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Future Opportunities and Challenges in Remote Sensing of Drought

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16.1 INTRODUCTION

The value of satellite remote sensing for drought monitoring was first realized more than two decades ago with the application of Normalized Difference Vegetation Index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR) for assessing the effect of drought on vegetation, as summarized by Anyamba and Tucker

(2012, Chapter 2). Other indices such as the Vegetation Health Index (VHI) (Kogan, 1995) were also developed during this time period and applied to AVHRR NDVI and brightness temperature data for routine global monitoring of drought conditions. These early efforts demonstrated the unique perspective that global imagers like AVHRR could provide for operational drought monitoring through near-daily, synoptic observations of earth's land surface. However, the advancement of satellite remote sensing for drought monitoring was limited by the relatively few spectral bands on operational global sensors such as AVHRR, along with a relatively short observational record.

Since the late 1990s, spectral coverage has been expanded with the launch of many new satellite-based remote sensing instruments, such as the Advanced Microwave Sounding Unit (AMSU), Tropical Rainfall Measuring Mission (TRMM), Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS), Gravity Recovery and Climate Experiment (GRACE), and Advanced Microwave Scanning Radiometer-Earth Observation System (AMSR-E), which have provided an array of new earth observations and measurements to map, monitor, and estimate a wide range of environmental parameters relevant to drought monitoring. As illustrated by the various remote sensing methods presented in this book, many components of the hydrologic cycle can now be estimated and mapped from satellite imagery, providing the drought community with a more complete and comprehensive view of drought conditions. Precipitation in the form of both rainfall (Story, 2012, Chapter 12; AghaKouchak et al., 2012, Chapter 13; Funk et al., 2012, Chapter 14) and snow cover (Kongoli et al., 2012, Chapter 15) can now be monitored over large areas through a combination of ground-based radar and satellite-based optical and microwave observations. Variations in the flux of water from the land surface to the atmosphere can also be assessed by applying new innovative techniques to thermal and shortwave data to estimate evapotranspiration (ET) as demonstrated by Senay et al. (2012, Chapter 6), Anderson et al. (2012b, Chapter 7), and Marshall et al. (2012, Chapter 8). In addition, new perspectives on vegetation conditions are provided by hybrid vegetation indicators (Wardlow et al., 2012, Chapter 3; Tadesse et al., 2012, Chapter 4) and estimates of biophysical parameters such as the fraction of absorbed photosynthetic active radiation (fAPAR) (Rossi and Niemeyer, 2012, Chapter 5). Lastly, unprecedented insights into subsurface moisture conditions (i.e., soil moisture and groundwater) are possible through the analysis of microwave (Nghiem et al., 2012, Chapter 9) and gravity anomaly (Rodell, 2012, Chapter 11) data, as well as land data assimilation systems (LDASs) incorporating remotely sensed moisture signals (Sheffield et al., 2012, Chapter 10).

Remote sensing advancements like these will be essential to meeting the growing demand for tools that can provide accurate, timely, and integrated information on drought conditions to facilitate proactive decision making (NIDIS, 2007). Satellite-based approaches are key to addressing the significant gaps in spatial and temporal coverage of surface station instrument networks providing key observations (e.g., rainfall, snow, soil moisture, groundwater, and ET) over the United States and globally (NIDIS, 2007). Improved monitoring capabilities are particularly important and timely given recent increases in spatial extent, intensity, and duration of drought events observed in some regions of the world, as reported by the Intergovernmental

Panel on Climate Change (IPCC, 2007). Drought impacts in many food-insecure regions could potentially intensify over the next century as climatic changes alter patterns of hydrologic variables like evaporation, precipitation, air temperature, and snow cover (Burke et al., 2006; IPCC, 2007; USGCRP, 2009). Numerous national, regional, and global efforts such as the Famine Early Warning Systems Network (FEWS NET), National Integrated Drought Information System (NIDIS), and Group on Earth Observations (GEO), as well as regional drought centers (e.g., European Drought Observatory) and geospatial visualization and monitoring systems (e.g., NASA/USAID SERVIR), have been undertaken to improve drought monitoring and early warning throughout the world. Well-established and emerging remote sensing tools will be able to help fill important data and knowledge gaps (NIDIS, 2007; NRC, 2007) to address a wide range of drought-related issues including food security, water scarcity, and human health.

16.2 FUTURE OPPORTUNITIES FOR SPACE-BASED DROUGHT MONITORING

Over the next decade, further progress in the application of satellite remote sensing for drought monitoring is expected with the launch of several new instruments, many recommended by the 2007 Decadal Survey on Earth Science and Applications from Space (NRC, 2007). These instruments will enhance current capabilities for monitoring specific variables (e.g., soil moisture and terrestrial water storage) and will make possible unprecedented wide-area measurement of surface water elevation and extent. In addition, increased assimilation of satellite observations into LDASs is expected to significantly improve model estimates of hydrologic states, like soil moisture and stream flow, for drought monitoring. In this section, several of these planned satellite-based sensors will be reviewed, as well as the increased use of remotely sensed data in LDAS models, to highlight opportunities that exist to advance the contributions of remote sensing for operational drought monitoring and early warning.

