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Drought Monitoring: Historical and Current Perspectives

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1 Drought Monitoring
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1.1 INTRODUCTION

Drought is a normal, recurring feature of climate throughout the world, with characteristics and impacts that can vary from region to region. Figure 1.1 illustrates the regular occurrence of drought within the United States between 1895 and 2010 with approximately 14% of the country, on average (plotted by black dotted line), experiencing severe to extreme drought conditions during any given year. Drought conditions can persist in a region for several years, as occurred in the United States in the 1930s, 1950s, and early 2000s, and tree ring and other proxy records confirm that multiple-year droughts are part of the long-term climate history for the United States and most other regions around the world (Woodhouse and Overpeck, 1998; Dai et al., 2004; Jansen et al., 2007). Drought has wide-ranging impacts on many sectors of society (e.g., agriculture, economics, ecosystems services, energy, human health, recreation, and water resources) and ranks among the most costly of

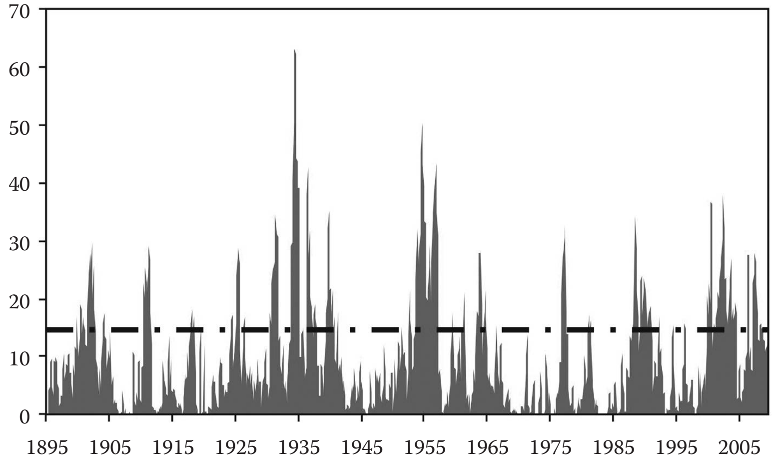

FIGURE 1.1 Percent area of the continental United States that experienced severe to extreme drought between 1895 and 2009 (histogram plots monthly values over this historical period). (Based on data from the National Climatic Data Center/NOAA, Asheville, NC.)

all natural disasters. For example, in the United States, drought affects more people than any other hazard (NSTC, 2005) and has resulted in 14 "billion-dollar" events since 1980 totaling more than $180 billion (U.S.) in damages and losses (NCDC, 2011). This amount represents 25% of all losses from billion-dollar weather disasters, including hurricanes and floods. Globally, drought along with other natural disasters affects more than 255 million people each year (Guha-Sapir et al., 2004), with an estimated $932 billion (U.S.) in losses since 2001 in the 42 countries ranked highest by the United Nations in terms of the combination of life expectancy, education, and income (Guha-Sapir, 2011). In developing nations, drought impacts can transcend economic losses, triggering severe famine and potentially human mortality.

Traditionally, drought response has been conducted in a very reactive, post-event fashion referred to as a "crisis" management approach. This book, *Remote Sensing of Drought: Innovative Monitoring Approaches*, is part of a book series that focuses on proactive, risk-based approaches to dealing with drought known as "risk" management. Risk management in drought response includes preparedness planning, mitigation, monitoring and early warning, and prediction to reduce the impacts of drought—both now and into the future. Drought monitoring, defined as tracking the severity and location of drought, is a critical piece in this risk-based paradigm. A substantial evolution in drought monitoring strategies has taken place during the past 50 years around the world, greatly improving the ability to provide relevant and timely drought information in terms of early warning to decision makers. Many of these efforts have emphasized climate- and hydrologic-based indicators and indices that track changes in components of the hydrologic cycle (e.g., precipitation, temperature, streamflow, and soil moisture), derived primarily from point-based, in situ observations.

Satellite remote sensing offers a unique perspective for operational drought monitoring that complements the in situ–based climate and hydrologic data traditionally used for this application. Spaceborne sensors provide synoptic, repeat coverage of spatially continuous spectral measurements collected in a consistent, systematic, and objective manner. In addition, satellite data are increasingly being looked upon to fill in or supplement data from existing observation networks, even in regions with abundant point-based data.

In 1960, the first meteorological satellite—the Television Infrared Observation Satellite (TIROS-1)—was launched, ushering in the era of satellite-based environmental monitoring and providing the basis for development of land observation satellites such as the Advanced Very High Resolution Radiometer (AVHRR), Landsat, and the Geostationary Operational Environmental Satellites (GOES). In the 1980s, satellite-based indices such as the Normalized Difference Vegetation Index (NDVI) became increasingly used for various environmental monitoring applications including drought monitoring (Goward et al., 1985; Tucker et al., 1986, 1991; Kogan, 1995a,b, 1997; Peters et al., 2002). During the past decade, a number of new satellite-based instruments have been launched that, accompanied by major advances in computing and analysis/modeling techniques, have resulted in the rapid emergence of many new remote sensing tools and products applicable for drought monitoring. These tools have moved beyond traditional vegetation index (VI) data, which provide information primarily related to vegetation health, to a suite of new environmental variables (precipitation, evapotranspiration [ET], soil moisture, and snow cover) that enable a more comprehensive view of drought conditions.

