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Abstract

Drought has had a significant impact on American agriculture. The Dust Bowl years of the 1930s came as the nation suffered from severe economic depression, causing devastating socio-economic impacts. The U.S. Department of Agriculture (USDA) established agencies and programs to help American farmers cope with drought and its far-reaching impacts. In order make program decisions during drought emergencies, USDA actively utilized available drought monitoring tools that were at its disposal. The Palmer Drought Severity Index (PDSI) was used for more than 30 years as a drought indicator beginning in the 1960s. The U.S. Drought Monitor, a much-improved composite index, was introduced in 1999 and was used as the USDA drought trigger shortly thereafter. A review of these programs and activities is presented.

Introduction

The 1930s are a benchmark for the U.S. Department of Agriculture's long history with drought monitoring and drought assistance for agriculture. That decade marked one of the worst droughts in American agriculture history, and it was made one of the worst by the "Great" economic depression. Thus, crop failures were compounded by a severely bad economy throughout the nation. The 1930s drought was the most widespread in areal extent, affecting about two-thirds of the country and extending into parts of Canada (Felch 1978). Agriculture was devastated throughout the Great Plains as farmers could not grow any crops, the bare soils were exposed to the hot winds, and severe dust storms of disastrous proportions expanded across the nation. Plains grasslands had been deeply plowed and planted to wheat. During the preceding years when there was adequate rainfall, the land produced bountiful crops. As the droughts of the early 1930s worsened, the farmers kept plowing and planting but nothing would grow. The ground cover that held the soil in place was gone. The Plains winds whipped across the fields, raising billowing clouds of dust to the sky. The sky could darken for days, and even the most well sealed homes would have a thick layer of dust on the furniture. In some regions, the dust would drift like snow, covering both rural areas and urban centers. Poor agricultural practices and years of sustained drought caused the Dust Bowl.

The Dust Bowl

The most visible evidence of how dry the 1930s became was the dust storm (Worster 1979). Tons of topsoil were blown off barren fields and carried in storm clouds for hundreds of miles. Technically, the driest region of the Plains—southeastern Colorado, southwest Kansas, and the panhandles of Oklahoma and Texas—became known as the Dust Bowl, and many dust storms started there. But the entire region, and eventually the entire country, was affected.

The Dust Bowl got its name after Black Sunday, April 14, 1935. More and more dust storms had been blowing up in the years leading up to that day. In 1932, the Plains experienced 14 dust storms. In 1933, there were 38 storms. By 1934, an estimated 100 million acres of farmland had lost all or most of the topsoil to the winds. By April 1935, there had been weeks of dust storms, but the cloud that appeared on the horizon that Sunday was the worst. Winds were clocked at 60 mph. Then it hit. "The impact is like a shovelful of fine sand flung against the face," Avis D. Carlson wrote in a New Republic article. "People caught in their own yards grope for the doorstep. Cars come to a standstill, for no light in the world can penetrate that swirling murk. We live with the dust, eat it, sleep with it, and watch it strip us of possessions and the hope of possessions. It is becoming real" (Hughes 1976).

The day after Black Sunday, an Associated Press reporter used the term *Dust Bowl* for the first time. "Three little words achingly familiar on the western farmer's tongue, rule life in the dust bowl of the continent – if it rains." The term stuck and was used by radio reporters and writers, in private letters and public speeches.

In the Central and Northern Plains, dust was everywhere. New scientific evidence suggests that the drought of the 1930s was the worst in North America in the last 300 years, but it may pale in comparison with droughts in prehistoric times. The data suggests that droughts may have lasted decades or even longer, much longer than the seven years between 1933 and 1940.

The impact of the Dust Bowl was felt all over the United States. During the same April as Black Sunday, 1935, one of FDR's advisors, Hugh Hammond Bennett, was in Washington, D.C., on his way to testify before Congress about the need for soil conservation legislation as a dust storm arrived in Washington all the way from the Great Plains. As a dusty gloom spread over the nation's capital and blotted out the sun, Bennett explained, "This, gentlemen, is what I have been talking about." Congress passed the Soil Conservation Act that same year. The Soil Conservation Act enacted the Soil Conservation Service, which is currently the Natural Resources Conservation Service (NRCS).

Climatic Extremes of the Late 1900s
There *were* several years of severe drought during the 1950s, but the development of center pivot irrigation systems helped alleviate some of that pain for those who could afford them. Over the last half of the 20th century, climate extremes increased in intensity and frequency around the world, with severe socio-economic impacts. Studies have shown that the number of natural catastrophes per decade has increased fourfold and the number of economic losses 14 times during the last half century. Increased frequency of climate extremes, manifested in droughts, floods, heat waves, and tropical cyclones, among other natural hazards, has significant (and sometimes devastating) impacts on agriculture. Extreme climatic variability within the long-term trends has a profound influence on the agro-ecosystem of a region.

In the United States, on average, drought causes $6 billion in agricultural losses annually, according to the National Climatic Data Center (NCDC). Agriculture changed dramatically after 1950, including new technologies, mechanization, seed hybrids, fertilizers and chemical use, and government policies that favored maximizing production. These changes have had many positive effects and reduced many farming risks as food production increased substantially. Thus, while new technologies generally helped American farms become larger and produce more during the latter part of the 20th century, farmers still had to cope with climate extremes and changing climate as part of their everyday farm management strategy to harvest their crops and nurture their livestock. People strove to get the most out of productive land, marginally productive land, or even unproductive land. However, there have also been significant costs. Prominent among these are topsoil erosion, groundwater contamination, water supply shortages, and the increasing economic costs of agricultural production.

