Session Title: Climatic water deficit and water balance in mountain systems: biophysics, ecohydrology, and impacts

Non-linear feedbacks between climate change, hydrologic partitioning, plant available water, and carbon cycling in montane forests

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Changes in both temperature and the amount and timing of precipitation have the potential to profoundly impact water balance in mountain ecosystems. Although changes in the amount of precipitation and potential evapotranspiration are widely considered in climate change scenarios, less attention has been given to how changes in climate or land cover may affect hydrologic partitioning and plant available water. The focus of this presentation is on how spatial transitions in ecosystem structure and temporal transitions in climate affect the fraction of precipitation potentially available to vegetation.

In most temperate mountain environments winter snows are a significant fraction of annual precipitation and understanding the partitioning of snow and snow melt is critical for predicting both ecosystem water availability and stream flow under future climate scenarios. Spatial variability in net snow water input is a function of the interaction of snowfall, wind, and solar radiation with topography and vegetation structure. Integrated over larger scales these interactions may result in between 0% and 40% sublimation of winter snowfall before melt, effectively excluding this water from growing season water balance. Once melt begins, variability in the partitioning of snowmelt is driven by the rate of melt, and somewhat less intuitively, by the timing of snow accumulation the previous fall. Early accumulating snowpacks insulate soils and minimize soil frost increasing infiltration of melt the following spring. In contrast, later snowfall results in colder soils, more soil frost, reduced infiltration, increased runoff during melt, and reduced plant available water during the following growing season. This change in hydrologic partitioning, mediated by the timing of snowpack accumulation, results in lower evapotranspiration (ET) and net ecosystem exchange (NEE) the following spring. These findings suggest that abiotic controls on the partitioning of precipitation may exacerbate or attenuate the effects of climate change on mountain water balance.

Use of Plant Hydraulic Theory to Predict Ecosystem Fluxes Across Mountainous Gradients in Environmental Controls and Insect Disturbances

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While mountainous areas are critical for providing numerous ecosystem benefits at the regional scale, the strong gradients in environmental controls make predictions difficult. A key part of the problem is quantifying and predicting the feedback between mountain gradients and plant function which then controls ecosystem cycling. The emerging theory of plant hydraulics provides a rigorous yet simple platform from which to generate testable hypotheses and predictions of ecosystem pools and fluxes. Plant hydraulic theory predicts that plant controls over carbon, water, energy and nutrient fluxes can be derived from the limitation of plant water transport from the soil through xylem and out of stomata. In addition, the limit to plant water transport can be predicted by combining plant structure (e.g. xylem diameters or root-to-shoot ratios) and plant function (response of stomatal conductance to vapor pressure deficit or root vulnerability to cavitation).

We evaluate the predictions of the plant hydraulic theory by testing it against data from a mountain gradient encompassing sagebrush steppe through subalpine forests (2700 to 3400 m). We further test the theory by predicting the carbon, water and nutrient exchanges from several coniferous trees in the same gradient that are dying from xylem dysfunction caused by blue-stain fungi carried by bark beetles. The common theme of both of these data sets is a change in water limitation caused by either changing precipitation along the mountainous gradient or lack of access to soil water from xylem-occluding fungi. Across all of the data sets which range in scale from individual plants to hillslopes, the data fit the predictions of plant hydraulic theory. Namely, there was a proportional tradeoff between the reference canopy stomatal conductance to water vapor and the sensitivity of that conductance to vapor pressure deficit that quantitatively fits the predictions of plant hydraulic theory. Incorporating this result into whole plant mass and energy exchange models allows prediction of plant carbon, energy and nitrogen exchange that fits recently collected data including plant sap flux, leaf gas exchange, eddy covariance towers and stand and watershed-scale biogeochemistry measurements. The results of our work will allow the next generation of ecosystem to regional scale coupled-biogeochemistry models to incorporate a simple plant hydraulic mechanism that will enable defensible predictions of carbon, water, energy and nutrient cycling with changing climate and land use.

Climatic Water Deficit in California: Regional Trends, Projections, and Landscape Impacts

A. L. Flint; 1; L. E. Flint; 1;

As the climate changes, landscapes respond to more than the usual suspects, air temperature and precipitation. Seasonal water availability is a proximal driver of vegetation, and is an integration of air temperature,
precipitation, radiation, wind, humidity, vegetation, and soils. Spatial variability in solar radiation drives differences in potential evapotranspiration; mesic north hillslopes and arid south hillslopes often support different vegetation assemblages. Soil depth and hydraulic properties define maximum storage of available water, and vary with slope position and soil type. Spatial resolution of these factors is essential for understanding the effects of climate change across complex landscapes.

