TOWARD GLOBAL DROUGHT EARLY WARNING CAPABILITY

Expanding International Cooperation for the Development of a Framework for Monitoring and Forecasting

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THE NEED FOR A GLOBAL DROUGHT EARLY WARNING FRAMEWORK. Drought has had a significant impact on civilization throughout history in terms of reductions in agricultural productivity, potable water supply, and economic activity, and in extreme cases this has led to famine. Every continent has semiarid areas, which are especially vulnerable to drought. The Intergovernmental Panel on Climate Change has noted that average annual river runoff and water availability are projected to decrease by 10%–13% over some dry and semiarid regions in mid and low latitudes, increasing the frequency, intensity, and duration of drought, along with its associated impacts. The sheer magnitude of the problem demands efforts to reduce vulnerability to drought by moving away from the reactive, crisis management approach of the past toward a more proactive, risk management approach that is centered on reducing vulnerability to drought as much as possible while providing early warning of evolving drought conditions and possible impacts. Many countries, unfortunately, do not have adequate resources to provide early warning, but require outside support to provide the necessary early warning information for risk management. Furthermore, in an interconnected world, the need for information on a global scale is crucial for understanding the prospect of declines in agricultural productivity and associated impacts on food prices, food security, and potential for civil conflict.

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DOI:10.1175/BAMS-D-11-00176.1

This paper highlights the recent progress made toward a Global Drought Early Warning Monitoring Framework (GDEWF), an underlying partnership and framework, along with its Global Drought Early Warning System (GDEWS), which is its interoperable information system, and the organizations that have begun working together to make it a reality. The GDEWF aims to improve existing regional and national drought monitoring and forecasting capabilities by adding a global component, facilitating continental monitoring and forecasting (where lacking), and improving these tools at various scales, thereby increasing the capacity of national and regional institutions that lack drought early warning systems or complementing existing ones. A further goal is to improve coordination of information delivery for drought-related activities and relief efforts across the world. This is especially relevant for regions and nations with low capacity for drought early warning. To do this requires a global partnership that leverages the resources necessary and develops capabilities at the global level, such as global drought forecasting combined with early warning tools, global real-time monitoring, and harmonized methods to identify critical areas vulnerable to drought. Although the path to a fully functional GDEWS is challenging, multiple partners and organizations within the drought, forecasting, agricultural, and water-cycle communities are committed to working toward its success.

ELEMENTS OF A GLOBAL DROUGHT EARLY WARNING SYSTEM.

Drought early warning. The purpose of an early warning system is to reduce vulnerability to a natural hazard by providing users such as relief agencies or national authorities the maximum possible lead time to put mitigation strategies into place.

To provide this lead time requires a weekly or daily rapid response monitoring system, possessing time scales short enough to detect episodic "flash droughts." These two key elements (a drought monitoring and a drought forecasting system) can provide the underlying information upon which to make informed decisions, as currently happens in national and subnational monitoring systems.

A key difference for a global system is the need to provide consistent and reliable information at global scales acknowledging inherit system uncertainties created, in part, by the disparity of the density of meteorological and hydrological station coverage, which in some regions may be insufficient for drought monitoring. At the same time, the monitoring and forecasting technologies must have sufficient granularity and skill to identify the spatial variability of current and future drought conditions. This article describes recent developments in global drought monitoring and forecasting tools that show promise for addressing these insufficiencies. Using state-of-the-art information technologies, these tools can be provided within a GDEWS to increase the lead time to enable drought mitigation measures to be put in place.

Global observing system for drought: Data sources and requirements. The first part of a GDEWS is a drought monitoring component. The diverse landscapes of the planet range from areas sustained by glacial meltwater in high-altitude terrain in central Asia to Amazonian rain forests influenced by the El Niño–Southern Oscillation. The forms that droughts assume in these diverse landscapes will match this complexity. One approach to drought classification that is being explored is the terminology developed by Van Loon and Van Lanen (2011) to describe the propagation of droughts over Europe from cold seasons into warm seasons, as well as terminology to denote drought propagation processes. Obviously, different terminology would be needed for tropical areas, such as Amazonia.

As shown in Fig. 1, a drought of long duration can continually draw down groundwater level (bottom time series) and surface water (time series second above bottom), as was the case in the Millennium drought in southeast Australia (Murray–Darling basin) from 2001 to 2009. The shorter, below-normal precipitation delivered in short events is "noisy," but the draw down and decline of groundwater table is sustained and continual, along with the decline of surface water elevation.

