Changes in Aridity in the Western United States

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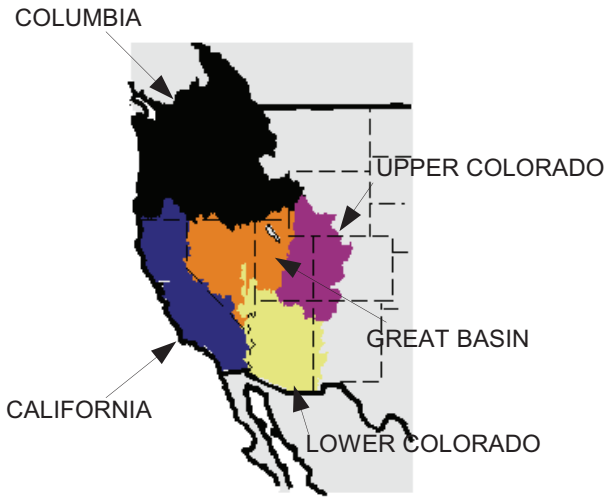
August 2007

Introduction

It is often remarked that most of the western US (Figure 1) is "always in drought," especially by visitors from wetter climates. The plants and landforms of the West, however, are more or less adapted to the region's relatively dry but variable climates, and so important variations in the levels of drought, or aridity, characterize the landscape. During "real" droughts, broad areas of the West are subjected to drier conditions than normal, imposing—at least temporarily—arid climatic conditions on many semiarid and even humid areas. In response to these climatic conditions, the hydrologic balances between waters that run off and those that evaporate back into the atmosphere are transformed temporarily in ways that color the entire region's water supplies and vegetation. In this article, we describe the major changes that droughts wreak on the "normal" partitioning of precipitation between evaporation and runoff, as depicted by a hydrological model that simulates historical variations of the region's surface hydrology.

Actual evapotranspiration (AET) is the combined flux of water to the atmosphere from soil surfaces and plants by evaporation and through plants by transpiration. AET depends on the availability of both water and energy. Potential evapotranspiration (PET) is the atmospheric demand of water from the soil and free water surfaces, and represents the amount of evapotranspiration that would occur if water were not a limiting factor. A body of previous research has demonstrated that there are well-defined connections between droughts and the ratio of AET/PET in the western US. This ratio is called evaporative efficiency or ß. Extremely low values of are common in arid regions where PET is high and lack of water limits AET rates. High values of ß occur in semi-humid and humid regions (usually at the top of the mountains in the West), where energy availability limits AET rates. Intermediate values of ß, when the annual demand for water is considerably higher than the supply of water but not as strong as in the arid regions, occupy the largest part of the western US; these regions are classified as "water limited" and include areas that are often described as semi-arid.

Figure 1.
Location of principal "basins" of the western US



"Green water" is a name given to AET by Falkenmark and Rockström (2004), with "blue water" the name given to the remaining fraction of water that is not consumed by evapotranspiration (P-AET). Blue water is thus the water that runs off into streams or recharges into aquifers. A key point in this article is how drought shifts the flow of water from blue to green. Even as it shifts water from blue outflows to green uses, in most cases, drought reduces the overall availability of water for evapotranspiration in a region, lowering the AET efficiency along with the total AET. This results in temporary increases in the aridity (as measured by ß) in the drought-affected region. Thus during a drought, regions that are semiarid on long-term average can experience hydroclimatic conditions similar to the ones normally found in arid regions. Similarly, during droughts, regions in which AET is energy-limited, on long-term average, can become water limited (or even extremely water-limited). The temporary increase in aridity of a region can have severe impacts on ecological systems in general, wildfire potential and soil erosion. This article also investigates the geographic extend of the changes in aridity conditions during droughts and pluvials.

