ARIZONA DROUGHT MONITORING

Gregg M. Garfin *
Climate Assessment for the Southwest (CLIMAS), University of Arizona, Tucson, Arizona, USA

1. INTRODUCTION

Arizona is located in the heart of the southwestern United States' "drought alley". Located between 31.2°-37.0° N, under the influence of the subtropical high, tucked between polar and subtropical jet streams, in the shadow of coastal ranges that wring heavy precipitation out of the winter westerlies, and at the northern limit of the North American Monsoon, most of the state has a pronounced bimodal precipitation peak, and high interannual variability influenced by the El Niño-Southern Oscillation (Sheppard et al., 2002). Moreover, the state is prone to multi-year and multi-decade drought, as a result of long-term variations in Pacific Ocean circulation (Schneider and Cornuelle, 2005; Brown and Comrie, 2004; 2002), and, perhaps, Atlantic Ocean circulation (McCabe et al., 2004).

Arizona, like most U.S. states, developed a drought plan in response to a drought crisis that was impossible to overlook. Between September 2001 and August 2002, Arizona logged 12 consecutive months of below average statewide precipitation; statewide precipitation was also below average during 12 out of the following 13 months. Drought impacts during 2002 included the 468,638 acre Rodeo-Chediski fire (at the time, the most widespread and severe fire in Arizona's history), reduction of rangeland cattle by ~50%, water shortages in rural communities, and the loss of 80% of endangered Sonoran pronghorn antelope herds (Bright and Hervert, 2005). In March 2003, Arizona's incoming governor convened a drought task force (DTF), and entrusted the DTF to develop a drought plan in one year, with the following mission (Governor's Drought Task Force, 2004):

- Timely and reliable monitoring of drought and water supply conditions in the state and an assessment of potential impacts;
- An assessment of the vulnerability of key sectors, regions, and population groups in the state and potential actions to mitigate those impacts;
- Assisting stakeholders in preparing for and responding to drought impacts, including development of a statewide water conservation strategy and public awareness program.

In this paper I review progress in developing and implementing Arizona drought monitoring; this review serves as a follow-up to Jacobs et al. (2005). I briefly mention methods and changes that have been implemented since fall 2004. I focus on unique aspects of Arizona drought monitoring, including local and county-level drought impacts reporting and citizen stewardship and science programs. I also provide brief overview of current and planned research and implementation of online drought monitoring tools, arising from the 2005-06 annual review and report to Arizona's Governor.

* *Corresponding author address:* Gregg M. Garfin, CLIMAS, The University of Arizona, 715 N. Park Ave. (2nd Fl.), Tucson, AZ 85721-0156; e-mail: gmgarfin@email.arizona.edu

2. DROUGHT MONITORING

2.1 *Background*

Drought monitoring is the backbone of drought preparedness, as envisioned in Arizona's operational drought plan. Formed during the summer of 2003, the Arizona drought monitoring technical committee (MTC) consists of representatives from state agencies (Arizona Department of Water Resources, Arizona Division of Emergency Management, Arizona State Lands Department), federal agencies (NOAA-National Weather Service, USGS-Water Resources Division, USDA-Natural Resources Conservation Service [NRCS]), private agencies (Salt River Project), and university programs (CLIMAS/University of Arizona, Office of the State Climatologist/Arizona State University, Arizona Meteorological Network [AZMET]). Since fall 2004, the MTC has provided monthly drought status reports to the director of the Arizona Department of Water Resources. The MTC also provides technical advice to an Interagency Coordinating Group charged with advising the Governor on emergency declarations, funding needs, and improvements to the operational drought plan.

Two unique aspects of Arizona's operational drought plan include:

- a three-person Statewide Drought Program, housed at the Arizona Department of Water Resources (ADWR),
- and Local Drought Impact Groups (LDIGs) – voluntary, county-level citizens groups tasked with communication of drought impact information to the MTC, and with developing and coordinating local drought preparedness, mitigation, and response efforts, including drought plans.

The MTC coordinates closely with both of these groups, as described later in this review.