The three principle goals of sustainable agriculture are environmental quality, economic profitability, and socio-economic equity. Stewardship of land and natural resources involves maintaining or enhancing this vital resource base for the future. This requires an interdisciplinary effort in both research and applications to ensure the vitality of these resources. A systems perspective is essential to understanding and achieving sustainability. The next section briefly discusses the responsibilities of each agency in USDA for weather and climate, especially as they focus on drought.

United States Department of Agriculture (USDA)

Natural Resources Conservation Service (NRCS)
On March 23, 1935, the USDA formed the Soil Conservation Service (SCS) as part of the Soil Conservation and Domestic Allotment Act of 1935. This act educated farmers on how to use their lands without damaging them and provided funds for planting trees to serve as wind breaks and

native grass to stop soil erosion. SCS changed its name to NRCS in 1994. NRCS has a national Water and Climate Center (WCC), which is responsible for climate information in natural resource assessment and conservation planning across the nation. Snowmelt provides approximately 80% of the streamflow in the West. The western reservoir system supplies irrigation water for agriculture and water reserves for major urban centers. Thus, during major drought episodes, competition between rural and urban sectors becomes particularly intense.

The NRCS/WCC established the Snow Survey and Water Supply Forecasting (SS/WSF) Program to collect snow information through a network of more than 600 Snow Telemetry (SNOTEL) sites and traditional snow courses and develop more than 4,000 water supply forecasts annually for water users in 11 western states and Alaska. A new emphasis in the SNOTEL program activity is on improved measurement precision and data quality, increased sampling frequency, timely data availability, and support for new water supply forecast services. Additional sites containing sensors for soil moisture and soil temperature have been established to supply data required for soils research and water balance and forecast modeling. Agricultural, municipal, industrial, hydropower, and recreational water users are the primary recipients of these forecasts. Coordinated water supply forecasts are critical to the federal government in administering international water treaties with Canada and Mexico along with states that manage intrastate streams and interstate water compacts. Water supply forecasts and climate information help irrigators make the most effective use of available water supplies for achieving their agricultural production goals. Farmers who collectively irrigate more than 10 million acres of land in the western United States benefit from these information products. Other federal agencies and private organizations also use water supply forecast information to help them carry out their missions.

Forest Service (FS)
FS has collected meteorological data to assist in the prediction and control of forest and range fires and in the management of smoke from prescribed burning. A national weather program was established to coordinate all FS meteorological activities and to meet the increasing need for diverse weather information. The major objectives of the program are to 1) improve quality control of weather data, 2) improve the design and operation of data collection from networks, 3) increase data recovery from the weather stations, and 4) upgrade station maintenance. Meteorological data collected from manual weather stations and Remote Automated Weather Stations (RAWS) support research of weather effects on forestry management, forest fires, smoke management, visibility protection in wilderness areas, and atmospheric disposition. FS currently operates more than 1,200 RAWS and manual stations, many in the western United States. Air temperature, relative humidity, dew point temperature, wind direction and speed, and precipitation are transmitted via NOAA's Geostationary Operational Environmental Satellite (GOES) telemetry or via radio modem. The primary use of the data is the calculation of fire danger rating for the FS and cooperating agencies. These data are also used by other resource managers, such as road engineers, wildlife biologists, and hydrologists who monitor precipitation; silviculturalists who are attempting to maximize tree-planting opportunities; and ecologists, soil scientists, and fisheries biologists who monitor the effects of runoff. The main secondary user of RAWS data is the National Weather Service for fire weather forecasting and flood warnings.

Agricultural Research Service (ARS)
The research efforts of ARS relate directly to the effects of climate on agricultural production and the natural resource base. They are directed toward developing technologies and systems for 1) managing precipitation and solar energy for optimum crop production, 2) improving our understanding of water-plant-atmosphere interactions, 3) optimizing the use of energy, water, and agricultural chemicals, 4) reducing plant and livestock losses from pests and environmental stress, 5) developing improved techniques for irrigation and drainage, and 6) minimizing the adverse effects of climate and weather, including atmospheric contaminants, on the environment.

National Institute of Food and Agriculture (NIFA)
NIFA coordinates research programs in the state agricultural experiment stations; the 1862, 1890, and 1994 Land Grant Distributions; and cooperating forestry schools. These institutions conduct a wide variety of research applicable to agriculture and range and forestry management.

Meteorological research at these institutions is conducted to improve our understanding of climatology and microclimatology as basic science and to evaluate their role in the control of agricultural, range, and forested ecosystem conditions and production capacity. A portion of each state's program is consolidated into broad regional research projects that address common research priorities. Research is conducted at multiple scales and addresses the need for understanding climatological effects on individual plants and animals as well as the interactive effects of climate on aggregated ecosystems. Specific areas of focus are 1) the impact of possible environmental changes on the sustainability and economic viability of agriculture and forestry; 2) developing an improved understanding of the fundamental mechanisms of plant, insect, and animal responses to environmental factors, water, temperature, light (including UV-B), and nutrient and atmospheric chemical composition; 3) providing the basic information needed to assess environmental conditions and the sustainability of crop, forest, and rangeland production; 4) research on the potential, interactive, and beneficial effects of farming, range, forestry, and other agricultural practices on water resources; and 5) advancing information networks that integrate, synthesize, and provide users with access to biological, chemical, physical, social, and economic information. The research is also coordinated with an extension network to deliver weather information and management advice to agricultural managers and the public.

