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ISTOCK/DOGUHAN TOKER

by Brad Rippey, Brian Fuchs, David Simeral, Deborah Bathke, Richard Heim, and Mark Svoboda

The 20th century featured immense scientific discoveries and advances. Astrophysics gained Einstein's life-altering theory of relativity, opening the door to nuclear weaponry and the mind-bending Big Bang theory. The medical field achieved stunning success in suppressing or vanquishing a host of deadly diseases, including polio and smallpox. And through advances in computing technology, meteorological forecasting moved from back-of-the-envelope calculations to supercomputers.

However, drought monitoring fell behind the curve of scientific advancement. Not until 1965, when the U.S. Department of Commerce published Wayne C. Palmer's "Research Paper No. 45: Meteorological Drought," was there even a complex mathematical definition of drought. In his foreword, Palmer explained that "meteorological science has not yet come to grips with drought. It has not even described the phenomenon adequately."

The Palmer Drought Severity Index (PDSI) was the earliest attempt to describe an imbalance between water supply and water demand, by integrating water supply (precipitation) and water demand (evapotranspiration, as computed from temperature) in a water-budget calculation that also included water storage in the soil. It also established an intensity scale for drought and identified when drought began and ended. Yet the PDSI was never really designed for national drought monitoring, as Palmer's focus was on the Great Plains and the western Corn Belt; born in 1915, he grew up in south-central Nebraska, shaped by the 1930s Dust Bowl.

Clearly, Palmer did not create the PDSI from thin air. He worked for years perfecting his equations, and many of his studies of U.S. droughts of the 1890s, 1910s, 1930s, and 1950s were published in the federal *Weekly Weather and Crop Bulletin* and other outlets, including the *Monthly Weather Review* and the *Bulletin of the American Meteorological Society*. Though not among six dozen references listed in "Research Paper No. 45," "A Simple Index of Drought Conditions," an article by James McQuigg of the U.S. Weather Bureau published in a 1954 issue (Volume 7, Issue 3) of *Weatherwise* might have influenced Palmer.

Palmer's 1965 work, as remarkable as it was for that time, was not the final word on drought. In 1968, three years after introducing the PDSI, he added the complementary Crop Moisture Index, recognizing that drought affects agriculture and hydrology on differing time scales—and at different soil depths.

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Photo from 1936 of an unidentified car in the Texas Panhandle with heavy clouds of dust in the sky, a typical phenomenon of the Dust Bowl.

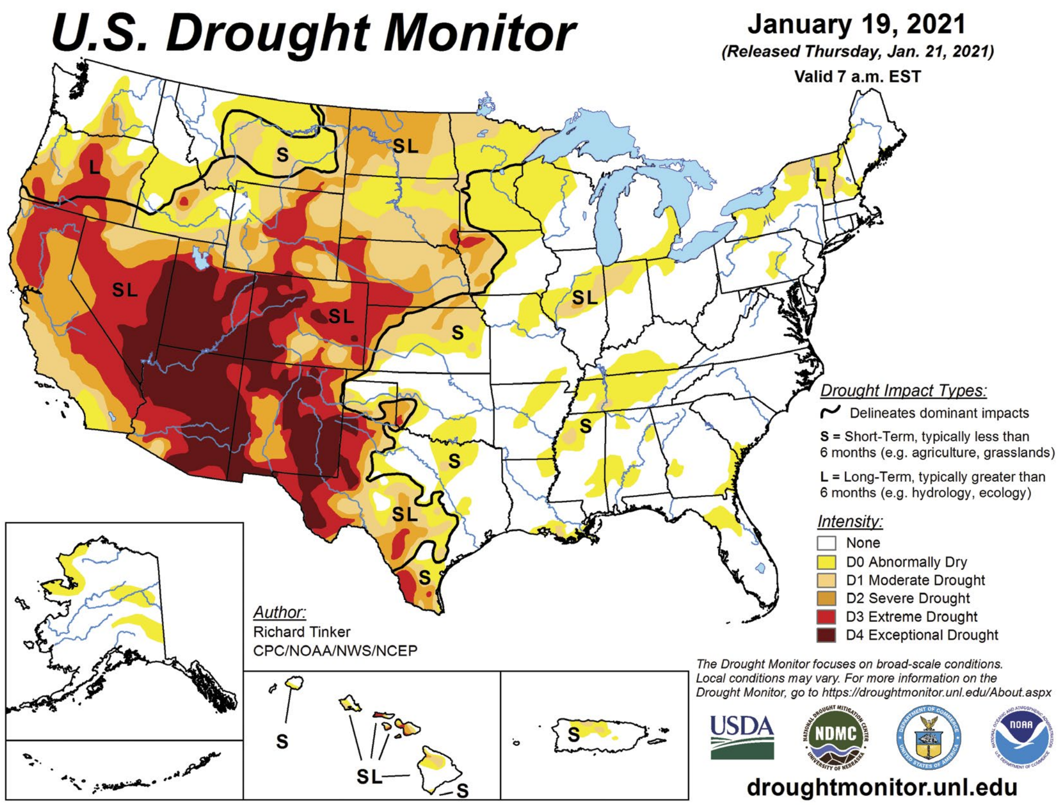
During the ensuing decades, various government and academic groups continued to tackle the amorphous issue of drought. In the 1980s at Colorado State University, Thomas McKee developed the well-regarded Standardized Precipitation Index (SPI). The SPI is renowned for its simplicity—only monthly historical precipitation data is needed to make calculations—making it an effective drought-monitoring tool in data-sparse areas such as islands and developing countries. However, the same ease with which the SPI can be calculated also reveals its limitations: no accounting for temperatures and related parameters, such as evapotranspiration; sensitivity to the period of record; and no consideration of rainfall intensity or runoff. To its benefit, the SPI can be computed for multiple time scales, from 1 to 60 months, although conflicting signals arise when some time scales indicate wetness and others point toward drought.

