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Drought and the California Delta—A Matter of Extremes

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> "And it never failed that during the dry years the people forgot about the rich years and during the wet years they lost all memory of the dry years. It was always that way."
>
> —John Steinbeck, *East of Eden*, 1962

California is in an extreme drought as a result of low precipitation in water year 2012, record low precipitation in 2013, and the remarkably dry first few months of 2014. We typically receive our largest precipitation totals in Decembers and Januaries (which provide about 36% of the precipitation in the Delta's catchment), and when those months are as dry as they were this year, subsequent months have to be unseasonably wet to avoid drought. Most of the current winter, especially December 2013–January 2014, was dry because a persistent ridge of high (atmospheric) pressures set up offshore, diverting storms away from California and into Alaska. That same diversion gave the Delta's catchment its warmest winter in 120 years, as well as bringing all that cold weather to the eastern US. While the February 2014 storms provided minor relief and momentarily slowed the spiral into deeper drought, the drought continues apace. Nonetheless, as harsh as it is, the current drought is not unprecedented in the Delta's history, and even less so in its prehistory. In this essay, we consider the ways that droughts in California arise from a few missing storms and from long-term variations and changes in climate, in order to identify drought-science needs for Delta management.

First, it is worth noting that, in the broadest sense, a drought is just "insufficient water to meet needs" (Redmond 2002), with a lot of ambiguity in that word "needs." For example, the current drought has reached the stage of being, to greater or lesser extents, a meteorological (precipitation), hydrological (streamflow), ecological, agricultural, municipal, and regional drought with groundwater, electrical-power, and regulatory overtones. Understanding, tracking, and predicting the progress of this drought and future droughts through all these dimensions is a too-neglected scientific arena that demands understanding across a wide range of time scales.

Drought is a familiar occurrence in California. Indeed, at a year-to-year or shorter time scale, California has a remarkably variable hydroclimate, experiencing larger year-to-year variations in precipitation than elsewhere in the U.S., with standard deviations of annual precipitation between 30% to 50% of long-term averages, compared to 10% to 30% nearly everywhere else (Dettinger et al. 2011). California's annual precipitation totals routinely vary from as little as 50% to greater than 200% of long-term averages, with those dry excursions forming our

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droughts. In large part, this extreme variability arises from the small number of storms that provide most of the state's precipitation each year. If a few large storms happen to bypass California in a given winter, precipitation totals are proportionally much reduced and we risk drought. Those few large storms are particularly important because droughts in California, and nationwide, almost always begin gradually—as month-by-month precipitation deficits build up—but tend to end abruptly in a single very wet month (about 70% to 80% of the time in California; Dettinger 2013). Those wet, drought-busting months are typically reflections of one or two extremely large storms, with almost half of the large drought-busting storms resulting from landfalling atmospheric rivers or "pineapple expresses." Improvements in forecasting the character and frequency of those crucial large storms, on time scales ranging from a week ahead to seasons ahead, could provide much needed early warnings for managers of drought effects in the Delta.

On longer year-to-year and decade-to-decade time scales, drought variations in parts of California are influenced by a variety of ocean–atmospheric interactions, including the well-known El Niños and La Niñas (acronymed as "ENSO"; e.g., Cayan and Webb 1992) and other less well known modes ranging from the 30- to 60-day tropical Madden–Julian Oscillation (MJO; Guan et al. 2012) to the 30- to 60-year Pacific Decadal and Atlantic Multidecadal oscillations (PDO and AMO, respectively; McCabe et al. 2004). However, most of the Delta's catchment lies astride a mid-latitude zone where there is no net average effect of ENSO and PDO on drought (Cayan and Webb 1992; McCabe et al. 2004). That is, some El Niños (or warm PDO years) bring some of the wettest years to the Delta, but others bring drought, so that they are not reliable predictors in the Delta (McCabe et al. 2004). Distant Atlantic influences are poorly understood and MJO effects appear only occasionally.

Nonetheless, observational and tree-ring records provide credible indications of potentially important regularities in the history of droughts in the Delta. Precipitation in the Delta's catchment shows drought episodes about every 15 years (brown bars and black curve, Figure 1A) throughout the 20th century, with the current drought falling more or less "on schedule" on this time scale. Note that the approximate 15-year time scale of these fluctuations means that they are not readily ascribed to ENSO cycles (with their about 3- to 7-year time scale), to PDO or AMO (with about 30- to 60-year time scales), nor, to our knowledge, to vagaries of MJO. Even more notably, on this time scale, the fluctuations arise almost entirely from large variations of the contributions to precipitation from our largest storms (red curve, Figure 1A) rather than more "normal" storms (green). Even more specifically, the quasi-decadal fluctuations of the past 60 years follow very closely the fluctuating numbers of pineapple-express landfalls on California's coast (Figure 1B), re-emphasizing the crucial need to understand California's most extreme storms (like pineapple expresses) even in the context of drought. In California's wild hydroclimate, droughts and extreme storms are thoroughly intertwined.