VIC Model and Data Sources

Hydrological fluxes and conditions simulated by the Variable Infiltration Capacity (VIC) macroscale land-surface hydrological model--originally developed at the University of Washington and Princeton (Liang et al. 1994)--provide the raw materials for the results presented here. VIC has been used extensively in a variety

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of water resources applications; from studies of climate variability, forecasting and climate change studies (e.g. Wood et al. 1997; 2004; Hamlet et al. 1999; Nijssen et al. 1997; 2001). The model's soil moisture estimations produce reasonable agreement with the few point measurements available, while VIC-simulated runoff validates well with observations when the model has been calibrated using streamflow data, giving us confidence that VIC results provide a useful depiction of how drought changes the area's water budgets. Daily AET values were obtained directly from the model's output while PET was computed from net radiation and relative humidity from VIC, and temperature and windspeed from the Hamlet and Lettenmaier (2005) dataset, using a Penman-Monteith equation (Penman 1948; Monteith 1965) as described in Shuttleworth (1993). For each gridpoint, PET was estimated as the weighted sum of the daily contributions from all vegetation types, including bare soil. The period of the simulations used here are from 1950 to 2003.

AET Efficiency

A classification of the West into regions with long-term average energy-limited, water-limited and extremely water-limited AET conditions is shown in Figure 2a. A limit of ß=0.63 was used as the threshold between energy-limited and water-limited AET regions in this article, because it corresponds empirically to western settings where annual-mean P is equal to annual-mean PET (Hidalgo et al. 2007). Regions with less than 0.2 are labeled regions of extremely water-limited or arid regions, according to Rind et al. (1990) and Hidalgo et al. (2007). With these definitions, energy-limited areas are located mainly in the high elevations of the West and in the coastal regions of Washington, Oregon and Northern California, accounting for 19% of the western US. Water limited regions fall in between the energy limited and arid regions, and occupy the largest fraction (51%) of the region. Most of the southern deserts, the low elevations of the Upper Colorado River Basin (UCRB) and the rain shadowed parts of Washington are classified as arid, accounting for 30% of the region.

From year to year, though, application of these same thresholds indicate large variations in the extents and locations of the three ß categories, as can be seen in the aridity maps for the 2002 drought and the 1983 pluvial (Figures 2b-c). In the drought-year 2002, low ß values, low enough to fall into the arid category, expanded to occupy 51% of the region, indicating widespread aridity conditions similar to those normally found in deserts. Conversely, in the wet year 1983, the arid category was reduced to only 15% of the West, and energy-limited conditions spread to 29% of the West.

The long-term ß regions shown in Figure 2a experience (and reflect) different long-term average seasonal cycles of hydroclimate (black curves, Figure 3). Precipita-

Figure 2.
Annual distribution of areas with energy-limited evapotranspiration (black), water-limited evapotranspiration (white) and extremely water-limited or arid regions (yellow).

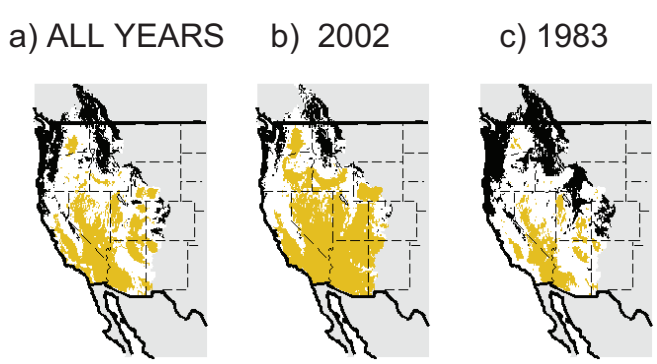
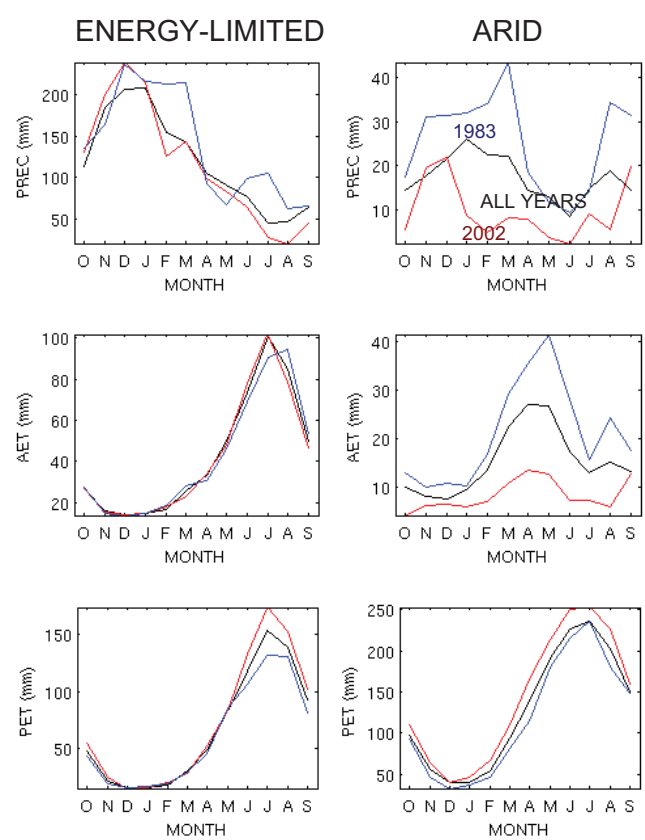


