



Climate variability and change in the drylands of Western North America

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ARTICLE INFO

Article history:

Received 24 March 2008

Accepted 28 July 2008

Available online 19 October 2008

Keywords:

Western North America

semi-arid regions

natural and anthropogenic climatic change

climate variability

paleoclimatic reconstructions

drought

ABSTRACT

We argue that it is important to expand the consideration of climate in the context of provision of ecosystem services in drylands. In addition to climate change, it is necessary to include climate variability on timescales relevant to human and ecological considerations, namely interannual to decadal and multidecadal. The period of global instrumental record (about a century and a half long at the very most) is neither an adequate nor an unbiased sample of the range and character of natural climate variability that might be expected with the climate system configured as it is now. We base this on evidence from W. N. America, where there has recently been a major multi-year drought, of a scale and intensity that has occurred several times in the last 2000 years, and on attempts to provide explanations of these phenomena based on physical climatology. Ensembles of runs of forced climate system models suggest the next 50 years will bring much more extensive and intense drought in the continental interior of North America. The trajectory followed by the supply of ecosystem services will be contingent not only on the genotypes available and the antecedent soil, economic and social conditions but also on climate variability and change. The critical features of climate on which patterns of plant growth and water supply depend may vary sharply during and between human generations, resulting in very different experiences and hence, expectations.

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1. Introduction

1.1. Climate, desertification and ecosystem services

It is commonplace to link the degradation of soil and vegetation characteristics of desertification with particular climates. These links have ranged from the taxonomic, in which particular climates are associated with desert conditions (Kottek et al., 2006), to the dynamic, in which the surface conditions of degraded vegetation and soil themselves interact with the atmospheric environment to reinforce the climatic conditions conducive to such degradation (e.g. Charney, 1975).

Neither of these views takes account of the role of humans and other organisms. In contrast, the *Millennium Ecosystem Assessment* (MEA) (2005) takes a more nuanced view, in which desertification is a subset of the possible changes that might occur in a landscape's capacity to provide a range of ecosystem services. In order to explore the range of possible trajectories of the landscape in this context, MEA argues that it is necessary to consider both climate (in this case anthropogenic climate change) and biodiversity loss. Both kinds of change independently and in combination can affect the provision of ecosystem services. Moreover, the ecological change associated with

these two factors will be further influenced by the effects of increasing atmospheric carbon dioxide concentrations on water use efficiency for some plants, and thereby affect the composition and structure of the vegetation. The MEA concluded, with “medium certainty” that, “... although climate change may increase aridity and desertification risk in many areas, the consequent effects on services driven by biodiversity loss and, hence, on desertification, are difficult to predict” (page 18).

We add a further element to this complex picture. In the earlier static views, climates were quantitative descriptions of conditions derived from some period of years, usually thirty, which were assumed to be representative of what might reasonably be expected at that place. In the MEA view, observed and expected climate change is added to this. We aim to convince the reader that it is important to expand the consideration of climate in this context to include climate variability on timescales relevant to human and ecological considerations, namely interannual to decadal and multidecadal.

We base this on what may be the most important finding of the recently burgeoning field of high-resolution Paleoclimatology (Hughes, 2002). This is that the period of global instrumental record (about a century and a half long at the very most) is neither an adequate nor an unbiased sample of the range and character of natural climate variability that might be expected with the climate system configured as it is now. Put another way, patterns of variation have existed in the past 1000–2000 years that have not been seen in the 20th century. Some of these patterns involve extreme climate

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conditions on time scales from interannual to multi-century, particularly droughts, likely to have major ecological and societal impacts were they to recur now. We know no reason why they should not.

2. Western North America as a representative region

2.1. Geography

Western North America is one of the largest contiguous regions of drylands in a highly developed region. As a result of this, it is a useful object for study of the interactions of climate change and climate variability with desertification, because it has been particularly well observed and recorded. The drylands of Western North America contain many kinds of desert vegetation and of desert climate, and numerous examples of the effects of intense resource use. So, they may be considered representative of many situations found around the world.

2.2. Climate teleconnections

Climatic conditions in this region are linked to those of other mid-latitude regions of descending air. Cayan et al. (1998) found decadal variability in precipitation in the Southwestern United States ...“to be aligned with opposing precipitation fluctuations in North Africa” (their page 3148). They discussed specific climatic mechanisms that might lead to this alignment, and indeed might cause decadal-scale variability throughout the dry mid-latitudes. It is also worth noting that such decadal variability accounted for 20–50% of the variance of annual precipitation in Western North America.

