SENSITIVITY OF SPRING-SUMMER DROUGHT TO WARMING IN MONTANE AND ARID REGIONS

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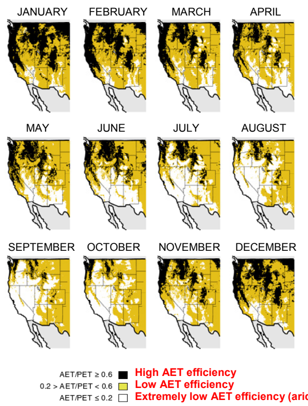
1. The ratio of AET/PET is an indicator of aridity and also of the availability of water for evapotranspiration

The western United States (US) was divided in regions of high and low actual evapotranspiration (AET) efficiency according to the monthly ratio between AET and potential evapotranspiration (PET). The AET/PET ratio is an indication of aridity and of the availability of water for AET.

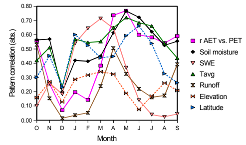


Average actual over potential evapotranspiration ratios (AET/PET) by month

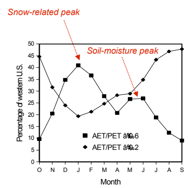
In regions of high AET/PET efficiency, increases in spring-summer average temperature (Tavg), at constant precipitation, would presumably be more easily reflected in significant increases in spring-summer AET, but also resulting in reductions in spring-summer soil moisture. Conversely, in regions of low AET efficiencies, increases in spring-summer Tavg result in marginal changes in AET and soil moisture. **This suggests that given no significant changes in precipitation, projected future warming associated with climate change may affect more strongly the soil moisture in regions of high AET/PET ratios.**

2.The AET/PET ratios contain information of the spatial distribution of the spring-summer soil moisture footprint of winter snowpack

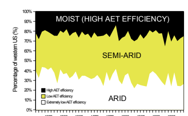
The monthly climatologies of the AET/PET ratios contain information on snow accumulation, but also contain information of the spatial distribution of spring-summer soil moisture.



Pattern correlations (abs.) between monthly climatologies of AET/PET ratio and the climatological patterns of the correlation (r) between AET and PET, soil moisture index, snow water equivalent (SWE), average temperature (Tavg) and runoff. Correlations of the AET/PET ratio with elevation and latitude patterns are also shown as reference.



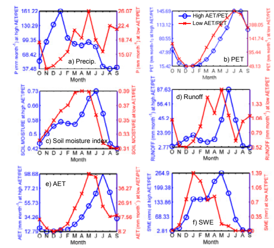
Average percentage of western U.S. classified as regions of high AET efficiency (square markers) and extremely low AET efficiency (rhombus markers).



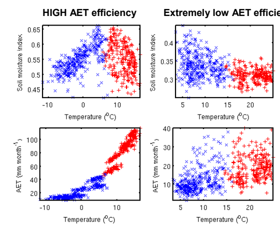
Annual-mean percentage of western U.S. classified as regions of high AET efficiency (square markers) and extremely low AET efficiency (rhombus markers) over time.

Aridity decreased in the Western US during the past half century, due to increases in precipitation

3. Warming strongly affects the wintertime rain/snow partition ratios and the spring-summer snowmelt and AET rates



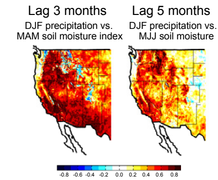
Climatologies of precipitation (P), potential evapotranspiration (PET), soil moisture index, runoff, actual evapotranspiration (AET), and snow water equivalent (SWE) for regions of high AET/PET ratios (circle markers) and extremely low AET/PET ratios ("x" markers).



Scatterplots of temperature versus fractional soil moisture index and AET for high and extremely low AET efficiency regions. May to September values are shown with '+' markers, and October to April with 'x' markers.

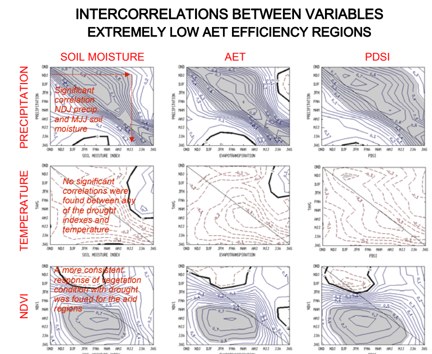
Scatterplots of Tavg versus soil moisture for the high AET regions suggest that during October to April, the combined effects of seasonal increasing volumes of rain and snowmelt is generally a higher order effect than the seasonal increases in AET (mostly sublimation), resulting in higher soil moisture as seasonal temperatures increase. Conversely, during May to September, the increases on AET rates due to warming are generally a higher order effect than the infiltration rates of the extra water provided by snowmelt, and therefore soil moisture decreases with seasonal increases in temperature.

4. Winter precipitation is an important determinant of spring-summer drought not only in the snow-covered areas, but also in a large part of arid and semi-arid regions.

