Abstracts for Talks and Posters presented at the CIRMOUNT-sponsored sessions at AGU, December 2007

Session Title: Climate Change in High Elevation Mountain Environments

Poster

The Hydrological Response of Snowmelt Dominated Catchments to Climate Change

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Hydrological systems dominated by snowmelt discharge contribute greater than half the freshwater resource available to the western United States. Globally, the contribution of mountain discharge to total runoff is twice the expected for their geographical coverage. Therefore, snowmelt dominated mountain catchments have proportionally a more prominent role than other systems to our freshwater resource. A changing climate, or even a more variable climate, could have a significant impact on these systems, and consequently on our freshwater resource. Ergo, a better understanding of how changes and variations in climate will influence mountain catchments is a necessity for improving future water management under predicted/proposed climate change. The research presented here is a first order analysis to improve our understanding of these systems by monitoring and analyzing high mountain catchments along the entirety of the Mission Mountain Front, Montana USA. The Mission Mountain Range is an ideal location for conducting this research as it runs directly north to south with elevations progressively increasing from 7600 feet in the northern section, to over 9700 feet at the southern end. The lower elevation catchments will be used as surrogates for variable climate change, while the high elevation catchments will be used as surrogates for a more stable, cooler, climate regime. We use a combination of USGS and Tribal stream gauges, as well as stage gauge loggers in the headwaters of the catchments, SNOTEL datasets, and weather station datasets. This information is used to determine if, how, and why the snowmelt hydrographs vary between catchments, within the catchments between the upper and lower segments, and the dominant driver or drivers of the hydrograph form in relation to changing climatic variables such as temperature and precipitation. This research will improve current comprehension of how mountain catchments respond to climatic variables, and additionally will expand upon the current understanding of general catchment hydrology.

Poster

Data gathering and simulation of climate change impacts in mountainous areas

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High mountains include species most at risk in a warming environment and are a critical link in the water supply chain for both human and natural systems. Scientists are monitoring and simulating these systems as snowpack depth changes, snowmelt timing changes, frozen soils melt and destabilize, and low elevation populations migrate upslope. Natural climate cycles and human activities interact with climate change trends and complicate the interpretation of the signal we observe. For ex. over the past 4 years in Yunnan (China), we documented that herbaceous alpine meadows are contracting as forest tree line advances and alpine shrub biomass increases. This is a result of interactions between human land use alteration and observed shifts in
climate. In North America as snowpack decreases, wolverines and lynx denning conditions are jeopardized as human pressure reduces their extent. Coarse scale vegetation shift models using downscaled future climate scenarios fail to capture complex terrain features and microclimatic conditions that can either ensure critical habitat for the in-situ survival of threatened species or make things worse (ex. rockfalls) for climate migrants. Recent simulation efforts focus on high resolution models that address aspect, slope, soil types, and microclimate variations that affect local and migrating plants, their associated pollinators and insect herbivores, modifying habitat availability for birds and mammals.

Talk

Elevation and Temperature Effects on Carbon Balance Near Alpine-treeline: Comparison of a Treeline and Non-treeline Tree Species

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Changes in carbon balance of trees may help explain temperature and range limits of conifers near alpine-treeline and the climate sensitivity of forest boundaries. Our objective was to determine which component of carbon balance most limit tree seedling growth at high elevation, and how growth processes vary in their response to temperature. We assessed relationships of temperature, carbon flux, and growth in whole seedlings of a treeline and non-treeline species (Abies lasiocarpa and Pseudotsuga menziesii, respectively) at two elevations near alpine-treeline in the Teton Range of Wyoming, USA. Seedlings were outplanted as they germinated in potting soil substrate in sites having sparse overhead canopy cover at 2450 m (high forest) and 3000 m (near treeline) elevations. Gas exchange and growth measurements were performed every 2-3 weeks when treeline was snow-free, in 2005 and 2006. Growth was less at the higher elevation in both species, and was associated with less needle area, root mass, and photosynthetic carbon assimilation (A) and respiratory efflux (R). However, R decreased more than A with cooling and at the higher elevation, causing an increase in A:R with elevation. The primary difference between species was greater growth, A, and R in the treeline species. Reductions in A per unit leaf area were expected at the higher elevation from previous studies, but were not observed. Notable differences in our experiment were the elimination of tree canopy (i.e. shading) differences that normally occur among elevations and are known to affect seedlings. Additionally, we did not detect any frost during our study periods, which resulted in part from local topography and snow pack patterns that distinguish the climate regime of the subject treeline. Moreover, microclimate measured beyond our study periods indicates that seedlings experience more frost at the lower compared to upper sites we evaluated, with the frosts typically occurring when the upper elevation site is snow-covered. The results of this study, along with consideration of differences in climate among treeline studies, have important implications for transferability of tree-climate information among treelines, and thus monitoring or predicting treeline change.

