



NOAA Drought Task Force 2016

Research to Advance National Drought Monitoring and Prediction Capabilities



Drought poses a significant, ongoing threat to the health, vitality, and prosperity of the United States and its citizens.

Periods of extreme dryness and their significant impacts on lives and the economy are woven throughout the history of our Nation, which derives enormous economic productivity from its vast agricultural system and access to abundant freshwater resources for industrial, municipal and recreational purposes.

Research-based knowledge, monitoring, prediction, management, and mitigation have proven invaluable in reducing the extent and impact of drought on our economy and society. To this end, the National Integrated Drought Information System (NIDIS) works to prepare people, communities, and governments to mitigate the impacts of drought through preparation, improved monitoring and prediction, and building information networks that extend from the local to the federal level. A critical component in building this capacity is research that helps us better understand, monitor, and predict droughts.

In partnership with NIDIS, the NOAA OAR Climate Program Office’s Modeling, Analysis, Predictions, and Projections program (MAPP), in coordination with other agency programs, works with the drought research and operational community, and NOAA Climate Test Bed to support research that advances capabilities undergirding the creation of a more drought-resilient

nation. This report documents how research has been improving operational capabilities to monitor the current state of drought, predict its onset and evolution from weeks to seasons, and better understand why drought occurs. Operational improvements have been accomplished by fostering a healthy pathway for the transition of research to capabilities.

The work reported here has involved a focused collaboration among NOAA Office of Oceanic and Atmospheric Research laboratories, Cooperative Institutes, and National Weather Service operational centers; other federal agencies and their laboratories; and critical involvement by the academic community. We believe such research collaborations, as a central part of NIDIS, have significantly supported the Nation’s capacity, preparedness and resilience in the face of drought.

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COVER PHOTO: Lake
 Oroville’s Bidwell Marina on
 September 5, 2014. Photo:
 California Department of
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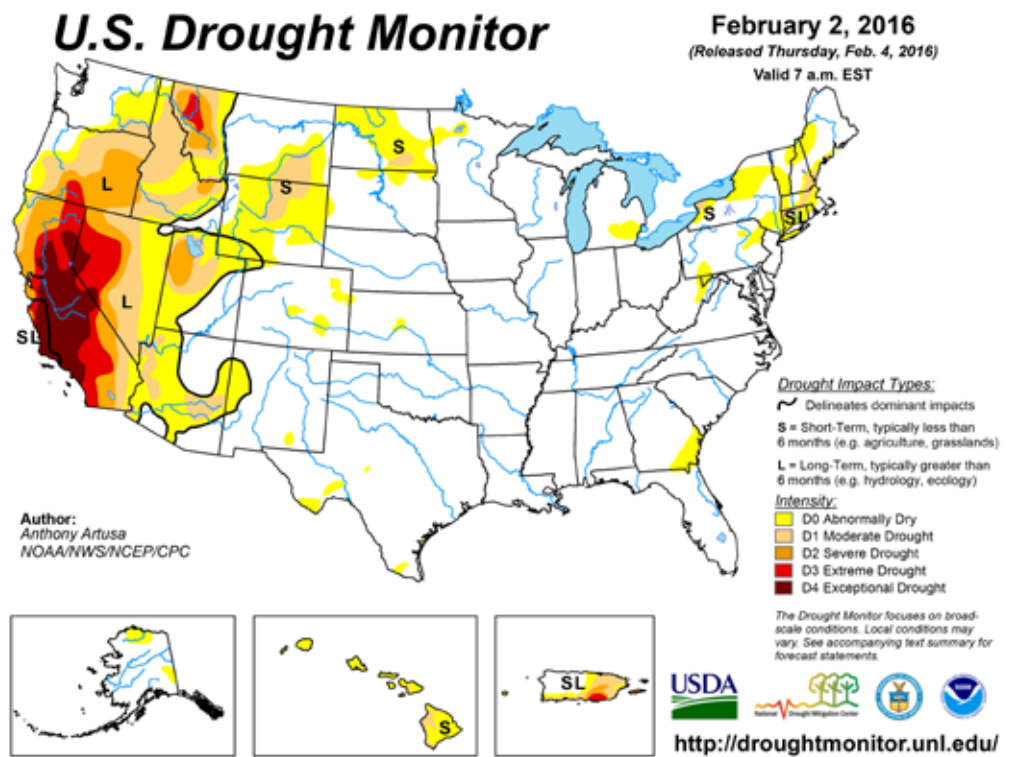
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EXECUTIVE SUMMARY

The past decade's investments enhanced and expanded monitoring and forecasting products

This report offers an overview of the state of science and practice in monitoring, forecasting and understanding droughts. It highlights the influence of research on advancing drought operations and capabilities, how this is being assessed, and opportunities for further progress. The goal of the report is to communicate the crucial role that research plays in advancing the development and implementation of the Congressionally-mandated National Integrated Drought Information System (NIDIS) early warning system. This report, written by members of the NOAA Drought Task Force from academic and federal institutions, is intended to communicate with a diverse set of readers, including the general public, public and private sector leadership, and users and stakeholders of drought products.

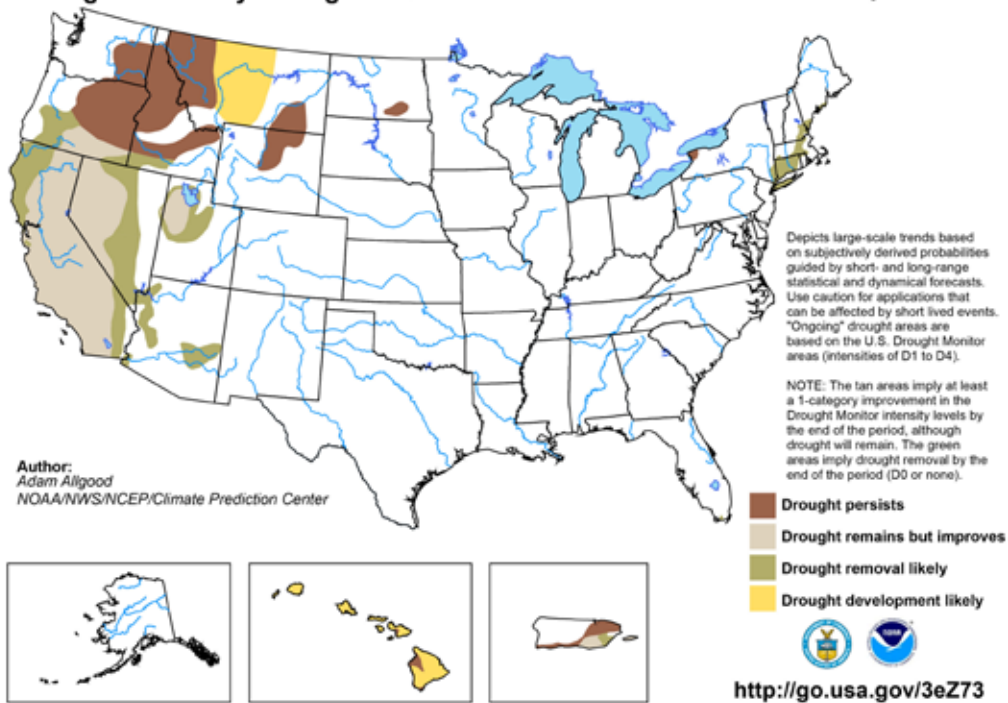
The U.S. Drought Monitor (USDM), which provides a weekly assessment of drought conditions throughout the United States, is the nation's flagship drought monitoring product and was first created in 1999 by NOAA's Climate Prediction Center (CPC), the National Drought Mitigation Center (NDMC) and the U.S. Department of Agriculture (USDA). The USDM has evolved and improved since then due to the efforts of a nationwide team of field experts and scientists to incorporate more ground-based observations, impacts, and new objective and quantitative input indices and analyses developed and tested as a result of drought research efforts. The primary prediction products associated with the USDM are the U.S. Monthly and Seasonal Drought Outlooks produced by the CPC. The



ABOUT THE MAP
 U.S. Drought Monitor maps are released every Thursday morning at 8:30 Eastern Time, based on data through 7 a.m. Eastern Standard Time (8 a.m. Eastern Daylight Time) the preceding Tuesday. The map is based on measurements of climatic, hydrologic and soil conditions, as well as reported impacts and observations from more than 350 contributors around the country.

U.S. Seasonal Drought Outlook Drought Tendency During the Valid Period

Valid for January 21 - April 30, 2016
Released January 21, 2016



THE 3-MONTH SEASONAL DROUGHT OUTLOOK

NOAA's Climate Prediction Center publishes the Seasonal Drought Outlook on the third Thursday of the month. Tools used to create the map include temperature and precipitation outlooks, forecasts and models; soil moisture tools; El Niño predictions and other materials as appropriate.

Investments in drought-related science, technology and information systems over the past decade have been key to enhancing and expanding the quality and range of drought monitoring and forecasting products. The NOAA Climate Program Office (CPO) Modeling, Analysis, Predictions and Projections (MAPP) Drought Task Force, established by CPO in 2011, was introduced to play a coordinating role for drought research funded by CPO/MAPP. Below are examples of research advances that have resulted from funding supplied by the MAPP program, which works in partnership and coordination with NIDIS and other federal agencies such as NASA, NSF, DOE, and USDA to support drought research.

Drought monitoring

New drought monitoring products such as surface hydrometeorological analyses based on satellite data and National Land Data Assimilation System (NLDAS) model simulations provide quantitative and reproducible estimates of current and historical surface moisture and energy conditions. The NLDAS multi-land surface model drought monitoring system, which is also used for forecasting, has been transitioned from experimental implementation to operational deployment at NOAA NCEP and is an input to the USDM. This new system offers the basis for a seamless national-scale hydrometeorological monitoring and prediction capability.

Drought prediction

An assessment of the NMME system for seasonal climate and drought prediction has been carried out as part of the NOAA Climate Test Bed

outlooks are presented as forecast maps produced as part of a merging of inputs from the official CPC temperature and precipitation outlooks, long lead forecasts including those from the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS), the North American Multi-Model Ensemble (NMME) system, short-term weather forecasts from NCEP and ECMWF, and current conditions from USDM. The NIDIS web site (<http://drought.gov>) presents the routinely updated USDM and Drought Outlook products.