Climatic water deficit (CWD), which describes these interactions of energy and water is calculated as potential evapotranspiration (PET) minus actual evapotranspiration (AET). We have calculated CWD using a water balance model that explicitly uses soil water storage estimated from mapped soil hydraulic properties and depth, which then provides a spatially explicit limit to AET, regardless of the available water supply. The model has been developed for California at 270-m spatial resolution for historical climate and four future climate projections.

Current and future changes in CWD are illustrated for California and show increases throughout the state for all climate scenarios, which project increases in air temperature and variable changes in precipitation. In application, as air temperatures rise and PET increases, limitations in soil storage will persist, regulating the amount of recharge and runoff and raising CWD, regardless of the direction of change in precipitation. When applied at this fine spatial scale, the model results indicate that mountainous topography with its complex environments can moderate change where soils are deep or steep topography reduces radiation load, potentially providing refugia or resilience to changes in climate.

Watering the Forest for the Trees: An Emerging Priority for Managing Water in Forested Landscapes
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Widespread threats to forests due to drought prompt re-thinking priorities for water management on forest lands. In contrast to the widely held view that forest management should emphasize providing water for downstream uses, we argue that maintaining forest health in the face of environmental change may require conserving water on forest lands specifically to reduce drought stress on vegetation. Management strategies to accomplish this include actions to: 1) conserve, retain, and store water on the landscape, either as snow or soil water; 2) reduce losses to evaporation and runoff; 3) increase plant available water through thinning or irrigation; and 4) encourage drought tolerant species. Hydrologic modeling reveals that specific management actions could reduce tree mortality due to drought stress. Adopting water conservation for vegetation as a priority for managing water on forest lands would represent a fundamental change in perspective and potentially involve tradeoffs with other downstream uses of water.

URL: www.fsl.orst.edu/wpg

How evaporative water losses vary between wet and dry water years as a function of elevation in the Sierra Nevada, California, and critical factors for modeling
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High altitude basins in the Sierra Nevada, California, have negligible summer precipitation and very little groundwater storage, making them ideal laboratories for indirectly monitoring changes in evaporative losses between wet and dry years. Dry years typically have greater potential evapotranspiration (ET) due to warmer June and July air temperatures, warmer summer water/soil temperatures, greater solar radiation exposure due to less frequent cloud cover, greater vapor pressure deficit, and longer growing seasons. However, dry years also have limited moisture availability compared to wetter years, and thus actual evapotranspiration is much less than the potential in dry years. The balance of these factors varies with elevation. Here, we use gridded temperature, precipitation, and snow data, along with historic streamflow records in two nested basins of the Merced River, California, and a simple model to determine the following: Annual ET increases in wetter years at midelevations (2100–2600 m), but this pattern can only be represented in model simulations that include some representation of water transfer between higher and lower elevation soil reservoirs. At higher elevations (>2600 m), greater water availability in wet years is offset by shorter growing seasons due to longer snow cover duration. These results suggest that models seeking to represent changes in ET in mountainous terrain must, at a minimum, include both hillslope processes (water transfer down steep slopes) and snow processes (timing of water and energy supply).

URL: http://faculty.washington.edu/jdlund/

The Effects of Soil Moisture Stress on Forest Recovery in the Entiat River Basin after Stand Replacing Fire

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The spatial heterogeneity of forest recovery following disturbance events over the last several decades can provide important scientific information about the role of hydroclimatological processes on vegetation recruitment. The Entiat Experimental Watersheds in north central Washington State exhibit interesting patterns on the landscape where young trees have not successfully established themselves following the 1970 stand replacing fire. These patterns include “stripes” of poor recruitment along the ridge lines, and significant differences in vegetation recovery in areas with broadly similar aspect, elevation, and slope. By constructing a physically based land surface model (using the Distributed Hydrology Soil and Vegetation Model, DHSVM) and empirically relating recovery processes to physical parameters (such as soil moisture and evaporative stress), we can map areas with a high probability of recurrent drought stress. In particular we evaluate the extent to which DHSVM can explain the observed patterns of forest regeneration since 1970 in the Entiat experimental watersheds, and explore the impacts of climate change on drought stress in the study region during summer months (June-August). In many areas of the experimental watersheds soil moisture stress simulated by the hydrological model is able to clearly identify areas of poor tree recruitment, supporting the hypothesis that soil moisture stress is the major control in these areas. Some areas of poor recruitment, however, are not well explained by the model simulations, highlighting the fact that other controls on recruitment are present as well. Under the climate change scenarios, drought stress typically increases due to loss of
snowpack, increased evaporation, and projected dryer summers, which increases both the likelihood of forest disturbance (fire, insects), while simultaneously increasing the cumulative area in the watersheds where recruitment is unlikely to be successful. The model provides explicit maps of these areas of poor recruitment that may help guide vegetation recovery strategies under a changing climate.