National Agricultural Statistics Service (NASS)
NASS monitors crop conditions in the United States and makes timely forecasts and estimates of crop acreage, yield, and production from survey information. The conventional survey component has three major sources of data: farmer reports, extension agency reports, and "objective" yield data such as plant counts, fruit counts, and fruit weights. Ongoing research continues to investigate models relating weather parameters to overall crop yield and individual yield components, such as corn ear weight and wheat head weight for operational use. Weather data from the NWS observing network has been an integral part of NASS's state crop reporting system. NASS's Remote Sensing Section develops map products utilizing satellite and ground-based weather data to provide supplementary information to help policy makers assess crop conditions and forecast crop production. These products are especially useful in years when floods or drought affect large areas. GIS-based yield forecasting, utilizing layers such as previous cropping history, soil types, field conditions, planting dates, varieties, plant populations, local weather, insects, and diseases, offers new potential tools in weather–yield analyses.

Farm Service Agency (FSA)
FSA uses agricultural weather data and related reports to trigger civil defense (in conjunction with the Federal Emergency Management Agency [FEMA]) and national or economic security programs. This includes food distribution, agricultural chemical supplies, and civil defense. FSA also uses agricultural weather for the Noninsured Crop Disaster Assistance Program and programs for dairy, trees, and livestock. The information is used to support Secretarial Disaster Designations, the Administrator for Physical Loss Designations, and the Presidential Emergency/Major Disaster Declarations, and by the Deputy Administrator for Farm Loan Programs for emergency and operating loans. FSA uses weekly agricultural weather information in commodity operations for the storage, transportation scheduling, and distribution of commodities. FSA also uses the data to support daily operation and policy decisions involving farm programs such as commodity loans, production adjustment programs and compliance monitoring programs, establishing and modifying reporting dates, and the release of conservation reserve acreage. Historical and current agricultural weather data are used for triggering the Emergency Conservation Program and for analyses of other environmental and conservation programs. FSA's Economic and Policy Analysis Staff uses weather data for commodity programs to develop supply, demand, and price estimates and to analyze the economic and outlay impacts of proposed FSA programs. FSA works with NASS, FAS, and the World Agricultural Outlook Board to assess the domestic and foreign commodity production for USDA commodity reports.

Risk Management Agency (RMA)
RMA uses weather data or analyses containing the data in Research and Development, Insurance Services (claims, underwriting, reinsurance, and field investigation), and Compliance. It is used directly or indirectly in establishing rates and coverage, high risk areas, planting and harvesting

dates, crop hardiness areas, and new crop programs and developing new crop models and current year loss estimates. RMA and reinsured companies also use specific weather data such as precipitation, wind, and temperature to establish if insurable natural conditions caused the loss. Some of the causes of loss for crop damage include drought, wind, frost, freeze, and excess moisture. Historical and current weather data are used by Insurance Services and compliance programs as an additional information resource in determining if losses are reasonable and if producers and reinsured companies are in compliance with the insurance contracts under the Standard Reinsurance Agreement (SRA).

World Agricultural Outlook Board (WAOB) and the Joint Agricultural Weather Facility (JAWF)
WAOB is located within the Office of the Chief Economist (OCE). WAOB's primary objectives are consistency, objectivity, and reliability of outlook and situation-related material, including weather information, developed within the U.S. Department of Agriculture. WAOB coordinates all weather and climate information and monitoring activities within USDA. WAOB also manages JAWF, which serves as the focal point in the Department for weather and climate information and impact assessment.

JAWF is jointly operated by WAOB of the USDA and the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce (DOC). Created in 1978, the primary mission of JAWF is to routinely collect data and information on global weather and agriculture, and to determine the impact of growing-season weather conditions on crops and livestock production prospects. NOAA meteorologists provide global weather information and products, weather analyses, and weather-satellite imagery for use in the agricultural assessments. A primary source of information is the standard meteorological station data provided over the World Meteorological Organization's Global Telecommunication System (WMO/GTS) and provided through NOAA's data network systems. WAOB agricultural meteorologists merge these data with climatological analyses and global agronomic data and derive indices that relate basic weather parameters to crop growth, to assess the weather's impact on potential agricultural production.

JAWF has the primary responsibility of disseminating global weather data to the other agencies within USDA. Thus, JAWF serves as the Department's focal point for current global agricultural weather information. To improve the Department's assessment capability with the increasing agency demands for greater spatial and temporal resolution, WAOB/JAWF has increased its resources to obtain domestic data from a variety of local and regional networks around the nation. These data networks concentrate on diverse agricultural areas where the success or failure of a crop season is strongly influenced by weather conditions.