(CTB). The system, based on the leading climate models in the U.S. and Canada, has shown skill improvements in most seasons and has helped improve estimates of forecast uncertainty. NMME-based drought forecasts are now routinely being produced. More generally, research has helped to quantify uncertainty in drought forecasts and to attribute them to uncertainties in initial land surface conditions, climate forecasts, model formulations and other factors, using both climate models and hydrologic models.

Understanding drought

Advanced fundamental understanding of North American drought mechanisms and predictability, critical to improving predictions, has been developed. For example, the importance and also limitations of La Niña and modulating phenomena in other ocean basins for driving drought in the Great Plains are now well established. In addition, leading causes of drought in California have been established. Better understanding of the role of internal (unforced) atmospheric variability in producing some of the most extreme droughts on seasonal and longer time scales has been developed, in addition to improved understanding regarding the role of land surfaces and changes in local and remote surface evaporation sources.

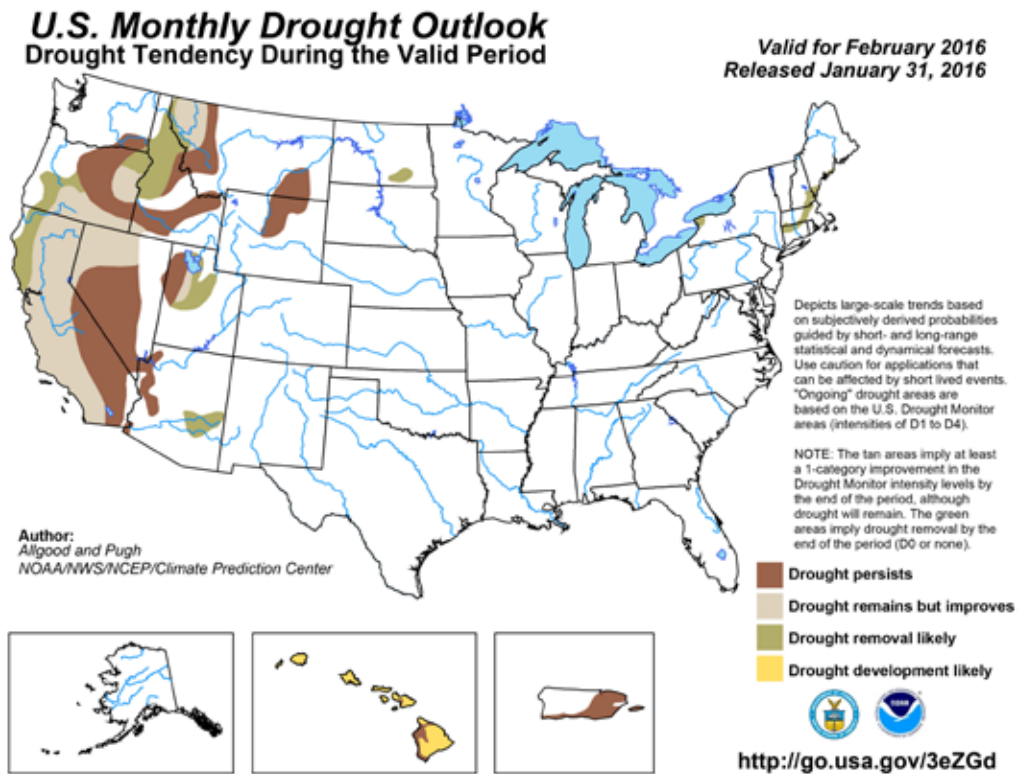
Assessing the development of improved capabilities

A Drought Capability Assessment Protocol that guides a more rigorous assessment of research toward new capabilities was developed. The protocol includes metrics for systematic assessments of whether research has improved drought monitoring and forecasting datasets, techniques and products. This assessment approach was developed by the NOAA Drought Task Force and is being adopted by the community.

There remain gaps, challenges and opportunities to further improve the nation’s understanding of drought and the capacity for drought monitoring and forecasting. Some of these include:

Drought monitoring:

- ◆ Assessing and improving the objectivity of new monitoring inputs for their integration into the USDM. Inputs include in-situ and satellite



THE MONTHLY DROUGHT OUTLOOK

The monthly outlook is published by NOAA's Climate Prediction Center at the end of the month for the following month.

A Drought Capability Assessment Protocol includes metrics for systematic assessments of whether research has improved drought monitoring and forecasting datasets, techniques and products.

observations, NLDAS and other modeling system outputs, expert opinions and drought impacts.

- ◆ Maintenance and expansion of the nation's in-situ, gauge-based observing networks for meteorological, climate and hydrologic variables (including soil moisture, snow and streamflow) and facilitation of the near real-time objective merging of relevant satellite data with in-situ observations.

Drought understanding and prediction:

- ◆ Improvements to the prediction of the full cycle of drought, including onset, duration, severity and recovery, via an enhanced prediction system as well as improved understanding of the key governing processes in the coupled ocean-atmosphere-land system, including their inherent predictability.
- ◆ Advances in climate forecasting provided by the NMME that contribute to improved drought forecasting via continued support and enhancement through systematic evaluation and further development.
- ◆ Leveraging the progress in NLDAS on hydrologic seasonal prediction systems and NMME for the development of a seamless, ensemble-based drought monitoring and prediction system based on the foundation provided by these tools.

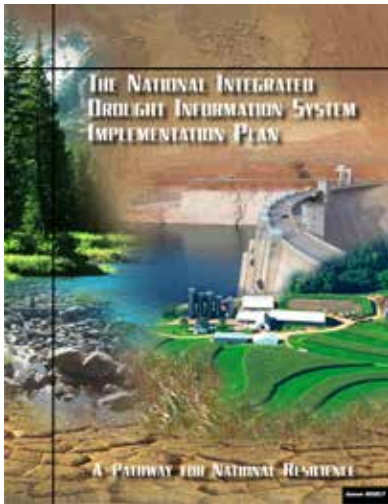
Enhancing the development of improved capabilities:

- ◆ Dedicated efforts are needed to conduct objective and systematic assessments of the drought monitoring and forecast capabilities, including the current baseline and improvements due to research and technology advances, following the Drought Capability Assessment Protocol.
- ◆ Enhanced research on operations/applications transition activities to integrate the latest advances in drought monitoring and prediction to support improved operational NIDIS products and drought information systems.

Technical details are purposefully omitted from this report and can be found in the report's Reference section and in a companion Special Collection of scientific papers titled "Advancing Drought Monitoring and Prediction" organized by the Drought Task Force in the Journal of Hydrometeorology (JHM)¹.

1. RESEARCH GOALS AND PARTNERS

National, state, local entities team up to improve prediction, monitoring, information



NIDIS' IMPLEMENTATION PLAN
Federal, state and local agencies, academic researchers, and other stakeholders conducted workshops and meetings to develop the steps in the 2007 NIDIS Implementation Plan.

The National Integrated Drought Information System’s (NIDIS)² Implementation Plan states, “Drought is among the most damaging and least understood of all natural hazards,” which causes tremendous economic and social impacts. Since 2000, 12 drought events have each caused greater than one billion dollars in economic impacts, with some events costing the country over \$10 billion³. To better prepare for and mitigate drought impacts, users and stakeholders need information on current droughts; on predictions for drought onset, evolution, and recovery over the next months, seasons and potentially years; and on regionally specific drought impacts. NIDIS was established in 2006 by the U.S. Congress and reauthorized in 2014 with the goal to develop a national early warning system to enhance drought preparedness and response. Attaining this goal requires a suite of research activities including those to advance our comprehension of drought and our capability to monitor and predict drought.

In this context, key NIDIS-relevant research objectives include:

- (i) **advancing the scientific understanding of the weather and climatic mechanisms** that lead to the onset, maintenance and recovery of drought;
- (ii) **improving drought prediction skill** by identifying and exploiting sources of drought predictability and related aspects such

Billion-dollar events to affect the U.S. from 1980 to 2014 (CPI-Adjusted)

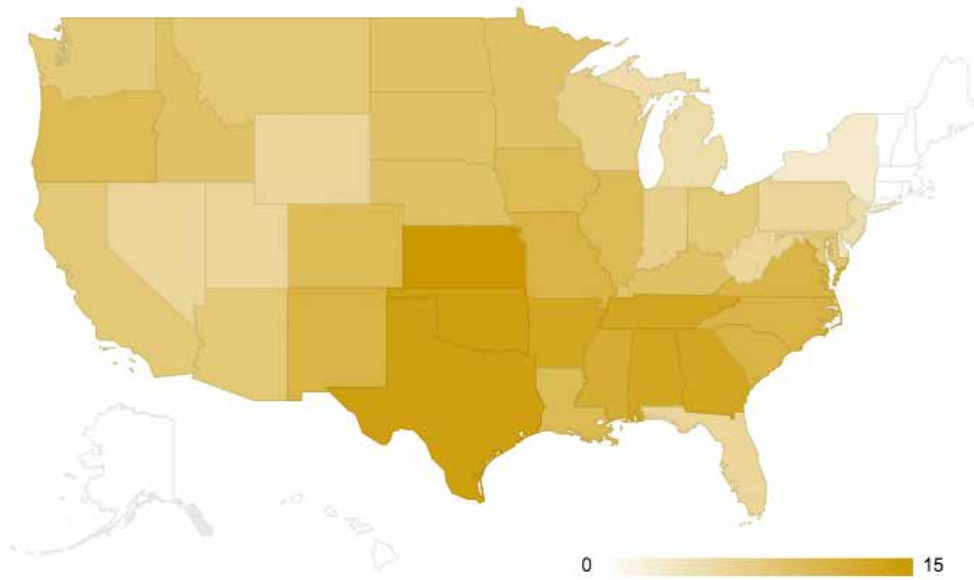
DISASTER TYPE	NUMBER OF EVENTS	PERCENT FREQUENCY	CPI-ADJUSTED LOSSES (BILLIONS OF DOLLARS) (1)	PERCENT OF TOTAL LOSSES	AVERAGE EVENT COST (BILLIONS OF DOLLARS)
Drought	22	12.4%	\$206	19.1%	\$9.4
Flooding	20	11.2%	\$88	8.2%	\$4.4
Freeze	7	3.9%	\$25	2.3%	\$3.6
Severe Storm	70	39.3%	\$155	14.4%	\$2.2
Tropical Cyclone	34	19.1%	\$539	50.0%	\$15.9
Wildfire	12	6.7%	\$26	2.4%	\$2.2
Winter Storm	13	7.3%	\$37	3.4%	\$2.8

DROUGHTS HAVE COST THE U.S. MORE THAN \$200 BILLION SINCE 1980

The National Centers for Environmental Information track weather and climate disasters with impacts costing a billion dollars or more. Between 1980 and 2014, 22 droughts have qualified for the list.