2.2 *Methods*

The Arizona MTC drought monitoring philosophy was developed in consultation with the National Drought Mitigation Center. The MTC had the benefit of evaluating efforts by many other U.S. states. The MTC strives to monitor drought in a timely and regular manner, providing as much early warning as possible when going into drought, and with a degree of caution and extra assurance when coming out of drought conditions. The MTC monitors, and conveys to stakeholders, drought status in three ways, as follows:

(1) objective multi-indicator drought status calculation for large geographic regions, using a limited number of indicators that meet rigorous data quality and length-of-record requirements; (2) indicator variable data reports and interpretation (in layperson-friendly language) for a wider array of indicators and forecasts; (3) evaluation of short period of record and/or subjective indicators and drought impacts reports. An indicator is defined as a quantity that reflects drought conditions, such as streamflow. A trigger is defined as specific values of the indicator that initiate and terminate each drought status level.

Objective drought status is calculated using a modified version of a method developed for the Georgia Drought Plan (Steinemann and Cavalcanti, 2006). The original method, described below, has been augmented, based on two years of experience; changes to the method are described in section 3. Drought status is calculated for large regions, U.S. climate divisions (Guttman and Quayle, 1996), in order to gain perspective on the state's overall drought condition, with some indication of coarse spatial variation. Climate divisions (CDs) were selected (Figure 1), because CD data are easily accessible and temporally continuous (monthly resolution), with no missing data. Drought status is associated with suggested mitigation and response actions, such as residential and industrial water restrictions, depending on the level of drought severity (Governor's Drought Task Force, 2004). Drought severity levels (also called "triggers") were chosen in consultation with the National Drought Mitigation Center and the DTF executive committee. The DTF executive committee's primary concerns were ease of implementation and interpretation of drought status; thus, the MTC chose 4 drought trigger levels and one "no drought" status level (Table 1).

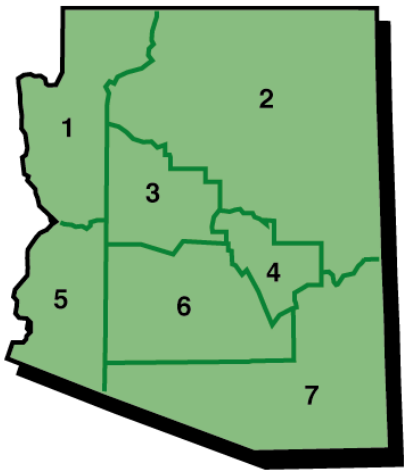

Figure 1. Arizona Climate Divisions.
http://www.ncdc.noaa.gov/img/onlineprod/drought/az.gif

Status	Description	Indicator Percentiles
0	No Drought	40.1-100.0 %
1	Abnormally Dry	25.1-40.0 %
2	Moderate Drought	15.1-25.0 %
3	Severe Drought	5.1-15.0 %
4	Extreme Drought	0.0-5.0 %

Table 1. Arizona Drought Trigger Levels.

Short-term drought status (≤ 1 year) is based on percentiles of 3-, 6-, and 12-month SPI (McKee et al.,1995). Long-term drought status (> 1 year) is based on percentiles of 24-, 36-, and 48-month SPI, streamflow from selected gages (personal communication, Chris Smith, USGS Arizona Water Science Center), and reservoir status (U.S. Bureau of Reclamation) for Arizona climate division 1, which has a tourism and recreation industry strongly affected by changes in reservoir levels.

The SPI, streamflow, and reservoir data are measured using different metrics and scales. In order to render the data ready for operational comparison, the raw data are first converted to percentile rankings. These rankings are then converted to drought status levels (0-4) for each indicator; the resulting drought status levels are averaged to determine the final drought status. The drought status levels are subject to two criteria, depending on whether drought status is getting more severe ("going in") or whether it is ameliorating ("going out"). When drought status is getting more severe, the final level must increase in severity for 2 months before the MTC increases drought status. When drought status is getting less severe, the final level must decrease in severity for 4 months before the MTC decreases drought status. These criteria were chosen to reduce the chances of rapid shifts in drought status, which make it difficult to implement drought management actions.