This chapter will highlight the complex nature of drought and the challenges it presents for effective monitoring and early warning efforts. The historical evolution of traditional drought monitoring techniques will be discussed, as well as the emergence of drought early warning systems (DEWS). Finally, the role—both past and present—of satellite remote sensing in drought monitoring is introduced, along with opportunities for improved monitoring capabilities provided by the new tools presented in this book.

1.2 DROUGHT MONITORING

1.2.1 Complexity of Drought: Definitions and Characteristics

Drought is a slow-onset natural hazard with effects that accumulate over a considerable period of time (e.g., weeks to months). Drought does not have a single universally accepted definition, which makes the identification and monitoring of key characteristics such as duration, severity, and spatial extent difficult. Drought originates from a deficiency of precipitation that results in a water shortage for some activity (e.g., crop production) or group (e.g., users of water resources) (Wilhite and Glantz, 1985). Drought can be characterized into three physically based perspectives—meteorological, agricultural, and hydrological (Figure 1.2). Timing, impact, and recovery rate differ between these three perspectives of drought, with shorter-term dryness being reflective of meteorological drought, an intermediate period of precipitation deficit representative of agricultural drought (i.e., the relationship between plant water demands and the amount of available water, particularly within the soil environment), and longer-term dryness

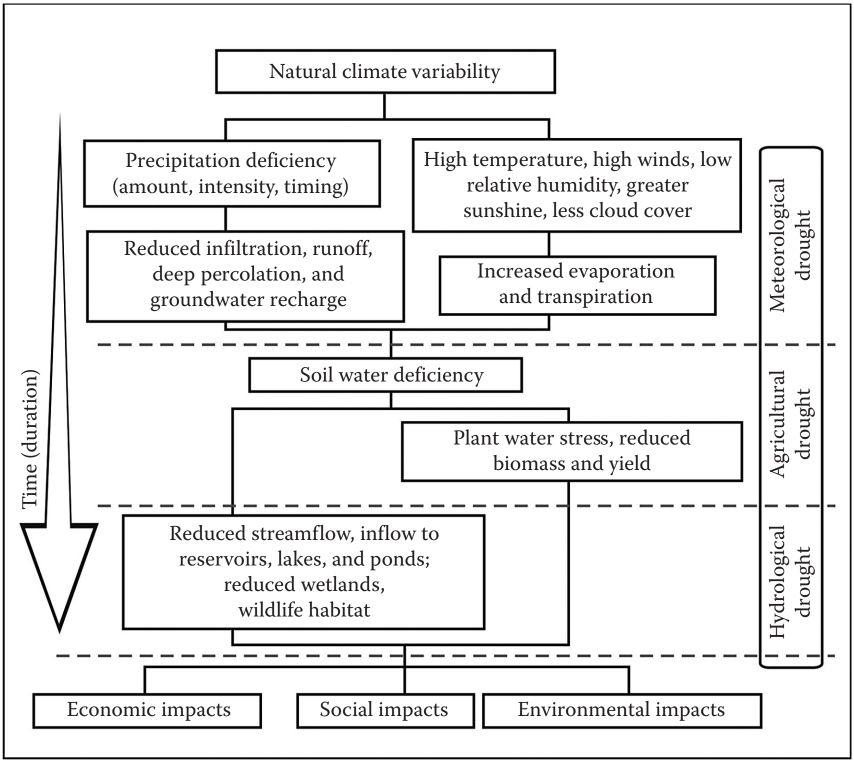

FIGURE 1.2 Physically based perspectives of drought (agricultural, hydrological, and meteorological) and associated impacts that define them. Many of these impacts have the capacity to be monitored by remote sensing techniques. (From Wilhite, D.A. In *Drought Volume I: A Global Assessment*, ed. D.A. Wilhite, New York, Routledge, 2000.)

indicative of hydrological drought (e.g., streamflow and/or groundwater reduction). As a result, drought designations among sectors may or may not coincide in space and time. For example, several weeks of dryness may result in vegetation stress triggering an agricultural drought classification but may have little effect on streamflow and groundwater, which would not result in a hydrological drought classification for the same event.

1.2.2 Monitoring and Early Warning for Drought Risk Management

Drought monitoring involves the continuous assessment of the natural indicators of drought severity, spatial extent, and impacts (Wilhite and Buchanan-Smith, 2005). Using that information to elicit an appropriate response is called *early warning*. Wilhite and Buchanan-Smith (2005) argue that a DEWS, which combines both assessment and decision-maker response, is integral to effective drought risk management. Decision makers require accurate early warning information to implement effective drought policies and response and recovery programs. An example of an early warning system in which drought is a primary consideration is the well-established

Famine Early Warning Systems Network (FEWS NET) that is in place to address food security issues for specific locations around the world. Components of a DEWS can vary and be adapted for any region to account for the needs and resources available within that region, but generally these components include a drought monitoring network, access to timely data, and analysis, synthesis, and dissemination of data that can then be used in decision support tools, communication strategies, educational efforts, and often a forecast element if one is available.