**Resilience of a Subalpine Ecosystem in the Southern Rocky Mountains to Past Changes in Hydroclimate and Disturbance Regimes**

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Concerns about the impact of predicted future water deficits on mountain ecosystems can be assessed through analyses of past ecosystem responses to hydrologic variability. Paleoecological records indicate that the composition of subalpine forests in western North America have been resilient to multiple influences over millennia, including severe droughts, insect outbreaks, and widely varying fire regimes. We evaluate the hypothesis that early-succession conifer forests with broad climatic tolerances, such as those dominated by lodgepole pine (Pinus contorta var. latifolia Engelm. ex Wats.) persist because forest dynamics are disrupted by frequent disturbance and climate variations. To assess this prolonged resilience, we use independently reconstructed vegetation, fire, and drought history for a small, forested watershed in southeastern Wyoming, based on sedimentary pollen and charcoal counts in conjunction with sedimentary lake-level indicators. Our data indicate that prominent vegetation shifts (from sagebrush steppe to spruce-fir parkland at ca. 10.7 ka and spruce-fir parkland to pine-dominated forest at ca. 8.5 ka) coincided with changes in effective moisture. However, once the modern subalpine, lodgepole pine forests establish at ca. 8.5 ka, similar hydroclimatic changes did not produce detectable changes in forest composition. Fire history data show that other aspects of the ecosystem were responsive to changes in effective moisture at multi-centennial-to-millennial timescales with prolonged fire-free episodes coinciding with periods of low effective moisture at >7.2-5.6 and 3.7-1.6 ka. Our results suggest that although current climate changes favor widespread disturbance in Rocky Mountain forests, the composition of these ecosystems could recover through succession dynamics over the next few decades to centuries.

**The Importance of Humidity Changes to the Future Water Balance over the Western U.S.: Divergences Between Global and Hydrological model Projections of the Future Humidity Trend**

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Near surface humidity is a key climatic control on evapotranspiration, along with other variables such as solar insolation and temperature. Humidity also plays an important role in modulating the occurrence of wildfires. We show that global climate models generally predict decreasing relative humidity (RH) in the mountainous parts of the western U.S. in coming decades, although with spread among the model results. The models project that atmospheric
moisture content in the region will increase, but the daily average temperature tends to increase faster, leading to declining RH. Fine-scale hydrological simulations driven by the global model results should faithfully reproduce these trends. We analyze the humidity trends obtained from the widely-used Variable Infiltration Capacity (VIC) hydrological model when it is driven by daily Tmin, Tmax, and precipitation from a global model. In this common case used in numerous published studies, we find that VIC does not preserve the original global model's humidity trends. Instead, the trends are biased in the positive direction, so that strong decreases in relative humidity are changed to weak decreases, and weakly negative or neutral trends in the original model are changed to positive trends. This error makes up to a 5% difference in estimates of basin-averaged future runoff, which is not negligible considering the oversubscription of current water resources in places such as the Colorado River. Local differences on wildfire or ecology are potentially much larger. The positive RH trend bias in the mountainous western U.S. is the result of an overly large positive trend in atmospheric moisture content, an error related to the aridity correction term VIC uses when calculating the humidity. However, this error does not seem fixable in the context of the current parameterization. The implication is that a new parameter related to the changing radiative balance of the Earth under anthropogenic climate change may be required to capture future humidity trends in a simple statistical framework.

The climatic water balance in an ecological context

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Because the climatic water balance describes the seasonal interactions of energy (heat and solar radiation) and water in biologically meaningful ways, it provides a powerful tool for understanding and predicting the effects of climatic changes on the terrestrial biosphere. I begin with a brief overview of the definitions and interpretations of the biologically most important water balance parameters -- actual evapotranspiration (AET) and climatic water deficit (Deficit) -- and how the particular approach used to calculate these parameters depends both on the goals of the study and on the available climatic data. Some authors have attempted to represent aspects of the climatic water balance with indices based on annual potential evapotranspiration (PET) and precipitation (P), such at P/PET or PET - P. However, these and related indices do not reflect soil water dynamics, snow dynamics, or the seasonal interactions of energy and water, and therefore have no biological interpretation. Consequently, such indices are more poorly correlated with ecological patterns and processes than AET and Deficit.

