months.

Q: What periods in the 2000s and 1950s did you compare?

JW: For the sake of being able to compare to other published studies, we looked at the four-year periods of 2000–2003 and 1953–1956. These years also arguably

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Warmer means drier, continued

represent when the most severe conditions occurred during each of the droughts.

Q: How did you analyze drought conditions?

JW: We looked at seasonal precipitation amounts, maximum and minimum temperatures, dew point temperatures, and vapor pressure deficits throughout the Southwest. The last two measures both can be thought of as an indication of moisture conditions in the atmosphere. The latter can be thought of as the atmosphere's ability to act like a sponge and take up moisture from soil and vegetation. In this study we strictly compared the state of the atmosphere near the Earth's surface, and not ground conditions such as reservoir levels or vegetation health.

Q: What is new and exciting about the results of this study?

JW: Hands down, the 2000s drought was significantly warmer than the 1950s drought, in particular maximum temperatures during the summer months and minimum temperatures from spring through early fall. These warmer conditions were widespread throughout the Four Corners region of the Southwest (Figure 1). If you were to draw a line basically straight down through the middle of Colorado and New Mexico, everything west of that line was 1–4 degrees Celsius (about 2–7 degrees Fahrenheit) warmer during the 2000s drought.

Warmer temperatures are important because temperature is a hydrologic variable. If you think of the atmosphere as a sponge, warmer temperatures allow that sponge to become larger, which means more moisture then can be taken up from soils, vegetation, and reservoirs. So, if you want a season to be drier, a good way to do that simply would be to make it warmer. And that is essentially what happened during the summers of the 2000s drought.

Q: How was precipitation different between the two droughts?

JW: There were differences between the two droughts, but it wasn't all drier or all wetter in one drought or the other. The differences were mixed, and here is where seasonality comes into play. The 2000s drought had less precipitation in early winter and from late spring through early summer in northern Arizona and nearby areas of neighboring states. The 1950s drought was significantly drier in Arizona and western New Mexico during fall and over most of New Mexico in early winter. Now, we didn't pinpoint the exact causes of the precipitation differences. But knowing at what time of year these differences occurred and being familiar with seasonal precipitation sources, one can begin to figure out such causes. For example, in the 2000s drought, it is possible that westerly frontal systems in late spring or the start of the monsoon in early summer didn't give us as much precipitation as during the 1950s drought. And in the 1950s drought, it is possible that the end of the monsoon or tropical cyclones from the Pacific Ocean in early fall didn't give us as much precipitation as during the 2000s drought.

Q: Why is temperature an important component of drought?

JW: Temperature can control the amount of moisture that the atmosphere can hold—that is, the size of the sponge that can take up moisture from soils and vegetation. As the atmosphere becomes warmer, the size of the sponge grows, and the atmosphere can take up more moisture. Now, there is an interesting twist to this relationship between temperature and the ability of the atmosphere to pull moisture from the surface. The size of the sponge grows faster when warming occurs during our summer than during the other cooler seasons. So, the relatively higher temperatures at the hottest time of the year during the 2000s drought made the sponge grow a lot and take up a lot of moisture from soil and vegetation.

Q: What are the impacts in the Southwest of warmer temperatures during droughts?

JW: We do not want a hotter and drier foresummer during drought. These conditions increase water demand. For example, I know that I used more water in recent years to keep the trees in my yard healthy. Air quality can suffer because hotter and drier conditions can lead to more dust in the air. Wildfire danger increases because hotter and drier conditions are better at drying out vegetation. And, what's worse, if you add a dry monsoon to the end of a hotter and drier foresummer, the wildfire season can continue further into the summer.

Q: Will warmer and therefore drier droughts in the Southwest be common in the future?

JW: First, drought is a normal part of our climate, and I have no reason to think that it will not occur in the future. The only question is when drought will occur. Second, I would bet on temperatures continuing to warm in the region, primarily due to human-caused climate change. So, I expect that any drought in the future would be warmer, and that the ability of the atmosphere to take up moisture from the surface – the size of the sponge – would be greater.

Q: What is the take-home message of your research?

JW: I'd like to think that we are helping people understand what a few degrees of warming means for the Southwest, in particular during drought. Given that the societal impacts of drought under warmer temperatures are mostly bad, and that the typically hottest and driest time of the year is hotter and drier, I haven't particularly enjoyed the 2000s drought, and I certainly would not look forward to the next one.

Climate Variability in the South

Robert Merideth *– Assistant Director and Editor-in-Chief, Udall Center for Studies in Public Policy, The University of Arizona*

Climate is an important and multifaceted aspect of the physical, social, and economic character of the Southwest. The relatively warm and sunny winter weather throughout much of the region is a principal attraction for new residents, visitors, and businesses. Yet, high summer temperatures, occasional floods, and periods of drought are something to be endured or overcome.

Over the centuries, societies have developed particular adaptive strategies to cope with the region's climatic extremes. Early inhabitants relied on relatively simple techniques for cropping, irrigation, and housing. Today, residents cope with the aid of complex water-storage and flood-control structures, irrigation canals, water-supply pipelines, groundwater pumping, air conditioning, and other technologies.

These modern responses, though, have come at a cost, requiring large-scale water transfers, heavy energy use, and extensive environmental modifications. In addition, the trends and realities in the Southwest mean that we may soon be reaching - or have already reached - limits to our adaptive capabilities. And, as some suggest, we may be approaching conditions of even greater vulnerability than those early residents.

Climate Patterns in the Southwest

The Southwest's climate shows great variation from place to place, season to season, and year to year. Ranging from high-elevation plateaus to low deserts, the Southwest generally sees cooler temperatures and greater precipitation at higher elevations and warmer, drier weather patterns at lower altitudes.

Most of the region's rainfall occurs in the summer, governed by the North American monsoon and occurring in brief, intense, localized thunderstorms. Winter precipitation falls more gently, over a longer period of time and over a larger area, and is considerably varied from one year to the next, depending on the El Niño and La Niña phenomena. Overall, the last century saw decade-to-decade shifts in precipitation patterns throughout the Southwest, with periods of wetter than average weather in the early and late part of the century and one period of extended drought in the 1950s.

Looking further into the past, climatic conditions can be detected in the measurements of tree-ring growth. These natural records reveal that precipitation patterns for the previous century have been somewhat atypical and generally wetter than usual, especially when compared to much longer-term patterns detected over the past two thousand years.

Social and Economic Factors

While it's impossible to predict the precise climatic conditions in store for the Southwest, it is important to recognize and understand the relationships between the climate and the region's social, political, economic and environmental conditions.

As one of the fastest growing regions in the United States, the Southwest is experiencing rapid population and economic expansions. But with this growth has come the conversion of land; an increased demand for water, energy, and other resources; increases in wastes and pollution; and strains on state and local government services.

Heat waves, snowstorms, floods, or extended droughts could affect crops, roadways, infrastructure, and reservoirs, but also might change energy demand, alter retail sales, increase insurance claims, or promote hospital admissions in ways that affect the service and retail sectors. Thus, significant or prolonged climatic events can have a direct impact on key economic sectors as well as an indirect impact on related sectors. Likewise, communities dependent on a single activity can be particularly vulnerable.

Climatic Impacts on the Southwest

In urban areas, demands for water and water supplies vary seasonally. During periods of drought, some municipal water providers can augment diminished surface-water supplies with groundwater, but there are concerns across the region about the overuse of groundwater resources.

Energy is another sector sensitive to climatic variability, where both supply and demand fluctuate with temperatures and precipitation. Mining operations have a distinct vulnerability related to climate: too little water for processing or too much water in either the mine itself or in the waste settling ponds can interrupt operations.

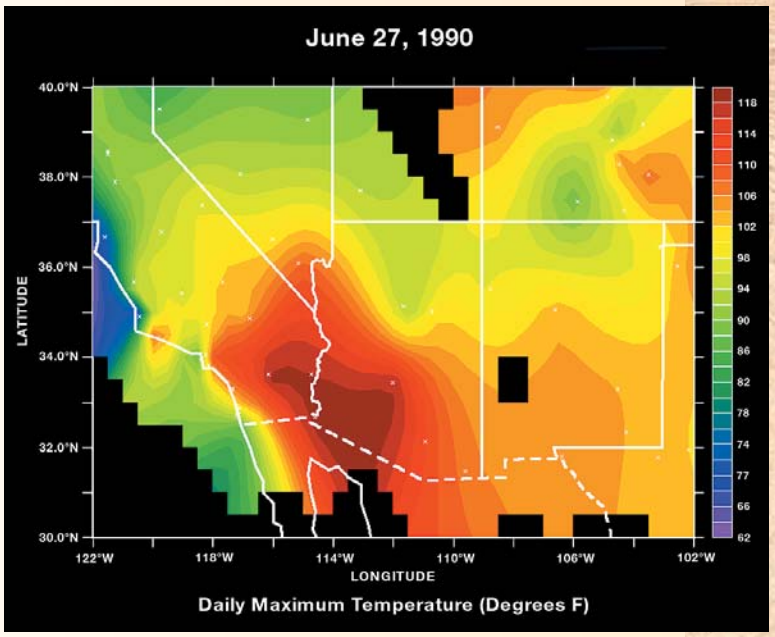
Agricultural production in the Southwest relies heavily on irrigation, using nearly 80 percent of all water consumed. Global economic demands are shifting the types of crops grown in the region, often to crops that are more water-intensive, such as alfalfa. Because agriculture tends to be concentrated in relatively small areas in the Southwest, climatic events could be localized but would affect much of the production.

Since the viability of rangelands is dependent on precipitation, climatic extremes can also have a large impact on ranching operations. Other stresses on ranching viability in the Southwest include rural land speculation and development

west

pressures, concerns over habitat protection, and changes in consumer dietary preferences.

Most recently, the effects of climatic variability have been seen in forest-fire frequency. Likewise, insect infestations, mortality and growth of species, and alterations in ecosystem composition have felt the effects of extreme climatic changes. Riparian areas and aquatic ecosystems can be affected by reduced surface-water flows, declining groundwater levels, losses of native vegetation, and changes in the timing and amount of precipitation. Climate also affects recreation and tourism: snowfall precipitation, river flows, and the vitality of forests, grasslands, riparian other natural or scenic areas attract tourists for snowing, fishing, hiking, birdwatching, and other activities.



Daily maximum temperature, June 27, 1990, when a major heat wave crossed the Southwest. From CLIMVIS, the climate visualization system from the National Climate Data Center, at lwf.ncdc.gov/oa/ferret/fsodlas/contour.html.

Finally, significant effects on human health can result from extreme temperatures or weather events, causing increased air pollutions like ground-level ozone; water and air-borne diseases such as valley fever; and vector-borne diseases such as hanta virus, dengue, and malaria.

Responses with Additional Benefits

While the Southwest's climate has varied a great deal over time, and there is every reason to expect it to continue to vary in the future, the rate and magnitude of these changes remains uncertain - especially given the influence of an overall global warming trend. Given that our present society and economy in the region developed during a relatively wet period, just a return to more typical, drier conditions recorded in tree-ring records would present major challenges and far-reaching consequences throughout the region.

In most instances, appropriate responses to climatic variability and change, such as water conservation, renewable energy production, urban growth management, open-space and ecosystem protection often have many more general benefits and can promote longer-term economic and environmental sustainability in the region.

Excerpted from "A Primer on Climatic Variability and Change in the Southwest" by Robert Merideth, published by the Udall Center for Studies in Public Policy and the Institute for the Study of Planet Earth (ISPE) at The University of Arizona. For a free copy, contact ISPE at (520) 792-8712 or the Udall Center at (520) 884-4373, www.udallcenter.arizona.edu.

Some Climate Lessons

Global connections.
When it comes to climate, no region is in isolation from any other. Climatic patterns and cycles may have their origins in one area but have widespread effects throughout the planet. Agricultural losses from natural hazards in the Midwest, livestock selloffs due to drought in Texas and Mexico, and increased energy demands due to heat waves in California or the Great Plains, all have an effect on the Southwest.

Information is key.
Information about climatic variability and change - whether it be in the form of six-month outlooks for precipitation, month-by-month forecasts of spring snowmelt and streamflow, weekly weather reports, or even short-term flash flood warnings - is key to being able to adapt, or respond to the impacts.

Coordinated planning and management.
There is a need for coordinated communication and interaction among the various individuals, agencies, and institutions involved in decision making, including those in drought management, flood response, energy provision, fire control, health care and disease prevention, and land and ecosystem management.

El Niño–Southern Oscillation: the causes, impacts in the Southwest, and future

By Zack Guido

El Niño and La Niña are words frequently tossed around to explain weather conditions in the Southwest. The sibling events, born thousands of miles away in the air over the tropical Pacific Ocean and in its waters, can deliver copious rain and snow to the region or cause widespread drought.

Perhaps no other natural phenomenon influences the weather and climate of the Southwest more than El Niño and La Niña. However, the causes and consequences of these events are mysterious to many people. How can changes off the coast of Peru ripple across the globe to steer rain away from Arizona? Why does El Niño soak southern Arizona during the winters but reduce snowfall in parts of the Rocky Mountains? Will climate change cause more El Niño or La Niña events, and if so, what does this mean for Arizona and New Mexico? Understanding the weather and climate of the Southwest isn't complete without a working knowledge of El Niño and La Niña.

The forces at play

El Niño and La Niña are part of the El Niño–Southern Oscillation (ENSO), a natural seesaw in oceanic sea surface temperatures and surface air pressure between the eastern and western tropical Pacific Ocean. The causes for this fluctuation have been studied since the 1950s, when ENSO became widely accepted in the scientific community.

ENSO's inner workings are complicated. The rotation of the Earth causes trade winds in low latitudes to blow hard from the east, pushing warm surface water in the tropical Pacific Ocean westward near the northern coast of Australia like a snow plow.

As the warm water pools, it works in tandem with intense solar rays to heat the surrounding air. The hot air then rises like a balloon, creating a zone of low air pressure.

As the air ascends, it cools and condenses, forming cotton-ball clouds that burst with rain. That air then travels east and descends near the coast of Peru and Ecuador. Sinking air piles on the Earth's surface, forming a high pressure zone that acts like a vice. The pressure difference squeezes air in the east toward the west, where it fills the void created by the hot, rising air.

In this way, a large circular pattern known as the Walker circulation is completed. Although the Walker circulation is always in motion, its movement is tuned by El Niño and La Niña events, which regulate sea surface temperatures and wind speed.

During El Niño events, the trade winds slacken, enabling an eastward migration of warm water. The center of rain follows, moving east to the middle of the Pacific Ocean near Tahiti.

La Niña events behave in the opposite way; the trade winds intensify and stack the warm surface water in the west even more than in normal years—the waters near Australia are often five feet higher than the ocean surface in the east during La Niña episodes (Figure 1). The area of intense rainfall is dragged back toward Australia.

One event often lasts less than a year and returns two to seven years later. In the meantime, the ocean and atmosphere are either in the la Niña or El Niño phase or

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Walker Circulation and the La Niña phase of ENSO

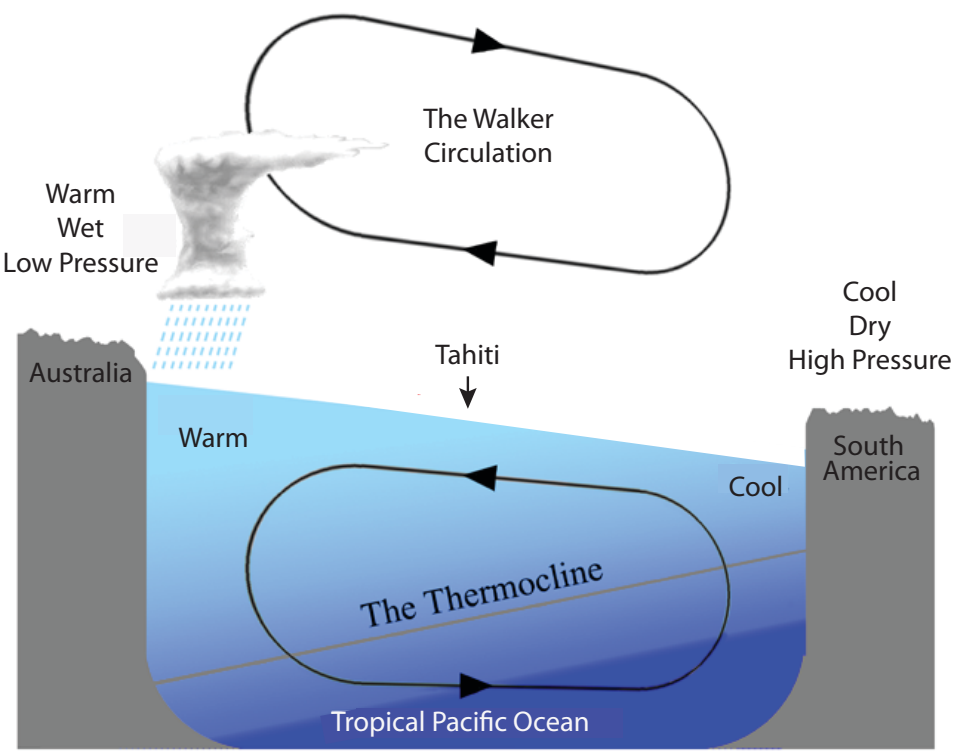


Figure 1. La Niña events modify the Walker circulation—the circular flow in air over the tropical Pacific Ocean—while moving the location of warm sea surface waters and intense rain. These changes, and those caused by El Niño episodes, impact the weather in the US Southwest.

El Niño, continued

hovering around the historical average, deemed "neutral" conditions.

The transition from one event to another is a natural example of a climate system regulating itself. ENSO events would become stronger and stronger without a switch. In a La Niña, for example, a self-reinforcing cycle would begin with strong trade winds, which would enhance the pressure difference between the east and west. This would in turn cause stronger winds, amplifying La Niña on and on.

This doesn't occur. Instead, El Niño and La Niña events flip-flop because the air and oceans respond to each other at different speeds. Winds react to the warming or cooling sea surface temperatures within days. It takes the ocean months to respond to changes in the winds. A memory of the departed winds is expressed as a wave that develops and propagates along a temperature boundary called the thermocline, which separates deeper, cold water from warmer, surface water.

For example, strong winds push warm water westward during a La Niña, which creates a valley in the thermocline and increases the thickness of the pool of warm water. The valley then migrates east toward Peru. When it reaches the coastal region it warms the water there, setting up conditions for an El Niño. The interval between one El Niño or La Niña and another is therefore determined by the speed of the subsurface wave.

Defining El Niño and La Niña

ENSO events are commonly defined by how high or low sea surface temperatures are compared to the average. An El Niño event is judged to have taken hold when average monthly temperatures in a defined region in the middle tropical Pacific Ocean exceed 0.4 degrees Celsius (approximately 0.7 degrees Fahrenheit) and endure for more than five consecutive months.

Higher temperature differences create stronger events. In the winter of 1997–1998, during one of the strongest El Niño events recorded, the average sea surface temperature difference was about 2.4 degrees C above average (approximately 4.3 degrees F). La Niña events have the same criteria but require that the temperature difference be greater than 0.4 degrees C below average.

To reveal how ENSO events alter atmospheric circulation, the Southern Oscillation Index, or SOI, evaluates the pressure difference in the central and western Pacific Ocean. The SOI is calculated based on the differences in air pressure anomalies between Tahiti and Darwin, Australia. A negative SOI, which is characteristic of El Niño events, indicates air pressure over Tahiti is less than at Darwin. Both the sea surface temperature index and the SOI are used together to help evaluate several factors, including the early and late stages of an ENSO event when conditions are not obvious, the duration of the events, and their strength.

The effect of ENSO on weather in the Southwest

El Niño and La Niña episodes tend to develop between April and June and peak between December and January, when sea surface temperatures reach their warmest and coldest states, respectively. As a result, changes to atmospheric circulation, and therefore weather, are most prominent in the winter.

The ENSO fingerprint on the Southwest is principally caused by shifting jet streams. During El Niño events, the Pacific jet stream is straighter and is pulled south (Figure 2), and storms form in the Pacific Ocean just west of California, in part because waters are warmer than average in this region during El Niño events. The combination of the jet stream and storms often results in a wet winter and increased rain and snow across California and the southern United States.

La Niña events, on the other hand, often bring dry conditions to Arizona and New Mexico. In La Niña winters, the jet streams take a more serpentine path. The Pacific jet stream usually carves north and enters North America through the northwestern US, bringing wetter-than-average conditions to that region and diverting storms away from the Southwest.

The effect El Niño and La Niña events have on the weather is nuanced. An El Niño does not always cause wet winters, nor does a La Niña consistently deliver dry conditions. Between 1896 and 2002 in Arizona, for example, about 50 percent of the winters experiencing an El Niño event received more than 115 percent of average precipitation, while roughly 25 percent of the winters received less than 85 percent of the average.

The amount of precipitation during ENSO events also changes by region in Arizona and New Mexico and beyond. During an El Niño, the southern regions of both states often receive more winter rain and snow than northern regions.

Critical winter precipitation for the Southwest also falls as snow in the headwaters of Arizona's most important river, the Colorado. About 70 percent of that water originates in the mountains of Utah, Wyoming, and Colorado. However, when the southern regions of the Southwest are wet, precipitation in the Upper Colorado River Basin is often average or below average.

For example, during El Niño events between 1896 and 2002, the Colorado portion of the Upper Colorado River Basin received less than 115 percent of average precipitation about 60 percent of the time; it experienced dry conditions in which rain and snow measured less than 85 percent of average nearly one-third of the time. During this same period, the Arizona portion of the Lower Colorado

continued on page 3

El Niño, continued

River Basin experienced wet conditions with rainfall greater than 115 percent of average about half of the time.

The impact of ENSO on summer weather is not as clear-cut as the changes that occur in winter. El Niño events often are associated with two phenomena that have opposite effects on precipitation in the Southwest. On one hand, an El Niño can stifle summer rains in Arizona and New Mexico because they can weaken and reposition the subtropical high that guides moisture into the Southwest. On the other hand, El Niño events also can foment a higher number of tropical storms, some of which deliver copious summer and fall rains to the region.

The future of ENSO

Debate continues about whether the character of ENSO events will change as the world warms in response to increased levels of greenhouse gases. One hypothesis suggests that a warmer world will cause stronger or more frequent El Niño events, which would help moderate warming because much of the heat released from the ocean during El Niño years eventually makes its way into space.

The other hypothesis calls for a spike in La Niña events, which would help mitigate global warming by sequestering some of the incoming heat into deeper waters. Because both El Niño and La Niña play a prominent role in the weather of the Southwest, changes will have consequences. A more La Niña-like future could strain already limited water resources, and more intense events could deliver more frequent floods or droughts.