Monitoring the physical processes by which droughts propagate through the hydrological cycle differently in different regional areas, as well as comprehensive monitoring of drought impacts on both groundwater and surface water, requires that multiple stores and fluxes of water be monitored: precipitation, soil moisture, evapotranspiration, snowpack, river flows, and groundwater (Fig. 1), along with agricultural productivity and natural ecosystem health. To do this globally is challenging because of the sparse network of in situ measurements of these variables. Many parts of the world, especially in the wet and dry tropics, are sparsely gauged, or the data are not easily available.

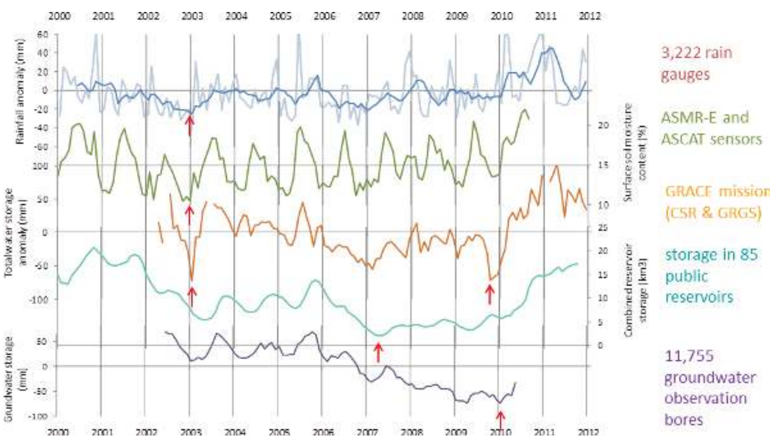

Fig. 1. An example of the propagation of drought through the hydrological system observed over the Murray–Darling basin during the Australian 2001–09 Millennium drought, from rainfall and near-surface soil moisture anomalies (top time series), to declines in streamflow and surface water storage (middle time series), and finally depletion of groundwater (bottom time series). This example highlights the diversity of variables that need to be monitored to capture the development of drought and its impact of different water-related sectors.

In lieu of in situ observations, there is an increasing reliance on satellite remote sensing and modeling. Remote sensing is well suited to global drought monitoring because of the extensive spatial coverage and frequent return periods, along with the emerging ability to provide retrievals of all components of the water cycle as well as vegetation health. Several mature and emerging products are available that show promise in the context of drought monitoring (Fig. 2). Hydrological modeling also plays a key role in providing global coverage, which has made large advances in recent years, contributing for several years to drought monitoring activities in the United States and elsewhere. However, there still exist large differences between models and biases relative to observations, especially in regions with low-density precipitation networks. A number of challenges must therefore be overcome before a global, comprehensive, and robust monitoring system is developed. First, the provision of truly global coverage can only be achieved by integrating satellite remote-sensing, modeling, and ground-based data. Errors in remote-sensing retrievals need to be reduced, and consistency in time and between products needs to be assured. Merging satellite data into models via assimilation methods holds great promise for removing biases in models and harmonizing data across products and variables.

Global drought forecasting. The second part of a GDEWS is a forecasting component with monthly and seasonal—as well as potentially interannual and decadal—lead times. These forecasts are provided by the individual organizational members of the partnership, such as the European Centre for Medium-range Weather Forecasting (ECMWF), the U.S. National Centers for Environmental Prediction (NCEP)/Climate Prediction Center (CPC), the Brazilian governmental Center for Weather Forecasts and Climate Studies (CPTEC), among others. These organizations provide ensembles of seasonal climate forecasts 1–15 months out based on atmospheric forecast models, initialized with sea surface temperatures and best estimates of land surface conditions (snow pack and soil moisture). A key test of the viability of a GDEWS is whether it can successfully and skillfully provide forecasts of high-enough reliability, while also providing sufficient lead time. Ensemble prediction systems have increased the lead time over which floods can be forecast, as, for example, by the Joint Research Centre (JRC)'s European Flood Alert System. At medium-range to seasonal time scales, the current skill of these systems in drought forecasting is generally limited to tropical and subtropical regions because of the strong teleconnections with ENSO activity, or is dependent on memory in the land system in midlatitudes where climate is generally much more unpredictable. For example, the failure of the "short rains" season during the October—December 2010 Horn of Africa (HoA) drought—the worst of the last 60 years—was forecast with some skill by the ECMWF seasonal forecast system because it was able to predict the La Niña event from June 2010 onward and its connection to the HoA rainfall (Figs. 3 and 4). The subsequent failure of the "long rains" season of March–May 2011 was not well predicted, however. Elsewhere in the midlatitudes, forecasts have been successfully enhanced by model merging and downscaling techniques. Tests of ensemble drought forecasting skill carried out by the European Drought Observatory (EDO) over the European continent were found to be more checkered. Seasonal predictions of temperature are generally more skillful than