Of critical importance, the effects of changing energy and water supplies on the climatic water balance are nearly orthogonal. For example, a plant community growing on shallow soils on a shaded slope and one growing on deep soils on a sunward slope often may have the same amount of measured soil moisture available to them. However, the dynamics of energy and water that resulted in the identical soil moistures were fundamentally different (decreased evaporative demand on the shaded slope versus increased water supply on the deep soils); the associated differences in AET and Deficit will therefore result in different plant communities occupying the sites, in spite of identical soil moistures. In the context of climatic change, the orthogonal effects of energy and water mean that increasing precipitation cannot be expected to counteract the effects of increasing temperature; for example, a warmer, wetter environment will support a fundamentally different biota than the original cooler, drier environment. Thus, a sharp distinction must always be made between the effects of changing energy and water supplies, and the terms “wetter” and “drier” must be carefully defined in terms of AET and Deficit.
An understanding of the relationships between the water balance and biotic patterns and processes in space -- particularly within the extreme topographic and edaphic complexity of mountain ranges -- provides a solid foundation for understanding and predicting the ecological effects of climatic changes in time. I will provide concrete examples, particularly from California’s Sierra Nevada, with emphasis on cases in which predictions may deviate from intuitive expectations.

**POSTERS**

**Session Title: Climate change and drought**

**Drought characteristics drive patterns in widespread aspen forest mortality across the western United States**

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Body: Widespread drought-induced forest mortality has been documented across the globe in the last few decades and influences land-atmosphere interactions, biodiversity, carbon sequestration, and biophysical and biogeochemical feedbacks to climate change. These rapid mortality events are currently not well-captured in current vegetation models, limiting the ability to predict them. While many studies have focused on the plant physiological mechanisms that mediate vegetation mortality, the characteristics of drought seasonality, sequence, severity and duration that drive mortality events have received much less attention. These characteristics are particularly relevant in light of changing precipitation regimes, changes to snowpack and snowmelt, and increasing temperature stress associated with climate change. We examine the characteristics of drought associated with the recent widespread mortality of trembling aspen (Populus tremuloides) across much of the western United States. We combine a regional model of watershed-level aspen mortality with in situ tissue isotopic analysis of water source to analyze the roles of drought seasonality, severity, and duration in this mortality event, including raw climate variables, derived drought indices, and variables generated by a climate envelope approach. We found that variables pertaining to spring temperatures and springsummer water deficit, especially during the peak severity of drought, best capture regional mortality patterns, though multi-year drought variables did improve the model. Field water isotopic analysis of aspen water source over a growing season and during moderate seasonal water stress corroborate the regional model by indicating that aspen clones generally utilize surface water with little plasticity during drought stress. These results suggest that drought characteristics can play an important role in mediating widespread forest mortality and have implications for the future vulnerability of trembling aspen forests to climate change.
Comparison of sap flux data from two instrumented tree species in a forested catchment with different levels of water stress

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Two trees were instrumented with heat pulse sapflux sensors in the Southern Sierra Critical Zone Observatory (SSCZO) within the Kings River Experimental Watershed (KREW) to better understand transpiration as it relates to water availability from deeper sources. At the first instrumented site, CZT-1, a White Fir (Abies concolor) was instrumented on a flat ridge with access to deep soil moisture. Extensive monitoring of shallow and deep soil regions confirm that there is significant soil water available from 100-400cm as the tree exhausts water from shallower depths. A root excavation of an adjacent tree shows the roots distributed from 30-150cm with limited roots available to access deeper soil water and water stored in the saprolite. At the second instrumented site, CZT-2, a Ponderosa Pine (Pinus Ponderosa) was instrumented with a similar suite of sap flow and soil sensors. The CZT-2 site is on a slight slope and is characterized by shallow soils (<90cm) with extensive cobbles and bedrock outcrops with limited access to deeper soil or saprolite water. The second site also sits in the open while the first site is more protected in a closed forest. The two sites show different responses to changes in rain and snow loading from above as well as soil drainage and water depletion from below. They also have different thresholds for transpiration shut down both due to late season water deficit and also during winter periods where air temperatures are high enough to permit photosynthesis. Sap flux data are supplemented by extensive soil water content and potential measurements around both trees as well as evapotranspiration measurements from a 50m flux tower located between the two instrumented trees.