To help resolve this debate, scientists are monitoring ENSO and using climate models to simulate future conditions. A recent study shows that the easterly trade winds have weakened and suggests this may be behind the prevalence of more El Niño-like conditions in recent years.

Other studies have documented a change in the location of intense rainfall and the pattern of sea surface temperatures of El Niño events, and a decrease in the vigor of the Walker circulation. Although these observations and projections are insufficient to foretell the future, it is clear that ENSO is on the move.

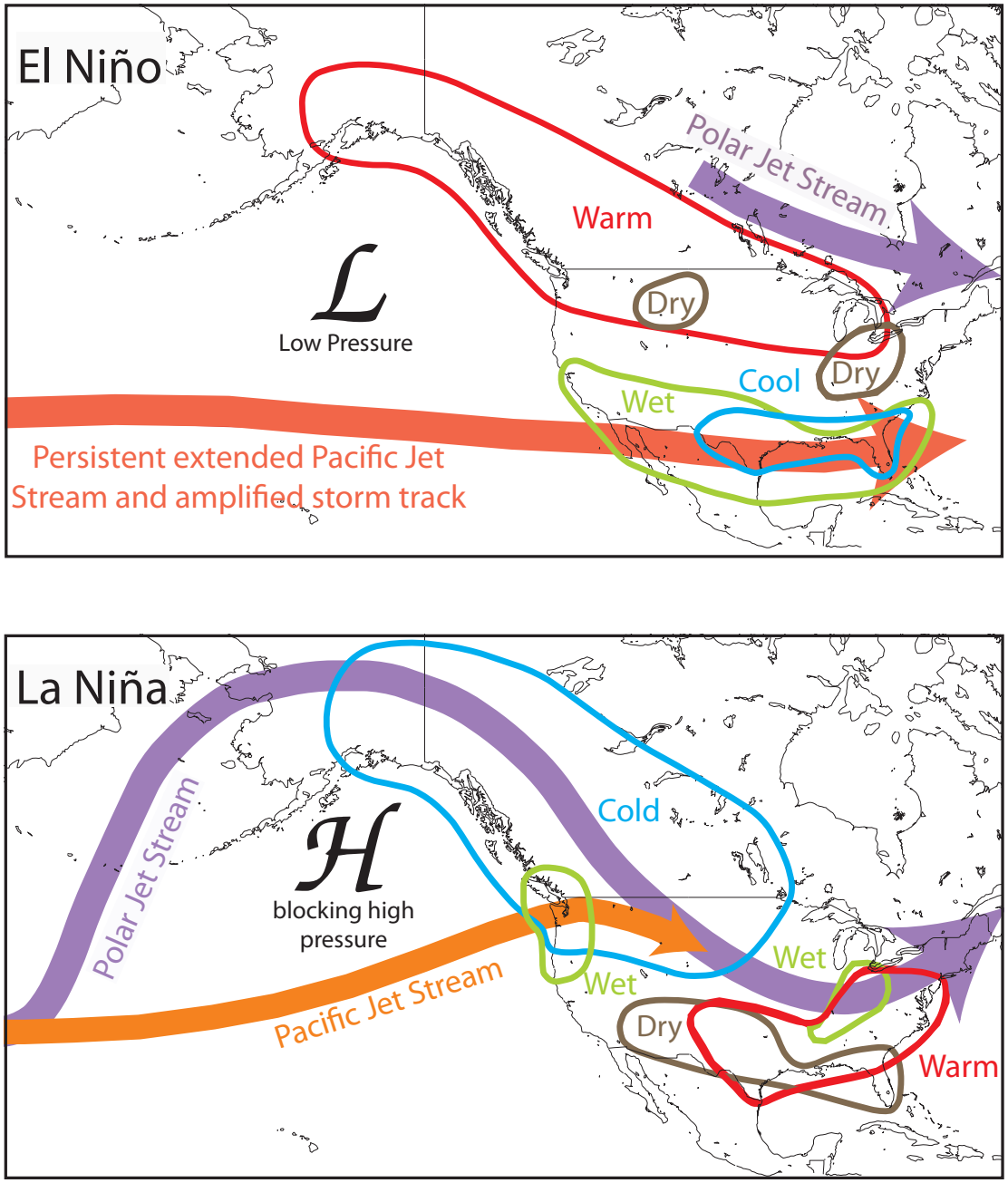
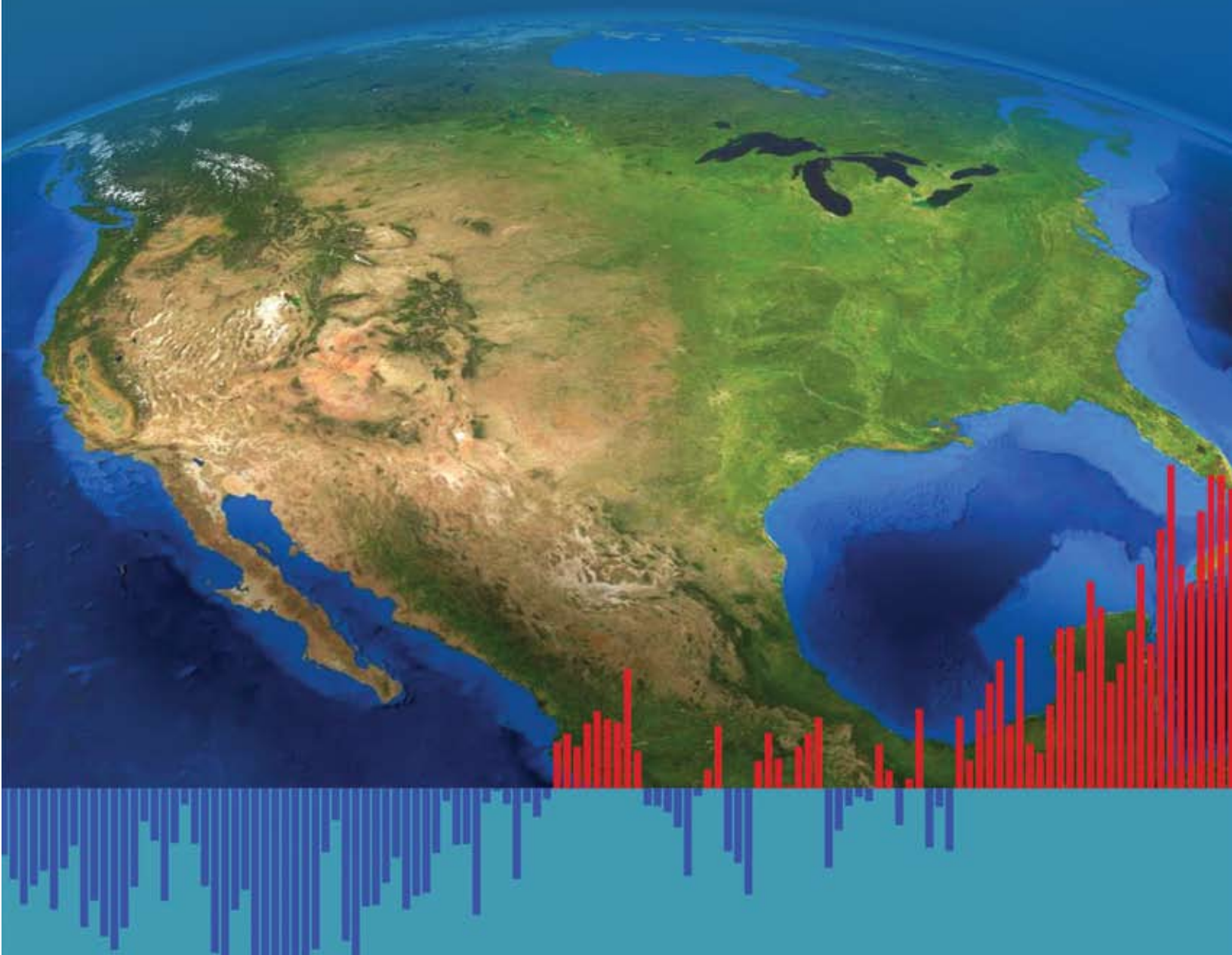


Figure 2. El Niño and La Niña events cause the path of the jet streams to move over the US in different locations, often causing wet winters during El Niño episodes and dry winters during La Niña events in the Southwest.

Global Climate Change Impacts in the United States

U.S. GLOBAL CHANGE RESEARCH PROGRAM



Executive Summary

Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases. These emissions come mainly from the burning of fossil fuels (coal, oil, and gas), with important contributions from the clearing of forests, agricultural practices, and other activities.

Warming over this century is projected to be considerably greater than over the last century. The global average temperature since 1900 has risen by about 1.5ºF. By 2100, it is projected to rise another 2 to 11.5ºF. The U.S. average temperature has risen by a comparable amount and is very likely to rise more than the global average over this century, with some variation from place to place. Several factors will determine future temperature increases. Increases at the lower end of this range are more likely if global heat-trapping gas emissions are cut substantially. If emissions continue to rise at or near current rates, temperature increases are more likely to be near the upper end of the range. Volcanic eruptions or other natural variations could temporarily counteract some of the human-induced warming, slowing the rise in global temperature, but these effects would only last a few years.

Reducing emissions of carbon dioxide would lessen warming over this century and beyond. Sizable early cuts in emissions would significantly reduce the pace and the overall amount of climate change. Earlier cuts in emissions would have a greater effect in reducing climate change than comparable reductions made later. In addition, reducing emissions of some shorter-lived heat-trapping gases, such as methane, and some types of particles, such as soot, would begin to reduce warming within weeks to decades.

Climate-related changes have already been observed globally and in the United States. These include increases in air and water temperatures, reduced frost days, increased frequency and intensity of heavy downpours, a rise in sea level, and reduced snow cover, glaciers, permafrost, and sea ice. A longer ice-free period on lakes and rivers, lengthening of the growing season, and increased water vapor in the atmosphere have also been observed. Over the past 30 years, temperatures have risen faster in winter than in any other season, with average winter temperatures in the Midwest and northern Great Plains increasing more than 7ºF. Some of the changes have been faster than previous assessments had suggested.

These climate-related changes are expected to continue while new ones develop. Likely future changes for the United States and surrounding coastal waters include more intense hurricanes with related increases in wind, rain, and storm surges (but not necessarily an increase in the number of these storms that make landfall), as well as drier conditions in the Southwest and Caribbean. These changes will affect human health, water supply, agriculture, coastal areas, and many other aspects of society and the natural environment.

This report synthesizes information from a wide variety of scientific assessments (see page 7) and recently published research to summarize what is known about the observed and projected consequences of climate change on the United States. It combines analysis of impacts on various sectors

such as energy, water, and transportation at the national level with an assessment of key impacts on specific regions of the United States. For example, sea-level rise will increase risks of erosion, storm surge damage, and flooding for coastal communities, especially in the Southeast and parts of Alaska. Reduced snowpack and earlier snow melt will alter the timing and amount of water supplies, posing significant challenges for water resource management in the West.

Society and ecosystems can adjust to some climatic changes, but this takes time. The projected rapid rate and large amount of climate change over this century will challenge the ability of society and natural systems to adapt. For example, it is difficult and expensive to alter or replace infrastructure designed to last for decades (such as buildings, bridges, roads, airports, reservoirs, and ports) in response to continuous and/or abrupt climate change.

Impacts are expected to become increasingly severe for more people and places as the amount of warming increases. Rapid rates of warming would lead to particularly large impacts on natural ecosystems and the benefits they provide to humanity. Some of the impacts of climate change will be irreversible, such as species extinctions and coastal land lost to rising seas.

Unanticipated impacts of increasing carbon dioxide and climate change have already occurred and more are possible in the future. For example, it has recently been observed that the increase in atmospheric carbon dioxide concentration is causing an increase in ocean acidity. This reduces the ability of corals and other sea life to build shells and skeletons out of calcium carbonate. Additional impacts in the future might stem from unforeseen changes in the climate system, such as major alterations in oceans, ice, or storms; and unexpected consequences of ecological changes, such as massive dislocations of species or pest outbreaks. Unexpected social or economic changes, including major shifts in wealth, technology, or societal priorities would also affect our ability to respond to climate change. Both anticipated and unanticipated impacts become more challenging with increased warming.

Projections of future climate change come from careful analyses of outputs from global climate models run on the world's most advanced computers. The model simulations analyzed in this report used plausible scenarios of human activity that generally lead to further increases in heat-trapping emissions. None of the scenarios used in this report assumes adoption of policies explicitly designed to address climate change. However, the level of emissions varies among scenarios because of differences in assumptions about population, economic activity, choice of energy technologies, and other factors. Scenarios cover a range of emissions of heat-trapping gases, and the associated climate projections illustrate that lower emissions result in less climate change and thus reduced impacts over this century and beyond. Under all scenarios considered in this report, however, relatively large and sustained changes in many aspects of climate are projected by the middle of this century, with even larger changes by the end of this century, especially under higher emissions scenarios.

In projecting future conditions, there is always some level of uncertainty. For example, there is a high degree of confidence in projections that future temperature increases will be greatest in the Arctic and in the middle of continents. For precipitation, there is high confidence in projections of continued increases in the Arctic and sub-Arctic (including Alaska) and decreases in the regions just outside the tropics, but the precise location of the transition between these is less certain. At local to regional scales and on time frames up to a few years, natural climate variations can be relatively large and can temporarily mask the progressive nature of global climate change. However, the science of making skillful projections at these scales has progressed considerably, allowing useful information to be drawn from regional climate studies such as those highlighted in this report.

This report focuses on observed and projected climate change and its impacts on the United States. However, a discussion of these issues would be incomplete without mentioning some of the actions society can take to respond to the climate challenge. The two major categories are "mitigation" and "adaptation." Mitigation refers to options for limiting climate change by, for example, reducing

heat-trapping emissions such as carbon dioxide, methane, nitrous oxide, and halocarbons, or removing some of the heat-trapping gases from the atmosphere. Adaptation refers to changes made to better respond to present or future climatic and other environmental conditions, thereby reducing harm or taking advantage of opportunity. Effective mitigation measures reduce the need for adaptation. Mitigation and adaptation are both essential parts of a comprehensive climate change response strategy.

Carbon dioxide emissions are a primary focus of mitigation strategies. These include improving energy efficiency, using energy sources that do not produce carbon dioxide or produce less of it, capturing and storing carbon dioxide from fossil fuel use, and so on. Choices made about emissions reductions now and over the next few decades will have far-reaching consequences for climate-change impacts. The importance of mitigation is clear in comparisons of impacts resulting from higher versus lower emissions scenarios considered in this report. Over the long term, lower emissions will lessen both the magnitude of climate-change impacts and the rate at which they appear. Smaller climate changes that come more slowly make the adaptation challenge more tractable.

However, no matter how aggressively heat-trapping emissions are reduced, some amount of climate change and resulting impacts will continue due to the effects of gases that have already been released. This is true for several reasons. First, some of these gases are very long-lived and the levels of atmospheric heat-trapping gases will remain elevated for hundreds of years or more. Second, the Earth's vast oceans have absorbed much of the heat added to the climate system due to the increase in heat-trapping gases, and will retain that heat for many decades. In addition, the factors that determine emissions, such as energy-supply systems, cannot be changed overnight. Consequently, there is also a need for adaptation.

Adaptation can include a wide range of activities. Examples include a farmer switching to growing a different crop variety better suited to warmer or drier conditions; a company relocating key business centers away from coastal areas vulnerable to sea-level rise and hurricanes; and a community altering its zoning and building codes to place fewer structures in harm's way and making buildings less vulnerable to damage from floods, fires, and other extreme events. Some adaptation options that are currently being pursued in various regions and sectors to deal with climate change and/or other environmental issues are identified in this report. However, it is clear that there are limits to how much adaptation can achieve.

Humans have adapted to changing climatic conditions in the past, but in the future, adaptations will be particularly challenging because society won't be adapting to a new steady state but rather to a rapidly moving target. Climate will be continually changing, moving at a relatively rapid rate, outside the range to which society has adapted in the past. The precise amounts and timing of these changes will not be known with certainty.

In an increasingly interdependent world, U.S. vulnerability to climate change is linked to the fates of other nations. For example, conflicts or mass migrations of people resulting from food scarcity and other resource limits, health impacts, or environmental stresses in other parts of the world could threaten U.S. national security. It is thus difficult to fully evaluate the impacts of climate change on the United States without considering the consequences of climate change elsewhere. However, such analysis is beyond the scope of this report.

Finally, this report identifies a number of areas in which inadequate information or understanding hampers our ability to estimate future climate change and its impacts. For example, our knowledge of changes in tornadoes, hail, and ice storms is quite limited, making it difficult to know if and how such events have changed as climate has warmed, and how they might change in the future. Research on ecological responses to climate change is also limited, as is our understanding of social responses. The section titled *An Agenda for Climate Impacts Science* at the end of this report offers some thoughts on the most important ways to improve our knowledge. Results from such efforts would inform future assessments that continue building our understanding of humanity's impacts on climate, and climate's impacts on us.

Key Findings

1. Global warming is unequivocal and primarily human-induced.

Global temperature has increased over the past 50 years. This observed increase is due primarily to human-induced emissions of heat-trapping gases. (p. 13)

2. Climate changes are underway in the United States and are projected to grow.

Climate-related changes are already observed in the United States and its coastal waters. These include increases in heavy downpours, rising temperature and sea level, rapidly retreating glaciers, thawing permafrost, lengthening growing seasons, lengthening ice-free seasons in the ocean and on lakes and rivers, earlier snowmelt, and alterations in river flows. These changes are projected to grow. (p. 27)

3. Widespread climate-related impacts are occurring now and are expected to increase.

Climate changes are already affecting water, energy, transportation, agriculture, ecosystems, and health. These impacts are different from region to region and will grow under projected climate change. (p. 41-106, 107-152)

4. Climate change will stress water resources.

Water is an issue in every region, but the nature of the potential impacts varies. Drought, related to reduced precipitation, increased evaporation, and increased water loss from plants, is an important issue in many regions, especially in the West. Floods and water quality problems are likely to be amplified by climate change in most regions. Declines in mountain snowpack are important in the West and Alaska where snowpack provides vital natural water storage. (p. 41, 129, 135, 139)

5. Crop and livestock production will be increasingly challenged.

Many crops show positive responses to elevated carbon dioxide and low levels of warming, but higher levels of warming often negatively affect growth and yields. Increased pests, water stress, diseases, and weather extremes will pose adaptation challenges for crop and livestock production. (p. 71)

6. Coastal areas are at increasing risk from sea-level rise and storm surge.

Sea-level rise and storm surge place many U.S. coastal areas at increasing risk of erosion and flooding, especially along the Atlantic and Gulf Coasts, Pacific Islands, and parts of Alaska. Energy and transportation infrastructure and other property in coastal areas are very likely to be adversely affected. (p. 111, 139, 145, 149)

7. Risks to human health will increase.

Harmful health impacts of climate change are related to increasing heat stress, waterborne diseases, poor air quality, extreme weather events, and diseases transmitted by insects and rodents. Reduced cold stress provides some benefits. Robust public health infrastructure can reduce the potential for negative impacts. (p. 89)

8. Climate change will interact with many social and environmental stresses.

Climate change will combine with pollution, population growth, overuse of resources, urbanization, and other social, economic, and environmental stresses to create larger impacts than from any of these factors alone. (p. 99)

9. Thresholds will be crossed, leading to large changes in climate and ecosystems.

There are a variety of thresholds in the climate system and ecosystems. These thresholds determine, for example, the presence of sea ice and permafrost, and the survival of species, from fish to insect pests, with implications for society. With further climate change, the crossing of additional thresholds is expected. (p. 76, 82, 115, 137, 142)

10. Future climate change and its impacts depend on choices made today.

The amount and rate of future climate change depend primarily on current and future human-caused emissions of heat-trapping gases and airborne particles. Responses involve reducing emissions to limit future warming, and adapting to the changes that are unavoidable. (p. 25, 29)

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Spotting Drought Before It's Too Late

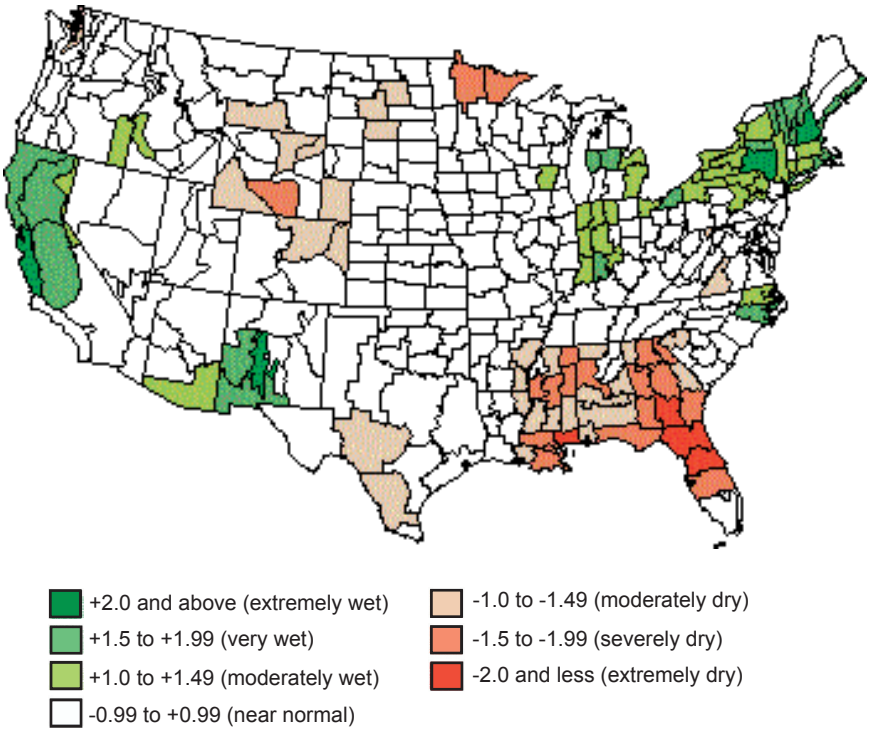
Drought is slow, but its costs and indirect effects add up to devastation that rivals that of hurricanes or floods. As with other disasters, early warning and preparedness saves lives and livelihoods. Unlike other disasters, caused by too much energy unleashed, drought is what isn't — when the atmosphere fails to deliver anticipated water supplies.

General definition: Drought is when a shortfall in precipitation creates a shortage of water, whether it's for crops, utilities, municipal water supplies, recreation, wildlife, or other purposes.

It takes more than a general definition to spot a drought in time to prevent its worst effects.

Drought planning usually involves picking or creating an index to identify and quantify departures from normal. Drought indices assimilate thousands of bits of data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible big picture that is far more useful than raw data for decision making. A drought index value is typically a single number associated with a description, such as "moderately dry."