Figure 3.
Climatologies of precipitation (P), actual evapotranspiration (AET), and potential evapotranspiration (PET) for regions of high AET/PET ratios. The climatologies were computed using the regions defined in Figure 2a.



tion (Figure 3, top panels) and runoff (not shown) are considerably larger in the energy-limited regions and tend to continue until later in the year. The energy-limited regions tend to exhibit later AET peaks (Figure 3, middle panels) because water persists in the soils longer from the greater spring-summer soil-moisture reserves of wintertime snow. Although PET is somewhat higher in the arid and semi-arid regions than in the energy-limited regions, the values are still the same order of magnitude as in the water-limited regions. Therefore it is the supply of water that makes the largest difference in determining aridity patterns, while the demand for water by ET plays a secondary but not inconsequential role.

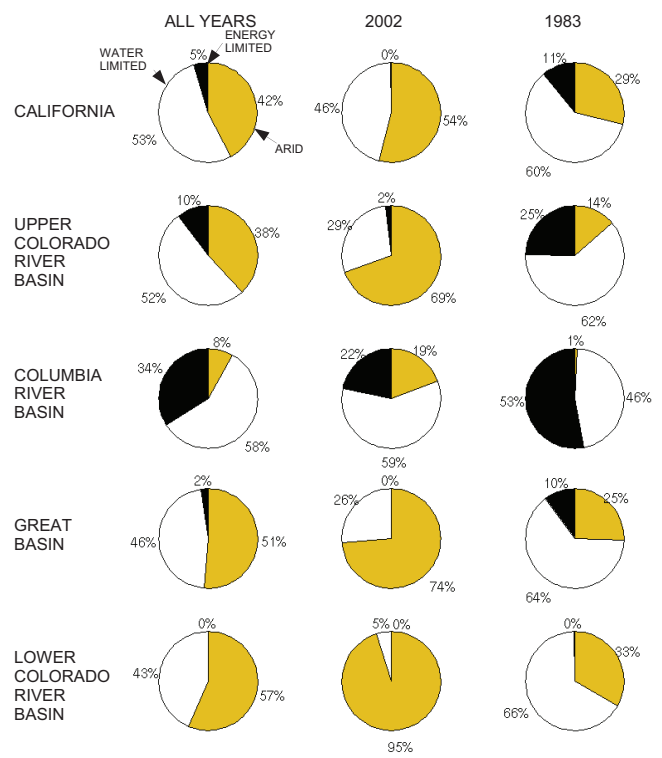
In the energy-limited regions, the effect of drought versus pluvial is evident in AET and PET only during the late spring and summer, because the water budgets can only respond to moisture during the energy-rich warm seasons. In contrast, in the arid regions, moisture availability is a dominant constraint in all seasons and the AET and PET differ all year long from wet to dry years. Only in deep winter do arid landscapes come close to approximating energy-limited in their AET and PET characteristics. However, it is in spring when the AET in arid regions by far most responsive to drought versus pluvial, because this is when water and energy becomes available. Therefore, even in the arid zone, the springtime onset of energy-availability is an important calendar event for determining AET (green water). In a warmer world, will earlier onsets of seasonally warm temperatures (energy-availability) play enough role to change the timing and magnitude of arid zone AET (and its flipside blue water)?