² <http://www.drought.gov/drought/>

³ <https://www.ncdc.noaa.gov/billions/events>



STATE-BY-STATE DROUGHT DISASTERS

NCEI’s billion-dollar-disaster database generated this map, which shows the states which have undergone droughts costing a billion dollars or more since 1980. Darker colors show more events. Kansas tops the list, with 15 billion-dollar events in the past 35 years, followed by Oklahoma and Texas with 14 each.

⁴ <http://DroughtTaskForce.aspx>

⁵ Research on socio-economic research and regional NIDIS applications is sponsored via the Climate Program Office Coping with Drought Program (<http://cpo.noaa.gov/ClimatePrograms/ClimateandSocietalInteractions/NIDISProgram/CopingWithDroughtInitiative.aspx>) and NOAA’s Regional Integrated Sciences and Assessments (RISA) program <http://cpo.noaa.gov/ClimatePrograms/ClimateandSocietalInteractions/RISAProgram/AboutRISA.aspx>.

⁶ Most recently “An International Global Drought Information System Workshop: Next Steps”, was held in Pasadena on the Caltech campus December 10-13, 2014 (<http://www.wcrp-climate.org/gdis-wkshp-2014-about>).

as the dependence on time scales, regions, seasons and variables, and improvements in forecast models and procedures;

(iii) **improving current drought monitoring capabilities**, including the exploitation of new data, methodologies and metrics that would improve society’s capability to manage drought; and

(iv) **improving drought information systems** through incorporating the latest advances in monitoring

and prediction, objective metrics relevant to various societal sectors and advanced information delivery platforms.

As mandated by Congress, NOAA leads the development of NIDIS, working with numerous partners across the federal, state and tribal governments, academia and the private sector. Since 2011, research to advance the understanding, monitoring and prediction of U.S. drought in support of NIDIS has been coordinated through a Drought Task Force⁴ (DTF) established by NOAA’s Office of Atmospheric Research, Climate Program Office, Modeling Analysis Predictions and Projections (MAPP) Program, which competitively sponsors DTF research activities⁵ jointly with NIDIS. This research includes testing new tools and methodologies for operations and applications via the NOAA Climate Test Bed (CTB).

The DTF works in coordination with the NIDIS program office and other relevant national and international research programs and includes experts across NOAA line offices (research and operational entities), other mission and science agency representatives, and leading academic scientists across the U.S. Some of those include the NASA NEWS program and the World Climate Research Program’s (WCRP) Global Water and Energy Exchanges Project (GEWEX) and Climate and Ocean: Variability, Predictability and Change (CLIVAR) programs.

As an example of international collaboration, the DTF represents an important contribution to the international WCRP Global Drought Information System (GDIS) initiative.⁶

2. DROUGHT MONITORING CAPABILITIES

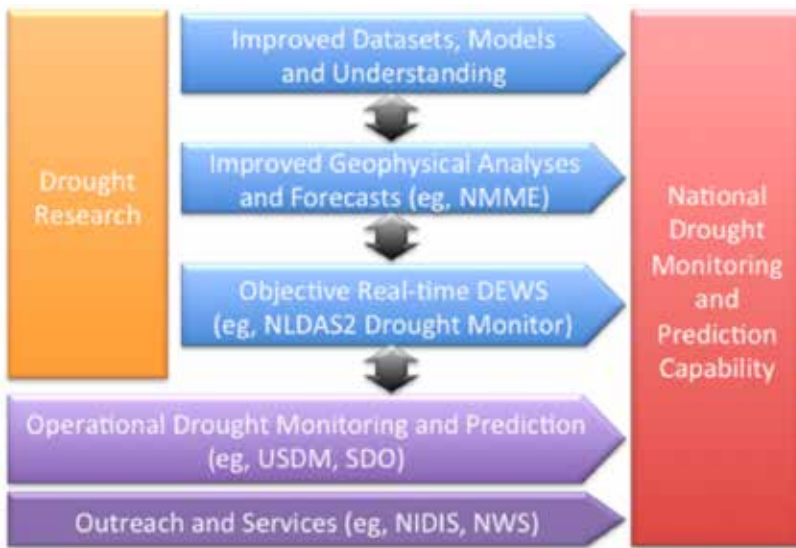
Building more detailed characterizations of drought

The overarching objective of drought monitoring research is to develop increasingly accurate, reliable, and high-resolution characterizations of the geophysical variables sensitive to drought through objective science-based methods, data, and understanding. Decades of sustained observations and significant investments in drought monitoring research, service, and information systems have produced our current operational monitoring capability. This capability comprises:

- (1) the **U.S. Drought Monitor** (USDM),
- (2) a broad range of quasi-operational **geophysical analyses** such as satellite vegetation imagery and various modeling efforts associated

with the North American Land Data Assimilation System (NLDAS) Project, and (3) several experimental and/or operational **Drought Early Warning Systems** (DEWS).

The impact of drought research on various elements of the monitoring (and prediction) capability is illustrated generally at left. Key research and development milestones in datasets, modeling and understanding; geophysical analyses and forecasts; and objective real-time DEWS are documented in this report as testimony of the value of research investments toward advancing drought monitoring.

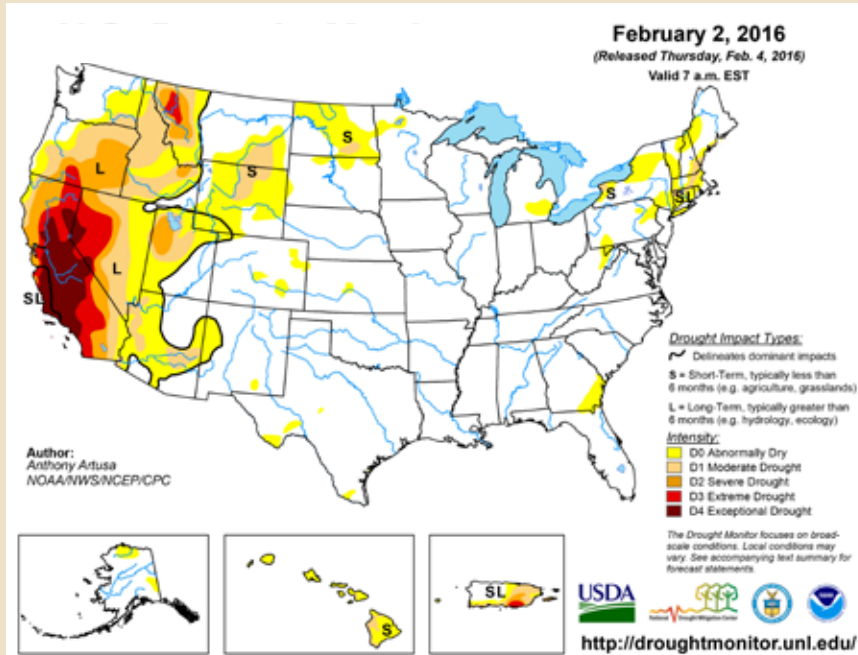


A RESEARCH FLOWCHART
The influence of drought research on U.S. drought monitoring and prediction capabilities.

2.1 THE U.S. DROUGHT MONITOR

The 1996 drought in the U.S. Southwest and southern Great Plains states led to the formation of drought task forces by the Federal Emergency Management Agency (FEMA) and the Western Governors Association (WGA), both of which emphasized the need for coordination and integration of federal and state-level responses to drought. One result of these initiatives was the National Drought Policy Act of 1998, which spurred a range of activities directed toward improving national resilience to drought. The USDM was created during the following year with the goal

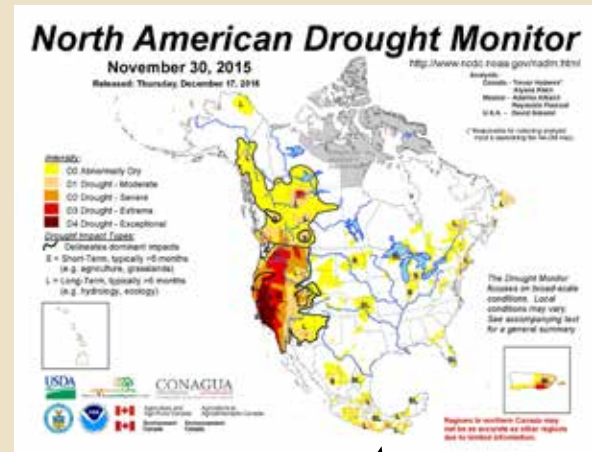
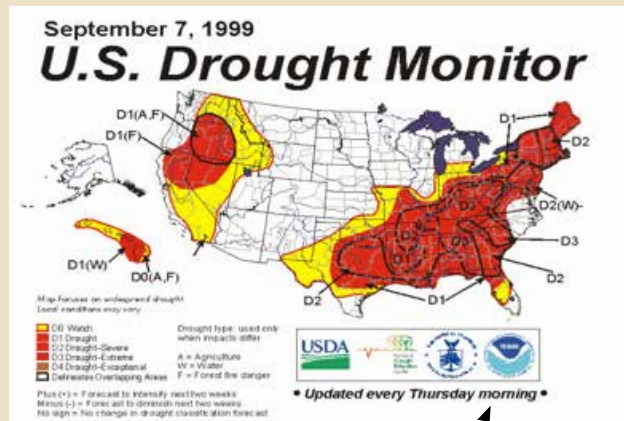
About the U.S. Drought Monitor



U.S. Drought Monitor maps of current drought conditions have been issued weekly since 1999. The USDM's steady increase in geographic scope and detail, collaborative participation, community acceptance, technology and range of inputs is summarized in the timeline below.

The weekly map provides a snapshot of current drought severity and spatial extent, and integrates a historical perspective through the use of a ranking percentile approach. The resulting classification scheme includes five categories ranging from D0

TIMELINE OF USDM DEVELOPMENT



Compare this first USDM with the current version, pictured directly above

The NADM is at <http://www.drought.gov/nadm/>

1998
NOAA's Climate Prediction Center and the National Drought Mitigation Center formulate the USDM concept and process.

1999
USDM launches **weekly maps** with a climate division focus and only a half dozen inputs, unveiled at a White House press conference; develops D0-D4 classification scheme for three impact types: A (ag), H (hydro) and F (fire).

