# BRISTLECONE PINE PALEOCLIMATIC MODEL FOR ARCHAEOLOGICAL PATTERNS IN THE WHITE MOUNTAINS OF CALIFORNIA

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Archaeologists are recognizing that prehistoric human populations have been a significant variable in the operation of past Californian ecosystem processes, and conversely, they have acknowledged that a changing environment constantly varied the constraints and opportunities for prehistoric cultural adaptation. Climatic factors like temperature and precipitation play a major role in tree growth and the resulting tree-ring widths. Temperature governs tree ring growth patterns in upper elevation subalpine trees in the presence of a sufficient amount of soil moisture. The connection between paleoclimate and archaeology is an evolving interdisciplinary field of study that aims to facilitate a better understanding of the impact of climate variability on archaeological patterns and settlements. In this research, I use a paleoclimatic model that is based on temperature inferences and precipitation reconstruction from tree-ring widths of bristlecone pine in the White Mountains of California to explain aboriginal subsistence-settlements in alpine villages in the White Mountains. Temperature inferences and precipitation reconstructions are compared visually and statistically with $^{14}C$ dates from archaeological sites. Results imply the role of water availability in the frequency and intensity of settlements, as 88% of the $^{14}C$ dates fall within wet periods. Two dates, A.D. 1530 and A.D. 1662 fall within drought periods, while the rest cluster around precipitation maxima. I provide an explanation of the observed subsistence settlements and tie those patterns to resource availability in the area over the past 1,000 years. The model presents a new approach in the application of long bristlecone pine chronologies to the understanding of archaeological settlements in the White Mountains. The coincidence of $^{14}C$ dates around precipitation maximum confirms that long term available resources are contingent on the availability of moisture, the key to life in the desert environment.

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## LATE HOLOCENE NORTH PACIFIC ATMOSPHERIC CIRCULATION AND EFFECTIVE MOISTURE IN THE SOUTHWEST YUKON TERRITORY, CANADA

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Air masses that influence the climate of the southern coast of Alaska and the interior southwest Yukon originate in the Bering Sea, the Gulf of Alaska, and the Arctic. Trajectories of these air mass systems are largely controlled by variations in the intensity and position of the semi-permanent Aleutian Low (AL). Decadal scale variability of the AL is evident from analyses of instrumental data and is described by climate indices such as the North Pacific Index (NPI) and the Pacific Decadal Oscillation (PDO). Previous paleoclimatic studies suggest that variations in AL intensity and/or position were an important control of Alaska and Yukon Holocene climate. Varying atmospheric circulation patterns superimposed on regional topography produce notably different climates on the coast and in the interior. We undertook multi-proxy studies of sediment cores from two lakes in the southwest Yukon with contrasting hydrological settings and analyzed oxygen isotopes to improve the detail and resolution of the regional climatic history. Results indicate that prominent atmospheric circulation shifts over the Gulf of Alaska correspond to effective moisture changes in low elevation interior regions and illustrate the spatially heterogeneous response to late Holocene regional climate change.

## GULF OF CALIFORNIA DIATOMS AND SILICOFLAGELLATES ARGUE FOR ENHANCED NORTH AMERICAN MONSOON DURING THE MEDIEVAL WARM PERIOD

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The Gulf of California (hereafter referred to as the "Gulf") is recognized as the dominant moisture source for the North American (Mexican) Monsoon. Mitchell and others (2002) relate the development of the monsoon in Arizona to the onset of warmer SST (>28°C) in the northern Gulf. *Azpeitia nodulifera*, a tropical diatom, enters the Gulf with tropical waters that advance up the eastern side of the Gulf during the late spring and summer. Sediment trap studies in the Guaymas Basin (central Gulf) suggest that *A. nodulifera* only occurs in significant numbers during periods with the warmest SST.

A high resolution study of diatoms in Guaymas Basin sediments deposited over the past 2,000 years reveals that the relative percentage of *A. nodulifera* was anomalously high (>20% of the tabulated diatom assemblage) between ~A.D. 900 and 1020 and again between ~A.D. 1100 and 1140. These same two intervals are marked by the increased abundance (up to 25% of the assemblage) of *Dictyocha* sp. aff. *D. aculeata*, a silicoflagellate indicative of warmer SST, and

by a reduction in *Octactis*, a winter upwelling productivity indicator. This evidence suggests that monsoonal conditions may have been enhanced in Arizona during these intervals within the Medieval Warm Period (MWP). We suggest that increased solar activity augmented SST warming in the central Gulf.

The MWP, between A.D. 900 and 1300, has been characterized in recent reconstructions by the presence of extensive drought in the American West and negative Pacific Decadal Oscillation (PDO) in the adjacent North Pacific. Enhanced monsoonal conditions in the Gulf of Mexico and Florida during the MWP, however, have been documented by others.

Mitchell, D.L., Ivanova, D., Rabin, R., Brown, T.J., and Redmond, K., 2002, Gulf of California sea surface temperatures and the North American Monsoon: mechanistic implications from observations: Journal of Climate, v.15, p. 2261-2281.

## MIGRATIONS OF WESTERN NATIVE AMERICANS AND THE FALL OF CAHOKIA: RESPONSES TO MIDDLE-TWELFTH AND LATE-THIRTEENTH CENTURY DROUGHT?

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Two intense and persistent droughts affected some Native American cultures in the middle twelfth and late thirteenth centuries, including the Anasazi, the Fremont, the Lovelock, and the Mississippian Cahokians. Tree-ring-based reconstructions of precipitation and temperature indicate that warm drought periods occurred between A.D. 1130 and 1180 and between A.D. 1275 and 1300. These droughts occurred during minima in the Pacific Decadal Oscillation and may have been associated with positive values of the Pacific Decadal Oscillation. Each of the Native American cultures was supported, to a greater or lesser degree, by resources which were precipitation dependent. Both the Four Corners region and Cahokia were sites of intense growth between about A.D. 1050 and 1130. By A.D. 1150, both cultures were undergoing stress, and by A.D. 1300 both cultures had collapsed and their residual populations had left their homelands. Migrations occurred within the Fremont homeland at A.D. 1150 and the homeland was essentially abandoned by A.D. 1300. In the case of the Fremont, an earlier drought, which occurred between A.D. 990 and 1060, may have had the greatest impact on their population. This drought also may have had an impact on the Anasazi, for it was at the end of this drought that people from Chaco Canyon migrated to the San Juan River and founded the Salmon Ruin greathouse. Detailed data do not exist on the number of Lovelock habitation sites or populations over time; however, the Lovelock appear to have left the western Great Basin and entered California by A.D. 1300.

## CLIMATE FLUCTUATIONS ON THE SUB-CENTURY SCALE: ARE WE ASKING THE RIGHT QUESTIONS?

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Climate variations in western North America show connections to a number of other subsystems, some quite distant. Why do similar cycles appear in the tree-ring records on different continents, and again in marine sediments along the California coast? Unless we wish to assume that, by chance, different subsystems oscillate at similar periods, and thus resonate with each other, we must look to astronomical forcing as a causal mechanism. The obvious sources for such forcing are fluctuating solar energy output and lunar tides (including solid-ground tides). The first alternative puts the system into chaos, and makes it unpredictable. The second leaves room for expectation and prediction. An argument is made for participation of astronomical forcing in climate change.

## A LATE HOLOCENE RECORD OF FIRE, VEGETATION, AND CLIMATE FROM A CIÉNEGA IN SONORA, MEXICO

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Straddling the international border that separates the southeast corner of Arizona, U.S., and the northeast corner of Sonora, Mexico, is the remains of a once vast desert ciénega (wetland). A perennially watered site surrounded by the arid lands of the North American Southwest, Ciénega de San Bernardino represents a rare opportunity to study past fire regimes, vegetation composition, and climate from sedimentary records. Charcoal particles, fossil pollen, and magnetic susceptibility of sediment samples will be analyzed in order to reconstruct the local paleoecology. Four radiocarbon dates have established chronological control and provided an age model, along with sediment, charcoal, and pollen accumulation rates. These dates constrain the are of sampled ciénega sediments to between ~4,330 cal yr B.P. to the present. Preliminary charcoal and magnetic susceptibility analyses show a pronounced change in fire regime that began at the onset of the Medieval Climate Anomaly. Fossil pollen analysis is currently underway. The results of this study will be integrated with the results of other studies in the region in order to provide a more complete regional paleoclimate picture. Paleoenvironmental information will be provided to land managers of the San Bernardino National Wildlife Refuge in Arizona and private landowners in Sonora to facilitate current restoration and preservation efforts targeting Ciénega de San Bernardino.

# A DIATOM RECORD OF LATE HOLOCENE CLIMATE VARIABILITY FROM TWO LAKES IN THE NORTHERN ROCKY MOUNTAINS

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Changing climate can cause long-term limnological, and ecological changes in the Rocky Mountain region. Changes at the species level could reflect shifts in larger-scale forcing mechanisms such as the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), or Atlantic Multidecadal Oscillation (AMO). Here we use a 2,000-year record of changes in the diatom species composition from Crevice Lake, Yellowstone National Park, and Reservoir Lake, MT to infer changes in limnological conditions driven by climate. Throughout this period in Crevice Lake, planktonic diatoms dominate, but changes in species dominance indicate varying nutrient levels over time. These changes in nutrient concentrations, particularly phosphorus, are believed to have climatic drivers. The duration of water column mixing, which is related to temperature and wind strength, determines the extent of nutrient recycling from deep waters. Unlike Crevice Lake, the diatom record from Reservoir Lake seems to reflect relative water depth, not seasonality of mixing.

In Crevice Lake, from 800-50 cal yr B.P., *Stephanodiscus minutulus*, a species that blooms during isothermal mixing is dominant. This suggests that during this period, the spring was long and cool, with extensive regeneration of phosphorus from the hypolimnion. The most dramatic change in species assemblage occurs just prior to the onset of the Little Ice Age, about 800 years ago. Prior to this time, *S. minutulus* was absent, and *Cyclotella bodanica* and *C. michiganiana* were the dominant species. These species are characteristic of lower nutrient concentrations during times of stable stratification and are interpreted to reflect warm summers with long periods of thermal stratification. These changes in species abundances suggest long-term trends in seasonal length and climate variation.

Preliminary results from Reservoir Lake, show changes between planktonic and benthic species. These drastic fluctuations in the biota could represent changes in relative water depth, with benthic assemblages correlated to shallow water depths, while planktonic assemblages imply deeper water. Analyses are still underway, so it is unclear if the timing of water level shifts in Reservoir Lake can be correlated with mixing changes in Crevice Lake.

## A COMPARISON OF VEGETATION AND FIRE HISTORIES FROM TWO SITES IN THE KLAMATH MOUNTAINS, NORTHWESTERN CALIFORNIA

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The Klamath Mountains of northwestern California are a floristic hotspot and their diversity likely results from a combination of geological, ecological and historical factors (*e.g.*, long-term climate change). To evaluate how climate change has influenced past composition, structure, and disturbance regime of the Klamath forests, vegetation and fires histories from two nearby sites, Bolan Lake (Briles and others, 2005) and Sanger Lake are compared. Bolan and Sanger Lakes lie 32 km apart and experience the same modern climate and vegetation. Comparison of the sites helps separate local site differences from regional responses to past climate variability. Fossil pollen from the sediment cores was examined at 40 to 100 year intervals in order to reconstruct the vegetation history. Stratigraphic changes in pollen percentages and accumulation rates provide information on changes in vegetation composition and structure. Fire histories were reconstructed from changes in charcoal accumulation rates (CHAR) in contiguous samples through the sediment lake cores. Such data provide information on variations in the magnitude and proximity of fire events, fire frequency, and types of fuel. Sediment properties, such as variations in magnetic susceptibility and organic content, disclose changes in sediment input and lake productivity.

Millennial-scale trends in pollen and charcoal records are similar at the two sites. For example, the late glacial forests are a subalpine parkland of *Artemisia*, Poaceae, *Pinus*, and *Tsuga* which experienced few or no fires. Closed forests of *Abies*, *Pseudotsuga*, and *Tsuga* developed between 14,000 and 11,000 cal yr B.P. Fires at Bolan Lake became more frequent than before, while at Sanger Lake, fires were infrequent as in the late glacial period. An open woodland of *Pinus*, *Quercus*, and Cupressaceae and more frequent fires characterize the early Holocene forests at both sites. In the late Holocene, closed forests of *Abies*, *Picea*, and *Pseudotsuga* became established and fire frequency declined from early Holocene levels, but was higher than during the late glacial period. At centennial time scales, the Bolan and Sanger charcoal records indicate a relatively higher fire frequency during the Medieval Climate Anomaly (A.D. 900-1400) and fewer fires during the Little Ice Age (A.D. 1450-1850).

## SEDIMENTARY CHARCOAL AS A PROXY FOR PAST DROUGHT

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As water resources become scarcer in the western United States, it is more important than ever to understand the temporal and spatial nature of past droughts. While instrumental records provide information on droughts of the last *ca*. 100 years (or less), this time frame is likely not

sufficient to understand the natural range of variability of drought occurrence and the climatic conditions associated with them. This project examines Holocene sedimentological charcoal records of fire from several sites across the western United States as a proxy for past droughts. Comparison of the fire records with other indicators of past drought suggests that sedimentary charcoal is a reasonable measure of effective moisture. Focus on the last 2,000 years indicates that the severity of historic droughts has been exceeded during this time period, which has implications for current and future water management policies.

## A HIGH RESOLUTION RE-EXAMINATION OF A PORTION OF THE MISSION CROSS BOG, NEVADA RECORD FROM 4,000 TO 2,000 YEARS AGO

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The first goal of this study is to reconstruct both regional and local paleoclimate within an area bordering the vegetative and hydrologic Great Basin using pollen and packrat midden analyses collected in the Jarbridge Mountains in northeastern Nevada. The pollen record gives a regional perspective on vegetation and climate change in the area while the packrat middens provide evidence of how species varied with climate change. The results of these proxy records will then be compared to previous research within the northern and central Great Basin to determine the local and regional scale of climate change. A high-resolution record from 4,000 to 2,000 years ago will identify critical climatic changes of the shorter duration wet and dry phases characterizing the late Holocene. An 18 m sediment core was recovered from Mission Cross Bog in July of 2005. Marie Allan previously examined Mission Cross Bog at a coarse resolution by Bob Thompson and at a higher resolution for the last 2,000 years. The second goal of this study is to use a systematic method to determine the definition of high resolution for this particular site, and to test whether there is a limit to high-resolution sampling. Samples will be taken at consecutively shorter intervals (*i.e.* every 250, 125, 60, and 30 years), and compared to determine changes (from one sampling interval to the next and from one taxon to another).

## THE EFFECTS OF HOLOCENE CLIMATE CHANGE ON FISH POPULATIONS IN OWENS VALLEY, CALIFORNIA

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The Great Basin is populated with lakes and stream systems that have no outlets. Consequently they are sensitive indicators of climate variation. Evidence of past aquatic changes is found in lake cores, relict stumps, and geomorphic features. Records of past fish populations provide another indicator of climate change. An ~8,000 year record of fish remains have been collected from archaeological sites in Owens Valley, California. Two fish species, tui chub (*Gila*

*bicolor*) and Owens sucker (*Catostomus fumeiventris*), appear to respond to changing aquatic conditions in different ways. The earliest fish assemblages (~8,000 years B.P.) are dominated by suckers, while the later assemblages (after 3,500 years B.P.) reflect a mix of sucker and chub. Overall body size from both fish, estimated from vertebrae size, indicate a trend toward smaller body size over time. Both of these trends appear to reflect species-specific difference in life history strategy, which favor certain traits during differing aquatic (and climatic) conditions. This study highlights the prospects and challenges in using archaeo-fish records for paleoenvironmental reconstruction in desert environments.