An important feedback loop occurs as drought monitoring and risk management strategies evolve, where better drought management drives the need for improved drought monitoring and, in turn, improved drought monitoring encourages more effective drought management (Wilhite, 2009). As drought risk management plans become more specific in space and time, the need for information at higher spatial and temporal resolutions increases. One example of this type of coevolution in drought monitoring and risk management has occurred over the past decade in the United States, where improvements in the U.S. Drought Monitor (USDM) (discussed in Section 1.2.4) have led to shifts in national agricultural policies, inspiring additional advancements in the spatiotemporal resolution of drought monitoring to support implementation of these policies at a local scale.

Satellite remote sensing can play an important role within a DEWS by providing synoptic, rapid repeat, and spatially continuous information about regional drought conditions. Remote sensing products will be looked upon to

1. Provide information at spatial scales required for local-scale drought monitoring and decision making that cannot be adequately supported from information derived traditional, point-based data sources (e.g., single area-based value over administrative geographic unit or spatially interpolated climate index grids)
2. Fill in informational gaps on drought conditions for locations between in situ observations and in areas that lack (or have very sparse) ground-based observational networks
3. Enable earlier drought detection in comparison to traditional climatic indices
4. Collectively provide a suite of tools and data sets geared to meet the observational needs (e.g., spatial scale, update frequency, and data type) for a broad range of decision support activities related to drought

1.2.3 Early Monitoring Strategies

Drought indicators and indices are variables that are used to describe the physical characteristics of drought severity, spatial extent, and duration (Steinemann et al., 2005). Within the drought monitoring community, the terms *indicator* and *index* are often used interchangeably. *Indicator* is a broader term that includes parameters such as precipitation, temperature, streamflow, groundwater levels, reservoir levels, soil moisture levels, snowpack, and drought indices. Indices are typically a computed numerical representation of a drought's severity or magnitude, using combinations of the climatic or hydrometeorological indicators listed earlier.

The earliest drought monitoring efforts tended to focus on either absolute precipitation amounts or on precipitation deficiencies, represented in terms of the departure from normal or the percent of normal (Heim, 2002). Other typical drought indicators were based on in situ measurements of related hydrologic variables such as streamflow, reservoir, soil moisture, and snowpack levels. As the need grew to provide historical context for assessing the relative severity of specific drought events, attempts were made to develop new indices and indicators that would robustly encapsulate the complexity of comparing droughts in different regions and climatic conditions (Steinemann et al., 2005).

The Palmer Drought Severity Index (PDSI; Palmer, 1965) was one of the first drought indices developed to enable assessment of relative drought severity at the national scale. The PDSI was subsequently adopted for policy implementation by a variety of federal drought programs, beginning in 1976 (GAO, 1979; Wilhite and Rosenberg, 1986; Heim, 2002). Alley (1984) identified three positive characteristics of the PDSI that contributed to its popularity: (1) it provided decision makers with a current assessment of the severity of drought 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. As attempts to use the PDSI in drought monitoring applications expanded, multiple limitations of the PDSI were recognized (Alley, 1984; Hayes et al., 1999; Heim, 2002). These limitations, among others, include the fact that the PDSI values are inconsistent across diverse climatological regions for spatial comparisons and that the empirical constants used by Palmer to represent climate and duration characteristics were determined from measurements made at a relatively small number of locations (Wells et al., 2004). Some of these limitations were addressed by Wells et al. (2004) in the formulation of the Self-Calibrated PDSI (SC-PDSI) that is now widely used (e.g., Dai, 2011), but other limitations still unique to the PDSI remain. One of these limitations is the built-in lag within the PDSI, identified by Hayes et al. (1999), which makes it difficult to use in rapidly evolving drought conditions.

Because of these limitations, other indices such as the Surface Water Supply Index (SWSI; Shafer and Dezman, 1982) and the Standardized Precipitation Index (SPI; McKee et al., 1995) were subsequently developed. The SWSI was originally calculated for the state of Colorado, taking into account historical hydrological factors within a basin (i.e., precipitation, streamflow, reservoir levels, and snowpack), and is now being calculated for many of the river basins across the western United States. The SPI, also developed in Colorado, was designed to quantify the precipitation deficit for multiple timescales with the understanding that a deficit has different impacts on groundwater, reservoir storage, soil moisture, snowpack, and streamflow. McKee et al. (1993) originally calculated the SPI for 3, 6, 12, 24, and 48 month timescales to address these different impacts, but the index can be calculated for any weekly or monthly timescale. Because the SPI is normalized based on the statistical representation of the historical record at every location, wetter and drier climates can both be represented in the same way. An SPI value also places the severity of a current event (either dry or wet) into an historical perspective because the frequency of each value is known. This is one feature that differentiates the SPI from the PDSI. This same technique can also be used to represent other standardized indicators and has led to the development of the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010), which incorporates both temperature and precipitation. The SPI is now the accepted standard worldwide and was recommended at a World Meteorological Organization (WMO) meeting held in December 2009 in Lincoln, Nebraska, as the primary meteorological drought index to be used by national meteorological and hydrological agencies to track meteorological drought.