2000
First USDM Forum organized and annual meetings begin; objective blends introduced; forecast component dropped.

2001
National Climatic Data Center (NCDC, now titled National Centers for Environmental Information, NCEI) joins author rotation; list-serve of contributors triples to 75 experts.

2002
North American Drought Monitor launched by NCDC; first use of USDM as a national trigger for a federal drought response (by the Farm Service Agency).

2003
The "fire" (F) impact type dropped; list-serve doubles to 150 experts; GIS adopted; inputs now include dozens of station-based and gridded datasets.

(abnormally dry) to D4 (exceptional drought) based on a ranked percentile approach.

A rotating USDM lead author uses their best judgment to reconcile differences in input analyses from a broad range of sources in constructing a draft USDM map. The draft map is reviewed by over 360 local- to national-level drought coordinators, agency leads and experts, and their feedback is incorporated by the lead author. The resulting final USDM map depicts a single severity category, for only one type of impact or for all facets of drought combined (i.e., meteorological, hydrological and agricultural are widely accepted drought types).

The USDM of 2015 is conceptually similar to the map introduced in 1999 (see map at left on timeline on page 10), although the informational inputs, technology and partnerships supporting the map have evolved.

CONTRIBUTORS TO THE USDM



The National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln (UNL)



U.S. Department of Agriculture (USDA) via the World Agricultural Outlook Board (WAOB) housed under the Office of the Chief Economist



National Centers for Environmental Prediction (NCEP) via the Climate Prediction Center (CPC)

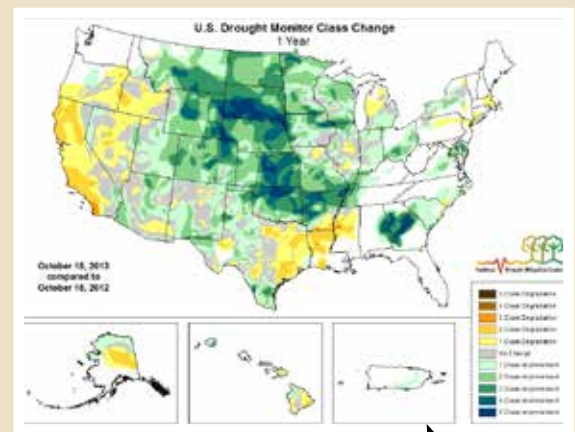
National Centers for Environmental Information (NCEI)



Western Regional Climate Center (WRCC)



Current conditions around the globe, interactive maps and information from regional drought groups are at <http://www.drought.gov/gdm/>.



Change maps can be customized to show how drought conditions have changed over different time spans.

2006

NIDIS begins; the USDA Livestock Assistance program and the Internal Revenue Service use USDM as a way to determine eligibility for drought relief.

2008

Western Regional Climate Center joins author rotation; regional, state and county displays created; incorporation of GIS weather and hydrological data; USDM included as trigger for relief in Congress' Farm Bill.

2010

NIDIS launches **Global Drought Information System** (GDIS), with Global Earth Observation System of Systems and World Meteorological Organization; integrates regional and national Drought Monitors.

2011

Drought impact types changed from "A" (ag) and "H" (hydro) to "S" (short term) and "L" (long term); USDM reaches 2 million visitors per year

2012

USDA Secretary of Agriculture uses USDM as a trigger to "fast track" drought disaster designations.

2013

USD**M Change Maps** added; new website/content management system platform with expanded web mapping services and archive launched

Since its inception, the USDM has advanced in various ways, but has always adhered to a “convergence of evidence” approach that draws on a nationwide team of field experts to synthesize an ever-growing suite of geophysical input analyses, and on-the-ground impact observations.

CONTINUED FROM PAGE 9

of providing a common understanding of the extent, intensity and duration of drought. Since its inception, the USDM has advanced in various ways, but has always adhered to a “convergence of evidence” approach that draws on a nationwide team of field experts to synthesize an ever-growing suite of geophysical input analyses, and on-the-ground impact observations. Pages 10 and 11 describe the USDM and its evolution in more detail.

The USDM is our nation’s flagship drought monitoring information product. Policymakers and media use the USDM to depict drought and allocate resources for drought relief. Since 2012, a USDA secretarial disaster “fast track” declaration is nearly automatic for a county shown in severe drought (D2) on the USDM for eight consecutive weeks, as well as for a county shown in extreme (D3) and exceptional (D4) drought at any time. A number of states also use the USDM or its input indices to trigger their local drought task force activities and drought declaration processes. For many stakeholders, the USDM and similar agency synthesis efforts are the mission-critical face of drought monitoring, and USDM maps provide the quantitative, categorical measure of the existence of drought.

2.2 IMPACTS OF RESEARCH TO IMPROVE NATIONAL DROUGHT MONITORING

Over the years, the research community at large has greatly expanded our nation’s drought monitoring capabilities, advancing the operational USDM through two pathways:

- 1) improving our understanding of drought processes and drought evolution; and
- 2) upgrading the range and sophistication of the geophysical analyses that are integrated by USDM authors to quantify drought severity in forming the USDM map.

In particular, drought research has spurred the development of objective and quantitative input indices and analyses. Such inputs have become a central feature of drought and climate monitoring because they provide a readily communicable description of relative drought severity and rarity, supporting the comparison of drought across a range of physical aspects, geography, and seasonality. For example, indices may aim to quantify drought-sensitive characteristics such as the humidity of the land surface, evapotranspiration rates, and runoff from rivers. Some indices, such as the Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and the surface water supply index (SWSI) are traditionally derived from direct, in-situ measurements, whereas others such as total soil moisture percentiles and the Standardized Runoff Index (SRI) rely on land surface simulation model outputs, a major area of recent research advances.

NOAA’s DTF has engaged in research to improve our understanding of the fundamentals of drought processes, and develop and demonstrate the value of datasets, methods and tools in supporting the USDM and the

overall drought monitoring capability including the development of:

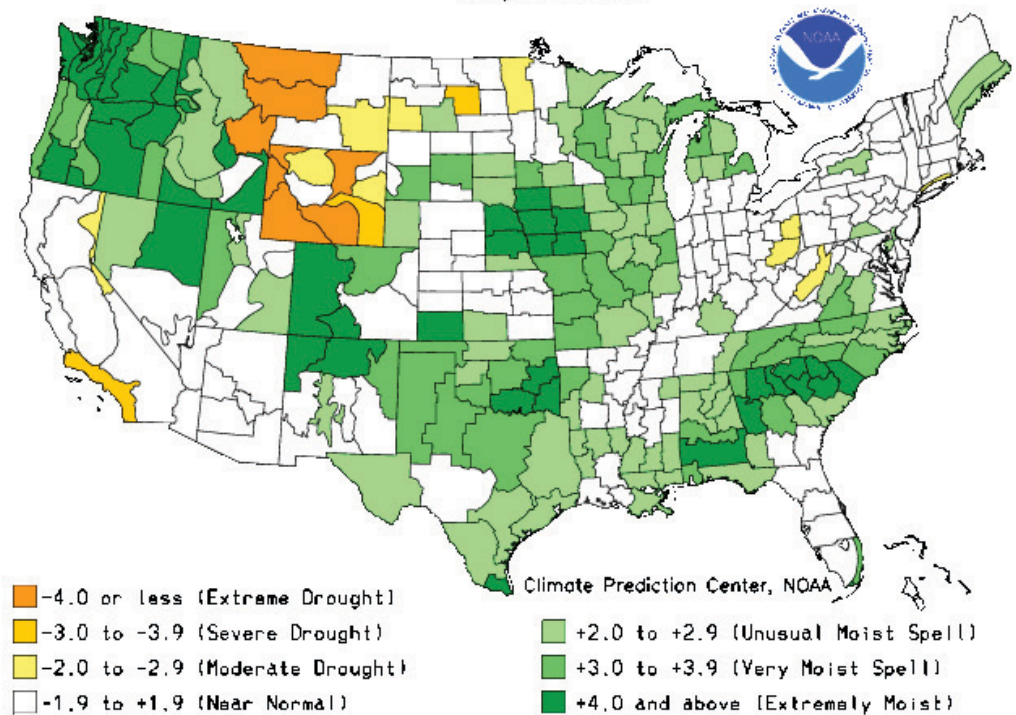
- (i) real-time operational of land surface models (LSMs) that quantifiably and reproducibly depict surface conditions using operational, real-time input data and long-term retrospective hydro-climate system datasets and reanalyses;
- (ii) observational surface analyses based on satellite remote sensing retrievals of drought-relevant parameters; and
- (iii) integrative drought indices and early warning systems.

Progress in these key areas is described below.

2.2.1 LAND SURFACE MODELING AND HYDROLOGIC REANALYSES

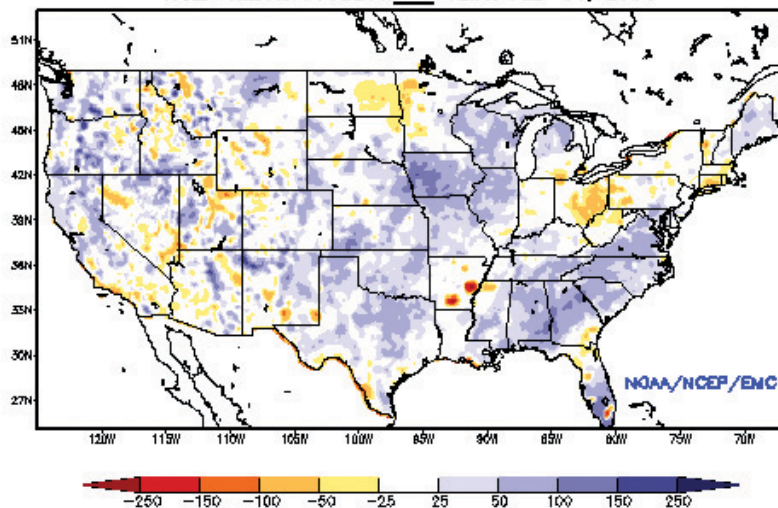
The North American Land Data Assimilation System (NLDAS) project commenced in 1999 and has since been steadily enhanced primarily through NOAA and NASA research programs. Housed at the NOAA NCEP Environmental Modeling Center (EMC), NLDAS now runs four land surface models at an hourly time-step over the continental U.S. (CONUS) and at 0.125 degree resolution. The observed forcing inputs (e.g., precipitation, temperature, humidity, wind speed, radiation) and land surface model outputs (e.g., soil moisture, snow-water equivalent, evapotranspiration, river discharge) represent a central thrust of science-based advances in drought monitoring, and are the core components of an effort to advance a national DEWS in support of NIDIS. For example, the USDM products currently make use of the CPC soil moisture analysis, but NLDAS modeling efforts surpass the CPC product in physical realism. Additionally, the USDM climate division precipitation analysis is now at a coarser resolution than the NLDAS precipitation input. Thus the NLDAS data products can now support a finer resolution and higher quality version of the USDM. An example of the NLDAS Drought Monitor soil moisture analysis is shown in the illustration on page 14.