## CLIMATE AND FIRE RELATIONS IN SUBALPINE FOREST OF THE UINTA MOUNTAINS, UTAH

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Over the last few decades growing concern over global warming and the increased frequency and severity of forest fires in the western United States has fueled interest in the relationships between climate and fire. The El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are known to affect seasonal rainfall amounts and be related to drought in the western United States. The frequency and severity of droughts have a significant influence on the frequency and severity of fire. Previous research in the western United States has shown that records of regional fires over the past few hundred years are strongly tied to drought associated with cycles of ENSO and the PDO. Therefore, potential changes in inter-annual and decadal climate patterns and resultant changes in precipitation may lead to an increase of drought-induced fire frequency and severity. Under a changing climate, understanding the connections between fire and climate variability is necessary to effective fire hazard assessment. This study will examine the occurrence of drought and large fires in the subalpine forest of the Uinta Mountains to determine if these events can be correlated with the variability of ENSO and the PDO. Using existing fire history data from watersheds on the southwest and the northeast slopes of the Uinta Mountains, I will investigate relationships between the composite fire histories and the Palmer Drought Severity Index, ENSO, and the PDO using superposed spectral analysis and cross spectral analysis. Given projected climate changes and recent studies showing that climate patterns have a significant influence on forest fire events, long-term fire planning, using climate data from ENSO and the PDO may be possible, allowing decadal management of forest systems.

## PROTOTYPE WEB TOOLS FOR THE WESTERN CLIMATE MAPPING INITIATIVE (WESTMAP)

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Several years ago at PACLIM we reported on the initiation of the Western Climate Mapping Initiative (WestMap). WestMap was conceived by a consortium that includes the University of Arizona/CLIMAS, the Western Regional Climate Center/Desert Research Institute, the PRISM climate mapping group at Oregon State University, along with collaborators at Scripps Institute of Oceanography/California Applications Project, NOAA Climate Diagnostics Center, and the USDA Natural Resource Conservation Service. WestMap evolved in response to high stakeholder demands for lengthy time series of fine (km) scale gridded climate data that can be aggregated to user-specified domains, and accompanying user-friendly resources. WestMap consists of three primary interwoven segments, 1) data development and operations; 2) error assessments, data analyses, and diagnostics; and 3) data access, visualization and educational resources. The project was recently funded by NOAA-NCTP, and in this paper we report on the development of prototype web tools and solicit feedback from PACLIM participants to help us maximize the potential utility of this tool for the climate data community in the western United States.

## TREE-RING RECONSTRUCTIONS OF NORTH AMERICAN DROUGHT: THE CURRENT STATE AND WHERE DO WE GO FROM HERE?

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Recent tree-ring reconstructions of summer drought over most of North America have revealed unprecedented periods of elevated aridity and megadroughts, particularly in the western United States (the "West") prior to A.D. 1600, with three particularly intense periods of drought occurring between A.D. 1021-1051, 1130-1170, and 1240-1265. These megadroughts fall within the time period variously described as the Medieval Warm Period or the Medieval Climate Anomaly (MCA). The MCA is also a period of overall increased aridity that lasted roughly 400 years (A.D. 900-1300) in the West. The annual severity of the MCA megadroughts does not appear to have differed greatly from those that have happened from A.D. 1300 to the present. Rather, they lasted in some cases 20-40 years, substantially longer than the most severe droughts known to have struck North America since A.D. 1850, which lasted at most, 10 years. It is now a major scientific challenge to explain how the maximum duration of drought in the West could have changed so much. The tropical Pacific is implicated through the development of persistent cool La Niña-like conditions in the eastern equatorial region, which is known to be drought

inducing over much of North America. However, the mechanism that would have forced the tropical Pacific into such a drought-prone state during the MCA is not well understood. High solar radiative forcing combined with reduced cooling from volcanic eruptions during the MCA have been implicated, but the level of radiative forcing contributed by sun during that time is at best, highly speculative.

A geographically expanded set of new drought reconstructions from tree rings is now being developed for North America. For the first time, this dataset will include almost all of Canada and Alaska. High-resolution (0.5° x 0.5°) gridded instrumental Palmer Drought Severity Indices have been prepared for this purpose and the tree-ring network used for reconstruction has been increased from 835 to over 1,200 chronologies, with more to be added in the future. In addition, a great deal of effort is being made to extend the lengths of the tree-ring chronologies used for reconstruction. This effort has been motivated by the realization that the reconstructions must extend back 500-1000 years to include the period of unusual megadroughts mentioned earlier. The realization that abundant quantities of sub-fossil wood are available for this purpose makes this feasible in many parts of North America.

## LONG-TERM RESEARCH IN ENVIRONMENTAL BIOLOGY: CHANGES IN GENETICS, PHYSIOLOGY AND ECOLOGY OF SIERRA WILLOW BEETLE POPULATIONS IN RESPONSE TO CLIMATE CHANGE

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Since 1981 we have investigated changes in populations of the willow leaf beetle (*Chrysomela aeneicollis*) in the eastern Sierra Nevada, California. During that time we have observed range expansion and contraction during wet-dry cycles. Starting in 1998, we have continuously recorded habitat temperatures and snowmelt dates at sites that bracket the altitudinal distribution of the beetle. We found that drainages differ significantly in summer temperature, with substantially cooler temperatures in a northern drainage (Rock Creek), compared to a central drainage (Bishop Creek), and a southern drainage (Big Pine Creek). Summer temperatures in Rock Creek often fall below levels that are lethal to beetles, and we have observed differences in mortality related to exposure to subzero extremes. We also found that beetle populations shifted upwards in elevation at Big Pine Creek, the warmest drainage, during recent warm dry years, but that this altitudinal shift did not occur in Rock Creek or Bishop Creek. Beetle abundance is lower in Rock Creek than Bishop Creek or Big Pine Creek. Beginning in 1988, we sampled genetic variation in these populations, which revealed variation across temperature gradients and elevations. These data suggest that the glycolytic enzyme phosphoglucose isomerase (PGI) allele frequencies shift in response to changes in climate. Since 1998 we have also investigated the specialist hunting wasp *Symmorphus cristatus*, one of the principal beetle predators, and have observed an upward shift in elevation as well as measuring temperature-related changes in foraging success. Using the University of California White Mountain Research Station, we plan to continue and expand these studies for at least 10 more

years. We will (1) monitor air temperatures and humidity along four elevation gradients and relate them to fluctuations in abundance of *C. aeneicollis* and two specialist predators, (2) quantify variation in physiological response to temperature in *C. aeneicollis* and its predators, (3) survey changes in frequency of the PGI allele in a drainage where the allele is polymorphic, and (4) quantify effects of climate on predatory wasp ecology and behavior. This work provides a unique opportunity to integrate studies of the mechanisms underlying population change with comprehensive data on climate, for native insect species in physically challenging environments.

## SEDIMENT GEOCHEMICAL RECORDS OF PRODUCTIVITY AND OXYGEN DEPLETION ALONG THE MARGIN OF WESTERN NORTH AMERICA DURING THE PAST 20,000 YEARS: TELECONNECTIONS WITH THE ATLANTIC AND CARIBBEAN

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Several published records from the margins of the Alta and Baja California have correlated anoxic intervals (laminated sediments) and warm sea surface temperatures with stadial intervals defined by the oxygen isotope composition of Greenland ice (Dansgaard-Oeschger (D-O) cycles). These intervals include all or parts of oxygen isotope stage 3 (OIS3; 60,000-24,000 cal yr B.P.), the Bölling/Allerød warm interval (B/A; 15,000-13,000 cal yr B.P.), and the Holocene. Organic carbon ($C_{org}$) and trace element proxies for anoxia and productivity, namely elevated concentrations and accumulation rates of molybdenum and cadmium in these laminated sediments suggest that productivity may be more important than ventilation in producing changes in bottom water oxygen conditions on open, highly productive continental margins. The main conclusion from these proxies is that during the last glacial interval (LGI; 24,000-15,000 cal yr B.P.), productivity was lower and bottom-water oxygen levels were higher than during OIS3 and the Holocene along the California margin. The $C_{org}$ and trace element profiles in the LGI-B/A-Holocene transition in the Cariaco Basin on the margin of northern Venezuela are remarkably similar to those in the transition on the northern Alta California margin. Correlation between D-O cycles in Greenland ice and gray-scale measurements in varved sediments in the Cariaco Basin is also well established. Synchronous climate-driven changes as recorded in the sediments on the California margin and in the Cariaco Basin and those recorded in Greenland ice support the hypothesis that changes in atmospheric dynamics played a major role in abrupt climate change during the last 60,000.

## NEOTROPICAL CLIMATE DYNAMIC AT THE LATE GLACIAL /HOLOCENE TRANSITION RECORDED BY POLLEN DATA OF SEDIMENTS FROM THE CARIACO BASIN, CARIBBEAN

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Palynological analysis of a deep marine sediment core from the anoxic Cariaco Basin, off the coast of Venezuela indicates the presence of unique pollen assemblages, which mirror the complex altitudinal zonation, and dynamics of coastal vegetation. The Cariaco Basin acts as a natural sediment trap for rapidly accumulating sediments of marine and terrestrial origin, and provides the chance to compare both signals. The pollen analysis encompasses the interval from 12 to 3 m in core MD03-2620, covering the Late Glacial/Bølling-Allerød transition, Younger Dryas, and the beginning of the Preboreal. The data show abrupt changes in dryness/wetness conditions as well as cooling/warming. The correlation of pollen data with sediment color density, oxygen isotopes, and titanium/iron ratios of other Cariaco Basin cores, as well as comparison of our data with vascular plant signals, shows that the increase in pollen productivity might be dictated not by warming, but by increasing discharge of terrigenous material from the continent. While the composition of the pollen assemblage remains relatively consistent, changes in the abundance of individual palynomorphs indicate variations in the composition of the ecosystem. These changes are representative of the modern altitudinal gradient. Thus, the Montaña rain forest prevailed over deciduous Montaña forest or Paramo elements during the Bølling-Allerød time, but did not replace them. At the end of Late Glacial Maximum and during the middle of the Younger Dryas, the forest became seasonally dry. At the end of Heinrich event I (*ca*. 15,500 cal yr B.P.) the largest offset of vegetation corresponds to another dry episode, correlated with a lake-level drop in northern South America and hiatuses of terrestrial sedimentation. Overall, the Neotropical region was not affected by the dramatic cooling during cold North Atlantic episodes such as the Younger Dryas, but the region experienced significant dryness.

## SOME EXAMPLES OF NINETEENTH CENTURY HISTORICAL FLOOD RECONSTRUCTIONS FOR CALIFORNIA

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Documentary data possess temporal resolution at sub-daily timeframes, as well as spatial resolution down to the block-scale, enabling detailed reconstructions of extreme climatic events. We present evidence from two historic nineteenth century flood events that occurred in California and the adjacent regions: the winter of 1849-50 and the winter of 1861-62. Both instrumental and detailed descriptive data were taken from records of the National Archives,

newspapers, and personal diaries located at archives scattered throughout the western United States. The diary dataset for the winter of 1849-50 was largely enhanced by documents written by the Forty-Niners of the California Gold Rush. Precipitation data were assessed quantitatively in magnitude and precipitation frequency, and these results were directly compared with the variability of the modern instrumental record. Spatial extent of the flooding was also assessed, particularly for the 1861-62 floods. The floods of the winter of 1849-50 are characterized by abnormally high precipitation frequency, but magnitudes of precipitation were not as highly anomalous. In contrast, the floods of the winter of 1861-62 far exceed those for any year in the modern climate record in terms of magnitude and spatial extent, with historical evidence of heavy flooding evident from southern Washington to southern California and eastward through most of Utah. Synoptic patterns for the anomalous 1861-62 flooding events probably relate to strong and very persistent moist southwesterly flow into California that followed abnormally cold conditions for earlier that winter. The reconstructions of both events illustrate the importance of natural meteorological variability and land use factors (*e.g.* gold mining and clearing of vegetation) on the social impact of major flood events in nineteenth century California.

## THE CHALLENGES OF DEVELOPING CLIMATE MONITORING INDICES FOR CALIFORNIA

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The state of California has numerous microclimates and a unique geography that may not vary through time in the same way. The precipitation patterns of the winters of 2004-2005 and 2005-2006 have demonstrated strong north-south gradients. Similarly, California exhibits significant changes in temperature and precipitation from the coast to the high Sierra Nevada. The question addressed here is how to represent the various climates and the degree of their variability in an abbreviated manner for communicating with policymakers, the public, and scientists. The intention is to develop an index or indices with near real-time monthly updates, beginning with temperature and precipitation. For this purpose the Summary-of-the-Day (TD-3200) dataset from the National Climatic Data Center, as updated by the pre-1948 TD-3206 dataset, will be relied upon. A number of criteria are considered for inclusion of stations. Long periods of record are desired, at least 50-100 years, with no more than 10-15% missing. Each climate and physiographic province should be adequately represented. Stations that exhibit pronounced inhomogeneities will not be favored. The same station set need not be utilized for both temperature and precipitation. Stations should have an adequate potential for continuation of observations in the future, and need to report near-real time for inclusion in the index or indices. Preliminary statewide and regional indices for temperature and precipitation will be presented.

## PLANKTONIC FORAMINIFERA INDICATE A NEGATIVE RELATIONSHIP BETWEEN THE CALIFORNIA CURRENT AND NORTHERN HEMISPHERE TEMPERATURES UNTIL THE 20$^{TH}$ CENTURY

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Isotopic records from planktonic foraminifera are developed from Santa Barbara Basin sediments to understand the nature of upwelling and hydrographic variability beyond the multiannual time scale in the California Current. The $\delta^{18}O$ measurements from several species of planktonic foraminifera are examined from two (five) year sampling intervals from A.D. 1737-2001 (A.D. 255-1955). There is a negative relationship between near surface temperatures of the California Current, inferred from the $\delta^{18}O$ of *Globigerina bulloides*, and northern hemisphere temperatures for nearly 1700 years prior to the 20$^{th}$ century, but a positive relationship in the 20th century. The negative relationship is apparent on multidecadal to centennial time scales, particularly during the peak warming (cooling) of the Medieval Warm Period (Little Ice Age) and suggests greater upwelling in the California Current during times of northern hemisphere warming. Comparison of $\delta^{18}O$ from *G. bulloides* with SST and abundances of several species of foraminifera that show a good relationship with SST indicates that the 20$^{th}$ century warming of the California Current is associated with different vertical ocean structure then previous warm periods. There is a greater thermal gradient in the near surface due primarily to increased ocean-atmosphere heat exchange as well as an underlying shoaling of isotherms from greater alongshore winds. The 20$^{th}$ century changes in hydrographic structure and the positive relationship with northern hemisphere temperatures are consistent with models and hypotheses of a greenhouse gas-induced warming. Patterns of atmospheric pressure and precipitation that vary with coastal SST may also differ during the 20$^{th}$ and 21$^{st}$ centuries relative to previous time periods.

## LATE HOLOCENE PLANKTONIC FORAMINIFERAL ASSEMBLAGE SHIFTS IN SANTA BARBARA BASIN, CALIFORNIA: INDICATORS OF RAPID ENVIRONMENTAL CHANGE

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Large-amplitude fluctuations in surface water and climate conditions along the California Margin had severe effects on the survival of the local flora and fauna. Humans are equally vulnerable, as these environmental changes have been linked to native Chumash cultural evolution and societal shifts. To understand and reconstruct environmental changes in surface ocean conditions through the Holocene we must examine the biogenic component of rapidly

accumulating sediments. The planktonic foraminifera of Santa Barbara Basin are sensitive to climate change over glacial/interglacial and stadial/interstadial time scales. Here we present a high resolution paleoceanographic record of planktonic foraminiferal assemblage change from ODP Site 893 that demonstrates this sensitivity continued through what is generally considered to be a warm stable climatic interval.

Absolute numbers of planktonic foraminiferal specimens decreased through the Holocene, from a peak of more than 30,000 specimens/cm$^3$ at 9,000 yr B.P. to several thousand during the last millennia. Eurythermal, high nutrient species *Globigerina bulloides* and *G. quinqueloba* show opposite abundance trends throughout deglaciation, with significant decreases in *G. bulloides* abundance during the late Holocene while *G. quinqueloba* increases in abundance. Significant assemblage shifts beginning at 4,000 yr B.P. are particularly pronounced in *Neogloboquadrina pachyderma* dextral/sinistral ratios. Large fluctuations in the dextral/sinistral ratio occur during this interval, varying between 0.50 and 0.95.