6-month Standardized Precipitation Index through August 2006



The Standardized Precipitation Index, based on precipitation values from more than 500 monitoring stations around the country, is computed monthly for a variety of time frames. For example, the SPI above compares precipitation values from March 2006 hrough August 2006 with all other recorded March through August data.

For resource managers concerned with meeting specific water supply needs, drought planning links a working definition of drought (sometimes based on an index) to triggers.

For example, Denver Water has created its own index. Drought declarations depend on its total predicted or actual reservoir storage on July 1. If that value falls below 80%, a Stage 1 Drought is triggered, and Denver Water initiates actions designed to yield a 10% reduction in water use. At a value of 65%, a Stage 2 Drought is triggered, and the water use reduction target is 30%, with mandatory water restrictions enacted. A value of 40% triggers a Stage 3 Drought, with prohibitions on most lawn watering and a water use reduction target of 50%. A Stage 4 Drought is triggered at 25%, with a goal of a 66% reduction in water use.

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Disciplinary Perspectives

How you measure drought depends on where you're coming from and what you're interested in. Traditionally, drought scholars have identified three main physical ways to measure drought:

meteorological: Meteorological drought is usually based on precipitation's departure from normal over some period of time. These definitions are usually region-specific, and presumably based on a thorough understanding of regional climatology. Normally, meteorological measurements are the first indicators of drought.

hydrological: Hydrological drought refers to deficiencies in surface and subsurface water supplies. It is measured as streamflow, and as lake, reservoir, and groundwater levels. There is a time lag between lack of rain or snow and less water in streams, rivers, lakes, and reservoirs, so hydrological measurements are not the earliest indicators of drought. When precipitation is reduced or deficient for a long time, this storage is reflected in declining surface and subsurface water levels.

agricultural: Agricultural drought occurs when there isn't enough soil moisture to meet the needs of a particular crop at a particular time. Agricultural drought is typically evident after meteorological drought but before a hydrological drought.

But drought's effects are widespread, and other people quantify drought by other measures and other effects. Economists, politicians, ecologists and social workers, among others, can each measure different effects of drought that result from the imbalance of water supply and demand.

Key Concepts

Drought is a normal part of virtually every climate on Earth. Drought isn't what we picture as "normal" weather, but history shows that droughts and floods are both part of the normal continuum of weather patterns.

Each place needs its own working definition of drought. Twenty inches of rain in a year would be slightly wetter than normal in Lubbock, Texas, but would be a severe drought in Nashville, Tennessee.

Weather isn't the only cause of drought. Drought results from both natural events, such as a long dry spell, and from human activities that increase demand for water. Expanding population, irrigation, and environmental awareness all put pressure on water supplies and increase vulnerability to drought.

Drought differs from aridity. Drought is a temporary deviation from normal. Aridity is a permanent feature of climates that receive little rain.

One rain doesn't necessarily end a drought. It can take months of below-normal precipitation to create a drought, and it often takes more than one good rainfall to catch up.

Drought is not the same as desertification, although some researchers speculate that the two are linked. Desertification is a long-term ecosystem change. The Food & Agriculture Organization of the United Nations describes desertification as "the sum of the geological, climatic, biological and human factors which lead to the degradation of the physical, chemical and biological potential of lands in arid and semi-arid zones, and endanger biodiversity and the survival of human communities."

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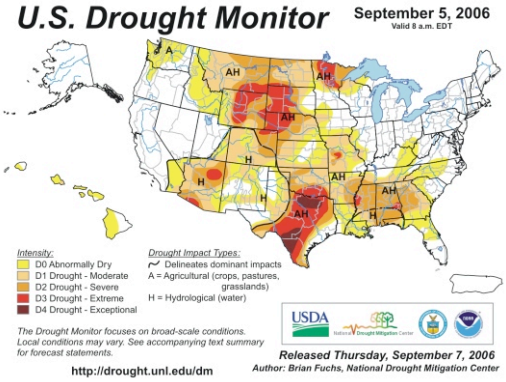
Products of the National Drought Mitigation Center

NDMC Website

The NDMC has an extensive and growing website — ***http://drought.unl.edu/*** — that promotes public awareness of drought and the need to plan for it. The site includes in-depth sections on monitoring, science, climatological analyses, historic analyses of impacts, planning methodologies, and mitigation strategies. It also includes an up-to-date collection of related links, access to NDMC publications, state drought plans and supporting documents, basic information for those new to the topic of drought, and a list of drought planners nationwide. The website typically receives about 25,000–30,000 visitors each month, about 10% of whom are from other countries.

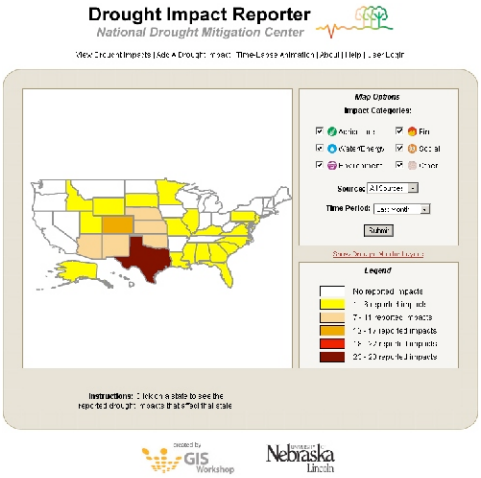
U.S. Drought Monitor

The U.S. Drought Monitor is a joint endeavor with the U.S. Department of Agriculture and the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. The Drought Monitor map summarizes information from numerous drought indices and indicators to provide a weekly overview of drought in the United States—where it is emerging, lingering, subsiding, or forecast. The map uses a new classification system to show drought intensity and type, similar to the schemes in use for hurricanes and tornadoes. It is produced and published weekly on the U.S. Drought Monitor website.
http://drought.unl.edu/dm/monitor.html



Drought Impact Reporter

The Drought Impact Reporter is an interactive tool developed by the NDMC to collect, quantify, and map reported drought impacts for the United States. It was created in response to the need for a national drought impact database. Information for the impact report database comes from a variety of sources, including on-line drought-related news stories and scientific publications, reviewed by NDMC staff; members of the public who visit the website and submit a drought-related impact; members of the media; and members of government agencies such as the National Oceanic and Atmospheric Administration (NOAA) and U.S. Department of Agriculture (USDA).
http://droughtreporter.unl.edu/



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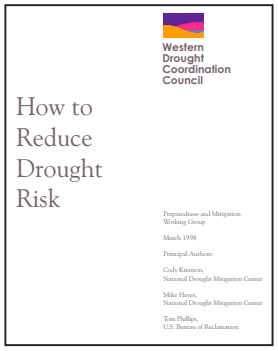
Drought Risk Guide

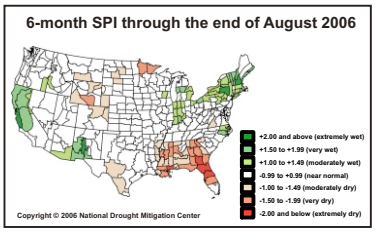
The NDMC helped produce How to Reduce Drought Risk as part of our work with the Western Drought Coordination Council.
http://drought.unl.edu/plan/handbook/risk.pdf



We've also incorporated the ideas in the risk reduction guide into "Drought Preparedness Planning: Building Institutional Capacity," featuring a 10-step drought-planning methodology developed by Dr. Donald Wilhite that has been adapted to fit the needs of governments at many levels in the United States and elsewhere.

Standardized Precipitation Index

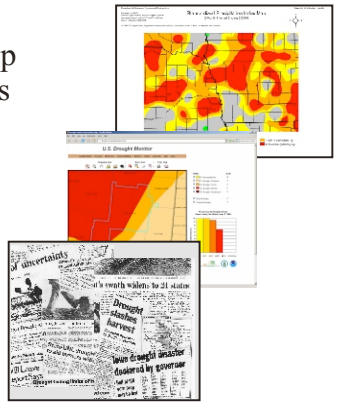
Each month we produce a suite of Standardized Precipitation Index (SPI) maps comparing the past 1, 3, 6, 9, and 12 months, and the year to date, of precipitation with the historic record. The NDMC's research has helped establish the SPI as a valuable tool for recognizing drought and triggering response and mitigation measures. The NDMC also advises a growing number of SPI users in the United States and in more than 20 countries around the world.
http://drought.unl.edu/monitor/spi.htm



NDMC–RMA Partnership Agreement Projects

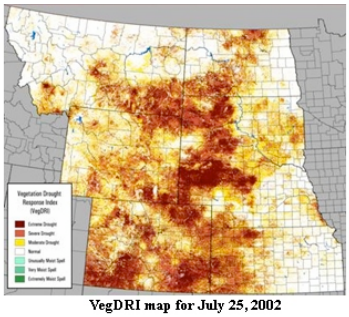
The NDMC, through a partnership agreement with the Risk Management Agency (RMA) of the U.S. Department of Agriculture, is developing six new products to help agricultural producers and advisors make better management decisions. The products are sub-projects of the Drought Risk, Impact, and Mitigation Information System:

1. Drought Risk Atlas
2. Vegetation Outlook (VegOUT)
3. Ranch Drought Planning
4. Drought Impact Reporter
5. Drought Portal Decision Support System
6. Economic Impacts of Drought



VegDRI Project

The NDMC, in collaboration with the U.S. Geological Survey's National Center for Earth Resources Observation and Science (EROS), recently developed a drought monitoring tool, the Vegetation Drought Response Index (VegDRI) for the seven states in the central United States. Combining satellite-derived vegetation data with climate and geophysical data, the VegDRI provides modeled output with sub-county scale information on drought-affected vegetation. Plans are underway to expand the tool to the contiguous United States and to tailor its use for producers to assess and manage risks associated with rangeland and forage failure caused by drought.
http://gisdata.usgs.net/website/Drought%5FMonitoring/



VegDRI map for July 25, 2002

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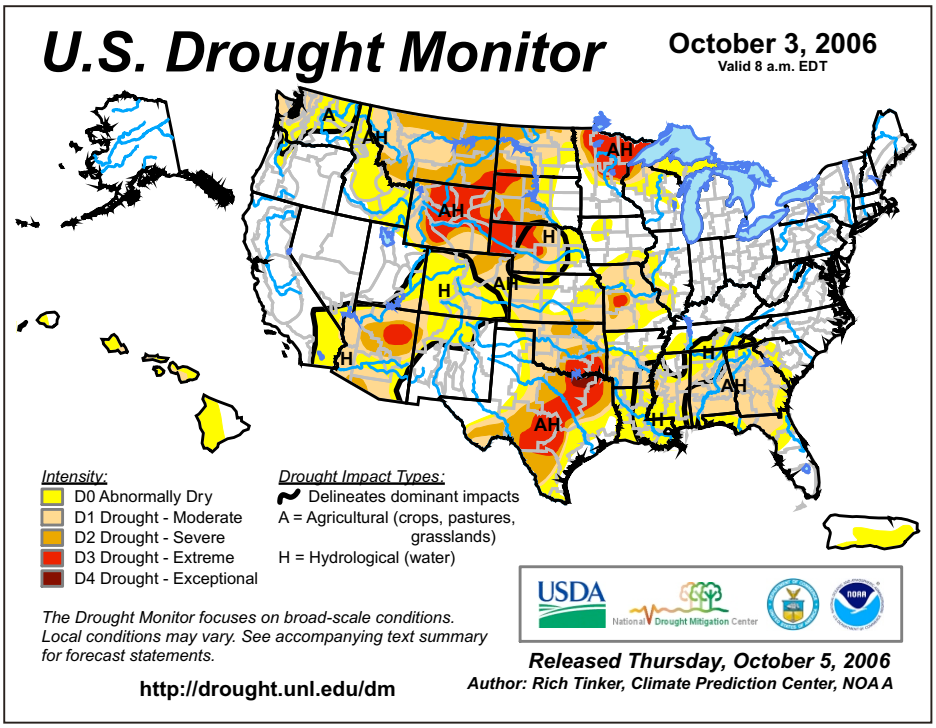
The U.S. Drought Monitor Map

About the Map

The Drought Monitor was unveiled August 11, 1999, at a White House press conference. The Monitor is the product of a partnership between the U.S. Departments of Agriculture and Commerce and the National Drought Mitigation Center at the University of Nebraska–Lincoln. Commerce Secretary William Daley introduced the Monitor in the midst of the worst drought to affect the eastern United States in several years, hailing it as an advance in drought monitoring and forecasting. Drought Monitor maps, produced weekly, summarize information from several different measurement systems onto a single, easy-to-read colored map.

The Drought Monitor provides a general, up-to-date summary of current drought across the 50 states, Puerto Rico, and the Pacific possessions. Its "big picture" gives the general public, media, officials, and others a common starting point for decision making. The map is not designed to depict local conditions or to replace drought warnings and watches issued by local or regional government entities. Local or state entities may—and should!—be monitoring indicators different from those used in the Drought Monitor to meet specific needs or to address local problems.



Interpreting the Map

D0–D4: The Drought Monitor summary map identifies general drought areas, labeling droughts by intensity, with D1 being the least intense and D4 being the most intense. D0 drought watch areas are either drying out and possibly heading into drought, or are recovering from drought but are not yet back to normal, suffering long-term impacts such as low reservoir levels.

A and H: Since *drought* means a moisture deficit severe enough to have social, environmental, or economic effects, we generally include a description of what the primary physical effects are:

A = agricultural (crops, pastures, and grassland)
H = water supplies (rivers, groundwater, and reservoirs)

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Map Key

D0, Abnormally Dry—Going into drought: short-term dryness slowing planting and growing crops or pastures. Coming out of drought: lingering water deficits; pastures or crops not fully recovered.

D1, First-Stage Drought—Some damage to crops, pastures; streams, reservoirs, or wells low; some water shortages developing or imminent; voluntary water use restrictions requested.

D2, Severe Drought—Crop or pasture losses likely; water shortages common; water restrictions imposed.

D3, Extreme Drought—Major crop/pasture losses; widespread water shortages or restrictions.

D4, Exceptional Drought—Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells, creating water emergencies.

How We Make the Map

Drought intensity categories are based on five key indicators and numerous supplementary indicators. The accompanying drought severity classification table shows the range of indicators for each dryness level. Because the ranges of the various indicators often don't coincide, the final drought category tends to be based on what the majority of the indicators show. The analysts producing the map also weight the indices according to how well they perform in various parts of the country during different times of the year. Also, additional indicators are often needed in the West, where winter snowfall has a strong bearing on water supplies.

Although the maps are based on the key indices and other measures of moisture, the final maps are adjusted to reflect real-world conditions as reported by numerous experts throughout the country.

This Map Does Not Replace Local Information

To keep the map from becoming too complex, the drought categories shown represent typical drought intensities, not every drought intensity, within the area. The map is not designed to depict local conditions or to replace drought warnings and watches issued by local or regional government entities. Local or state entities may be monitoring indicators different from those used in the Drought Monitor to meet specific needs or to address local problems. As a consequence, there could be water shortages or crop failures within an area not designated as being in drought, just as there could be locations with adequate water supplies in an area designated as D3 or D4 (extreme or exceptional) drought.

Drought Category	Palmer Drought Index	CPC Soil Moisture Model	USGS Weekly Streamflow	Standardized Precipitation Index	Short- & Long-Term Drought Indicator Blends
D0	-1.0 to -1.9	21-30	21-30	-0.5 to -0.7	21-30
D1	-2.0 to -2.9	11-20	11-20	-0.8 to -1.2	11-20
D2	-3.0 to -3.9	6-10	6-10	-1.3 to -1.5	6-10
D3	-4.0 to -4.9	3-5	3-5	-1.6 to -1.9	3-5
D4	-5.0 or less	0-2	0-2	-2.0 or less	0-2

National Integrated Drought Information System Drought Portal

By Christina Alvord, Western Water Assessment

Introduction

A new clearinghouse for drought information is now available. The U.S. Drought Portal, (http://www.drought.gov) released on November 1, 2007, features drought information, resources, and products useful in monitoring emerging and ongoing droughts, assessing impacts, and providing mitigation and preparedness strategies. The Drought Portal is a part of the National Integrated Drought Information System (NIDIS), a cross-agency effort to minimize vulnerability by collaborating drought management, planning, and preparedness on a national, state, and regional scale. It features updated drought information including hydrological, agricultural, and metrological conditions useful to a wide spectrum of user groups.

The Drought Portal was based on the need to assimilate, archive, and quality- control data and drought information, and to address drought questions, information gaps, and user needs in a consolidated location. The Drought Portal is intended as a localized tool to foster communication and partnership between NIDIS personnel, experts, and users to develop early detection and preparedness strategies. A goal of the Drought Portal is to provide a customized approach to drought information by providing a "My Page" feature, allowing users (decision makers, producers, general public, etc) to select and save products, content, data, and/or indices specific to their knowledge level and information needs.

Content selection and organization is based on providing users with tools and resources necessary in early drought detection and is available on the county, regional, and national scale. Three main boxes on the homepage feature the latest U.S. Drought Monitor, the Drought Impact Reporter, and the U.S. Seasonal Outlook, which provides information on current conditions, impacts, and expected persistence (Figure 15a). The Drought Portal features data and information from federal and non-federal sources, as well as an overview of NIDIS, drought education, planning, and research. A searchable database allows users to find specific products or resources, and a scroll of recent national drought news features drought information from a regional perspective.

From the homepage, users click on topic headings or the main boxes for related products and resources categorized by methodologies, sector, topic, and regional resources. Information is categorized in several ways to appeal to multiple user groups,

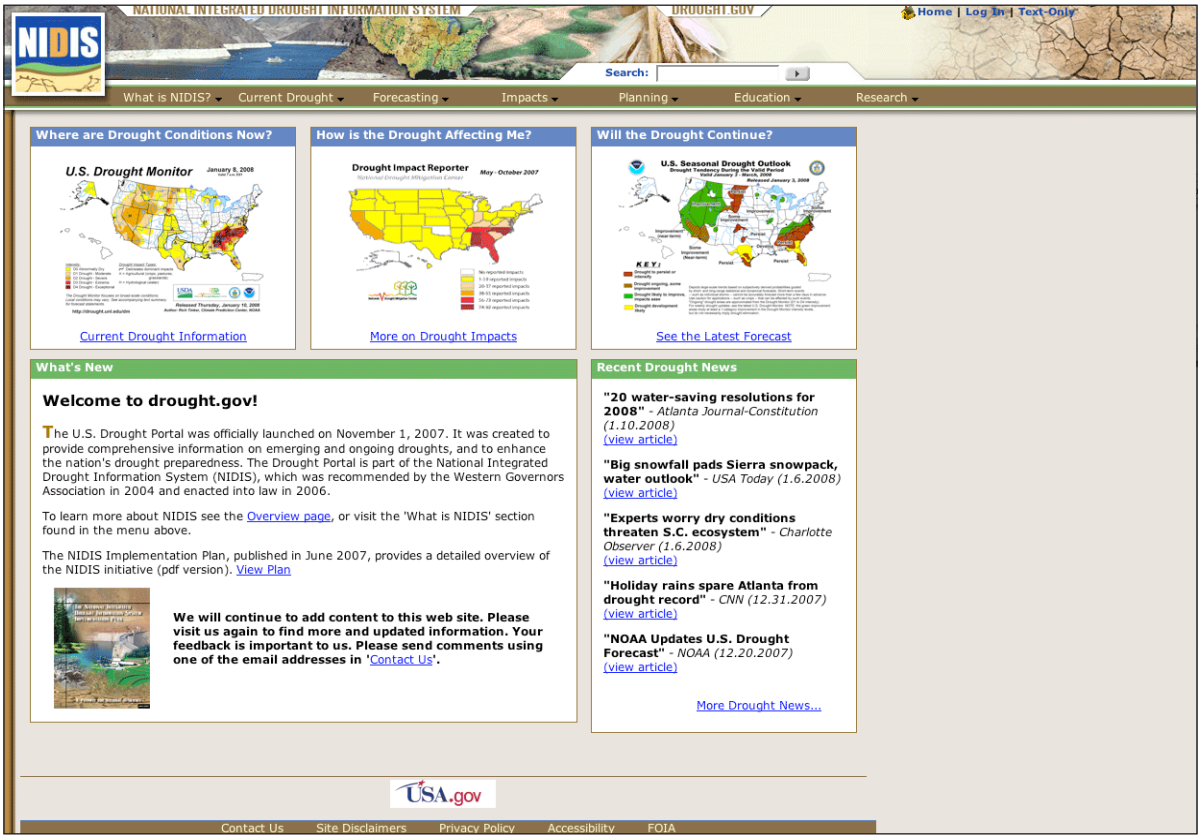

Figure 15a. The NIDIS Drought Portal homepage features drought information organized by topic, an introduction to NIDIS, and articles of regional interest.

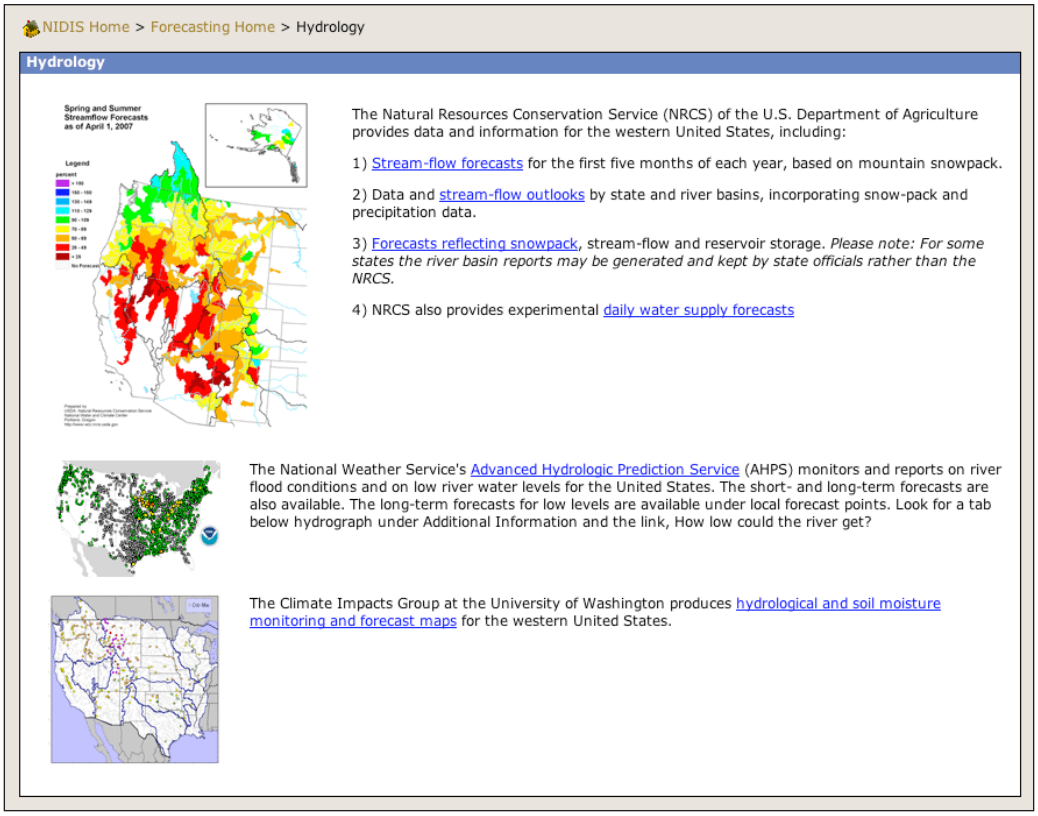

Figure 15b. Snapshot of "hydrology" webpage located under the "Forecasting" tab on the homepage. Each subtopic heading features one or more products and links, allowing users to view and compare data and products from a variety of agencies.

and level of drought knowledge For example, under the "Current Drought" homepage tab, sub topic headings include drought indicators, hydrological monitoring, remote sensing, wildfire, paleoclimatic data, water quality, and local, state, and regional resources. Each topic and the majority of sub topic headings feature one or more national drought products such as the Palmer Drought Severity Index (Current Drought section) or the NRCS streamflow forecasts (Forecasting section) (Figure 15b).