2.3 Evaluating Calculated Drought Status

In 2004, the MTC evaluated the aforementioned system of indicators and triggers in two ways: (a) by expert stakeholder assessment, and (b) by subjective assessment of the MTC members. A small cross-section of stakeholders (n = 10) from the cooperative extension, wildlife management, tourism, municipal management, water resources management, and land management sectors compared data and subjective observations from their operations, for the period 2000-2004, with hindcast drought status, using the objective method described above for the climate divisions relevant to their operations. The MTC garnered written assessments from the stakeholder participants, as well as holding a workshop and discussion. The participants' assessments accorded well with calculated monthly

drought status over the evaluation time period; long-term drought status provided a particularly good match with stakeholder assessments. It should be noted that the stakeholder evaluations were conducted at a time when drought status, especially water supply conditions, was still quite severe (Figure 2).

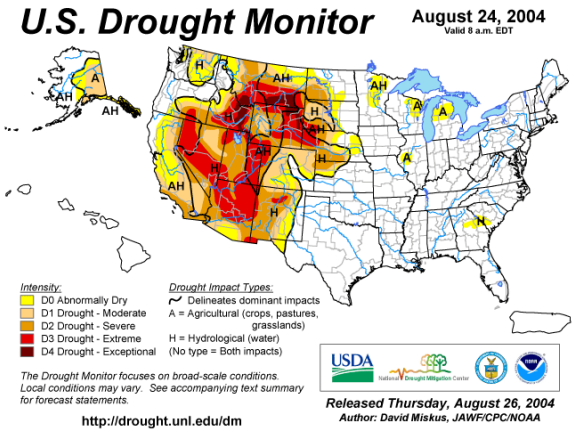

Figure 2. U.S. Drought Monitor for August 24, 2004, portrays Arizona drought status when stakeholders and the MTC evaluated the Arizona drought status calculation system.

The subjective analyses conducted by the MTC members evaluated different combinations of lag factors applied to *going in* and *going out* drought status. Lag factor combinations included everything from 0 lag going in to 6 month lag going out. The MTC noted a reasonable correspondence between calculated drought status using a 2-month *going in* lag, and a 4-month going out lag. Longer *going out* lags resulted in exceedingly slow change in drought status; shorter lags resulted in changes deemed too rapid. The calculated status seemed to accord particularly well with well known wet and dry periods (the wet 1982-83 El Niño episode, the wet early 1990s, dry conditions during the late 1980s and mid-1990s, the wet 1997-98 El Niño, and fire, rangeland, water resources, and wildlife impacts [catalogued from news reports] as drought got more severe between 1999-2004). The MTC noted some disparities between calculated drought status and observed winter conditions during particular years, primarily due to (a) the occasional lack of correspondence between snow observations and SPI in the drought status calculations and (b) a lack of spatial specificity inherent in use of CD data. For the wet and snowy winter of 1998, there was a lack of correspondence between short-term SPI indicators and snow water equivalent (SWE) data for CD 4, primarily due to the influence of 12-month SPI (relatively dry) in the short-term calculations. For the dry winter of 1986, short-term drought status, based on SPI (showing non-drought or abnormally dry conditions) was under-calculated when compared with percentiles of SWE. Similarly, short-term drought status was under-calculated (moderate drought; level 2) for the relatively snow-less winter of 1981 (subjectively estimated status, level 4); again, SPI-12 substantially influenced the calculation. Given the relatively few disparities, the committee agreed to use the 2-month *going in* and 4-month *going out* lags for drought calculation.

3. IMPLEMENTATION AND ADJUSTMENTS

Since October, 2004, when the state began implementation of the Arizona Drought Preparedness Plan, the MTC has made several adjustments to drought calculation and presentation of drought status information. Initially, the MTC reported drought status only to the director of the Arizona Department of Water Resources (ADWR). However, in 2005, the Legislature appropriated funding to the ADWR for a Statewide Drought Program. The funding enabled ADWR to enhance its drought website, and to provision a small staff for the purpose of implementing various aspects of the drought plan and coordinating drought communication. Beginning in 2006, the MTC monthly drought status reports have been displayed on the ADWR Statewide Drought Program website (http://www.azwater.gov/dwr/drought/DroughtHome.html). The drought status reports include maps of calculated short- and long-term drought status, as well as reports on individual indicators, including temperature, precipitation, reservoir levels, streamflow, mountain snowpack and precipitation, vegetation health, and NOAA seasonal temperature, precipitation, and drought forecasts. The Statewide Drought Program website also includes information on the Interagency Coordinating Group, Local Drought Impact Groups (described below), a program to garner drought planning information from Arizona water providers (as mandated in 2005 Arizona legislation), and resources for stakeholders.