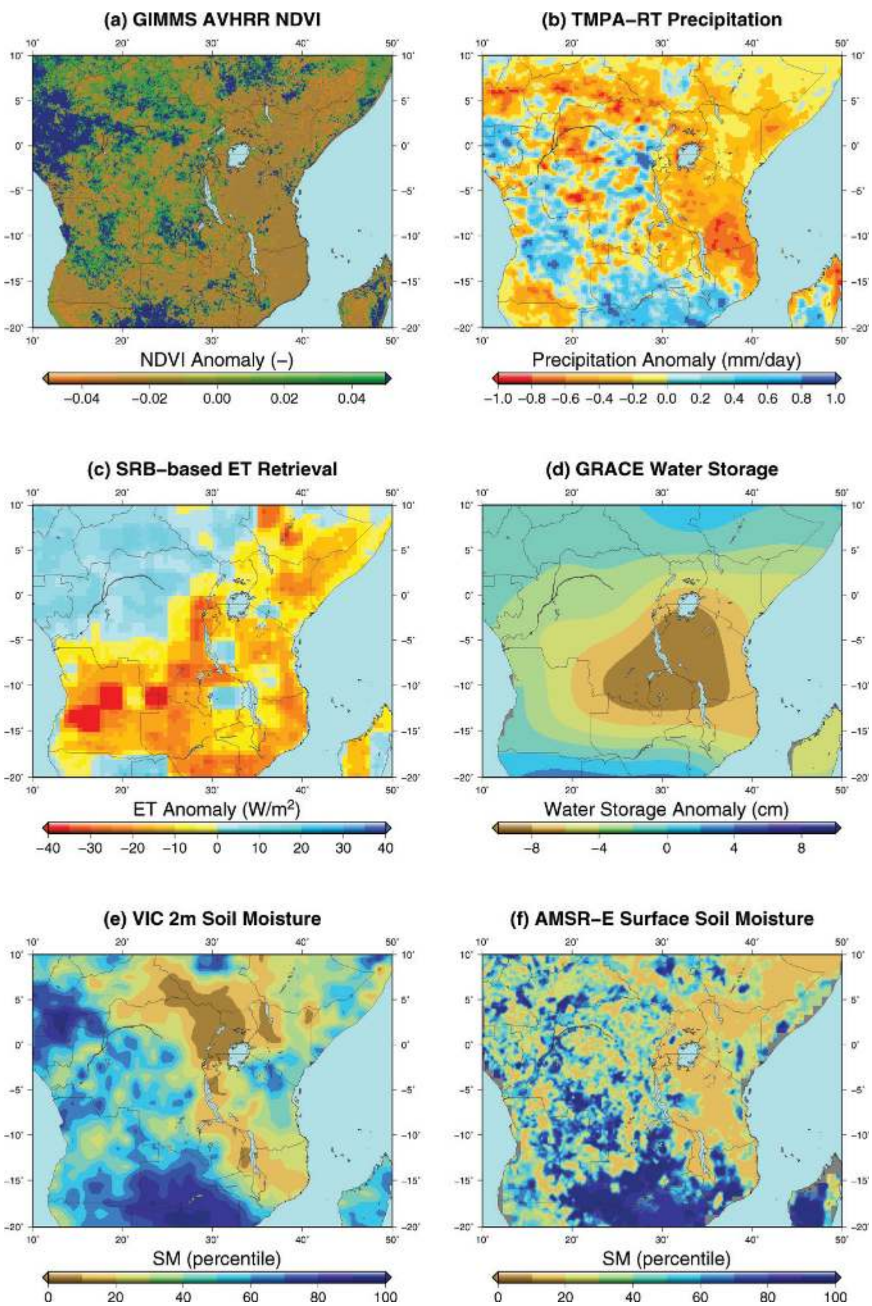

Fig. 2. Examples of drought monitoring and assessment for the drought of 2006 in eastern Africa from a variety of satellite remote sensing and model products, many of which are now operational and can contribute to a global drought monitoring system. (a) Normalized Difference Vegetation Index (NDVI) from the Global Inventory Modeling and Mapping Studies (GIMSS) Advanced Very High Resolution Radiometer (AVHRR) product. (b) Precipitation anomaly from the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) satellite-based product. (c) Evapotranspiration anomaly derived from the Surface Radiation Budget (SRB) product. (d) Water storage anomaly from the Gravity Recovery and Climate Experiment (GRACE) gravimetric satellite sensor. (e) Soil moisture percentile from the VIC land surface model. (f) Soil moisture percentile from retrievals based on the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) satellite sensor.

precipitation and can provide warning of heat-related droughts, as evidenced by successful predictions of summer heat waves for the Russian Federation in 2010 and Europe in 2003.

Global drought information integration and delivery. The third component is the integrated drought information system backbone into which the various components of the GDEWS are connected, which provides a consistent framework to combine different layers of drought information crossing different spatial and time scales. As a consequence of