Future Development

In coming months, members of the Drought Portal working group will continue to add content including GIS applications and database development, and expand customization options for individual users. The Drought Portal working group encourages user feedback regarding the utility, content and format. You can submit feedback by clicking on "Contact Us" link located at the top right corner of the homepage for email information.

NIDIS

The development of the Drought Portal fulfills a milestone goal for NIDIS and is a key step in centralizing early warning detection, response, and prevention efforts. NIDIS was created to improve the nation's capacity to manage drought risk, provide tools and information needed to assess potential impacts, and to better respond to and mitigate the effects of drought. NIDIS is comprised of an Executive Council, Program Office, and Implementation Team that oversees five technical working groups: Public Awareness and Education, Engaging Preparedness Communities, Integrated Monitoring and Forecasting, Interdisciplinary Research and Applications, and the Drought Portal. The five technical working groups consist of representatives from a variety of federal, state, and tribal agencies selected to provide diversity in geography, expertise, and/or affiliation. WWA affiliate, Roger Pulwarty, is acting Director of the NIDIS Program Office. For more information about NIDIS, including organization, current research, and future goals, go to the Drought Portal homepage and click under "What is NIDIS?" or download the NIDIS Implementation Plan pdf (see On the Web box).

On the Web

- USDP available at URL: http://www.drought.gov.
- NIDIS Implementation Plan pdf available at URL: http://www.drought.gov/pdf/NIDIS-IPFinal-June07.pdf.

Monitoring snowpack and forecasting streamflows in the Southwest

By Zack Guido

It came in a caravan of white. Since mid-January, a trail of storms crossed the mountains and deserts of the Southwest, leaving the Verde River, Upper Salt River, Upper Gila River basin, and the Little Colorado River basins blanketed in snow.

The large snowpack bodes well for spring river flows in the Southwest. Forecasts for all major rivers in the upper reaches of their watersheds in Arizona and most upper basins in New Mexico suggest at least a 50 percent chance that spring streamflows will be more than 150 percent of average—good news for reservoirs such as the San Carlos Reservoir, which was nearly empty at the beginning of 2010.

Streamflow forecasting is the principal reason why the Natural Resources Conservation Service (NRCS) monitors nearly 2,000 stations and focal points around the West using automated snow telemetry (SNOTEL) stations and manual measurements. These forecasts are integrated into management to help water managers, for example, decide how much water to dole out to irrigation districts and the amount to release from reservoirs. The importance of the forecasts merits a closer look at how snowpack is measured and monitored and how streamflows are forecasted.

Snow Monitoring

Near the summit of Mormon Mountain outside Flagstaff, Ariz., a large rubber pillow filled with anti-freeze is spread on the bare ground. When snow accumulates, sensors inside the pillow measure the weight and calculate the water content in the snow, often called snow water equivalent, or SWE. A nearby pole supports weather devices that monitor air temperature and solar radiation, among other climate variables, and a rain gauge measures the precipitation.

Seven hundred automated SNOTEL systems like the Mormon Mountain station pepper the high country in the West. Each hour the stations transmit radio waves that bounce off the ionized wake of micro-meteorites, dust-size particles that constantly disintegrate in the upper atmosphere. Several NRCS hubs in the West receive the data, administer quality control, and release the information for public consumption.

In Arizona and New Mexico, about 40 SNOTEL stations have been established where snows often accumulate. Most are situated in remote places at elevations between 8,000 and 9,000 feet. The NRCS installed these stations in Arizona beginning in late 1970s.

"Most stations are located in meadows or open areas and near the crests of ridges separating watersheds," said Dino De Simone, Water Supply Specialist for the NRCS. Sites are often on north aspects; if they were

continued on page 4

Figure 1. The Beaver Spring SNOTEL site is located in northeastern Arizona near the border with New Mexico. Most SNOTEL and snow course sites are located at high elevations and in clearings where tree canopy does not obstruct precipitation. A typical station contains a rain gauge (the rusty-looking feature in the photograph), solar panels, weather sensors, and a snow pillow (outlined by the three visible poles in the foreground). Photograph courtesy of Dino De Simon, NRCS.

Monitoring snowpack and forecasting streamflows in the Southwest, continued

placed on the southern slopes that receive the brunt of the winter sun they wouldn't be measuring much snow in Arizona.

The value of snow surveys was recognized long before engineers discovered how to reflect radio waves off cosmic dust. In the mid-1930s sites were selected for manual measurements. Surveyors skied or snow-shoed into the remote sites, called snow courses, to collect data about twice a month. Many of these snow courses are still operational today and account for about 60 percent of the 1,950 automated and manual monitoring sites in the West, including Alaska.

Snow course sites have the same characteristics as SNOTEL—they sit near basin divides, at high elevation, and away from the tree canopy—and the SWE and snow depth measurements at snow courses are made at six locations in a 50-foot transect. They have one major drawback, however: they are periodic, made only when someone visits the site, so weeks can pass without insight into the snowpack conditions. In that time, intense storms can dump copious snow or rain, or a warm spell can cause rapid melting that elevates flood risk.

New Mexico has 23 SNOTEL and 39 snow courses (Figure 2). Arizona has 21 and 23 respectively, including the newest station, which was installed in October in the Four Corners region of Arizona. SNOTEL stations have made data collection easier and more rapid, but snow courses remain vital.

"We still want to have manual measurements to help ground-truth the SNOTEL data," De Simone said. "When we install a new station we often locate them near a snow course. If the measurements are similar over a five-year period, the snow course site isn't necessary."

Automated SNOTEL stations are high tech compared to the old fashion stations.

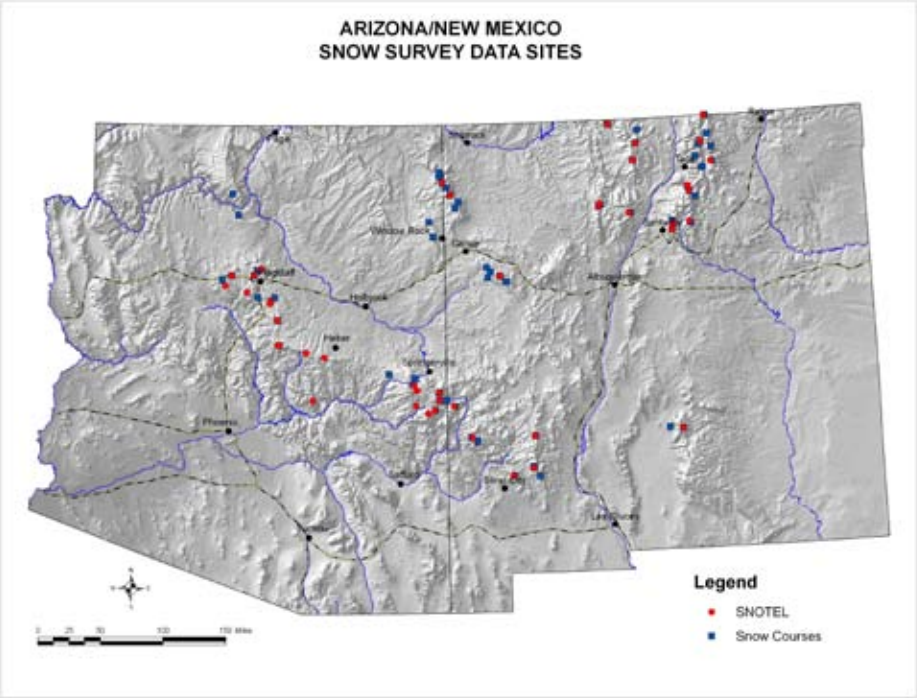

Figure 2. There are 21 SNOTEL stations and 23 snow courses in Arizona, while New Mexico tallies 23 and 39, respectively. Map courtesy of Dino De Simon, NRCS.

The basic SNOTEL station provides snowpack, water content, snow depth, precipitation, and air temperature data. The more sophisticated SNOTEL stations also are equipped to measure soil moisture and temperature at various depths.

The data generated by SNOTEL and snow course measurements are used by researchers, state climatologists, and fire and forest managers. The greatest value of the information, however, is found in the streamflow forecasts that are built on the snow measurements. These forecasts are used by irrigation districts and for reservoir operation, domestic water use, power generation, and flood control.

Streamflow forecasting

Most of the usable water in the western states originates as mountain snowfall. This snowfall accumulates during winter and spring, several months before the snow melts and appears as streamflow. Because the runoff from snow is delayed, estimates of snowmelt runoff can be made in advance.

In Arizona, forecasts from spring streamflow are made every two weeks between January 1 and April 1. Forecasts are issued once a month and continue through May 1 for New Mexico and through June 1 for the Upper Colorado River Basin states, where snow tends to linger on the landscape.

The NRCS bases its streamflow forecasts on a statistical model that uses historical relationships between SWE at a given date, total precipitation since the water year began on October 1, and the spring streamflow. A linear relationship between these three variables allows estimates of spring runoff to be computed as long as the SWE and total accumulated precipitation is measured.

The model works well in snow-dominated systems like the Upper Colorado River Basin, said Angus Goodbody, forecast hydrologist for the NRCS. But forecasting for Arizona and southern portions of New Mexico is challenging because a

continued on page 4

Monitoring snowpack and forecasting streamflows in the Southwest, continued

single large precipitation event can swamp the winter totals, and temperatures at higher elevations often can be above the freezing point, melting snow before spring arrives.

"We deal with the trickiness in Arizona by forecasting streamflows every two weeks, which allows us to see big storms approaching," said Goodbody.

But, he said, the statistical model prevents early winter forecasts from projecting high spring streamflows generated by extremely wet winters, like this year. Even though forecasters knew El Niño increased the likelihood of big storms, the streamflow forecasts were low in the beginning of the winter, said Goodbody.

Forecasts of spring runoff at the beginning of the winter, for example, can give a broad brush new of what to expect, Goodbody said. Most of the error in long-lead forecasts comes from one unknown variable—future weather—and forecasters will never be able to hone in on a specific streamflow forecast number until weather forecasting improves, he continued.

Forecasts become more accurate as the winter unfolds and more of the total precipitation has fallen. In snow-dominated basins like those in the upper Colorado River, measurements of SWE and total precipitation since October 1 made on April 1 can explain 80–90 percent of the expected streamflow in June. The other 10–20 percent comes from the whims of the weather.

The NRCS is not the only organization in the business of streamflow forecasting. The National Weather Service has 13 River Forecast Centers (RFC) in the U.S. that also issue forecasts. For the Colorado River basin, the RFC uses a similar statistical approach as the NRCS but also incorporates a hydrologic model. These two groups generate independent forecasts, discuss each together, and then issue one official forecast after reconciling the differences, if any.

Is the drought over?

For the 2009–10 winter, all of the major river basins monitored by SNOTEL stations in Arizona had more than twice the average snowfall as of March 15. It's a similar story in central and southern New Mexico; stations in the Mimbres watershed, which drains the southwestern corner of the state, posted more than three times the average snowfall.

After one of the driest monsoon seasons on record, the constant stream of winter storms improved or expunged short-term drought conditions in the region, leaving some to wonder if the drought is over.

"It's hard to argue that short-term drought is not over in many parts of the Southwest," said Mike Crimmins, a climate science extension specialist for the University of Arizona and affiliate of the Climate Assessment for the Southwest (CLIMAS). Rain and snow since about December 1 will help moisten the deep soils, which will dampen fire risk in the spring. Rivers will swell in the spring, and extra water will flush through the system in some basins with reservoirs near full capacity. This will likely inject more water into aquifers, although how much is anyone's guess. Trees and winter vegetation also will flourish.

There are caveats, however. The winter storms bypassed the Upper Colorado River Basin; as a result, forecasts suggest that spring streamflow into Lake Powell will be around 67 percent of average.

In addition, it is difficult to assess the effects of one season's drought on the following season. The dry monsoon season, for example, likely caused grasses to release fewer seeds. There is a chance that even with an average monsoon season in 2010, pastures will be less robust because fewer seeds germinated. Another nuance is that the ecosystem of the Southwest is primed for seasonal rain. If it comes, all is green. If it doesn't, drought recurs.

"Drought comes and goes rapidly," Crimmins said. By the time summer rolls around, most of the wet winter will be a distant memory.

Drought Indices

By Dr. Michael J. Hayes, Climate Impacts Specialist, National Drought Mitigation Center, with Christina Alvord and Jessica Lowrey, WWA

This article originally appeared in a longer form on the National Drought Mitigation Center (NDMC) webpage, http://drought.unl.edu/index.htm. The NDMC works to minimize impacts and vulnerabilities of drought by providing risk management strategies and recommendations.

Introduction

Drought indices assimilate data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible big picture. A drought index value is typically a single number, far more useful for decision-making than raw data. Although none of the major indices is inherently superior, some indices are better suited for certain regions or uses than others. For example, the Palmer Drought Severity Index (PDSI) is useful for large areas of uniform topography and is widely used by the U.S. Department of Agriculture to determine when to grant emergency drought assistance. On the other hand, decision makers in western states, with mountainous terrain and complex regional microclimates, often supplement PDSI values with other indices such as the Surface Water Supply Index (SWSI), which takes snowpack and other unique conditions into account, and the Standardized Precipitation Index, (SPI) which identifies emerging droughts sooner than the PDSI and is computed on various timescales. The National Drought Mitigation Center (NMDC) now uses the SPI as its primary tool to monitor moisture supply conditions. This article provides an introduction to major drought indices used in the United States, however other indices do exist or are in development.

Percent of Normal Precipitation

Overview: The percent of normal is a simple calculation well suited to the needs of TV weathercasters and general audiences.
Pros: Quite effective for comparing a single region or season.
Cons: Easily misunderstood, because "normal" is a mathematical construct that does not necessarily correspond with expected weather patterns.

The percent of normal precipitation is one of the simplest measurements of rainfall for a location. Analyses using percent of normal are very effective when used for a single region or a single season. It is calculated by dividing actual precipitation by normal precipitation—typically considered to be a 30-year mean—and multiplying by 100%. This can be calculated for a variety of time scales, including monthly, seasonal, annual, or water year. Normal precipitation for a specific location is considered to be 100%.

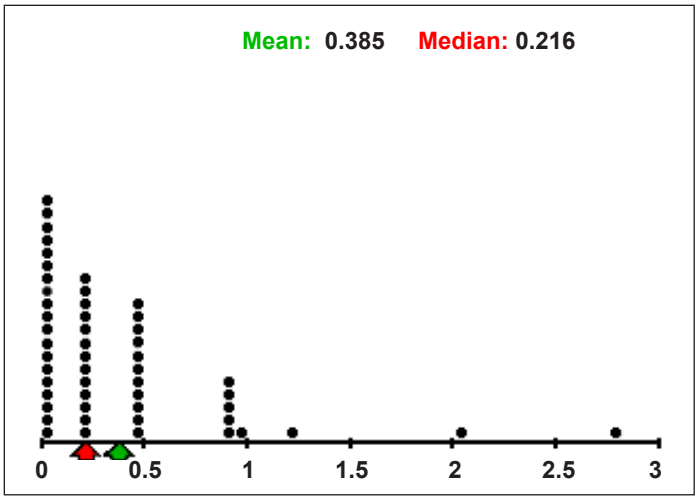

Figure 1a. Example of hypothetical data showing how the mean can be higher than the median. If the majority of data points are low, a few high data points skew the distribution, resulting in a higher mean value in comparison to the median.

A disadvantage of using the percent of normal precipitation is that the mean, or average precipitation is often not the same as the median precipitation. Median precipitation is the middle value of all the individual precipitation measurements; it is always the 50th percentile. Precipitation on monthly or seasonal scales is not normally distributed, so use of the percent of normal implies a normal distribution where the mean and median are considered to be the same. In the west, although precipitation amounts are often low, there also are some very wet days. The resulting distribution gives a mean (normal) that is higher than the median because the infrequent wet events skew the distribution (Figure 1a). The actual amount of precipitation tends to be closer to the median than the mean. Therefore, if one is expecting average (normal) precipitation on any given day, he will usually get a value that is below average.

Because the value of normal depends on time and location, one cannot compare the frequency of the departures from normal between time periods or locations. This makes it difficult to link a particular value of a departure with a specific impact occurring

as a result. Therefore, mitigating the risks of drought based on the departures from normal is not a useful decision-making tool when used alone (Willeke et al., 1994).

The Palmer Drought Severity Index (PDSI) and other Palmer Indices

Overview: The PDSI is a soil moisture algorithm calibrated for relatively homogeneous regions.
Who uses it: Many U.S. government agencies and states rely on the Palmer to trigger drought relief programs.
Pros: It was the first comprehensive drought index developed in the U.S.
Cons: Palmer values may not identify droughts as early as the other indices; it is less well suited for mountainous land or areas of frequent climatic extremes; it is highly complex.

The Palmer Drought Severity Index (PDSI) is a meteorological drought index, which provides a standardized measurement of moisture conditions to compare between locations and over time (Palmer, 1965). The PDSI estimates duration and intensity of drought events by measuring departure of the moisture supply based on a supply-and-demand concept of the water balance equation. The PDSI incorporates precipitation and temperature data, and local Available Water Content of the soil from an unspecified period that best corresponds to past 9-12 months. Past conditions are incorporated because long-term drought is cumulative, so the intensity of drought at a particular time is dependent on the current conditions plus the cumulative patterns of previous months. From the inputs, all the basic terms of the water balance equation are determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. The equations are described in Palmer's original study (1965) and in the more recent analysis by Alley (1984). By accounting for moisture conditions in the past, the PDSI estimates when a drought (or wet spell) begins, ends, and the duration of the event (Palmer, 1965; Alley, 1984). The Palmer Hydrological Drought Index (PHDI) is a derivative of the PDSI. It is based on daily inflow (precipitation) and soil moisture storage (Karl and Knight, 1985).

The PDSI generally ranges from -4.0 to +4.0 and it is designed so that, an extreme drought (-4.0) in one climate division has the same meaning in terms of the moisture deficit as an extreme drought in any other climate division (Alley, 1984). The PDSI is typically calculated on a monthly basis, and a long-term archive of monthly PDSI values for every climate division in the United States is available from the National Climatic Data Center from 1895 through the present. In addition, weekly PDSI values are calculated for the climate divisions during every growing season and are available in the Weekly Weather and Crop Bulletin (see On the Web box).

Palmer Classifications	
4.0 or more	Extremely Wet
3.0 to 3.99	Very Wet
2.0 to 2.99	Moderately Wet
1.0 to 1.99	Slightly Wet
0.5 to 0.99	Incipient Wet Spell
0.49 to - .49	Near Normal
-0.5 to -0.99	Incipient Dry Spell
-1.0 to -1.99	Mild Drought
-2.0 to -2.99	Moderate Drought
-3.0 to -3.99	Severe Drought
-4.0 or less	Extreme Drought

Figure 1b. The PDSI classification ranges from -4.0 or less (extreme drought) to 4.0 or more (extremely wet).

Alley (1984) identified three primary benefits of the PDSI. The PDSI provides decision makers with a measurement of the abnormality of recent weather events for a region and places current conditions in a historical perspective. It also provides spatial and temporal representations of historical droughts. The PDSI has been widely used for a variety of applications across the U.S. It is most effective at measuring impacts sensitive to soil moisture conditions, such as agriculture (Willeke et al., 1994). It has also been useful as a drought-monitoring tool and been used to trigger actions associated with drought contingency plans (Willeke et al., 1994). Finally, water managers find it useful to supplement PDSI values with PHDI values as a way to analyze additional hydrological information important to water management decisions in the West.

The limitations of the PDSI involve its inability to fully characterize hydrologic, climatic, and geographical parameters and variance in such parameters within river basins, in the US or in other countries (Alley, 1984; Karl and Knight, 1985). Drawbacks include:

- The values quantifying the intensity of drought and signaling the beginning and end of a drought or wet spell were arbitrarily selected based on Palmer's study of central Iowa and western Kansas and have little scientific meaning.
- The PDSI is sensitive to the Available Water Content of a soil type. The two soil layers within the water balance computations are simplified and may not be accurately representative of a location. Thus, applying the index for a climate division may be too general.
- Snowfall, snow cover, and frozen ground are not included

- in the index. All precipitation is treated as rain, so that the timing of PDSI values may be inaccurate in the winter and spring months in regions where snow occurs.
- The natural lag between when precipitation falls and the resulting runoff is not considered. In addition, no runoff is allowed to take place in the model until the water capacity of the surface and subsurface soil layers is full, leading to an underestimation of runoff.
- The PDSI does not account for streamflow, lake and reservoir levels, and other longer-term hydrologic impacts of drought (Karl and Knight, 1985).
- Human impacts on the water balance, such as irrigation, are not considered.
- The PDSI is applied within the United States but has little acceptance elsewhere (Kogan, 1995).
- The "extreme" and "severe" classifications of drought occur with a greater frequency in some parts of the country than in others (Willeke et al., 1994). "Extreme" droughts in the Great Plains occur with a frequency greater than 10%. This limits the accuracy of comparing the intensity of droughts between two regions and makes planning response actions more difficult.

Crop Moisture Index (CMI)

Overview: A Palmer derivative, the CMI reflects moisture supply in the short term across major crop-producing regions.
Pros: Identifies potential agricultural droughts.
Cons: Not useful in long-term drought monitoring.