Drought Severity Index by Division
Weekly Value for Period Ending JAN 30, 2016
Long Term Palmer



PALMER DROUGHT SEVERITY INDEX
The Palmer (PDSI), devised in 1965, was the first drought indicator to assess moisture status comprehensively. It uses temperature and precipitation data to calculate water supply and demand, incorporates soil moisture, and is considered most effective for unirrigated cropland. It primarily reflects long-term drought and has been used extensively to initiate drought relief measures.

Ensemble-Mean - Current Total Column Soil Moisture Anomaly (mm)
NCEP NLDAS Products Valid: FEB 04, 2016

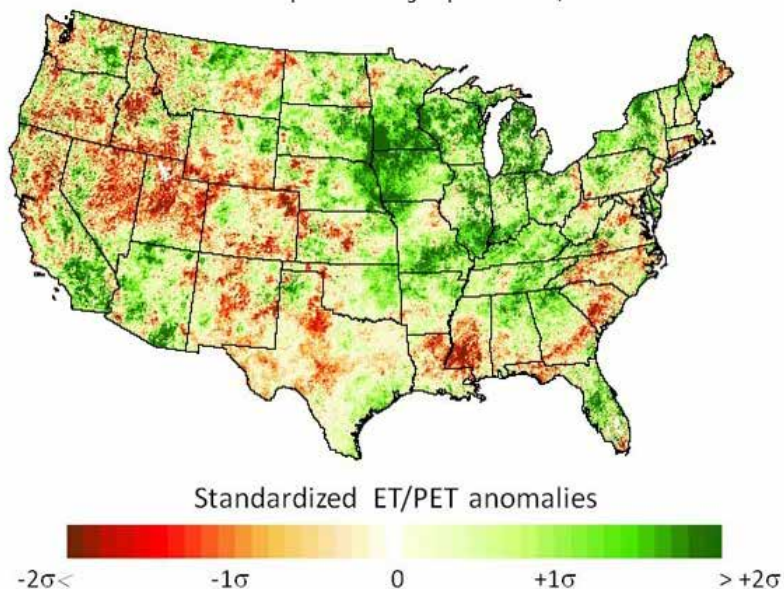


NLDAS DRIVEN SOIL MOISTURE ANOMALIES

Anomalies are difference between normal observed soil moisture conditions and current conditions, measured in millimeters. Areas in cold colors are wetter than normal while areas in warm colors are drier. (<http://www.emc.ncep.noaa.gov/mmb/nldas/drought/>)

Evaporative Stress Index 4km

1 month composite ending September 30, 2015



USDA EVAPORATIVE STRESS INDEX

The Evaporative Stress Index (ESI) describes temporal anomalies in evapotranspiration (ET), highlighting areas with anomalously high or low rates of water use across the land surface. (<http://hrs1.arsusda.gov/drought/>)

used for characterizing current droughts, as part of the USDM. For example, rapid-onset droughts are typically driven by warm air temperatures, a lack of cloud cover and often with high winds that enhance evaporation and dry soils. The remotely sensed ESI captures these phenomena and can provide an early warning of drought impacts on agricultural systems.

Another success of the last decade of research has been the application and refinement of this modern class of hydrological models toward objective (i.e., automated and reproducible) drought analysis, including extended retrospective forcing datasets to support hydrologic reanalyses that are nearly a century long.

2.2.2 REMOTELY SENSED OBSERVATIONAL ANALYSES

In addition to LSM-derived drought-related analyses, research supported by various agencies including NOAA has led to the development of new strategies for using satellite data to monitor drought (and floods), which can provide an assessment of drought characteristics independent of LSM analyses.

Like most current LSMs, the NLDAS models do not include a dynamical vegetation component, and therefore do not capture the reduction in evaporation that can arise from vegetation changes caused by drought (e.g., crop damage or delay). In this regard, the Evaporative Stress Index (ESI), shown in the figure at lower left, provides a thermal infrared satellite-based index to estimate evapotranspiration (ET) deficits, and may provide complementary information to the NLDAS systems.

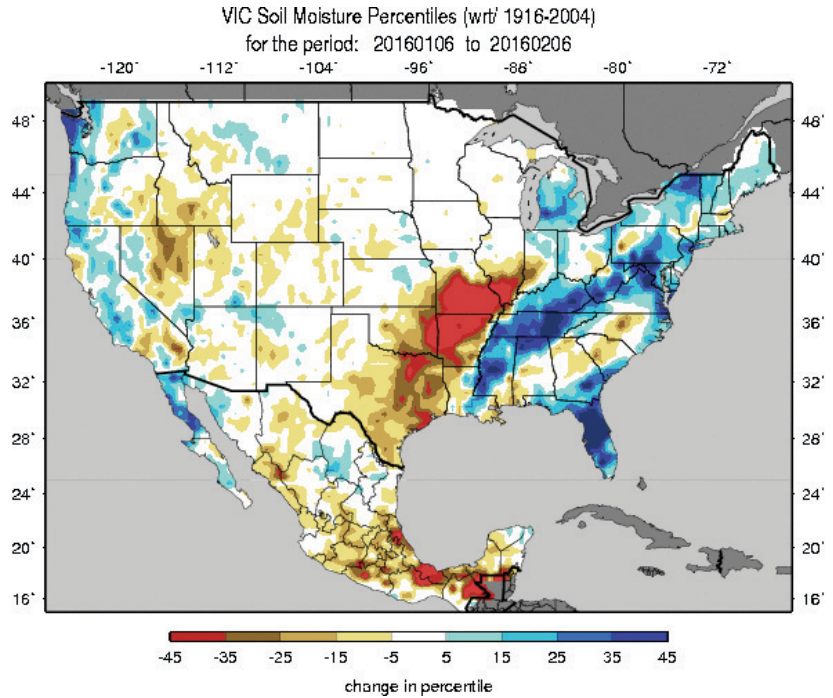
A key success in this area has been the expansion of near-real time satellite-based analyses that are relevant to drought, particularly those describing vegetation and evapotranspiration. These products further add to the information resources that can be

2.2.3 NATIONAL AND GLOBAL DROUGHT MONITORING (EARLY WARNING) SYSTEMS

Numerous drought products and innovations have emerged from the research efforts described above, among which are newly derived indices and new objective strategies for integrating indices and multiple sources of information. Examples of real-time operational systems that apply modern LSMs for drought quantification and prediction include the University of Washington’s Experimental Surface Water Monitor shown at right; the Princeton University’s Drought Monitor, Global Integrated Drought Monitoring, and Prediction System (GIDMaPS); and the NCEP NLDAS Drought Monitor.

Focus has also turned toward reproducible approaches for integrating multivariate output from these systems, such as in the case of the Objective Blended NLDAS Drought Index, or the Multivariate Drought Severity Index, both of which are drought classification methods to combine multiple monitoring indices into a single category of drought severity. Drought monitoring system websites, drought information clearinghouses (e.g., <http://www.drought.gov>), outreach efforts, and web services make such products ever more accessible to the drought management community, including the USDM authors.

These research products and the resulting advances in the USDM have been key to advancing NIDIS goals and have potential utility beyond CONUS, of key importance in the effort to develop a GDIS. For example, NOAA has supported efforts toward the development of global drought monitoring approaches through the development of the NCEP Global LDAS (GLDAS; covering 50°S to 50°N), and the more recent extension of the Surface Water Monitor and NLDAS multi-model monitoring to a near global system, which uses multiple LSM model outputs to form ensemble drought-related indices. The effort identified that the lack of data for both input and verification of monitoring in many regions of the world is a major challenge. Previous studies show that reliance on satellite data will be particularly important for the development of a GDIS, including providing information in areas where data is sparse. On the other hand, the use of satellite data compounds the challenge of developing a temporally consistent analysis system. Several algorithms and models have been developed specifically to address the issue of temporally consistent drought climate data records and can potentially provide the basis for a global drought early warning system.



UNIVERSITY OF WASHINGTON’S EXPERIMENTAL SURFACE WATER MONITOR

The map options on this site (<http://www.hydro.washington.edu/forecast/monitor/>) shows percentiles for soil moisture, Snow-Water Equivalents (SWE) and other variables with respect to the climatological period (1916-2004 for CONUS and 1926-2004 for Mexico). Maps update daily, with a lag of 1-2 days.

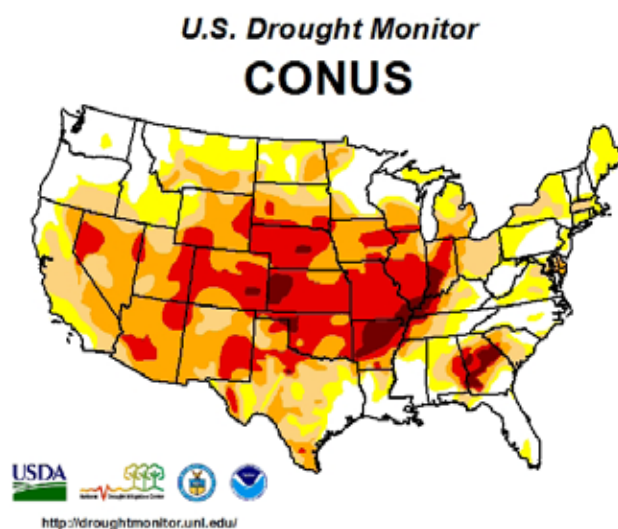
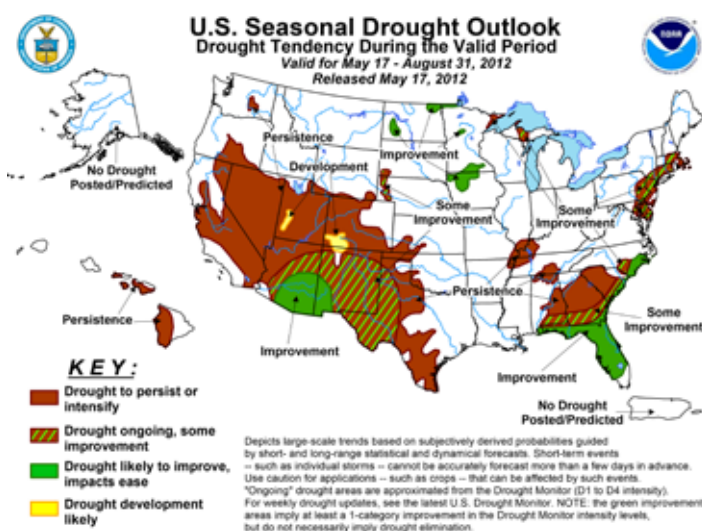
3. DROUGHT PREDICTABILITY AND PREDICTION CAPABILITIES

Models of possible futures, analyses of past events inform forecasting, predictions

The overarching goals of drought prediction research have been to improve our understanding of the physical mechanisms of drought that can enable prediction (i.e. the potential predictability of drought events and their meteorological forcings), and to improve prediction skill through full utilization of the sources of predictability by advanced systems and through model development. Specifically, NOAA's DTF research seeks to better understand the physical mechanisms and advance the ability to predict various aspects of drought including onset, duration, severity, and recovery. In order to achieve these objectives, the DTF has developed a research framework that focuses on the analysis of specific major drought events over North America, thereby providing researchers a common frame of reference for assessing progress utilizing the Drought Capability Assessment Protocol described in Section 4, page 23.