Assemblage data suggest more dramatic environmental change than indicated by oxygen isotope records derived from planktonic foraminifera. While *N. pachyderma* dextral/sinistral ratios are dominated by the dextral morphology during the early Holocene, substantial decreases in the ratio occur beginning at 4,000 yr B.P. and show marked variability until the present day. As sinistral *N. pachyderma* have not been found in modern Santa Barbara Basin assemblages since the 1920s, dextral/sinistral ratio decreases of up to 0.50 suggests that sea surface temperatures were much cooler during the intervals 4,000 to 3,500, 1,500 to 1,200, and 800 to 200 yr B.P. During these intervals, increases in the sinistral morphology coincide with increases in *G. quinqueloba*. ODP Site 893 is located at the confluence of the cool, relatively fresh California Current and the warm, saline countercurrent. We suggest during these cool intervals the California Current dominated surface water masses in the basin, leading to a less strongly stratified thermocline. These results correlate with an intense drought period from 1500 to 1200 yr B.P. in the American southwest that has been documented by numerous studies. The planktonic foraminiferal assemblage shifts are consistent with work of Kennett and colleagues, who proposed that rapid cultural evolution of the native Chumash during the medieval period (A.D. 500-1300) was a response to an anomalously cool, dry, and variable climate. These results document a highly variable late Holocene climate on the California margin, similar to the variability found in a number of studies from other regions, suggesting an atmospheric teleconnection.

## APPLYING A PROCESS-BASED MODEL OF TREE-RING FORMATION TO HIGH ELEVATION TREES

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High elevation bristlecone pines (*Pinus longaeva*), including those in the White Mountains of California have experienced a dramatic increase in annual ring width increment in the 19$^{th}$ and 20$^{th}$ centuries. This increase is unique in the past 5,000 years. To examine potential

causes of variation in ring width, we applied a process-based model which first uses principles of tree biology and climate data rather than statistical predictions to derive annual growth increments. The Vaganov-Shashkin tree-ring model uses the principles of limiting factors to calculate conifer tree-ring formation integrated over the growing season from daily temperature, precipitation, and sunlight. We used meteorological data from station records of daily precipitation and mean temperature from the comprehensive Global Daily Climatology Network that are, somewhat unusually, available for two high elevation stations in the White Mountains to simulate local bristlecone pine tree-ring chronologies. Missing temperature data are replaced by linearly interpolated values; missing precipitation data were simply set to zero. Temperature is partially corrected for elevational differences by using an adiabatic correction for the mean elevation difference between the actual tree-ring chronologies and the meteorological stations. Increased tree ring growth is more evident at higher elevations. This is evident in both actual and simulated ring width, showing that climate data alone can produce this larger upward trend in annual growth increment at higher elevations. We explore how climate and possible $CO_2$ fertilization might combine to produce the observed trends in high elevation tree growth in western North America.

## DEVELOPMENT OF A HISTORIC SEA SURFACE TEMPERATURE RECORD USING THE OXYGEN ISOTOPIC SIGNAL FROM ANNUAL GROWTH RINGS OF GEODUCK CLAMS

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Geoducks (*Panopea abrupta*) are long-lived (>100 years), large, subtidal clams that are found along the Pacific coast of North America, but are most abundant from Puget Sound to southeast Alaska. These clams deposit well-defined annual growth bands within their shell each winter. Sclerochronological analysis of these growth rings indicates that ring growth is associated with temperature; the oxygen isotopic signal captured within the annuli should also reflect sea surface temperature. In order to test this hypothesis thin-sections were obtained from individual clams from the hinge, as well as from along the axis of maximum growth. These sections were then sampled at the annual growth band increment for oxygen and carbon isotopes. Geoducks used in this study were collected in 2000 from Puget Sound. Preliminary results indicate that the oxygen isotope record appears to be recording annual variability in sea surface temperature.

## WESTERN CLIMATE IN MEDIEVAL TIME: TROPICAL AND GLOBAL CONNECTIONS TO THE GREAT CALIFORNIA DROUGHTS

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Evidence for pervasive dry conditions with episodes of severe drought in the western U.S. between approximately A.D. 500 and 1300 has been well documented over the past two decades. The evidence for this Medieval Climate Anomaly (MCA) comes from a wide variety of proxy records including tree rings, pollen reconstructions, fire-related records, fossil trees, marine cores, and pedological studies. Recently available marine proxy records indicating that the tropical Pacific was in a La Niña-like state during Medieval time suggest a likely causal mechanism for the medieval climate anomalies in the West.

We will describe the character and extent of the MCA as seen in some of the proxy records described above, reconstructions of medieval atmospheric circulation patterns from statistical and AGCM results, and in quantitative estimates of precipitation amounts during the California megadroughts obtained from several methods including lake level and river flow reconstructions. Evidence relating to the "tropical Pacific hypothesis" for medieval climate change in the western U.S. will be discussed. Extension of this evidence to modern regional climate anomalies from around the planet places the medieval western droughts within the context of global Medieval climate change.

## THE EXTINCTION OF NORTH AMERICA'S PLEISTOCENE MAMMALS

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Toward the end of the last Ice Age, North America lost an astonishing set of mammals, from mammoths, mastodons and giant ground sloths to sabertooth cats and giant bears. The best known explanation for these extinctions maintains that they all occurred around 11,000 years ago and were caused by the first arrival of human hunters in the New World. This view has been widely adopted by ecologists and conservation biologists and is beloved by the popular media. It makes good press and adds intuitively appealing spice to popular works on human impacts on the environment. However, it gets very little support from the archaeological and paleontological records. How little will become clear from this presentation, which will range from the peopling of the New World and the nature of North America's Pleistocene faunas to the Magdalenian hunters of southern France and the fate of their reindeer prey.

## 625 YEARS OF SALINAS RIVER STREAMFLOW RECONSTRUCTED FROM BLUE OAK TREE RINGS

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The Salinas Valley in California is known as America's salad bowl and is home to a $3.5 billion crop industry based largely on groundwater irrigation. Saltwater intrusion associated with long-term aquifer overdraft has ruined thousands of hectares of productive agricultural lands and threatens major municipal wells. Recharge of these alluvial aquifers comes primarily from precipitation and subsequent infiltration from the Salinas River and its tributaries. A 60-year record of estimated full natural monthly flow is available at Paso Robles in the upper basin. This record exhibits dramatic inter-annual to decadal variability, including the epic drought of 1976-1977. Old growth blue oak (*Quercus douglasii*) woodland is widely distributed in and near the drainage basin of the Salinas River and the radial growth of this species is remarkably sensitive to annual precipitation totals. A new network of 400- to 700-year long blue oak tree-ring chronologies has recently been developed. These exceptional time series are highly correlated with Salinas River flow records at Paso Robles and other gauging stations along the river. A 625-year reconstruction of annual mean flow at Paso Robles explains 75% of the variance during the instrumental period, and indicates many zero flow years equal to the drought of 1976-1977 and extreme decade-long droughts more severe than any measured during the instrumental period from 1940 to present. Mean flow between 1917 and 1931 is estimated to have been less than half of normal. This 15-year drought appears to be the worst in the last 625 years and coincides with the development of new pumping technology and the first signs of seawater intrusion in the lowest reaches of the valley. This extreme drought was immediately followed by a prolonged pluvial, perhaps the wettest period in the reconstruction. This long-term perspective on hydrologic variability should be useful in the multi-million dollar efforts at water management in the Salinas basin.

## LOCAL MODES OF ATMOSPHERIC VARIABILITY: A CASE STUDY OF SOUTHERN CALIFORNIA

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We examine the primary modes of local atmospheric variability in a 6-km regional atmospheric model of the southern third of California. The model was forced by reanalysis of boundary conditions over the period 1995-2003. The region is approximately the same size as a

typical grid box of the current generation of general circulation models used for global climate prediction and reanalysis product generation, and so can be thought of as a laboratory for the study of climate at spatial scales smaller than those resolved by global simulations and reanalysis products. We find that the simulated circulation during the October to March wet season, when variability is most significant, can be understood through an objective statistical classification technique in terms of three wind regimes, which we label "Santa Ana", "Onshore", and "Common Northwesterly". The composite surface wind patterns associated with these regimes exhibit significant spatial structure within the model domain, consistent with the complex topography of the region. These regimes also correspond nearly perfectly with the simulation's highly-structured patterns of variability in hydrology and temperature, and therefore are the main modes of local climate variability. Surprisingly, the regimes are approximately equally likely to occur regardless of the phase of the classical large-scale modes of atmospheric variability prevailing in the Pacific-North American sector. The high degree of spatial structure of the local regimes and their tightly-associated climate impacts, as well as their ambiguous relationship with the primary modes of large-scale variability demonstrates that the local perspective offered by the high resolution model is necessary to understand and predict the climate variations of the region, including its response to past and future climate forcing.

## HYDROLOGIC IMPLICATIONS OF 20$^{TH}$ CENTURY WARMING IN THE WESTERN U.S.

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Observed changes in temperature and precipitation have reduced spring snowpack and caused earlier snowmelt over much of the western U.S. We summarize a series of integrated studies using both observations and hydrologic models in which we have evaluated the implications of these changes for runoff timing, the seasonal cycle of soil moisture recharge and depletion, evaporation, and flood risk. In areas of the West that have substantial snow accumulation in winter, warming temperatures have resulted in increased runoff in winter and less runoff in summer, earlier peak runoff in spring, and earlier soil moisture recharge in spring. Evaporation, while apparently increasing somewhat in many areas, has so far had relatively minor effects in comparison with interannual variations in precipitation. Natural flooding regimes are affected by warming via seasonal changes in antecedent snowpack and contributing basin area during storms.

These hydrologic changes, although broadly characteristic of the West as a whole, vary spatially as a function of mid-winter temperature regimes. Mountains near the Pacific Ocean, which typically have mild temperatures and heavy precipitation, have mostly seen large downward trends in spring snowpack and consequent changes in timing of stream flow and soil moisture recharge, all of which can be numerically attributed to rising temperatures. Colder

inland areas are less affected by temperature, and in these regions precipitation changes are the dominant driver of observed hydrologic changes. Simulated changes in natural flood risks that accompany large scale warming are a complex function of mid-winter temperature regimes, but are also related in some cases to basin topography, the seasonal timing of storms, and other factors. In strongly snowmelt-dominanted river basins, flood risks in most cases have declined as a result of 20$^{th}$ century warming, due to reductions in spring snowpack. For river basins near the freezing level in mid-winter the effects of warming on flood risks vary widely and increases or decreases in flood risks can occur in response to warming depending on the relative importance of changes in effective basin area and antecedent snow conditions that are coincident with storms. In rain dominant basins flood risks, although affected somewhat by systematic changes in soil moisture, are largely stationary in response to warming.

Changes in precipitation, which are the dominant driver of flood risk and annual stream flow volume changes, have not yet been shown either globally or locally to be responding markedly to increased greenhouse gases. This contrasts with the situation for temperature. Therefore, future hydrologic variability in the West should be controlled by decadal-scale variations in precipitation combined with systematic and largely monotonic increases in temperature.

## PREDICTING CLIMATE CHANGE ON A GREEN PLANET: THE DAUNTING CHALLENGE

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Missing from current climate models are feedback mechanisms coupling climate and ecosystems. Results from analysis of past climate change, from ongoing climate manipulations in ecosystems, and from observations of ecosystems along climate gradients will be presented. I show that climate-ecosystem feedbacks are likely to be large and positive, and thus future warming may be considerably more intense than is currently anticipated. Nevertheless, there are huge gaps in our understanding of ecosystem responses to global warming.

## DROUGHT VARIABILITY CONTRASTS BETWEEN MONTANE AND ARID PARTS OF THE WESTERN US.

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Hydrologic model analyses demonstrate fundamental differences in the response and susceptibility to drought of montane, arid, and intermediate zone portions of the western United

States. The analyses were conducted using the Variable Infiltration Capacity model (VIC). Several major dry episodes during the last five decades are included in this model-guided historical analysis, which is augmented by experiments involving changes in temperature and precipitation superimposed upon the observed climatic forcing.

In montane regions, sufficient runoff soil moisture from snowpacks tends to be available during spring and early summer, so that actual evapotranspiration (AET) is limited primarily by the energy available. In these regions, spring and summer dryness is not determined by deficits in winter precipitation but by anomalously warm summer temperatures. In arid regions, summer dryness is governed by deficits in both winter and warm-season precipitation, but is not significantly affected by summer temperature. In lowland arid regions, the impact of winter precipitation upon subsequent soil moisture is very strong at lags of three months, although in some regions like southern California, significant correlations were found at lags of five months. In montane regions, the storage of winter precipitation in the natural reservoirs provided by snowpack adds a longer memory, up to five months, to those provided by soil moisture storage alone.

At annual time scales, total precipitation is the primary control on total soil moisture and runoff. However, warming trends may be expected to result in wetter than historical soils during winter and early spring (due to larger rain/snow ratios and earlier snowmelt) and drier conditions during late spring and summer (due to increased AET rates).

## DURATION AND MAGNITUDE OF MID-HOLOCENE MEGADROUGHT RECORD FROM FLATHEAD LAKE, MONTANA AND PROBABLY LINK TO VOLCANIC FORCING

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Holocene abrupt climate changes are commonly explained by variations in ice-sheet dynamics, ocean circulation, solar forcing, or internal variability of the ocean–atmosphere system (*e.g.*, changes in SST or the magnitude and frequency of ENSO events). In contrast, the effects of volcanic eruptions as a driving mechanism for abrupt climate changes in the Holocene are relatively poorly understood. We present a variety of data sets from Flathead Lake, Montana to propose that the eruption of Mount Mazama ~7,600 cal yr B.P. caused a decade-long megadrought in western North America. Analysis of high resolution reflection seismic profiles, sediment cores, exposed Quaternary sediments, and geochemical and hydrological modeling studies from Flathead Lake suggests that precipitation in the Flathead Lake drainage area fell to ~20% of its present day level for a period lasting for several decades, resulting in a megadrought that far exceeded in magnitude and duration that of any historic drought in the region. The increase in volcanic particles and aerosols from the eruption decreased effective solar radiation and caused a major shift in global climate leading to the megadrought in the northern Rocky Mountains. Published paleoclimate studies for this time frame suggest contemporaneous abrupt shifts of climate in many other parts of the world. We infer that cooler conditions in the northern hemisphere resulting from the eruption shifted the mid-latitude high pressure zone and the ITCZ

southward, producing long lasting winter-like conditions in the northern hemisphere and relatively warmer conditions in the southern hemisphere.

## LINKS BETWEEN DIURNAL CYCLES OF WIND AND TEMPERATURE IN COMPLEX TOPOGRAPHY

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Analyzing a 6-km-resolution atmospheric simulation of southern California from 1995 to the present, we characterize climatological diurnal cycles of surface air temperature and winds and uncover dynamic links between them. The large daily warming and cooling over land induces expected flows across the coastline and elevation isolines, causing convergence (divergence) at mountaintops during the day (night). As expected, the daytime sea breeze component of this flow pattern reduces daily maximum temperatures in the zone between the coast and adjacent mountain ranges. However, because the regional atmosphere is generally stratified, this flow pattern also results in cooler air being advected upslope during daytime and warmer air being drawn downslope at night. This suppresses temperature diurnal cycle amplitude not only in the coastal zone but also at the highest elevations. Because stratification is greater in the coastal zone than in the desert interior, these thermal effects of diurnal winds are not uniform, introducing significant spatial structure into the shape of the temperature diurnal cycle as well as its amplitude. In the coastal zone, the nighttime advective warming is large enough to counter the effects of radiative cooling, so that temperatures remain steady throughout the night. In the interior, by contrast, advective warming is smaller than radiative cooling, leading to a continuous nighttime drop in temperature. Similarly, during the day the larger advective cooling in the coastal zone causes daily temperature maxima to occur approximately two hours earlier than in the interior. The geographical variations in the shape of the diurnal temperature cycle also induce secondary diurnal wind anomalies, which manifest themselves either as rotation in diurnal winds or deviations in the timing of maximum flow. We confirm that these characteristics of temperature and wind diurnal cycles are also found in a network of 30 observation stations in the region, giving confidence to the simulation's realism and our study's findings. We speculate that the dynamic links between the two diurnal cycles may also be found in other regions of complex topography, their importance is dependent on the degree of stratification of the regional atmosphere.

