



# Applied climatology: drought

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## I Introduction

By linking climatic variations with the fundamental biological requirement of water availability, drought is a primary topic within applied climatology. Drought acts as a unifying climatological approach that provides valuable information for agricultural, ecological, and hydrological applications. While a lack of water is straightforward to comprehend and appreciate, a wide array of approaches are used in the analysis of drought. However defined, drought can be thought of as an extended period of time where water availability is lower than expected or needed.

With growing population and resource pressures, as well as a number of severe and ongoing droughts worldwide, this is an active time for drought research. There has been a wide range of recent developments in drought research that include near real-time monitoring, improved drought reconstructions via proxies, and high-resolution simulations of future drought conditions. Although proxy records of drought continue to play an important role in the characterization of drought conditions, this brief report will focus on three topics within drought research that are most relevant to applied climatology: (1) modern drought monitoring using instrumental products, (2) impacts of recent

climatic change on drought variability, and (3) modeling of modern and future drought. In all cases, a selection of the recent literature on precipitation variations and associated drought conditions is reviewed, synthesized, and critiqued.

## II Modern drought monitoring and analysis

Despite a number of well-documented limitations (Guttman *et al.*, 1992; Heim, 2002; Keyantash and Dracup, 2002), the Palmer Drought Severity Index (PDSI) continues to be a central approach in drought monitoring. The PDSI is useful because it (1) incorporates cumulative anomalies of both moisture supply and demand and (2) has recognized categories of moisture deficit and surplus, even though the categories themselves are somewhat obscure. Use of the term 'PDSI' also can be somewhat ambiguous, as there are a number of different formulations, including recent contributions that allow spatial comparisons to be more meaningful (Wells *et al.*, 2004) and that improve the identification of drought onset (Rhee and Carbone, 2007).

The complexity and limitations of the PDSI – primarily its lack of spatial and temporal stationarity, which make spatial comparisons difficult and change-detection

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problematic – has led to the use of a number of alternative methods. These alternatives are as simple as the percent of long-term precipitation or as sophisticated as the Standardized Precipitation Index (SPI; McKee *et al.*, 1993), which is straightforward and has a more substantial statistical foundation than the PDSI. The SPI applies a transformation to non-normal precipitation distributions so that quantiles on the fitted distribution can be directly related to the same quantile on a normal distribution (for which an associated *z*-score can be determined). Although the SPI is based solely on precipitation variations at a given location, and therefore does not include terms for bi-climatic water demand, the PDSI and nearly all other measures of drought are driven primarily by precipitation variations. That is, potential evapotranspiration usually is less variable than precipitation. This supposition may need to be revisited, however, in light of recent and future climatic change.

A number of recent products now provide weekly or monthly drought monitoring using both the PDSI and SPI, such as the USA Drought Monitor (Wilhite *et al.*, 2005; <http://www.drought.unl.edu/dm/monitor.html>) and the North American Drought Monitor (Lawrimore *et al.*, 2002). While these mostly graphical products are useful for monitoring droughts as they occur, they could be made more valuable by providing long-term, consistent data sets that can be used for subsequent research. The North American Drought Monitor, for instance, provides a few drought indices for Alaska, Canada, and Mexico at the station level, whereas areas within the continental USA have only course-resolution divisional data available. Climate-division data provide complete spatial and temporal coverage (ie, there are no missing data since climate-division data are derived from averaging data from multiple stations), but they lack spatial specificity and the changing numbers and distributions of stations within the divisions can induce spurious trends

(Keim *et al.*, 2005). Divisional data have a long history, nonetheless, and monthly PDSI values continue to be calculated over the 344 climate divisions in the contiguous United States (available from 1895 to the present at <http://www1.ncdc.noaa.gov/pub/data/cirs/>).