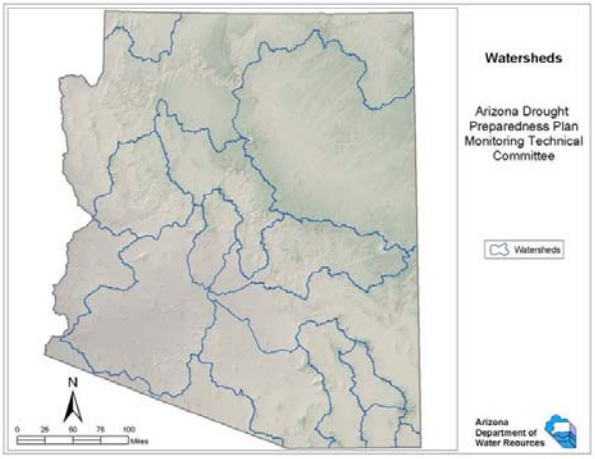

Figure 3. Arizona surface watersheds. Figure courtesy of Andy Fisher, Arizona Department of Water Resources.

Extreme temporal variability in precipitation between the institution of the drought plan and the present created drought monitoring challenges, and allowed the MTC to evaluate and fine-tune the objective drought status calculations. These two years were characterized by a wet, but spatially variable, 2004-2005 winter, the

exceedingly dry fall and winter of 2005-2006, and the intensely wet 2006 Arizona summer monsoon season. The MTC determined that the 2-month lag built into the going in status poorly portrayed the rapid amelioration of short-term drought conditions during winter 2004-05 and summer 2006. Thus, the MTC removed the lag from short-term drought status depiction. In response to stakeholder suggestions, the MTC adopted the use of 16 surface watersheds (Figure 3), in contrast to 7 CDs, as the spatial level of analysis to portray drought status. The watershed depiction makes for more rational combination of streamflow and meteorological data. As mentioned above, the MTC consults a variety of short-term and subjective drought indicators, in order to corroborate calculated drought status, and to assess drought status on a finer spatial scale, if necessary. During the course of the last 2 years, the MTC has adjusted the calculated drought status twice (June, 2005; September, 2006); reports from county extension and resource conservation agents provided drought impact assessment information that was critical to the drought status adjustments. Figure 4 shows typical Arizona monthly drought status maps, and Figure 5 shows the weekly U.S. Drought Monitor map associated with roughly the same time period.

4. LOCAL DROUGHT IMPACT GROUPS

The Arizona Drought Preparedness Plan recommends that each county form drought impact groups, with the goals of garnering drought impact information for the monitoring technical committee, particularly on the economic and societal impacts of drought; coordinating drought response and mitigation efforts; and developing mitigation and response strategies, including identification of resource needs, and regional/county/municipal drought plans. All of the aforementioned activities are voluntary. The Plan specifies that county cooperative extension and county emergency management lead and coordinate the LDIG development process.

The Statewide Drought Program began LDIG implementation during autumn 2005, with a pilot project in southeastern Arizona's Cochise County. Cochise County was selected, because it did not emerge from moderate to severe drought status during the 2004-05 winter, which was relatively wet throughout most of the state. Members of the MTC, including CLIMAS, the National Weather Service, and the state climate extension specialist, have been active partners in implementing the LDIGs. Initial LDIG meetings were difficult and sometimes confusing; however, once the program focused on the potential economic, legal, and environmental stewardship benefits of developing LDIGs, county and municipal officials, and other interested parties, including resource management agencies and NGOs participated. The pilot LDIG effort was probably helped by two factors, (1) the Plan did not specify regulatory mandates, and (2) drought conditions were prevalent during the initial phases of the process.