# HIGH-RESOLUTION $TEX_{86}$ PALEOTEMPERATURE RECONSTRUCTION IN A.D. 1850-1987 VARVED SEDIMENT FROM THE SANTA BARBARA BASIN, CALIFORNIA

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Schouten and others (2002) introduced a new biomarker proxy for water temperature that is based on the relative distribution of different types of glycerol dibiphytanyl glycerol tetraethers (GDGT) produced by crenarchaeota. Originally crenarchaeota were thought to be extremophiles, but in recent years they have been shown to be ubiquitous and abundant in seawater and in some lakes. Crenarchaeota change the relative distribution of their outer-membrane lipids (GDGT) to adapt to different temperatures, by increasing the number of cyclopentane rings (from zero to four) as water temperature rises (Wuchter and others, 2004). This proxy is called $TEX_{86}$ and seems to be diagenetically stable and not sensitive to other environmental factors such as salinity and nutrient availability. By measuring the relative amounts of GDGT that are preserved in dated sediments we can determine the temperature at which the organisms were living. $TEX_{86}$ analyses of varved sediments from the depocenter of the Santa Barbara Basin yielded an A.D. 1850-1987 time series of sub-surface water temperatures, most likely reflecting conditions below 75 m water depth. A comparison with regional sediment-based and instrumental SST records indicates that our $TEX_{86}$ data do not record the warming of surface waters during El Niño events. Statistical time series analyses suggest that the Pacific Decadal Oscillation (PDO) mainly influences the $TEX_{86}$ record. Our $TEX_{86}$ time-series, as well as instrumental and foraminifer-based Santa Barbara Basin temperature records (Field and others, 2006), show that the Santa Barbara Basin study area has been warming during the last ~150 years. Alkenone-based ($U^{k'}_{37}$) sea surface temperature reconstructions are the only exception. The different behavior of alkenones may be rooted in a deepening of the haptophytes' habitat in the water column and/or a shifting seasonal bias in alkenone production.

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## VEGETATION AND CLIMATE CHANGES IN THE WESTERN U.S. DURING THE LAST 250,000 YEARS: THE RECORD FROM BEAR LAKE, UTAH-IDAHO

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Pollen analysis of a 120-m-long core (BL00-1) from Bear Lake, Utah-Idaho, has resulted in the reconstruction of the vegetation and climate over the last two glacial-interglacial cycles. An average sampling interval of 650 years (30 cm) for the past 250,000 years allows for submillenial-scale analysis of vegetation and climate. The pollen results are very consistent with the isotopic and carbonate content data of the SPECMAP record. Three intervals with abundant endogenic aragonite and enriched $\delta^{18}O$ and $\delta^{13}C$ (Bright and others, in press) have been interpreted as warm and dry periods, correlated with the interglacials OIS 1, 5e and 7a. Our pollen data show a similar pattern of warm and dry periods, but in addition, we are able to identify OIS 1 – 7, and substages OIS5a through OIS5e. Pollen from interglacials OIS 1, 5, and 7, and interstadial OIS 3 contrast with that from glacials by having higher percentages of desert shrub taxa (*Sarcobatus, Ambrosia,* and Amaranthaceae-Chenopodiaceae), as well as *Juniperus* and *Quercus*, indicating warm and dry conditions. On the other hand, glacial periods (OIS 2, 4, and 6) are characterized by higher percentages of conifers such as *Abies*, *Picea*, *Pseudotsuga,* and *Pinus*, suggesting colder and perhaps wetter conditions. These high-resolution pollen data allow subdivision of OIS5 and 7 into five substages (5a-5e and 7a-7e) as in the marine $\delta^{18}O$ isotopic curve of Shackleton (1969). The warmest period of the last 250,000 years may be OIS5e, with the highest percentages of *Juniper*, *Quercus,* and *Sarcobatus*. This study will allow greater refinement of the Bear Lake sedimentary sequence. It is also one of the most complete and continuous pollen records of the last 250,000 years in the western U.S.

## TIMESCALE DEPENDENCE OF THE ENSO-PRECIPITATION TELECONNECTION IN THE WESTERN U.S.

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It is well-established that the winter precipitation distribution in the western U.S. is significantly correlated with the state of ENSO, such that warm (El Niño) conditions tend to enhance precipitation in the south, and reduce it to the north, while cold (La Niña) conditions produce the opposite pattern. This correlative analysis of the ENSO-precipitation teleconnection has proven useful for purposes of long-range hydroclimatic prediction, but misses important

aspects of the relationship, and fails to explain precipitation variability across the region and specifically, in the middle latitudes. Regional precipitation is shown here to correlate significantly with ENSO conditions, but in a manner that is timescale-dependent. Since 1930, warm ENSO conditions tend to enhance regional precipitation at multidecadal (>40 yr), decadal (10-20 yr), and ENSO (4-6 yr) timescales, whereas cold ENSO conditions significantly enhance precipitation at the biennial (2.1-2.2 yr) timescale. This mixed ENSO influence largely explains why correlations with regional precipitation are small, and suggests that separating ENSO processes by timescale will enhance predictive power in long-range forecasting. These findings also indicate that the traditional 'north-south' response to ENSO is largely a statistical artifact of multiple ENSO processes with different timescales, rather than a quasi-linear response of the mid-latitude atmosphere to the state of ENSO.

## DECADAL DROUGHT CYCLES IN THE WESTERN UNITED STATES AND THEIR POSSIBLE ORIGINS

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Century-long instrumental hydrologic records from the western U.S. exhibit cyclicity at a period of approximately 15 years. This behavior is evident in time series of regional mean winter precipitation and annual flows of the Sacramento, San Joaquin, and Snake Rivers. This decadal cycle has increased in amplitude in recent decades and accounts for observed multi-year droughts, including 1976-1977, 1987-1992, and 2000-2003, and lesser droughts extending back to the late 19$^{th}$ century. The proposed cause of these decadal droughts is the interaction of the annual cycle with a quasi-biennial (QB) cycle which has an impact on both western U.S winter precipitation and ENSO. The QB oscillation of ~2.13 years produces an amplitude modulation of ~15 years, which is translated into shifts in mean precipitation due to the asymmetry of its effects. The precipitation variability that is characteristic of the QB is more effective at enhancing decadal precipitation than reducing it. Thus, active QB stages coincide with wetness and high interannual precipitation variability, while quiescence in the QB oscillation tends to produce persistent drought conditions and low year-to-year precipitation variability.

## THE MEDIEVAL DROUGHTS HYPOTHESIS: A MIDTERM EVALUATION

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Inspired by Stine's findings from Mono Lake (Stine, 1994) and Graumlich's (1993) tree-ring study from the southern Sierra Nevada, California, archaeologists have for over a decade, been considering the possibility that prehistoric societies were affected by anomalously severe droughts during the Medieval Climatic Anomaly (MCA; A.D. 800-1350). Decreased production

at the Coso obsidian source, dramatic increases in bead production and sociopolitical complexity in the Channel Islands, subsistence and tool changes on the central California coast were among the trends initially attributed to drought-related demographic stresses. As the search for signs of unusual cultural changes during the MCA has broadened, some early patterns have been negated or found to be more complex than originally thought, while others have been strenghtened. Review of the archaeological evidence for drought-related cultural changes in prehistoric California during the MCA suggests, however, that the overall hypothesis remains viable.

Graumlich, L.J., 1993, A 1000-year record of temperature and precipitation in the Sierra Nevada: Quaternary Research, v. 39, p. 249–255.

Stine, Scott, 1994, Extreme and persistent drought in California and Patagonia during Mediaeval time: Nature, v. 369, p. 546–549.

## SOUTHWEST DROUGHTS SINCE 250 B.C: THEIR IMPACT ON ENVIRONMENTS AND EARLY CULTURES, AND ON DIRE PREDICTIONS OF FUTURE CLIMATES

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Southwest droughts track with the 556-year Phase Cycle and its 2/1(278 yr) and 4/1(139 yr) resonances referenced to A.D.1433. The definition in the Southwest of the 278-year Sub-phase Cycle was originally based on time-frequency analyses of numerous dated and buried archaeological sites, trees, soils, and unconformities. Stratigraphic relations indicate joint development in these features formed during drought intervals. Subsequent burial occurred during following wetter/cooler intervals marked by higher water–table levels, landslides, and flood plain deposition.

Recently published tree-ring indices from long-lived trees near Grants, New Mexico clearly demonstrate the same resonance timing of droughts back to the beginning of the Christian era. Similarly, buried archaeological sites exposed in washes in Colorado are contemporaneous with dated sites on Black Mesa, Arizona, thus recording a similar cyclical history of erosion and deposition.

Regional distribution of tree-ring-dated surface archaeological sites indicate population expansion into intermediate elevations of the Colorado Plateau during wetter intervals and counter movements to wetter/cooler higher elevations, and to valley bottoms with perennial water supplies. According to the resonance model, the droughts were centered close to 235 B.C., A.D. 43, 321, 460, 599, 738, 877, 1016, 1155, 1294, and 1433. During the A.D. 1155 drought, the western part of the Colorado Plateau was largely abandoned. During the drought that occurred around A.D.1300 (the Great Drought of early researchers) the rest of the Colorado Plateau region was abandoned, but with some of the population retuning to the area and expanding during the ensuing wetter/cooler interval, only to again relocate during the following 15th century drought into the higher Mogollon Rim region. Some of this population dispersal

was evidently into established pueblos with perennial water supplies in the nearby Rio Grande Valley.

Analysis of tree-ring records continues in order to determine the presence of higher frequency components using full-, half- and third-cycle smoothing. Despite increased regional variability with increased frequency, many records show strong tendencies to oscillate with the 22 yr cycle, and/or with its 2/1 (11 yr) resonance. In addition, some records show strong phasing with the resulting beat cycle of about seven years. Stream flow records from New England to California, which have been collected since 1911, emphasize this beat cycle.

Elements of the same resonance patterns are evident in scores of instrumental and paleoclimatic time series. These patterns are recorded as systematic changes in vegetation, water temperature and salinity; sea- and lake–levels, aerosols, atmospheric gases, and stable isotopes. These cycles are present at sites in Alaska, Canada, Greenland, the United States, Iceland, Scandinavia, Germany, Russia, Switzerland, China, Tunisia, Egypt, Argentina, Chile, Brazil, Antarctica, and from Atlantic and Pacific Ocean cores.

Much can still be learned about climatic processes, regional variability, and controlling mechanisms. Nevertheless, sufficient evidence is available to demonstrate that past climate was strongly oscillatory in character at frequencies ranging from seasonal to tens of thousands of years. This strong natural oscillatory character seriously affects the validity of using a small segment of the past record to predict unidirectional future climatic trends - such as is being done in predictions of dire consequences from solely human-induced global warming since the Industrial Revolution (since 1850).

## DROUGHT RELATED PROCESSES IN THE MOUNTAINOUS WESTERN U.S.

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The susceptibility of the western U.S. to drought is due to an increasing reliance on snowpack to meet the demand fro water. This problem is exacerbated by annual precipitation variability during the winter. On average, many regions are near the limits of naturally available water, and may exceed those limits in some years that are still within the range of natural variability.

Processes controlling seasonal snowpack variability in mountainous regions of the western U.S. are presented. These processes are conditionally applicable to all mid-latitude, north-south oriented mountain ranges, such as the Sierra Nevada, Cascades, and Great Basin ranges. Examples are presented for the Colorado Rockies.

Windward and leeward slopes, and higher and lower elevations, receive snow in differing amounts and in different patterns that are related to synoptic circulation. Winters dominated by either zonal or meridional flow, interacting with regional topography, are responsible, and these are often ENSO phase related.

Winters dominated by strong zonal (westerly) flow often occur during La Niña, and have at least average snowpacks on the western (windward) slopes, and at higher elevations on

leeward slopes. Lower elevation, leeward-side snowfall is below average. Meridionally dominated winters, often an El Niño signature, tend towards the opposite situation.

The temporal characteristics of snowfall are different, as well. With zonal flow, very frequent, small snowfall events occur, favoring leeward-side upper elevations, whereas with meridional flow, large but infrequent events occur, often favoring the lower elevation leeward-side slopes. On a multi-year scale, a combination of the two flow regimes can produce a drier, mid-elevation zone on the leeward slopes.

## LATEST PLEISTOCENE-HOLOCENE VEGETATION CHANGE AT BLUE LAKE, WESTERN BONNEVILLE BASIN, UTAH

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The marshes at Blue Lake, Utah, contain a long and well-dated series of sediments that cover the last 40,000 years, representing the entire history of the last rise-and-fall cycle of Pleistocene Lake Bonneville and the Holocene. This site is located about 40 km south of West Wendover, Nevada, on the margin of the Great Salt Lake Desert. Our investigations of sediment cores taken from the marshes include analyses of pollen, inorganic carbon, other microfossils, and sediments. The Blue Lake locality has the potential to provide one the best-documented and responsive records of latest Pleistocene and Holocene regional environmental change in the western Bonneville Basin. Preliminary results highlight the history of lake and marsh system development during the past 40,000 years, and striking patterns of vegetation change that occurred in the surrounding terrestrial environment during the Holocene.

## CONTINUOUS RECORDS OF DROUGHT VARIABILITY AND POSSIBLE CAUSES FROM SOUTHERN CALIFORNIA AND THE SIERRA NEVADA

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Instrumental records of precipitation variability in southern California extend back only slightly more than 100 years and are too short in duration to capture the full magnitude of natural drought severity and duration. These short records are also insufficient to elucidate the presence or persistence of low-frequency periodicities in precipitation variability which might be expected from forcing factors such as the Pacific Decadal Oscillation (PDO). The short instrumental records can be augmented by a rich array of proxy climatic archives available in California. Two of the most useful of these are tree rings and the detailed analysis of lake sediments. Both

archives offer the potential of providing proxy climate records extending back centuries to millennia. Analysis of such archives from southern California and the Sierra Nevada reveal some important insights into natural drought severity, duration, and periodicity. In addition, paleoclimate archives can provide information on potential forcing factors that drive droughts. Both tree-ring and lake sediment studies suggest that the state, and west in general, has experienced droughts over the past 2,000 years that are more severe and more sustained than those encountered over the past century of instrumental records. Tree-ring records also allow for the analysis of the geographic extent of drought – an important question in southern California due to reliance on local, northern Californian and Colorado Basin water. Most troubling in the records from tree-rings and other archives is evidence for apparent megadrought conditions that persisted over much of the west for a prolonged period between A.D. ~900 and 1300. New lake sediment archives, coupled with tree-ring evidence suggest that such periods of prolonged aridity may not be atypical of the long-term California climate over the past 3,000 years. The cause of such persistent events must lie in the coupled ocean-atmosphere system. California is particularly sensitive to conditions in the eastern Pacific such as the PDO. A tree-ring-based reconstruction of the PDO suggests that this mode of variability has been important over the past 200 years, but has flickered on and off when viewed over the past 1,000 years. The PDO reconstruction further suggests a general change in the mean-state of the index coincidental with the A.D. ~900–1300 dry period.

## A HOLOCENE RECORD OF ENVIRONMENTAL CHANGE AND SEDIMENT SOURCE CONTRIBUTIONS TO A TIDAL SALT MASH IN SAN FRANCISCO BAY

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Analyses of sediment cores from a tidal marsh located on the margin of San Pablo Bay, a sub-basin of the San Francisco Bay estuary, have produced a late Holocene record of changing environmental conditions. Organic sediments reveal changing vegetation patterns, which reflect changes in salinity and suggest that between 3,400–2,000 cal yr B.P., conditions on the surface were relatively fresh compared to modern salinity. This period was followed by a trend towards higher salinity after 2,000 cal yr B.P. until approximately 700 cal yr B.P. Conditions appear to have been fresher 200 years ago than today, which may be a consequence of up-stream management practices. Grain-size analysis suggests that three flood events washed coarse-grained sediment from local hill slopes onto the marsh surface. Sediment chemistry was used to determine the various sources of sediment deposited on the marsh. The abundance of 18 elements was measured using ICP-MS, and the results were used to distinguish between sediments from local sources (the hills surrounding the site) and sources from San Pablo Bay. The sediments from San Pablo Bay are a mixture of material arriving through the Sacramento-

San Joaquin delta and from other tributaries to San Pablo Bay. Increased local sediment input, particularly of coarse material, can be indicative of high local rainfall events, possibly related to El Niño conditions.