The Crop Moisture Index (CMI) uses a meteorological approach developed by Palmer (1968) to monitor week-to-week crop conditions. In comparison to the PDSI, which monitors long-term meteorological wet and dry spells, the CMI was designed to evaluate short-term moisture conditions across major crop-producing regions. It is based on weekly mean temperature and total precipitation within a climate division, and incorporates the CMI value from the previous week. The CMI responds rapidly to changing conditions, and it is weighted by location and time, so weekly maps of the U.S. can be used to compare moisture conditions at different locations. The CMI is part of the USDA/JAWF Weekly Weather and Crop Bulletin (see On the Web box).

Because the CMI is designed to monitor short-term moisture conditions for a developing crop, it is not a good long-term drought-monitoring tool Its rapid response to changing short-term conditions may provide misleading information about long-term conditions. For example, a beneficial rainfall during a drought may allow the CMI value to indicate adequate moisture conditions, while the long-term drought at that location persists. Another limiting characteristic is that the CMI typically begins and ends each growing season near zero. This prevents the CMI from being used to monitor moisture conditions outside the general growing season, especially in droughts that extend over several years. In addition, the CMI may not be applicable during seed germination at the beginning of the growing season.

Surface Water Supply Index (SWSI)

Overview: The SWSI is designed to complement the Palmer Indices in western states where mountain snowpack is a key element of water supply. The SWSI is calculated by river basin, based on snowpack, streamflow, precipitation, and reservoir storage.
Pros: It represents water supply conditions unique to each basin.
Cons: Changing a data collection station or water management policies requires that new algorithms be calculated; the index is unique to each basin, which limits interbasin comparisons.

The Surface Water Supply Index (SWSI) was designed to complement the Palmer Indices for moisture conditions across the state of Colorado (Shafer and Dezman, 1982), however, now most western starts calculate their own SWSI (see page 12 for the current Colorado SWSI). The Palmer Indices are not designed for large topographic variations across a region, and do not account for snow accumulation and subsequent runoff. In contrast, SWSI incorporates mountain snowpack levels and was designed specifically to asses surface water conditions. The objective of the SWSI is to incorporate both hydrological and climatological features into a single index value for each major river basin in the west (Shafer and Dezman 1982). These values are standardized to allow comparisons between basins. Four inputs are used to calculate SWSI: snowpack, streamflow, precipitation, and reservoir storage. Because water supply is dependent on the season, snowpack, precipitation, and reservoir storage are used to compute SWSI during the winter (November-April). During the summer months, (May-October) streamflow replaces the snowpack component in the SWSI equation.

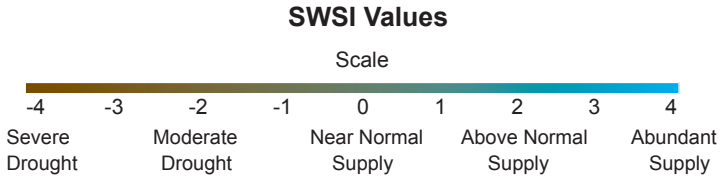

Figure 1c. SWSI scale ranges from -4, (severe drought) to +4 (abundant water supply).

The SWSI has been used, along with the PDSI, to trigger the activation and deactivation of the Colorado Drought Plan. It has been modified and applied in other western states as well, such as Wyoming and Utah. One of its advantages is that it is simple to calculate and gives a representative measurement of surface water supplies across the state. In addition, each input component (streamflow, reservoir storage, snowpack, etc.) is given a weight depending on its typical contribution to the surface water within each basin. Therefore it gives a more accurate picture of water supplies than the other indices that primarily focus on precipitation inputs.

The SWSI has several limitations. Because the SWSI calculation is unique to each basin or region, it is difficult to compare SWSI values between basins or regions (Doesken et al., 1991). If any existing stations are discontinued within a basin or region, new stations must be added with new frequency distributions for each input component to ensure SWSI is calculated the same each month. Extreme events also cause a problem if the events are beyond the historical time series, so the index must be reevaluated to include these events within the frequency distribution of a basin component. Changes in water management within a basin, such as flow diversions or new reservoirs, mean that the entire SWSI algorithm for that basin needs to be redeveloped to account for changes in the weight of each component. Thus, it is difficult to maintain a homogeneous time series of the index (Heddinghaus and Sabol, 1991).

Standardized Precipitation Index (SPI)

Overview: The SPI is an index based on the probability of precipitation for any time scale.

Pros: The SPI can be computed for different time scales, can provide early warning of drought and help assess drought severity, and is less complex than the Palmer. Many drought planners appreciate the SPI's versatility.

Cons: SPI values based on preliminary data may change.

The Standardized Precipitation Index (SPI) reflects the impact of drought on the availability of different water resources. It is designed to quantify the impacts of precipitation deficit on groundwater, reservoir storage, soil moisture, snowpack, and streamflow for multiple time scales. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. Therefore, SPI was originally calculated for 3, 6, 12, 24, and 48–month time scales. The SPI is used operationally to monitor conditions across Colorado since 1994 (McKee et al., 1995), and is being monitored at the climate division level for the contiguous United States by the NDMC and the Western Regional Climate Center (WRCC). The NDMC and High Plains Regional Climate Center also provides daily SPI maps broken down by region and for the United States (see On the Web box; see page 11 for current SPI maps of the IMW region).

SPI Values	
2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Figure 1d. SPI values range from -2 (extremely dry) to +2.0 (extremely wet). The IWCS SPI page is 11.

The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation (Figure 1d). Because the SPI is normalized, wetter and drier climates can be represented in the same way.

While the SPI can monitor wet periods, it is typically used to assess the length and magnitude of drought events. A drought event occurs when the SPI is continuously reaches an intensity of -1.0 or less (Figure 1d). The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month that the event continues. Drought magnitude is the positive sum of the SPI for each month during the drought event.

Based on an analysis of stations across Colorado, the SPI is in the mild drought category 34% of the time, in moderate drought 9.2% of the time, in severe drought 4.4% of the time, and in extreme drought 2.3% of the time (McKee et al., 1993). Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI. The 2.3% of SPI values within the "Extreme Drought" category is a percentage that is typically expected for a very unlikely event (Wilhite 1995). In contrast, the Palmer Index reaches its "extreme" category more than 10% of the time across portions of the central Great Plains. This standardization allows the SPI to determine the rarity of a current drought, as well as the probability of the precipitation necessary to end the current drought (McKee et al., 1993).

Conclusion

While the PDSI is the oldest and most well known, the SPI is the most widely used index for understanding the magnitude and duration of drought events. Most water supply planners like the SWSI, but they find it useful to consult one or more other indices before making a decision. It is important to know the benefits and limitations of each index in order to decide which one is the most useful for any particular application. Users should consult agencies such as the NDMC, the WWA, and State Climatologists for additional information and insight on strengths and weaknesses of each index.

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On the Web

- Weekly updated Palmer Drought Severity Index (PDSI): http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/palmer.gif.
- NOAA Weekly Crop Moisture Index (CSI) maps: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/cmi.gif.
- USDA/JAWF Weekly Weather and Crop Bulletin: http://www.usda.gov/oce/weather/pubs/Weekly/Wwcb/index.htm.
- SWSI information can be found on the NRCS website for each western state.
- Monthly Surface Precipitation Index (SPI) maps: http://drought.unl.edu/monitor/spi.htm; http://www.wrcc.dri.edu/spi/spi.html.
- SPI program files: http://drought.unl.edu/monitor/spi/program/spi_program.htm.

NIDIS Remote Sensing Workshop: Showcase of Products & Technologies

By Christina Alvord of WWA

Three knowledge assessment workshops are scheduled for 2008 by the National Integrated Drought Information System (NIDIS). These workshops are intended to foster collaboration and partnerships between the scientific community and decision makers, in order to better monitor, manage, and prepare for drought on local, regional, and national scales. Each workshop addresses a different element of monitoring and planning for drought, providing user groups and decision makers with a valuable review of selected drought science, products, and research topics. Information about all three NIDIS workshops is available at: http://www.drought.gov.

Introduction

The NIDIS workshop, "Contributions of Satellite Remote Sensing to Drought Monitoring," was held on February 6-7, 2008 in Boulder, Colorado for over thirty researchers, scientists, and natural resource managers representing a variety of universities and federal, state, and local agencies. The workshop provided participants with an overview of available satellite remote sensing technologies and products for cross-sector applications in drought monitoring, management, and planning in the United States. In turn, participants provided recommendations regarding the utility and presentation of remote sensing technologies, including input for near-term modifications to operational products and ideas for future development and research. User groups were represented by local water managers from Denver Water, City of Aurora, Colorado Water Conservation Board, and the Upper Colorado Water Conservancy District. Three state climatologists served as lead panelists to facilitate discussion between producers and users. This article responds to a workshop recommendation to better inform user groups about remote sensing products and applications. This article introduces several technologies and products for monitoring vegetation health, snow and precipitation extent and cover, and soil moisture and ET conditions. These products have cross-sector applications for monitoring emerging and ongoing drought conditions.

Satellite Remote Sensing

Satellite remote sensing generally refers to the process of observing and recording the transmission of electromagnetic energy that radiates and reflects from terrestrial and atmospheric surfaces. These transmissions correspond to specific portions of the electromagnetic spectrum (EMS). Observations (or data) collected from different wavelengths in the EMS reveal information about surface characteristics and processes. Data from the visible, infrared and microwave portions of the EMS are used for monitoring various aspects of drought, including vegetation health and cover, evapotranspiration, precipitation amount and locale, soil moisture, snow cover extent, snow water equivalent (SWE), and snowpack temperature (Figure 1a). Although observations from certain parts of the spectrum lend themselves better to specific surface properties, some drought indicators are hybrids of data collected from multiple areas. Observations collected by satellites are integrated into standardized indices (e.g., Normalized Difference Vegetation Index (NDVI), Palmer Drought Severity Index, (PDSI), Standardized Precipitation Index (SPI), or assimilated into land, water, or energy balance models (Figure 1b). In addition, satellite remote sensing observations are increasingly used in conjunction with ground and/or airborne measurements. Data produced from satellite observations are typically presented in map form to show the spatial variation of a drought-related index.

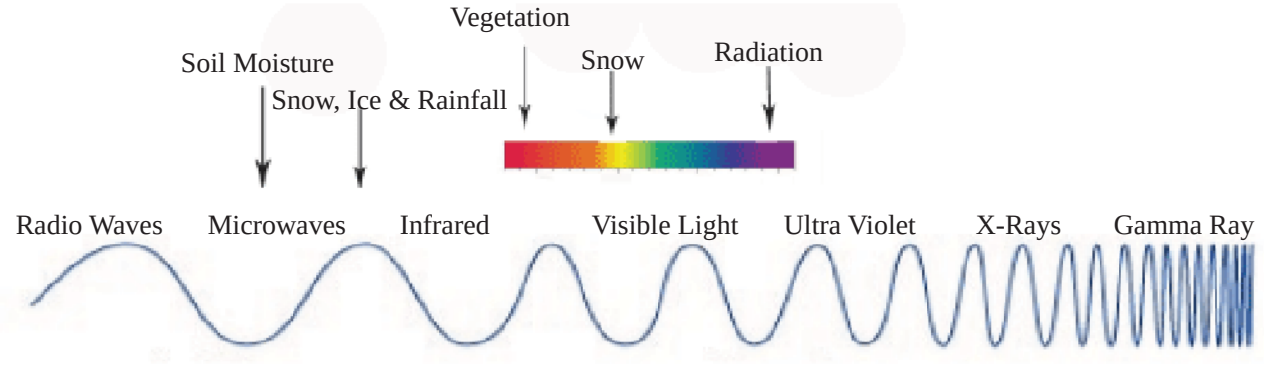

Figure 1a: Visual representation of the electromagnetic spectrum (EMS) and the observed parameters that best respond to different wavelengths.

Remote sensing-based systems augment information available from conventional data sources, (i.e. instrument stations) and provide consistent continuous coverage at frequent intervals. Disadvantages of satellite remote sensing include the inability to obtain data through cloud cover (with the exception of microwave sensors), the need to correct for extraneous atmospheric effects that can complicate spatial and temporal extrapolation, and the need for long-standing financial commitment to operate and maintain satellites and ground data reception and processing systems. Finally, confidence in data and trends using satellite remote sensing is related to the level of maturity and length of historical data streams collected by satellites. For example, datasets and corresponding products and technologies used to monitor vegetation health and snow extent have longer records than those used to monitor evapotranspiration (ET) and soil moisture.

Precipitation and Snow Cover Products

Precipitation and snow cover products provide estimates of precipitation amount, timing, location, and the extent of snow cover. Approaches to monitoring precipitation and snow using satellite based observations are inherently different. Precipitation is detected while it is still carried in the atmosphere (microwave and thermal infrared), and snow properties are detected by monitoring conditions at the ground surface (visible, infrared, and microwave). Snow and ice are highly reflective surfaces and have distinct signals in the visible, infrared, and microwave portions of the EMS, and thus these wavelengths are well-suited to monitoring snow characteristics (Figure 1a). Observed and modeled snowpack characteristics derived using remote sensing observations include snow water equivalent (SWE), snow depth, surface and profile snowpack temperatures, snowmelt, surface and blowing snow sublimation, and snow-surface energy exchanges.

Remote sensing measurements of precipitation are indirect and they rely on relating either thermal infrared cloud top temperatures and/or microwave scattering to rain rates using empirical methods. Thermal infrared images are acquired every 15-30 minutes by geostationary satellites, while microwave images are acquired every few hours by polar orbiting satellites. Though acquired less frequently microwave observations are imperically superior since scattering is a direct response to the presence of raindrops in the atmosphere. Precipitation may or may not be occurring below cold clouds, so thermal infrared estimates of cloud top temperatures are less reliable than microwave observations.

Precipitation Analysis, daily 4 km, 24 hr totals for the continental U.S. from the NWS

The NWS River Forecast Centers (RFCs) integrate precipitation station observations with the NWS Surveillance Doppler Radar to generate daily 4x4 km gridded precipitation estimates for the U.S and Puerto Rico. These gridded rainfall estimates integrate satellite observations where radar coverage is missing. Visualization options allow users to generate products for different time frames (i.e. precipitation estimates in the last 7, 30, or 60 days), zoom into desired RFC region or state, and overlay major river systems and RFC, state, city, and county boundaries.

Product URL:

Precipitation analysis: http://water.weather.gov/

Contact: Victor Murphy, NWS, Victor.Murphy@noaa.gov

Snow Data Assimilation System (SNODAS) from NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC)

NOHRSC integrates satellite remote sensing of snow cover, airborne data, and in situ (snow depth and water equivalent) measurements into the SNODAS model. SNODAS integrates all snowpack observations (e.g. SWE, snowpack temperature,

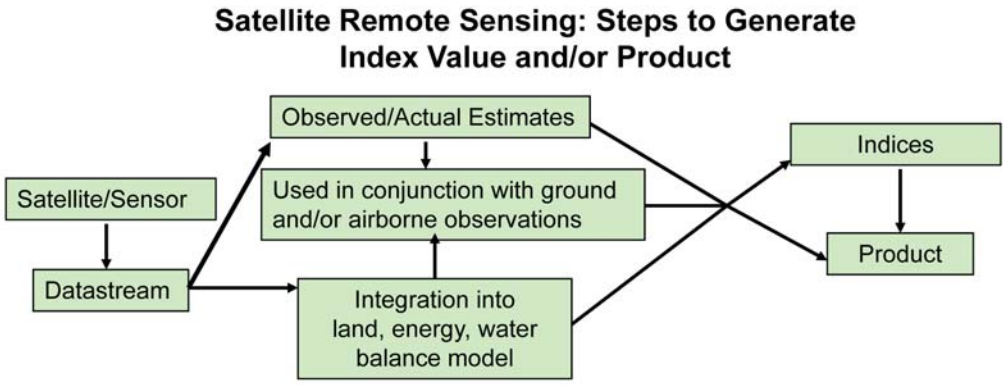

Figure 1b: Schematic depicting steps to generate index value and/or product using remote sensing data. Observations collected from one or multiple satellites or sensors are processed into datastreams. Datastreams are used to derive actual conditions, integrated in a land, energy, or water balance model or combined with ground and/or airborne observations to generate an index value and/or product for use in drought management.

snowmelt, etc) with corresponding topographic observations (e.g. elevation, vegetation cover) and atmospheric observations (e.g. air temperature) for a given area. SNODAS then models surrounding snowpack conditions based on what is known about the snowpack, topography, and atmospheric conditions for the observed area. Multiple snowpack products are extrapolated from SNODAS, including daily 1-km grids of snowpack characteristics (e.g. SWE, snow depth, surface and profile snowpack temperatures, snowmelt, and surface and blowing snow sublimation; Figure 1c).

Product URLs:

SNODAS products are housed at the National Snow and Ice Data Center, URL: http://nsidc.org/data/docs/noaa/g02158_snodas_snow_cover_model/index.html

The National Snow Analysis (NSA) website (www.nohrsc.noaa.gov/nsa) at NOHRSC provides maps and text descriptions of multiple snowpack characteristics based on SNODAS. NSA options include customization features, allowing users to tailor products by region, parameter observed (e.g., SWE, snow depth, snowpack temperature), with corresponding topographic observations (e.g. elevation, vegetation cover) and atmospheric observations (e.g. air temperature) for a given area.

Evapotranspiration (ET) and Soil Moisture Products

ET is the combination of transpiration of water into the atmosphere by plants and direct evaporation from the soil surface. ET rates are depressed during drought due to reduced availability of moisture. Low ET rates are associated with higher than normal land surface temperatures. Remote sensing of land-surface temperature (LST) derived from thermal-infrared (TIR) data can be used to indirectly monitor changes in ET and detect drought conditions.

Estimates of moisture content of the upper soil layer using satellite remote sensing are made from direct processing of microwave image data as well as by land data assimilation models. This is especially valuable in areas that lack sufficient ground-based soil moisture observations. Passive microwave data are sensitive to changes in soil moisture in the first few centimeters of the soil column, while active microwave systems are most sensitive to changes in wetness at the surface itself. In both instances results are optimal in landscapes with sparse vegetative cover because bare ground provides the clearest signal for measuring soil moisture, while the water content of plant leaves can obscure that signal. As a result, direct remote sensing of soil moisture is better suited for arid landscapes such as the western U.S.

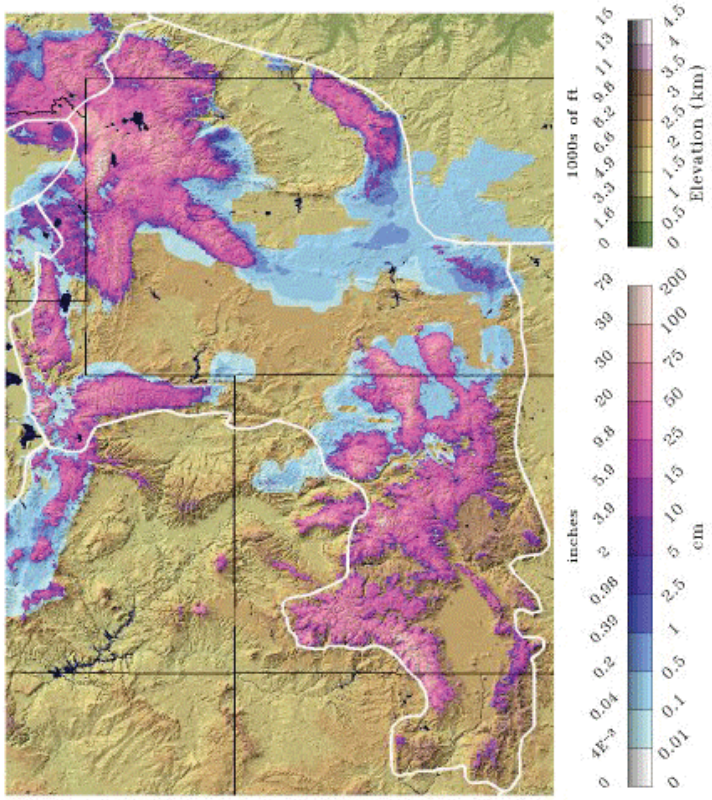

Figure 1c: SWE estimates (inches) for the Central Rockies on May 1, 2008. The National Operational Hydrologic Remote Sensing Center's (NOHRSC) SNODAS model integrates daily ground based, airborne, and satellite snow observations to generate estimates of snowpack characteristics for the continental U.S.. The National Snow Analysis (NSA) products (http://www.nohrsc.noaa.gov/nsa/) extrapolate estimates for individual snowpack characteristics based on SNODAS output and allow users to customize products by parameter, region, or time frame.

Evaporative Stress Index (ESI) using ALEXI surface energy balance model from the U.S. Department of Agriculture (USDA)

ESI equals 1 minus the ratio of actual ET to potential ET, and values range from 0 (ample moisture) to 1 (stressed). Data for ESI is generated by synthesizing land surface temperature (LST) observations using thermal-infrared band data with surface energy balance model (ALEXI). ESI values show good spatiotemporal correspondence with other precipitation based drought indices, but at a higher spatial resolution. Hourly and daily maps of ESI will be available on the web in fall 2008 for continental U.S. at the 5-10 km spatial scale.

Contact: Martha Anderson, USDA, martha.anderson@ars.usda.gov

ET Mapping from Riverside Technology (RTI)

RTI produces maps of ET using thermal observations from two satellites (MODIS and Landsat). These are integrated into a surface energy balance model (METRIC). Customized ET maps

using METRIC range from 120 m to 1 km spatial scale with 4 to 16 day composites. ET maps are used to develop multi-temporal and spatial scale products, which are integrated into water management decision support systems, such as the South Platte Decision Support System (SPDSS) in Colorado. This should improve forecasts of potential water demands for reservoir operations irrigation scheduling, and well augmentation.

Product URL:

ET Mapping: http://snake.riverside.com/waterdss/.

Contact: Graeme Aggett, Riverside Technology, gra@riverside.com

Vegetation Health (Crops, Rangeland, Forest) Products

Vegetation products are used for monitoring cropland, rangeland, and forest health for evaluating agricultural production, fire danger, and land cover change. Vegetation stress is caused by precipitation and soil moisture deficit and this leads to a decrease in plant photosynthetic capacity and moisture content. Thus, information about vegetation stress acquired by remote sensing can help monitor agricultural and rangeland drought.

Plant canopies under stress are drier and contain less chlorophyll than leafy, green, robust canopies. Plant photosynthetic capacity and moisture content can be detected and quantified using visible and infrared satellite observations. Satellite observations are aggregated to produce vegetation indices or products for multiple vegetation stress indicators, including leaf area index (total leaf surface of vegetation divided per unit area of ground), plant growth (vigor), vegetation cover, and biomass production (kg of plant matter/square meter).Vegetation indices are analyzed to target or highlight anomalous departures from an expected "normal" level of plant health. Infrared and visible satellite observations are integrated into a number of vegetation or drought indices, including, but not limited to, the Normalized Difference Vegetation Index (NDVI), the Vegetation Health Index (VHI), and the Vegetation Drought Response Index (VegDRI), a proxy for the Palmer Drought Severity Index (PDSI). Products range from 250-m to16-km spatial resolution with 7 to 16 day temporal frequency.