By the late 20th century, it was apparent to the meteorological community that a fresh way of thinking about drought was needed. The venerable PDSI was still widely used—and sometimes misused—in a variety of publications and state drought plans. Often, the PDSI's limitations were glossed over, as if the product had been created for all drought-monitoring purposes. Further, new and competing drought

PALMER FAMILY ARCHIVES

Wayne Palmer through the years. From left to right: "Senior Portrait, Nebraska, USA"; "New York City with family, 1943"; and "Wayne Palmer, 1971".

U.S. DROUGHT MONITOR



A sample weekly Drought Monitor change map from January 22, 2021.

indices—beyond the PDSI and the SPI—arose in the 1990s with the advent of modern computing and the promise of the Internet. As the dawn of the 21st century approached, drought scientists began to wonder if, instead of choosing one drought index over the others, there was a way to integrate them all.

A New Partnership

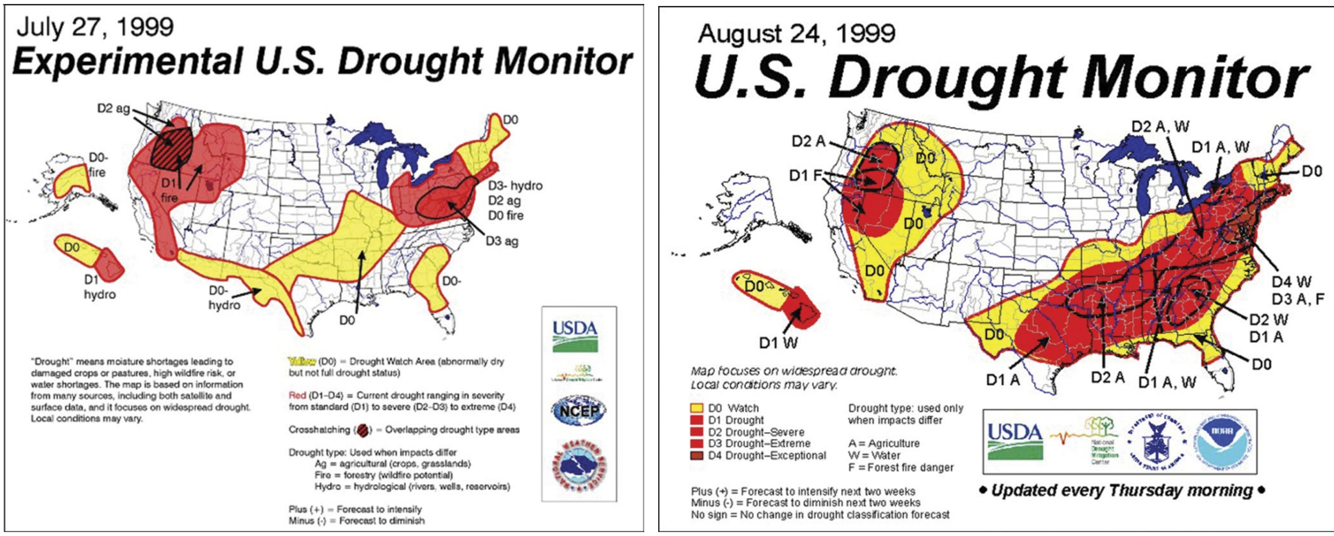
In the late 1990s, National Drought Mitigation Center (NDMC) founding director Don Wilhite assigned climatologist Mark Svoboda to find every drought-related index, indicator, and tool that existed. Svoboda made a presentation on drought mapping at the 1998 American Meteorological Society annual meeting. Another attendee, Douglas Le Comte of the NWS's Climate Prediction Center, offered to join forces in helping to combine various drought indices into a single map. "That's where the idea was born to make a high-resolution [drought] map from combining several indicators," said Svoboda, who is now the NDMC director.