Basic Mission of JAWF
The primary mission of JAWF is to routinely collect global weather data and agricultural information to assess the impact of growing-season weather conditions on crops and livestock production prospects (Puterbaugh et al. 1997). JAWF meteorologists monitor global weather conditions and crop developments on a daily basis and prepare real-time agricultural assessments. These assessments keep USDA commodity analysts, the OCE, and the Secretary of Agriculture and top staff well informed of worldwide weather-related developments and their effects on crops and livestock. OCE/WAOB agricultural meteorologists at JAWF prepare special assessments when adverse or anomalous weather conditions (e.g., droughts, heat waves, freezes, floods, and hurricanes) occur in major crop-producing regions. These special assessments are prepared using Geographic Information System (GIS) to overlay weather data, crop information, and any other special data for the detailed analysis. When integrated with economic analyses, these crop-weather assessments provide critical information to decision makers formulating crop production forecasts, trade policy, and disaster relief. Inputs from JAWF are integrated into USDA's monthly foreign crop production estimates. The Senate and House Agricultural Committees periodically request agricultural weather briefings that focus on the severity and impact of drought.

Daily JAWF agricultural assessments are prepared to keep USDA commodity analysts and the Secretary of Agriculture and top staff informed of worldwide weather conditions and their effects on crops and livestock. Each morning, a written summary of current weather affecting agriculture in

United States is sent to the Secretary's office. Furthermore, alerts of anomalous weather conditions impacting agriculture around the globe are included in a daily report of agricultural developments that is sent to USDA policy makers each afternoon.

Inputs from JAWF are integrated into USDA's monthly foreign crop production estimates. JAWF provides an objective procedure for translating the flow of global weather information into assessments of crop-yield potentials, which are then integrated into USDA's analytical process for estimation of global area, yield, and production statistics. These data are in turn used to evaluate global supply use estimates. The evaluation of a crop's yield response is based upon the cumulative effects of weather during crop development. The crop's response to anomalous weather is a function of crop type and growth stages.

JAWF serves as the USDA focal point for weather data received from the Global Observing System, a worldwide network of nearly 8,000 meteorological reporting stations managed by the World Meteorological Organization (WMO). The WMO data are stored and maintained at JAWF in a sophisticated data warehouse that utilizes advanced database technology. These data are used at JAWF and other USDA agencies for a number of agricultural applications. The agricultural meteorologists of OCE/WAOB/JAWF merge these weather data with climatological analyses and global agronomic data to determine the weather's impact on crop development and yield potential. A major source of domestic weather and climate data that are often used in special operational crop and weather analyses for the United States comes from the NWS's Cooperative Observer (COOP) Network of more than 3,500 daily reporting stations.

Weekly Weather and Crop Bulletin (WWCB) and other USDA Publications
Weekly domestic and international crop-weather assessments are published in the *Weekly Weather and Crop Bulletin (WWCB),* which is JAWF's flagship publication (Motha and Heddinghaus 1986). The *WWCB* is jointly produced by USDA/OCE/WAOB, USDA/National Agricultural Statistics Service (NASS), and the DOC/NOAA/NWS/NCEP/CPC. First published in 1872 as the *Weekly Weather Chronicle,* the publication has evolved over the past 138 years into one that provides a vital source of information on weather, climate, and agricultural developments worldwide. The publication is a unique example of how two major departments (USDA and DOC) within the federal government can cooperate, combining meteorology and agriculture to provide a service that benefits the economic well-being of the nation. Data and information contained within the *WWCB* are generated by the efforts of thousands of people, including about 3,000 county extension agents, NASS crop reporters, field office personnel, state universities, National Weather Service Forecast Offices, and more than 5,000 weather observers, mostly volunteer, working with the NWS. The *WWCB* highlights weekly meteorological and agricultural developments on a state, national, and international scale, providing written summaries of weather and climate conditions affecting agriculture as well as detailed maps and tables of agrometeorological information that is appropriate for the season.

The *WWCB* emphasizes the cumulative influence of weather on crop growth and development. Weather conditions influence important farming operations such as planting and harvesting, and greatly influence yield at critical stages of crop development. The *WWCB* also provides timely weather and crop information between the monthly *Crop Production* and *World Agricultural Supply and Demand Estimates* reports, issued by USDA/NASS and USDA/OCE/WAOB, respectively. The *WWCB* is available in electronic form from the OCE web site at http://www.usda.gov/oce/weather/index.htm.

The main users of the *WWCB* include crop and livestock producers, farm organizations, agribusinesses, state and national farm policy makers, and government agencies. Information contained in the *WWCB* keeps farmers, commodity analysts, economists, and producers up-to-date on worldwide weather related developments and their effects on crops and livestock. The *WWCB* provides critical information to decision makers formulating crop production forecasts and trade policy. Agricultural statistics are used to plan and administer other related federal and state programs in such areas as consumer protection, conservation, foreign trade, education, and recreation. Crop and weather reports are especially important in farming areas. A dry or wet planting season may prompt farmers to switch to another crop. A poor grain harvest may affect the feeding activities of cattlemen. A regional drought can boost planted acres elsewhere to offset the expected production decline. Government policy makers may adjust farm programs to meet the changing conditions.

Knowledge of historical climate data and agricultural production patterns in agricultural regions around the world is critical in JAWF's assessments of weather's impact on crop yields. In September 1994, OCE/WAOB/JAWF published the *Major World Crop Areas and Climatic Profiles,* Agricultural Handbook No. 664 (Joint Agricultural Weather Facility 1994). This reference handbook provides the framework for assessing the weather's impact on world crop production by providing information on climate and crop data for key producing regions and countries. Coverage includes major agricultural regions and crops, including coarse grains, winter and spring wheat, rice, major oilseeds, sugar, and cotton. World maps show the normal crop developmental stage by month. An electronic version of the handbook was developed to provide periodic updates to the printed version as additional data become available. The electronic version is available from the OCE web site at: http://www.usda.gov/oce/weather/pubs/Other/MWCACP/index.htm.