2.3. A wealth of natural archives

A further, compelling reason for our focus on Western North America is its extraordinary wealth of developed natural archives of climate variability in recent millennia, including abundant ancient trees growing under climatic stress, geomorphologic features associated with glacier activity and lake level changes, and laminated marine sediments. This permits an unusual degree of cross-checking between completely independent natural archives. The annual resolution and multi-millennial length of many of these records allows them to yield information on climatic fluctuations on all time scales from interannual to multi-millennial.

3. Climate change

There is growing evidence that the climate of the Western U.S. has undergone a number of changes in the last three decades. These include a widespread and substantial decline in precipitation together with sustained warming (Fig. 1), with some amplification of warming trends at higher elevations (Diaz and Eischeid, 2007). These climate trends combine to produce a smaller fraction of precipitation as snow, earlier snowmelt, and changes in stream flow (e.g. Cayan et al., 2001). Warmer summers also contribute to greater evaporative loss. This has resulted in an increase of the area that would meet the Koeppen “desert” classification during a recent severe drought in the region (Fig. 2). Using a multivariable detection and attribution methodology, Barnett et al. (2008, page 1080) demonstrated that “the majority of the observed low-frequency changes in the hydrological cycle...over the western United States from 1950 to 1999 are due to human-caused climate changes from greenhouse gases and aerosols”. They note that the changes already observed “differ in length and strength from trends expected as a result of natural variability...and differ in the specific ways expected of human-induced effects”.

4. Climate variability

4.1. Time scales of variability

Using the instrumental record, climate variability in the Western United States, in particular in precipitation, has been demonstrated to occur on interannual and decadal time scales (Diaz, 1983; Dettinger et al., 1998). This variability exists in the spatiotemporal domain, so that, for example, there are “regional north–south contrasts that appear at many timescales” (Dettinger et al., 1998, page 3109). Much of this variability has been linked to antecedent conditions over the Pacific Basin, for example the El Niño–Southern Oscillation phenomenon on interannual time scales (Bradley et al., 1987; Kiladis and Diaz, 1989), and indices of sea surface temperature on decadal time scales in both the Pacific (Mantua et al., 1997) and Atlantic Oceans (McCabe et al., 2004). These marine influences may interact to modify their expression in the hydroclimate of different parts of the continent (Gershunov and Barnett, 1998). In order to detect the existence of climate variability on longer timescales, multi-decadal to centennial, for example, it is necessary to use the kinds of natural archives mentioned above. Moreover, because of the size of the region (~30° of latitude by ~30° of longitude), it is necessary to first consider the record from sub-regions.

4.2. Paleoclimatic evidence

4.2.1. California and the Great Basin

Giant sequoia (*Sequoiadendron giganteum* (Lindley) Buchholz 1939) tree rings from the western flanks of the Sierra Nevada show variations in the frequency of extreme single year droughts in the Central Valley of California over the last 2100 years (Hughes and Brown, 1992; Brown et al., 1992; Hughes et al., 1996). The incidence of such droughts on a century time scale has varied more than threefold, with highest frequencies in the 3rd and 4th, 8th and 9th, and 15th and 16th centuries. The 20th century frequency was slightly below the 2100 year mean. Not only tree rings show that there is a greater tendency for droughts to be intense and persistent between AD 400 and AD 1600. Stine (1994) identified extreme low stands in Mono Lake, a closed basin on the California/Nevada border, lasting from the early 10th century to the end of the 11th and from the beginning of the 13th to the middle of the 14th, coinciding with droughts seen in the rings of drought-sensitive bristlecone pine (*Pinus longaeva* D.K. Bailey 1970) from the neighboring White Mountains (LaMarche, 1974; Hughes and Graumlich, 1996), in the Sierra Nevada (Graumlich 1993; Graybill and Funkhouser 2000) and in the Great Basin (Hughes and Funkhouser 1998). Stine (1994) inferred that these low stands of Mono Lake resulted from a precipitation deficit of 35% or more over many decades, far more intense and greater in duration than at any time since European settlement in the region. Graham and Hughes (2007) used a completely independent approach to reconstruct the level of Mono Lake for the past 2000 years. They calculated the inflow to the lake from moisture sensitive tree-ring series in the Sierra Nevada. From this they reconstructed natural changes in the level of the lake, which has no outflow, using a water balance model for the lake. They identified two low stands of very similar magnitudes, and duration, to those proposed by Stine (2004) (Fig. 3). Graham and Hughes (2007) attributed the 70–100 years offset between their reconstructed low stands and those described by Stine (2004) partly to problems in their modeling, but “primarily to bias in the calibration of the ¹⁴C ages of the fossil vegetation” (their page 1207). It is notable that these were by far the deepest low stands in their reconstruction, and that their relative timing and depth corresponds so closely to Stine’s observations.

Further evidence that these multidecadal to century-scale features in the tree-ring reconstructions represent real fluctuations in hydroclimate comes from comparison of the tree-ring based reconstruction

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