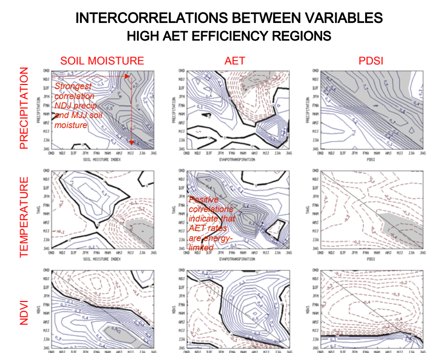


Correlation patterns between seasonally-averaged winter (DJF) precipitation versus MAM soil moisture index (lag three), and MJJ soil moisture index (lag five).

5. The connection between winter precipitation and spring-summer drought in high AET efficiency regions is governed by the thermodynamics of snow processes and therefore very sensitive to warming.

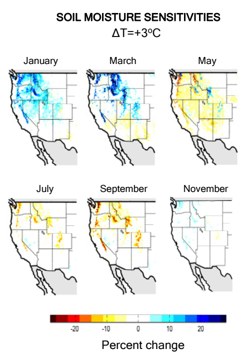


In arid regions, the three drought indexes showed similar correlations with Precipitation, Temperature and NDVI, suggesting that drought can be measured similarly using any of these indicators. The connection with vegetation greenness is also more consistent in the arid regions. Temperature does not have a significant effect on drought in these regions.



Regions of high evaporative efficiency present a longer lag between winter soil moisture and spring-summer precipitation. Soil moisture and PDSI are generally coupled during the summer, but the PDSI tends to present a strong persistence, leading to overestimate the strength of the correlations between winter and summer drought. AET in high AET efficiency regions is generally decoupled with the other drought indexes. In the high AET efficiency regions, Tavg is negatively correlated with drought (soil moisture and PDSI) during the summer and positively correlated with AET from November to July. The positive correlation between Tavg and AET in these regions is an indication that AET is not limited by water-availability, but instead is limited by the energy available.

6. Changes in soil moisture due to prescribed changes of temperature and precipitation, support the notion that spring summer drought in regions of high AET efficiency would be more affected by warming through significant increases in spring AET, while changes in precipitation affect drought conditions in the arid regions



7. Conclusions

- Winter precipitation is an important determinant of spring-summer soil moisture in montane and arid regions
- In the high AET efficiency regions, strong correlations were found between DJF precipitation and MJJ soil moisture (lag 5 months).
- In the arid regions (extremely low AET efficiency), DJF is strongly correlated with MAM soil moisture (lag 3 months), although significant correlations were found in some regions (i.e. Southern California and parts of the Central Valley) at lags 5 months.
- Temperature is an important controlling factor of spring-summer soil moisture in regions of high AET efficiency, but it is uncorrelated to soil moisture in the lowlands.
- Even that there is no sigificant seasonal correlation between temperature and PDSI in the arid regions, changes in temperature could still translate in th expansion of arid regions as the potential evapotranspiration would increase. This could have adverse consequences for ecossystems and wildfire potential for the transition regions.
- In the case of soil moisture, the largest changes in spring summer soil moisture occur in the high AET regions (as expected by the high sensitivity of spring summer AET and soil moisture to temperature changes). This suggests that given no significant changes in precipitation, projected future warming associated with climate change may affect more strongly the soil moisture in regions of high AET/PET ratios.
- The arid regions showed the strongest connection between soil moisture and vegetation conditions

8. ACKNOWLEDGMENTS

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APPENDIX: DATA SOURCES

The main hydroclimatic dataset used in this analysis was produced using the VIC (Liang et al. 1994) macroscale land-surface hydrological model originally developed at the University of Washington. A variety of hydrological parameters such as soil moisture, SWE and runoff can be estimated with the model using as input daily meteorological data along with soil and vegetation properties. We ran the model using soil and vegetation properties information at 1/8 degree resolution obtained from the North American Land Data Assimilation Systems (NLDAS; http://ldas.gsfc.nasa.gov), along with the daily gridded meteorological data (maximum and minimum temperature, precipitation and windspeed) for the western US from 1950 to 1999 obtained from the Surface Water Modeling group at the University of Washington from their web site (http://www.hydro.washington.edu/Lettenmaier/gridded_data/index_maurer.html), the development of which is described in Maurer et al. (2002). PET was computed using net radiation and relative humidity from VIC, along with Tavg and windspeed obtained from the Maurer et al. (2002) data using the Penman-Monteith equation (Penman 1948; Monteith 1965) as described in Shuttleworth (1993). For each gridpoint, PET was estimated as the weighted sum of the contributions from all vegetation types -as well as bare soil- at daily time-scales. The daily PET values were then aggregated to produce monthly totals.
A PDSI dataset for the contiguous US was computed using the 1/8 x 1/8 precipitation and Tavg data from the Maurer et al. (2002) dataset using a computer program from the National Climatic Data Center. Monthly remote sensed NDVI data at ¼ x ¼ degree resolution from 1981 to 1999 were obtained from the Global Inventory Modeling and Mapping Studies (GIMMS) data set (Pinzon and Tucker 2004; Tucker et al. 2005). The GIMMS data form part of the International Satellite Land-Surface Climatology Project (initiative II) data archive (Hall et al. 2005). An alternative VIC dataset was interpolated to the ¼ x ¼ degree resolution from the original 1/8 x 1/8 degree resolution to match the NDVI data in cases when the interaction between the VIC variables and NDVI was needed. The NDVI is a proxy indicator for vegetation greenness.