Question: What lessons can be drawn from comparisons of modern droughts? How have droughts in the last century been influenced by vegetation?

Methods:

Land Cover

Coarse vegetation types were obtained from the University of Maryland vegetation classification scheme via the North American Land Data Assimilation System, accessed online. Predominant classifications were assigned by grid cell based upon the highest fraction between seven land cover types: Bare, Forest, Cropland, Woodland, Grassland, Urban, and Water. If a grid cell was initially classified as Bare and the fractional cover was less than .5, a simple algorithm reclassified the cell as the type with the next largest fractional cover.

Gridded Hydrological Data

The University of Washington National Hydrological Prediction System provided gridded climate data for the period 1915 to 2014. Data were simulated by the variable infiltration capacity (VIC) model at daily time step in the water balance equation, forced with observation station climate, LDAS vegetation, and climatological wind, providing daily values of Actual Evapotranspiration (AET), Precipitation (P), Temperature (T). Potential evapotranspiration (PET) was calculated using the Penman – Montieth equation with the above forcings. AET was subtracted from PET to derive daily moisture deficit (MD). Daily values were aggregated to monthly time steps: average monthly T and monthly totals of P, MD, AET, and PET. 30 year mean and standard deviations were calculated from the period 1961 to 1990 as period climate.

Drought Cores

Water year annual totals of MD by grid cell were derived and standardized with the R function scale (MDAS). Nine drought indices were calculated from a moving window as:

sum ( MDAS i – n > s : MDAS i >s)

Where i is the final year of the window, n is the length (in years) of the window, and s is a threshold standard deviation value. We examined n = 2, 3, and 5, at s = 0, 1, and 2. Comparisons between index values were based upon percentages of total area per year inundated with a drought core of given length and magnitude. We considered number of large scale droughts (greater than 20% coverage), number of distinguishable drought cores (DC), and reduction of time period (with n length drought windows, n-1 years were removed from the beginning of the climate record). Comparisons based upon percent area inundated by drought was augmented by a separate index based upon drought intensity (DI). We characterized DI as the sum of MDAS values in each DC over the various drought windows examined.

Drought analysis by vegetation type

To facilitate comparison of drought cores across regions, we compared climate relationships between coarse vegetation types. We standardized P, T, and MD by month using the R function scale and masked grid cells by the coarse vegetation types noted above. Seasonal autocorrelations (AC) were calculated with lags between 0 and 30 with the R function ACF. AC values were compared with a Kruskal-Wallis H Test with a .05 significance level.

Comparisons to Study Period Climate

Recent literature examines the effects of increasing temperature and variable precipitation on drought and other disturbances. We plotted continuous MD values as a response to cumulative water year P and average water year T, with the T/P coordinates of grid cells inundated by drought superimposed on top in order to visualize the relative effects of T and P on drought cores. Climatic ratios were developed to compare climatic effects between years. These were defined as:

A ratio of T/P of MDAS greater than two to T/P of MD less than 2 was developed to compare the climatic effects on drought severity between years.

The choice of MDAS greater or less than two was used in order to differentiate very severe drought grid cells from severe drought grid cells. In addition, MD values of drought cores were plotted against AET and 30 year MD to visualize characteristics of the areas droughts have affected over the study period.

**RESULTS**

Drought Criteria Selection

After considering various combinations of thresholds and drought lengths, a length of three years and a threshold of one standard deviation away from the period mean. Peak drought periods are revealed regardless of window or threshold; however, our chosen criteria reduces the number of slightly dry periods and highlights the large, severe droughts of the study period (Table 1).

Trends of droughts

~35% of the study area was affected by drought cores over the study period. The first half of the period (1920:1968) saw drought cores primarily in a band extending from the Pacific Northwest towards Texas, with the eastern border of Colorado experienced 6 instances of drought cores during the first half of the century. Drought cores in the second half of the century (1968 : 2014) shifted towards Wyoming, the western Rockies, and California. 2014 in particular was responsible for the majority of the drought cores in California and Utah. The Lake Tahoe region and the area south of the Petrified Forest National Park in Arizona experienced multiple drought cores during the second half of the century.

The 1940s and the 1970s through the 1990s were noticeably wetter then the remainder of the century. Three year droughts were sparse and scattered across the southwest and northwest in the 40s, northeast Montana in the 80s, and the corner of Utah, Idaho, and Wyoming in the 90s.

Spatial characteristics of largest drought cores

The drought cores are the largest spatially in drought windows ending in 1936, 1931, 2002, 2014, 1956, and 1961. We define drought intensity as the sum of normalized anomalies in the drought window. The 9 most intense windows were 2014, 1931, 1936, 1956, 2002, 2013, 1937, 1935, and 1961. We excluded 1937, 2013, and 1935 from further analysis because of their proximity to remarkably intense windows, though they were significant in terms of spatial extent and intensity. The six years selected had the largest area inundated by drought after three years of moisture deficit anomaly greater than 1 standard deviation. Each layer shows the moisture deficit greater than 1 standard deviation after 1 year (the first layer), 2 years (the second layer) and 3 years (the third layer). The total extent of the 2014 drought covers California and the Southwest, but the cores were in the Sierra Nevadas, the LA Basin, and the Great Salt lake. 1936 on the other hand saw drought cores in the northern Rockies, Yellowstone, and the great plains. Anomalous moisture deficit did affect California, Nevada, and Utah during the 1931 drought window, but the core of that drought was in the Pacific Northwest and Idaho.

The 1936 drought began with a large area experiencing severe moisture deficit. Over the course of three years, that area decreased to an area that with much less severe moisture deficit. 2012 began with more severe drought in the Rockies, but as the drought progressed, moisture deficit in Utah and California increased significantly. The eastern side of the 1931 drought core experienced a similar increase of severity, but not to the extent of the 2014 drought.

We were concerned that droughts could not be compared by region, although we had previously standardized each grid cell’s MD against its own 1918:2014 mean. LDAS vegetation maps, though static, were built from vegetation observations in the latter part of the century. We considered these coarse maps sufficient to compare early century and late century vegetation because literature indicates that vegetation changes accelerated post 1970.

The MDAS values in 2014 were driven by higher temperature rather than very low precipitation.

MD, T, and P during largest drought cores

The six droughts can be separating into three groups by their pre-window patterns. 2002 and 1961 begin with annual moisture deficit below the period mean for two years previous to the drought; 1936 and 1956 begin above the period mean, and then begin the drought window high, dip low, then increase slightly through the window; and 1931 and 2014 begin below the period mean at year -4, then slowly increase to the highest md00 at year 0. 2014 displays the greatest moisture deficit anomaly at year 0 and at year -1. Precipitation was depressed during the three-year window for all droughts and the year following year 0 for five of the droughts. Year -3 (2011) saw high variability of precipitation for the 2014 window, though the mean was slightly below the period mean. 2014 developed an upward trend in mean temperature over the drought window unlike the other five droughts. 1931 had a slight upward trend but began with very low temperatures and ended with a mean temperature value at least two points below mean 2014 core temperature.