16.2.1 Soil Moisture Active Passive

The Soil Moisture Active Passive (SMAP) mission, which is currently scheduled to be launched in the 2014–2015 time frame (NASA, 2010), is intended to provide global measurements of soil moisture and freeze/thaw state, with drought monitoring and prediction as targeted applications (Entekhabi et al., 2010). SMAP includes both an L-band radar and an L-band radiometer, which will allow global mapping of soil moisture at a 10 km spatial resolution with a 2–3 day revisit time under both clear and cloudy sky conditions. By combining coincident radiometer and radar measurements, SMAP will provide much higher spatial resolution soil moisture mapping capabilities than previous instruments such as AMSR-E (Nghiem et al., 2012, Chapter 9) and the European Soil Moisture and Ocean Salinity (SMOS; Kerr et al., 2010) mission, which generate products at 25 and 50 km resolutions, respectively. The SMAP 10 km soil moisture product will be achieved by combining higher accuracy but coarser spatial resolution (40 km) radiometer-based soil moisture retrievals with higher resolution radar data (1–3 km) that have lower retrieval accuracy. In addition, the integration of these two types of data enables soil moisture to be estimated under a wider range of vegetation conditions. Radar backscatter is highly influenced by land cover and only performs adequately in low vegetation conditions (Dubois et al., 1995), whereas the L-band radiometers have improved sensitivity to soil moisture under moderate vegetation cover. SMAP measurements will provide "direct" sensing of surface soil moisture in the top 5 cm of the soil profile (Entekhabi et al., 2010). Because many applications such as drought monitoring require information about soil moisture in the root zone, the SMAP mission will also provide estimates of soil moisture representative of a 1 m soil depth by merging SMAP observations with land surface model estimates in a soil moisture data assimilation system (Reichle, 2008).

16.2.2 SURFACE WATER AND OCEAN TOPOGRAPHY

The Surface Water and Ocean Topography (SWOT) mission is designed to provide water surface elevation (WSE) measurements for ocean and inland waters including lakes, reservoirs, rivers, and wetlands. The primary SWOT instrument will be an interferometric altimeter that utilizes a Ka-band synthetic aperture radar (SAR) interferometer with two antennas to measure WSE (Durand et al., 2010a). Over inland water, SWOT will directly measure the area and elevation of water inundation with a spatial resolution on the order of tens of meters. Specific observational goals include a maximum 10 day temporal resolution and the capability to spatially resolve rivers with widths >50–100 m and water bodies with areas >250 m^2. The vertical accuracy requirement of the WSE measurements is set at 10 cm over 1 km^2 area and river slope measurements within 1 cm per 1 km distance (Biancamaria et al., 2010). Several predecessor radar altimetry missions including Topex/Poseidon (Morris and Gill, 1994; Birkett, 1995, 1998; Maheu et al., 2003; Hwang et al., 2005; Birkett and Beckley, 2010; Cheng et al., 2010), Jason-1 and -2 (Shum et al., 2003), and the Environmental Satellite Radar Altimeter (ENVISAT RA; Frappart et al., 2006; Medina et al., 2008; Lee et al., 2011) have proven the science and utility of radar altimetry data for monitoring inland water dynamics (Alsdorf et al., 2007). Initial results in applying simulated SWOT data to characterize surface elevation changes of inland water bodies have been promising (Durand et al., 2008; Lee et al., 2010a). SWOT is anticipated to provide new information to better measure and understand the spatiotemporal dynamics of surface water (i.e., areal extent, storage, and discharge) globally, which would have tremendous benefit for many applications, including water resource management and hydrological drought monitoring and prediction. The SWOT mission is currently targeted to be launched in 2020 (NASA, 2010). In the meantime, several efforts have explored the expected accuracy of SWOT products for measuring change in storage of lakes (Lee et al., 2010a) and water surface profiles (Schumann et al., 2010), as well as the depth and discharge (Durand et al., 2010b) of rivers.

16.2.3 GRACE FOLLOW-ON AND GRACE II

The GRACE mission has provided new insights into terrestrial water storage for drought monitoring as summarized by Rodell (2012, Chapter 11). GRACE is able to monitor groundwater changes, as well as variations in shallow and root-zone soil moisture content (Yeh et al., 2006; Rodell et al., 2007, 2009; Tiwari et al., 2009; Famiglietti et al., 2011). Outputs from GRACE related to surface and root-zone soil moisture and groundwater storage are now being applied in operational drought monitoring activities (Houborg et al., 2010; Rodell, 2012, Chapter 11). The National Research Council Decadal Survey (NRC, 2007) recommended that NASA launch an advanced technology gravimetry mission (GRACE II) toward the end of the decade. The proposed mission would replace the microwave interferometer with a laser and also fly at a lower altitude with a drag-free system, enabling perhaps an order of magnitude improvement in spatial resolution and making GRACE II directly applicable to a wider range of water resource characterization and management activities globally (NRC, 2007). However, taking into account the value of GRACE for many applications beyond drought monitoring, including measurement of ice sheet and glacier mass losses, groundwater depletion, and ocean bottom pressures, NASA has given preliminary approval to a GRACE Follow-On (GRACE FO) mission targeted for launch in 2016. GRACE FO would reduce an expected data gap after the terminus of GRACE and provide time for the technology developments required for GRACE II. The configuration of GRACE FO would be similar to GRACE, with incremental technological improvements that should afford some level of error reduction/increased spatial resolution.