Drought is one of the most costly natural disasters affecting the United States. In the summer of 1999, the U.S. Drought Monitor was developed to help assess drought conditions in the United States. The Drought Monitor is a collaborative effort between federal and academic partners, including OCE/WAOB/JAWF, NOAA/NWS/CPC, NOAA/NESDIS/National Climatic Data Center, and the National Drought Mitigation Center (NDMC) at the University of Nebraska–Lincoln. Approximately ten lead authors rotate the responsibility of preparing the Drought Monitor. Produced on a weekly basis, the Drought Monitor is a synthesis of multiple indices, outlooks, and impacts depicted on a map and in narrative form. The official Web site for the Drought Monitor is http://www.drought.unl.edu/dm/monitor.html.

The Drought Monitor is released each Thursday at 8:30 a.m. eastern time. Because the Drought Monitor is prepared in a GIS format, it can be overlaid on agricultural data to create agricultural weather products that quantify the spatial extent of drought affecting various agricultural commodities. These agricultural weather products, along with the Drought Monitor, serve as the main source of information for briefing the Department's Drought Task Force on U.S. drought developments.

The North American Drought Monitor (NADM) is a cooperative effort between drought experts in Canada, Mexico, and the United States to monitor drought across the continent. The NADM was initiated in 2002 and is part of a larger effort to improve the monitoring of climate extremes on the continent. Issued monthly since March 2003, the NADM is based on the end-of-month U.S. Drought Monitor analysis and input from scientists in Canada and Mexico. Major participants in the NADM program include the entities involved with the production of the U.S. Drought Monitor, as well as Agriculture and Agrifood Canada, the Meteorological Service of Canada, and the National Meteorological Service of Mexico. The NADM Web site is http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/nadm-map.html.

USDA Drought Monitoring Programs

This section discusses the tools USDA has had at its disposal to make decisions to cope with drought in the United States. A fairly extensive network of weather stations was established throughout the United States in the late 1800s, operated by the U.S. Weather Bureau. The USDA assumed management of the U.S. Weather Bureau on July 1, 1891, when all weather instrumentation and staff were transferred from the Army Signal Corps to the Department of Agriculture. The Weather Bureau remained in USDA until 1940, when it was transferred to the Department of Commerce. Before the 1960s, operational drought monitoring was based mainly on analyses of precipitation deficiencies and temperature patterns in agricultural areas. Moisture deficiencies during the crop seasons combined with temperature anomalies were indicators of various levels of drought severity.

Palmer Drought Severity Index (PDSI)

In 1965, Wayne Palmer, a researcher for the U.S. Weather Bureau (now the National Weather Service), developed an index to "measure the departure of the moisture supply" (Palmer 1965). Palmer based his drought index on the supply-and-demand concept of the water balance equation, taking into account more than just the precipitation deficit at specific locations. The Palmer Drought Severity Index (PDSI) uses temperature and rainfall in a formula to determine the degree of dryness. The PDSI was developed in 1965 following two decades of severe drought episodes in the United States (the 1930s and the 1950s). Using historical data, Palmer was able to devise an index based on only temperature, precipitation, the available water content of the soil, and Thornthwaite's method for calculating potential evapotranspiration. The PDSI is most effective in determining long-term drought over a matter of several months, but it is not good with short-term forecasts over a matter of weeks. A peculiarity of the Palmer Index is backtracking—i.e., values previously reported for past months may be changed on the basis of the newly calculated values for the present month. Thus, using the index as an "operational" index is problematic because it may not be known until a later date whether the Palmer Index is actually in a dry or wet spell (Heddinghaus and Sabol 1991). Because of this tendency to change the index values at a later time, the index may not be representative of current conditions.

The objective of the PDSI was to provide a measurement of moisture conditions that were "standardized" so that comparisons using the index could be made between locations and between months (Palmer 1965). Palmer developed the PDSI to include the duration of a drought (or wet spell). His motivation was as follows: an abnormally wet month in the middle of a long-term drought should not have a major impact on the index, and a series of months with near-normal rainfall following a serious drought does not mean that the drought is over. Therefore, Palmer developed criteria for determining when a drought or a wet spell begins and ends, which adjust the PDSI accordingly.

The PDSI is a "meteorological" drought index and responds to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by the PDSI ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts (Karl and Knight 1985). The PDSI is calculated based on precipitation and temperature data, as well as the local available water content (AWC) of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Human impacts on the water balance, such as irrigation, are not considered. The PDSI is slow to detect fast-emerging droughts, and does not reflect snowpack, an important component of water supply in the western United States. Thus, the PDSI is not accurate in the winter or early spring months, nor is it particularly useful in the west where irrigation is an important factor in the water balance. Complete descriptions of the equations can be found in the original study by Palmer (1965) and in the more recent analysis by Alley (1984).

The PDSI varies between less than -4.0 and greater than +4.0. Palmer arbitrarily selected the classification scale of moisture conditions (see Table 1) based on his original study areas in central Iowa and western Kansas (Palmer 1965). Ideally, the PDSI is designed so that a -4.0 in South Carolina has the same meaning in terms of the moisture departure from a climatological normal as a -4.0 in Idaho (Alley 1984). The PDSI has typically been calculated on a monthly basis, and a long-term archive of the monthly PDSI values for every Climate Division in the United States exists at the National Climatic Data Center from 1895 through the present. In addition, weekly Palmer Index values (actually modified PDSI values; Heim 2005) are calculated for the Climate Divisions during every growing season and are available in the *WWCB*.