The use of satellite-based remote sensing for drought monitoring began in the 1980s with the application of NDVI data from the operational NOAA AVHRR instrument (Tucker et al., 1986, 1991; Hutchinson, 1991; Eidenshink and Hass, 1992). The NDVI (Rouse et al., 1974; Tucker, 1979) was a simple mathematical transformation of two commonly available spectral bands (visible red and near infrared) on AVHRR and other satellite instruments and had been shown to have a strong relationship with several biophysical parameters of vegetation (e.g., leaf area index and green biomass) (Asrar et al., 1989; Baret and Guyot, 1991). Early work by Hutchinson (1991) and Tucker et al. (1991) among others, discussed in more detail in Chapter 2 (Anyamba and Tucker, 2012), demonstrated the value of NDVI data for drought monitoring, serving as a simple metric to assess vegetation conditions (Tucker, 1979). Time series of AVHRR NDVI data have readily been used to support operational drought monitoring systems worldwide, including FEWS NET and national efforts in countries such as Australia. Kogan (1995a) developed a set of drought indices from time series of AVHRR NDVI and thermal infrared data, available in near-real time at http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php. The NDVI-based Vegetation Condition Index (VCI) and the thermal-based Temperature Condition Index (TCI) are indicators of land-surface vegetation and moisture conditions, respectively, and are expressed as an anomaly or departure of the current index value relative to its longer-term climatology (historical minimum and maximum boundary values). The Vegetation Health Index (VHI) is a weighted combination of the VCI and TCI reflecting the integrated effects of moisture and temperature on vegetation. These indices have been widely used to assess drought conditions (Kogan, 1995a,b, 1997, 2002; Unganai and Kogan, 1998; Rojas et al., 2011) and have been integrated into operational monitoring systems (Heim, 2002). The use of these satellite-based VIs over the past 20+ years has demonstrated the valuable complementary information that remotely sensed data can provide for drought monitoring, but their application has been limited primarily to the characterization of agricultural drought.

This process of evolution in the development and application of drought indicators and indices has led to the understanding that, in the majority of cases, no single indicator or index can represent the diversity and complexity of drought conditions across the temporal and spatial dimensions affected by drought (Hayes et al., 2005; Mizzell, 2008). In most applications, it is best to use a combination of indicators when monitoring drought. However, this option can be very confusing for the decision makers, who often do not know about the characteristics of each indicator (Mizzell, 2008).

1.2.4 U.S. and North American Drought Monitors: Hybrid Monitoring Approaches

With the recognition that no one indicator or index can fully capture the multi-scale, multi-impact nature of drought in all its complexity, there has been a movement to develop a "composite" index approach that is "hybrid" in nature and combines many parameters, indicators, and/or indices into a single product. The presentation of drought information in a single map with a simple classification system is preferred by decision makers and the general public in contrast to multiple maps depicting various indicators with differing classification schemes. In order for tools and indices to be accepted and readily used by decision and policy makers, it is important to understand and follow this simple premise. Naturally, the ability also exists to extract and analyze the inputs to the composite indicator individually to determine how a specific indicator is contributing to the hybrid product.

The most prominent composite indicator approach used within the United States is the weekly USDM (Svoboda et al., 2002) (Figure 1.3), which was initiated in 1999 and is globally considered the current state-of-the-art drought monitoring tool. The USDM is not a forecast, but rather an assessment or snapshot of current drought conditions. The USDM product is not an index in and of itself, but rather a combination of indicators and indices that are synthesized using a simple D0–D4 drought severity classification scheme that utilizes a percentile ranking methodology (Table 1.1) and addresses both short- and long-term drought across the United States. The key indicators/indices used in the USDM focus on monitoring major components of the hydrologic cycle, including precipitation, temperature, streamflow, soil moisture, snowpack, and snow water equivalent. Various indices, such as the SPI and PDSI, are incorporated with other in situ data (e.g., streamflow) and remotely sensed VIs and are collectively analyzed by experts using a "convergence of evidence" approach to determine a drought severity classification. In fact, the VHI (Kogan, 1995a) discussed earlier was one of the first indicators included in the production of the USDM. Recently, the USDM has also experimented with or integrated several remotely sensed indicators or indices including the Vegetation Drought Response Index (Brown et al., 2009; presented in

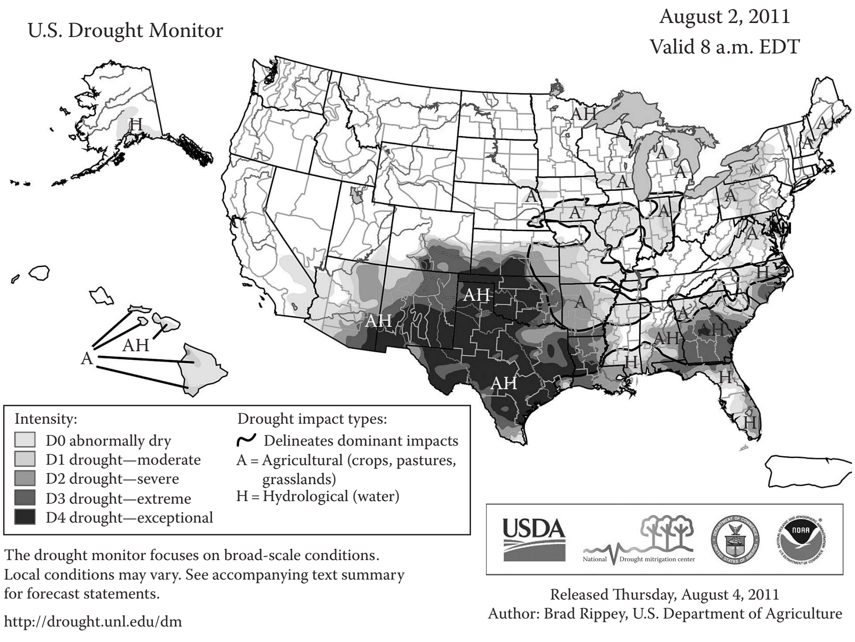

FIGURE 1.3 USDM map for August 2, 2011.