## EVALUATION OF HYDROLOGIC INDICES FOR FORECASTING WESTERN U.S. SEASONAL WATER SUPPLY

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Forecasting seasonal runoff is an important challenge in the western U.S. because the timing and volume of summer (dry season) streamflow plays a critical role in managing water supply and delivery systems. Beginning in January of each year, observations of the snow pack throughout the west begin to provide invaluable information on the amount of runoff expected in late spring and summer. The quality of such water supply forecasts also benefits, in some locations, from the consideration of synoptic climate indices – *e.g.*, using sea surface temperature anomalies to characterize ENSO or PDO state, which have been shown to have predictable teleconnections to land surface hydrology months in advance. These two sources of forecast information complement each other, with climate/SST state information providing predictability at long lead times (3-9 months), and observed snow and other moisture states of local catchments providing skill at shorter lead times (1-4 months). However, since similar SST anomalies can produce widely different future hydrology outcomes, information at intermediate lead times describing how a particular teleconnection or climate pattern is evolving on a macro-scale level (especially regarding precipitation anomalies) may provide additional insight into future spring and summer runoff. In this study, we explore the use of a long-term land surface hydrology data set to define hydrologic indices with potential predictive value, and to assess where these might enhance predictability already achievable using local observations and climate indices. We find one candidate index with potential value in the Pacific Northwest, but little improvement in forecasting seasonal water supply in the southwestern U.S. relative to existing climate and observation-based indices.

## ASSOCIATIONS OF MULTI-DECADAL SEA-SURFACE TEMPERATURE VARIABILITY WITH U.S. DROUGHT

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Persistent climatic anomalies (*i.e.* pluvials and droughts) are related to decadal to multi-decadal (D2M) variability in the climate system. This D2M variability is noticeable in a number of climatic and hydroclimatic time series. In particular, D2M variability of North Atlantic sea-surface temperatures (SST) has been related to D2M variability of European climate, and more recently with D2M variability of North American climate. Analysis of global SST indicates that D2M variability in the North Atlantic Ocean statistically explains as much of the D2M variability in U.S. hydro-climate as does D2M variability in the Pacific and Indian Oceans. An analysis of the major U.S. droughts during the last century indicates that North Atlantic SST were warm in the 1930's, 1950's, and in the drying trend that began in the late 1990's. In contrast, both the early (1905-1920) and late 20$^{th}$ century (1965-1995) pluvials were associated with cool North Atlantic SST. The D2M variability of tropical Pacific Ocean SST appears to not only be related to drought occurrence in the U.S., but also has influence over where drought occurs. When tropical Pacific SST are warm (cool), drought is most likely in the northern (southern) U.S. Findings suggest that SSTs in all of the oceans have some relation with U.S. hydro-climate, but SST in the North Atlantic may have the strongest and most consistent association on D2M time scales. These associations are also evident in proxy records for North Atlantic SST and western North American drought over the past 500 years. The underlying mechanisms for these associations, which may entail both summer and winter precipitation, remain undetermined, however, and the North Atlantic may be "aliasing" for low-frequency variability in the tropical oceans. Proximate causes aside, hydroclimatic persistence on these timescales introduces significant non-stationarity in hydroclimatic conditions, with critical implications for water resource management.

## MULTI-BASIN DROUGHT AND ARIZONA WATER SUPPLY—A TREE-RING PERSPECTIVE

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The water supply of metropolitan Phoenix and surrounding areas depends primarily on runoff from the mountains of east-central Arizona. With increasing water demand, imported

water from the Colorado River has come to be relied upon as a buffer during times of drought. An important question for water planners is the probability of severe sustained hydrologic drought simultaneously reducing runoff from Arizona watersheds and the Upper Colorado River Basin. To address this question, networks of tree-ring chronologies covering the period 1521-1964 were applied in reconstructions of annual streamflow for the Upper Colorado River Basin (Lees Ferry) and for the Salt+Verde+Tonto (SVT) basins in Arizona. The reconstructions account for 70% and 77% of the calibration variance of the observed flows for Lees Ferry and the SVT, respectively. A cross-spectral analysis shows strong and significant coherency between annual reconstructed flows in the two river systems across all frequency bands, with greatest coherency at decadal and longer timescales. Joint-drought events, defined as both annual reconstructions simultaneously below the 0.25 quantile, are much more frequent than expected by chance. On the other hand, in 444 years of reconstruction, there were no cases of drought on the SVT coincident with extreme wetness (above 0.75 quantile) on the Colorado. Joint-drought events tend to cluster in the time, suggesting that multi-year reservoir storage may not always be able to mitigate the impact on water supply. Seasonal composite maps of 500-mb height departures indicate that positive winter anomalies dominate the western United States in joint-drought years, and suggest an eastward shift of the center of the high anomalies from the preceding fall.

## EXTENDED DROUGHT IN THE GREAT BASIN IN THE LAST TWO MILLENIA RECONSTRUCED FROM POLLEN RECORDS

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Pollen, algae, and macroscopic charcoal microfossils preserved in sediments from lakes, meadows, springs, and fens in the Great Basin preserve a record of periodic extended droughts across the Great Basin. In this paper I present data from four sites across northern Nevada, Pyramid Lake in western Nevada, Kingston Meadow and Newark Spring in central Nevada, and Mission Cross Bog in northern Nevada. The highest resolution record comes from Pyramid Lake. At that site, the last 2,500 years appear to have had recurrent persistent droughts. The timing and magnitude of droughts identified in the pollen record compares favorably with previously published $\delta^{18}O$ data from Pyramid Lake. The timing of these droughts also agrees with the ages of submerged rooted stumps in the eastern Sierra Nevada and woodrat midden data from central Nevada. The other three sites, while analyzed at a lower resolution, also record persistent periods of drought that coincide with the Pyramid Lake record, suggesting that these events had a regional impact on northern Nevada. Prolonged droughts in the Pyramid record appear to correspond with the timing of ice drift minima (solar maxima) identified from North Atlantic marine sediments.

## ROCK GLACIERS AND PERIGLACIAL ROCK/ICE FEATURES IN THE CENTRAL-EASTERN SIERRA NEVADA: UPDATES ON CLASSIFICATION, MAPPING, CLIMATE RELATIONSHIPS, AND WATER MONITORING

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Rock glaciers and related periglacial features are common but little-studied structures in mountain ranges of the world where conditions are high, relatively dry, and have adequate sources of shattered rock. These features are abundant in cirques and canyons of the Sierra Nevada south of Lake Tahoe, where they occur in a variety of forms. While many appear to be relict and likely do not contain ice, a large proportion shows indications of activity, suggesting embedded or underlying ice. We present updates on mapping and classification from ground surveys of nearly 400 features in the eastern Sierra Nevada. Eighteen types are described, including relict and active forms. These range from 3932 m to 2225 m and occur predominantly on NNW to NNE exposures. Because these features have been little studied in this region, their hydrologic role, relationship to climate, and structural dynamics remain unknown. To assess climate relations, we are overlaying mapped locations with the PRISM climate model. For hydrologic analyses, we have begun preliminary monitoring of outlet streams, including water chemistry (6 sites), water temperature (20 sites), seasonal stream persistence (20 sites), and stream flow (7 sites). We also set up rudimentary transect lines at six sites to assess movement. Initial results from water chemistry analyses show high concentrations of alkalinity, calcium, magnesium, and sulfate relative to Sierra Nevada surface streams, suggesting active physical and chemical weathering. Water samples also have high nitrate concentrations, suggesting nitrate is being concentrated in the outlet streams, as values are about 10 times the concentrations of Sierra Nevada precipitation. In addition to new classification and mapping results, we present summaries of climate relations for the features by type, discuss preliminary water chemistry results, describe monitoring efforts installed in summer 2005, and outline plans for future work.

## DRY REGIMES IN HISTORICAL CLIMATE RECORDS OF THE WESTERN UNITED STATES

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Historical (documentary) climatic reconstructions at daily resolution provide detailed information of climatic variability and drought at decadal and interannual timescales. Although

relatively longer records for North America exist for the eastern half of the continent and in Mexico, much unexploited daily documentary evidence and early instrumental records exist from various western North American archives extending back to the mid-late nineteenth century. Challenges that must be overcome for successful historical climatic research include 1) extensively utilizing historical and archival skills in finding old records, 2) digitization aspects, 3) application of corrections on early instrumental data concerning instrument exposures and different time observations, integration of different standards of observation from various networks (*e.g.*, Surgeon General, Smithsonian Institution, and private diaries), 4) qualitative interpretation, 5) integration of historical records with respect to the modern (twentieth century) record, and 6) integration of historical reconstructions with other high resolution paleoclimatic proxies such as tree-rings. We illustrate how historical climatologists should approach these challenges by describing several examples as related to precipitation frequency and magnitude. Precipitation frequencies from both early instrumental and documentary evidence are among the most reliable and plentiful climatic indicators for the historical climatologist, as these reconstructions can often be directly compared with modern climatic data, and they generally represent more homogeneous responses to changes in synoptic-scale atmospheric circulation. We focused our precipitation frequency reconstructions for selected areas centered in Santa Fe, New Mexico, Austin, Texas, Yuma, Arizona, and Sitka, Alaska, with records extending back to at least around 1850 (1828 for Sitka). The precipitation frequency reconstructions for the southwestern U.S. locations reveal substantial variations of dryness at the interannual and decadal scales, with no evidence of a persistent late-nineteenth century drought. Seasonal variations of dryness at Yuma correspond closely to the detailed documentation of hazardous sandstorms. The winter precipitation frequency record from Sitka corresponds to variations as related to the Pacific Decadal Oscillation. We also reconstructed the spatial extent of the prominent 1864 drought over the West, which particularly exhibited strong negative precipitation anomalies over California but also extending to other areas in the interior (*e.g.* Salt Lake City, Utah). We also explored the inverse relationships of Great Plains/Southwest warm-season precipitation in some case studies of the historical records, such as in 1849 and 1860, utilizing a combination of instrumental and documentary datasets.

## FOREST DISTURBANCE REGIME VARIABILITY ON THE WASATCH PLATEAU, CENTRAL UTAH, USA

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In the western U.S., the effects of widespread bark beetle infestations are considered to be as ecologically significant as high intensity wildfire. In Utah, the primary beetles are the mountain pine beetles, for which several pine species serve as host, and the spruce bark beetle, which lives in Engelmann spruce. The 1990s in western North America were accompanied by outbreak populations of spruce bark beetle (*Dendroctonus rufipennis* Kirby) in high elevation spruce/fir ecosystems, where hundreds of thousands of acres of subalpine forests experienced high levels of tree mortality. These outbreaks have led scientists and forest managers to question whether such bark beetle outbreaks may be early signals of human-induced climate warming or

are just consequences of sustained warmer than average temperatures. Given the relatively brief period of human settlement in the western U.S. and the infrequent occurrence of spruce bark beetle infestations, long term environmental indices are critical in understanding the role of these insects as agents of forest disturbance over longer time periods. Paleoecological reconstructions using lacustrine sediments may help us better explain the 'natural' frequency and past severity of bark beetle outbreaks during the Holocene. Such data would provide an understanding of how subalpine forest disturbance agent interactions have evolved over the Holocene, particularly the spruce bark beetle and fire, and how the severity of disturbance by these agents is modified by climate dynamics.

## A 20,000 YEAR RECORD OF HYDROLOGIC AND CLIMATIC CHANGE AT BEAR LAKE, UTAH/IDAHO

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Future climate warming could have major impacts on the hydrologic system of the western United States. Analyses of hydrologic measurements indicate that over the last 40 years snowpack has decreased and snowmelt has arrived earlier, but these records are insufficient to determine whether such changes are part of a long-term trend or outside of natural variability. Requisite long-term (hundreds to thousands of years) records of hydrologic change can be recovered using proxies, such as diatoms, which are preserved in alpine lake sediments.

Diatoms are sensitive indicators of changes in lake level and salinity, proxies for effective moisture, and lotic inputs. These single-celled algae are preserved in lake sediments, and are used here to record past hydrologic and climatic change at Bear Lake, a large (~282 $km^2$), deep (~63 m) lake, located on the border of Utah and Idaho (42º N, 111º 20’ W). Bear Lake is situated under the mean position of the winter jet stream. Over time, shifts in the position of this boundary may have resulted in variations in the timing and amount of precipitation to the lake. During years with intensified monsoons, Bear Lake can also receive higher than usual amounts of summer precipitation. Although Bear Lake was historically topographically closed, in 1918 a series of canals joined Bear River to Bear Lake, which caused significant hydrological and chemical change to the lake.

Diatoms were analyzed from two sediment cores, BL96-1 and BL96-2, retrieved from Bear Lake to provide a ~20,000 year record of hydrologic and climate change. Approximately 600 diatoms were counted in each of ~50 samples from each core. In order to summarize the diatom data, principal components analyses (PCA) were used. These analyses suggest that the first PCA axis for the 96-1 and 96-2 datasets represents variations in variables related to effective moisture (*i.e.*, habitat availability and salinity), whereas the second axis for 96-2 represents changes in variables related to stream inputs (*i.e.*, nutrients and habitat availability). Several lines of evidence indicate that prior to ~18,000 cal yr B.P., the Bear River and Bear Lake were connected. Diatom, oxygen isotope and carbonate data suggest that stream inflows continued to

be high, perhaps as a result of a connection between Bear River and Bear Lake, until ~12,000 cal yr B.P. Between ~12,000 and 9,500 cal yr B.P., Bear Lake was topographically closed, but stream inflows peak again between ~ 9,500 and 7,500 cal yr B.P., perhaps indicating a reconnection between Bear River and Bear Lake. Although diatoms at Bear Lake track changes in fluvial inputs, it is uncertain whether these changes are climatically driven.

Following ~7,500 cal yr B.P., the lake is topographically closed and its hydrologic balance is probably largely controlled by changes in effective moisture. Diatom analyses indicate that lake levels at Bear Lake were lower during this period compared to the rest of the ~20,000 yr record; however, there are several distinct shifts in the lake's hydrologic balance recorded after ~7,500 cal yr B.P. The timing and duration of these shifts is distinct from changes recorded in the Pacific Ocean and Sierra Nevada, but may be similar to changes in drift ice recorded in the North Atlantic.

## RECORDS OF THE LAST GLACIAL-INTERGLACIAL TRANSITION IN THE BONNEVILLE BASIN, U.S.A.

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Signals of millennial-scale hydrologic events dominate the records of paleo-shoreline sediment in the Bonneville basin. The Bonneville basin is the largest and deepest hydrologically closed sub-basin in the Great Basin of North America. Because of this characteristic, the timing and magnitude of each hydrologic event in the Bonneville basin is thought to closely reflect those of climatic events on the regional or even global scale. By examining the paleo-shoreline sediment records with 80 radiocarbon dates, a chronology was generated to show exactly when and how hydrologic events occurred in the Bonneville basin during the last glacial/interglacial transition period. In this chronology, all pluvial cycles appear to have begun and ended abruptly (typically less than 200 years). Moreover, the timing and magnitude of major pluvial events in the Bonneville basin seem to have coincided well with the hemispheric to global millennial-scale climatic events during the last deglaciation. The surface elevation of the lake was at or near overflow level during: Heinrich Event 1 (18,000-15,000 cal yr B.P.), the Bølling/Allerød warming period (14,700-12,900 cal yr B.P.), and the beginning of the Holocene Epoch (11,500-9,000 cal yr B.P.). During the Younger Dryas cooling period the lake was not as extensive. Significantly enhanced summer precipitation appears to have played a crucial role for these pluvial cycles in the Bonneville basin. As summer insolation was approaching its maximum in the northern hemisphere around 11,000 cal yr B.P., the Bonneville basin might have been affected by a strengthened North American monsoon system. The timing and magnitude of hydrologic events, especially after 15,000 cal yr B.P., in the Bonneville basin shoreline record also closely resemble those of GISP 2 and the Cariaco Basin. It remains to be seen whether the agreement between records indicates that the abrupt reorganization of atmospheric and oceanic circulation occurred simultaneously in the Pacific and Atlantic regions in the northern hemisphere during the last deglaciation.

