# 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 Index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR) for assessing the effect of drought on vegetation, as summarized by Anayamba 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 such as AVHRR could provide for operational drought monitoring through their near-daily, global observations of Earth's land surface.  However, the advancement of satellite remote sensing of drought was limited by the relatively few spectral bands of operational global sensors such as AVHRR, along with a relatively short period of observational record.

Since the late 1990s, spectral coverage was expanded with the launch of many new satellite-based, remote sensing instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS),Gravity Recovery and Climate Experiment (GRACE), Advanced Microwave Scanning Radiometer - Earth Observation System (AMSR-E), Tropical Rainfall Measuring Mission (TRMM), Advanced Microwave Sounding

Unit (AMSU), [mr1]which have provided an array of new Earth observations and measurements to map, monitor, and estimate a wide range of environmental parameters that are well suited for drought monitoring.  As illustrated by the various remote sensing methods presented in this book, many components of the hydrological cycle can now be estimated and mapped from satellite, providing the drought community with a more complete and comprehensive view of drought conditions.  Precipitation inputs (and deficits) in the form of both rainfall (Story, 2012; Chapter 12 and AghaKouchak et al., 2012; Chapter 13) and snow (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.  Natural water consumption on the land surface can also be assessed with new innovative techniques applied to thermal data to estimate evapotranspiration (ET) as demonstrated by Senay et al. (2012; Chapter 6), Anderson et al. (2012; Chapter 7), and Marshall et al. (2012; Chapter 8).  In addition, new perspectives on vegetation conditions are provided by new hybrid vegetation indicators (Wardlow et al., 2012; Chapter 3 and Tadesse et al., 2012; Chapter 4) and estimates of biophysical parameters such as the fraction of absorbed photosynethetic active radiation (fAPAR) (Rossi and Niemeyer, 2012; Chapter 5).  Lastly, unprecedented insights into sub-surface 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 incorporating remotely sensed moisture signals (Sheffield et al., 2012; Chapter 10).

Such remote sensing advancements are of paramount importance given the increasing 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 significant gaps in the spatial and temporal coverage of current surface station instrument networks providing key moisture observations (e.g., rainfall, snow, soil moisture, ground water, and ET) over the United States and globally (NIDIS, 2007). Improved monitoring capabilities will be particularly important given increases in spatial extent, intensity, and duration of drought events observed in some regions of the world, as reported in the International Panel on Climate Change (IPCC) report (IPCC, 2007). The risk of drought is anticipated to further increase in some regions in response to climatic changes in the hydrologic cycle related to 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 and Early Warning System (FEWS), National Integrated Drought Information System (NIDIS), and Group on Earth Observations (GEO), as well as the establishment of regional drought centers (e.g., European Drought Observatory) and geospatial visualization and monitoring systems (e.g, NASA SERVIR) have been undertaken to improve drought monitoring and early warning systems throughout the world. The suite of innovative remote sensing tools that have recently emerged will be looked upon to 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

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 in monitoring specific variables (e.g., soil moisture and terrestrial water storage) and will enable estimation of new parameters such as surface water elevation and storage.  In addition, integration of new satellite observations into land data assimilation systems (LDAS) is anticipated to improve various modeling outputs (e.g., soil moisture and streamflow) that can be utilized for drought monitoring.  In this section, several of these new satellite-based sensors will be discussed, as well as the increased role of remotely sensed data in LDAS models, to highlight opportunities that exist to further advance the contributions of remote sensing for operational drought monitoring and early warning.