Gridded data are a potential improvement over the use of artificial climate divisions and Dai *et al.* (2004) have produced a gridded, monthly data set of PDSI from 1870 to 2002 over global land areas (updated through 2005; <http://www.cdc.noaa.gov/cdc/data.pdsi.html>). Although the  $2.5^\circ \times 2.5^\circ$  latitude/longitude grid chosen by Dai *et al.* (2004) is useful for assessing large-scale variations in drought, the coarse resolution limits the utility of these data for regional analysis. There are a number of spatial interpolation methods that could produce reliable drought data sets derived from instrumental records at much higher spatial resolution (Daly *et al.*, 2002; Jolly *et al.*, 2005; Robeson and Ensor, 2006). In addition, continental- or global-scale data sets that include satellite-derived products (Peters *et al.*, 2002; Ji and Peters, 2003; Bayarjargal *et al.*, 2006; Anderson *et al.*, 2007) or that use downscaling methods (eg, Liang *et al.*, 2006; Benestad *et al.*, 2007; Schoof *et al.*, 2007) would be a welcome addition to drought analysis and research. Widely available reanalysis data sets (eg, Mesinger *et al.*, 2006) have great potential for adding to the analysis of historical drought variability and they are just starting to be used for these purposes (Mo and Chelliah, 2006).

### **III Recent climatic change and drought conditions**

In terms of recent climatic change and its implications for drought, temperature and precipitation variations have been well studied and documented (IPCC, 2007). Nonetheless, there still are a number of unresolved questions regarding data quality and the attribution of temperature and precipitation change to specific causes, such as

the proportion of change due to greenhouse gases, aerosols, land-cover change, etc (eg, Davey and Pielke, 2005; Hale *et al.*, 2006). Even given a warming climate, most droughts are dominated by precipitation variations rather than temperature effects, although the two tend to be closely coupled over continental land areas during summer (Trenberth and Shea, 2005). Further, evapotranspiration over land is closely related to precipitation variability over land (Qian *et al.*, 2006); therefore terrestrial precipitation change with time is the most direct driving force when interpreting drought variability. As such, a brief summary of recent research on precipitation variability is given below.

The analysis of precipitation over global land areas continues to be an active research area (Chen *et al.*, 2002; Mitchell and Jones, 2005; Smith *et al.*, 2006). These studies, along with ongoing precipitation monitoring at climate research centers, such as the National Climatic Data Center and the Climatic Research Unit, have recently been reviewed under the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007). For that report, the primary focus was on linear trends in terrestrial average precipitation; however, most of the data sets have non-linear trends with time, so linear trend estimates are not always meaningful over the period of record. The lack of consistency of precipitation estimates between these data sets and in the AR4 analysis demonstrates the complexity of monitoring precipitation. Yet, at the same time, the inconsistencies are somewhat remarkable given that terrestrial and annual averaging is being performed. Spatial and temporal averaging tends to produce precipitation estimates that become more reliable with greater levels of aggregation (Willmott *et al.*, 1996).

In addition to studies that estimate linear trends with time, research results that derive functional relationships from instrumental and satellite observations are particularly valuable. The Clausius-Clapeyron equation,

for example, shows that saturation vapour pressure increases by about 7% for every 1°C increase in temperature; however, global precipitation has been expected to increase at about half that rate (Allen and Ingram, 2002; Huntington, 2006). Recent estimates of the rate of change of precipitation with respect to changes in temperature (made directly from satellite observations), however, show that precipitation is increasing at nearly the same rate as the Clausius-Clapeyron relationship predicts (Wentz *et al.*, 2007). Whether this pattern continues for decades to come has profound implications for the global water cycle and drought variability.

While global and terrestrial precipitation averages – and their response to temperature change – are of inherent scientific interest, spatial patterns of precipitation trends are even more informative. As with the global averages, most regions have variations over the 1901–2005 period that are not easily summarized by linear trends (IPCC, 2007). Southwestern North America, for instance, has a mix of positive and negative trends in annual precipitation over the 1901–2005 period (IPCC, 2007), yet has experienced an extended, if intermittent, recent drought. For most regions, what is more relevant than the annual average is the variation in seasonality of precipitation which, when combined with temperature changes, drives changes in drought duration and intensity (Andreadis and Lettanmaier, 2006). Even with changing precipitation and temperature distributions, many regions that are now experiencing drought have experienced stronger and longer droughts in the recent past (Cook *et al.*, 2007), illustrating how increases in water use tend to exacerbate modern drought conditions (Pielke *et al.*, 2005).