Normalized Difference Vegetation Index (NDVI) products from NOAA, NASA, and U.S. Geological Survey (USGS)

NDVI is an indicator of vegetation canopy photosynthesis, and it has been widely used to monitor vegetation at regional and global scales (1km^2-16 km^2). NDVI correlates well with Standardized Precipitation Index (SPI) during the growing season in the central Great Plains and has strongest correlation in areas with low soil water holding capacity. NDVI is a numerical transform of visible red (absorbed by chlorophyll) and near infrared (reflected by the spongy mesophyll layer of leaves) response in spectral bands that are sensitive to changes in plant growth. NDVI typically ranges from 0.1 up to 0.8, with higher values associated with greater density and greenness of the plant canopy. Surrounding soil and rock values are close to zero.

Product URLs:

United States/1 km NDVI from AVHRR satellite dataset: http://ivm.cr.usgs.gov/viewer/viewer.htm (for recent maps) and http://edcsns17.cr.usgs.gov/Earth Explorer/ (to order 1 km AVHRR data products).

Contact: Jeffrey Eidenshink, USGS, jeidenshink@usgs.gov

United States/250 m-500 m-1 km NDVI from NASA: MODIS satellite dataset: ftp://elpdl02.cr.usgs.gov/eMODIS/ (for historical and expedited data).

Contact: Calli Jenkerson, ADNET, contractor for USGS, jenkerson@usgs.gov

Global/4 km AVHRR NDVI and Vegetation Health Indices: http://www.orbit.nesdis.noaa.gov/smcd/emb/vci/VH/index.html(for historical and current maps).

Contact: Felix Kogan, NOAA, felix.kogan@noaa.gov

VegDRI produced by the National Drought Mitigation Center (NDMC) and the USGS

The Vegetation Drought Response Index (VegDRI) is a hybrid drought indicator, integrating satellite remote sensing and surface observations to characterize the intensity and spatial pattern of drought-induced vegetation stress (Figure 1d). VegDRI generates 1 km resolution maps by integrating two satellite-based observations (percent average seasonal greenness[1] and start of season anomaly[2], two climate-based indices: PDSI and SPI, and five

[1]Percent average season greenness is the percent of green vegetation for a given period from the start of the growing season in comparison to historic average.

[2]Start of season anomaly is the difference in the date when photosynthetic production surpasses base or winter photosynthetic production as compared to a historical normal, typically expressed in terms of an early, average, or late start of growing season.

biophysical characteristics) land cover type, soil available water capacity, ecological setting, percent irrigated agriculture, and elevation. VegDRI is available for 22 states in the central and western U.S. and will expand across the eastern U.S. in 2009.

Product URL:

VegDRI http://www.drought.unl.edu/vegdri/VegDRI_Main.htm.

Contact: Brain Wardlow, NDMC, bwardlow2@unlnotes.unl.edu and Jesslyn Brown, USGS, jfbrown@usgs.gov

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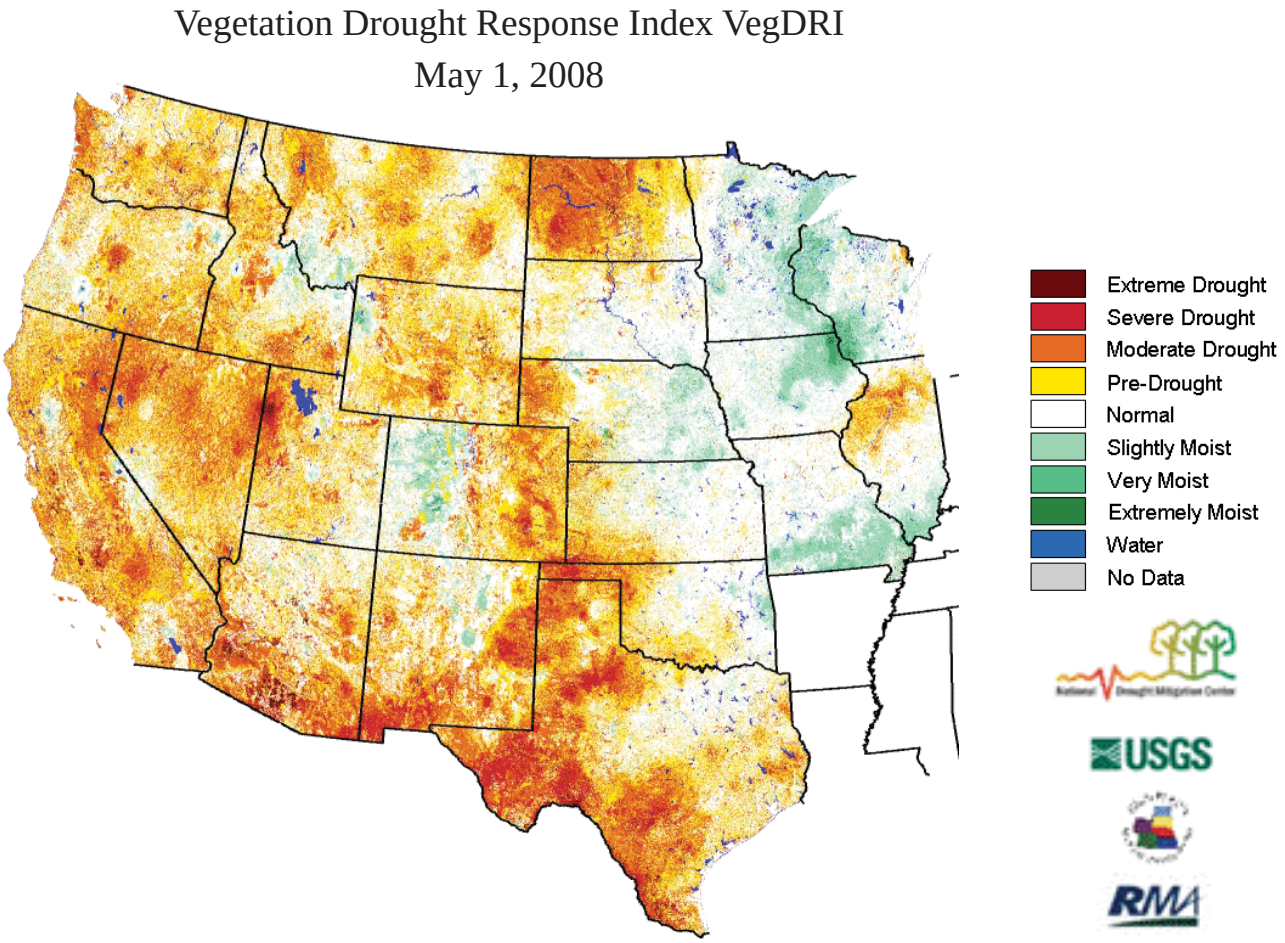

Figure 1d. The VegDRI calculations integrate satellite-based observations of vegetation conditions, climate data, and other biophysical information such as land cover/land use type, soil characteristics, and ecological setting. VegDRI maps have with a 1-km^2 spatial resolution and are produced every two weeks. The coverage of VegDRI will expand across the eastern U.S. in May 2009.

On the Web
-For information on NIDIS, including data resources, visit: www.drought.gov.
-Remote sensing product explanations including extended abstracts, workshop presentations, and other information are currently available at: http://wwa.colorado.edu/current_projects/nidis_remote_sensing_workshop.html.

Improve Your Climate Vocabulary!

Courtesy of NOAA Climate Diagnostic Center

Forecast 1) A statement predicting how or when an event or condition will occur drawing on a collection of guidance tools or predictions. 2) To estimate or calculate in advance, especially to predict (weather conditions) by analysis of meteorological data.

Outlook A forecast provided with considerable lead time that certain conditions may develop. Often depicted as the likelihood, through probabilities, that the average temperature and total precipitation for the outlook's valid period will be above, below, or near normal (median for precipitation).

Guidance Forecast models and tools (either statistical or numerical) used by forecasters in creating "official" forecast products.

Prediction An objective forecast of the future state of the atmosphere generated by running a climate/weather forecast model or a simpler empirical model based on data analysis.

Experimental Product A product that is tentative or under development; an informal, unrecognized, unvetted model for future prediction. The National Weather Service (NWS) makes experimental products available for testing and evaluation for a specified, limited time period for the explicit purpose of obtaining customer feedback.

Operational Product A product that provides consistent timely delivery of sanctioned data, products or services; produced on a reliable and continuous basis.

Official Product A product issued by an organization as a sanctioned expert opinion of position. For example, real-time current *official* weather observations, forecasts, and warnings are issued by the NWS for use by the national and international community.

Average or Climate normal A number computed as an arithmetic mean of some climate variable (e.g. temperature, precipitation, snowpack level) over a long time period, usually 30 consecutive years. This number may or may not be the expected or most likely occurrence at any given time. This is especially true with precipitation in dry climates, such as the desert in the U.S. Southwest, and temperatures at continental locations which frequently experience large swings from cold to warm temperatures.

Climatology The expected values of temperature, precipitation or other climate variables for a given location and time of year.

Anomaly The deviation of a climate variable (usually temperature or precipitation) in a given region over a specified period from the long-term average value for the same region. The current standard is to calculate anomalies as the departure from a 30-year average.

Tercile A way to divide a climate variable's historic occurrence into three categories: below normal, near normal, and above normal. Terciles divide data into three categories that have the same chance of occurring. For example, in a 30-year climatology of precipitation/temperature the 10 driest/coldest years belong in the below-normal tercile, the 10 wettest/warmest years belong in the above-normal tercile, and the other 10 years belong in the near-normal tercile. These numbers translate into the probability of a randomly chosen year in that set as having a 33.3% chance of being in the below-normal tercile, 33.3% chance of being in the near-normal tercile, and 33.3% chance of being in the above-normal tercile. Seasonal climate outlooks are often given in terms of the chances of being in one of the tercile categories, based on the historic climate data from the past, which is usually the past 30 years.

Climate Variability Fluctuations in time about the average conditions.

Climate Change A sustained departure from the previous climate conditions.

Climate information The data, products and services that can be used for decision support by policy makers and resource managers from all levels of government, all sectors of the economy and society, all levels of major corporations, small businesses, and individual users. Examples of climate information include current conditions, climatology, forecasts, outlooks and guidance.

On the Web

http://www.cpc.ncep.noaa.gov/products/outreach/glossary.shtml
http://www.srh.noaa.gov/oun/severewx/glossary.php
http://k12.ocs.ou.edu/teachers/glossary/
http://iri.columbia.edu/outreach/meeting/MediaWS2001/Glossary.html
http://amsglossary.allenpress.com/glossary
http://www.bom.gov.au/lam/glossary/
http://www.bom.gov.au/climate/glossary/

The Intermountain West Climate Summary is published monthly by Western Water Assessment, a joint project of University of Colorado and NOAA Climate Diagnostics Center, researching water, climate and societal interactions.

Climate data: the ins and outs and where to find what

This article is the first in a two-part series. Part One discusses the National Weather Service's Cooperative observer program and the related Historical Climate Network. In April, Part Two will describe PRISM data, and data from Remote Automated Weather Stations (RAWS) and the Arizona Meteorological Network (AZMET).

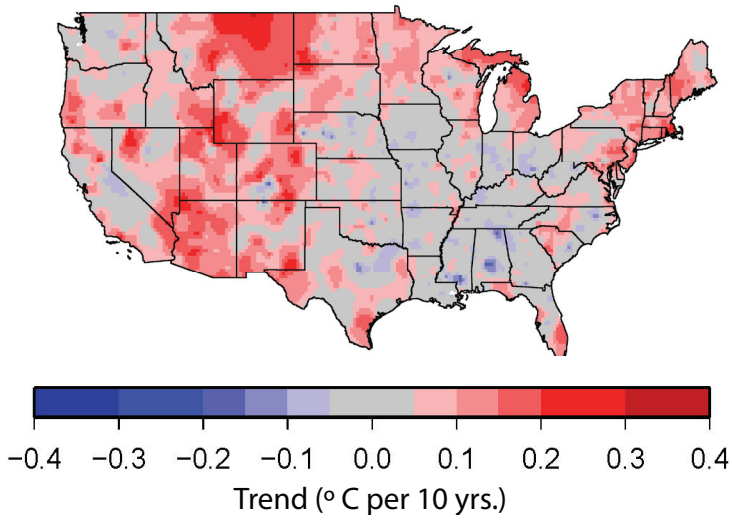

Figure 1. Adjusted maximum temperature in the HCN version 2 data for the period 1895–2007. Every 0.1 degree Celsius equals about 0.18 degrees Fahrenheit.
Source: modified from Menne et al. 2008

Many active weather and climate monitoring networks have collected data for more than 100 years, providing ranchers, forecasters, businesses and others with information they need. But all data are not created equal. Every data set has issues, some more than others. Knowing the details of the data will help match the proper data set to the question at hand.

While some networks bounce information off satellites every minute, others require people to read thermometers once a day and report the values by phone. Some networks have stations in sunny, windy places to monitor fire risk, and others are located in rural areas for farming purposes. And while some have no quality control, others are put through rigorous statistical algorithms and culled into data sets that represent the best and the brightest information.

A wealth of climate data is available, like temperature, precipitation, and snow depth. Learning the advantages, limitations, and Web site locations of each data set is difficult. Two programs in particular, the Cooperative Observer Program (COOP) and the Historical Climate Network (HCN), can help researchers understand climate change and natural variability; influence when ranchers decide to purchase hay and farmers plan crop cycles; aid businesses in correlating product demand and climate; and help resource management agencies allot water to irrigation districts.

Cooperative Observer Program

The Coop network has contributed more to the understanding of climate trends and extremes than any other data source. It contains daily measurements that began in 1890. Since then, the majority of stations have been operated by volunteers. Historically, there have been about 32,000 stations in the U.S. Currently, there are more than 12,000 active sites.

The National Weather Service administers the network, but the National Oceanic and Atmospheric Administration's National Climate Data Center (NCDC) archives it, performs the quality control, produces subsets of the data, and disseminates it in a variety of formats.

Coop observations include once-a-day recordings of the maximum and minimum temperatures, the temperature at observation time, precipitation totals, snowfall totals, and depth of snow at observation time. Many Coop observers provide additional hydrological or meteorological data such as evaporation and soil temperature.

The advantages of the Coop data are the high density of stations, the longevity of the record, daily measurements, and the fact that the data are relatively raw for those who want to perform more rigorous quality control. There are also several shortcomings. First, to analyze changes in the climate through time, more quality control is needed to adjust the data for changes in the time of observation, equipment, and surrounding environment. For example, protocols for the time of observation periodically changed, with pre-1940 recordings occurring at midnight and more recent recordings occurring at 7 am. This change caused jumps in the data. Second, many stations have missing data because measurements are not automated.

While the Coop data is not adjusted for some inconsistencies, NCDC does provide quality control on the raw data. NCDC assures that the minimum temperatures are not greater than the maximum and that the values are reported in the right columns and are not alarmingly greater than neighbor stations.

Accessing daily data costs $2 for each station, or free if the user has a server domain of .edu, .gov, .us, .k12. Monthly data, however, is provided free of charge by the Regional Climate Centers (RCC). This data for Arizona and New Mexico is housed at the Western Regional Climate Center.

continued on page 4

Climate data, continued

U.S. Historical Climate Network

The HCN is a smaller subset of Coop stations that consist of the stations with long and complete records with minimal station changes. The network arose from the need for an accurate and unbiased climate record suitable for detecting and monitoring changes in regional climate. The HCN consists of 1,221 stations; almost all of them have at least 80 years of mean monthly temperature and total monthly precipitation data, were active in 1987, and have experienced few station changes, such as relocations. In some cases, however, these criteria were modified to have a uniform distribution of HCN stations across the U.S. HCN stations span only the 48 contiguous U.S states; a separate data set is available for Alaska, although it lacks the same quality control. There are 25 HCN stations in Arizona and 28 stations in New Mexico.

Like its parent, the HCN data includes daily maximum and minimum temperature, daily precipitation, and daily snowfall totals. Unlike the Coop data, the HCN data have more rigorous quality control, which consists of the following:

1. Using data from surrounding stations to identify potential errors (when values are greater than 3.5 standard deviations from the mean) and outliers (when values are greater than 5.0 standard deviations from the mean).
2. Adjusting temperature data for bias introduced by changing times-of-observation—this adjustment alone changed the temperature trend by 0.3 degrees Fahrenheit (F) between 1960 and 1990.
3. Adjusting temperature to account for artificial errors caused when mercury thermometers were replaced by electronic temperature sensors.
4. Accounting for changes in the data resulting from station relocations and other station changes.
5. Generating data from appropriate nearby stations that fill in for days when observations where not made—data are only generated when records have too many missing values.
6. Correcting for the non-climatic warming caused by urban development.

Although HCN data are quality-controlled in various ways, most data adjustments are based on notes provided by the observer. These notes document, for example, when the observer moved the station, when he or she changed the observation time, and when the thermometer was updated. However, the notes are not always complete—observers may not report replacing a broken thermometer with one calibrated differently. Nevertheless, The HCN data are the best records available for estimating regional temperature trends. They have been used by the Intergovernmental Panel on Climate Change and the U.S. Climate Change Science Program.

Recently, the NCDC created an updated version of the HCN data, called HCN version 2. Version 2 makes a few modifications to quality control and effectively addresses bias introduced by poorly located stations, according to a journal article published this year in the Bulletin of the American Meteorological Society. This is important because proximity of Coop and HCN stations to brick houses, asphalt, and air-conditioning equipment can influence temperature data.

In the journal article, the HCN version 2 was analyzed, generating decadal trends for the period 1895–2007. Not surprisingly, many locations in both Arizona and New Mexico displayed strong warming trends over this period (Figure 1). Currently, this information is only available in monthly summaries. Next year, daily data will likely be available.

Coop and HCN provide long records that correspond to the climate at a particular location. But they also form the foundation of modeled climate data that enable a variety of users to obtain climate information at any location, circumventing the problem of relating a distant station's record to a site with a higher elevation and a different aspect. This gridded PRISM data, along with networks that capture extreme climate conditions and conditions in rural areas, will be addressed in the next issue.

For questions or comments, please contact Zack Guido, CLIMAS Associate Staff Scientist, at zguido@email.arizona.edu or (520) 882-0879.

Related Links

Cooperative Observer Program

1. Daily data:
http://cdo.ncdc.noaa.gov/dly/DLY

2. Monthly data for New Mexico:
http://www.wrcc.dri.edu/summary/Climsmnm.html

3. Monthly data for the Arizona:
http://www.wrcc.dri.edu/summary/Climsmaz.html

U.S. Historical Climate Network

1. Daily and monthly data:
http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html

2. HCN monthly values:
http://www.ncdc.noaa.gov/oa/climate/research/ushcn/

Climate data: the ins and outs and where to find what

By Zack Guido

This article is the second in a two-part series. Part One, featured last month, discussed the National Weather Service's Cooperative Observer Program and the related Historical Climate Network. This article describes data from Remote Automated Weather Stations (RAWS) and the Arizona Meteorological Network (AZMET), and data generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) statistical technique.

Not enough data is bad. Too much data is overwhelming. But not knowing what data exists and where to find it is worse.

Hundreds of weather stations in the Southwest dot the landscape, piping measurements to many different users. The National Weather Service (NWS), for example, intertwines the information in models that help forecast tomorrow's weather, while a coordinated group of federal wildfire agencies eyes data from different stations to monitor fire risk. The Arizona Cooperative Extension uses data from yet another network to derive "degree days" from temperature measurements, which allow farmers to estimate an outbreak of the infamous pink bollworm.

While climate and weather data support many actions, it is often difficult for users outside each data network's administration to track down and understand the data. Three networks—Remote Automated Weather Stations (RAWS), the Arizona Meteorological Network (AZMET), and data generated by a sophisticated algorithm called the Parameter-elevation Regressions on Independent Slopes Model (PRISM)—offer detailed data that may have gone unnoticed to some.

While RAWS and AZMET capture extreme conditions and weather representative of agricultural areas, PRISM meshes observations from several networks into a mathematical model that estimates climate for small grid-boxes that span the entire U.S. All three, along with the Cooperative Observer Programs (Coop) and the Historical Climate Network (HCN), which were discussed in the March *Southwest Climate Outlook*, can help researchers understand climate change, businesses relate product demand to climate, and resource managers dole water to irrigation districts, among other uses.

Remote Automated Weather Stations

The RAWS network was established principally to help fire managers predict fire behavior and monitor the conditions of fuels, such as standing and fallen trees. As a result, the stations have been systematically located in remote areas that capture extreme conditions, including windy areas and sites that receive a hefty dose of sunlight—areas that are the most susceptible to fire. RAWS are generally not sited on northern facing slopes, which receive less sunlight than southern aspects. While RAWS are predominantly used for fire-risk assessments, the data also assist in air quality monitoring and research.

Nearly 2,200 RAWS are strategically located throughout the United States. There are 130 stations in Arizona and New Mexico, and the oldest stations have been active since the mid-1980s. Most RAWS are operated by the wildland fire agencies, such as the National Forest Service, the Bureau of Land Management, and the U.S. Fish and Wildlife Service.

RAWS record weather conditions every minute to every hour, depending on the variable being measured, and transmit the information via satellite to the National Interagency Fire Center and the Western Regional Climate Center (WRCC). This allows users to obtain real-time information. Most RAWS record temperature, precipitation, wind speed and direction, barometric pressure, and relative humidity; some stations also record the moisture and temperature of fire fuels. The data are free and most easily accessed at the WRCC.

The RAWS data have some limitations. First, the data available to the public are not quality controlled. The raw values recorded at the stations are the same as those archived at the WRCC. Second, not all stations in the western U.S. continuously collect data—some stations sleep in the winter when fire risk is low, particularly those at higher elevations. In addition, some stations are portable and are moved during the year and between years. Because micro climate can impact weather conditions, data from portable stations are not useful for long-term analysis without careful inspection. Furthermore, some RAWS data are not well annotated, making it difficult to decipher which stations moved and the site characteristics of the new and old locations.

Like all networks, RAWS have a specific purpose, which influences how data is recorded. To monitor fire risk, for example, wind speeds are measured at a height of 20 feet and are averaged over 10 minutes. Weather stations at airports, in contrast, measure wind speeds at 33 feet and the values are averaged over two-minutes. Knowing these and other RAWS data issues can help make this detailed dataset useful.