Soil Water and Thermal Gradients in the Vadose Zone: Assessing Evapotranspiration, Recharge Rates and Shifts in Phreatophytic Water Source
Soil water and temperature are important variables in energy and water balance studies, particularly to processes involved in evapotranspiration (ET), which provides a direct link between the balances and is crucial for closing the water budget. With a large uncertainty in precipitation rates from interannual variability and increased demand for water resources, understanding these processes is critical when assessing the movement of mass and energy through the vadose zone. Stress on the long-term water supply could lead to a potential shift of water source by phreatophytes. We seek answers to the following questions: Can we use soil temperature to estimate ET and downward water fluxes? Do changes in temperature signals follow shifts in water sources for plants? Although ET and recharge rates are primarily driven by atmospheric demand and water availability, to what extent does soil temperature change these rates? Data were analyzed from an array of soil water and temperature instruments, including TDR and heat dissipation sensors at multiple points from 30 to 500 cm, and fiber optic distributed temperature sensing at depth increments of 1.14 cm. ET data were obtained from an eddy covariance (EC) system and groundwater depth was measured using a pressure transducer in a well. Instruments were installed in Spring Valley, NV, a site dominated by Big Sage and Greasewood. ET dominates water loss at the site from March through September. We hypothesize that groundwater recharge did not occur within the valley floor during 2010-2011. Data indicate that snowmelt and precipitation percolates to ~300 cm depth (water contents increasing from 0.06 in Oct-2010 to 0.10 in May-2011). Gradual water content increases at 400 and 500 cm were measured; however, groundwater levels rose sharply from early October 2010 to approximately mid-June 2011, suggesting a high capillary fringe. Diurnal variation of soil temperatures are observed to ~50 cm depth and seasonal variation observed to ~500 cm. Sensors recorded multiple cold wetting fronts in March through April 2011. Using groundwater depth, changes in ET, precipitation, and soil moisture, we will correlate changes in temperature with infiltration and changes in source water. Furthermore, inverse parameter estimation of water content in a numerical model (HYDRUS 1D) will be simulated and compared to the results.

Assessing the climatic water deficit in a changing climate: A new index to evaluate the potential importance of subsurface storage in mountain ecosystems

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Understanding how increases in temperature may affect seasonal cycles in the climatic water balance across the western U. S. is crucial to identify areas in mountain ecosystems that are most susceptible to climate changes. Where seasonal cycles of precipitation and evaporative water demand occur asynchronously, mountain ecosystems
are dependent on the capacity of the subsurface to retain excess water accumulated during the wet season for use during the dry season (as rock- or soil-moisture). Conversely, in areas where annual cycles in precipitation and evaporative demand occur more synchronously, the reliance on subsurface storage is vastly reduced. The climatic water deficit and surplus was estimated across the western U. S. under historical (1971-2000) and potential future conditions based on the A1B emissions scenario using a suite of 12 GCM outputs for the mid 21st century at 800-m resolution. Gridded outputs include the monthly potential evapotranspiration, monthly and annual water surplus and deficit, and the projected change in both annual surplus and deficit, which define potential sub-annual changes in the water balance at each grid element. These products were used to derive a novel index that uses the synchronicity of surplus and deficit to evaluate the relative importance of subsurface storage to sustain mountain ecosystems. This new storage index is based on the ratio of the minimum amount of either annual surplus or deficit and the amount of total annual precipitation. Grid cells with index values near zero would have little need for moisture storage because the location is either in surplus or deficit for the majority of the year. Grid cells with higher values closer to one are characterized by precipitation that occurs at times when potential evapotranspiration is very low (winter) and hence subsurface storage helps to meet evaporative demands during the dry season. The resulting map of storage dependence indicates a mid-elevation band within many western U. S. mountain ranges where the potential role of subsurface storage in sustaining ecosystems is large due to the asynchrony of water surplus and deficit. This research helps identify where future research on shallow subsurface storage would be most beneficial, and conversely, in what areas the seasonal storage component of the water balance is of lower importance to the future of mountain ecosystems.


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Body: Detailed physical and chemical studies of trees that die and survive during drought provide insight into the historic conditions and physiological mechanisms that underpin episodes of tree mortality. We seek to deduce key physiological parameters that influenced the mortality and survival of piñon pine (Pinus edulis) during relatively warmer (2000’s) and cooler (1950’s) droughts in the southwestern U.S. Using recently sampled and archived tree-ring specimens of trees that died and survived during the 2000’s and 1950’s droughts, we constructed time series from two measurements that serve as integrated parameters of whole-tree physiological function: radial growth and stable carbon isotope ratios (δ13C) in tree-ring cellulose. We focused our efforts on addressing two hypotheses: 1) piñon trees that died had hydraulic characteristics that predisposed them to succumb to drought and associated bark beetle outbreaks through either hydraulic failure or carbon starvation; 2) dead tree growth and δ13C should be more responsive to climate than surviving trees if drought and temperature driven stress are the ultimate drivers of tree death. We further hypothesize that if dying trees respond to drought by closing their stomata to avoid hydraulic failure, they limit their ability to photosynthesize and should exhibit lower growth and more positive δ13C than trees that survive. Conversely, if trees that died maintained relatively open stomata and succumbed to drought via hydraulic failure, they should exhibit more negative δ13C than trees that survive. Leading up to the 2000’s drought, growth in trees that died was lower than in surviving trees, consistent with our
expectation. δ13C in trees that died was more negative than in surviving trees but both growth and δ13C of trees that died were less responsive to climate than surviving trees, counter to our initial hypotheses. Our δ13C results are consistent with the hypothesis that the trees that died maintained higher stomatal conductance during drought and hence ran a greater risk of hydraulic failure than trees that survived. An alternative hypothesis is that trees that died had lower leaf area per unit root area, which could also explain higher growth in surviving trees. However, this explanation is inconsistent with previous published results on leaf area of piñon pines that died and survived during the 2000’s drought. Notably, tree growth data extending back further in time reveals that growth of live and dead trees was similar until the 1950’s drought, when growth trajectories diverged. The mechanism underlying this growth divergence is not yet clear, but this result suggests an important role of previous droughts in predisposing trees to die during subsequent droughts. This raises the possibility of increased future mortality if drought frequency increases even in the absence of changes in drought severity. We are currently expanding our analyses to trees that died and survived across multiple sites covering both the 2000’s and the 1950’s drought, which will allow us to compare mortality mechanisms across landscapes and between droughts of different magnitudes and temperature profiles.