16.2.4 VISIBLE/INFRARED IMAGER RADIOMETER SUITE

The Visible/Infrared Imager Radiometer Suite (VIIRS) is the next-generation moderate resolution imaging radiometer launched onboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), platform in 2011, and scheduled for the subsequent series of Joint Polar Satellite System (JPSS) satellites (Lee et al., 2010b). The VIIRS instrument will be the operational successor to AVHRR and MODIS (Townshend and Justice, 2002), collecting data in 22 spectral bands spanning the visible as well as the near, middle, and thermal infrared (TIR) wavelength regions (Lee et al., 2006). The spectral bands of VIIRS were chosen primarily from two legacy instruments, AVHRR and MODIS, both of which have greatly contributed to drought monitoring tools, as discussed in earlier chapters. VIIRS is designed to provide daily global coverage at spatial resolutions of 370 m (5 bands) and 740 m (17 bands) (Lee et al., 2006). In addition, several data products, termed environmental data records (EDRs), will be produced from the VIIRS observations (Lee et al., 2006), including vegetation indices (NDVI and the Enhanced Vegetation Index, EVI) (Justice et al., 2010), land surface temperature (LST), and snow cover—each of which can be used for operational drought monitoring. The generation of VI and LST products from VIIRS is critical for extending the historical time series previously established with AVHRR and MODIS. The placement of a VIIRS instrument on the NPP platform was intended to provide continuity for observational data streams from instruments on NASA's Terra and Aqua platforms (Townshend and Justice, 2002). This will be followed by VIIRS instruments on a series of JPSS platforms that are planned to be operational into the 2023–2026 time period (Lee et al., 2010b). Future availability of VIIRS VI and LST data for drought monitoring will be needed for tools such as the Vegetation Drought Response Index (VegDRI, Brown et al., 2008; Wardlow et al., 2012, Chapter 3) and for the estimation of ET (Anderson et al., 2007; Senay et al., 2007) and ET-derived indices (Anderson et al., 2012a, 2012b, Chapter 7).

16.2.5 LANDSAT DATA CONTINUITY MISSION

Along with recommendations for new missions, the NRC Decadal Survey also stressed the need for maintaining critical long-term earth surveillance programs such as Landsat. The Landsat satellite series has been routinely collecting global earth observations in the visible and near-infrared bands since 1972 (15–60 m spatial resolution) and the thermal band since 1982 (60–120 m spatial resolution). The resulting data set is the only long-term civilian archive of satellite imagery at scales of human influence, resolving individual farm fields, deforestation patterns, urban expansion, and other types of land use and land cover change. Landsat 7 (currently active) has functioned well past their expected lifetime. The Landsat Data Continuity Mission (LDCM) is scheduled for launch no earlier than January, 2013, and will carry the Operational Land Imager (OLI) that will continue six heritage shortwave bands as well as two new coastal and cirrus bands with a 30 m spatial resolution. LCDM will also carry the Thermal Infrared Sensor (TIRS) to collect TIR data in two channels to facilitate split-window atmospheric correction. TIRS will enable continued global mapping of ET and vegetation stress at field scale (Anderson et al., 2012a).

The revisit period of individual Landsat satellites (16 days or more, depending on cloud cover) is not ideal for operationally monitoring rapid changes in vegetation and moisture conditions associated with drought events. However, the Landsat series has the potential to provide 8 day (2 systems) or 5 day (3 systems) coverage if multiple systems are deployed concomitantly in staggered orbits. Increased temporal frequency could also be achieved by increasing the swath width of data collection. The potential also exists to fuse high-spatial/low-temporal information from Landsat with lower-spatial/daily maps from MODIS/VIIRS to produce daily maps of vegetation indices and ET at the Landsat scale (Gao et al., 2006; Anderson et al., 2012a). Such fused imagery could significantly address the growing need for high-resolution (subcounty) information about yield reduction and other drought impacts.