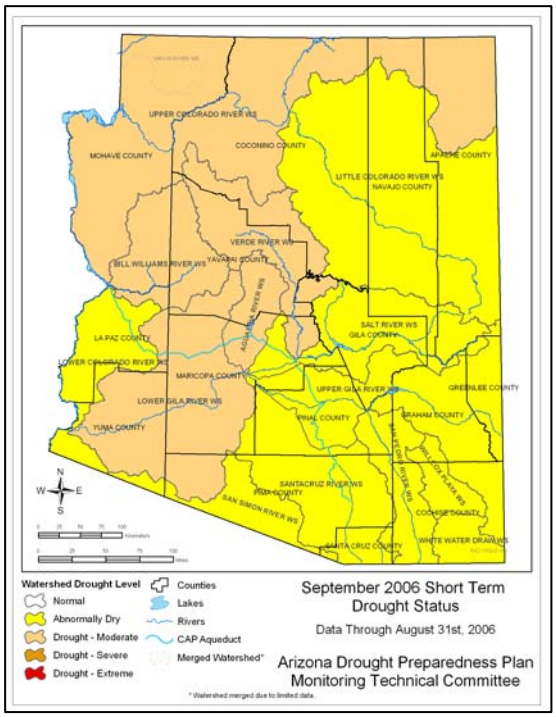

Figure 4. Short-term (top) and long-term (bottom) Arizona monthly drought status as portrayed by the Arizona Drought Monitoring Technical committee. Data are complete through August 31, 2006.

Decisions made early in the process by Cochise County LDIG leaders provided a model for development

of LDIGs in other counties. The first key decision was specification of the size and composition of a steering committee. Cochise County LDIG members recommended 9 steering committee members, composed of representatives of government, emergency management, key stakeholder groups (water providers, farm service agency), and interested citizens. Six steering committee members are selected by the County Board of Supervisors, and three members are elected at large. All committee meetings are open to the public, although only committee members have voting status. Another key leadership decision was to form three committees to conduct LDIG business: (1) education and outreach; (2) drought planning and coordination; (3) drought monitoring.

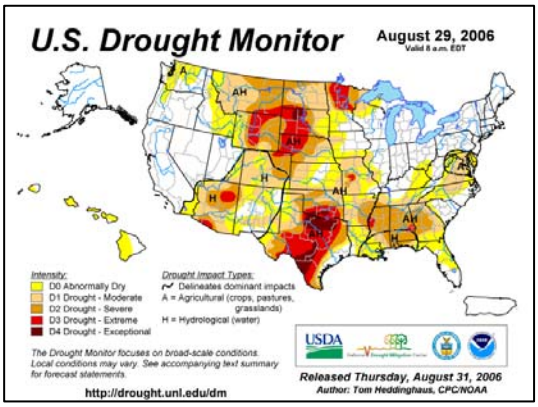

Figure 5. Weekly U.S. Drought Monitor status for the time period corresponding to Figure 4. U.S. Drought Monitor Data are complete through August 29, 2006.

CLIMAS and Cooperative Extension, along with stakeholders in the Cochise LDIG monitoring work group, worked closely to develop a system for reporting and recording drought impacts. After several iterations, the partners decided to report impact status relative to previous conditions, with the option of specifying economic or other impact information. The list of impacts followed the model of the Colorado Drought Plan, and was tailored to Arizona stakeholder needs through successive refinements. Arizona Cooperative Extension, in collaboration with the University of Arizona's Office of Arid Lands Studies (OALS) has developed a prototype web interface for volunteers to input impacts data (http://java.arid.arizona.edu/ccdis/). Impacts to be reported by LDIG volunteers include the status of seeps, springs, and stock ponds; range impacts, ecological impacts (such as vegetation condition of indicator species, wildlife habitat, etc.); water table declines (including subsidence); soil conditions, and others. Project partners, including Extension, OALS, CLIMAS, the NSF DIREnet project at Northern Arizona University (http://www.mpcer.nau.edu/direnet/), and the State Climatologist have submitted a proposal to develop a more robust user interface and capabilities to display drought impacts information. In addition, Dr. Abe Springer of Northern Arizona University is developing protocols for monitoring seeps and springs for drought early warning; the MTC plans to incorporate Springer's methods in LDIG activities.