#### **IV Simulations of future drought**

Using models to understand and detect the response of the climate system to perturbations – such as those due to variations in CO<sub>2</sub> or aerosols – is a primary theme in modern climatological research. The primary method

used to study these changes is numerical modeling, particularly global and regional climate models (GCMs and RCMs). As a result, there have been a number of recent studies that use climate models to estimate the sensitivity of drought to various scenarios of future atmospheric conditions. As with recent climatic change, drought is a useful and convenient concept in the study of future climates, as it synthesizes the thermal and hydrologic components of the climate system. There is generally an expectation of an 'enhanced' or 'energized' hydrologic cycle due to increases in greenhouse gases. Increasing concentrations of greenhouse gases generally act to increase the moisture-holding capacity of the atmosphere and, thereby, increase the rates of both evapotranspiration and precipitation on a global scale (Huntington, 2006). There are a number of complicating factors, however, such as large-scale circulation changes and alterations in local convection due to greenhouse-gas induced feedbacks, land-cover change, and space-time variability of aerosols. The mix of forcings and possible responses certainly calls for the use of complex models, but the results of these studies must continue to be viewed with caution, as precipitation in particular is one of the most poorly modeled GCM variables.

Meteorological drought has been assessed in the Hadley Centre GCM (HadCM3) using the PDSI, showing that greenhouse gases and aerosols both have an influence on a recent drying trend (Burke *et al.*, 2006). When the model is used with scenarios of future atmospheric emissions, some regions become 'wetter' and some 'drier', but the net effect is a trend towards substantial increases in extreme drought. The magnitudes of the simulated results are staggering: the proportion of the land surface in 'moderate', 'severe', and 'extreme' drought is predicted to increase from 25%, 10%, and 1% in these three categories currently to 50%, 40%, and 30% by the end of the twenty-first century.

Using multimodel ensembles and annual precipitation minus evapotranspiration (P–E) as the metric of drought, Seager *et al.* (2007) also find substantial model-based drying in southwestern North America during the twenty-first century. Interestingly, Seager *et al.* (2007) separated the overall modelled P–E change into three separate components, with contributions from moisture divergence, mean circulation, and transient eddies. The majority of the increase in drought conditions in the GCMs is due to mean circulation changes, with the Hadley Cell extending poleward – a model result that is physically consistent with our understanding of transient greenhouse-gas-induced climatic change. The interaction between transient eddies and mean circulation changes is perhaps the most uncertain component of both modern and future drought in southwestern North America – and most of the middle and high latitudes.

While it behoves us to use models to estimate future variations in the water cycle, such simulations are still at a rudimentary stage. While simulations using RCMs provide higher spatial resolution and resolve fine-scale processes related to precipitation intensity and type more clearly than GCMs (Leung *et al.*, 2004), profound processes that alter precipitation patterns and associated feedbacks continue to be identified (Pan *et al.*, 2004). Many of these relevant processes still are not included – or are not well modelled – by current climate models. Changing CO<sub>2</sub> concentrations, for instance, induce physiological effects on plants, which in turn alter rates of evapotranspiration. Many of these effects have not been included in global-scale simulations in meaningful ways. Betts *et al.* (2007), for instance, demonstrate that, relative to pre-industrial levels, doubled CO<sub>2</sub> concentrations increase global runoff by 6%, due to plant stomatal controls. The profound impacts of these physiological mechanisms, their interaction with large-scale atmospheric circulation, land-cover

change, and associated feedbacks, are largely unexplored in the context of twenty-first-century water dynamics. In addition, greenhouse gases other than CO<sub>2</sub> do not have the same physiological impact, so the primary focus of the climate community on radiative forcing of greenhouse gases – and not on the physiological (or other) effects – may be illustrative of our lack of sophistication in simulating future climate conditions.

## V Final comments

As a persistent and sometimes extreme form of climatic variability, drought has far-reaching implications and continues to be a vital topic of research. As documented in this brief progress report, considerable advances in drought monitoring, analysis, and modeling are being made. For many key drought indicators, however, there still are limited analyses of temporally extensive and spatially high-resolution databases. Analyses of these developing high-quality databases (Mo and Chelliah, 2006; Mesinger *et al.*, 2006) are essential for addressing questions related to the specific nature of historical drought variability. As reported here, observed trends and variations in precipitation and drought have been described extensively; however, we know much less about the expected values of these quantities. Analysis of expected variations in drought – under both natural variability and changing climatic conditions – can be derived from physically based models or historical variability of drought measures, but should include both spatial and temporal aspects of expected drought variability. Multivariate assessments of drought duration, intensity, and severity also are useful contextual approaches (González and Valdés, 2006). Only through the careful assessment of the spatial and temporal distributions of drought conditions, and by including all relevant bioclimatic processes, can we fully understand current and future droughts and place them in their proper context.