16.2.6 NEXT GENERATION GEOSTATIONARY SATELLITES

Whereas polar orbiting satellites provide only periodic snapshots of land surface conditions (typically once per day or longer), diurnal variability in key environmental variables relating to surface water and energy balance (such as LST and solar radiation) can be readily observed with geostationary satellites, albeit at coarser spatial resolution. With advanced spacecraft and instrument technology, the Geostationary Operational Environmental Satellite "R" series (GOES-R) will replace the current GOES-N series to meet operational data needs of the National Oceanic and Atmospheric Administration (NOAA), providing higher spatial and temporal resolution over the full hemispherical disk covering North and South America. The launch of the first GOES-R series satellite is scheduled for 2015 (http://www.goes-r.gov/), carrying the Advanced Baseline Imager (ABI) instrument—a 16 band imager with 2 visible bands, 4 near-infrared bands, and 10 infrared (3.5–14 μm) bands (Schmit et al., 2005). Spatial resolutions of the ABI visible and IR channels will be 0.5 km and 1–2 km, respectively, compared with the 1 km and 4 km of the GOES-N series. In addition, the full disk coverage rate of ABI will be 5 min instead of the 30 min of the current GOES. Derived baseline data products with potential application for drought monitoring will include downward surface solar insolation, reflected solar insolation, and LST and will be generated with <1 h latency (http://www.goes-r.gov/products/baseline.html). The potential for developing ET and drought products from GOES-R ABI observations will be explored by the GOES-R Risk Reduction program (Guch and DeMaria, 2010).

Current geostationary coverage over Europe and Africa is provided by the Meteosat series operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Instruments on the Meteosat Second Generation (MSG) satellites, first launched in January 2004, include the Spinning Enhanced Visible and Infrared Imager (SEVIRI), with a total of 12 bands that generate images by scanning the earth every 15 min. The High Resolution Visible (HRV) band provides data at 1 km sampling, while the other bands sample at 3 km spatial resolution (http://www.eumetsat.int/Home/Main/Satellites/MeteosatSecondGeneration/). Data products generated from MSG SEVRI observations that are relevant to drought monitoring include downwelling surface longwave and shortwave fluxes, LST, leaf area index (LAI), and ET (http://www.eumetsat.int/Home/Main/DataProducts/Land/index.htm?l=en). For continuation of MSG data streams, two more MSG satellites are tentatively scheduled for launch in 2012 and 2014, and planning is underway for a Meteosat Third Generation (MTG) satellite series with improved spatiotemporal and spectral coverage (http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/Instruments/).

To support global monitoring applications, several efforts are underway to assemble and often intercalibrate observations from an international system of geostationary satellites. These archives include the National Centers for Environmental Prediction (NCEP)/Climate Prediction Center (CPC) 4 km/3 h global infrared data set, the NOAA 10 km/3 h International Satellite Cloud Climatology Project (ISCCP) B1 data rescue project (Knapp, 2008), and the Global Monitoring for Environment and Security (GMES) 5 km/1 h Geoland2 project (Lacaze et al., 2010). Insolation and surface temperature products derived from these data can be used to drive global remote sensing models of ET and soil moisture status.

16.2.7 GLOBAL PRECIPITATION MISSION

The Global Precipitation Measurement (GPM) mission is the next-generation, dedicated precipitation measurement mission (Smith et al., 2004), which builds on the successful legacy of TRMM. TRMM is a joint venture by NASA-Japan Aerospace Exploration Agency (JAXA) and has provided unprecedented data on precipitation characteristics since its launch in 1997, surpassing its expected lifetime by many years. TRMM products have been used successfully as precipitation-related information inputs to regional drought monitoring, especially for less-developed regions with few sources of accurate rainfall measurements, supporting FEWS NET and the Princeton African Drought Monitor (Sheffield et al., 2008). Building on TRMM, the goal of GPM is to develop a next-generation remote sensing precipitation system that provides frequent, global, and accurate precipitation measurements for basic research, applications, and operational monitoring.

The GPM will consist of a "core" satellite that will carry a set of precipitation sensors, plus a constellation of satellites of "opportunity" that have a range of active and passive microwave (PMW) instruments, but, at the least, all will carry a PMW radiometer. The core satellite will be used as a calibration reference for the constellation of support satellites. The core satellite is being developed jointly by NASA/JAXA and is similar to the TRMM satellite. It will carry a dual frequency (Ku/Ka band) precipitation radar (DPR) and a high-resolution multichannel PMW rain radiometer (GPM Microwave Imager, GMI). The DPR will have higher sensitivity to light precipitation than the TRMM precipitation radar and will provide three-dimensional structure data of storm events. The GMI will for the first time use a set of frequencies to retrieve precipitation particle sizes that are crucial for making more accurate precipitation rate retrievals and will better distinguish between light, moderate, and heavy precipitation. The core satellite will be complemented by a European Space Agency (ESA) core satellite (European contribution to the Global Precipitation Mission, EGPM), which will have the capability to measure light to moderate drizzle and snowfall at mid- to high latitudes. The constellation will have a mixture of sun-synchronous and non-sun-synchronous orbits that will allow retrievals of precipitation rates globally, with approximately 3 h sampling for each point on earth for about 90% of the time. The expected launch date for the core satellite is 2013.