Arizona Meteorological Network

AZMET—a service of the Cooperative Extension at The University of Arizona— provides meteorological data and weather-based information to agricultural and horticultural interests operating in southern and central Arizona. Each hour, AZMET stations record numerous climate and weather variables that have been useful for irrigation districts, golf courses, cotton and citrus growers, fertilizer and pesticide companies, researchers, and others.

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Climate data, continued

The earliest AZMET stations began operating in 1987, and 28 stations are currently active. The stations are located in both rural and urban agricultural areas and are often positioned in open spaces over grass and away from buildings. As a result, the data is not as affected by urban heat island effects, which can amplify temperature and alter other climate variables. One asset of AZMET is that it measures many climate and weather variables, including air temperature, soil temperature at two depths, precipitation, wind speed and direction, solar radiation, and humidity. From those measurements, AZMET calculates heat units and chill hours, which help characterize the life stages of plants, and evapotranspiration. Because the data are recorded hourly, the dataset is rich and detailed. Furthermore, AZMET stations measure climate and weather variables not collected by other networks, including evapotranspiration. A census of data collection organizations indicates that AZMET is the only network to monitor evapotranspiration continuously in Arizona.

Another positive feature of the AZMET network is that stations are well maintained, which helps create consistent data. A technician visits each site at least every three months and erects a temporary station with laboratory-calibrated sensors. A comparison of the results between the official and temporary stations helps AZMET evaluate the reliability of the data and ensure accurate measurements. In addition, AZMET changes the wind speed and solar sensors each year and changes the temperature and humidity sensor every two years to prevent sensor failure or measurement drift. Many other networks change equipment only after problems occur, often making it difficult to locate in the data when values became inaccurate.

AZMET data also are quality controlled, although not as rigorously as the HCN network. Most quality control is performed by computer statistical analysis, in which measurements are cross-checked with nearby stations to make sure that one station is not recording artificial conditions. Additional computer programs comb the data for negative values or uncharacteristically extreme values. The presence of these anomalies tells technicians to review the data manually. Each morning at about one a.m., the data is transferred onto a Web server where it is free and available to the public.

Like RAWS, however, AZMET data have limitations. First, the period of record is relatively short: a maximum of 22 years, and only 12 stations span this period. AZMET data is therefore not as useful for deriving long-term climate trends as other networks such as the

Network	Data Source	Climate Variables	Recording Intervals	Record Length	Primary Application	Quality Control
Coop	12,000 active Coop stations; ~170 in AZ and ~180 in NM	1. Maximum temp. 2. Minimum temp. 3. Daily total precip. 4. Daily total snow 5. Others	Once a day	1880 – present; varies by station	Support public services with near real-time data	Some quality control after data acquisition
HCN	1,221 stations selected from Coop network	1. Maximum temp. 2. Minimum temp. 3. Daily total precip. 4. Daily total snow	Once a day	Most stations have data for 80 years or more	Detect and monitor changes in regional climate	Extensive quality control after data acquisition
RAWS	2,200 remote automated stations; 130 in AZ and NM	1. Temperature 2. Precipitation 3. Wind speed 4. Relative humidity 5. Others	Minute to hourly	Many stations became active in the mid-1980s	Monitor fire-risk	No quality control
AZMET	28 automated stations in rural and urban areas in AZ	1. Temperature 2. Precipitation 3. Evapotranspiration 4. Others	Hourly	1986 – present; varies by station	Support agriculture and horticulture in southern and central Arizona	Some quality control after data acquisition; routine station maintenance
PRISM	Coop, SNOTEL, local stations, and statistically generated data	1. Maximum temp. 2. Minimum temp. 3. Average temp. 4. Precipitation	Monthly	1895 – present	Produce detailed, high-quality spatial climate datasets	Depends on data source

Coop: Cooperative Observer Program; HCN:Historical Climate Network; AZMET: Arizona Meteorological Network; PRISM: Parameter-elevation Regressions on Independent Slopes Model; RAWS: Remote Automated Weather Stations; SNOTEL: snow telemetry

Table 1. Characteristics of common sources of climate and weather data.

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Climate data, continued

HCN. Also, the station density is sparse, except in the Phoenix area, and the data is predominantly limited to southern and central Arizona. Finally, the data is representative of agricultural locations, providing information that is suitable for aiding agricultural decisions but not as appropriate for understanding the climate of ranchlands or assessing the urban heat island as other data sources.

Parameter-elevation Regressions on Independent Slopes Model

All monitoring stations, including Coop, HCN, RAWS, and AZMET, measure weather and climate conditions at a location. But climate can vary dramatically across short distances and over small elevation changes. Even Coop, which has 170 active stations in Arizona, cannot adequately cover the entire state. What about the weather in areas between the stations?

To fill in data gaps between stations, Oregon State University developed PRISM, an observation-based statistical algorithm that uses measurements made at monitoring stations from several data networks. PRISM generates climate data for a 2.5 by 2.5 mile (or four-kilometer) grid that covers the continental United States.

The PRISM model computes climate values in a sophisticated way. Essentially, the model overlays a grid on a three-dimensional relief map of the U.S. and marks the grid-boxes containing monitoring stations. It then assigns the observed values for precipitation, temperature, and other variables to each box with an established station. After this, boxes remain that do not have stations. PRISM populates these grids with climate values, for each box, derived from the unique relationship between climate and elevation, coastal proximity, topography, distance to known observations, and aspect. The PRISM algorithm is specifically designed to generate realistic climate data for areas prone to complex weather, such as mountainous regions, places in rain shadows, and regions near water.

PRISM has been used to create a continuous monthly climate data for 1895 to the present. The length of record and the fine spatial resolution make PRISM data unique, meeting the needs of resource managers, land-use planners, researchers, and many other stakeholders.

PRISM data, however, have some drawbacks. Monitoring stations at higher elevations are few and far between, and therefore some people believe that PRISM data for higher elevations is less reliable. Also, any statistical procedure introduces additional sources of error. In addition, only monthly data are available.

Until recently, PRISM data were not easily analyzed without specialized software. However, the need for more accessible, fine-scale climate datasets spawned the Western Climate Mapping Initiative (WestMap), a collaborative effort between The University of Arizona, The Desert Research Institute, and Oregon State University. CLIMAS also played a role, helping identify demand for Web-based PRISM data.

WestMap has developed a Web-based climate analysis and mapping tool that enables users to download and graphically display PRISM data for the western U.S. The tool allows users to query data for different time periods and regions, download the data in a common format, and create maps and charts. For example, users can obtain monthly data for any period between 1895 and the present for a user-defined area, such as a single location, an entire state, or a watershed. Users may also create custom maps to suit their needs.

Conclusion

Weather and climate data come from many sources and possess unique qualities. While stations in the RAWS network are in remote, sun-baked areas, PRISM sites are virtual. While many HCN stations span more than 80 years, AZMET stations have made measurements since 1987. And while Coop stations and RAWS have minimal quality control, HCN and AZMET are processed with a finer-tooth comb.

Regardless of which networks are used, however, knowing the ins and outs of each will help match the proper dataset to the question at hand and can help enable businesses, farmers, researchers, natural resource managers, and others to more effectively make decisions.

For questions or comments, please contact Zack Guido, CLIMAS Associate Staff Scientist, at zguido@email.arizona.edu or (520) 882-0879.

Related Links

Arizona Meteorological Network

1. Access all AZMET data and encounter more information: http://ag.arizona.edu/AZMET/

Remote Automated Weather Stations

1. Access data through a map interface, hosted by Western Regional Climate Center: http://www.raws.dri.edu/index.html

2. RAWS home page provides overview of RAWS program: http://www.fs.fed.us/raws/

PRISM

1. User-friendly graphical interface for accessing PRISM data for Western U.S., developed by WestMap: http://www.cefa.dri.edu/Westmap/Westmap_home.php

2. Access datasets for entire U.S. via Oregon State University: http://www.prism.oregonstate.edu/

Evaluating forecasts with the RPSS

By Zack Guido

In response to user feedback, the Southwest Climate Outlook has changed its temperature and precipitation forecast verification highlights to incorporate a more accurate evaluation method, the Rank Probability Skill Score (RPSS). To the mathematically wary, this name likely causes anxiety. Indeed, the RPSS is an equation and is complicated. But it helps answer a critical question: have the forecasts been accurate? Knowing this helps users incorporate the forecasts into decisions, such as when to purchase hay to avoid high costs or how much water to dole to irrigation districts.

Scientists often evaluate a forecast by calculating its skill, which is the accuracy of a forecast in relation to another, reference forecast. A "skillful" forecast shows improvement over the reference forecast. For example, a poker player may say he or she can beat the house more often than losing. If the game played has 50:50 odds, the poker player must win more than 50 percent of the games to show skill over the odds (the reference forecasts).

The National Oceanic and Atmospheric Administration's Climate Prediction Center (NOAA-CPC) began forecasting successive three-month periods in 1994, and these forecasts spanned two weeks to 13 months into the future. But the usefulness of these forecasts depends on their accuracy. If the forecasts have been historically worse than simply using a coin to predict the weather, than what value do they have?

To help address this question for readers, the Southwest Climate Outlook verification pages will present the average RPSS calculated for all the temperature and precipitation forecasts issued since 1994 for four different lead times. The RPSS is calculated by the Forecast Evaluation Tool, which was developed by The University of Arizona in partnership with NOAA, NASA, the National Science Foundation, and the University of California-Irvine.

In essence, the RPSS communicates how much more or less accurate the CPC forecasts have been than the reference forecast. The reference forecast for the CPC forecasts is equal probabilities that temperatures or precipitation will be one of three categories—"above," "below," or "neutral"—or a 33 percent chance for each category. These forecasts give probabilities, for example, that temperature will be similar to the 10 warmest, coolest, or normal temperatures observed during the period 1971–2000. This equal probability is often referred to as a climatology forecast.

The actual formula of the RPSS is complicated and is beyond the scope of this article. The two important characteristics of the RPSS, however, are easily articulated. First, the higher the RPSS value, the better the forecast; the RPSS value is the percent improvement the forecast exhibits over the reference forecast. Positive values also give an indication that the forecasts and the actual weather conditions are similar—the higher the RPSS, the more similar the forecast and the actual conditions. Negative values, on the other hand, mean that the forecast is less accurate than the climatology forecast.

Second, the value of the RPSS incorporates the degree of correctness or incorrectness. This "ranked" scoring system values correct forecasts and incorrect forecasts differently—some inaccurate forecasts are worse than others. For example, if a forecast indicated a 90 percent chance for "above" temperatures but temperatures were actually "below," the RPSS would be lower than if the forecast stated a 40 percent chance for "above" temperatures.

The usefulness of forecast verifications such as the RPSS becomes apparent in the example of an early forecaster. In 1884, Sergeant John Finley began forecasting tornado occurrences east of the Rocky Mountains. Shortly thereafter, he reported a 95.6–98.6 percent forecast accuracy. Other scientists, however, pointed out that the accuracy could have been 98.2 percent had he simply always forecasted no tornados. Although Finley's forecasts seemed accurate, they were not the best forecasts. Had an RPSS been calculated, it would have been negative.

While forecasts will continue to be made—each additional year helps make the RPSS more robust—knowing the accuracy of past forecasts will help evaluate the usefulness of the current forecast.

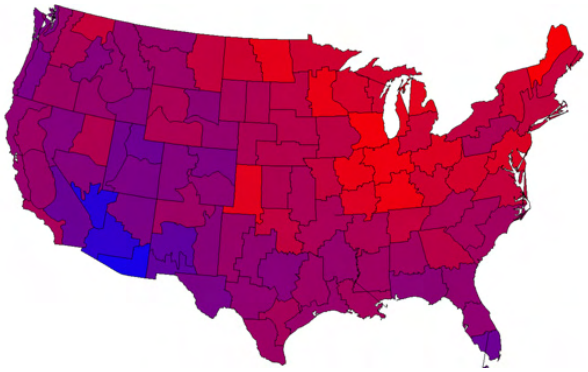


Figure 1. The new verification highlights incorporate a more sophisticated measure of forecast performance than the highlights featured in the past. The new color maps like this one that help readers visualize the historical accuracy of the forecasts.

For questions or comments, please contact Zack Guido, CLIMAS Associate Staff Scientist, at zguido@email.arizona.edu or (520) 882-0879.

Selected Web Resources for Drought and Climate Information in the Four Corners Region

Sponsor Sites w/ Multiple Resources and Links

- US Drought Portal (NIDIS) – http://www.drought.gov
- Western Regional Climate Center (WRCC) - http://www.wrcc.dri.edu/
- Climate Assessment in the Southwest (CLIMAS) - http://www.climas.arizona.edu/
- National Drought Mitigation Center (NDMC) - http://drought.unl.edu/
- Western Water Assessment (WWA) - http://wwa.colorado.edu/
- U.S. Geological Survey - http://water.usgs.gov/

Summary Reports with Data, Graphics, and Interpretation

- WWA Intermountain West Climate Summary - http://wwa.colorado.edu/IWCS/index.html
- CLIMAS Southwest Climate Outlook - http://www.climas.arizona.edu/forecasts/swoutlook.html

Paleoclimate/Paleohydrology Records

- Treeflow – Tree-ring reconstructions of *streamflow* – http://treeflow.info
- Tree-ring reconstructions of gridded summer *PSDI* for North America - http://www.ncdc.noaa.gov/paleo/pdsi.html

Historical Climate Records

- WRCC – Historical Climate Data - http://www.wrcc.dri.edu/CLIMATEDATA.html
- NWS Co-op Weather Stations in Four Corners- http://www.wrcc.dri.edu/summary/Climsmco.html

Current Observations

- *Temp/Precip/other weather obs*
    - NWS Pueblo - http://www.crh.noaa.gov/pub/
    - NWS Flagstaff- http://www.wrh.noaa.gov/fgz/
    - NWS Phoenix- http://www.wrh.noaa.gov/psr/
    - NWS Tucson- http://www.wrh.noaa.gov/twc/
    - NWS Albuquerque, NM- http://www.srh.noaa.gov/abq/
    - WRCC – Current Observations - http://www.wrcc.dri.edu/CURRENTOBS.html
- *Precipitation (rain, snow, hail) only*
    - CoCoRaHS Colorado - http://www.cocorahs.org/state.aspx?state=co
    - NRCS Snotel sites - http://www.co.nrcs.usda.gov/snow/prec/index.html
- *USGS Waterwatch- http://waterwatch.usgs.gov/*
- *Natural Resources Conservation Service Snow Surveys/Snowtel-* http://www.wcc.nrcs.usda.gov/snow/
- *ENSO*
    - NOAA CPC ENSO Diagnostic Discussion - http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.html

Drought Monitoring

- *Multiple indicators*
    - US Drought Portal (NIDIS) – www.drought.gov (plus Drought Impacts)
- US Drought Monitor - http://drought.unl.edu/DM/MONITOR.html
    - WRCC – Monitoring - http://www.wrcc.dri.edu/CURRENTOBS.html
- Western U.S. Climate Anomaly Maps - http://www.wrcc.dri.edu/anom/
- *Standardized Precipitation Index* (SPI) – US - http://www.wrcc.dri.edu/spi/spi.html

Forecasts

- *Temperature/Precipitation*
  - NWS Weather Forecasts – see NWS Forecast Offices above
  - NOAA Climate Prediction Center Outlooks (6-10 days to seasonal) - http://www.cpc.ncep.noaa.gov/
- *Streamflow & Water Supply*
  - Water Supply Forecasting - http://www.nrcs.usda.gov/programs/snowsurvey/
- *Drought*
  - NOAA Climate Prediction Center US Seasonal Drought Outlook - http://www.cpc.noaa.gov/products/expert_assessment/seasonal_drought.html

Climate Change Impacts & Adaptation

- US Global Change Research Program - http://www.globalchange.gov/
- Global Climate Change Impacts in the US Report - http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts
- Synthesis and Assessment Products (SAP) Reports- http://www.globalchange.gov/publications/reports/scientific-assessments/saps

CLIMATE PROGRAM OFFICE

National Integrated Drought Information System

Where can water resource managers, farmers, forestry officials, and other planners get the information they need to plan for or mitigate drought conditions?

The National Integrated Drought Information System (NIDIS) provides dynamic and easily accessible drought information for the Nation. Among the decision makers who are benefitting from this source of authoritative, reliable information are farmers making decisions about crops, forestry professionals planning ahead for the next fire season, and urban water managers preparing for high-demand seasons. NIDIS provides data that help decision makers assess the risk of having too little water and prepare for and mitigate the effects of drought. Still in its initial phases, NIDIS is continually developing more robust services and regional decision support resources.

NIDIS Objectives

- Develop the leadership and networks required to implement an integrated drought monitoring and forecasting system at federal, state, and local levels.
- Foster and support a research environment focusing on risk assessment, forecasting, and management.
- Create an "early warning system" on drought and drought impacts to provide accurate, timely, and integrated information.
- Develop interactive systems, such as the U.S. Drought Portal, as part of the early warning system.
- Provide a framework for public awareness and education about droughts, impacts, and preparedness.

PRA, Wikimedia Commons

Lake Powell, Arizona, viewed from a plane in May 2007. Lowered water levels expose a prominent "bathtub ring" on the canyon walls.

Approaches

NIDIS integrates basic and applied research performed by NOAA and other agencies into an adaptive decision-support environment for resource managers, farmers, and other water users. Utilizing existing infrastructure and data available through federal, state, and tribal partners, NIDIS provides one-stop access to the experience and expertise of NOAA's Regional Climate Centers and Regional Integrated Sciences and Assessments teams, the U.S. Department of Interior, the U.S. Department of Agriculture, the National Drought Mitigation Center, and other research groups.

A broad range of federal, state, and local agencies, academic researchers, and other stakeholders collaborated with the NIDIS team to develop a detailed implementation plan that will meet the Nation's needs for drought information. In accordance with the plan, NIDIS recently conducted the Nation's first assessment on the status of drought early warning systems. The assessment will serve as a guide for development of relevant monitoring and forecasting systems as well as education efforts that can be tailored for specific watersheds, coastal zones, or geographic regions.

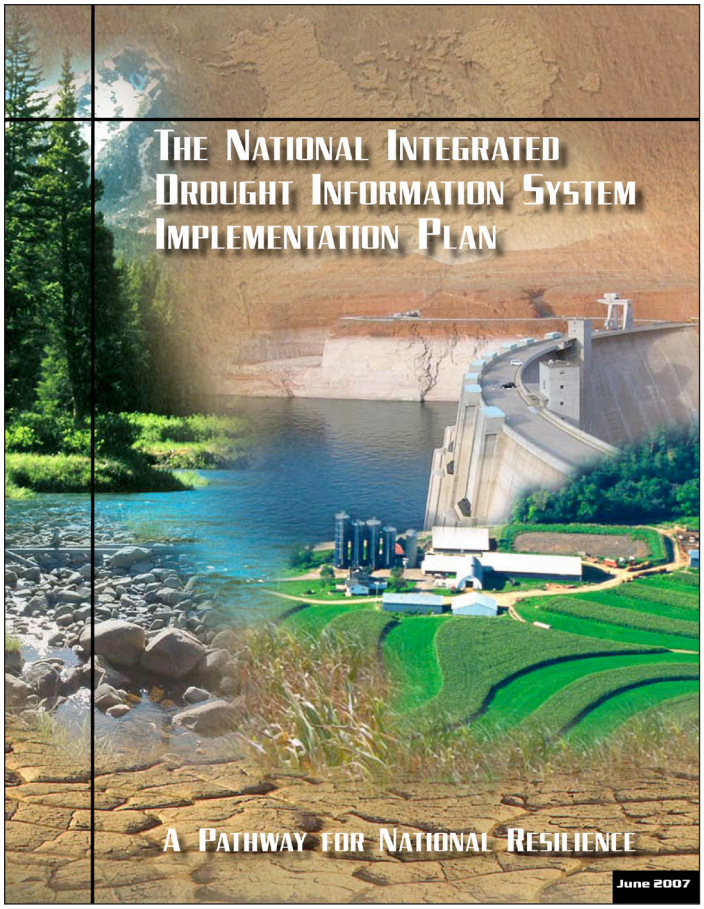
National Integrated Drought Information System (NIDIS) http://www.drought.gov

Email: oar.cpo.nidis@noaa.gov

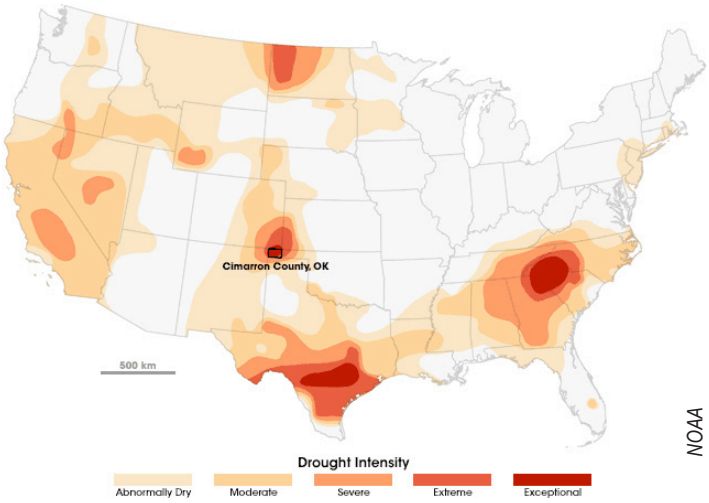
U.S. Drought Portal

Initial goals of the NIDIS program include completing development of the U.S. Drought Portal, a Website that features a range of services related to drought. This interactive system will provide:

- Early warning about emerging and anticipated droughts;
- Quality-controlled data about droughts from climate observations as well as projections from computer models;
- Historical data on past droughts for comparison to current conditions;
- Decision support services for managing the impacts of droughts; and
- A forum for a range of stakeholders to discuss drought-related issues.



Cover of the NIDIS Implementation Plan, released in June 2007. The document is available at www.drought.gov.



In the first half of 2008, an exceptional drought descended on the High Plains, centered on Cimarron County, Oklahoma. This map shows the extent of drought in the continental United States on July 22, 2008.

NIDIS Accomplishments

In June 2004, the Western Governors' Association envisioned an information system that would provide water users at all levels of government with the ability to assess their drought risk in real time and before the onset of drought, in order to make informed decisions that may mitigate a drought's impacts. Subsequently, the NIDIS Act of 2006 (Public Law 109-430) established the NIDIS program. Since its inception, the core team:

- Established the NIDIS Program Office and Team, involving more than 40 agencies, states, and tribes;
- Developed and released the NIDIS Implementation Plan;
- Launched the publicly accessible U.S. Drought Portal and upgraded its operation to include Web Map Services;
- Completed the procurement process for the first set of soil moisture and temperature sensors to be installed at 60 U.S. Climate Reference Network sites; and
- Conducted user needs assessments for stakeholders at a range of workshops. Goals of these workshops were to generate an initial design for a drought early warning system for the southeastern U.S., reconcile climate projections over the Colorado Basin, and assess seasonal potential for wildfire across North America. Details and summaries of these workshops are available online at http://www.drought.gov.