regional characteristics in climate and ecosystems, each country has its own set of core indicators for operational drought monitoring, resulting in systems that differ from country to country. These different monitoring methodologies and the drought indicators of each of these individual systems must first be integrated. This is the precursor to the second step of importing these underlying systems into the Integrated Drought Information System (IDIS), and subsequent steps to repackage the drought information to make it more valuable to users. This second step, for example, allows geographic information system (GIS) tools to be combined with data mining and visualization tools to assemble a holistic view of drought episodes occurring simultaneously across the world, illustrating their impacts

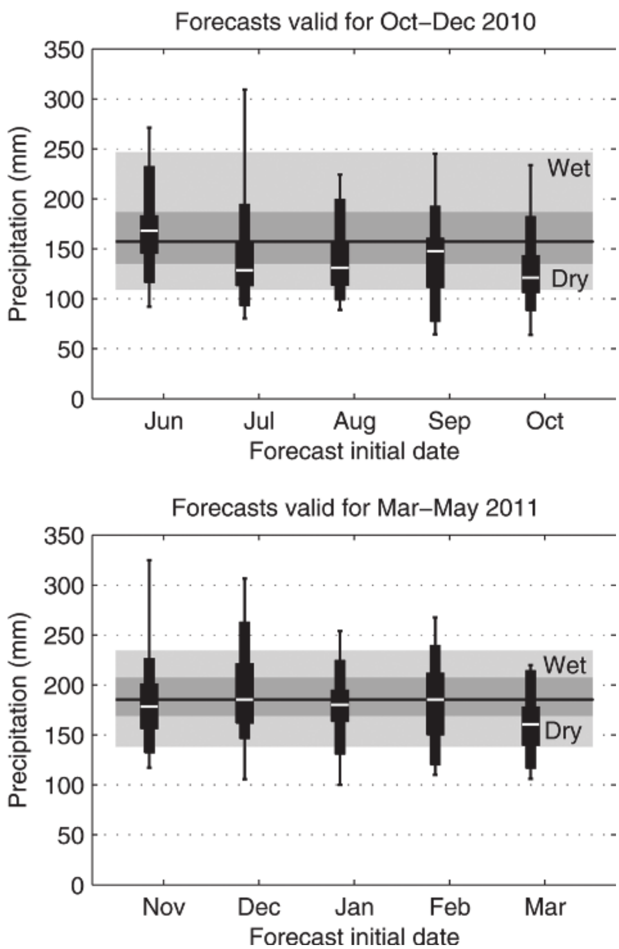

Fig. 3. Distribution of the seasonal forecasts from the ECMWF seasonal forecast system of accumulated precipitation for (top) Oct–Dec 2010 and (bottom) Mar–May 2011 in the Horn of Africa. The shaded areas indicate the model climate distribution (dark gray; percentiles 30–70) and dry and wet conditions (light gray; percentiles 10–30 and 70–90). The horizontal axis displays the different forecast initial dates represented as box plots extending from the minimum (whiskers) to percentiles 10, 30, 70, 90, and maximum. Precipitation anomalies are departures from the 1979–2010 mean.

on surface, groundwater, and agricultural crop production.