Forest Mortality in High-Elevation Pine Forests of Eastern California, USA; Influence of Climatic Water Deficit
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Widespread mortality in high-elevation forests has been increasing across western North American mountains in recent years, with climate, insects, and disease the primary causes. Subalpine forests in the eastern Sierra Nevada, by contrast, have experienced far less mortality than other ranges, and mortality events have been patchy and episodic. This situation, and lack of significant effect of non-native white-pine blister rust, enable investigation of finescale response of two subalpine Sierran species, whitebark pine (Pinus albicaulis, PiAl) and limber pine (P. flexilis, PiFl), to climate variability, in particular, climatic water deficit (CWD). We report similarities and differences between the two major mortality events in these pines in the last 150 years: 1988-1992 for PiFl and 2006-ongoing for PiAl. The ultimate cause of tree death was mountain pine beetle (Dendroctonus ponderosae), with climatic factors preconditioning stress in both species. Our studies include intensive ecology-plot analyses (both species) and regionwide air-survey forest-mortality detection mapping (PiAl only). We used climatic data from historic weather station data; for CWD, we modeled values from PRISM regional climate projections downscaled to 270 m and applied these to a regional water-balance model. The strongest correlations of ring-width (a measure of tree growth) in both species to climatic variables were to CWD: PiFl, -0.29 and -0.54 for live and dead trees, respectively; PiAl , -0.19 for both live and dead trees. Correlations of ring-widths to 2-year lagged CWD were higher than to current-year means: PiFl, -0.34 and -0.44 for live and dead trees, respectively; PiAl, -0.43 and -0.46, live and dead trees, respectively. Mean annual CWD values of the mortality plots in the intensive study were 181 mm (PiAl) and 289 mm (PiFl); air surveys showed significantly higher CWD values for PiAl mortality stands than live forests (387 mm and 307 mm, respectively). Correlations of growth to other climatic variables were weaker but significant. In PiFl these were to water-year precipitation and minimum temperature; for PiAl, they were to water-year precipitation. The strength of CWD relationships with forest mortality in two subalpine pine species suggests important physiological processes interacting
An Empirical Topoclimatology Model for Regional and Landscape Scale Assessments of Water Balance and Related Ecological/Hydrological Processes in Complex Topography

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Within mountain ecosystems, water balance plays a significant role in landscape-scale patterns of vegetation primary production and species distributions. However, predicting changes in water balance across mountain ecosystems and subsequent impacts on ecological processes is increasingly challenging due to the significant climatic gradients associated with complex topography. In consequence, without topographically-informed, high resolution climate inputs, many ecosystem and hydrology models are limited in resolving key water balance controls at the landscape-scale. While several widely used, smaller scale climate datasets already exist (e.g., Daymet, PRISM), they often do not contain all the necessary climate variables for process-based models, do not have the required temporal extent/resolution, or do not properly account for local topographic influences. Given these limitations, a first version of a new empirical topoclimatology model (TopoMet) has been developed to produce spatial grids of daily minimum and maximum temperature, precipitation, solar radiation, and humidity. TopoMet interpolates daily weather station temperature and precipitation observations to a spatial grid using a combined SYMAP interpolation algorithm and a modified Daymet elevation model. Daily solar radiation estimates are made using basic sun-earth geometry and the reformulated Bristow-Campbell model of MT-CLIM. Vapor pressure deficit is also estimated via MT-CLIM where it is modeled as a function of daily minimum and daytime temperatures. TopoMet includes extensive weather station quality assurance procedures and an independent observation infilling algorithm that can both infill missing observations and extend weather station observations in time through the modeling of relationships with neighboring stations. Currently, TopoMet has been run to produce an initial conterminous United States historical daily climatology (1950-2009) at ~800m resolution that can be used as input to ecological/hydrological models and to downscale coarse climate projections for climate impact assessments. Future versions will incorporate atmospheric reanalysis data to better model not only the climate-forcing effect of elevation, but other landscape-scale topographic controls such as cold air drainage and slope/aspect variations.