TABLE 1.1
USDM Classification and Ranking Percentile Scheme

USDM Category	Description	Ranking Percentile
D0	Abnormally dry	30
D1	Moderate	20
D2	Severe	10
D3	Extreme	5
D4	Exceptional	2

Source: Svoboda et al., 2002. The Drought Monitor. *Bulletin of the American Meteorological Society*, 83(8): 1181–1190.

Chapter 3 by Wardlow et al., 2012) and the multisensor hybrid rainfall estimate tool that combines radar with rain gauge data made available by the National Oceanic and Atmospheric Administration (NOAA)–National Weather Service (NWS) Advanced Hydrological Prediction Service (AHPS) program (presented in Chapter 12 by Story 2012). Despite these efforts, the integration of remote sensing information into the USDM has been limited, but tremendous opportunity exists to incorporate data from new satellite-based tools retrieving various parameters of the hydrologic cycle.

The USDM has adopted a ranking percentile approach to drought classification (further discussed in Svoboda et al., 2002), which allows the user to directly compare and contrast indicators originally having different units and periods of record into one comprehensive indicator that addresses the customized needs of any given user. The approach also allows for flexibility and adaptation to the latest indices, indicators, and data that become available. The overall USDM "process" can be described as a blending of objective science, based on the ranking percentile approach, and subjective expert experience, as well as guidance provided through the integration of impacts, reports, and other data from approximately 300 local experts throughout the United States. In addition, a set of short- and long-term Objective Drought Indicator Blend maps that combine different sets of indicators and indices with variable weightings (depending on region and type of drought) are also used to guide the USDM map development process. The impacts labeled on the USDM map are (A) for agricultural and (H) for hydrological drought. As another sign of its continual evolution and response to needed change by the user community, the USDM is currently going through a process to replace the current (A) and (H) impact labels to a broader (S) for short-term and (L) for long-term drought impacts. This change was a response to the need for an accounting of stress on the unmanaged (nonagricultural) environment (i.e., ecosystems), as well as moisture deficits during the winter in agricultural regions (agricultural drought designations are not assigned during dry winter months under the current USDM classification scheme). The new labels allow for more flexibility as to which sectors are impacted by both short- and long-term droughts. More details and information on the USDM, its classification scheme, and the objective blends can be found at http://droughtmonitor.unl.edu.

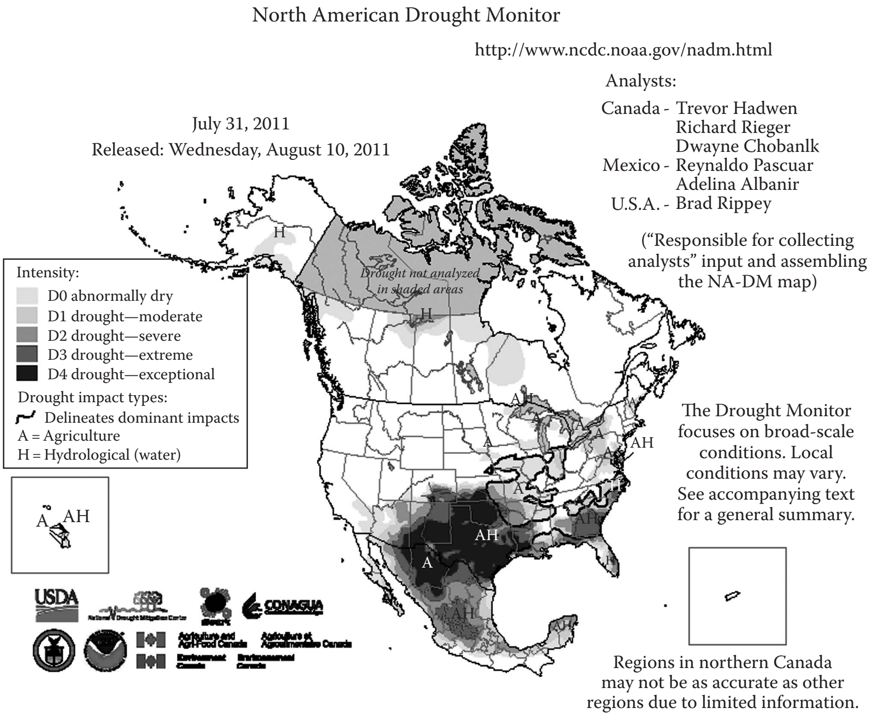

FIGURE 1.4 NADM map for February 2011.