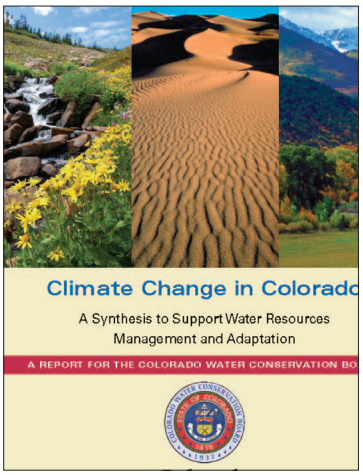
The Western Water Assessment (WWA) produces useful information about natural climate variability and change to natural resource managers in the Intermountain West. WWA is a collaborative government and university research institute, funded through NOAA's Climate Program Office, and uses multidisciplinary teams of experts in climate, water, law, and economics to work with decision makers across the region.

In the West, many of the impacts of climate change will be delivered through changes in the hydrologic cycle that have affected, and will continue to affect, water resources. WWA has focused on building relationships and networks of water-resource decision-makers, and has used these relationships to develop practical research programs and useful informational products. WWA involves researchers and staff from NOAA's Earth System Research Laboratory and National Climatic Data Center and the University of Colorado at Boulder's Cooperative Institute for Research in Environmental Sciences. Some of WWA's projects are highlighted below.

WWA's Mission is To identify & characterize regional vulnerabilities to climate variability and change, and to develop information, products, and processes to assist decision makers throughout the Intermountain West.

Climate Change in Colorado

In October 2008, WWA released the Climate Change in Colorado report at the Governor's Conference on Mitigating Risks of Drought and Climate Change. The report—commissioned by the Colorado Water Conservation Board in support of Governor Ritter's Colorado Climate Action Plan—is a synthesis intended to support water resources, management, and adaptation efforts throughout the state. The report was a finalist for the Governor's Research Impact Award. It also provided a springboard for several climate initiatives within the state, and the authors have given more than 30 public presentations about the report. As a follow-up, WWA is developing a Colorado Climate Roadshow, working with colleagues to adapt a NOAA Climate 101 training workshop for Colorado stakeholders.



Intermountain West Climate Summary (wwa.colorado.edu/IWCS/)

The Intermountain West Climate Summary (IWCS) is WWA's most prominent outreach and education product. WWA distributes the IWCS to more than 400 decision makers, scientists, and climate information providers. The IWCS provides the latest climate and forecast information in a simple, compact document aimed at managers, planners, and policy makers with water-related interests. During an extensive evaluation in 2008, WWA found that the IWCS is improving awareness and understanding about forecasts and climate phenomena; facilitating a dialog among potential users, researchers, and operational providers of climate information; and improving climate literacy.

BLM Photo

Reconciling Streamflow Projections

WWA is leading an effort to reconcile future Colorado River streamflow projections by evaluating the various methods and models being used. They hope to understand why different modeling approaches produce varying flow reduction amounts. Within the Upper Colorado River Basin, projected reductions in naturalized streamflow by the mid 21st century tied to climate change range, from about 6 to about 45 percent. This wide range makes it difficult for decision makers and water managers to prepare and plan for potential future reductions in streamflow resulting from climate change. In 2008, WWA led a series of discussions culminating in a "model bakeoff," with the intention of narrowing the range of projections so that decision makers can identify vulnerabilities and develop planning strategies. Initial findings were presented in a meeting involving water managers, non-governmental organizations, tribes, and consultants. WWA is also trying to understand how this physical information feeds into the decision making process. Initial findings from this work indicate that there is broad and deep confusion over the variety of available climate change scenarios and how differences affect Colorado River flow projections.

Stakeholder Engagement & Collaborations

WWA is a trusted source of climate information for stakeholders and decision makers. Collectively, WWA researchers gave more than 60 public talks and seminars, were cited or quoted by the media more than 75 times, sponsored several streamflow and drought workshops in the Intermountain West, and served as members of many committees and organizations. Our partners are diverse, including non-governmental organizations, local water providers, state universities and governments, and federal agencies.

Future Projects & Directions

Decision Support for the Colorado River System

Reconciling Colorado river flow projections; impacts of climate change and dust on water resources; inflows between Lakes Powell and Mead.

Climate Adaptation and the Adaptation-Mitigation Nexus

Drought impact and climate change vulnerability assessments, and research at the nexus of energy, water, and climate.

Ecological Vulnerabilities, Impacts, and Adaptation

Forests, climate change, and water resources; climate change impacts on public lands in the Upper Colorado River Basin; pine beetle effects on water quality.

wwa.colorado.edu

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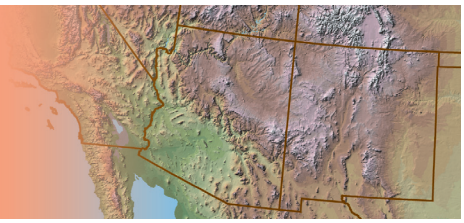
CLIMAS



Climate Assessment for the Southwest

CLIMAS Vision

The emerging Southwest, a place of incomparable natural beauty and a rich cultural heritage, is also a national icon of demographic and environmental change. Rapid population growth and dramatic climate variability are interacting to change the physical and social landscape of the region. As these changes unfold, new challenges are posed, new adaptations are required, and new opportunities arise. Climate variability and change are having ever-increasing impacts on human livelihoods and quality of life in the Southwest.

The Climate Assessment for the Southwest (CLIMAS) project is a leader in advancing climate research to address the unique human and ecological needs of the region. CLIMAS works directly with stakeholders to create tools useful for reducing vulnerability to climate variability and change—and for creating opportunity in the face of uncertainty. Sustained dialogue between scientists and knowledge users fosters development of tools that support economic and environmental vitality in the Southwest.

Who Participates in CLIMAS?

Located at the University of Arizona, CLIMAS brings together a multidisciplinary team of social, ecological, and physical scientists to conduct research on climate and its impacts in the southwestern United States and the adjacent Mexico border area. Researchers collaborate with state and federal agencies, the private sector, communities, and individuals to develop science-based products useful for planning and decision making. Such collaborations build understanding and credibility for climate science and for NOAA products.

CLIMAS Payoffs

CLIMAS research and outreach begins with assessment of decision maker needs and decision-making contexts. Through interactions with stakeholders and agency partners, we develop research projects, information products, and tools to facilitate better informed decisions. This is an iterative process and continued assessment is one of the keys to our many successes.

Air Quality: CLIMAS research allows managers to analyze the climatic and human-caused contributions to ozone and particulate exceedances of federal air-quality standards. To foster collaboration with air quality experts, CLIMAS has brought together a consortium of Southwest air quality managers, and has initiated an annual discussion series on air-quality and climate.

Rural Impacts: To reduce social vulnerabilities to extreme climatic conditions, and to promote viable coping strategies, CLIMAS developed a GIS-vulnerability assessment tool that combines hydroclimatic and socioeconomic data with detailed ethnographic assessments of diverse rural livelihoods.

Health: CLIMAS developed the first climate-based experimental forecasts of valley fever (*coccidioidomycosis*) outbreaks in the Southwest. The product is used by southern Arizona medical researchers and professionals.

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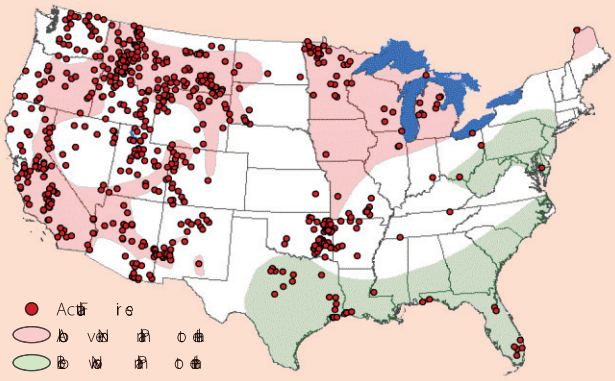
CLIMAS is part of the NOAA Regional and Integrated Sciences and Assessments (RISA) program

http://www.ispe.arizona.edu/climas/

Wildland Fire: [illegible]



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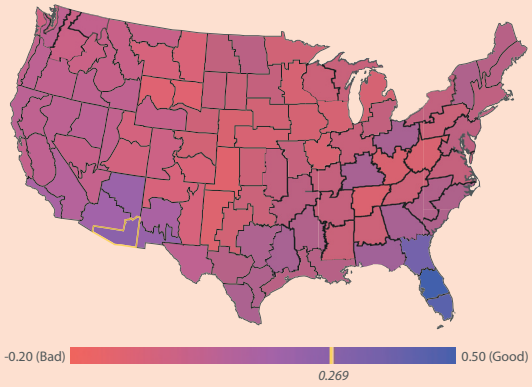


Forecast Evaluation: CLIMAS developed an interactive web tool that stakeholders can use to evaluate the skill of seasonal climate forecasts issued by the NOAA Climate Prediction Center for 120 regions across the continental United States. Users can evaluate how well the seasonal climate outlooks have matched the subsequent actual climate conditions for the regions, lead times, seasons, and performance criteria relevant to their specific decision-making situations. The National Interagency Fire Center, Association of State Climatologists, and National Weather Service have all used the tool in climate forecast training.

Figure 2. Forecast skill for NOAA-CPC outlooks issued August–October for precipitation in December–April. Skill varies significantly across the country. Note the high skill in southern Arizona and Florida.

Extension and Outreach: The monthly CLIMAS Southwest Climate Outlook serves close to 2,000 stakeholders in Arizona and New Mexico. With NOAA funding, CLIMAS placed the nation's first water resources extension specialist and its second climate extension specialist. These specialists organized a Cooperative Extension-CLIMAS workshop on forest management in a changing climate.

U.S.-Mexico Border Cooperation: Through its pioneering work with U.S. and Mexican colleagues in evaluating transboundary climate impacts and fostering use of climate information, CLIMAS is contributing to efforts to improve water planning and environmental sustainability on both sides of the border.

The Future

CLIMAS has opened the door to a much wider use of climate knowledge and information in the Southwest. At the same time, the project has only begun to meet stakeholder needs. Continuing to sustain stakeholder partnerships, build trust, and increase the capacity of stakeholders to incorporate climate information and forecasts into their decision making is fundamental to meeting these demands. Also essential is working with stakeholders in a continual assessment of their needs. This, in turn, provides insights that can guide interdisciplinary climate research on the important issues for which decision support is most critically needed.

To meet the growing stakeholder demand for new climate understanding, CLIMAS will continue to leverage RISA funding with university, state, private, and federal interagency research partnerships. At the same time, CLIMAS will expand collaborations with key experts and decision makers to develop decision-support tools and products, and to move the products into operational status through state, federal, and private partners. Assessing the usability of the products, as well as how the products are used, will help ensure that improvements to CLIMAS tools and products keep pace with increasingly sophisticated stakeholder needs.

Partners

Key to CLIMAS success are research and knowledge transfer partners; their cooperation and expertise multiply the NOAA investment in CLIMAS.

Selected NOAA Partners

Climate Diagnostics Center
Climate Prediction Center
Climate Services Division
Colorado Basin River Forecast Center
National Weather Service Forecast Offices
NWS Office of Climate, Water, and Weather Services
Regional Climate Centers
Regional Integrated Sciences and Assessments (RISA) projects

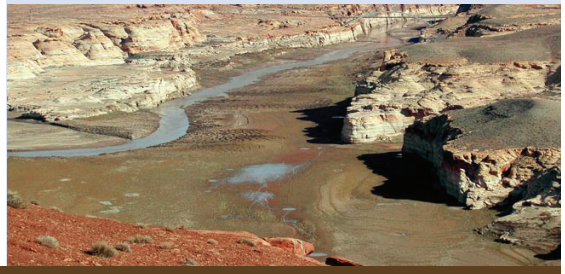
Agency and Academic Partners

Arizona Cooperative Extension
Arizona Department of Health Services
Arizona Department of Water Resources
Colegio de Sonora
Desert Research Institute
NASA Application Programs
National Drought Mitigation Center
National Interagency Fire Center
Oregon State University
Scripps Institution of Oceanography
USDA-Natural Resources Conservation Service
U.S. Bureau of Reclamation
U.S. Environmental Protection Agency
University of New Mexico
Upper San Pedro Partnership
Western Governors' Association

Water Resources: Without a doubt, water is the most critical resource issue in the U.S. Southwest. CLIMAS research and partnerships continue to produce important insights and decision tools for water management under conditions of climate variability and change.

- **Drought Response:** CLIMAS provided research and guidance for the development of the Arizona Drought Preparedness Plan. CLIMAS co-chairs the state drought monitoring committee and advises the Arizona Department of Water Resources.
- **Snowpack and Streamflow:** CLIMAS developed experimental landscape-wide snow estimates, using NASA and NOAA sources, and is developing tools that use the data to improve streamflow predictions.
- **Water Policy:** Sustained CLIMAS research on the potential implications of climate variability and change for water policy contributed to successes in introducing climate information into water management decisions.
- **Water Economics:** CLIMAS expertise in climate and resource economics proved essential to formal agreements reached in the largest tribal water-rights settlement in the history of the United States.

The level of Arizona's Lake Powell reservoir has declined steadily during the last five years of drought; reaching 35 percent of capacity in January 2005. Photo: John Dohrenwend



National Drought Mitigation Center

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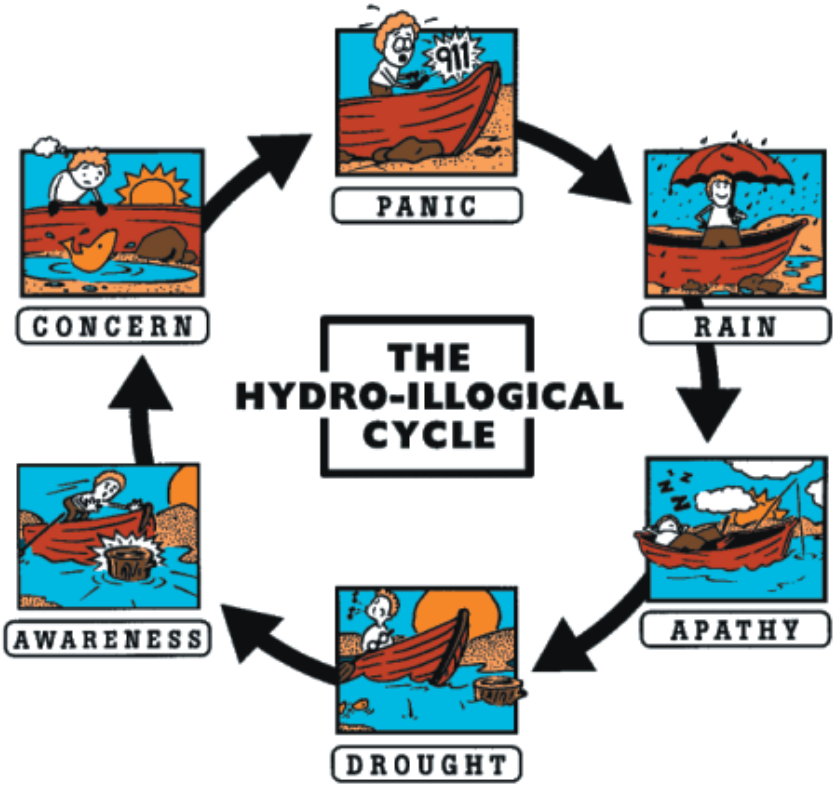
Mission

The National Drought Mitigation Center helps people and institutions develop and implement measures to reduce societal vulnerability to drought. The NDMC stresses preparedness and risk management rather than crisis management. Most of the NDMC's services are directed to state, federal, regional, and tribal governments that are involved in drought and water supply planning.

Background

The NDMC, established in 1995, is based in the School of Natural Resources at the University of Nebraska–Lincoln. Its director, Dr. Donald A. Wilhite, professor of climatology and drought policy specialist, has been studying governmental responses to drought, developing planning methodologies, and identifying appropriate policy instruments for more than 20 years. In addition to working with U.S. states, he has served as a consultant to governments worldwide and to the United Nations.



It's our job to even out the naturally occurring peaks and valleys in people's motivation to plan for drought. In this country, most of us are blessed with a well-protected, plentiful supply of food, and unlike faster-moving natural disasters, drought generally leaves structures intact, if dusty. As disasters go, drought lacks drama. But analysis reveals that it typically costs United States taxpayers at least as much as other disasters, and that it takes a heavy toll on farm families, the environment, and other areas in ways that are hard to measure. For more on drought impacts, please see:

http://drought.unl.edu/risk/impacts.htm

Activities

- drought monitoring
- fielding media inquiries
- advising policy makers
- collaborative research
- K–12 outreach
- workshops for federal, state, and international governments and organizations
- maintaining an active web site
- presentations at professional and academic seminars, workshops, and conferences
- providing data to and answering questions for the general public

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An Overview of NOAA's Colorado Basin River Forecast Center

The NOAA National Weather Service has 13 River Forecast Centers (RFCs) located within major river basins throughout the U. S. The mission of the RFCs is to produce the Nations river, flood and water supply forecasts in support of saving lives and property and to enhance the economy and environment of the country. RFC Hydrologists are the technical experts in operational river and water management forecasting. RFC products and services support many NWS programs including: Flash Flood, River Flooding, River Forecasts, Recreation, Reservoir Management, Drought, and Seasonal Water Supply.

The Colorado Basin River Forecast Center (CBRFC) is responsible for the entire Colorado Basin and the Great Basin, including all or part of seven states with an area of 303,450 square miles (Figure 16a). The basin includes topography ranging from elevations of 200 to over 14,200 feet, from dry desert regions to snowy alpine areas. The basin is distinct in that nearly 80% of the runoff Basin comes from snowmelt, and it has the largest evaporation rates of any RFC. Flooding events range from flashy arroyos due to thunderstorms in the southwest, to longer term rises resulting from snowmelt of large snowpacks.

The CBRFC works closely with local Weather Forecast Offices (WFOs) within the RFC's area of responsibility (Figure 16a). The RFCs provide river forecasts and other hydrologic technical support to the WFOs. In turn, the WFOs prepare Flood Watches, Flood and Flash Flood Warnings and disseminate these products and River Flood Warnings to local emergency managers, media, and the public. The CBRFC also works closely with the Natural Resource Conservation Service, which collects data on snowpack and analyzes streamflows, to issue joint seasonal volume forecast products. The CBRFC distributes much of its products and services through an interactive web page located at: http://www.cbrfc.noaa.gov. Many features of the web page allow a user to customize their request for giver forecasts and data (Figure 16b). Seasonal water supply and reservoir supply and snowmelt peak flow products are also available on their web page.

The text of the article is adapted from a CBRFC publication.

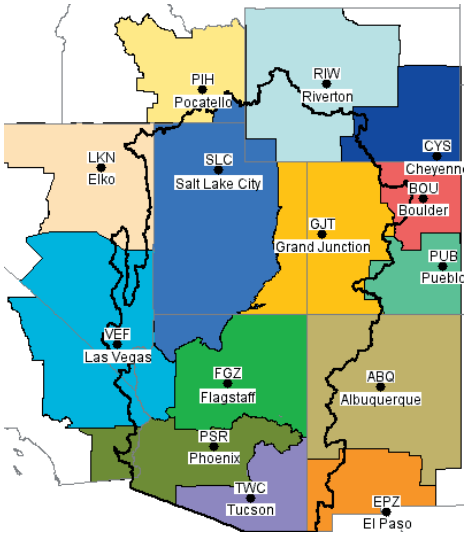

Figure 16a. Map showing NWS weather forecast offices in the western U. S. with an outline of the area that is the responsibility of the Colorado Basin River Forecast Center.

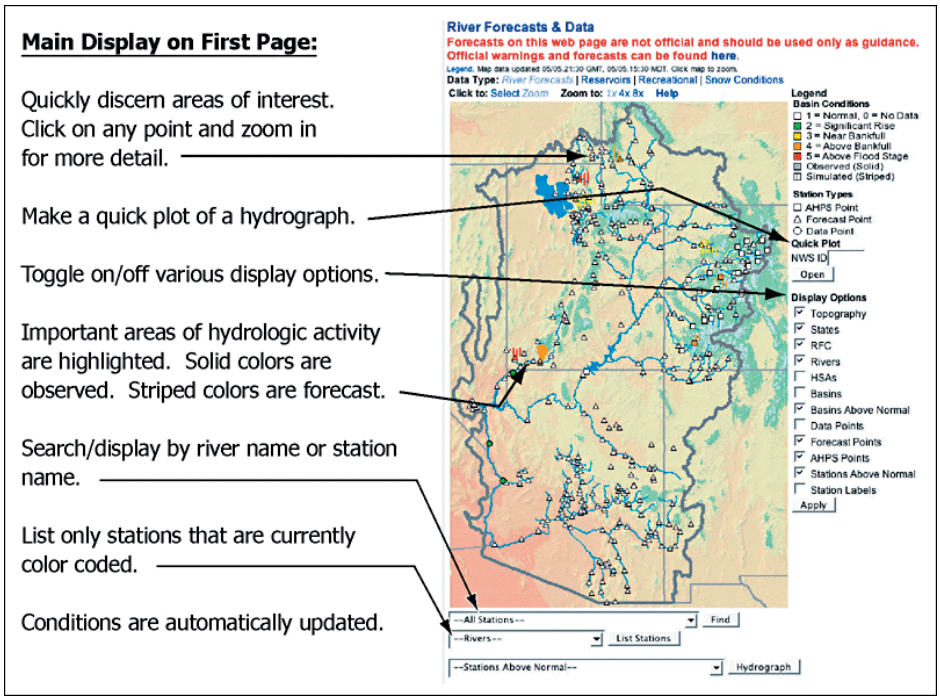

Figure 16b. Interactive map of the Colorado River Basin as seen on the CBFRC website. Text explains all the interactive user choices.

On the Web

The Colorado Basin River Forecast Center's website can be found at: http://www.cbrfc.noaa.gov/.

The Intermountain West Climate Summary is published monthly by Western Water Assessment, a joint project of University of Colorado and NOAA Climate Diagnostics Center, researching water, climate and societal interactions.

CLIMAS
Climate Assessment for the Southwest

NIDIS
NATIONAL INTEGRATED DROUGHT INFORMATION SYSTEM

NOAA

National Drought Mitigation Center

USGS
science for a changing world

Western Water Assessment