Table 1. PDSI classifications.

PDSI Classifications for Dry and Wet Periods

Drought Severity	**Class**
4.00 or more	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient dry spell
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
-4.00 or less	Extreme drought

There are considerable limitations when using the Palmer Index, and these are described in detail by Alley (1984) and Karl and Knight (1985). Drawbacks of the Palmer Index include:

- The arbitrary designation of drought severity classes resulted in rather loosely defined categories such as “severe” and “extreme.” The values quantifying the intensity of the 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.
- The two soil layers within the water balance computations are simplified and may not be accurately representative for a location. The model assumes the capacities of the two layers are independent of seasonal or annual changes in vegetation cover or root development. These temporal changes are particularly important in cultivated areas.
- 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 the runoff.
- Potential evapotranspiration is estimated using the Thornthwaite method. This technique has wide acceptance, but it is still only an approximation. Thus, there is no universally accepted method of computing potential evapotranspiration.

What is most difficult to discern is onset and cessation of drought. This is, of course, dictated by the definition of drought and by appropriate terminology. However, several weeks or months may pass before it is truly recognized that a drought is occurring. A drought can end just as gradually as it began. Thus, drought is often referred to as a creeping disaster. Within a short period of time, the amount of moisture in soils can begin to decrease. The effects of a drought on flow in streams and rivers or on water levels in lakes and reservoirs may not be noticed for several weeks or months. Water levels in wells may not reflect a shortage of rainfall for a year or more after a drought begins.

The PDSI was being used widely for many operational monitoring activities, in which the onset and end of drought was of importance. Heddinghaus and Sabol (1991) noted the operational problem in the PDSI formulation and presented an improved solution. The original formulation was not continuous, but was measured from the beginning of a wet or dry spell that was determined by calculating a 100% “probability” that the opposite spell was over. Problems arose in using the

PDSI as an operational index since often it was not known until a later date when the drought or wet spell ended. Thus, in 1989, a modified method to compute the PDSI was begun operationally (Heddinghaus and Sabol 1991). This modified PDSI differs from the PDSI during transition periods between dry and wet spells. During transition periods, the modified PDSI takes the sum of the wet and dry terms after they have been weighted by their respective probabilities. This method eliminates the flipping between positive and negative values when the probabilities cross 50%. The modified index is continuous, likely to be more normally distributed, and is similar to the original PDSI during established wet or dry spells.

Despite these drawbacks, the PDSI has been popular and has been widely used for a variety of applications across the United States. It was relatively effective for measuring soil moisture conditions impacting agriculture (Willeke et al. 1994). In fact, the PDSI was the first comprehensive drought monitoring index and was used for about three decades in the United States, from the mid-1960s to the 1990s. The PDSI was widely utilized by a variety of users: the press and news media to depict areas and severity of drought across the United States; private consultants to describe U.S. crop conditions and assess commodity markets; hydrologists to survey levels of streamflow, lakes, reservoirs, and groundwater; agricultural meteorologists, economists, and policy decision makers to estimate soil moisture, rangeland conditions, and economic impacts; researchers to study spatial and temporal characteristics of dry and wet episodes; and foresters to indicate conditions for fire ignition and potential severity (Heddinghaus and Sabol 1991).

The PDSI was used by USDA and a number of states to trigger drought relief programs, and was used to start or end drought contingency plans (Willeke et al. 1994). Alley (1984) identified three positive characteristics of the Palmer Index that contribute to its popularity: 1) it provided decision makers with a measurement of the abnormality of recent weather for a region; 2) it provided an opportunity to place current conditions in historical perspective; and 3) it provided spatial and temporal representations of historical droughts. Several states, including New York, Colorado, Idaho, and Utah, used the Palmer Index as one part of drought monitoring systems, and a number of states included the PDSI in their criteria for evaluating drought in their state drought plans.

Despite significant limitations that have been fully documented and evaluated, the PDSI has been used for a wide variety of applications and has a historical archive. Moreover, early warning systems and state drought plans have used the PDSI criteria as one of the factors in their drought programs. Thus, while the PDSI was limited in its capabilities to fully address drought monitoring, it was recognized as a first major step for nearly three decades toward an effective integrated drought monitoring tool.

During periods of drought, state governments also issued bans on open burning in an effort to reduce the risk of wildfire, based on the PDSI. In an example application of a climate forecast for the Northern Rockies, seasonal temperature forecasts using Pacific sea surface temperatures and proxies for soil moisture (PDSI) allow managers to anticipate extreme fire seasons in the Northern Rockies with a high degree of reliability. As is often the case with climate forecasts, however, forecasts for the Northern Rockies do not provide a large degree of precision: while they can indicate whether a mild or active wildfire season is likely, they cannot provide a precise estimate of the amount of area burned or suppression expenditures given a mild or extreme forecast (Westerling et al. 2003).

The Forest Service has developed statistical relationships between number and location of large fire events in the West and climate, drought, and fire index variables. They found that a model to predict large fire occurrences using monthly mean temperature and the PDSI showed potential to distinguish areas of high probability of large fires from areas of low to moderate probability of large fires. The model was superior to predictions based on historical fire frequency.