The North American Drought Monitor (NADM) (Lawrimore et al., 2002) (Figure 1.4) was developed 3 years after the USDM in 2002 and is a monthly product forged from a partnership between several entities in Canada, Mexico, and the United States. As with the USDM, the NADM blends science and art. The ranking percentile principal used in the USDM is also applied to the NADM, but the inputs vary slightly depending on which indicators are readily available to the respective agencies involved in each country. As the process stands now, each country follows the same basic methodology, utilizing their own indicators to create a depiction of drought within their borders. A variety of data inputs are used among the countries to develop their respective national drought monitor maps, which are then merged into the continental NADM map. However, the specific types of variables, as well as the general data quality and density of in situ observations, vary widely from country to country and can lead to transboundary issues in terms of the agreement in drought patterns depicted at the international border. To date, the application of remote sensing products with continental coverage within the NADM has been extremely limited. Satellite remote sensing has the capability to acquire seamless, consistent, and objective data that traverse these three countries to provide common data inputs into the NADM map development process and help address transboundary drought depiction discrepancies that may arise. Other regional, multi-country monitoring efforts, such as FEWS NET and the European Drought Observatory being developed by the European Union's Joint Research Centre, are heavily reliant on satellite remote sensing to address discontinuities in ground-based data resources from country to country. Currently, the monthly NADM author (which rotates between the three countries) is responsible for working out the merging of the geographic information system (GIS) shape files and reconciling any disputes along the borders. Impact and data information are exchanged in working out any differences in an interactive fashion until all are resolved. More information and details on the NADM can be found at http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/index.html.

1.2.5 Emerging Drought Early Warning System Initiatives

1.2.5.1 National Integrated Drought Information System

The National Integrated Drought Information System (NIDIS), signed into U.S. Public Law in December 2006, is the first coordinated effort to develop a U.S. DEWS. It is a NOAA-led partnership among federal, state, tribal, and local organizations with the goal of improving the nation's capacity to proactively manage drought-related risks by providing decision makers with the best available information and tools to assess the impact of drought and to better prepare for and mitigate its effects. NIDIS has three general tasks:

1. Provide an effective DEWS that
   a. Collects and integrates information on the key indicators of drought and drought severity
   b. Provides timely information that reflects state and regional differences in drought conditions
2. Coordinate federal research in support of a DEWS
3. Build on existing forecasting and assessment efforts

The development of regional DEWS is a major effort of NIDIS, which has the goal of developing expert-driven, issue-based decision support tools and informational products that characterize local-scale drought conditions within the region and address key drought-related decision-making activities. Experts within each region were collectively tasked with identifying key decisions and issues associated with drought, assessing their current monitoring capacities and data gaps, and developing and implementing the customized DEWS. Currently, four regional DEWS efforts are underway: the Upper Colorado River Basin (UCRB), the Four Corners Tribal Lands area, the state of California in the western United States, and the Apalachicola-Chattahoochee-Flint (ACF) River Basin in the southeastern United States (Figure 1.5). By design, the NIDIS regional DEWS are tailored for local-scale monitoring (i.e., county, state, watershed, and/or region) in support of specific applications as compared to the USDM, which is national in scope and intended to provide a holistic view of drought conditions. As a result, the regional DEWS will have different data requirements than the USDM, and the informational needs among the DEWS can vary in terms of the spatial scale and types of variables. For example, the UCRB

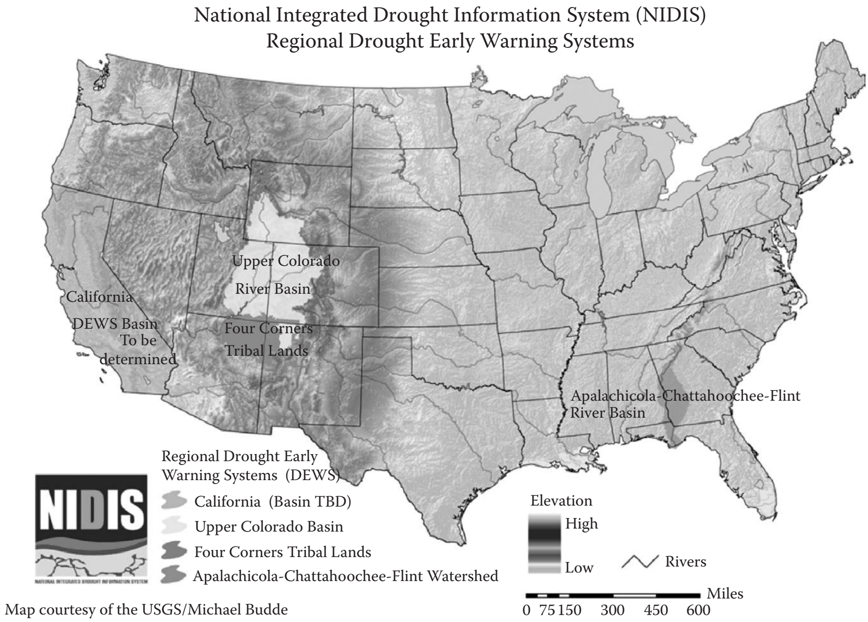

FIGURE 1.5 Locations of the NIDIS regional drought early warning systems.