Invited Talk

Complex Patterns in Climate and Atmospheric Nitrogen Deposition Influence Rocky Mountain Ecosystems

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Long-term monitoring of physical and biogeochemical characteristics in Loch Vale watershed, Rocky Mountain National Park, has revealed complicated patterns in temperature, precipitation, and atmospheric nitrogen deposition. July mean and maximum temperatures have increased since 1985 by 0.1-0.2 °C, while March mean and maximum temperatures became 0.1-0.3 °C colder. There is no long-term trend in annual or monthly precipitation; annual totals range 75-140 cm yr⁻¹. Atmospheric N deposition has increased approximately 2% yr⁻¹ since 1985, and there are strong upward trends in July and September deposition. A combination of observations, ecosystem modeling (DayCent-Chem model), and structural equation modeling (SEM) suggests this alpine/subalpine catchment is responding physically, biologically, and chemically. Observed stream discharge was greater than measured precipitation in several recent years, indicating melt from glacier ice contributes to flow. Model results suggest a strong increase in alpine microbial activity and plant N uptake, and a moderate increase in forest microbial activity driven by increased temperatures and increased N deposition. Alpine lichen activity appears to also have been significantly stimulated. There has been a significant increase in observed stream nitrogen concentrations and flux. Annual mean stream N concentrations in alpine/subalpine Loch Vale watershed of Rocky Mountain National Park have increased from approximately 1.0 to 1.5 mg NO₃⁻ L⁻¹ between 1991 and 2005; the annual amplitude has also increased. Mean annual N efflux from the catchment doubled between 1991 and 2005. SEM suggests N loss from Loch Vale appears to result most strongly from the combined influence of temperature and precipitation on stream flow, and secondarily from the influence of terrestrial nitrogen cycling.

**Poster**

**Hydrology and Biogeochemistry of Three Alpine Proglacial Environments Resulting From Recent Glacier Retreat**

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Proglacial environments, formed by glacier retreat, exhibit distinct characteristics in discharge, water temperature, water residence time, and ion, carbon, and suspended sediment fluxes. The unnamed alpine glacier at the headwaters of the Wheaton River, Yukon, Canada, provides a unique setting to compare deglaciation processes that result in three different proglacial environments. The glacier has evolved from occupying one large catchment (4 km²) to two smaller catchments (each 2 km²) via glacier thinning and net mass loss, forming two lobes separated by a medial moraine. Climate and bedrock geology are similar for the subcatchments, providing a natural laboratory to compare deglaciation processes. This study compares the biogeochemistry and hydrology of three outlet streams from this glacier; one stream drains a proglacial lake which is fed by the lower west lobe, a second stream drains the upper west lobe, and a third stream is the major drainage outlet for the east lobe. Hydrological monitoring over the 2006 melt season (June-August) and analyses of water samples for ion content and carbon chemistry indicate certain discrete characteristics for each stream and thus aid in the understanding of climate-induced glacier retreat on hydrochemistry, hydrology, and carbon dynamics in remote high elevation environments.

**Poster**

**Integration of Classification Tree Analyses and Spatial Metrics to Assess Changes in Supraglacial Lakes in the Karakoram Himalaya**