### 16.2.1  Soil Moisture Active/Passive (SMAP)

The Soil Moisture Active/Passive (SMAP) mission, which is currently scheduled to be launched in the 2014-2015[mr2] time frame (NASA, 2010), is intended to provide global measurements of soil moisture and freeze/thaw state, with drought monitoring and prediction as a targeted application (Entekhabi et al., 2010).  SMAP includes both L-band radar and radiometer instruments, which will allow global mapping of soil moisture at a 10-km spatial resolution with a 2-3 day revisit time.  Combining the coincident radiometer and radar measurements from SMAP will provide much higher spatial resolution soil moisture mapping capabilities than previous instruments such as AMSR-E (Nghiem et al., 2012) 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 accuracy but coarser spatial resolution (40 km), and higher spatial resolution radar data (1 to 3 km) that has 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 surface conditionscover 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 (SWOT)

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 land, 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 greater than 50- to 100-m and water bodies with areas greater than 250-m$^2$. The vertical precision requirement of the WSE measurements is set at 10 cm over 1-km$^2$ area and river slope measurements within 1 cm over a 1-km distance (Biancamaria et al., 2010). Initial results in applying simulated SWOT data for characterizing surface water changes of inland water bodies have been promising (Durand et al., 2008; Lee et al., 2010). SWOT is anticipated to provide new information about the spatio-temporal 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 hydrologic drought monitoring and prediction. The SWOT mission is currently targeted to be launched in 2020 (NASA, 2010), but several recent efforts have explored the expected accuracy of SWOT products for measuring surface water storage of lakes (Lee et al., 2010) 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

GRACE mission, which hasThe Gravity Recovery and Climate Experiment (GRACE) has provided new insights into terrestrial water storage for drought monitoring as summarized by Rodell (2012, in Chapter 11). GRACE has demonstrated the abilityis able to monitor groundwater changes, as well as variations in shallow and root-zone soil moisture content (Famiglietti et al., 2011; Rodell et al., 2009; Tiwari et al., 2009; Rodell et al., 2007; Yeh et al., 2006). Outputs from GRACE related to surface and root-zone soil moisture and groundwater storage are now being applied in operational drought monitoring activities (Rodell, 2012 in Chapter 11; Houborg et al., 2010). The National Research Council Decadal Survey (NRC, 2007) recommended that NASA launch an advanced technology gravimetry mission (GRACE II) towards the end of the decade. A Gravity Recovery and Climate Experiment-II (GRACE-II) mission has been recommended by the National Research Council Decadal Survey (NRC, 2007) to extend the time series gravity field observations from the original ~~GRACE mission, which has provided new insights into terrestrial water storage for drought monitoring as summarized by Rodell (2012, in Chapter 11). GRACE has demonstrated the ability to monitor groundwater~~

~~changes, as well as variations in shallow and root-zone soil moisture content (Famiglietti et al., 2011; Rodell et al., 2009; Tiwari et al., 2009; Rodell et al., 2007; Yeh et al., 2006). Outputs from GRACE related to surface and root-zone soil moisture and groundwater storage are now being applied in operational drought monitoring activities (Rodell, 2012 in Chapter 11; Houborg et al., 2010).~~ The proposed GRACE-II willmission 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, making GRACE II have improved spatial resolution and will provide information about variations in groundwater storage and other sub-surface moisture at a spatial scale more directly applicable to 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. GRACE-II has been recommended for launch in the 2016-2020 time frame (NRC, 2007), which could result in a data gap considering GRACE was launched in 2002 and had an expected 5-year lifetime. In response, a GRACE Follow-On (GRACE FO) mission has been proposed in the interim to continue the time series of gravitational field measurements until the GRACE-II mission can be developed (NASA, 2010).