We are not arguing that this 15-year drumbeat of droughts in the 20th century is some reliable long-term predictor of future drought years. Nonetheless, its regularity is tantalizing, and is not restricted to the brief instrumental periods of the 20th Century. It also shows up in a variety of tree-ring reconstructions from central and northern California, and is a recurring feature of drought reconstructions for the past 500 years (e.g., St. George and Ault 2011, among others). However, before about 1500 AD in recent streamflow reconstructions for the Central Valley (Meko et al. 2014), both this 15-year variation and variations on the PDO scale become, at best, intermittent in California tree-ring records, so that there are no guarantees that such "cycles" will always be there.

The mechanism behind the approximate 15-year drumbeat of drought in the Delta's catchment is a research challenge that has been neglected. But the great benefits that could be obtained from understanding and ultimately predicting drought varia-

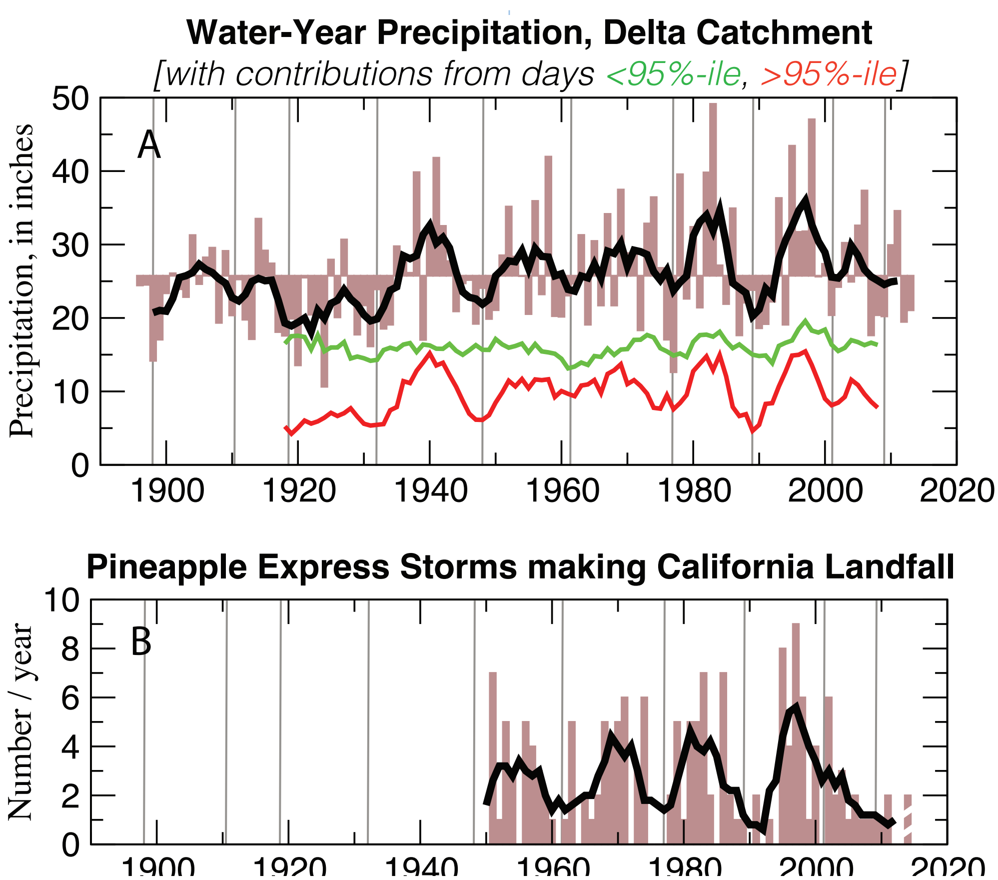

Figure 1 **(A)** Water-year precipitation totals (brown bars and black curve) in the Delta's catchment, 1895–present based on updated monthly Abatzoglou et al. (2009) data, and 5-year moving averages of contributions to these totals from the wettest 5% of wet days (days with precipitation >95th percentile; red curve) and all other wet days (<95th percentile; green curve) based on updated daily Hamlet et al. (2005) data, 1916–2010, and **(B)** numbers of pineapple-express storms making landfall between 35°N and 42.5°N per water year (using counts from Dettinger et al. 2011, updated through March 2014). Heavy curves are 5-year moving averages in both frames; vertical grey lines are approximate centers of persistent droughts in upper panel.

tions in the Delta's catchment should be motivation enough to undertake the difficult and, frankly, potentially unrewarding research needed to uncover the nature of these slow and seemingly regular drought variations in the Delta's catchment, in this area where the usual suspects (ENSO/PDO) fail.

In addition to this decadal character of drought in California's prehistory, paleoclimatologists find strong evidence—in sources ranging from tree-ring widths to lacustrine and riverine deposits to entire submerged or buried tree stumps—of several 60- to 100-year-long and extremely severe "mega-droughts" during the past 2,000 years (Stine 1994). They also find evidence that the Delta's 20th Century drought regime was more benign than in almost any comparable length of time during the past two millennia (Ingram and Malamud–Roam 2013). Thus, it appears that the droughts that California has managed historically have only been examples of "the easy stuff." Consequently, developing a realistic perspective on the kinds of droughts that our plans for the Delta need to accommodate requires a better understanding of prehistoric droughts, and this is going to require more complete paleo-records and studies throughout the Delta's watershed.