Their collaboration culminated in the creation of the U.S. Drought Monitor (USDM), which celebrated its 21st anniversary in 2020. Every week since the Drought Monitor was unveiled at a White House press conference on August 11, 1999, the NDMC, the U.S. Department of Agriculture (USDA), and the NOAA have teamed up to release the Drought Monitor.

Prototype versions of the Drought Monitor, issued in the late-spring and early-summer of 1999, show rather crudely drawn and designed maps that were constructed using CorelDRAW 8. However, the Drought Monitor got a quick boost in the summer of 1999 due to the development of exceptional drought (D4) in the mid-Atlantic. Today's maps differentiate only between long-term (L) and short-term drought (S), but original authors like to joke that the USDM only came into existence because of "political drought"— the fact that in the late summer of 1999, exceptional drought was centered over the nation's capital.

The torrid pace of the USDM advancing from a concept to an operational drought-monitoring tool, which occurred in less than six months, may be a record for a product involving academia and multiple federal agencies. What quickly emerged with the USDM was a classification system for drought that would be—according to a 2002 article published in the *Bulletin of the American Meteorological Society*—"as recognizable to the public as the Fujita tornado intensity scale (F0-F5) and the Saffir-Simpson hurricane intensity scale (Categories 1-5)."

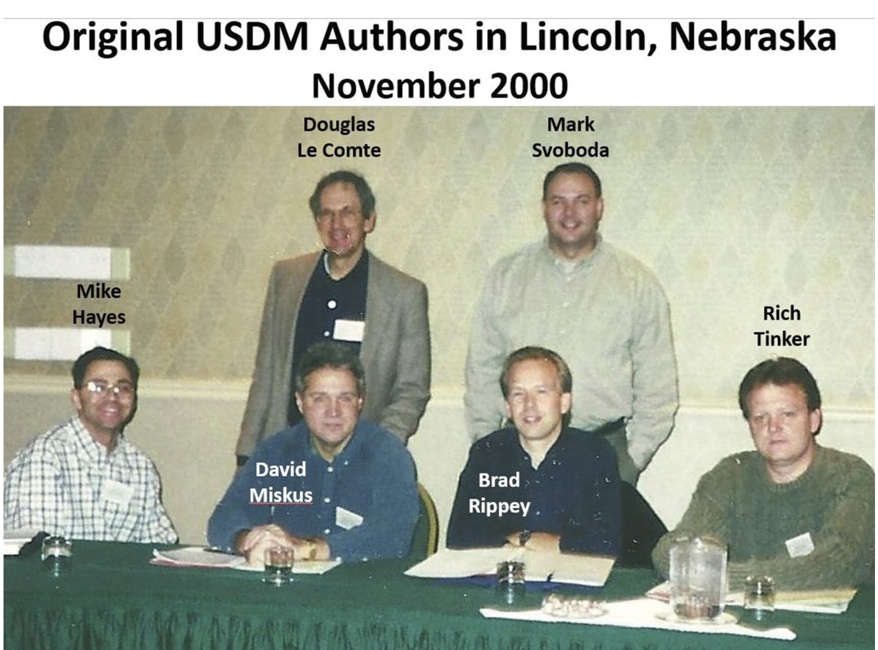
U.S. DROUGHT MONITOR



Experiment in Drought: The USDM was thrust into the operational limelight in mid-August 1999 when exceptional drought developed over the Nation's capital.