### 16.2.4 Visible/Infrared Imager Radiometer Suite (VIIRS)

The Visible/Infrared Imager/Radiometer Suite (VIIRS) is the next-generation, moderate resolution imaging radiometer that will be on-board the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), scheduled for a 2011 launch, and the subsequent operational NPOESS series of satellites (first satellite scheduled for launch in 2014) (Lee et al., 2010). 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 wavelength regions (Lee, 2006). The spectral bands of VIIRS were chosen primarily from two legacy instruments, AVHHR and MODIS, which have both greatly contributed to several remote sensing tools for drought monitoring 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, will be produced from the VIIRS observations (Lee, 2006) including vegetation indices (NDVI and EVI, Enhanced Vegetation Index) (Justice et al., 2010), land surface temperature (LST), and snow cover/depth data, 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 datastreams from instruments on NASA's Terra and Aqua platforms (Townshend and Justice, 2002). This will be followed by VIIRS instruments on a series of NPOESS platforms that are planned to be operational into the 2023-2026 time period (Lee et al., 2010). Future application of VIIRS VI and LST data for drought monitoring will support tools such as the Vegetation Drought Response Index (VegDRI, Brown et al., 2008 and Wardlow et al., 2012 in Chapter 3) and estimation of ET (Anderson et al., 2007) and ET-derived indices (Anderson et al., 2011 and Anderson et al., 2012 in Chapter 7).

### 16.2.5 Landsat Data Continuity Mission (LDCM)

Along with prescribing 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 have been 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 dataset 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 cover change. Both Landsats 5 and 7 (currently active) have functioned well past their expected lifetimes. The Landsat Data Continuity Mission (LDCM) is scheduled for launch in December 2012, 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 a30-m spatial resolution. The Thermal InfraRed Sensor (TIRS) will collect thermal infrared data in two split-window channels to facilitate atmospheric correction. TIRS will enable global mapping of ET and vegetation stress at sub-field scales.

While the revisit period of individual Landsat satellites (16 days or more, depending on cloud cover) is not particularly well-suited for operational monitoring rapid changes in vegetation and moisture conditions associated with drought events, multiple staggered systems could provide 8-day (2 systems) or 5-day (3 systems) coverage. 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., 2011). Such fused imagery could significantly address the growing need for high-resolution (sub-county) information about yield loss 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. With advanced spacecraft and instrument technology, the Geostationary Operational Environmental Satellite “R” series (GOES-R) will replace the current GOES-N series to meet the National Oceanic and Atmospheric Administration’s (NOAA) operational data needs, 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 sixteen band imager with two visible bands, four near-infrared bands, and ten infrared (3.5 to 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, compared with the 1 km and 4 km of the GOES N series, respectively. In addition, the full disk coverage rate of ABI is 5 minutes instead of 30 minutes of the current GOES. From the enhanced GOES-R ABI observations, data products of downward surface solar insolation, reflected solar insolation, and LST are among the 21 baseline data products that have potential application for drought monitoring, and will be generated with less than 1 hour 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 minutes. The High Resolution Visible 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 long-wave and short-wave fluxes, LST, and ET (http://www.eumetsat.int/Home/Main/DataProducts/Land/index.htm?l=en) For continuation of MSG datastreams, 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/MeteosatThird Generation /Instruments/).

To support global monitoring applications, several efforts are underway to assemble and often inter-calibrate 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-hr global infrared dataset, the NOAA 10-km/3-hr International Satellite Cloud Climatology Project (ISCCP) B1 data rescue project (Knapp, 2008), and the Global

Monitoring for Environment and Security (GMES) 5-km/1-hr 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 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 2020's) includes a hyperspectral imaging spectrometer and a multispectral thermal imager, which in combination will acquire 210 bands of spectral data (within the 400 to 2,500 nm range). In the current design, HyspIRI will collect data at 60-m spatial resolution and have 5-day temporal revisit interval for thermal acquisitions and 16-day 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 spatio-temporal 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 Snow and Cold Land Processes SCLP mission (proposed launch between 2016 and 2020) will consist of a combination of active (X- and Ku-band synthetic aperture radars or SARs) and passive (K- and Ku-band radiometers) microwave sensors to characterize snow cover and snow water equivalent, which could assist drought monitoring by providing information about the expected soil moisture recharge and snowmelt runoff. The SCLP mission has been recommended for a LEO to provide sub-kilometer spatial resolution with complimentary 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 to 6 days) when needed (NRC, 2007). A Microwave Imager/Sounder (MIS) instrument is also being actively developed for the latter NPOESS mission, which will build upon heritage sensors such as AMSR-E and WindSat (Li et al., 2010) and provide observations for soil moisture estimation.