16.2.8 Other Proposed Sensors

Several other proposed satellite-based instruments hold potential for supporting operational drought monitoring in the future. The Earth Science Decadal Survey identified the Hyperspectral Infrared Imager (HyspIRI) and Snow and Cold Land Processes (SCLP) missions as two future efforts that are anticipated to provide relevant drought information. The HyspIRI mission (proposed launch in the 2020s) includes two instruments: a visible shortwave infrared (VSWIR) imaging spectrometer operating between 0.38 and 2.5 μm at a spatial scale of 60 m with a swath width of 145 km and a TIR multispectral scanner operating between 4 and 12 μm at a spatial scale of 60 m with a swath width of 600 km. In the current conceptual design, HyspIRI will collect data at 60 m spatial resolution and have a 5 day revisit interval for thermal acquisitions and 19 days for hyperspectral imaging. Early warning of drought is a specific societal benefit of HyspIRI listed in the Decadal Survey (NRC, 2007). Early signs of ecosystem changes due to drought stress, reflected in altered plant physiology (e.g., water and carbon flux changes), may be spectrally identifiable in the hyperspectral data provided by HyspIRI, while the high spatiotemporal resolution thermal imagery will be valuable for early detection of changes in plant water use due to soil moisture deficits, along with associated plant stress revealed in rising canopy temperatures.

The SCLP mission (proposed launch between 2016 and 2020) will consist of a combination of active (X- and Ku-band SARs) and passive (K- and Ku-band radiometers) microwave sensors to characterize snow cover and snow water equivalent, which should benefit drought monitoring by providing information about the expected soil moisture recharge and snowmelt runoff. The SCLP mission has been recommended for a low earth orbit to provide subkilometer spatial resolution with complementary higher resolution capabilities between 50 and 100 m and a temporal resolution of approximately 15 days to detect intraseasonal changes, with more frequent imaging capabilities (3–6 days) when needed (NRC, 2007).

16.2.9 Enhancement of Land Data Assimilation Systems with Remotely Sensed Data

The suite of existing and planned remotely sensed data products has the potential to provide a holistic view of drought and the hydrologic cycle in general. As these products give different and independent views of hydrologic states and fluxes, and the condition of vegetation, they provide complementary information that will help users robustly identify emerging droughts for different applications that rely on joint assessment of multiple variables (e.g., U.S. Drought Monitor, USDM). However, this potentially comes at a price because of inconsistencies in the assessments from individual products (Sheffield et al., 2009; Gao et al., 2010). This is in part because the products represent different quantities and scales and because of inherent inaccuracies in the instruments, algorithms, and assumptions. A desirable but challenging goal is to merge collections of products into a physically consistent representation of the land surface to enhance drought monitoring from a multivariate, multiuser perspective.

Sheffield et al. (2012, Chapter 10) described the potential to meet this challenge through direct insertion or assimilation of remote sensing products into the NLDAS land modeling and assimilation system. LDAS provide, through modeling, a physically consistent and continuous depiction of all major components of the land surface water cycle. However, model output can be sensitive to errors in the model input data (in particular, precipitation) and the model structure and parameterizations (e.g., rooting depth and soil moisture holding capacity). Assimilation enables integration of observational data, such as from remote sensing, into the modeling to correct for these errors. This improves the representation of important state variables, such as root-zone soil moisture, that are not directly available from remote sensing. Land data assimilation also provides a physically based framework for merging independent remote sensing products into spatially and temporally continuous fields of data.

Future improvements in land data assimilation for drought monitoring will leverage remote sensing products in a number of ways. A key enhancement goal is to improve the simulation of land surface conditions through the use of remotely sensed precipitation, especially in sparsely monitored or topographically complex regions. The planned GPM (Smith et al., 2004) will be a key factor to meet this goal with its global coverage at unprecedented spatial and temporal sampling (3 hourly and 0.25°). Assimilation of individual remote sensing products into land surface models has been demonstrated with GRACE data (Zaitchik et al., 2008), thermal (e.g., Crow et al., 2008) and microwave (e.g., Reichle et al., 2007) soil moisture retrievals, lake and river level altimetry (e.g., Andreadis et al., 2007), and microwave/visible snow retrievals (e.g., Dong et al., 2007). Assimilation of these products improves skill levels when compared to ground observations. The benefit to drought monitoring is beginning to be evaluated for large-scale applications (e.g., Bolten et al., 2010; Houborg et al., 2010). Furthermore, the complementary information (e.g., in terms of spatial and temporal coverage) contained in each of these assimilation products has not been exploited to its full potential through assimilation into a land model. Several promising avenues are emerging to do this, including joint assimilation of thermal-infrared and microwave soil moisture (Hain, 2010; Hain et al., 2011) and multiscale assimilation approaches (Pan et al., 2009). The latter approach combines products with complementary information at different scales—for example, coarse-resolution GRACE data and high-resolution thermal-infrared or microwave soil moisture.

16.3 CHALLENGES FOR THE REMOTE SENSING COMMUNITY

Over the past decade, the remote sensing community has made tremendous strides in advancing the application of satellite information for operational drought monitoring and early warning and is expected to continue to do so thanks to future missions including those highlighted in the previous section. The drought community is beginning to reap the benefits of these efforts through the array of new information generated from new types of satellite observations using advanced analytical tools and modeling approaches. However, several challenges need to be addressed to more fully integrate remote sensing data into routine drought monitoring and sustain the momentum established by the innovative tools that have recently emerged. Some of these key challenges in establishing remote sensing as a credible, and valuable, source of drought information are highlighted in the following.