## References

- Allen, M.R.** and **Ingram, W.J.** 2002: Constraints on future changes in climate and the hydrological cycle. *Nature* 419, 2224–32.
- Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.A.** and **Kustas, W.P.** 2007: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology. *Journal of Geophysical Research* 112, D11112, DOI: 10.1029/2006JD007507.
- Andreadis, K.M.** and **Lettenmaier, D.P.** 2006: Trends in 20th century drought over the continental United States. *Geophysical Research Letters* 33, L10403, DOI: 10.1029/2006GL025711.
- Bayarjargal, Y., Karnieli, A., Bayasgalan, M., Khudulmur, S., Gandush, C.** and **Tucker, C.J.** 2006: A comparative study of NOAA-AVHRR derived drought indices using change vector analysis. *Remote Sensing of Environment* 105, 9–22.
- Benestad, R.E., Hanssen-Bauer, I.** and **Førland, E.J.** 2007: An evaluation of statistical models for downscaling precipitation and their ability to capture long-term trends. *International Journal of Climatology* 27, 649–65.
- Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H.** and **Webb, M.J.** 2007: Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* 448, 1037–42, DOI: 10.1038/nature06045.
- Burke, E.J., Brown, S.J.** and **Christidis, N.** 2006: Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology* 7, 1113–25.
- Chen, M., Xie, P.** and **Janowiak, J.E.** 2002: Global land precipitation: a 50-yr monthly analysis based on gauge observations. *Journal of Hydrometeorology* 3, 249–66.
- Cook, E.R., Seager, R., Cane, M.A.** and **Stahle, D.W.** 2007: North American drought: reconstructions, causes, and consequences. *Earth-Science Reviews* 81, 93–134.
- Dai, A., Trenberth, K.E.** and **Qian, T.** 2004: A global data set of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5, 1117–30.
- Daly, C., Gibson, W.P. Taylor, G.H. Johnson, G.L.** and **Pasteris, P.** 2002: A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22, 99–113.
- Davey, C.A.** and **Pielke, R.A. Sr** 2005: Microclimate exposures of surface-based weather stations – implications for the assessment of long-term