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Alpine glacier responses to climate change reveal increases in retreat with corresponding increases in production of glacier melt water and development of supraglacial lakes. The rate of occurrence and spatial extent of lakes in the Himalaya are difficult to determine because current spectral-based image analysis of glacier surfaces are limited through anisotropic reflectance and lack of high quality digital elevation models. Additionally, the limitations of multivariate classification algorithms to adequately segregate glacier features in satellite imagery have led to an increased interest in non-parametric methods, such as classification
and regression trees. Our objectives are to demonstrate the utility of a semi-automated approach that integrates classification-tree-based image segmentation and object-oriented analysis to differentiate supraglacial lakes from glacier debris, ice cliffs, lateral and medial moraines. The classification-tree process involves a binary, recursive, partitioning non-parametric method that can account for non-linear relationships. We used 2002 and 2004 ASTER VNIR and SWIR imagery to assess the Baltoro Glacier in the Karakoram Himalaya. Other input variables include the normalized difference water index (NDWI), ratio images, Moran’s I image, and fractal dimension. The classification tree was used to generate initial image segments and it was particularly effective in differentiating glacier features. The object-oriented analysis included the use of shape and spatial metrics to refine the classification-tree output. Classification-tree results show that NDWI is the most important single variable for characterizing the glacier-surface features, followed by NIR/IR ratio, IR band, and IR/Red ratio variables. Lake features extracted from both images show there were 142 lakes in 2002 as compared to 188 lakes in 2004. In general, there was a significant increase in planimetric area from 2002 to 2004, and we documented the formation of 46 new lakes. It appears that lake-size increments occur mostly in the lower part of the ablation zone, whereas most of the new lakes are formed in the upper part of the ablation zone. The classification-tree outputs are intuitive and the data-derived thresholds eliminate commonly subjective visual determination of threshold values. Semi-automated methods thus have the potential of eliminating laborious visual multi-temporal analysis of glacier-surface change, thereby producing consistent and replicable results needed to assess the trends of alpine-glacier response to climate change in the Himalaya.

**Poster**

Hydrological and Ecological Sensitivities to Climate Change for Four Western U.S. Mountain Ecosystems.

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National Parks in Western U.S. mountain ecosystems are rapidly changing as a result of the direct and indirect effects of climate change. With warming temperatures, these systems are expected to experience earlier melt and reductions in snow accumulation. The impact of these changes on other hydrologic patterns, such as summer streamflow, and ecosystem structure and function maybe significant, but is likely to vary across the Western U.S. Park managers need quantitative estimates of these potential changes for development of long-term management strategies. A systematic approach can be used to define where and why these mountain ecosystems are affected by climate, focusing on net ecosystem exchange, net primary production, evapotranspiration, and streamflow trends. We used RHESSys, a spatially distributed, dynamic process model of water, carbon, and nitrogen fluxes, to examine the interplay between ecological and hydrological sensitivities to climate in four National Parks across the Western U.S., including watersheds in the North Cascades (WA), Glacier (MT), Rocky Mountain (CO), and Yosemite (CA) National Park. Analyses show while some systems are more hydrologically sensitive to climate variations, others are more ecologically sensitive. For example, with warm temperatures, the greatest reduction of summer streamflow is likely to occur in Glacier, while greatest sensitivities of vegetation responses, e.g. transpiration, net primary productivity, are predicted for the Cascades. Understanding the degree to which these watersheds are sensitive to climate variability and change will help to predict site specific vulnerabilities and allow park managers to tailor climate change management plans to individual locations.

**Talk**

New stratigraphic constraints on Holocene glacier advances at Mt. Baker, Washington

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New data from a lake sediment core and moraine exposures at Mt. Baker, WA, indicate that a purported early Holocene glacier advance occurred earlier, likely at the end of the Pleistocene. Previous workers used 14C ages associated with small cirque moraines on the SW flank of Mt. Baker, along with the apparent absence of a distinctive scoria (set SC; 8850 14C yr BP, ~9900 cal yr BP) from other moraines on Mt. Baker, as evidence for an advance at ~8400 14C yr BP (~9450 cal yr BP). Such an advance is important to test because it would contrast with glacial records throughout most of the rest of western North America. A 1.2-m sediment core collected from Pocket Lake, which is dammed by one of the previously dated cirque moraines, contains three tephras: Baker set BA (~5800 14C yr BP; 6600 cal yr BP), Mazama ash (6800 14C yr BP; 7600 cal yr BP), and a basal set of ash beds that are tentatively identified as Baker set SC. The lowest macrofossil in the core, ~2 cm above the top of the basal ash beds, yielded an age of 7640 ± 50 14C yr BP (~8400 cal yr BP), consistent with the tephra being SC. Initial geochemical analyses of the tephra also support this identification. These findings indicate that the previous age on the cirque moraine, from organics near the surface of the till, provides a minimum rather than a direct age for the advance that formed the moraine. A 14C age of 11,400 ± 110 14C yr BP (~13,300 cal yr BP) on bulk sediments below the basal ash is likely contaminated and therefore too old. Tephra overlying other ridges at Mt. Baker that were previously identified as post-SC, early-Holocene moraines has been identified as set SC. The ridges thus are actually pre-SC rather than post-SC in age; they may not be moraines in any event. Meanwhile, abundant 14C ages on tills below Deming Glacier indicate both Younger Dryas and Neoglacial advances, but no early Holocene advances. Together, these observations indicate that glaciers in the Mt. Baker area advanced during the YD, were of minimal extent during the early Holocene, and readvanced during the Neoglacial. The similarity of glacier fluctuations here to those in British Columbia and elsewhere in the North Cascades suggests a coherent history of Holocene climate change over a broad area of the northern Cordillera.