### 16.2.8 Enhancement of Land Data Assimilation Systems with Remotely Sensed Data

The suite of existing and future planned remotely sensed data products have the potential to provide a holistic view of drought and the hydrological cycle in general. As these products give different and independent views of hydrological 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 assessments of multiple variables (e.g., U.S. Drought Monitor, USDM). This potentially comes at the price, however, because of inconsistencies in the assessments from individual products (Sheffield et al., 2009; Gao et al., 2010), in part because the products represent different quantities and scales, but also because of inherent errors 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 multi-variate, multi-user perspective.

Sheffield et al. (2012; Chapter 10) described the potential to meet this challenge through direct use or assimilation of remote sensing products into the NLDAS land modeling and assimilation system. Land data assimilation systems provide, through the modeling, a physically-consistent and continuous depiction of all major components of the land surface water cycle. However, they are subject 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). The assimilation part enables merging of observational data, such as from remote sensing, into the modeling to correct for these errors, and improve the representation of quantities, such as root zone soil moisture, that are not directly available from remote sensing. It also forms a framework for merging independent remote sensing products in a physcically-consistent way into continuous fields of data in space and time.

Future improvements in land data assimilation for drought monitoring will leverage from remote sensing products in a number of ways. A key enhancement is to improve simulation of land surface conditions through use of remotely sensed precipitation, especially in sparsely monitored or topographically complex regions. The planned NASA-JAXA (Japan Aerospace Exploration Agency) Global Precipitation Mission (GPM) (Smith et al., 2004) will be a key element in this, given its unprecedented spatial and temporal sampling (3 hourly and 0.25 degree) globally and the legacy of use of TRMM based precipitation products. Assimilation of individual remote sensing products into land surface models has been tested such as for 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 gives various levels of increase in skill when compared to ground observations, but the benefit to drought monitoring needs to be evaluated and this is now starting to happen for large-scale applications (e.g., Houborg et al., 2010; Bolten et al., 2010). The complementary information contained in each of these products, however, has not been exploited to its potential through joint 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 multi-scale assimilation approaches (Pan et al., 2009) that combine 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 through future planned missions such as those highlighted in the previous section. The drought community is beginning to reap the benefits of these efforts through the array of information generated from new types of satellites observations using advanced analytical tools and modeling approaches. However, there are several challenges that still need to be addressed to more fully integrate remote sensing data into drought monitoring and sustain the momentum established by the innovative tools that have recently emerged. This section will highlight some of these key challenges in establishing remote sensing as a credible, and valuable, source of drought information.

### 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 observations and 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 applications such as drought monitoring, as well as 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, color scheme, and update schedule should be acquired early in the process to guide product development. For drought applications, framing the current condition or state of specific environmental variable (e.g., soil moisture) within a historical context (e.g., percent of historical average) is required rather than the actual observation/estimate. Several examples of historic contextual products developed for drought monitoring were presented earlier in the book including percentiles (Rodell, 2012 in Chapter 11), standardized z-score anomalies (Anderson et al., 2012 in Chapter 7 and Marshall et al., 2012 in Chapter 8), percent change (Nghiem et al., 2012 in Chapter 9), and percent of historical average (Anyamba and Tucker, 2012 in 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; in Chapter 3), Anderson et al. (2012; in Chapter 7), and Rodell (2012; in Chapter 11) that apply a color palette used by the USDM to their maps, which 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 within a drought context is important for effectively 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 should 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 spatio-temporal 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), statistical data (e.g., crop yields), and ground-level expert observations, as well as spatial 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 are 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 spatio-temporal 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 varying drought severity levels of drought 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 prior 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 because several sensors presented in this book having 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 inter-play between a natural event (i.e., precipitation deficit) and the demand for water by human-use and natural 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. While 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 relative 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.