An example of this approach to multisystem integration is the North American Drought Monitor (NADM), which merges drought measurements over Mexico, the United States, and Canada. The NADM began with the U.S. Drought Monitor approach that aims to express multiple meteorological, hydrological, and agricultural drought indicators and data as four categories of increasing drought intensity using a percentile ranking. The conversion of a percentile scale can be applied to different data sources at a given location or even to data from different locations stitched together into a larger geographical entity (e.g., different nations merged into a continent or different continents merged into a global product).

The EDO approach chooses a set of core indicators, as selected by a group of key stakeholders, and these indicators are subsequently implemented and monitored at local, watershed, national, and subcontinental levels. The use of the same indicators permits seamless up-and-down scaling between the levels. Examples of such core indicators include the Standardized Precipitation Index (SPI), soil moisture deficiency (or anomaly), and vegetation water stress (fraction of absorbed photosynthetic active radiation), to which a combined indicator for agricultural drought was recently added. Others related to river runoff, groundwater, and snowpack are under discussion.

This EDO approach is being expanded to include the display of Latin American drought-related information, using EDO indicators, as part of the EuroCLIMA collaboration program between Europe and Latin America. Another independent South American continent-wide monitoring effort has been launched by the Brazilian governmental Center for Weather Forecasts and Climate Studies (CPTEC), using soil moisture percentiles and SPI, combined with 1-month forecasts. The CPTEC effort, with assistance contacting drought managers across South America provided by Argentina SMN, has already begun the development of a continental Latin American drought network. The EDO and NADM approaches have shown possible pathways for stitching together detailed drought information at local levels to provide drought coverage for an entire continent, and the ensuing South American coverage can then be made available in the Global Drought Monitoring Portal.

The EDO approach is also being extended to the continent of Africa. A European-financed project, the Seventh Framework Drought Early Warning System for Africa (DEWFORA) includes 1) testing of a continental African Drought Observatory, using the common drought indicators; 2) estimating soil moisture anomalies through deployment over Africa of the LISFLOOD hydrological model; 3) studying drought monitoring and forecast possibilities at river basin level in four specific case studies active over eastern Africa (Upper Nile basin), southern Africa (Limpopo basin), western Africa (Niger basin), and North Africa (Oum Er Rbia basin); and 4) medium-range and 6-month seasonal forecasts from ECMWF seasonal and monthly prediction systems. This forecasting work was presented above for the Horn of Africa. DEWFORA focuses on eastern and southern Africa, and is not an independent effort but rather is networked with the climate outlook centers in each of these areas. Another building block for an African continental-scale drought monitoring system is the Princeton University experimental African Drought Monitor, installed at the western (Sahel) and eastern African (HoA) regional drought-monitoring centers, using the variable infiltration capacity (VIC) model to screen for soil moisture anomalies. Rather than base drought monitoring entirely upon precipitation measurements from a very low-density synoptic grid, pilot projects are testing whether thermal-band evapotranspiration drought indicators (Fig. 2) can provide supplemental early warning to the Famine Early Warning Systems Network (FEWSNET), for crop outlooks in the GEO Global Agricultural Monitoring System (GEOGLAM) as well as organizations such as Oxfam.

Such continental-scale networks provide the prerequisites, out of which combined drought information may then be imported into the portal (Fig. 5). The Global Drought Information System (also known as the Global Drought Monitoring Portal [GDMP]), hosted by the U.S. National Integrated Drought Information System (NIDIS) at the NOAA National Climatic Data Center (NCDC), has provided a demonstration of the feasibility to construct and maintain such a global system, and provides, at present, monthly monitoring coverage for North America, Europe, Australia, and Africa, and global coverage of precipitation deficiency through SPI and the Global Historical Climatology Network.

The Global Drought Monitoring Portal is networked through internet web services so that from within the portal, users can access and be transferred to the regional or national drought monitoring centers, where the users can then find much more information. At the same time, the GIS capabilities of the portal allow different layers of drought information crossing different spatial and time scales to be reassembled, using auxiliary tools and visualized in forms more valuable to users and decision makers within each area. Some of the "plug in" capabilities of this information system will include 1) the drought catalog, showing historical droughts and their causes and drivers (which likely will vary from region to region); 2) seasonal forecasts of drought development and recovery; and 3) maps of drought risk, vulnerability, impacts, mitigation, and responses.