By early Fall 1999, six lead authors were placed into the USDM rotation. The stable included product founders Mark Svoboda (NDMC) and Douglas Le Comte (NWS/Climate Prediction Center), along with four others: Michael Hayes of the NDMC, Brad Rippey of the USDA, and David Miskus and Rich Tinker of the NWS/Climate Prediction Center. Today, as then, each week's author is responsible for the final product, leading a grueling three-day, drought-monitoring rotation for the Lower 48 states, as well as Alaska, Hawaii, and Puerto Rico.

A brief glimpse into a modern-day USDM author's weekly shift starts when the previous Drought Monitor is released on Thursday morning. Most lead authors try to get an early start by looking at drought hot spots on Thursday and Friday, even though each drought-monitoring period lasts for a week, ending Tuesday morning. The challenging work begins on Monday morning, when the author examines dozens of indices and indicators—including soil moisture, streamflow, and groundwater; precipitation-driven indices like the SPI; newer evapotranspiration-oriented tools; and satellite- and vegetation-based products. By the time an initial draft map has been disseminated late Monday, there are still a few hours left in the drought-monitoring period—which can be



BRAD RIPPEY

First Meeting: The six original USDM authors met for the first time in Lincoln, Nebraska, in November 2000, at the inaugural U.S. Drought Monitor Forum.

problematic when a heavy-precipitation event is underway. Additional drafts are released on Tuesday and Wednesday, all while feedback is received from a large network of trusted advisers. Once the map has been finalized late Wednesday, it is prepared for a Thursday morning release while the author completes a narrative that summarizes key changes and provides supplemental drought information.

Today, Svoboda describes the USDM as an effort to capture the collective strengths of a variety of drought products and to mask their deficiencies; to "heighten awareness of drought as one of the most impactful of all [natural] hazards; to take into account impacts; to make the map simple, understandable, and thus usable; and to have a built-in validation network of experts on the ground as a sanity check and to provide local data, impacts, and knowledge through an iterative process."

The Drought Monitor Comes Alive

The concept of the USDM to provide a weekly assessment of drought came with many challenges, some of which remain today. As with any operational product, real-time data input was needed. In the late 1990s, the Internet was still in its infancy and many drought products had not yet been digitized. Some of the data—which included precipitation, streamflow, modeled soil moisture, and the PDSI—were available only at a coarse scale, limiting the spatial resolution of drought assessment.

However, the flexibility of the fledgling USDM—a unique blend of physical data and local input, including impact information and validation from field experts—allowed the initial team of six lead authors to independently analyze each dataset and easily add new modeled, satellite-based, and data-driven products as they were carefully vetted and tested. Even today, scientists continue to develop and test new drought products; occasionally, new tools are added to the weekly monitoring process.

Throughout its two-decade history, the USDM process has been truly unique. No other drought product combines real-time local and expert evaluation with a database that has grown from a handful of indices to dozens of input parameters. Indeed, the USDM was the first true composite, or hybrid, drought product placed into operational status, combining an array of input and data into a single map.

Yet, on occasion that same process has been met with criticism. One of the chief complaints is that the USDM cannot be replicated, as there is no mathematical formula used to create each map. There has never been a USDM reassessment or reanalysis because there is no way to recreate the product. Certainly, there is no perfect answer to the criticism, but preliminary studies have determined that for the nation as a whole, the weekly USDM snapshot outperforms any individual drought index or indicator.

From the first map to the present day, one of the key contributions of the USDM has been to define drought intensity using percentile rankings. The map's first category, abnormal dryness (D0), is not drought, but rather is indicative of an area on the verge of slipping into drought or having emerged from drought. The other four categories, ranging from D1 (moderate drought) to D4 (exceptional drought), describe droughts that, based on historical data, have a statistical probability of recurring once per 5–100 years.

Questions that have arisen from using percentile rankings include: (1) Why have I experienced several exceptional (D4) droughts in the last 20 years? (2) If I've experienced a 500-year drought, is there another drought category beyond D4? (3) How does the USDM account for climate change?