## THE RELATION OF COMMERCIAL CATCHES OF HIGHLY MIGRATORY FISHES TO CHANGES IN THE CALIFORNIA CURRENT ENVIRONMENT

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Highly migratory fish species (HMS) contribute millions of dollars to the economies of California, Oregon, and Washington when they migrate into the range of West Coast fishermen. Availability and catch of particular HMS varies from zero to thousands of metric tons (t) depending on environmental variations. Recent studies of the 1930-2000 period suggest that the California Current System (CCS) is strongly affected by relatively few modes of physical variability. These include equatorial (EQ) and unidirectional trend (TRN) modes and a mode similar the Pacific Decadal Oscillation (PDO'). Empirical Orthogonal Function (EOF) analyses of the NOAA/NMFS/SWFSC California Commercial Fish Data Base (CACom) and comparison of the time variation of the EOF to environmental indices has shown that environmental forcing associated with the EQ, TRN and PDO' components are integrated by CCS ecosystem dynamics and are observed by changes in the species composition in the commercial landings. Bluefin tuna (*Thunnus thynnus*) and albacore (*Thunnus alalunga*) had an inverse abundance relationship in EQ mode. Skipjack (*Euthynnus pelamis*) and swordfish (*Xiphias gladius*) responded to the increases of ocean temperature and southward wind stress of the TRN mode. The PDO' variability appears related to bonito (*Sarda chiliensis*) and yellowfin tuna (*Thunnus albacares*) availability off the west coast of the U.S. All of these HMS are important species to recreational and commercial fishers. Yellowfin tuna is one of the more important commercial species of the eastern Pacific Ocean. Together the three EOF modes corresponding to EQ, TRN and PDO' account for more than 55% of the variance in the CACom data set that includes the 29 species making up more than 80% of the total California commercial landings in every year during the 1930-2000 period. These results may provide bases for prediction techniques that will aid in the effective management and exploitation of these species when they are within range of West Coast fishers.

## A CLIMATE MODEL PERSPECTIVE ON DROUGHT IN THE WESTERN U.S.

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The western U.S. has experienced pronounced drought in recent years, as well as, in the paleo-record. Predictions of future climate change in the region show a large effect on the hydrological cycle solely from changes in temperature affecting the fraction of precipitation falling as snow and the timing of spring runoff. To go beyond the temperature effects to get a more complete picture of future hydrological changes requires validating the model's depiction of drought over long timescales. Do models reproduce the observed frequency, duration, and intensity of droughts? Do they simulate the links between larger scale climate fluctuations and

drought over the western U.S.? In this study we evaluate drought as seen in two fully coupled O-A GCMs used for climate change research: the Parallel Climate Model (PCM), and NCAR's CCSM3 run at T85 resolution. An 8,000-year tree-ring record of drought in the southwestern U.S. shows a great degree of variability, with long wet periods alternating with long droughts. Both models have similar variability in their simulation of precipitation, as can be determined from their multi-century control model runs. Composites of model conditions during drought eras, compared to dry eras, suggest the important role of the North Pacific Oscillation (NPO) and, to a lesser degree, ENSO in decadal drought. Observations suggest drought over the central and western U.S. is also related to the Atlantic Meridional Oscillation (AMO). CCSM3-T85 reproduces this link during some centuries, but has characteristics almost opposite that observed during other centuries. The relationship between the AMO and drought may be non-stationary, or it might be that a 100 year record of observations is too short to make a firm conclusion on the role of the AMO on drought.

## DROUGHTS, FOREST FIRES, AND EROSION IN THE NORTHERN ROCKY MOUNTAINS, U.S.A., DURING THE LAST TWO MILLENNIA

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Climate-driven relationships among fire, fuels, and geomorphic response have been shown to exist on seasonal to multi-millennial timescales. We investigated changes in fire regimes and geomorphic response in central Idaho northern ponderosa pine (*Pinus ponderosa)* and Yellowstone National Park mixed conifer forests over the last 8,000 years by radiocarbon dating and interpreting the record of fire-induced sedimentation preserved in alluvial fans. Both Idaho and Yellowstone fan records show a peak in fire-related debris flows between ~1,000-800 cal yr B.P., corresponding with drought conditions throughout much of the western U.S. ~1,050-650 cal yr B.P. Comprehensive drought-area indices for the western U.S. indicate that ~810-775 cal yr B.P. is the most extreme period of multidecadal drought in the last 1,200 years, and that other significant multidecadal droughts occurred at 1,014, 916, and 697 cal yr B.P. (Cook and others, 2004). In dry low-elevation ponderosa forests of Idaho, large fire related debris flows ~1,000-800 cal yr B.P. represent over a quarter of the total dated fan thickness, however, the highest frequency of fire-related erosional events occurred as small events during inferred cool episodes such as the Little Ice Age (~500-350 cal yr B.P.), when greater effective moisture promoted grass growth and low-severity fires. Conversely, in moister, high-elevation Yellowstone, inferred cool intervals centered on ~2,800, 1,400 and 350 cal yr B.P. are characterized by minimal fire-related sedimentation and correspond with cool episodes in the North Atlantic (Bond and others, 2001). McCabe and others (2004) suggest that warming in the North Atlantic is associated with recent large-scale droughts in the U.S. Thus, both modern and paleo-records appear to indicate that North Atlantic temperatures have a strong relationship with drought conditions in the western U.S.

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## HIGH RESOLUTION ANALYSIS OF SUBFOSSIL CHIRONOMIDS IN THE SIERRA NEVADA, CALIFORNIA PROVIDES EVIDENCE OF LATE 20th CENTURY WARMING

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High-resolution chironomid stratigraphies were developed for three subalpine lakes in the Sierra Nevada of California to assess whether these lakes have been affected by recent climate change evident in regional instrumental records for the 19th and 20th centuries. Indirect gradient analysis of the chironomid fauna indicates that the lakes have experienced similar unidirectional change in community composition over the 20th century with two of the lakes showing particularly sharp gradients of change since the 1970s. A previously developed chironomid-based transfer function for surface water temperature, applied to the chironomid assemblages preserved in these lakes, provided quantitative temperature estimates of surface water temperatures spanning the 20th century. The data indicate that all three sites experienced temperature changes during the 20th century; specifically, above average water temperatures characterized the late 20th century and below average surface water temperatures occurred between A.D. 1910 and 1980. Close correspondences exist between the chironomid-inferred temperature profiles and mean July temperatures measured at Fresno, California during the period A.D. 1895-2001. It appears that climate change has an overriding influence on the composition of the chironomid communities within these three lakes. This study demonstrates that sub-fossil chironomid analysis can provide detailed records of community response to local perturbations and to regional climatic changes at sub-decadal time scales and also reveals that the midge communities in subalpine lakes in the Sierra Nevada have already been affected by recent climate change.

## USING PALEOECOLOGICAL TECHNIQUES TO ADDRESS SITE ABANDONMENT AT RANGE CREEK, UTAH

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The effect of climate variability on prehistoric human settlement patterns has emerged as an important field of study over the past decade. Climate controls are identified as causes for site abandonment and changes in settlement patterns due to drought and subsequent agricultural decline in southwestern North America. Paleoecology offers the opportunity to interpret archaeological settlement patterns by providing information on agriculture, climate change, and fire regimes from sedimentary proxies. Fossil pollen and charcoal accumulations entrained in wetland sediments are specifically relevant to correlating climatic forcing to prehistoric site abandonment. Paleoarchaeological research conducted in Range Creek, Utah seeks to identify the climate mechanisms that may have directly led to or at least contributed to site abandonment around A.D. 1250. A core was obtained from Cherry Meadows and sediments were analyzed for pollen, charcoal, magnetic susceptibility, and loss on ignition. Stratigraphic layers surrounding the years of abandonment (A.D. 1250) were examined at higher resolution whereas pre-abandonment (A.D. 900-1250) and post-abandonment (after A.D. 1250) sections of the core were examined at lower resolution to establish baseline influx data for pollen and charcoal.

## WESTERN CLIMATE UPDATE: PACLIM YEAR 2005-2006

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During the 13-month interval between the "PACLIM Surrogate" of MTNCLIM 2005 and PACLIM 2006, the major ongoing drought in the Southwest took a substantial hit. A precipitation pattern very reminiscent of El Niño, without benefit of its actual presence (by most accounts), brought the wettest cool season on record to much of the region. Meanwhile, an equally unusual dry winter in the Pacific Northwest gave way to an extended wet spring and early summer, providing a kind of soft landing for that region. A cool June gave way to the hottest month ever recorded in many western cities, with an extended mid-month period of hot days that tied records for longevity. The Southwest monsoon was the second latest on record. The Hawaiian Islands were also both warm and wet in July. Fairbanks noted snow on the last day of August, and the same day Honolulu ended a streak of 155 consecutive days with above-average temperatures. The astonishing Atlantic hurricane season much overshadowed the lackluster Pacific hurricane season, which had 15 named storms (average 15.5), 7 hurricanes (average 9.0), two of which reached major status as Category III (average 4.3). The winter of 2005-2006 has so far brought nearly the exact opposite from the previous winter in western precipitaton. A weak La Niña developed and helped cause one of the driest winters on record thus far in the desert Southwest. The Colorado River inflow to Lake Powell is nonetheless

expected to be just slightly above average for the second year in a row, albeit for entirely different reasons. The winter season thus far has been much above average in temperature, continuing a series of warm western winters.

## VENTILATION OF THE NORTH PACIFIC THERMOCLINE OVER THE PAST CENTURY: RADIOCARBON AND BENTHIC FORAMINIFERAL EVIDENCE FROM THE SANTA BARBARA BASIN

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By volume considerations alone, the ventilation of the interior North Pacific Ocean must play a crucial role in global climate dynamics on timescales of decades to centuries. However, the sub-thermocline dynamics of the North Pacific remain largely inaccessible beyond sparse instrumental observations spanning the last twenty years. The annually laminated sediments of the Santa Barbara Basin provide a unique opportunity to document subsurface variability over the last few centuries. The radiocarbon age of benthic foraminifera from a box core removed at the basin bottom (578 m) was measured at biennial resolution through 1938 to create a continuous benthic $\delta^{14}C$ record. In addition to $\delta^{14}C$ analysis, benthic foraminiferal species assemblages were quantified at the same resolution through 1900. Upon comparison with instrumental measurements, radiocarbon results demonstrate that benthic foraminifera faithfully capture the $\delta^{14}C$ of bottom water dissolved inorganic carbon. Furthermore, these data illustrate the potential of benthic foraminiferal radiocarbon as a tracer of past bottom water properties: significant excursions in radiocarbon are observed over documented basin renewal events of the late 20$^{th}$ century. Radiocarbon can serve as a particularly diagnostic indicator of basin ventilation because of the steep vertical gradient of $\delta^{14}C$ near the Santa Barbara Basin sill depth. While the abundance of several benthic foraminifera taxa appears to exhibit a pattern of decadal variability similar to that observed in the $\delta^{14}C$ measurements, the population of one chloroplast-bearing species (*Nonionella stella*) experiences unprecedented growth over the late 20$^{th}$ century. Continuation of these records will be an effective means for discriminating the mechanisms of natural subsurface variability and to resolve the interaction between bottom water chemistry and benthic ecosystems.

# WATER YEAR 2006 IN NORTHERN CALIFORNIA
# THE HOLIDAY SEASON MONSOON

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Each water year is different and Water Year 2005-2006 was no exception in California. The preceding year had a cool and wet spring during April and May. As a result, most major reservoirs filled with carryover on October 1 entered the new season about 20 percent above of average. October was relatively dry except for a big storm in the south. November was near average. Looking at ENSO patterns and other long range forecasts we predicted a generally dry winter, but one punctuated by a somewhat greater risk of a "pineapple connection" storm. We also thought there would be a wet north–dry south pattern.

The first half of December was on track. Then starting on December 18 we got a series of Pacific storms, one every 2 or 3 days, which lasted into the middle of the first week of January. The storms were relatively warm, with rain up to fairly high elevations and mainly affected the northern third of the State. Because the storms moved inland at moderate speeds, no really high water was produced. Then, on December 31, a storm stalled and we got 5 inches of rain in one day in the northern Sierra Nevada. Some fairly large floods were produced from the San Francisco Bay area and Sacramento north to the Oregon border. The floods at the end of 2005 were quite large, but generally not up to the volume of the really big floods of 1986 and 1997. Some local areas on the upper Russian and Napa Rivers did have extreme flood flows and the lower Eel River did slightly exceed the 1997 flood. Levels on the major rivers of the Sacramento River region, the one day flood flow probably approached a 25-year event while the three day amounts were in the 10- to 15-event year range. However, the high runoff coincided with the high year-end astronomical tides and so the Sacramento-San Joaquin delta was threatened with near record flood stages.

A surprising amount of precipitation, mostly rain was carried over the crest of the Sierra Nevada onto the normally dry leeward side causing flooding on the Truckee and other east side rivers. Sierraville, in the upper Feather River watershed northwest of Reno, gathered about 6 inches on the wettest day, which is probably a new daily record. Even Reno had a 24-hour total of 1.72 inches, which is about 20% of a seasonal total. By the time the storm series was over on January 4, some intervals had been cold enough to bring snow to the higher elevations, so that the regional snowpack was average or better for that point in the season.

We did not consider the end-of-year flood event a real pineapple express storm because most of the moisture seemed to come from the southwest north Pacific, with origins near the Philippines. The moist air was picked up by strong mid-Pacific jet stream winds and directed it to either northern California or the Pacific Northwest. A similar pattern might have occurred in December 1955, but we didn't have the satellites then to track moisture bands. Another day like December 31, however, would have produced a major flood in northern California. The continuing parade of storms made it seem like a holiday season monsoon for the West Coast.
The author will go on to describe weather and water conditions from mid-January to the late March time of the workshop.

## MODELING AND UNDERSTANDING NORTH AMERICAN DROUGHTS OF THE LAST MILLENNIUM

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The period of instrumental records of ocean surface temperatures (since 1856) contains six severe multiyear droughts over North America of which the most recent began in 1998 and may not yet be over. Large ensembles of climate model simulations of the 1856 to 2005 period demonstrate that these droughts were the result of persistent multiyear changes in sea surface temperatures (SST). Tropical Pacific SST are the dominant influence with all the droughts coinciding with persistent La Niña-like conditions. It is shown that the droughts fit into a coherent global scale reorganization of atmospheric circulation and hydroclimate. Interactions between transient eddies and the mean circulation induce subsidence in mid-latitudes which is the ultimate cause of the droughts.

Tree-ring records of the middle and late nineteenth century are used in conjunction with instrumental records and model simulations to understand the fidelity of proxy drought reconstructions. Tree-ring records are then examined to characterize the sequence of severe, multidecadal, droughts that afflicted the Great Plains and West during the Medieval period. It is shown that these droughts are akin, in spatial pattern and year-to-year variability, to the more recent, shorter, droughts of the last century and a half. This suggests a common origin in tropical Pacific SST. Evidence is presented from various proxies around the globe to suggest that the Medieval period was characterized by La Niña-like conditions that lasted for decades and even centuries. It is suggested, tentatively, that this was a result of external forcing of the climate system by changes in solar irradiance and volcanism.