Interagency Agrometeorological GIS Applications: The U.S. Drought Monitor
In 1999, government and university scientists began working together to produce the U.S. Drought Monitor (USDM), a weekly product designed to provide a single snapshot of the spatial extent and intensity of drought across the United States (Svoboda et al. 2002). Drought experts from four organizations are responsible for coordinating USDM production each week. These institutions include the NWS Climate Prediction Center (CPC), National Climatic Data Center (NCDC), National Drought Mitigation Center (NDMC), and the World Agricultural Outlook Board (WAOB). On a rotating basis, an individual from one of these organizations serves as the product author for the week, and typically authors the product for two consecutive weeks. Each Monday, the author consults data from numerous sources, including products derived from various quantitative observational networks, model output, satellite and radar imagery, and subjective reports. The author uses these data to prepare a first draft of the USDM for that week and distributes the draft via an email list server to approximately 250 experts, including fellow authors and climate and water experts from around the country. Members of the drought list provide input, including validation and suggestions, to the author, who uses this information to refine the analysis. Through an iterative process, the author prepares and distributes at least two and as many as three drafts of the USDM on Monday, Tuesday, and Wednesday of each week to obtain the best product possible. The final product and an accompanying text summary are posted every Thursday at 0830 LT on the USDM web site (http://www.drought.unl.edu/dm/monitor.html).

In 2002, the USDM authors began using ArcGIS to create the USDM, with each USDM author obtaining ArcGIS training to help familiarize them with the software. This training provided the basics necessary to create and draw drought areas, annotate the map, and print and export the product. ArcGIS provides a mode to more precisely quantify the spatial extent and intensity of drought across the United States. This analytical capability enables users to more accurately assess the impacts of drought on many of the nation's resources, including agriculture, forests, water supplies, transportation, energy use, and the economy. For example, WAOB meteorologists have used ArcGIS and the USDM product to examine the spatial extent and intensity of drought relative to major domestic crop and livestock areas. Such analyses have helped WAOB meteorologists and economists obtain a better understanding of how livestock inventories, pasture and range conditions, and crop sowing patterns vary in response to drought.

North American Drought Monitor
Building upon the early success of the USDM in 2002, the USDM authors began collaborating with drought experts from Canada and Mexico to create a North American Drought Monitor (NADM) product. The primary goal of the NADM is to provide an assessment of drought across the continent. In addition to the four U.S. organizations that coordinate development of the USDM, the major contributors from Canada and Mexico include Agriculture and Agrifood Canada, the Meteorological Service of Canada, and the National Meteorological Service of Mexico (SMN - Servicio Meteorologico Nacional). In contrast to the USDM, which is produced weekly, the NADM is created monthly. Similar to the USDM, the NADM is prepared using ArcGIS. The United States contribution to the NADM each month is the most recent weekly USDM analysis. Currently, Mexican drought experts share their input on the spatial extent and intensity of drought within Mexico, but a USDM author draws the Mexican drought areas in ArcGIS. In contrast, the Canadian contribution to the NADM is prepared entirely by Canadian drought experts. The Canadian analysis is then merged with the U.S. and Mexican analyses in GIS to create the NADM each month.

Although the NADM is being made available to the public each month, the product remains experimental as this collaboration continues to grow. The NADM analysis can be found on the NCDC web site at http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/index.html.

In recent decades, numerous organizations have begun to recognize the enormous benefits of using GIS to display, manage, and statistically evaluate spatial data and the relationships among multiple datasets. One feature that makes GIS so valuable is that the system is not discipline specific. A GIS can be used to map and analyze any dataset that has a spatial component, such as economic, landmark, population, and transportation data. For agricultural meteorologists at the

WAOB, GIS has become an important tool for displaying and analyzing agrometeorological data. Several examples were presented above in which WAOB meteorologists have used GIS to display and analyze agricultural and meteorological data. Additional examples demonstrated how GIS can be used to overlay these datasets to visualize and assess the spatial extent and intensity of favorable or unfavorable weather relative to major crop-producing areas worldwide.

USDA Drought Assistance Programs
However, even before the concept of NIDIS was developed, various agencies with USDA were actively working toward the creation of a comprehensive system to provide the public with early-warning agricultural weather information and drought disaster assistance. USDA's WAOB takes part in several department-wide activities, including the coordination of weather-related activities among USDA agencies and representation of the department's interests in meteorological policy to outside agencies and organizations. WAOB, NRCS, FS and FSA have coordinated weather and climate activities over the past 50 years to ensure a seamless flow of data, products, and information to meet agency requirements, from the perspective of both producers of information and users of information.

FSA and Risk Management Agency (RMA) utilize the Drought Monitor as an aid to identify drought-stricken areas and to provide disaster assistance where needed. A number of USDA programs provide drought assistance to the agricultural community. Many of these programs are based on disaster declarations by the U.S. Secretary of Agriculture, who currently keeps up to date on the latest drought conditions with the U.S. Drought Monitor, which shows the status of the severity and duration of drought in each state at the county level. During severe drought, FSA issues the Emergency Conservation Program (ECP) to provide emergency water assistance for livestock and for irrigation systems for orchards and vineyards. ECP also provides funds for rehabilitating damaged farmland. FSA releases emergency haying and grazing land through the Conservation Reserve Program (CRP) and helps producers recover from production losses due to drought through the Emergency Loan Assistance (EM) program. The Emergency Disaster Designation and Declaration Process allows producers to apply for low-interest emergency (EM) loans in designated counties through FSA. The Noninsured Crop Disaster Assistance Program (NAP) provides financial assistance to producers of noninsurable crops when low yields, loss of inventory, or prevented planting occur because of drought or other natural disasters. RMA offers crop insurance policies for a large number of crops as one risk management option. Producers should always carefully consider how a policy will work in conjunction with their other risk management strategies. FSA also provides surplus USDA stocks of nonfat dry milk to livestock producers in areas hardest hit by continuing drought, based on the USDM.