A separate effort by Cooperative Extension and the NSF Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas at the University of Arizona (SAHRA) helped spur the monitoring activities along. These partners developed a citizen weather monitoring project called RAINLOG (www.rainlog.org), to garner precipitation and drought observations. RAINLOG distributes plastic rain gauges to willing participants; the participants can log their precipitation totals and remarks daily through a user-friendly web interface. Software calculates simple statistics (e.g., cumulative precipitation) and displays precipitation totals and statistics through a map interface. Funding for the project has been provided by SAHRA, Cooperative Extension, and Salt River Project. Several television stations have co-sponsored the website through the enthusiastic participation by their broadcast meteorologists.

Two major challenges facing the MTC are (a) the incorporation of LDIG drought impact information into Arizona MTC monthly reports, and (b) interpretation of LDIG drought impact reports. These issues will require methodological innovations, because some of the data are qualitative, reporting may be sporadic, and RAINLOG data observations use non-standard gages, gage heights, and time of reporting. However, literature on the use of historical documents to reconstruct past climates may provide methodological insights (e.g., Casty et al., 2005; Pfister, 1992; Wigley et al., 1986, 1985). In the interim, as initial LDIG impact data begin to accumulate, CLIMAS, Arizona Cooperative Extension and other partners have initiated a series of workshops to build the capacity of citizens to understand drought monitoring issues, reporting methods, and web-based tools and information pertaining to drought. Until rigorous methodologies are developed, the MTC intends to use the LDIG drought reports to corroborate calculated drought status, and to provide near real-time updates of drought impacts and environmental conditions.

5. PLANS FOR THE FUTURE

The MTC and Statewide Drought Program (SDP) have ambitious plans to improve Arizona drought monitoring, drought information, and outreach to the public. The MTC and SDP are in the process of submitting an annual report and recommendations for improvements to the Arizona Drought Preparedness Plan to the Governor and Arizona Legislature. Among the recommendations are the following:

- *Improvements to the network of observations.* Recommended improvements include implementing soil moisture monitoring, expansion of the SNOTEL network within

Arizona (especially in northwestern and southeastern Arizona), expansion of meteorological observation networks to include more high elevation meteorological stations, expansion of meteorological observation networks to include more observations in the Colorado Plateau region of northern Arizona, and expansion of streamflow gauge networks.

- *Monitoring Technical Committee membership.* The MTC recommends expanding membership to include natural resource land management agencies and native nations and tribes.
- *Groundwater monitoring.* The Arizona Department of Water Resources is in the process of developing a network of operational drought monitoring groundwater wells. ADWR plans to enhance its network of near-real-time transducer-equipped groundwater monitoring wells. The aforementioned will require extensive testing and data analysis.
- *Trigger and indicator sensitivity analysis.* The MTC recommends a rigorous and systematic analysis of drought indicators and triggers used to calculate monthly drought status. The sensitivity analysis will follow the methods of Steinemann and Cavalcanti (2006), and will include assessment by stakeholders, as well as comparison with drought impacts information garnered from natural resource land management agency databases and newspaper reports.
- *Improved drought monitoring tools and web resources.* The MTC and SDP, in conjunction with existing efforts by the Arizona Flood Warning System (ADWR, Salt River Project, and others) and Arizona Hydrologic Information System (SAHRA), are working to implement a drought data information system, including decision support tools for stakeholders. The first phase of this activity includes the adoption of South Carolina's dynamic drought index tools, and improvements to the LDIG drought impact reporting system web site.

In addition to the aforementioned, CLIMAS, Arizona Cooperative Extension and other partners plan to conduct additional capacity-building workshops, to enhance the ability of Arizona stakeholders to use MTC monthly drought reports and various online drought information tools. Workshops will be modeled after annual capacity building engagements with the Arizona Hydrological Society and the Southeastern Arizona Ag Day & Trade Show (see http://www.ispe.arizona.edu/climas/conferences.html for more information).