The simple answers are the following: (1) Like 50- to 100-year flood events, exceptional droughts can occur in a given location more than once or twice per century; the odds of experiencing D4 in a particular year are somewhat independent of previous occurrences. (2) Because of limitations on data availability prior to the 20th century, it is impractical to define drought intensity beyond D4, which has an expected return frequency of once per 50–100 years. (3) The USDM analysis is dependent on the periods of record for each dataset driving the analysis; data that captures changing climate will be reflected in the USDM.

Teamwork

Through more than two decades, the guiding principles of the USDM have remained unchanged. Drought depictions are driven by percentile rankings and refined by local expertise. However, there have been notable changes within the monitoring framework. Within five years of the USDM's creation, the transition to using a geographic information system was complete, allowing the drought map to be drawn using dozens of interchangeable data overlays

Intensity	Description	Return Frequency	Percentile Ranking
D0	Abnormally dry	Once per 3–5 years	20th–30th
D1	Moderate drought	Once per 5–10 years	10th–20th
D2	Severe drought	Once per 10–20 years	5th–10th
D3	Extreme drought	Once per 20–50 years	2nd–5th
D4	Exceptional drought	Once per 50–100 years	1st–2nd

showing a variety of indicators and indices at various time scales. The flexibility of using a geographic information system permits a seamless transition between authors—and an easy way to ingest newly vetted datasets. As a result, the USDM has evolved into a high-resolution product that matches the ever expanding array of observed, satellite, and gridded data.

Meanwhile, an original roster of about two dozen USDM contributors—mostly climate scientists—has grown to nearly 500 participants. The nationwide drought group, which primarily communicates via an email listserv, is loosely organized by state and region. USDM authors have greatly benefited from listserv interactions, as participants are able to provide local expertise and on-the-ground drought reporting. Ensuring that the USDM depiction matches drought impacts is a key component of the feedback process. Each week, the lead author is responsible for creating several USDM drafts to allow for input to be shared and concerns to be aired—and to provide transparency regarding the final map.

In the 21-year history of the USDM, there have been just 27 lead authors covering more than 1,100 weekly shifts. Three of the original six authors—Rich Tinker, Brad Rippey, and David Miskus—remain in the rotation, although Miskus plans to retire in 2021. Collectively, Tinker, Rippey, and Miskus have covered nearly 400 shifts, more than one-third of the total. Ten current lead authors have been responsible for well over one-half of the total shifts.

USDM Usage and New Drought Terminology

For a poorly understood phenomenon such as drought, there is a constant need to educate the public, as well as appointed or elected officials. Unlike highly visible disasters such as hurricanes, tornadoes, wildfires, and winter storms, which sometimes exact property damage at a rate of millions or billions of dollars per hour, drought is a

USDM Authorships by Individual
August 18, 1999 – January 19, 2021

BRAD RIPPEY

Name/Organization	Shifts	Name/Organization	Shifts
* Rich Tinker, CPC	144	Laura Edwards, WRCC	19
* David Miskus, CPC	129	* Deborah Bathke, NDMC	19
* Brad Rippey, USDA	102	Chris Fenimore, NCEI	16
Mark Svoboda, NDMC	86	Jessica Blunden, NCEI	14
* Richard Heim, NCEI	86	* Curtis Riganti, NDMC	13
* Brian Fuchs, NDMC	80	Candace Tankersley	10
Douglas Le Comte, CPC	54	Ned Guttman, NCEI	9
Eric Luebehusen, USDA	54	Jay Lawrimore, NCEI	9
Anthony Artusa, CPC	43	* Brad Pugh, CPC	8
* Dave Simeral, WRCC	41	Tom Heddinghaus, CPC	7
Michael Brewer, NCEI	33	Scott Stephens, NCEI	6
Michael Hayes, NDMC	29	* Adam Hartman, CPC	6
Matt Rosencrans, CPC	28	Michael James, CPC	2
		Karen Gleason, NCEI	1

*** Denotes active USDM author**

USDM Authorship History: From 1999–2020, only 27 individuals have served as a lead author; currently, there are ten authors, three of whom have been in the rotation since 1999.

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creeping phenomenon. Impacts start slowly but can last for months or years—and are often equally stubborn to subside.