The research challenges related to improving drought forecasting are significant. Major research thrusts and advances are related to

- 1) testing and transitioning improved forecasting capabilities into operational systems;
- 2) understanding the chains of uncertainty from the forecast models



SUMMER 2012 DROUGHT OUTLOOK AND USDM

The seasonal drought outlook (left), and U.S. Drought Monitor (right) for summer 2012. The outlook depicts the expected evolution of drought over a 3.5 month period, in this case forecasting from an initial condition of May 17 though the end of August. The outlook communicates where drought is expected to develop, persist, intensify, or improve. The drought monitor provides a categorical view of current drought conditions in the United States by classifying drought into four categories with an additional category depicting drier-than-normal conditions. The significant drought in the central U.S. was not anticipated in the outlook.

through the hydrologic models to the assessment of current conditions and forecasts important to NIDIS and users; and

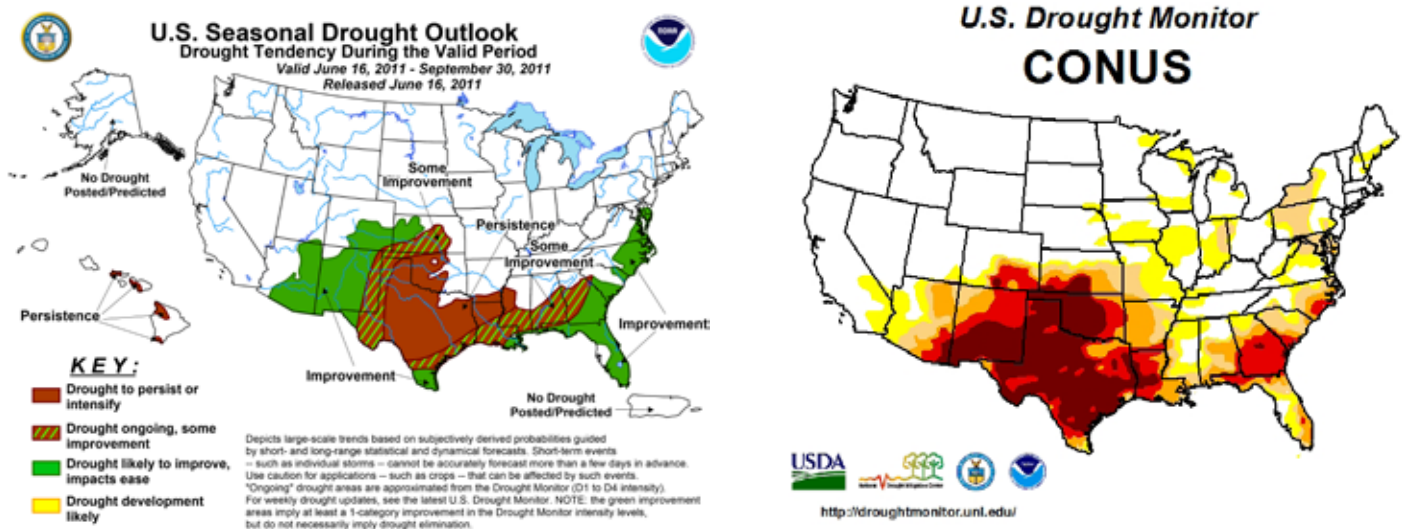
3) understanding sources and limits of predictability of the coupled ocean-atmosphere-land system that are critical to assessing the potential for improved drought forecasts.

3.1 CURRENT OPERATIONAL AND EXPERIMENTAL PREDICTION CAPABILITIES

The U.S. Monthly Drought Outlook (MDO) and Seasonal Drought Outlook (SDO)⁷ produced by NOAA/NCEP CPC rely on forecaster expertise to combine information sources such as the official CPC temperature and precipitation outlooks, long-lead forecasts including from the NCEP’s Climate Forecast System (CFS), short-term forecasts from NCEP’s Global Forecast System (GFS) and ECMWF forecasts, and current drought conditions from the USDM. This process produces a forecast map of changes in drought severity from the current USDM. Maps at the bottom of Page 16, for example, illustrate the SDO forecasts (left) preceding the 2012 drought that was soon to emerge in the Upper Plains (right). For the 2011 Tex-Mex drought (see maps on bottom of this page), the SDO (left) generally performed better than in 2012, despite predicting some improvement in areas where drought actually persisted.

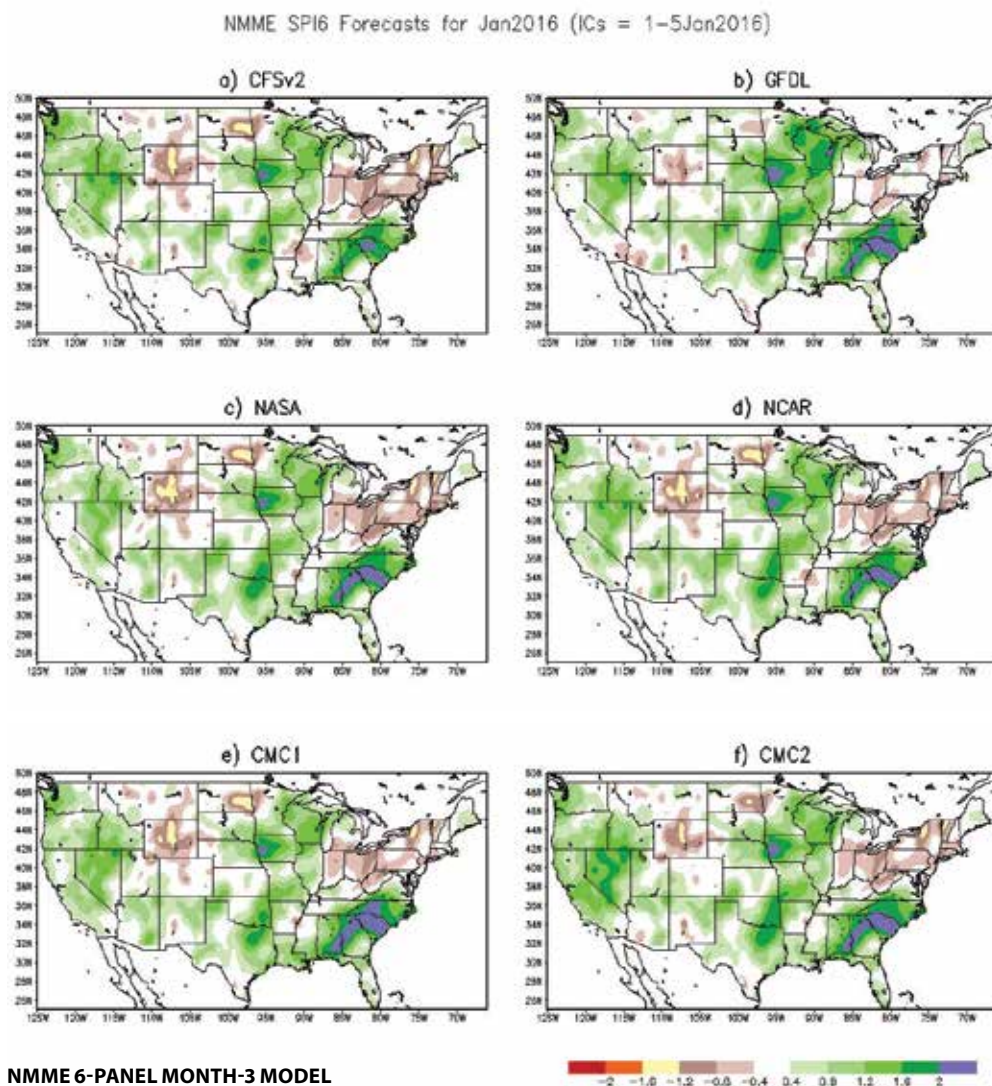
The DTF case study analyses of these events, which incorporates the 2011 Tex-Mex drought, indicate that droughts in the Southern Great Plains region, are more highly influenced by El Niño Southern Oscillation (ENSO) SST anomalies in the tropical Pacific, and therefore better predicted by

⁷http://www.cpc.ncep.noaa.gov/products/expert_assessment/sdo_summary.html



SUMMER 2011 DROUGHT OUTLOOK AND USDM

A similar comparison of the Drought Outlook map and U.S. Drought Monitor as shown on page 16, but for summer 2011. The conditions in the southern U.S. and particularly Texas were well-anticipated by the Outlook.



NMME 6-PANEL MONTH-3 MODEL FORECAST GRAPHIC

Seasonal Precipitation Index Outlook with a one-month lead time for models contributing to the NMME. Green and blue areas are expected to be wetter-than-average while brown and burnt areas are expected to be drier.

<http://www.cpc.ncep.noaa.gov/products/Drought/Figures/SPI/Prediction/spi6.models.L1.gif>

This system has been undergoing development and testing through the NOAA Climate Test Bed since 2011 with support from the NOAA CPO MAPP Program, together with NSF, DOE and NASA programs.