- temperature trends. *Bulletin of the American Meteorological Society* 86, 497–504.
- González, J.** and **Valdés, J.B.** 2006: New drought frequency index: Definition and comparative performance analysis. *Water Resources Research* 42, W11421, DOI: 10.1029/2005WR004308.
- Guttman, N.B., Wallis, J.R.** and **Hosking, J.R.M.** 1992: Spatial comparability of the Palmer Drought Severity Index. *Water Resources Bulletin* 28, 1111–19.
- Hale, R.C., Gallo, K.P., Owen, T.W.** and **Loveland, T.R.** 2006: Land use/land cover change effects on temperature trends at USA Climate Normals stations. *Geophysical Research Letters* 33, L11703, DOI: 10.1029/2006GL026358.
- Heim, R.R.** 2002: A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society* 83, 1149–65.
- Huntington, T.G.** 2006: Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319, 83–95.
- IPCC** 2007: *Climate change 2007: the physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
- Ji, L.** and **Peters, A.** 2003: Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. *Remote Sensing of Environment* 87, 85–98.
- Jolly, W.M., Graham, J.M., Michaelis, A., Nemani, R.** and **Running, S.W.** 2005: A flexible integrated system for generating meteorological surfaces derived from point sources across multiple geographic scales. *Environmental Modelling and Software* 20, 873–82.
- Keim, B.D., Fischer, M.R.** and **Wilson, A.M.** 2005: Are there spurious precipitation trends in the United States Climate Division database? *Geophysica Research Letters* 32, L04702, DOI: 10.1029/2004GL021985.
- Keyantash, J.** and **Dracup, J.A.** 2002: The quantification of drought: an evaluation of drought indices. *Bulletin of the American Meteorological Society* 83, 1167–80.
- Lawrimore, J., Heim, R.R., Svoboda, M., Swail, V.** and **Englehart, P.J.** 2002: Beginning a new era of drought monitoring across North America. *Bulletin of the American Meteorological Society* 83, 1191–92.
- Leung, L.R., Qian, Y., Bian, X., Washington, W.M., Han, J.** and **Roads, J.O.** 2004: Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change* 62, 75–113.
- Liang, X.-Z., Pan, J., Zhu, J., Kunkel, K.E., Wang, J.X.L.** and **Dai, A.** 2006: Regional climate model downscaling of the USA summer climate and future change. *Journal of Geophysical Research* 111, D10108, DOI: 10.1029/2005JD006685.
- McKee, T.B., Doesken, N.J.** and **Kleist, J.** 1993: The relationship of drought frequency and duration to time scales. In *Preprints, 8th Conference on Applied Climatology, 17–22 January, Anaheim, CA*, Boston, MA: American Meteorological Society, 179–84.
- Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P.C., Ebisuzaki, W., Jovíæ, D., Woollen, J., Rogers, E., Berbery, E.H., Ek, M.B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D.** and **Shi, W.** 2006: North American Regional Reanalysis. *Bulletin of the American Meteorological Society* 87, 343–60.
- Mitchell, T.D.** and **Jones, P.D.** 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25, 693–712.
- Mo, K.C.** and **Chelliah, M.** 2006: The modified Palmer Drought Severity Index based on the NCEP North American Regional Reanalysis. *Journal of Applied Meteorology and Climatology* 45, 1362–75.
- Pan, Z., Arritt, R.W., Takle, E.S., Gutowski, W.J. Jr, Anderson, C.J.** and **Segal, M.** 2004: Altered hydrologic feedback in a warming climate introduces a ‘warming hole’. *Geophysical Research Letters* 31, L17109, DOI: 10.1029/2004GL020528.
- Peters, A.J., Walter-Shea, E.A., Ji, L., Vina, A., Hayes, M.** and **Svoboda, M.D.** 2002: Drought monitoring with NDVI-based standardized vegetation index. *Photogrammetric Engineering and Remote Sensing* 68, 71–75.
- Pielke, R.A. Sr, Doesken, N., Bliss, O., Green, T., Chaffin, C. Salas, J.D., Woodhouse, C., Lukas, J.L.** and **Wolter, K.** 2005: Drought 2002 in Colorado – an unprecedented drought or a routine drought? *Pure and Applied Geophysics* 162, 1455–79, DOI: 10.1007/200024-005-2679-6.
- Qian, T., Dai, A., Trenberth, K.E.** and **Oleson, K.W.** 2006: Simulation of global land surface conditions from 1948 to 2004. Part I: Forcing data and evaluation. *Journal of Hydrometeorology* 7, 953–75.
- Rhee, J.** and **Carbone, G.J.** 2007: A comparison of weekly monitoring methods of the Palmer Drought Index. *Journal of Climate* 20, 6033–44.
- Robeson, S.M.** and **Ensor, L.A.** 2006: Daily precipitation grids for South America (Comment). *Bulletin of the American Meteorological Society* 87, 1095–96.
- Schoof, J.T., Pryor, S.C.** and **Robeson, S.M.** 2007: Downscaling daily maximum and minimum temperature in the Midwestern USA: a hybrid empirical approach. *International Journal of Climatology* 27, 439–54.

- Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.-P., Harnik, N., Leetmaa, A., Lau, N.-C., Li, C., Velez, J. and Naik, N.** 2007: Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316, 1181–84.
- Smith, T.M., Yin, X. and Gruber, A.** 2006: Variations in annual global precipitation (1979–2004), based on the Global Precipitation Climatology Project 2.5° analysis. *Geophysical Research Letters* 33, L06705, DOI: 10.1029/2005GL025393.
- Trenberth, K.E. and Shea, D.J.** 2005: Relationships between precipitation and surface temperature. *Geophysical Research Letters* 32, L14703, DOI: 10.1029/2005GL022760.
- Wells, N., Goddard, S. and Hayes, M.J.** 2004: A self-calibrating Palmer Drought Severity Index. *Journal of Climate* 17, 2335–51.
- Wentz, F.J., Ricciardulli, L., Hilburn, K. and Mears, C.** 2007: How much more rain will global warming bring? *Science* 317, 233–35.
- Wilhite, D.A., Svoboda, M.D. and Hayes, M.J.** 2005: Monitoring drought in the United States: status and trends. In Boken, V.K., Cracknell, A.P. and Heathcote, R.L., *Monitoring and predicting agricultural drought: a global study*, Oxford: Oxford University Press.
- Willmott, C.J., Robeson, S.M. and Janis, M.J.** 1996: Comparison of methods for estimating time-averaged precipitation using data from the USA. *International Journal of Climatology* 16, 1103–15.

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