16.3.1 Engagement of the User Community

Active engagement and communication between the remote sensing community and drought experts throughout the development of a new tool is important for the successful integration of satellite observation products into drought monitoring. The Earth Science Decadal Survey (NRC, 2007) emphasized this need for a stronger linkage between remote sensing scientists and end users to better define the data/information requirements for an application such as drought monitoring, as well as to improve the knowledge and capacity of users to apply these new types of satellite-derived products for their respective applications. Recommendations by drought experts regarding the type(s) of information, cartographic presentation, and update schedule should be acquired early in the process to guide product development. For drought applications, framing the current condition or state of a specific environmental variable (e.g., soil moisture) within a historical context (e.g., percent of historical average) is more important than delivery of the actual observation/estimate itself. Several examples of historic contextual products developed for drought monitoring were presented earlier in the book, including percentiles (Rodell, 2012, Chapter 11), standardized z-score anomalies (Anderson et al., 2012b, Chapter 7; Marshall et al., 2012, Chapter 8), percent change (Nghiem et al., 2012, Chapter 9), and percent of historical average (Anyamba and Tucker, 2012, Chapter 2). Appropriate cartographic color schemes for the maps are also important in order to present the information in a consistent format that is easily interpretable by drought experts. Examples were presented in this book by Wardlow et al. (2012, Chapter 3), Anderson et al. (2012b, Chapter 7), and Rodell (2012, Chapter 11) that apply a color palette used by the USDM in their maps; this palette has become commonly accepted in the drought community. Drought experts should also be actively engaged in the validation of remote sensing products. Their expert feedback and analysis is important for defining the performance and utility of a new tool or product for drought monitoring. These evaluation exercises also allow them to better understand the information being presented and how to best apply it, which will lead to more widespread integration into drought applications. Lastly, collaborative strategies need to be developed between the drought monitoring and remote sensing communities to optimally integrate satellite-based information into a coherent overall narrative that characterizes drought conditions in a meaningful way (NIDIS, 2007).

16.3.2 Accuracy Assessment

Accuracy assessment of remotely sensed information for drought monitoring is challenging, given the spatiotemporal complexity and differing sectoral definitions of drought (Wilhite and Glantz, 1985). Each drought event is unique, and its characteristics can vary in terms of onset, duration, intensity, and geographic extent. A number of qualitative and quantitative assessment techniques have been used, including comparisons with in situ measurements (e.g., soil moisture and precipitation), crop statistics (e.g., yields), and ground-level expert observations, as well as spatial and temporal pattern matching with other drought index maps (e.g., USDM). Although each technique has its own merits, there is no current consensus about the most appropriate set of methods to use for validation. The specific technique(s) selected is usually determined by the “ground truth” data that are available and the specific variable being validated. As a result, a “convergence of evidence” approach that collectively analyzes the findings from several assessment methods is needed to gain a more complete perspective of the accuracy and utility of a specific remote sensing tool or product for drought monitoring. Considerable work in the area of accuracy assessment is still needed in order to more fully realize the contribution of remote sensing for this application. In this section, some key points of emphasis to further advance the validation of remote sensing information for drought monitoring are discussed.

16.3.2.1 Extended and Near-Real-Time Assessment Campaigns

Given the complexity and spatiotemporal variability of drought, an extended accuracy assessment both temporally and geographically is needed to fully characterize the ability of a remote sensing tool to detect and monitor drought severity levels across diverse environments. Ideally, the assessments would be conducted in near real time to capitalize on the current drought information being reported (e.g., visual ground assessments, impacts, and media reports) and in situ data (e.g., rainfall, stream flow, and soil moisture) being collected. However, such an assessment campaign would require a considerable investment in time and resources. Retrospective analysis and case studies of previous drought events can be used to supplement a near-real-time assessment. However, many in situ observations and reports that would be useful for a thorough assessment are often difficult to locate or are not retained after a period of time. In addition, the relatively short operational period of a specific instrument can also limit the historical drought events that can be analyzed. Several sensors presented in this book have less than a decade of observations.

16.3.2.2 Consideration of Drought Impacts

Documentation of drought impacts on both natural and human systems is improving, allowing us to better quantify and understand the effects of drought that result from the complex interplay between a natural event (i.e., precipitation deficit) and the demand for water by humans and ecosystems (Wilhite et al., 2007). Several volunteer "citizen science" efforts such as the Drought Impact Reporter (DIR, http://droughtreporter.unl.edu/), the Community Collaborative Rain, Hail, and Snow Network (CoCoRAHS, http://www.cocorahs.org/), and National Phenology Network (NPN, http://www.usanpn.org/) have recently emerged to report both direct (e.g., reduced crop productivity) and indirect (e.g., reduced farm income) impacts of drought, resulting in a wealth of new ground-based drought information that could be utilized for validating remote sensing information. Although some impact data may not be directly comparable to remote sensing output in the way that traditional instrumental observations are (e.g., precipitation, soil moisture, or stream flow), they can provide a measure to verify relative changes and trends in drought conditions expressed in a satellite-derived product. In addition, linking these documented impacts with remote sensing–derived results is an important step in informing potential users of how these products relate to specific environmental condition(s) relevant to their application. Expansion of systematic impact archiving efforts outside the United States will be important for evaluating global drought monitoring tools.