Talk
Changes in the timing of snowmelt and associated runoff in the Colorado Rocky Mountains

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Previous studies have documented changes in the timing of springtime runoff in the Western United States, with runoff occurring up to two weeks earlier in 1950 than in the 2000. Changes were most pronounced in the Sierra Nevada, Cascades, and northern Rocky Mountains. Few statistically significant changes were identified in Colorado, despite local observations of earlier than normal snowmelt during many recent spring seasons. To further elucidate recent trends in snowmelt timing and associated runoff in Colorado, data from 72 SNOTEL sites and 40 high-elevation streamflow-gaging stations with minimal upstream diversions were tested for trends during 1978 to 2004. Trends were tested using linear regression, as was done in the previous studies, and using the Regional Kendall test (RKT), which is a relatively new test derived from the Seasonal Kendall test. The RKT provides increased power of trend detection in short records with substantial interannual variability. Results indicated that although few sites exhibited statistically-significant trends using linear regression, the RKT identified pervasive earlier snowmelt and runoff throughout the State, with an average change of 0.5 days per year. The RKT revealed important regional variations in the snowmelt- and runoff-timing trends. The strongest trends were in the western and southern parts of Colorado; trends in the north-central part of the State were relatively weak, perhaps because of an increase in upslope storms. Changes in snowmelt timing were strongly correlated with increasing springtime air temperatures, which showed strong positive (warmer) trends during the study period. In contrast with previous studies, this study identified significant shifts in the timing of snowmelt and associated runoff towards earlier in the year in Colorado, and the shift is related to springtime warming.
Talk
Response of Rwenzori (Uganda - DR Congo) Glaciers and Mountain Lake Ecosystems to Climate Change: Past, Present, Future

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Ice caps and glaciers in the mountains of tropical Africa are expected to disappear within two decades as a result of human-induced global warming. Loss of permanent ice from Africa’s mountains will have profound effects on Afroalpine ecosystems, as well as the hydrology and temperature regime of Africa’s unique, alpine cold-water lakes. Consequently, there is an urgent need to document the baseline climatic, environmental, and biological conditions in Africa’s mountains against which to evaluate future changes. While climatic, limnological, and ecological monitoring can provide key insights into modern conditions, sediments accumulating on the bottom of alpine glacial lakes chronicle the history of central African climate and environmental dynamics, and can thus produce the historical perspective needed for resource conservation. In this context, over the course of three field expeditions (2005-2007) we surveyed virtually all lakes (19) on the Ugandan side of the Rwenzori Mountains, Uganda-Congo, to evaluate the sensitivity of these high-mountain lake ecosystems to climate change and glacier melting. We installed temperature and humidity loggers to monitor ongoing climate change, calibrated paleolimnological proxy indicators (sediment composition, organic carbon, biomarkers, aquatic biota) in surface sediments in relation to their present local lake environment, and analyzed gravity cores from selected lakes to document the history of recent glacier recession and ecosystem response. Here, we present an overview of the currently available climatic and environmental data sets, with a focus on sediment core data. Through comparison of the sedimentary history of glaciated and non-glaciated lake basins, we show that recent glacier recession started around 1880 AD, broadly coincident in timing with declining East African rainfall as documented by regional lake level datasets. However, our data do not suggest rapid glacial expansion coincident with the initiation of this wet phase in the early 19th century, highlighting the complexity of the relationship between tropical alpine glaciers and climate. Glacier recession starting at 1880 AD is accompanied by declining aquatic primary productivity, recorded in the isotopic composition of sedimentary organic matter. Together, our data show that Rwenzori’s high-elevation lakes are responsive to alpine glaciation and constitute a unique laboratory to assess quantitatively the relationship between the extent of its glaciers, changes in central African climate, and ecosystem processes.