To compare the water budgets of the great river basins in the West, long-term and extreme-year differences between the total areas in the three aridity categories are summarized in Figure 4. On the long term, the Columbia River basin is the most humid region, with the highest percentage of energy-limited areas (34%) and the lowest percentage of arid regions (8%). The Lower Colorado River basin is the most arid region with 57% arid and no energy-limited area. California, in this case the entire state, is largely consumed by water limited (53%) and arid (42%) landscapes with the reminder of about 5% in the energy-limited category. These fractions change dramatically during severe droughts and pluvials. In 2002, areas that are climatologically water-limited became temporarily extremely water-limited (arid) and regions that are climatologically energy-limited became water-limited. During the 1983 pluvial, the opposite occurred and arid and the extent of water-limited regions were sharply reduced. During 2002, drought energy-limited conditions were all but eliminated from all the basins, except the Columbia River basin. The Lower Colorado River basin experienced the largest absolute increase in arid areas (38% of the basin) during the 2002 drought, the Columbia River basin experienced the largest percentage change (138% increase), and California's arid fraction increased to 54% and its energy limited fraction decreased to only 1%. In 1983, the Columbia River Basin experienced the largest absolute increase in energy-limited areas (19% of the basin), the Great Basin presented the highest percentage change (400% increase), and in California it more than doubled to 11% while arid regions dropped to 29% of the total area of the state.

Distribution of Blue and Green Water in the West

Blue water—considered here to be the sum of runoff plus recharge generation at each model grid cell (prior to routing down rivers and aquifers or into various reservoirs)—ranges widely among the western river basins, between 9% of the precipitation supply in the Lower Colorado River basin and over 50% in the Columbia River basin (Figure 5). Green water is the water that evapotranspires (prior to any routing to other

Figure 4.
Average percentages of basin areas in three hydrological conditions: energy-limited AET (black), water-limited AET (white) and extremely water-limited AET or arid (yellow).

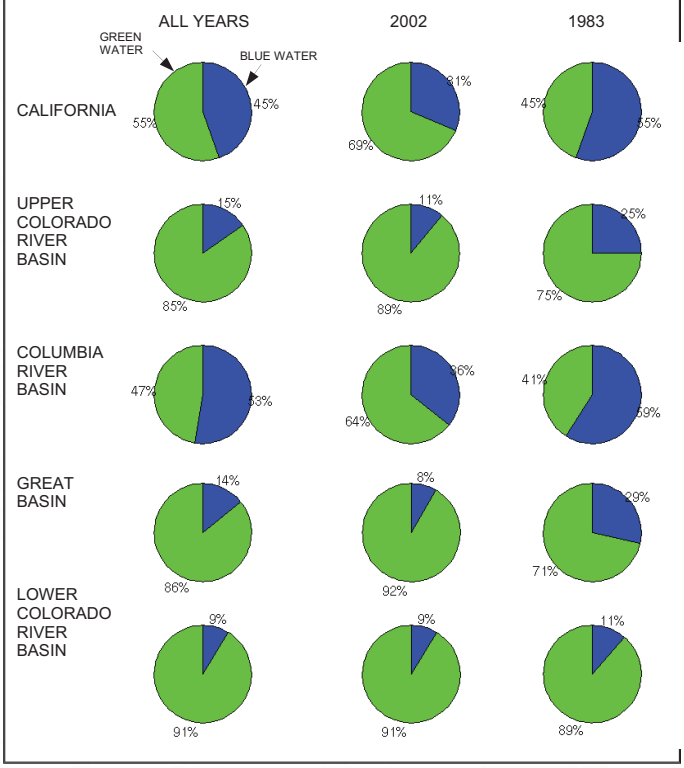


areas) and amounts to the remainder of the precipitation after blue water has been subtracted. The largest sources of blue water in the West are the high-altitude or high-latitude zones of energy-limited AET, so the basins with the largest and wettest energy-limited areas yield the largest fractions of blue water. Blue water is also a higher fraction of the supply of water from precipitation in coastal watersheds along the west coast than in the basins of the interior West. Notably, among the crucial Upper Colorado, California, and Columbia River basins, the (percentage) yields of blue water from the Colorado are significantly less overall than in the other two basins, so that overall the green water fraction from the Upper Colorado River basin: 85% of the total, is more similar to the Great Basin and Lower Colorado Basin deserts than the other major river basins. On average only the Columbia has greater blue water than green water fraction, but during the 1983 pluvial the dominance of the blue water fraction also occured in California. Importantly, the relative fractions of green water increase sharply during drought and decrease during pluvials (Figure 5).