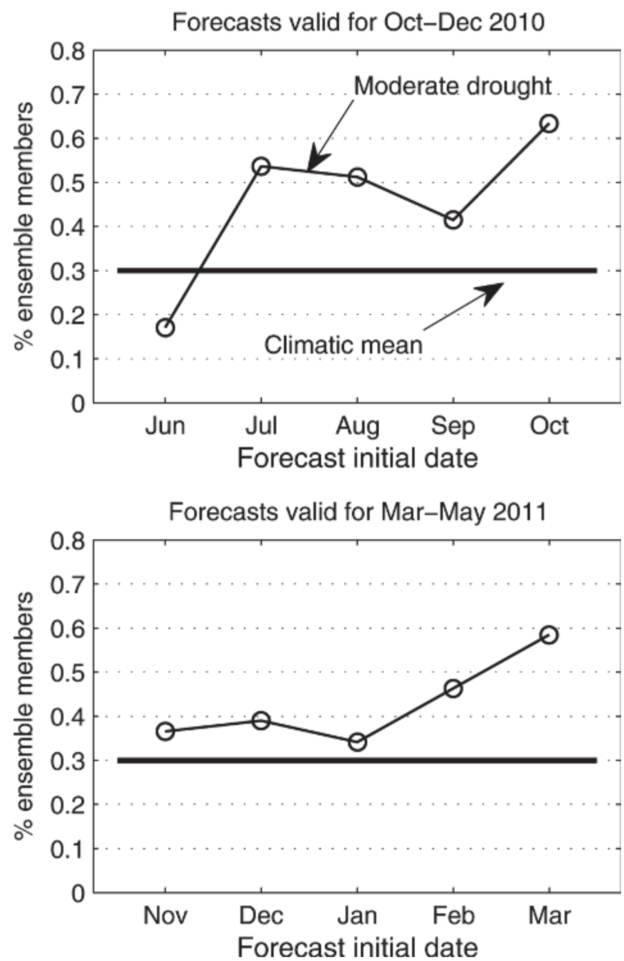

Fig. 4. Fraction of ensemble members from the ECMWF seasonal forecast system indicating moderate drought (defined as precipitation below the 30th percentile of the model climatology) for (top) Oct–Dec 2010 and (bottom) Mar–May 2011 in the Horn of Africa. The horizontal axis displays different forecast initial dates.

INTERNATIONAL COOPERATION FOR GLOBAL DROUGHT MONITORING AND FORECASTING. Within the last three years, considerable progress has been made in bringing together the partners and components necessary for the development of a Global Drought Early Warning System. The notion of a GDEWS had been first proposed (by Jay Lawrimore, NOAA) at a 2007 Group on Earth Observations (GEO) South Africa Plenary Meeting, but not until 2010, during the Beijing GEO Ministerial Summit, was a demonstration given of the feasibility to construct and maintain a simpli-