Drought-Caused Forest Decline In The Trans-Baikal Lake Area

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One of the important consequences of observed and predicted climate change is regional desertification and conversion of forest lands into steppes. We documented progressive forest decline in the trans-Baikal Lake mountains (center point coordinates ~ 51°30’N/116°30’E). This area has a sever continental climate and is a transition area between the Siberian taiga and Mongolian steppes and deserts. Forests are dominated by birch and occupy north-facing mountains slopes (with elevations up to 1200 m). Southern facing slopes are typically covered by grass communities.
Analysis of field measurements and satellite temporal data showed an increasing forest decline during the last decades (i.e., 1990-2010). The typical pattern of forest decline was ring-like with the forest die-back starting in the boundary area around the outside of the stand within the forest-grass transition zone. This decline was likely caused by decreases in precipitation and soil water content. During the last two decades summer precipitation decrease was > 10% (P>0.05), and is now 270 ±30 mm/yr. Similarly, hydrothermal index value decreased to about 12% (P>0.05). Satellite-derived forest decline correlates with precipitation and hydrothermal index decreases. Soil studies showed highest water content values within soils of healthy stands, with minimum values within the dead stand areas, and intermediate within the transition zone. Satellite-based estimates of the total area with drought-caused forest decline was about 106 ha. Along with the observed decline of birch stands, two others climate-caused phenomena were noted within the study and adjacent areas during the last decades: a significant increase of fire frequency and decrease of lake surface area.

Spatial patterns of interaction among climate variability and change, soil water deficit and transpiration in small mountain catchments of Southern Sierra Critical Zone Observatory

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In snow-dominated mountain systems, a warming climate alters soil water deficit through changing the timing and magnitude of moisture inputs as precipitation and snowmelt and through changes in the timing and magnitude of evapotranspiration losses. The net effect of climate warming on soil water deficit and associated ecosystem processes ultimately depends on the interaction between changes in inputs and outputs and on vegetation, micro-climate and soil properties that control the sensitivity of soil water to changes in input/output drivers. In mountain environments, steep spatial gradients result in substantial variation in atmospheric forcing and vegetation and soil properties over relatively short spatial scales, which necessitate providing finer-scale assessment of climate change impact. Measurements of soil moisture and forest responses to climate are often made at plot scales but are limited in spatial coverage. Coupled eco-hydrologic models, applied at relatively fine (m) scales provide a method of extrapolating findings from local measurements and exploring hillslope and watershed scale impacts of climate warming on moisture deficit. In this study, we use RHESSys (Regional hydro-ecologic simulation system) combined with spatially intensive monitoring of coupled ecohydrologic variables at the Southern Sierra Critical Zone Observatory (SSCZO), located in the Sierra National Forest, California. We initially use the model to identify clusters of distinctive water deficit behavior as summarized by indices of summertime soil moisture and transpiration recessions. The resulting clusters demonstrate that both elevational differences in energy availability and topographic controls on drainage are first order controls on spatial patterns of summertime moisture deficit and tree transpiration. We then use these initial model clusters to guide soil moisture and sapflux data collection. The collected data are used to characterize soil moisture deficit and transpiration for each cluster evaluate and improve the model predictions. Our initial results highlight the importance of adequate representation of micro-climate patterns as controls on summer moisture deficits and transpiration. We then use the model to show how spatial patterns of summertime moisture deficit and transpiration may change under future climate scenarios. We apply two approaches which are 1) using 2 and 4 °C uniform temperature adding to the historic meteorological records and 2) using a downscaled GCM climate projection.
Projected Bioclimatic Change for the San Francisco Bay Area

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Past and future climate data for the San Francisco Bay Area were classified using the Rivas-Martinez (R-M) system to group long-term annual climate averages into categories with biotic significance based on thermotypic and ombrotypic regimes. Bioclimatic maps were generated at 270 meter resolution for ten San Francisco Bay Area counties for six 30-year periods from 1911 to 2100 which include the historical 1) 1911-1940, 2) 1941-1970, 3) 1971-2000, and future 4) 2011-2040, 5) 2041-2070, and 6) 2071-2100. Historic averages were generated from PRISM climate data. Future climate projections were generated from two IPCC-based future scenarios (A2 and B1) and two coupled atmosphere-ocean general circulation models (NOAA Geophysical Fluid Dynamics Laboratory and the Parallel Climate Model). Strong congruence was found among the boundaries for historic bioclimates and current vegetation types. However, future scenarios had varying patterns of losses and gains in bioclimatic classes and these tracked mesoclimate gradients. Comparisons between projected bioclimatic categories and modeled future climatic water deficit show strong correspondence except in zones of deep alluvial deposits. Maps show areas of bioclimatic stability, e.g. areas that did not change under any future projection, versus areas with significant bioclimatic shifts in all future scenarios. These analyses and maps will be useful for assessing natural resource vulnerability to climate change and natural resource conservation-based climate adaptation decisions.
Effects of climate change on climatic water deficit and wildfire in Greater Yellowstone Ecosystem forests