NOAA's tally of Billion-Dollar Weather and Climate Disasters lists 28 droughts in the United States over the last 40 years, with an average cost of $9.4 billion per event or $6.2 billion per year. During the historic U.S. drought of 2011–2013, lack of rainfall inflicted more than $60 billion in damage to the U.S. economy, mainly to agriculture.

As early as 2002, U.S. government officials recognized that the USDM could be used to appropriately direct agricultural disaster assistance. During a severe Western drought in 2002–2003, the USDA used the USDM depiction to direct emergency deliveries of nonfat dry milk—an important nutritional supplement for livestock when hay is scarce or prohibitively expensive due to drought. In the summer of 2006, with nearly one-half of the country experiencing drought, attention again turned to the USDM to trigger aid in the form of $50 million in state block grants for livestock producers.

Since 2008, the USDM has been used to provide direct payments to livestock producers in drought-affected regions. In the last decade, more than $7 billion in direct drought disaster assistance has flowed to producers through a provision—the Livestock Forage Disaster Program—in a series of congressionally approved Farm Bills. Since 2012, USDA secretarial drought disaster declarations have been tied to the USDM depiction—an automatic trigger for a previously lengthy process that involved gubernatorial letters to the Secretary of Agriculture.

As the USDM has evolved, some new terminology has appeared. The "convergence of evidence" approach describes the method used by USDM authors to arrive at a certain designation. Rarely, all products point toward similar drought intensity—a true convergence of evidence. More commonly, a nuanced approach is used to resolve differing drought intensities for various products and across multiple time scales. The simplest example involves heavy rain falling in an area experiencing exceptional drought (D4). The long-term component of drought remains D4, or at best improves slightly, while the short-term component of drought clearly improves. The remaining drought carries an "L" designation, for long-term drought. Most long-term drought indictors, such as reservoir storage and groundwater levels, still converge toward a serious drought situation.

The opposite situation involves short-term dryness in an area experiencing long-term wetness. Shallow-rooted plants are particularly susceptible to topsoil moisture depletion, especially when combined with extreme heat. USDM co-founder Mark Svoboda coined the term "flash drought"—a play on flash flood—to describe such a fast-developing drought situation. A recent study, titled "Flash Drought Characteristics Based on the U.S. Drought Monitor" and published in the journal *Atmosphere*, defined a flash drought as an event with greater than or equal to two categories degradation in a four-week period based on the USDM.

What the Future Will Bring

Looking to the future, Svoboda believes that as computing evolves and allows for further combination of drought indicators using "deep learning," the Drought Monitor process will improve but not be overridden by technological advances. When the USDM celebrated 20 years, Svoboda commented that "we have a process called the Drought Monitor. It also involves ownership of people on the ground, those [more than 400] evaluators that are now part of the Drought Monitor network. Once they… have a voice, and they have ownership, then we [have] the buy-in and credibility on the ground, and no single indicator or model integrated validation [is] better than the USDM."

The idea of combining the attributes of many inputs has pushed the USDM to the forefront. Around the world, the USDM is recognized as the gold standard for drought monitoring. A partner product, the North American Drought Monitor—a monthly collaboration between scientists in Canada, Mexico, and the United States—has been in existence since 2003. Several other countries, including Brazil, South Korea, and the Czech Republic, have applied the USDM methodology.

USDM authors hope in the future to involve more citizen scientists. USDM currently uses two online systems enabling farmers, ranchers, homeowners, and others to input valuable information regarding drought impacts in their communities: the Drought Impacts Reporter (https://droughtreporter.unl.edu/submitreport/) and the CoCoRaHS Condition Monitoring Resource (https://www.cocorahs.org/Content.aspx?page=condition). The authors use these systems to focus on areas where drought impacts are being felt by people on the ground. With the growth of the citizen scientist movement, the hope is that more engagement with local conditions will provide an even richer dataset for the authors of the USDM. W

U.S. Drought Monitor authors BRIAN FUCHS is a climatologist at the National Drought Mitigation Center at the University of Nebraska; DAVID SIMERAL is an associate research scientist in climatology at the Desert Research Institute in Reno, Nevada; DEBORAH BATHKE is a climatologist at the National Drought Mitigation Center at the University of Nebraska; and RICHARD HEIM is a meteorologist at NOAA's National Centers for Environmental Information. Former Drought Monitor author MARK SVOBODA is a climatologist at and the Director of the National Drought Mitigation Center at the University of Nebraska.


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