## COASTAL AND EQUATORIAL OCEAN TEMPERATURE TRANSECTS – UPDATE

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The upper ocean temperature records for the coastlines that support the world's major marine fisheries, along with equatorial transects, provide an array of insights into the status, changes, and trends that are useful in interpretation of both sources and consequences of ecological changes. Since we last updated these records in 1991, there have been dramatic changes in the number and distribution of ocean observations. A general downward trend in number and more limited distribution is observed in the monthly mean temperature values along all the transects, although the equatorial sections seem to be relatively well covered when compared to most other regions. The variations exhibit distinctly different patterns, with recent decades of warming on the west coast of the Americas being strongly linked to ENSO warm events. The eastern North Atlantic has its own general positive temperature increase, while the

western North Atlantic exhibits distinct, partitioned opposite trends from north to south. The explanation for these regional differences is complex, with abrupt cooling in the Arctic signaling the end of the deliveries of water from the warm pool to higher latitudes and between basins during recent ENSO warm events into the higher latitudes. The expected general decline in warm events as per various historical relations between solar activity and ENSO frequency and intensity (Anderson, 1989; Landscheidt, 2004) suggest that the next decades will indeed continue to cool, with the northeast Atlantic-Barents Sea ice cover likely to expand once again, as it did after the remarkable 1920-1930 warming (Bengsten and others, 2004).

## CLIMATE CHANGE AT A SNAIL'S PACE: PALEOESCARGOT REGISTER PAST CLIMATE

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Freshwater mollusks are sensitive to fluctuations in hydrology. When physical and geochemical factors in lake, spring, or wetland environments vary in response to climate change (such as increased evaporation and temperature resulting from drought conditions), molluscan assemblages record those changes. In this way, mollusks can record climate change, provided that their hydrologic environment is linked to climate variability.

Mollusks can record hydrology in two primary ways. The first is molluscan response to change in the solute composition (or dominant ions) of natural waters. Solute composition is the proportion of bicarbonate-carbonate, sulfate, and chloride anions, and sodium, calcium, and magnesium cations. The solute composition of hydrologic settings may change (solute evolution) in space and time owing to various physical and chemical processes operating within the water. The ultimate driver of solute evolution is commonly climate change. The second way mollusks can respond to hydrologic variation is in the $\delta^{18}O$ value of shell material, or biogenic carbonate ($\delta^{18}O_{(gastropod)}$). Different hydrologic systems have characteristic isotope systematics, and those isotope signatures can be used to infer the hydrologic setting (*e.g.*, lacustrine, spring, or wetland) and variation within that setting. Solute composition and $\delta^{18}O_{(water)}$ vary if the inflow is less than outflow during much of the year. If inflow equals outflow, as in a spring or flow-through wetland, both parameters may be relatively stable. A system that is less variable in temperature oscillation and/or $\delta^{18}O_{(water)}$ will have less variable $\delta^{18}O_{(gastropod)}$ than more variable systems.

Determining a seasonal signal from either solute composition or $\delta^{18}O_{(gastropod)}$ is problematic because certain physico-chemical thresholds must be crossed for mollusks to show a response to solute composition and confounding factors interplay in producing $\delta^{18}O$ values. However, good agreement between the mollusk record and other climate proxies such as pollen, carbonates, organic matter, and $\delta^{18}O$ values from *Chara* and ostracodes has been demonstrated at ~25-year-resolution in sediment collected from Pahranagat Lake in southern Nevada. In spite of some limitations, the distribution of mollusks in space or time can provide an excellent record of past hydrologic setting and past climate.

## CALIFORNIA PRECIPITATION HISTORY RECONSTRUCTED FROM THE NETWORK OF BLUE OAK CHRONOLOGIES

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A new network of high-quality tree-ring chronologies is under development that will cover most of the drainage basins of the Sacramento and San Joaquin Rivers. The network is based entirely on a single tree species, the blue oak (*Quercus douglasii*), which is a California endemic found from the lower forest border up into the mixed conifer zone in the Coast Ranges, Sierra Nevada, and Cascades. Blue oak tree-ring chronologies are exceptionally sensitive to winter-spring precipitation totals, Sacramento and San Joaquin streamflow, and to seasonal variations in salinity in San Francisco Bay. Our goal is a dense network of 50 blue oak chronologies for hydroclimatic reconstruction, along with detailed mapping of the large remnants of relatively undisturbed ancient blue oak woodland still present on rugged terrain in California. Large tracts of ancient forest with individual blue oaks over 400 years old have been located, particularly in the Diablo Range and in the Cascade foothills west of Mt. Lassen. Well-replicated collections have been obtained from 36 separate blue oak woodlands encircling the Great Valley. Thirty tree-ring chronologies have been completed thus far, 25 of which are over 400 years long. All of these chronologies are based on living trees and relic wood, and the longest is 711 years (1293-2003) in the Santa Ynez Valley. A 625-year long reconstruction of Salinas River annual mean flow has been completed which explains 75% of the variance in the instrumental record during the 20$^{th}$ century (see Griffin and others poster). Using the PRISM climate dataset, water year precipitation totals have been interpolated to the available blue oak collection sites and used to reconstruct site-specific precipitation at 22 locations. The available data indicate that the highest variance in blue oak growth and inferred precipitation occurs in the south Coast Ranges and the lowest in the Cascades. Consecutive three to four-year regimes of drought have been common in the regional and statewide blue oak data for the past 400 years, recurring typically every 14 years. The two most severe decadal droughts occurred statewide during the 1840's and 1920's, while the most extreme decadal wet periods occurred during the 1740's, 1790's, and 1940's.

## TOO CLEVER TO BE UNDERSTOOD: IDENTIFYING PERIODS OF INCREASED ARIDITY IN SAN FRANCISCO BAY MARSH SEDIMENTS

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Livingstone cores collected from three marshes on the northern margin of San Francisco Bay provide a confusing record of late Holocene climate fluctuation in central California. Variations in the composition of the diatom flora in each core were used to reconstruct the

salinity history at the site. The records illustrate the complex interaction between local and regional climatic processes.

Conditions at Rush Ranch and Petaluma marsh suggest the conditions along the central coast my have begun to dry out prior to the beginning of the Medieval Warm Period. Both sites indicate that fresh water became increasingly abundant during the transition from the Medieval Warm Period to the Little Ice Age. The Benicia State Park site is dominated by a freshwater diatom flora through much of the Medieval Warm Period, and conditions only become brackish at the beginning of the Little Ice Age.

The Rush Ranch site, located near the distal end of a slough connected to Suisun Bay, contains a 3,000 year record of regional climate variability. Periods of reduced fresh water flow occurred between 3,000 to 2,700 cal yr B.P., 1,750 to 750 cal yr B.P., and from about A.D. 1930 to the present. The longest record, about 3,700 years, was collected in Benicia State Park. This site reflects only the most significant changes in precipitation within the watershed. Freshwater diatoms increase rapidly in abundance at about 3,200 cal yr B.P. Conditions remained relatively stable until about 550 cal yr B.P. From about 500 cal yr B.P. until European contact, conditions were more saline. During this period, sediment deposition may have only occurred in the summer and fall when river flow rates were lower, leading to a more brackish diatom flora.

The difference in the timing and duration of the fresher and more saline intervals at the Rush Ranch and Benicia State Park sites is largely controlled by proximity to the main channel of the Sacramento-San Joaquin River system. The distance from the mouth of the tidal channel to the Rush Ranch site appears to have a dampening effect on the expression of climate variation. For example, the transition from brackish to fresher conditions takes place between 3,200 and 3,100 cal yr B.P. at Benicia State Park, but does not occur until several hundred years later at Rush Ranch. Likewise, the subsequent transition from fresher to more brackish conditions occurs 150 to 200 years earlier at Rush Ranch. The upper brackish interval at Rush Ranch (1,750 to 750 cal yr B.P.) lasts about a millennium, but only the most extreme period of increased salinity during this time is recorded at Benicia State Park.

The record at Petaluma marsh is strongly controlled by local conditions. This site is less influenced by snowmelt from the Sierra Nevada and is more strongly affected by variations in precipitation in the Coast Range. Beginning about 1550 cal yr B.P., the conditions become more saline, and with the exception the period between about 700 and 500 cal yr B.P., continued to increase in salinity to the present. This shift in the flora may be influenced by marsh accretion, which led to longer periods of exposure during the summer and fall.

## LATEST PLIOCENE AND QUATERNARY DIATOM FLORAS OF THE LAKE TAHOE BASIN, CALIFORNIA AND NEVADA, USA

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Despite an active research program at Lake Tahoe, few attempts have been made to understand the conditions that existed within the watershed prior to European contact. A greater understanding of the Quaternary history of the basin would not only benefit local stakeholders, but would also enhance the knowledge of the entire Truckee River system.

Lake Tahoe has been called one of the most oligotrophic lakes in the world. Historically, the lake has contained low levels of phosphorus (5 μg/L) and nitrogen (100 μg/L). As a result, the abundance of phytoplankton and zooplankton is also low. Over the past century anthropogenic inputs have caused parts of the lake to become seasonally mesotrophic. The impact of climate variability on the nutrient load in the lake is poorly known. Detailed analysis of the pre-European contact record is necessary in order to unravel the complex interaction between natural and human inputs to the watershed.

Dredge samples collected from slump blocks and surface sediments in the deep basin and surface samples collected at a number of sites around the margin of Lake Tahoe have been analyzed for diatoms and chrysophyte stomatocysts. The deep lake basin diatom flora is dominated by planktonic, oligotrophic, alkaliphilic taxa such as *Cyclotella bodanica* and *C. ocellata*. Planktonic and obligate planktonic taxa (*Aulacoseira distans*, *Fragilaria crotonensis*, *Stephanodiscus* spp.) found close to shore and benthic taxa are representative of oligotrophic to eutrophic conditions *Frustulia rhomboides*, *Tetracyclus glans*, *Achnanthes minutissima*, *Epithemia* spp., *Rhopalodia gibba*, *Meridion circulare*). Several samples of diatomaceous sediment collected near Tahoe City, California, on the west side of the lake, contain taxa that are representative of shallow, more eutrophic conditions and at least one of these samples contains a late Pliocene species (*Tertiarius* sp.), which suggests that at least locally, the lake at that time was shallower and was subject to a higher influx of nutrients. Similar late Pliocene taxa were found in lacustrine deposits interbedded with the volcanic rocks of the Sonoma Volcanics in northern California.

## THE MADDEN-JULIAN OSCILLATION AND EXTREMES IN NORTH AMERICAN PRECIPITATION:RELATIONSHIPS AND FORECAST IMPLICATIONS

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The Madden-Julian Oscillation (MJO) has been associated with a number of extreme precipitation events in western North America. However, the mechanisms for, and predictability of, these associations are not clear. We have examined the influence of the MJO on North Pacific-North America (NPNA) circulation and precipitation anomalies during the boreal winter, with an emphasis on the dynamic relationships that affect the initiation and development of the anomalies. We constructed lagged composites of MJO events during 1979-2005 based on MJO convective phase, amplitude, and month determined from the Wheeler RMM1/RMM2 index of MJO activity. Our analyses of NPNA anomalies were based primarily on the National Centers for Environmental Prediction reanalysis data set. We focused our investigations on the impacts on NPNA circulation and precipitation of: (1) the amplitude and location of the convective component of the MJO; (2) the location of the subsidence component of the MJO; and (3) concurrent El Niño or La Niña events.

We found that the NPNA response to the MJO is sensitive to the amplitude and location of both the convective and subsidence components of the MJO, and to the existence of concurrent El Niño or La Niño events. El Niño or La Niño events affect the extratropical response to the MJO by altering the equatorial Rossby-Kelvin wave response to the convective

and subsidence components of the MJO. This, in turn, affects the anomalous extratropical wave trains initiated by the MJO, and alters the strength and location of the resulting NPNA precipitation anomalies. Our results have allowed us to identify characteristic patterns in the shape and orientation of the extratropical wave trains associated with the MJO that can be related to the location and intensity of extreme NPNA precipitation. We conclude that more complete analysis and forecasting of the temporal and spatial characteristics of the MJO have the potential to improve medium and long-range forecasts of NPNA circulation and precipitation.

## EPIC DROUGHT IN THE INTERMONTANE WEST: NEW FINDINGS FROM THE TRANS-SIERRA AND THE NORTHERN ROCKIES

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Evidence from an increasing number of sites in California and western Nevada demonstrates that rivers, marshes, and lakes (some hydrographically open, others closed), were drawn to, and maintained at, remarkably low levels by drought during two century-plus periods of the Middle Ages. In sharp contrast to these persistently (though probably not uniformly) dry periods is the interval of approximately 50 years that separated the droughts. Two sites, in particular, show that this intervening period was exceptionally wet: Mono Lake rose to its third-highest stand of the past ~4,000 years, and Owens Lake appears to have attained its highest level of the middle and late Holocene.

In 1994 I referred to these two severe and persistent dry spells as "epic droughts," and proposed the term "Medieval Climatic Anomaly" to characterize the aberrant conditions that beset not only the trans-Sierran west (which showed large swings in moisture availability), but many other areas of the world as well (some of which swung between extreme wet and dry, while others experienced aberrant warming and cooling).

Here I will update the trans-Sierran record of the Medieval Climatic Anomaly, focusing on three new sites: Owens Lake, Walker Lake, and several subalpine lakes of the southern Sierra Nevada; and I will discuss other, mostly lesser, droughts of the past two millennia that can be inferred from the Mono Lake record.

I will also present preliminary findings from my first field season of Comer-sponsored drought research in the northern Rocky Mountains—specifically from the rivers of the Bitterroot Mountains, and from the lakes and marshes in and around Glacier National Park. Among other things, this research points to a severe drought sometime within the past several hundred years that greatly reduced stream flow, desiccated marshes, and lowered lakes.

## HOLOCENE DROUGHT VARIABILITY IN THE NORTHERN ROCKY MOUNTAINS: A HIGH-RESOLUTION MULTI-PROXY RECONSTRUCTION OF PAST LAKE LEVELS FROM FOY LAKE, MONTANA

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In the Northern Rockies of Montana, drought variability in 20th-century climate records is explained almost entirely by deviations from the monthly mean precipitation. To examine the potential influences of large-scale ocean-atmospheric circulation patterns on drought for this region, monthly data, including normalized precipitation totals, the Palmer Drought Severity Index (PDSI), and Pacific Decadal Oscillation (PDO) for the period 1900-2005 were decomposed into their dominant oscillatory components, using singular-spectrum analysis, and the records were compared for spectral cohesion. Climate records of both normalized precipitation totals and PDSI showed recurring frequencies in common with the PDO. Spectral coherence with the PDO was strongest at inter-annual frequencies, suggesting a strong likelihood that ENSO variability acts to modify precipitation patterns, and hence drought recurrence.

To examine how this relationship may have changed throughout the Holocene, we collected a thirteen-meter-long sediment core from Foy Lake, Montana. Sediment was analyzed for fossil diatoms, pollen, charcoal, sediment chemistry, and oxygen isotopes at decadal to sub-decadal resolutions, spanning approximately 13,000 years. Continuous varve couplets were persistent in the lower and upper sections of the core, which permitted analysis of the 20th-century record at an annual scale and comparison to instrumental climate records. The upper varved section of the record, representing the last 2,200 years, was analyzed at a resolution of approximately five years. Spectral analysis of both oxygen isotope and diatom data indicated that severe droughts recurred with multi-decadal (50 to 70 year) frequency throughout most of the late Holocene, suggesting a PDO-like driving mechanism. Similar patterns of PDO-like multi-decadal drought frequencies were persistent throughout the diatom record from the Holocene, recurring with greater consistency during the middle Holocene, when temperatures were warmer than today.

## SPATIAL INHOMOGENEITIES IN WINTER PRECIPITATION ANOMALIES IN THE SOUTHWESTERN UNITED STATES

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Between the months of December and March, storm systems from the Pacific Ocean periodically cross the desert southwestern of the United States causing widespread precipitation. Ocean-atmosphere teleconnections such as El Niño and La Niña can cause large interannual variations in winter precipitation at broad spatial scales, but topographic features play a pivotal role in the spatial distribution of precipitation through orographic processes. Conventional

climatological wisdom holds that deviations from average rainfall during the winter rainy season are temporally and spatially uniform across the region. However, detailed data analyses demonstrate that occasionally sub-regions within the Southwest have anomalously dry/wet winters that do not correlate with the surrounding region. Using PRISM 4-km gridded precipitation data and the recently released North American Regional Reanalysis, we examine the nature and causes of these sub-regional spatial anomalies. We identify local and regional atmospheric factors that may cause the anomalies, and we highlight those areas most prone to deviations from broader regional patterns. Understanding these phenomena may lead to improved seasonal climate predictions for the desert southwest.