In addition to FSA, NRCS undertakes emergency measures through the Emergency Watershed Protection Program (EWP) to purchase flood plain easements for runoff retardation and soil erosion prevention to safeguard lives and property from drought and floods. NRCS provides technical assistance to monitor climate and hydrologic conditions necessary to produce water supply forecasts in the western United States. The FS uses the National Fire Danger Rating System to monitor and predict the conditions for wildland fires throughout the fire season using daily input from more than 1,500 weather stations in their fire weather network to run various models and algorithms, and they closely monitor input data for the USDM.

National Drought Policy Commission (NDPC)
In July 1998, the U.S. Congress enacted Public Law 105-199, the National Drought Policy Act. This law created the National Drought Policy Commission, hereafter referred to as NDPC, to advise Congress on the formulation of a national drought policy based on preparedness, mitigation, and risk management rather than on crisis management. The law directed the Commission to conduct a thorough study of ongoing drought programs, to present a strategy that shifts from an ad hoc federal action toward a systematic process similar to those for other natural disasters, and to integrate federal programs with state, local, and tribal programs to ensure a coordinated approach to drought response.

The task was immense. Although drought occurs frequently in most areas of the United States, there was no coordinated, national policy that focused on reducing the impacts of this natural disaster. Many states and local governments include drought in their comprehensive risk management, water management, land use, and long-term planning strategies. Some have devised separate drought plans. State, local, and tribal governments must deal individually with each federal agency involved with drought assistance. Although the federal government plays a major role in drought, there is no single federal agency in a lead or coordinating position regarding drought. Thus, crisis or reactive management generally typifies the federal response to drought emergencies rather than planning and proactive mitigation measures that can be more effectively carried out at the state and local level under the umbrella of a national drought policy.

To succeed in the development of a national drought policy, the guiding principles should include favoring preparedness over insurance, insurance over relief, and incentives over regulation. Research priorities should be set based on the potential of the research results to reduce the drought impacts in the particular regions and for the particular sectors of concern. Finally, it is essential to coordinate the delivery of federal services through effective collaboration with all appropriate nonfederal entities to ensure that all partnerships are fully established.

The National Drought Policy Commission established five goals of national drought policy. Goal 1 calls for proactive mitigation and planning measures, risk management, public education, and resource stewardship as key elements of effective national drought policy. Goal 2 urges greater collaboration to enhance the nation's observation network and information delivery system to improve public understanding of and preparedness for drought. Goal 3 recommends that comprehensive insurance and financial strategies be incorporated into drought preparedness plans. Goal 4 recognizes that a safety net of emergency relief based on sound stewardship of natural resources and self-help must be maintained. Goal 5 requires coordination of drought programs and response in an effective, efficient, and customer-oriented manner and creates the National Drought Council to coordinate federal drought programs and ensure effective service delivery in support of non-federal drought programs. The Secretary of Agriculture was the federal co-chair of the National Drought Council, as proposed by the drought legislation.

Although the national drought policy was never fully achieved, parts of the NDPC goals have been implemented. From Goal 2, the National Integrated Drought Information System (NIDIS) Act was signed into law in 2006 (Public Law 109-430). The NIDIS Act calls for an interagency, multi-partner approach to drought monitoring, forecasting, and early warning, led by the National Oceanic and Atmospheric Administration (NOAA). NIDIS has been developed to characterize current drought conditions, forecast future conditions, and provide a better basis to identify triggering mechanisms for federal drought assistance.

Summary

USDA has been actively involved in drought monitoring, disaster assistance, emergency relief, and crop insurance related to agricultural drought, especially since the Dust Bowl years of the 1930s. USDA established agencies and programs to help farmers cope with drought and improve agricultural management strategies. The PDSI was used for more than 30 years as a drought indicator until USDA partnered with NOAA and the National Drought Mitigation Center to develop and implement the U.S. Drought Monitor. Fortunately, the USDM has been successful in its decade of operational application for agricultural drought monitoring to identify appropriate levels of drought to trigger disaster assistance and emergency response. Success has come slowly. The Natural Resources Conservation Service provides technical assistance to monitor drought, climate, and hydrologic elements in the western United States. The Forest Service provides technical assistance to monitor and predict conditions associated with drought for wildland fires throughout the fire season. The Risk Management Agency provides financial assistance to manage risk for agricultural producers in order to improve the economic stability of agriculture. The National Institute of Food and Agriculture provides grants and supporting research for environmental services to promote farming systems that support soil conservation and sustainable agriculture and contribute to climate change mitigation. In 2008, the USDA Farm Bill for the first time identified the

USDM as the official criteria for FSA to trigger authorization for disaster program payments for specific farm programs. The farm bill is a 5-year program.

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