Invited Talk
Climate Change Has Cascading Ecological Effects on Mountain Ecosystems

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Evidence that ecosystems of the Northern Rocky Mountains are responding to climate change abounds. Alpine glaciers, as iconic landscape features, are disappearing rapidly with some glaciers losing one half of their area in five years. A model developed in the 1990s to predict future rates of melt has proved too conservative when compared to recent measurements. The largest glaciers in Glacier National Park are almost 10 years ahead of schedule in their retreat. The cascading ecological effects of losing glaciers in high-elevation watersheds includes shifts in distribution and dominance of temperature-sensitive stream macroinvertebrates as stream volume dwindles (or disappears) in later summer months and water temperatures increase. Critical spawning areas for threatened bull trout (Salvelinus confluentus) will be lost without the consistent supply of cold water that melting snow and ice provide and raise management questions regarding the efficacy of recovery efforts. Snowpacks are documented as becoming smaller and melting earlier in the spring, facilitating the invasion of subalpine meadows by trees and reducing habitat for current alpine wildlife. Even vital ecosystem disturbances, such as periodic snow avalanches that clear mountain slope forests, have been shown by tree-ring studies to be responsive to climatic trends and are likely to become less prevalent. Monitoring of high-elevation mountain environments is difficult and has largely been opportunistic despite the fact that these areas have experienced three times the temperature increases over the past century when compared to lowland environments. A system of alpine observatories is sorely needed. Tighter integration of mountains studies, and comparisons
among diverse mountain systems of the western U.S. has been initiated by the USGS-sponsored Western Mountain Initiative and the Consortium for Integrated Climate Research in Western Mountains to begin addressing this need.

Talk

A century of glacier change in the American West

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Over the past 100 years glaciers in the American West (exclusive of Alaska) have largely receded. The magnitude of the recession varies across the west, with the greatest loss in Montana and California (>50% area loss) and the least loss on the stratovolcanoes (>35%) of the Pacific Northwest. The variations can be broadly characterized by elevation. Our results suggest that increased mass loss caused by increased summer temperatures affect all glaciers, whereas increasing winter temperatures, that change the phase of precipitation from snow to rain adversely affect those glaciers less than 3000m in elevation. The high glaciers (>3000m) of California and Colorado appear to be immune to variations in snowfall making them sensitive to variations in temperature alone. We infer that these very small, steep glaciers can only hold a given amount of snow beyond which extra snow avalanches or is blown off. Conversely, during winters of little direct snowfall, additional snow may be added through wind drift from the surrounding terrain. The relatively little glacier shrinkage on the stratovolcanoes is due to the high altitude of the glacier accumulation zones. An east to west decrease in glacier shrinkage from Montana through Washington is due to enhanced winter precipitation along the west coast that somewhat buffers ice loss due to summer temperatures and winter precipitation phase changes.

Invited Talk

Effects of Recent Climate Change on Facultative and Spontaneous Torpor in Alpine Habitats

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Mean annual air temperatures have increased in North America by 1.0°C during the past 100 years, and are predicted to increase by 4-8 °C further within the next 70 years. Hibernating mammals may be particularly sensitive to climate change since body temperatures during torpor are strongly influenced by ambient temperature. We conducted 3-7 year studies on the relationship between ambient (air/soil) temperature and the torpor patterns of free-ranging facultative and spontaneous hibernators. The facultative hibernation of eastern chipmunks (Tamias striatus) in New York State and the spontaneous hibernation by golden-mantled ground squirrels (Spermophilus lateralis) in the mountains of California were continuously monitored using temperature sensitive radiocollars during winters of 2000-01 through 2006-07. Mean air/soil temperatures during the winter 2001-02 were much greater than those observed during the same periods of 2000-1 and 2002-3 winters at both sites, and the winter of 2001-2 was one of the warmest measured in both New York State and California since 1895. Consequently T. striatus during the winter 2001-2 had: a) fewer individuals using torpor, b) reduced the time spent in torpor by 96%, and, c) increased energy expenditure by 100% when compared to the torpor patterns of the same population during the colder winters of 2000-1/2002-3. Likewise, S. lateralis during the winter of 2001-2 had: a) delayed the entrance into hibernation by a mean of 12.2 days, b) increased mean body temperatures by an average of 5.4 C during torpor, and, c) increased metabolic rate during torpor by 75% when compared to the torpor patterns of the same population during the winters of 2000-1/2002-3.