16.3.3 SPATIAL RESOLUTION AND SCALE

Higher spatial resolution drought information is being increasingly demanded in efforts to understand and address local-scale impacts on the ground, ranging from the county to field or parcel scale. A prime example is the USDM, which is a composite indicator of many data inputs (e.g., climate and hydrological indices and indicators and expert feedback) that depicts drought conditions as a series of severity contours in map form across the United States (Svoboda et al., 2002). The USDM was designated in the 2008 U.S. Farm Bill (Food, Conservation, and Energy Act of 2008 – H.R. 6124; http://www.usda.gov/documents/Bill_6124.pdf) as the primary tool to establish county-level agricultural producer eligibility for drought disaster assistance. Some data inputs used in USDM development lack the spatial resolution to discern local-scale drought patterns, making the depiction of county- to subcounty-scale drought a challenge. Despite this fact, USDM contours are used operationally by the U.S. Department of Agriculture (USDA) Farm Service Agency (FSA) to establish county-level eligibility for drought disaster assistance.

Eligibility is established for an entire county if the USDM assigns any area of the county with a specific drought designation over a specified time period; thus, the ability to more accurately characterize drought patterns and conditions at this critical subcounty spatial scale is needed to administer such a program.

Although in situ instrument networks providing essential climatic and hydrologic data to the USDM and other drought monitoring applications cannot themselves satisfy these spatial resolution requirements (NIDIS, 2007), satellite remote sensing can be employed to map effects of drought at these critical scales. Maps at 100 m spatial resolution from satellite imagery are capable of resolving drought impacts associated with individual cropped fields and other land parcels, whereas 1 km imagery is well suited for subcounty-level assessments. Such drought products will primarily use satellite imagery in the optical and thermal wavebands, where such spatial resolutions are achievable. They will focus on drought response variables, such as vegetation cover fraction/fraction of absorbed photosynthetically active radiation or ET, rather than climatic driver variables such as precipitation, which are typically more homogeneous on average at the 100–1000 m scale. For example, robust operational water stress mapping at the field scale would facilitate assessment of drought stress response as a function of crop type and phenological stage and would be invaluable for estimating end-of-season yields for different crops. In contrast, at the 10 km scale, it is difficult to establish the specific land-cover type most affected by an ongoing drought and what components of the landscape are predominantly contributing to the coarse-scale stress signal.

Innovative approaches are needed to generate spatially scalable drought indicators that could be applied globally at the 10–50 km scale to monitor regional food/water security, regionally at the 1 km scale to assist in national to continental decision-making activities (e.g., crop insurance payments, basin-level and transboundary water issues, and multinational monitoring tools such as the North American Drought Monitor), and locally at the 100 m parcel level for landscape-level applications (e.g., irrigation scheduling, rotational livestock grazing, and reservoir water management). In addition to supporting an array of drought applications, these spatially scalable drought indicators calculated over targeted drought-affected areas will improve our understanding of the linkages between moisture deficits and specific vegetation response, as well as the consistency in the drought information conveyed by the indicator calculated at various spatial resolutions. The challenge will be to develop robust drought indicators that are consistent in accuracy and over the extended period of record needed to define baseline normal conditions across this range of scales, particularly at the highest spatial resolutions where temporal sampling is much less frequent.

Such efforts would be benefited by a high spatiotemporal resolution, visible-NIR/thermal sensor such as NASA's HyspIRI, but as discussed in the following, data continuity requirements make such short-term NASA research missions of limited value for developing operational drought monitoring tools. Consequently, collaborations between remote sensing scientists and drought experts should be established in coordination with early-stage mission activities of new sensors. An example is the applications working group developed for the upcoming NASA SMAP mission (http://smap.jpl.nasa.gov/science/wgroups/applicWG/), tasked with testing and demonstrating the applicability of the new data sets for drought monitoring in order to justify potential operational follow-on missions to support these types of operational applications (as discussed in the next section). In addition, the development of disaggregation techniques similar to the Disaggregated Atmosphere Land Exchange Inverse (DisALEXI) model (Norman et al., 2003) and LDAS should be pursued (demonstrated by Rodell (2012, Chapter 11)) to enable data from coarser resolution, high repeat frequency satellite instruments (e.g., MODIS) to be applied at the higher spatial resolution of lower repeat frequency sensors (e.g., Landsat Enhanced Thematic Mapper) to meet the demands of global, continental, national, and subnational drought applications.