### 16.3.3 Spatial Resolution and Scale

Higher spatial resolution drought information is increasing being required to understand and address local-scale impacts on the ground ranging from the county to field/parcel scale. A prime example is the USDM, which is a composite indicator of many data inputs (e.g., climate and hydrologic 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), 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. Many data inputs used in USDM map development lack the spatial resolution to discern local-scale drought patterns, which makes the depiction county to sub-county-scale drought in the USDM challenging. Presently, significant gaps exist in the spatial coverage of in situ station instrument networks providing essential climatic and hydrologic data to the USDM and other drought applications with the greatest data shortfalls on the county and state levels (NIDIS, 2007).

While no in-situ network provides this level of spatial detail across a full country or continent, 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 sub-county level assessments. Such drought products will use primarily 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 (fAPAR) or ET, rather than climatic driver variables such as precipitation, which are typically more homogeneous on average at the 100- to 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.

Ideally, innovative approaches are needed to generate spatially-scalable drought indicators that could be applied globally at the 10- to 50-km scale to monitor regional food/water security;

regionally at the 1-km scale to assist in national to contintental decision making activities (e.g., crop insurance payment dispersal, basin-level and transboundary water disputes, and multi-national 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 an 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 spatio-temporal resolution visible-NIR/thermal sensor such as NASA’s HyspIRI; but as discussed below, data continuity requirements make these type of short-term NASA research missions of limited value for developing operational drought monitoring tools. As a result, collaborations between remote sensing scientists and drought experts should be established in coordination early-stage mission activities of new sensors similar to the applications working group developed for the upcoming NASA SMAP mission (http://smap.jpl.nasa.gov/science/wgroups/applicWG/) to test and demonstrate the applicability of the new data sets for drought monitor in order justify potential operational follow-on missions to support these type of operational applications as discussed in the next section. In addition, the development of disaggregation techniques similar to the Disaggregated Atmosphere Land Exhange Inverse (DisALEXI) model (Norman et al., 2003) and land data assimilation systems should be pursued (demonstrated by Rodell et al. (2012) in Chapter 11) for essential remotely sensed drought indicators that 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) in a effort to provide a broader range of spatial and temporal coverages that accommodate the demands of global, continental, national, and sub-national drought applications.

### 16.3.4 Long-Term Data Continuity

Long-term, sustained data records are key for operational drought monitoring in order to provide a meaningful historical context to establish the relative severity of a current drought compared to prior events. From a climate perspective, a 30-year observational record is the accepted minimum length 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 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 long-term data continuity plans be to 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 Landsat Data Continuity Mission (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, multi-sensor time series is ‘cross walking’ or translating the data among the instruments to develop a seamless long-term datastream that can be used for monitoring purposes. Prime examples of this are efforts to inter-calibrate of spectral data from the AVHRR instrument series to develop a compatible long-term NDVI time series (Tucker et al., 2005; Eidenshink, 2006), and the merging of 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) where 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 various natural systems and processes, as well as many sectors of society. This natural hazard can further exacerbate many important issues facing society today including food security, water resource 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 hydrological 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 –sub-surface moisture conditions, providing a more complete picture of environmental conditions to drought experts than ever before available. These innovative techniques and new types of Earth observations 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 cross cuts 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 will support both scientific research and real-world decision making relating to drought development and 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 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 will provide critical inputs for better understanding the spatio-temporal evolution and climatic drivers of droughts. This type of research is necessary to build a strong science element upon which drought risk management strategies and monitoring tools can be developed (Wilhite and Pulwarty, 2005). From a decision making perspective, a key activity for the remote sensing scientist will be to translate satellite-based Earth observations and derivative products into useful, interpretable information for decision makers with various and often non-scientific 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 in the future to maximize the utilization of remote sensing observations in operational systems for drought monitoring and early warning.

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