Talk

Recent Relationships of Tree Establishment and Climate in Alpine Treelines of the Rocky Mountains
Changes in the forest structure of alpine-forest or treeline boundaries may be a significant climate response of mountainous regions in the near future. A particularly important point of climate sensitivity for treelines is the initial survival and establishment of tree seedlings - a demographic bottleneck that may be particularly suited to early detection of treeline responses to climate change. However, concise information on climate sensitivity of seedling establishment has come primarily from direct observations of seedlings over short time periods encompassing a few years. Dendrochronological approaches have revealed tree establishment patterns at more extensive time scales of decades to millennia, but at coarser temporal resolutions. Climate variations that most directly affect initial tree seedling establishment occur at annual or smaller time scales, and climate for seedlings is modulated by landscape factors such as neighboring plant cover. Our objective was to assess climate sensitivity of tree establishment at treeline at these finer temporal and spatial scales, with consideration of treeline features that alter the climate for seedlings. Our approach combined direct observations of seedling emergence and survival with dendrochronology of older seedlings and saplings that were still small and young enough (less than 25 years and 20 cm height) to allow detecting the year of establishment and associated factors. Surveys for subject seedlings and saplings were performed for 2 years across the gradient from forest into treeline alpine in the Beartooth, Teton, and Medicine Bow mountains of Wyoming USA. No seedlings or saplings were detected above the highest elevation adult trees or krummholz, but there were up to 0.3 seedlings per square meter in subalpine meadows close to forest (within the timberline zone) where changes in tree abundance appear possible in future decades. Correlations of establishment and summer temperature ranged from weak in whitebark pine (Pinus albicaulis) and Engelmann Spruce (Picea engelmannii) to significantly positive for subalpine fir (Abies lasiocarpa). Seedling establishment was consistently associated with microsite features such as resident trees and herbs that alter sunlight and temperature for small seedlings, and the effect was strongest for subalpine fir and least evident for whitebark pine. For all species and treelines, establishment in microsites with the least amount of overhead tree cover (furthest from forest in the alpine, in exposed locations) occurred in years with warmer summer temperatures. These patterns of establishment are consistent with previous and current experimental studies of terrestrial and solar radiation and temperature effects on tree seedlings at treeline. Our findings indicate that local treeline response to climate variability may vary as a function of current landscape patterns of tree and herb cover, and tree species assemblages that are unique to different treelines. Local shifts in tree species composition that are ongoing may thus pose a significant issue in forecasting future treeline change.

Poster

High-altitude varve records of abrupt environmental changes and mining activity over the last 4000 years in the Western French Alps (Lake Bramant, Grandes Rousses Massif)

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Two twin short gravity cores and a long piston core recovered from the deepest part of proglacial Lake Bramant (Grandes Rousses Massif, French Alps), under and overlying a large slump identified by high-resolution seismic profile, allow the investigation of Holocene natural hazards and interactions between human activity and climatic changes at high-altitude. Annual sedimentation throughout the cores (glacial varves) is identified on photographs, ITRAX (high-resolution continuous microfluorescence-X) and CAT-Scan (computerized axial tomography) analyses and is supported by (1) the number of dark and light laminations between dates obtained by radionuclide measurements ($^{137}$Cs, $^{241}$Am), (2) the correlation of a slump triggered by the nearby AD 1881 Allemond earthquake (MSK intensity VII) and of a turbidite triggered by the AD 1822 Chautagne regional earthquake (MSK intensity VIII), (3) the number of laminations between two acceleratory mass spectrometry (AMS) $^{14}$C dates, and (4) archaeological data. In Lake Bramant, dark layers are coarser, contain less detrital elements, but more neoformed elements and organic matter content. These darker laminations result from calm background sedimentation, whereas the lighter layers are finer and rich in detrital elements and reflect the summer snowmelt. Traces of mining activity during the Roman civilization apogee (AD 115-330) and during the Early Bronze Age (3770-3870 cal BP) are recorded by lead and copper content in the sediments and probably result from regional and local mining activity in the NW Alps. Warmer climate during the Bronze Age in this part of the Alps is suggested by (1) two organic deposits (4160-3600 cal BP and 3300-2850 cal BP) likely reflecting a lower lake level and smaller glaciers and (2) evidence of a different vegetation cover around 2500 m a.s.l. The onset of clastic proglacial sedimentation between 3600-3300 cal BP and since 2850 cal BP is synchronous with periods of glacier advances documented in the Alps and high lake levels in west-central Europe. This major change in proglacial sedimentation highlights the development of a larger St. Sorlin glacier in the catchment area of Lake Bramant.