DEWS has a primary focus on water resource management (e.g., hydroelectric power, agricultural/commercial/municipal water use, and interbasin transfers), particularly related to water supply from mountain snow melt. Despite having considerable in situ measurement capabilities (e.g., rain, snowpack, and stream gauges) in the UCRB, large data gaps still exist with poor spatial coverage over many areas of this large region and insufficient information for key variables (e.g., precipitation, ET, and snow water equivalent) at certain locations (e.g., low elevations) and spatial scales. Similarly, the other regional DEWS have their own unique data gaps for certain variables and data sets at relevant spatial scales.

1.2.5.2 Efforts to Build a Global Drought Early Warning System

Over the past 3–5 years, several efforts have begun to focus on the establishment of a virtual-based Global DEWS (GDEWS). The National Drought Mitigation Center (NDMC) has been an advocate of such a system for more than a decade now in what was originally proposed to the WMO as a Global Drought Preparedness Network (GDPN). The concept was based on the idea that individually, many countries lack or are unable to improve their capacity to cope with drought but collectively, through global, regional, and national partnerships, resources, information, and experiences can be shared and leveraged to reduce the impacts of drought. The idea would involve setting up a series of continental-based virtual regional networks, starting with North America, which already has the NADM in operation, and expanding to other efforts in Australia, Europe, South America, Africa, and Asia. The initial NADM activity in North America would serve as a blueprint for these future efforts throughout the world.

More recently, NIDIS, the Group on Earth Observations (GEO), and WMO have promoted similar yet different approaches that could ultimately be combined in part to produce a GDEWS. Through their work in the United States, NIDIS has already established a potential framework for a Global Integrated Drought Information System (GIDIS) on their web portal (drought.gov) and has begun to integrate various regional and continental drought monitors, remote sensing data sets, and other data resources from around the world. By capitalizing on agreed-on interoperability standards, services, and deliverables, the potential to collaborate virtually in the global arena to establish a GDEWS is growing rapidly.

The WMO has taken a somewhat more holistic approach toward the development of an Integrated Drought Management Programme (http://www.wmo.int/agm) that would target governmental, intergovernmental, and nongovernmental organizations in drought monitoring, prediction, risk reduction, and management. The goal would be to develop a global coordination of efforts to strengthen drought monitoring, prediction, early warning, and risk identification and develop a drought management knowledge base that captures mitigation and best practices in dealing with this hazard.

GEO (http://www.earthobservations.org) has also begun to look at integrating drought and DEWS into their 10 year action plan and via the Global Earth Observation System of Systems (GEOSS) information within their societal benefit areas through data and information sharing, communication, and capacity building in order to address the growing worldwide threat of drought. At the GEO Ministerial Summit in 2007, it was agreed to build on existing GEO programs to work toward establishing a GDEWS within the coming decade to provide regular drought warning assessments as frequently as possible during a drought crisis. The GEO vision is to build a global drought community of practice with an end goal of producing a global drought monitor.

Although considerable progress has been made, there are still several challenges to overcome in establishing DEWS at any scale or in any region of the world. Some of the primary challenges include the following (partial list taken from WMO, 2006):

1. Meteorological/hydrological data networks are inadequate in terms of spatial distribution and/or density, and quality long-term data records are lacking for many networks and/or stations.
2. Data sharing within government agencies/ministries and between countries and regions is inadequate, although some regions (e.g., European Commission's Joint Research Centre, European Drought Observatory [EDO], and the Drought Management Centre for Southeast Europe [DMCSEE]) are beginning to leverage resources and work together on this topic.
3. Information delivered through DEWS is often too technical or in complex formats, limiting its use by decision/policy makers and the general public.
4. Existing drought indices are sometimes inadequate for detecting the early onset and end of drought.

Although this is not a complete list of all challenges faced in developing a GDEWS, satellite remote sensing holds considerable potential to begin addressing these specific challenges, as will be discussed further in Section 1.3. Lastly, the development of an effective GDEWS and necessary data inputs requires a commitment of resources, which can be a challenge for all regions of the world. Typically, support for such a system many times comes down to political will and capitalizing on a severe drought as a focusing event to spur action, albeit in a reactive crisis management fashion.

1.3 SATELLITE REMOTE SENSING OF DROUGHT: A NEW ERA

As drought monitoring and DEWS activities continue to evolve around the world, the demand will continue to increase for consistent, high-quality data sets and observations in support of applications across a range of spatial scales (i.e., local, national, regional, and global). Given the general limited density of stream and rain gauges and soil moisture measurements in existing observational networks and the lack of resources globally to enhance, maintain, and expand these networks, as well as institutional barriers that limit data sharing, in situ–based data sets by themselves will be unable to meet these growing demands. The unique characteristics of satellite remote sensing data will be looked upon to assist in closing this informational gap, improving our capacity to track drought, particularly at the global scale.