The NMME system⁸ leverages the considerable research and development activities on coupled model prediction systems carried out at universities and various research labs and centers throughout North America. The NMME-based Standard Precipitation Index (SPI) is computed specifically for drought prediction applications. Experimentation with this system has demonstrated that the increased size of forecast ensembles and the diversity of models in NMME in general are enhancing the seasonal forecast skill beyond the current NCEP operational dynamical model (CFSv2) and enabling estimates of model forecast uncertainty.

NOAA is currently transitioning the NMME system into its operational forecast suite. Research is also exploring how to use NMME meteorological forecasts as forcing for hydrological forecasting systems to assess future land-surface conditions.

The southeastern U.S. precipitation forecast skill of the NMME system

dynamical forecast models. Analysis of the 2012 upper Midwest drought indicated that natural (unforced) and more chaotic atmospheric variability, unlinked to SST anomalies, led to conditions that resulted in the less easily predictable drought. This drought emerged quickly during the spring of 2012 and has been referred to as a “flash drought”. Unresolved is the possibility that land-atmospheric feedbacks enhanced and prolonged the drought. This issue is actively being studied by DTF researchers.

The newly developed seasonal NMME forecast system offers the potential to analyze these two droughts as well as drought predictions more broadly across a number of models that will further our understanding of drought prediction capabilities and also help to define forecast uncertainties.

⁸ Kirtman et al. 2014

typically equals or surpasses that of individual models throughout most seasons and lead times, but the skill tends to be low overall for summer seasons. There is a tendency for the southeast U.S. region to show more skill in winter seasons than summer seasons and NMME is generally able to predict winter season variability. During the 2006-07 southeast U.S. drought, the NMME showed moderate skill at short leads during more extreme seasonal phases of this drought, but a lack of skill at long leads particularly during the driest phase of the drought.

Of particular note are the ongoing scientific assessments from the NMME project participants that have deepened our knowledge about the inter-model variability of forecasts and the strengths and challenges of using a multi-model ensemble system for drought forecasting.

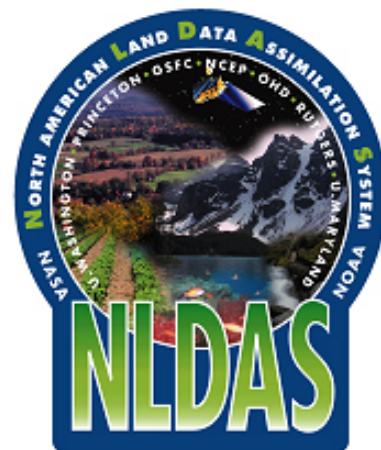
Another notable research success has been the development and transition of experimental operational hydrologic/land surface prediction systems from academic institutions (such as Princeton University) to NOAA as part of the NOAA Climate Test Bed. The resulting climate-land surface (CFSv2-VIC LSM) seasonal forecasting system offers a seamless monitoring-seasonal forecasting capability. This transition is part of broad long-lasting and ongoing collaborations among NOAA NCEP (particularly EMC and CPC), academic institutions and NASA that started with NLDAS multi-LSM drought monitoring (now in operations at NCEP), evolved into the development of experimental drought forecasting at the University of Washington and Princeton University, and culminated in the current CFSv2-VIC LSM transition.

Future planned collaborative activities ultimately aim at a seamless drought/land surface monitoring and probabilistic prediction system across the sub-seasonal to seasonal timescales, building on the seasonal NMME and other relevant multi-model systems.

3.2 HYDROLOGIC MODEL UNCERTAINTY CHARACTERIZATION IN DROUGHT MONITORING AND PREDICTABILITY

Watershed states in drought monitoring and prediction are commonly estimated through hydrologic modeling, yet efforts to characterize hydrologic model uncertainty are a notable weakness of current drought monitoring and prediction research and related practice. Comprehensive multi-model ensembles or probabilistic approaches that have become more widespread in atmospheric modeling (i.e., for weather or climate prediction) are rare in hydrology. The NLDAS employs, for example, a four-model ensemble, in contrast to the 20-25 times larger climate forecast ensemble being generated as part of the NMME.

Recent DTF research has sought to overcome these limits to hydrologic modeling uncertainty characterization in part by developing a unifying model framework. The framework facilitates the use of a broad range of model configurations (physics, structure, parameterizations and parameter estimates that can encompass the four existing models of NLDAS) for



A GOAL OF MORE PRECISION

The goal of the North American Land Data Assimilation System (NLDAS) is to construct quality-controlled, and spatially and temporally consistent, land-surface model (LSM) datasets from the best available observations and model output to support modeling activities. Specifically, this system is intended to reduce the errors in the stores of soil moisture and energy which are often present in numerical weather prediction models, and which degrade the accuracy of forecasts.

<http://ldas.gsfc.nasa.gov/nldas/>



SEVERE DROUGHT HIT THE CENTRAL U.S. IN 2012

Remains of a corn field near Sigel, Illinois, taken on July 1, 2012. Photo courtesy of Aaron Greuel.

modeling applications. This range of modeling and choices exposes a variety of hydrologic estimation and prediction outcomes, leading to better characterization of hydrometeorological prediction uncertainty than the use of a small collection of models. DTF research also includes development of probabilistic forcing datasets for land surface models, thus characterizing uncertainty in model inputs and the impact of input uncertainty on the portrayal of drought.

Hydrologic uncertainty characterization is still a nascent area of research, yet this is an important component of a strategy for improving the fidelity and statistical reliability of drought monitoring and prediction systems. Although the USDM and SDO are currently deterministic (single-value) analyses and forecasts, this modeling research will support their future enhancement towards probabilistic products.

3.3 DROUGHT MECHANISMS AND PREDICTABILITY

DTF research projects have had a long-term focus on improving our understanding of various hydrological and coupled processes of the land, ocean and atmosphere and how these contribute to the development of drought and specifically determine the potential to predict drought.

In particular, there has been considerable focus on the more recent 2010-12 period of intense droughts over the U.S., with Texas and northern Mexico experiencing record drought during 2010-2011 and the U.S. Central Plains feeling the grip of intense heat and drought during the summer of 2012. The key findings are the following:

- ◆ Substantial progress has been made in our understanding and

quantification of the role of SSTs in producing drought over North America. The importance of La Niña in the southern Great Plains is now well established, and there are new results to suggest that the other oceans (Indian and Atlantic) can play an important role in either enhancing or suppressing the role of the Pacific.

- ◆ We now have a better appreciation of the role of internal atmospheric variability in producing some of the most extreme droughts, limiting the predictability of such events (e.g., the 2012 drought) on seasonal and longer time scales. Similarly, the significance of initial drought conditions in forecasts beyond seasonal scales has also been identified. Such analyses require data assimilation to generate the initial conditions for forecasts, in order to ensure highly accurate initial state estimates. The combined effect of initial drought conditions and internal atmospheric variability poses another significant research avenue for drought predictability.
- ◆ Research has improved our understanding of the role of land surface processes/feedbacks in drought, and the potential benefits of increased model resolution. It was demonstrated that high resolution precipitation forecasts will only be effective in improving (large-scale) streamflow forecasts in areas with limited evaporation from land surfaces. It was also found that changes in local and remote surface evaporation sources of moisture supplying precipitation over land are more a factor during droughts than in wet periods over much of the globe.
- ◆ Further studies have highlighted the role of uncertainty in drought forecasts with analyses utilizing ensemble data assimilation, to quantify uncertainty in initial conditions, and Bayesian multi-modeling, to quantify model uncertainty. The findings confirmed that conventional tools for hydrologic forecasting at drought time and space scales are overconfident. More comprehensive accounting of these uncertainties may lead to reliable drought forecasting.

The importance of La Niña in the southern Great Plains is now well established, and there are new results to suggest that the other oceans (Indian and Atlantic) can play an important role in either enhancing or suppressing the role of the Pacific.

4. ASSESSING THE IMPACTS OF DROUGHT RESEARCH

How are researchers doing? Setting a standard for usefulness through metrics

It is difficult to specify a single metric that can be applied to all types of drought research. Thus, the Protocol suggests an initial set of useful metrics and a broader philosophy to ensure their relevance to the assessment goals.

Assessing the value of drought research toward improving national drought capabilities in monitoring and prediction is important, yet difficult, because drought is multi-faceted and there is no single measurement of the severity of drought. Key components of our nation's drought capability such as the operational USDM and MDO/SDO integrate our steadily improving geophysical analyses in a subjective, expert-guided manner, and there is no objective standard by which to assess the impact of new methods or data on the relative accuracy of current USDM ratings.

With the importance and the challenges in mind, the DTF developed a Drought Capability Assessment Protocol to guide researchers toward quantifying the benefits of their research with respect to existing drought monitoring and prediction capabilities. The Protocol is aimed at enabling scientists to provide quantitative answers to the basic question:

Is my research effort improving upon current capabilities to monitor or predict drought, and by how much?

The Protocol centers its attention on four high-profile North American droughts and requires the use of drought-specific performance metrics that are applied, where appropriate, to standard evaluation periods and datasets. According to the Protocol, assessment metrics are to be applied to quantify the ability of new tools or methodologies to detect (for monitoring) or forecast (for prediction) critical features of drought. Unlike the evaluation of a less-variable capability (e.g., climate prediction), it is difficult to specify a single metric that can be applied to all types of drought research. Thus, the Protocol suggests an initial set of useful metrics and a broader philosophy to ensure their relevance to the assessment goals:

- ◆ Use criteria that separate drought conditions from other geophysical system states
- ◆ Describe key geophysical drought features that are of interest to decision makers in applications sectors and motivated by societal impacts. Examples include the onset, severity, duration, and evolution in intensity of a drought variable.

The Protocol proposes a number of analytical elements to support these guidelines.⁹ The Protocol is an initial effort towards establishing metrics for the evaluation of progress in drought monitoring and prediction, and may see further refinement and implementation via DTF and the broader community engagement.

⁹These are described on page 23 and the full protocol is described in <http://cpo.noaa.gov/sites/cpo/Reports/MAPP/>

THE PROTOCOL

Assessing the ability of new tools or methodologies to detect or forecast critical features of drought

This Protocol developed by the Drought Task Force guides researchers to follow the principles described in the main text through applying several analytical elements: (1) assessment metrics, (2) verification periods and datasets, and the (3) use of baselines for benchmarking new methods, dataset products or capabilities. These are described in the following sections.

1 Assessment metrics

Metrics should be assessed by lead time for prediction, but not monitoring, and other conditional factors should be considered where warranted.