**Poster**

**Satellite Observations of Glacier Advances and Retreat in the Western Karakoram**

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Debris-covered alpine glaciers around the world have been retreating and downwasting. This suggests glacier response to atmospheric warming. Recent studies in the eastern Himalaya have shown systematic retreat for many glaciers. In the western Himalaya, however, systematic and quantitative data are not yet available to determine glacier sensitivity and mass balance trend. Given the paucity of bench-mark glaciers in the Himalaya, remote-sensing-based studies are required to obtain baseline information and produce estimates of advance and retreat rates. Consequently, our objectives were to assess glacier fluctuations in the western Karakoram of Pakistan as a part of the Global Land Ice Measurements from Space (GLIMS) project. Specifically, we used multi-temporal satellite data (ASTER 09/13/2004, Landsat TM 10/15/1992, and Landsat MSS 07/15/1992) to quantitatively assess terminus fluctuations. Results indicate that more than 50 percent of the sampled large and large-medium sized glaciers are advancing, and/or exhibit similar terminus positions to past positions. For example, Bualtar Glacier is advancing at the rate of 11 m/yr. On the other hand, most of the small-medium to small glaciers, such as Mani Glacier are retreating (15 m/yr). Some of these glaciers have also shown strong downwasting characteristics in the form of increased frequency and size of supraglacial lakes. Collectively, our results indicate that these glaciers may be responding differently to the current climatic conditions than in the eastern Himalaya (east of the Karakoram) and Wakhan Pamir region (northwest of the Karakoram). These quantitative results from remote-sensing studies also indicate that glacier fluctuations in this region are spatially and temporally complex. These complexities may be governed by multi-scaled topographic effects, as well as by variations in winter precipitation and decreases in summer temperature from increased cloudiness, as suggested by others.

**Talk**

**Observing Seasonal and Diurnal Hydrometeorological Variability Within a Tropical Alpine Valley: Implications for Evapotranspiration**

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Conditions of glacier recession in the seasonally dry tropical Peruvian Andes motivate research to better constrain the hydrological balance in alpine valleys. There is an outstanding need to better understand the impact of the pronounced tropical hygric seasonality on energy and water budgets within pro-glacial valleys that channel glacier runoff to stream flow. This paper presents a novel embedded network installed in the glacierized Llanganuco valley of the Cordillera Blanca (9ºS) comprising eight low-cost, discrete temperature and humidity microloggers ranging from 3470 to 4740 masl and an automatic weather station at 3850 masl. Data are aggregated into distinct dry and wet periods sampled from two full annual cycles (2004-2006) to explore patterns of diurnal and seasonal variability. The magnitude of diurnal solar radiation varies little within the valley between the dry and wet periods, while wet season near-surface air temperatures are cooler. Seasonally characteristic diurnal fluctuations in lapse rate partially regulate convection and humidity. Steep lapse rates during the wet season afternoon promote upslope convection of warm, moist air and nocturnal rainfall events. Standardized grass reference evapotranspiration (ET0) was estimated using the FAO-56 algorithm of the United Nations Food and Agriculture Organization and compared with estimates of actual ET from the process-based BROOK90 model that incorporates more realistic vegetation parameters. Comparisons of composite diurnal cycles of ET for the wet and dry periods suggest about twice the daily ET0 during the dry period, attributed primarily to the 500% higher vapor pressure deficit and 20% higher daily total solar irradiance. Conversely, the near absence of rainfall during the dry season diminishes actual ET below that of the wet season by two orders of magnitude. Nearly cloud-free daylight conditions are critical for ET during the wet season. We found significant variability of ET with elevation up through the valley. Humidity and temperature measurements were analyzed to show significant effects of elevation and proximity to melt-water lakes on vapor pressure deficit.