16.3.4 Long-Term Data Continuity

Long-term, sustained data records are essential for operational drought monitoring in order to provide a meaningful historical context to establish the relative severity of a current drought compared to previous events. From a climate perspective, 30 years is the accepted minimum length of an observational data record required to obtain a representative sample of the distributional characteristics (i.e., normal range of conditions or values) of key drought variables such as precipitation (Guttman, 1994; WMO, 2010). The observational records of most operational satellite-based instruments are much shorter. AVHRR is a primary exception, with a series of sensors onboard NOAA's family of polar orbiting platforms that have collected near-daily global image data since the early 1980s. However, many newer instruments such as MODIS and GRACE, which are providing data products that are increasingly being used for drought monitoring, have data records that approach or exceed a decade in length. It is critical that remote sensing observations and products essential for drought monitoring be identified and that long-term data continuity plans ensure their continued availability into the future. Long-term data continuity is vital for building the historical records necessary for anomaly detection, as well as maintaining a consistent and reliable data input for operational drought monitoring systems.

Some continuity efforts are underway, such as the development of VIIRS as an operational replacement for AVHRR and extension of the MODIS, and the LDCM to extend the 30+ year Landsat record (Wulder et al., 2008). Other planned missions such as GRACE-II and SMAP are also intended to continue observations of terrestrial water storage and soil moisture observations, respectively. A critical task for developing and extending a long-term, multisensor time series is intercalibration of data among the different instruments to develop a seamless long-term data stream that can be used for monitoring purposes. Prime examples of this are efforts to intercalibrate spectral data from the AVHRR instrument series to develop a consistent long-term NDVI time series (Tucker et al., 2005; Eidenshink, 2006) and the merging of the historical AVHRR NDVI data record with the more recent MODIS NDVI data (van Leeuwen et al., 2006) using a phenoregion-based translation approach (Gu et al., 2010).

Long-term data continuity is a challenge given the budgetary constraints of many space agencies and other organizations responsible for supporting the collection of satellite-based earth observations. International collaborations that leverage activities among these various groups may be necessary to collectively support the acquisition of critical earth observations (NRC, 2007) needed to support operational applications including drought monitoring worldwide. One such effort was highlighted by Nghiem et al. (2012, Chapter 9): the Oceansat-2 scatterometer from the Indian Space Agency is now being used to supplement the microwave data that had been provided by the NASA QSCAT instrument, which failed in November 2009, to estimate soil moisture conditions in support of drought monitoring. Similar collaborative efforts will be important in the future to support the global drought monitoring effort.

16.4 FINAL THOUGHTS

Drought is a common feature of climate throughout the world with a broad footprint of impacts influencing natural systems and many sectors of society. This natural hazard can further exacerbate many important challenges confronting society today, including food security, freshwater availability, and economic sustainability. As a result, there has been a paradigm shift in drought management from reactive, crisis-based approaches to more proactive, risk-based strategies to reduce societal vulnerability to drought (Wilhite and Pulwarty, 2005). Monitoring is a cornerstone of effective drought risk management, providing critical information to facilitate informed decision making to reduce risk and mitigate the effects of drought.

The satellite remote sensing community has been challenged and will continue to be tasked with providing unique data sets for assessing key components of the hydrologic cycle related to drought. Collectively, the potential of remote sensing to address this need is now beginning to be realized, as evidenced by the numerous new tools and techniques presented in this book. A full array of satellite-based information is now available to characterize precipitation inputs and surface and subsurface moisture conditions, providing a more complete picture of drought conditions than ever before available. The innovative techniques and new types of earth observation that are now being applied for drought monitoring have laid the groundwork for further innovations, as new tools mature and new data from the proposed missions highlighted in this chapter become available.

A strong emphasis has been placed on the effective application of information from remote sensing–based earth observations for "societal benefits" (NRC, 2007). The influence of drought cuts across many of the key societal benefit areas identified by both the Decadal Survey on Earth Science and Applications from Space (NRC, 2007) and the GEO Global Earth Observation System of Systems (GEOSS), including agriculture, climate, disasters, ecosystems, health, and water. Applications of satellite-based information support both scientific research and real-world decision making related to drought and its impacts (NRC, 2007). From a scientific standpoint, the suite of current and future remote sensing tools highlighted in this book will allow many components of the hydrologic cycle and environment (e.g., land use and land cover change) to be collectively analyzed using a systems approach to advance the science of drought monitoring and early warning. Remote sensing provides critical inputs for better understanding the spatiotemporal evolution and climatic drivers of droughts. Such research is necessary to build a strong scientific basis upon which drought risk management strategies and monitoring tools can be developed (Wilhite and Pulwarty, 2005). From a decision support perspective, the remote sensing scientist must be able to translate satellite-based earth observations and derivative products into useful, interpretable information for decision makers who often have nonscientific backgrounds. In order to improve capacity to use remote sensing–derived information in drought applications, drought experts and other decision makers should be involved in specifying their information requirements (accessibility, data types and formats, latency, and update frequency). Several chapter authors discussed tailoring data products from their tools based on feedback from the drought community, and similar efforts are encouraged to maximize the utilization of remote sensing observations in operational systems for drought monitoring and early warning.

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