The suite of new instruments on both global imagers and geostationary platforms that have become available since the late 1990s has ushered in a new era in the remote sensing of drought. Satellite-based sensors and missions such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), Tropical Rainfall Measuring Mission (TRMM), and Gravity Recovery and Climate Experiment (GRACE) are collecting near-daily global data at varying spatial resolutions ranging from 250 m to hundreds of kilometers across the visible, infrared (near, middle, and thermal), and microwave portions of the electromagnetic spectrum, as well as for the earth's gravitational field. This has resulted in a rapid development of many new innovative remote sensing techniques characterizing various components of the hydrologic cycle relevant to drought. The chapters in this book will describe many of these new tools that monitor key hydrologic components (Figure 1.6), including ET (Chapters 6 through 8 in this book), groundwater (Chapter 11), rainfall (Chapters 12 through 14), snow cover (Chapter 15), soil moisture (Chapters 9 through 11), and vegetation health (Chapters 3 through 5). In addition, other remote sensing efforts are underway to estimate or retrieve other components such as surface water levels (Durand et al., 2008; Lee et al., 2011) and streamflow (Durand et al., 2010) that will not be covered in detail in this book. Unlike the past, where AVHRR VI data were the primary remote sensing products used to assess drought (primarily the effects of agricultural drought), the capability now exists to analyze various components of the hydrologic cycle either individually or collectively to define drought conditions. These new types of remote sensing data sets, in combination with traditional in situ–based, hydroclimate index and indicator data, should provide a more complete depiction of current drought conditions for decision makers.

A number of efforts, highlighted in several chapters of this book, are currently underway to assess the accuracy of these new satellite remote sensing tools and their utility within drought monitoring systems, such as the USDM. It is clear that

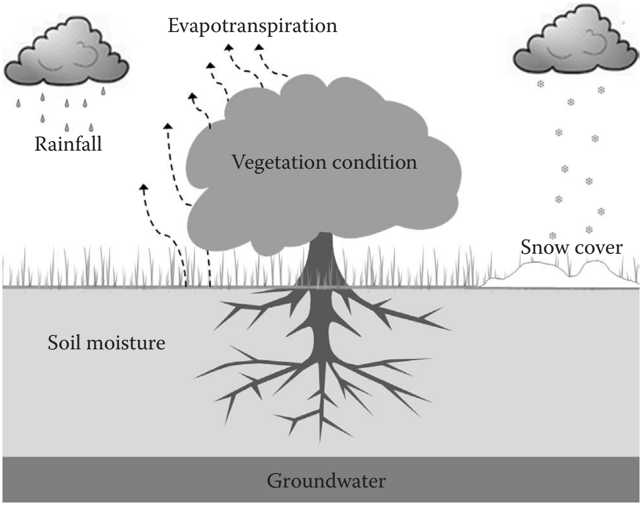

FIGURE 1.6 Components of the hydrologic cycle relevant to drought that can be estimated or retrieved from satellite remote sensing tools presented in this book.

satellite remote sensing represents both a time- and cost-efficient means for collecting key information for drought monitoring over large geographic areas and in data-poor regions lacking gauge-based observational networks. However, there is a clear need to better bridge the research-to-operations hurdle in integrating remote sensing products from both a historical and a real-time operational basis. Drought monitoring and early warning systems have key operational requirements in terms of the latency, update interval, and format of the data inputs, as well as the specific metric(s) (e.g., percent of historical average) used to summarize the retrieved variable from the satellite data (e.g., soil moisture). Given that limited resources are often allocated to maintain and synthesize the input data into useful information for DEWS, clear communication and coordination between the remote sensing and drought monitoring communities is needed to maximize the value of these new remote sensing products. Many examples of these efforts to customize data products from various remote sensing tools for drought monitoring systems are presented throughout this book, including the adoption of commonly accepted cartographic color schemes to depict varying drought conditions, the development of techniques to downscale coarse resolution data to higher spatial resolutions to accommodate more local-scale monitoring (in Chapter 7, Anderson et al., 2012; and Chapter 11, Rodell, 2012), and the temporal extension of remotely sensed time-series variables calculated from limited satellite observational records using land data assimilation techniques to provide a longer historical context for anomaly detection (in Chapter 10, Sheffield et al., 2012; and Chapter 11, Rodell, 2012).

1.4 CONCLUSIONS AND OUTLOOK

Given the complex dimensions of drought and the challenges they pose for routine drought monitoring, it is essential that we continue to find innovative and robust ways to quantify and more effectively communicate the impacts of this hazard as part of an operational DEWS approach. For those who are only concerned with one aspect of drought (e.g., impacts of hydrological drought on reservoir levels), then monitoring, analysis, and assessment may be much more focused on one or a few indicators. In most cases, however, a much more comprehensive and multifaceted approach will be necessary when monitoring drought events. Composite indicators such as the USDM allow a user to remain flexible in utilizing new tools, indices, and indicators as they become available and/or useful for a particular region or a particular season.

Integration of remotely sensed indicators and indices continues to gain acceptance and traction as their history and application expands, and as drought monitoring experts and other decision makers become more familiar with their strengths and limitations. The current capability of remote sensing to estimate and retrieve an increasing number of variables related to the hydrologic cycle (as shown in Figure 1.6) illustrates the tremendous potential these new remote sensing tools have to support a wide range of drought applications that vary in terms of the specific variables and the spatial scale of the data that are required. Supplementing the current set of traditional drought monitoring tools with remote sensing data and products is logical given the limitations associated with ground-based observational networks, and the use of remotely sensed data will continue to grow as the satellite period of record lengthens and more people within the drought community become comfortable with fully utilizing such information in an operational setting. A DEWS that nests a global-to-local scale drill-down approach, which utilizes composite indicators that contain remotely sensed variables, will assist in moving the global drought community forward to better monitor drought at multiple spatial scales and for various sectors well into the twenty-first century.

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