Effects of climate change on climatic water deficit and wildfire in Greater Yellowstone Ecosystem forests

Climate change is likely to alter wildfire regimes, but the magnitude and timing of potential climate-driven changes in regional fire regimes are not well understood. Westerling et al (2011) considered how the occurrence, size, and spatial location of large fires might respond to climate projections in the Greater Yellowstone ecosystem (GYE), a large wildland ecosystem dominated by conifer forests and characterized by infrequent, high-severity fire. They developed statistical models that related climate data (1972–1999) to the occurrence and size of fires >200 ha in the northern Rocky Mountains. Cumulative deficit was particularly important for modeling extreme value distributions for fire size, and was also a statistically significant predictor of the occurrence and number of large fires.

Most of the area burned in large fires in the GYE from 1972-99 occurred in 1988 in extremely large fires. Climate projections imply that conditions associated with extreme fires in the region will become more common in coming decades. Thus, in order to estimate climate change impacts on GYE fire regimes, it was imperative that models capture extremes in fire occurrence and particularly fire size distributions. We will discuss the role of cumulative deficit versus other climate variables and land-surface characteristics in modeling extremes in fire activity in the GYE and the Northern Rockies more generally.

Westerling et al (2011) used their suite of models with downscaled climate projections from three global climate models to predict fire occurrence and area burned in the GYE through 2099. All models predicted substantial increases in fire by midcentury, with fire rotation reduced to <20 y from the historical 100–300 y for much of the GYE. Years without large fires were common historically but are expected to become rare as annual area burned and the frequency of regionally synchronous fires increase. These findings suggest a shift to novel fire–climate–vegetation relationships in Greater Yellowstone by midcentury because fire frequency and extent would be inconsistent with persistence of the current suite of conifer species. Deficit and actual evapotranspiration have been shown to be good predictors of the occurrence of coarse vegetation types (Stephenson 1998). We will present maps showing the shifts implied by three climate projections in the spatial patterns of climatic conditions historically associated with current
Droughts in the early 1950s and early 2000s significantly accelerated tree mortality rates in the Southwestern United States. During the early 2000s, forest inventory data indicate that the proportion of dead piñon pine, ponderosa pine, and Douglas-fir trees doubled in the Southwest. The 2000s drought peaked in 2002 and was the most severe drought in at least 100 years. In 2011, precipitation, dew-point, and wind data indicate the intensity of the 2002 drought has been surpassed in a number of ways. Measurements of water potential in piñon pine trees in northern New Mexico indicate that, at present, trees have less access to soil moisture than in 2002 when widespread mortality occurred.

How do these recent droughts compare to those of the last 1000 years? We used records of annual tree-ring widths from 309 populations of piñon pine, ponderosa pine, and Douglas-fir throughout the Southwestern United States to reconstruct a single record of regional drought stress from 1000–2005 AD. This record indicates that the last Southwestern drought similar in intensity to one in the early 2000s occurred in the late 1600s. Both of these droughts, however, paled in comparison to a mega-drought that occurred from 1575–1595. The emergence from this megadrought, around 1600 AD, appears to mark a transition period from a time when droughts similar to the early 2000s drought were much more common. Tree-age studies indicate a scarcity of Southwestern trees with rings extending back beyond the mega-drought of the late 1500s. This suggests that (1) the late-1500s mega-drought triggered a massive die-off of forests and/or (2) the higher frequency of drought events prior to the mega-drought sustained a much more sparse forest population than the one that has thrived from the 1600s through present.

Given this apparent plasticity of Southwestern forests, a change in the forest population should be underway if higher temperatures contribute to forest drought stress. The Southwestern tree-ring record indicates that this is the case. During the 20th century, tree-ring widths correlated very positively with total winter precipitation and very negatively...
with spring–summer maximum temperature. This indicates that Southwestern forest growth is significantly impacted by both the amount of water delivered before the growing season and temperature during the growing season. We conclude that in the absence of a significant increase in winter precipitation, continued warming should lead to a more sparsely populated Southwestern forest population, similar to the one that appears to have existed during 1000–1600 AD.