ACKNOWLEDGMENTS

The author would like to acknowledge the contributions of the Statewide Drought Program (Arizona Department of Water Resources), the members of the Arizona Drought Monitoring Technical Committee, and the University of Arizona contributors to the US Drought Monitor. This abstract is a summary of collaborations between the aforementioned entities during the last two years. The SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) NSF Science and Technology Center at the University of Arizona developed the Rainlog web site. Programmers at the University of Arizona Office of Arid Lands Studies developed the Drought Impacts Reporting System for the Local Drought Impact Groups. Funding for the CLIMAS portion of this work comes from the NOAA Climate Program Office and from a TRIF grant through the Arizona Water Sustainability Program administered through SAHRA.

REFERENCES

Bright, J. L. and J. J. Hervert, 2005: Adult and fawn mortality in Sonoran pronghorn. *Wildlife Society Bulletin*, **33(1)**, 43–50.

Brown, D.P. and A. C. Comrie, 2002: Sub-regional seasonal precipitation linkages to SOI and PDO in the Southwest United States. *Atmospheric Science Letters*, **3**, 94-102.

Brown, D. P. and A. C. Comrie, 2004: A winter precipitation 'dipole' in the western United States associated with multidecadal ENSO variability. *Geophysical Research Letters*, **31**, doi:10.1029/2003GL018726.

Casty, C., H. Wanner, J. Luterbacher, J. Esper, and R. Bohm, 2005: Temperature and Precipitation Variability in the European Alps Since 1500. *International Journal of Climatology,* **25(14)**, 1855-1880.

Governor's Drought Task Force (Arizona), 2004: Arizona Drought Preparedness Plan: operational drought plan. Phoenix, Arizona Department of Water Resources, 34 pp. (http://www.azwater.gov/dwr/drought/files/Arizona_Drought_Preparedness_PlanFINAL100804.pdf)

Guttman, N.B. and R.G. Quayle, 1996: A historical perspective of U.S. climate divisions. *Bulletin of the American Meteorological Society*, **77(2)**, 293-303.

Jacobs, K. L., G. M. Garfin, B. J. Morehouse, 2005: Climate Science and Drought Planning: The Arizona Experience. *Journal of the American Water Resources Association*, **41**, 437-445.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt, 2004: Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Sciences*, **101(12),** 4136-4141.

McKee, T.B., N.J. Doesken, and J. Kleist, 1995: Drought monitoring with multiple time scales. Preprints, *9th Conference on Applied Climatology*, Dallas, TX, American Meteorological Society, 233–236.

Pfister, C., 1992: Monthly temperature and precipitation patterns in Central Europe from 1525 to the present: a methodology for quantifying man made evidence on weather and climate. In: Bradley R.S., Jones P.D. (eds.), *Climate since 1500 A.D.*, pp. 118-143. London.

Schneider, N. and B. D. Cornuelle, 2005: The Forcing of the Pacific Decadal Oscillation. *Journal of Climate*, **18**, 4355-73.

Sheppard, P.R., A.C. Comrie, G.D. Packin, K. Angersbach and M.K. Hughes, 2002. The climate of the Southwest. *Climate Research*, **21**, 219-238.

Steinemann, A. C., and L. F. N. Cavalcanti, 2006: Developing multiple indicators and triggers for drought plans. *Journal of Water Resources Planning and Management,* **132(3)**, 164-174.

Wigley, T.M.L., N.J. Huckstep, A.E.J. Ogilvie, G. Farmer, R. Mortimer, and M.J. Ingram, 1985: Historical climate impact assessments. In: R.W. Kates, J.H. Ausubel and M. Berberian (eds.), *Climate Impact Assessment: Studies of the Interaction of Climate and Society*, SCOPE Publication 27. London: John Wiley and Sons, pp.529-563.

Wigley, T.M.L., G. Farmer, and A.E.J Ogilvie, 1986: Climate reconstruction using historical sources. In: A. Ghazi and R. Fantechi (eds.), *Current Issues in Climate Research*. Dordrecht: D. Reidel Publ. Co., pp. 97-100.