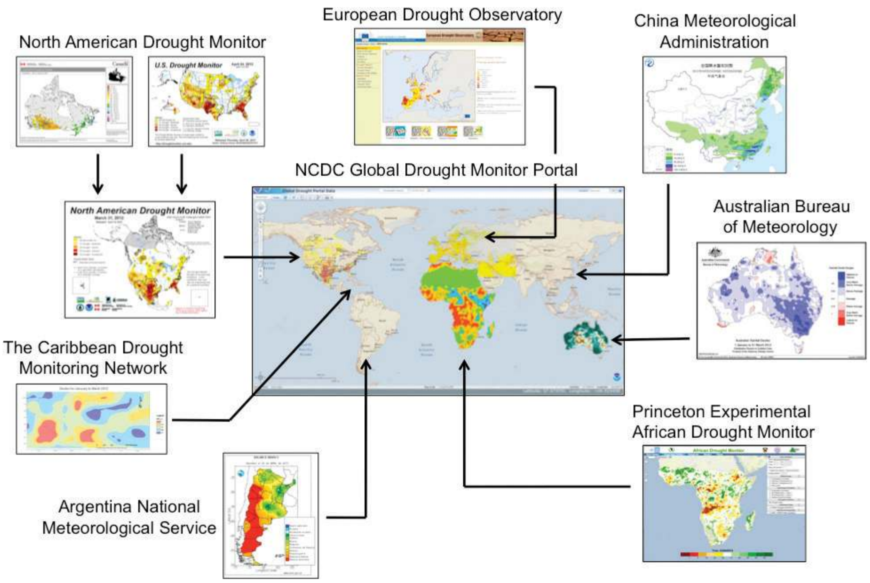

Fig. 5. The conceptual framework for a Global Drought Early Warning System (GDEWS). The system follows a bottom-up approach that merges real-time information from national and regional systems along with global coverage from remote sensing and modeling into a global system. The (NCDC) Global Drought Monitoring Portal (GDMP) is shown in the center, which is the current operational demonstration of such a global drought information system.

fied first approximation of the system—the GDMP, whose development continues under the new GEO 2012–15 work plan.

Across another front, the World Meteorological Organization (WMO), the United Nations (UN) Convention to Combat Desertification (UNCCD), and UN agencies are promoting the development of national drought policies and integrated drought management that support changing the approach of communities and countries from reactive crisis management to proactive risk management. These measures include effective monitoring and early warning systems to deliver timely information to decision makers, effective impact assessment procedures, proactive risk management measures, and preparedness plans aimed at increasing the coping capacity. To address these issues, a high-level meeting on national drought policies was organized in Geneva on 11–15 March 2013. The WMO and the Global Water Partnership Integrated Drought Management Program (IDMP) have plans to develop a drought knowledge base that is potential component of the GDEWF.

Another example of a building block is the European Union Seventh Framework Global Water Scarcity Information Service (GLOWASIS), which enhances seasonal meteorological and hydrological forecasting through the use of improved monitoring data from in situ and satellite products. The GLOWASIS portal also displays global maps of water scarcity and water stress, identifying sites where user demands for water outstrips supply.

Further impetus is being provided by the multipartner World Climate Research Program (WCRP) workshop that was convened in Frascati, Italy, in April 2012 to discuss the needs and steps necessary for the first developmental stage of a GDEWF, which was named the Global Drought Information System (GDIS). The workshop was equally divided among user group and drought information service providers on the one hand and, on the other, scientists who presented the latest research on drought monitoring and forecasting technologies and understanding of drought mechanisms, particularly for some high-profile drought and heat wave episodes. The workshop participants recommended the following as basic elements of a GDIS: 1) an experimental real-time global monitoring and prediction system; 2) a drought catalogue summarizing our understanding of worldwide drought; and 3) a research component centered on internationally coordinated case studies of recent high-profile droughts.

TOWARD THE GLOBAL DROUGHT EARLY WARNING FRAMEWORK. The Global Drought Early Warning System aims to add an overarching global component to existing regional and national drought monitoring and forecasting capabilities. Such a network and partnership of drought experts across the world will provide a framework to consistently improve forecasts and ongoing monitoring efforts, while assembling and further improving available forecasts at a supernational level. The GDEWS will also, in multimodel mode, display and make available estimates of model uncertainty and varying model skill with regard to droughts of a different nature and scale. This knowledge will help to improve modeling and forecasting tools and help make tools available to countries that currently do not have them. Further, the partnership provides an impetus to integrate new goals of satellite missions and Earth observations: 1) to reduce uncertainty and biases in areas of sparse ground-based grids, and 2) to enable sampling and monitoring of multiple stores of water to derive more effective, physically based pictures of drought. A further goal is to improve speed of delivery for early warning, as well as distil and integrate satellite, ground-based, and crop-based meteorological and hydrological information having different formats into a unified, user-friendly form to assist in drought-related activities and relief efforts across the world, along with combined early-warning tools and information, global real-time monitoring, and harmonized methods to identify critical areas vulnerable to drought.

The idea of a GDEWS began in Africa,where it was realized that droughts had become so widespread and severe that *regionally* coordinated crisis management was warranted. The recognition of the scale of the challenge has since expanded from the regional to the global, and the role of water as a planetary limiting factor is becoming increasingly recognized and acknowledged. As crises continue to grow as the result of climate change and increased human pressure, moving toward a more proactive risk-management capability, using real-time drought monitoring and forecasting at all scales, will help enhance water security, increase national resilience, and reduce international conflict.

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