Collectively, these historical and prehistorical lessons provide a necessary but incomplete framework for thinking about the Delta's future droughts. Climate change is busily rewriting drought landscapes around the world, including here in California. Warming of California's climate is already happening, and additional warming in the future is essentially certain, even if we all stopped emitting greenhouse gases tomorrow. Proportionally, more precipitation is already falling as rain rather than snow, and snowpacks are melting earlier in the year. These warming-induced changes alone are propelling us into a future with more runoff arriving during cool seasons (when demand for water is less and the desire for flood-control space behind our dams is greatest) and less runoff in warm seasons (when demands for water are large and likely to grow with warming temperatures). Warming-induced increases in evaporation also may reduce the amount of runoff and recharge from each unit of precipitation that falls (Cayan et al. 2010). Thus warming alone would be enough to aggravate California's potential for hydrological, ecological, and other drought impacts. Notably, in this context, this winter was about +2 °C warmer than 20th century normal in the Delta's catchment, or analogous to average winter conditions being projected for about 50 years from now (Cayan et al. 2013). Thus, this particular drought may offer special lessons about Delta droughts under climate change.

Along with warming, future precipitation in the Delta's catchment is rendered increasingly uncertain under climate change by projections of potential disruptions of the intensities and rates of arrival of storms to feed the estuary (Polade et al. 2014), especially in the San Joaquin Valley (Cayan et al. 2013). For some perspective, recent projections of streamflow in the latter half of the 21st century yielded "critically dry" water years 8% more often (than in 1951–2000) in the Sacramento Valley and 32% more often in the San Joaquin Valley (Null and Viers 2013). Thus, droughts are projected to become more frequent and more severe with climate change. To plan for these changes, we need to more fully explore and quantify what projections of 21st century climate change imply about droughts in the Delta and, especially, about the many dimensions of drought there. Notably, the deep connection between extreme storms and drought in California indicated previously suggest that this quantification will need to address more than "just" average precipitation changes.

To be clear: Projected droughts in current climate-change projections still pale alongside the very real possibility of a naturally occurring relapse into medieval mega-drought conditions. Thus, climate change does not mean that we can ignore lessons from the past. Nonetheless, climate change is an element of our drought future that we can predict more confidently than those mysterious mega-droughts, and so remains an issue we also cannot afford to ignore.

RECOMMENDATIONS

The current drought raises issues across the time scales. It certainly was aggravated by near-term weather conditions that held strong winter storms at bay this winter, and, if history is any guide, only the arrival of some very large storms will fill the deficits that it has formed. The lack of major storms in the past several years is roughly in keeping with the slow quasi-decadal drumbeat of California's largest storms and droughts over the past several hundred years. But is this the beginning of a mega-drought? Will the El Niño that appears to be developing in the tropical Pacific necessarily end this drought? Is it the result of climate change? These questions are pressing, but the answer in each case is "probably not, but time will tell." Two or three years into this drought is far too early to draw such conclusions. It is, however, high time to recognize that these possibilities are quite real, and need to be part of plans and decision-making in the Delta. So, to better inform decision-making, several pressing science needs have been identified:

- Improved knowledge, monitoring, and prediction of the development, spread, and decline of Delta droughts in all their natural and societal dimensions.

- Expanded collection, understanding, and use of paleoclimatic records.
- More complete projections of the Delta's future drought regime under climate change.
- Better tracking, forecasting, and integration of the large drought-busting and drought-preventing storms into near-term drought responses and planning.
- Improved understanding of long-term variations of our largest storms, which dictate the occurrence of droughts here (see Figure 1), as a basis for quantifying drought risks and recurrences.

In dealing with droughts, Delta science programs draw on a large and vibrant science and engineering community from a variety of agencies and institutions. However, externally funded drought-science and climate-science programs exist—programs targeted specifically at making modern climate and drought information directly applicable and actionable for California—that could help move forward the science needs listed above. For example, the California-Nevada Climate Applications Program (*http://cnap.ucsd.edu/*) under NOAA's Regional Integrated Science and Assessments program focuses on human dimensions of climate applications. The new Department of the Interior-funded Southwest Climate Science Center (*http://www.swcsc.arizona.edu/*) is focused somewhat more on landscape and ecosystem issues. Pilot studies of the National Integrated Drought Information System (*http://www.drought.gov/drought/regional-programs/california/california-home*) are now underway in California, with a focus on developing early warning for droughts and drought management. California's ongoing program of biennial Climate Change Assessments (*http://climatechange.ca.gov/climate_action_team/reports/climate_assessments.html*) offers strong climate-change emphases. Thus far, Delta science efforts have mostly paralleled rather than directly engaged with these kinds of programs, but the current drought should be a great incentive and opportunity for more engagement to tackle the drought-science challenges that Delta management efforts face.

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