## PALEO-VEGETATION EVIDENCE FOR PERIODIC DROUGHT IN THE GREAT BASIN

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Arid and semi-arid ecosystems of the Great Basin are highly sensitive to climate change. The recent extensive die off of many species that has occurred across the Southwest and Great Basin during the recent drought are evidence of this sensitivity. A better understanding of the relationships between Holocene climate change, particularly periodic drought, and the associated vegetation dynamics will not only improve our understanding of past changes, but also help anticipate the affects of future changes. Evident in the vegetation data available for the Great Basin are millennial-scale climate oscillations operating over the Holocene. Other proxy data from the region also reflect these oscillations, including periods of major droughts that may have lasted as long as 300 to 700 years. These droughts caused major vegetation changes, particularly in riparian communities. This included changes in species composition and evidence of species migrations. Oscillations in Great Basin vegetation show correspondence with global level records of climate change and periodic drought, particularly for records from the North Atlantic. Vegetation responses to the long-term drought cycles evident in the past have implications for the kinds of vegetation changes that may occur in response to the types of climate changes that are apparently coming in the future.

## STUDYING CLIMATE WITH MAGNETIC MEASUREMENTS OF SEDIMENTS AND SOILS

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Over the years, rock magnetists and paleomagnetists have developed many techniques for determining the nature of the magnetic carriers in rocks and sediments. These techniques are used extensively to study the remanent magnetization of geologic materials and to establish the

validity of paleomagnetic studies. However, in many situations, the mineralogy, concentration, and grain-size of the magnetic carriers can be strongly influenced by environmental processes. Environmental magnetism is a relatively new field of geophysics that uses the magnetic properties of soils and sediments as tracers of paleoclimatic and other environmental processes. For example, cold, dry conditions are more likely to result in mechanical weathering and in the formation of larger grains of detrital magnetite, whereas warm, wet conditions are more likely to result in chemical weathering and in the formation of smaller grains of detrital magnetite containing a higher percentage of hematite. Both the magnetic grain size and the magnetite/hematite ratio can be easily determined using magnetic measurements. In a similar way, the nature and degree of the transformations of iron that have taken place in a soil can provide information about the duration of a soil-forming episode and its intensity. An important aspect of environmental magnetism is that its techniques are relatively rapid, simple, nondestructive, and inexpensive. In addition, and perhaps more significantly, environmental magnetism can be used to address problems that may be inaccessible using other chemical and physical techniques.

## CLIMATE VARIABILITY AND PREHISTORY IN THE SOUTHERN MAYA LOWLANDS

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Multi-proxy analyses on a sediment core from Lago Puerto Arturo in the northern Peten, Guatemala, provide an ~8,700 year record of climate variability and human activity. A relatively wet early Holocene is followed by increasingly dry conditions beginning around 5,700 cal yr B.P. Drier conditions persist until ~1,000 cal yr B.P. The period from ~3,500-1,000 cal yr B.P. coincides with a significant reduction in forest taxa and the presence of *Zea* pollen, which is evidence for settlement by the prehistoric Maya. Although drought has been suggested as a possible cause for abandonment of the region between A.D. ~800-1,000, evidence from Lago Puerto Arturo shows ecological disturbance and agricultural activity at this time. It was not until more humid conditions set in around A.D. 1,000 that the area was permanently abandoned. A 200 year periodicity in the $\delta^{18}O$ data suggests that solar activity may be an important forcing mechanism of Yucatan climate. Proxy records include pollen, stable isotope, magnetic susceptibility, and sediment chemistry analyses.

# AN 11,000-YEAR-LONG RECORD OF FIRE AND VEGETATION HISTORY FROM BATTLE GROUND LAKE, WASHINGTON

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An 11,000-year long, decadal-resolution record of fire history from Battle Ground Lake, WA (elev. 154 m), was reconstructed using macroscopic charcoal analysis. The record was then compared with pollen and regional paleoclimatological data. The charcoal influx record shows a general increase in fire frequency from ~8 fire episodes/1,000 years at the beginning of the Holocene until the middle Holocene (~6,500 cal yr B.P.), when the fire frequency peaked at ~14 fire episodes/1,000 years. The vegetation during this period was xeric (*e.g.*, *Quercus* and members of the Poaceae), due to the warm, dry conditions that prevailed at that time. A decrease in the fire frequency from its peak in the middle Holocene to ~4 fire episodes/1,000 years at present was accompanied by a shift to more mesic vegetation surrounding the site, marked by a decrease in *Quercus* and an increase in *Pseudotsuga*, *Abies*, and Cupressaceae (cedar), as the regional climate became wetter with less summer drought. Although the regional climate likely changed gradually over the past 6,500 years, major changes are seen in the charcoal influx record, most notably after 3,000 cal yr B.P. At this time, as fire frequency decreased, the magnitude of the charcoal influx peaks more than doubled, as did the time between fire events. The change in fire activity after 3,000 cal yr B.P. was accompanied by little change in the vegetation, except a major increase in *Pteridium*-type pollen and a further increase in Cupressaceae. Because there is no major evidence of a regional climatic shift at that time, it is possible that human activity near the site may have influenced the change in fire activity seen at ~3000 cal yr B.P., or it may be that fire activity is sensitive to climate variability on shorter time scales than those that influence vegetation. A higher-resolution analysis of a 65-cm short core from the site reveals in greater detail the fire activity over the past ~600 years; there have been two major fire episodes, and possible re-burn events occurred within 5-10 years of each initial fire. The Battle Ground record illustrates the role that interactions between fire and vegetation, as well as the direct effects of climate, have in shaping a region's environmental history. Although this record provides important information on the fire, vegetation, and possibly human history of the northern Willamette Valley, several additional sites are concurrently being studied to gain an understanding of these changes during the Holocene across the WillametteValley.

## INTER-HEMISPHERIC TELECONNECTIONS, ENVIRONMENTAL DISEQUILIBRIUM, WIDESPREAD FIRE, AND SOIL EROSION DURING PERIODS OF ABURPT CLIMATE CHANGE THROUGH THE HOLOCENE, NORTHERN SIERRA NEVADA, CALIFORNIA, U.S.A.

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Evidence of the synchroneity of abrupt climate change events (ACCE) in Greenland ice cores and across the Western Hemisphere is accumulating. I present evidence that catastrophic fires and erosion in the northern Sierra Nevada during the Holocene coincided with drought and cooler temperatures, and the deposition of soot in central Greenland, suggesting that common drivers affected both regions. This conclusion is reinforced by results from studies in the Sierra Nevada and central Rocky Mountains. We hypothesize that ACCE caused severe environmental disequilibrium, massive plant die-off, catastrophic fire, and severe erosion over large areas of the western United States.

## RECONSTRUCTING PAST DISTURBANCE OF SPRUCE BEETLE (*DENDROCTONUS RUFIPENNIS)* FROM LAKE CORE SEDIMENT

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The relationship between fire and insect infestation, climate change, vegetation composition, and human impact has attracted considerable interest from a wide variety of professionals. Examination of plant remains, charcoal particles, and insect remains in sediments from wet meadows and small ponds can extend the record of vegetation history, forest disturbance, and ecosystem effects to ancient times – beyond the period provided by historical records, ethnographic evidence, and fire-scarred tree-ring records. The spruce beetle (*Dendroctonus rufipennis*) is a known Engelmann spruce (*Picea engelmannii*) pest whose impact may increase with future temperature increases. We have been studying sediment cores from a small subalpine lake in Colorado in order to reconstruct spruce beetle outbreaks over time. Initial research (Anderson and Smith, submitted) documented the pollen record of the 1940's outbreak, and suggested an earlier outbreak between A.D. 790 and 1140. Each of these outbreaks occurred during a period of below-average precipitation, as determined from reconstructed PDSI. More recent research has concentrated on recovering the remains of the beetles in shallow-water cores, and comparing these occurrences with the pollen, plant macrofossil, and charcoal (fire) records. Gaining a more comprehensive knowledge of the relationship between climate change and insect infestation will allow researchers and land

managers greater insight into the impact of climate change and human disturbance on the forest ecosystem.

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## THE LAST 1,300 YEARS IN NORTHERN YELLOWSTONE NATIONAL PARK BASED ON MULTIPROXY DATA FROM CREVICE LAKE

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Pollen, charcoal, diatoms, stable isotope, and geochemical records were analyzed in high-resolution in cores obtained from Crevice Lake, a varved-sediment lake in northern Yellowstone National Park. The objective was to reconstruct the vegetation, fire, and ecohydrologic history of the watershed for the period from A.D. 600-1917 and compare the results with the PDSI reconstructions of Cook and others (2004). Pollen percentages and accumulation rates (PAR) provide information on vegetation and flowering season conditions. Charcoal accumulation rates (CHAR) provide information on fire activity, including fire size or intensity and fire frequency. Diatoms disclose the nature of spring nutrient status, time of ice off, and duration of lake stratification, with *Cyclotella bodanica* as an indicator of prolonged summer stratification. The $\delta^{18}O$ values over the last 300 years correlate well with reconstructed discharge for the Yellowstone River (Graumlich and others, 2003), suggesting a relationship between $\delta^{18}O$ and winter precipitation. Organic carbon ($C_{org}$) is a qualitative indicator of organic productivity, and certain elements such as sulfur (S) and molybdenum (Mo) are indicators of anoxia and sulfate reduction.

From A.D. 600-1150, high values of *C. bodanica* suggest long periods of summer stratification, and higher S and Mo concentrations and pyrite formation indicate more oxygen-deficient bottom waters. High concentrations of $C_{org}$ imply higher organic productivity or low degradation due to anoxia. Low charcoal and high pollen accumulation rates imply small and/or frequent, fires and long flowering periods. Between A.D. 600-900, high $\delta^{18}O$ values suggest dry conditions. From A.D. 900 to 1100, low $\delta^{18}O$ values and abundant *C. michiganiana* imply wet winters, and warm summers with prolonged stratification. Charcoal and pollen data indicate continued frequent or small fires and long flowering periods, and upper treeline was at a higher elevation at this time (K. Pierce, unpubl. data). The period from A.D. 1150-1700 features high variability in PDSI values, including extreme dry and wet intervals. Low $\delta^{18}O$ values match a PDSI wet interval at A.D. 1300, suggesting high winter precipitation. A shift from *C. bodanica* to *Stephanodiscus medius* and *S. minutulus* indicates longer or cooler springs than before, and low CHAR and PAR indicate low fire activity and poor flowering. Between A.D. 1400 and 1525, low $\delta^{18}O$ values correspond with high CHAR peaks suggesting infrequent severe fire events during a wet interval. From A.D.1500 to 1700, an increase in $\delta^{18}O$ values and a slight

rise in *C. bodanica* indicate warmer spring conditions, prolonged summer stratification, and perhaps shorter winters, with less precipitation, than before. From A.D. 1700 to 1800, the proxy data indicate dry conditions (high $\delta^{18}O$), lengthy summer stratification (high *C. bodanica*), large or severe fires (high CHAR), and increased forest cover (high PAR and arboreal pollen percentages). PDSI reveals modest drought event in mid-1800s, associated with winter precipitation (low $\delta^{18}O$) near Crevice Lake. Greater seasonality during this period may explain the diatom mixture of *C. bodanica*, *S. medius*, and *S. minutulus*. A large fire event was recorded at *ca*. 1850 and fires have been small or absent since then.

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## WATERSHED-SCALE HYDROCLIMATIC TRANSITIONS ACROSS THE U.S. CONTINENTAL DIVIDE

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Water, already a scarce resource in the semi-arid western United States, has become an increasingly threatened commodity due to population growth pressures, natural climate variability, and the prospect of future climate change. Much of the West is in the midst of a multi-year drought that has placed a renewed sense of urgency on water availability issues. The characterization of variability over relevant space and time scales has emerged as one of the top needs concerning the hydrological cycle. The first step of a multi-scale investigation to address that need has been undertaken through analysis of historical climate and hydrology data to provide better understanding of current hydroclimatic connections at the watershed scale. The study area is located near the headwaters of two important western river systems, the Snake and Yellowstone Rivers. Results of data analysis indicate that there is a strong relationship between upper atmospheric circulation and Snake River stream flow. Historical data from Snake River and Yellowstone River stream flow gages, located approximately 80 km apart, indicate that over the past 70 years, the flow of the two rivers is synchronous (both below average, both above average, or both near average) in less than half of the years examined. In the next stage of this study, which will include stream flow and climate reconstruction using tree-ring data, these historical data will be used for calibration and as synoptic analogs for understanding circulation-growth relationships.

## COLORADO DROUGHT: PAST AND PRESENT

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Drought is a major feature of the climate of Colorado and adjacent regions. The early inhabitants of this area recognized that droughts were a fact of life, as did some of the first Anglo-American explorers. The political and legal history of the State of Colorado reflects an awareness of the quantity, seasonality, and distribution of water resources in the state. The Colorado River at Lees Ferry was one of the first gage records to be reconstructed from tree rings, and this 450-year reconstruction reinforced the reality of periodic and recurring droughts. In spite of this history, the recent drought in Colorado appears to have taken some water managers by surprise, but it has resulted in a new awareness of the impact of sustained drought on the state, and the entire Colorado River Basin. The drought and its economic, environmental, and political consequences have rekindled interest in extended records of stream flow that can be derived from tree rings. Recent reconstructions for the Upper Colorado River Basin present some good news and some bad news for water resource managers, and raise questions about how to deal with the implications of the paleohydrologic record in the context of the Colorado River Compact and the Law of the River. As water managers begin to consider these data, the challenge to paleoscientists is to present the information in the stream flow reconstructions in a way that is relevant to water management concerns, and to work collaboratively to find the best ways to incorporate reconstructions into water resource planning and decision-making.

## AGE CLASS STRUCTURE OF PINYON WOODLANDS, CLIMATE VARIABILITY AND PREHISTORIC PINE NUT PROCUREMENT

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An emerging research problem in paleoecology and archaeology is the effect of prehistoric human activities on past ecosystems. Modification of fire regimes and maintenance of vegetation types by prehistoric burning is well known but there are other vegetation management methods and resource utilization patterns that had the potential to alter vegetation associations to various degrees. An example is the pine nut procurement system of the Paiute (*Nümü*) in the eastern Sierra Nevada and western Great Basin. The Owens Valley Paiute and their predecessors have been collecting pine nuts, which were once a staple food, from singleleaf pinyon pine (*Pinus monophylla*) groves for at least the past 2,000 years. According to informants, the groves were historically managed by pinching new growth on the trees to produce more female cones, removing lower branches to prevent fire "laddering", and cleaning duff and other debris under the trees to also reduce fire risk and increase the efficiency of pinecone collecting. The cumulative effects of this activity on the ecology of pinyon groves over a long period of time are not known. Pinyon has been migrating north from a glacial refugium in the southern Great Basin since the past 10,000 years as climate warmed, and has expanded into

the eastern escarpment of the Sierra Nevada since the late 19th Century. Within this general trend the tree species has responded to lower frequency climate change. A problem is to separate human effects from the effects of climate variability. A network of prehistoric pine nut collecting camps is distributed throughout the pinyon woodlands of the eastern Sierra Nevada. The camps are located in pinyon groves that were persistently used for pine nut procurement. Other areas in the woodland in-between and at an ineffectual distance from the camps were not likely to have been harvested. It is proposed that comparing the age-class structure and tree-ring chronologies of pinyon stands both in and away from areas of prehistoric influence may determine the effects of pine nut procurement and pinyon grove management by showing any change in population structure through time that differs significantly from changes due to climate variability. A beginning in this research project has been made by defining the age-classes of a stand of pinyon growing on a prehistoric site that functioned as a pine nut procurement camp on the northeast escarpment of the White Mountains, California. An initial assessment of the age classes indicates that peaks in establishment seem to occur during warm periods and low establishment numbers occur during cool periods. Precipitation does not seem to be a strong factor in age-class distribution.