During drought years like 2002, the blue water fractions of the water budgets of the river basins decline, except for the Lower Colorado River basin. The water budget of the Lower Colorado is so arid in the long term that a drought year does not much change the overall (fractional) partitioning between blue and green water yields. The water budget of the Upper Colorado also varies only moderately from the long-term pattern in drought years like 2002. Elsewhere, the drought year 2002 resulted in reductions of the blue-water fractions of about one-third of the long-term blue-water components. These shifts towards smaller fractions of blue water reflect the tendency for runoff and recharge to decline even more in a drought year than does precipitation. The fact that the Colorado River basin (upper and lower) varied less in this regard indicates that runoff effects from droughts in that basin are more proportional (less enhanced relative) to the driving precipitation changes than are runoff effects in other Western basins, largely because so much less of the Colorado runoff comes from energy-limited landscapes. Note, however, that although the Upper Colorado River basin has a higher percentage of energy-limited landscapes than California (Figure 4), on average California has a larger percentage of blue water than the Upper Colorado River basin (Figure 5).

During wet years like 1983, the blue-water fractions of the water budgets increase in all the river basins. The blue-water fractions in the Great Basin increase most (proportionally to long-term fractions) and the blue-water fraction in the Lower Colorado increases least. Notably the blue-water fraction in the Upper Colorado basin increased by about two thirds of its long-term (fractional) contribution. These increases, like the flipside of the drought effects, reflect the tendency for runoff and recharge to increase more, in relative terms, than does precipitation in wet years.

Figure 5.
Average percentages of green and blue water for basins in the western US.



Conclusions

Droughts change the geographic distributions of hydrologic conditions across the West landscape. Arid conditions occupied as little as 15% of the western US landscape in 1983 and swelled to as much as 51% during the 2002 drought. Water supplies, plants and animals adjusted as best they could to drought-pluvial changes—whether of short or long duration--in order to weather the episodic character of historical droughts. The partitioning of whatever precipitation falls between blue water (runoff and recharge) and green water (consumptive use by either evporation or evapotranspiration) also varies with drought and pluvial.

Climate warming, which is already occurring over the West and very likely to be amplified in following decades, may expand extent of arid conditions within the western US. Two separate mechanisms have been suggested: higher evaporation demands in a warmer climate and the

potential for more frequent droughts (Seager et al. 2007). The former would be expected to push western water budgets towards larger green-water fractions and smaller blue-water fractions. On the basis of analyses presented here, any persistent reductions in precipitation might be expected to shift water budgets even more towards less overall blue-water generation and more green-water use, because the blue fractions decline more than the precipitation in drought years. Green-water components of the western water budgets are vital parts of the western landscape and ecosystems but represent components that are largely beyond human uses and management. Thus, increases in green-water demands in a warming world must be viewed, to a certain extent, as necessary evils, not to be stopped unless we want very desolate future landscapes indeed.

Shifts in the mean aridity of the west, associated with climate change, even if small compared to the historical year-to-year variations, will be superimposed onto those kinds of variations. That superposition is likely to yield new extremes, both in the areas subjected to unusual aridity and in the severity of drought episodes, so that future drought extremes may be particularly challenging. Because most western landscapes are adapted to accommodate past drought variability that often has been dominated by short-term drought episodes, a gradual but persistent increase in aridity associated with current projections of climate change may be especially important for the redistribution of the species and desertification.

The responses of the western landscapes to long-term droughts or creeping aridity are not likely to be simple, as illustrated by the multivaried changes shown here. More monitoring of soil moisture and other drought-sensitive variables is needed in order to detect changes, and to some extent avoid unpleasant surprises as the western climate changes in response to increasing greenhouse-gas concentrations in the atmosphere. Better monitoring will also provide foundations for proper improvements in hydrologic models and predictions, and for calibration of remote-sensing observations. Such measurements will be of increasing value as this century unfolds and—in the case of soil moisture--have only recently become feasible for widespread deployment. Given the importance and complexity of drought impacts and the possibility of more frequent and perhaps more intense drought in the future, a proactive approach to monitoring is ever more necessary.

Acknowledgments

We thank Andy Wood, Dennis Lettenmaier and Alan Hamlet at the University of Washington for sharing VIC and VIC input data. This work was funded by the California Energy Commission through the California Climate Change Center at Scripps Institution of Oceanography, by NOAA's RISA program through the California Applications Program, and by DOE.

This paper will also be published as a California Energy Commission report

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