Key predictand(s) for drought variable (e.g., soil moisture, streamflow)	Metric(s) and skill scores comparing
Onset and recovery of drought condition	Lead time of prediction Error of identification
Duration and severity of drought condition	Error, bias, correlation (time, value)
Indication (detection, prediction) of drought condition: deterministic	Categorical metrics: Critical Success Index (CSI), Equitable Threat Score (ETC) Probability of Detection (POD), False Alarm Rate (FAR), and others.
Probability of drought condition: probabilistic	Brier Skill Score (binary); secondarily, Brier decompositions for reliability and resolution
Value of variable, overall Value given drought occurring in the observed or forecast period	1. Error, bias, correlation (of ensemble mean or median for probabilistic) 2. Ranked Probability Score (CRPS)

2 Verification periods and datasets

The verifications will be conducted on 30+ year period (1982-2013) if hindcasts or retrospective simulations are available, and/or selected case studies. Four cases have been selected for specific drought events at specified time and region.

1. Winter 2001-Spring 2002 severe western U.S. drought event
2. Fall 2005-Summer 2008 sustained southeast U.S. drought period
3. The 2010-2011 water-year drought over the Southern Plains

4. The 2012 summer drought over the Central Great Plains.

Many verification data in drought categories and hydrologic fields are indices or ad hoc products. There is a need to use caution regarding the uncertainties of all those products. The verification data include:

- ◆ **Precipitation and temperature:** station observations and gridded analyses where appropriate
- ◆ **Drought categories:** USDM categories and NLDAS.
- ◆ **Hydrologic fields:** In-situ observations or derived analyses are a primary verification resource. For predictions, verification fields may also include observation-driven analyses (e.g., streamflow) or simulations (e.g., from NLDAS).

3 Baselines and benchmarking

The use of familiar operational or current capability baselines is critical to making drought research relevant for potential transition to operational usage. Primary baselines include but are not limited to:

- ◆ For monitoring or assessment capabilities: USDM categories or individual input analyses; output analyses from the NLDAS Drought Monitor (e.g., percentile maps of soil moisture for the root zone or total column, SWE, runoff); SNOTEL-based SWE analyses, NCDP PDSI, VegDRI, USGS streamflow and Evaporative Stress Index from satellite.
- ◆ For prediction capabilities: CFSv2 or IRI's SPI forecast; CPC NMME based SPI forecasts over the United States, CPC Monthly and Seasonal Drought Outlooks, Streamflow, precipitation, and soil moisture predictions by Ensemble Streamflow Prediction or by statistical water supply forecasting procedures.

The benchmarking activities apply the assessment metrics over the selected verification period or case studies, focusing on variables including precipitation, temperature, snow water equivalent, soil moisture, evaporative variables, runoff, streamflow, for the periods, case studies or regions described above.

Assessments of future new capabilities should follow the same approach but apply the metrics to new methods or models to the variables, periods and regions defined in this protocol. The improvements and impacts will be compared to the benchmark performance values.

5. TOWARD FUTURE PROGRESS

What lies ahead: Transitioning research into operational capabilities, products, actions

Another institutional challenge is maintaining the nation's in situ, gauge-based observing networks for meteorological, climate and hydrologic variables.

The investments in drought-related science, technology and information systems over the past decade have clearly enhanced and expanded the quality and range of drought data products, the number of people engaged in drought-related activities (such as the NIDIS Drought Early Warning Pilot projects), and our understanding of drought as a phenomenon in the U.S. The benefits of those research efforts are only fully harnessed when commensurate investments are made to support integrating and transitioning the research advances into operational drought monitoring and prediction capabilities and products and supporting greater interaction between operational and research entities.

Such integration and a formal pathway for development and testing (or ingesting) improvements into operations are thus a critical, overarching need and an outstanding challenge.

Other crosscutting needs are for objective and systematic assessments of current capabilities and the identification of capability improvements. These will systematically measure the progress and impacts of research, and help guide the prioritization of future research investments.

Additional gaps, challenges, and opportunities toward future progress in drought monitoring, predictability, and predictions are described below.

5.1 DROUGHT MONITORING

The scientific and technological advances suggest that there may be commensurate advances in the accuracy of official USDM drought category maps, yet as noted above, it is difficult to quantify the presumptive resulting increase in categorical accuracy. Progress toward drought characterizations that are reproducible, can be benchmarked systematically to support the assessment of capability upgrades, and for which uncertainty can be quantified, will likely depend on transitioning toward more objective and reproducible approaches for integrating drought monitoring data, while also leveraging expert opinion and accommodating the variability of drought impacts.

Currently, USDM considers many experimental inputs generated by the research community, such as NLDAS soil moisture and satellite-based vegetation monitoring products. The challenge is to determine the need and feasibility to objectively integrate all the inputs into the USDM.

Another institutional challenge is maintaining the nation's in situ, gauge-based observing networks for meteorological, climate and hydrologic variables. A number of key measurements are either sparse or

**SNOTEL WORK**

Julie Koeberle replaces a snow depth sensor at the Cool Creek, Idaho, Snotel station in April 2011. NRCS photo.

declining, which impairs the evaluation and implementation of model-based products. Critical drought variables such as soil moisture and evaporation are not well observed, though several past initiatives have helped. Examples include the establishment of the Ameriflux network in 1996 to provide observations of water, energy and momentum on an hourly bases, or the NRCS SNOTEL, SCAN, and NOAA-CRN networks for soil moisture, snow and meteorological variables.

Temporal or spatial coverage limitations in our observing networks and suboptimal reporting characteristics lead to scientific challenges as well. Many measurement stations that are active in the historical period do not report in real-time due to insufficient gauge automation.

To the extent that monitoring challenges are institutional, they may be addressable through concerted agency program and infrastructure development and greater integrated support for transition of research into services that include building operational capacity.

NIDIS can play a significant role in coordinating interagency data, networks and tools towards a common DEWS. Now that satellite-based remote sensing platforms are available or are about to be launched for soil moisture (AMSR2, SMOS and SMAP), precipitation (GMP) and water levels (SWOT), one challenge that needs to be met is the near real-time objective merging of these satellite data with in situ observations.

Finally, there are large uncertainties in drought monitoring, including the geophysical analyses of the NLDAS system. The current paradigm in operational drought monitoring can support user risk-based decision making through advancing techniques to quantify uncertainty.

Uncertainties can also be handled through techniques such as model parameter estimation and data assimilation, which are accepted as central components of quantifying and reducing model uncertainties. Ensemble data assimilation methods in particular provide effective frameworks to account for these different factors contributing to uncertainty, leading to more accurate modeling of drought.



PACIFIC NORTHWEST DROUGHT
A dead apple orchard near Prosser,
Washington, 2015. Photo: State of
Washington Department of Ecology.

5.2 DROUGHT PREDICTABILITY AND PREDICTION

Improving the prediction of the full life cycle of droughts requires a better understanding of how predictable water and energy signals propagate through the ocean-atmosphere-land system. This in turn should shed light on the necessary model improvements for advancing drought predictions as well as the fundamental predictability limitations imposed on our ability to produce skillful forecasts of the various facets of drought including precipitation, temperature, soil moisture, snow and runoff.

The development of the NMME seasonal forecast system is a significant success in demonstrating the potential for forging a collaboration of operational and research groups focusing on both the generation of forecasts and their analysis. Key issues that remain to be resolved include sustaining continued support for the NMME as an operational system that can be used as the basis of drought prediction, and exploring whether the scientific community can enhance the prediction signal from raw model output through techniques such as forming an optimally-weighted ensemble conditioned on the phase of teleconnection patterns for major climate phenomena such as ENSO, the Pacific Decadal Oscillation (PDO) or the North Atlantic Oscillation (NAO).

Ultimately, it is key to improve the prediction systems that contribute to the NMME, via continued investments in model development, data assimilation and High Performance Computing infrastructure that can allow experimentation at high resolution, more sophisticated models and larger ensembles.

Since the processes that initiate or terminate drought may occur at sub-seasonal timescales, it is important to develop understanding and prediction capabilities that extend to those timescales. An important goal for NOAA and the drought impact community is the concept of seamless monitoring and forecasting of drought. Based on the success of NLDAS and VIC-based hydrologic prediction systems, the next logical goals in the seamless monitoring-prediction system would be implementing a system that integrates the four NLDAS drought monitoring LSMs with the CFSv2 seasonal forecasting system, and then the NMME suite of seasonal forecasting models together with the suite of NLDAS LSMs to offer a comprehensive multi-model subseasonal and seasonal drought monitoring-forecasting system. This framework would provide unprecedented quantitative and probabilistic drought monitoring and prediction capabilities.

There is also a need to develop a plan to systematically document current and experimental monitoring and forecasting system skill against the assessment metrics presented on page 23.

A reasonable first step would be to review the metrics and skill scores for the key predicted quantities to determine if the current drought monitoring and forecasting systems provide the historical information needed for a systematic assessment over the last 20 years, and the information going forward in time.

The second step would be to compute the metrics and determine if the nation's capabilities and skill for drought monitoring and forecasting has changed over the last ~20 years.

An important outcome of the analysis of these historical assessment metrics would be an "approved" list of common metrics that all monitoring and forecasting systems would produce. This would allow for a quantifiable comparison of approaches (current and proposed).

The final step would be to incorporate the assessment protocols and "approved" metrics operationally, and to require their evaluation by developers of new (experimental) monitoring and forecasting systems (e.g. NMME forecasts). For new systems, this suggests the assessment metrics would be generated for hindcast datasets that would come out of the experimental systems.

Despite good progress, there are still important limitations to our understanding and ability to predict various aspects of drought, including onset, duration, severity, and recovery. Making improvements requires that we extend skillful precipitation forecasts beyond one-month lead. Doing so will involve better isolating the information content of the SST signal (spatially and temporally) in so far as what aspect of the SST drive the atmospheric response over North America.

Land initialization is another key source of predictability, which is widely accepted at one- to two-month lead times, but is potentially important for forecasts of longer lead time. In addition to improving land-atmosphere coupling in climate models, there are uncertainties about the sensitivities to the land models, including how the skill of lead times vary with LSM, and how the skill in both soil moisture and streamflow depend on the model physics.

Recent advances in the development of ultra-high resolution global climate models offer new capabilities for addressing these challenges.

An important goal for NOAA and the drought impact community is the concept of seamless monitoring and forecasting of drought.

DROUGHT TASK FORCE MEMBERS 2011-2014

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