Talk

Twentieth Century Bristlecone Pine Tree Rings Near Upper Tree Limit Wider Than in Recent Millennia

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Unusually wide tree-rings have been observed in recent decades in bristlecone pines from widespread locations at high elevations (3100 m.a.s.l. and above) near the upper forest border in the western USA. We present an enhanced and extended dataset from such environments, and report only results based on unmodified raw ring widths. These wide rings are unique in the context of at least the last 3700 years. Sites at similar elevations, but further below the upper tree limit, do not show this increase. The implications of these observations for possible explanations of the growth increase will be discussed, in the context of environmental changes unique to recent times. These will include the possible effects of increasing atmospheric concentrations of carbon dioxide on the trees’ water use efficiency, enhanced nutrient availability related to pollution, shifts in seasonal climatic patterns, and mountain climate conditions unique to the 20th and 21st centuries. Particular attention will be given to this last explanation, and in particular to the possibility of uniquely “Anthropocene” patterns of vertical change and their consequences for tree growth.

Talk

Effects of Climate and Fire on Thermal Habitats Within Mountain Stream Networks: An Example With a Native Charr Species

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Climatic trends associated with warming air temperatures, changing hydrology, and increasing fire activity will affect thermal
regimes in mountain streams. Because most aquatic species are ectotherms, disruptions of these ecosystems will be significant as the distributions of thermal habitats change. Although local stream temperature models have frequently been developed, network-scale models necessary for conservation are generally lacking. Using a new class of spatial statistical model that accommodates network topology and multiple types of spatial autocorrelation based on instream and Euclidean distance, we modeled the effects of geomorphology, climate, and fire on stream temperatures across a 6th-order network in central Idaho. Satellite imagery of riparian vegetation pre- and postfire was used to quantify the amount of solar radiation reaching the stream and consequent effects on temperature. Climate covariates were derived from weather and flow gauging stations and relevant geomorphic features were derived from digital elevation models. The spatial models yielded more accurate parameter estimates than traditional regression models and offered improved predictive ability for the temperature metrics examined (e.g., $R^2$ \$0.60 vs. 0.85). Upon completion, the spatial models were used to assess changes in the distribution of thermally suitable habitats for bull charr (Salvelinus confluentus) over a 15 year period with extensive fire activity. Habitat losses were spatially variable, as were the relative effects of the covariates. In general, the greatest habitat loss was attributable to the effects of fire and recent trends of increasing air temperatures and decreasing flows played lesser roles. Our results suggest that impairment and loss of aquatic habitats due to climate change can be caused by direct or indirect effects and may occur as gradual trends or during episodic disturbances. If future efforts to conserve aquatic species are to succeed, models that incorporate the spatial complexity of landscape responses to ongoing climate trends are needed.

**Talk**

**Climate Forced Alpine Tundra Ecosystem Dynamics: A Model Approach**

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Insights concerning the future evolution of alpine ecosystems depend on understanding and simulating their response to climate change. Comprehensive studies of these regions require novel spatio-temporal computational models of climate-forced landscape/ecosystem interactions. As part of the International Polar Year (IPY) we are examining alpine tundra landscapes and ecosystems in the Kluane region of southwest Yukon, Canada. Based on the combination of long-term geophysical and ecological field studies and driven by different climate change scenarios, such a model is being used to explore the range of possible future scenarios for the region. As the first step in building such a complex model, we present a simplified, grid-based model to demonstrate potential changes in plant community distribution driven by key climate variables such as temperature and precipitation. A linear orographic precipitation model is used to downscale climate data which, in combination with a digital elevation model, forms the geophysical input for the model. Simplified ecological rules describing the potential state transition of different plant communities and land cover types are incorporated in the model in a cellular automation fashion. The response of the ecosystem to several different climate scenarios will be presented, including a set of North American Regional Reanalysis climate data. This simplified model is used to demonstrate the potential of such interdisciplinary simulations to gain deeper understanding of ecosystem evolution with climate change.

**Poster**

**Climate Influence on Shifts in the Deep Canyon Ecoline, 1977 - 2007**

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The Deep Canyon Transect in the Santa Rosa Mountains of Southern California spans 2560 m in elevation and four major plant communities: desert scrub, Sonoran pinyon-juniper woodland, montane chaparral, and mixed conifer forest. The plant species distributions of the Deep Canyon Transect were compared from 1977 to 2007 and the causes of change were examined. We
hypothesized plant species distributions to move upwards in elevation in response to climate warming and increasing climate variability. In 1977, Jan Zabriskie surveyed plant species coverage along a 400 m isocountour every 122 m in elevation along the transect. Following Zabriskie, I resurveyed these sites in 2006 — 2007 and compared species coverage. The set of the ten most widespread species spans all elevations, plant communities, and functional types of Deep Canyon. The mean elevation increase for these ten species is 64.7 m, within a two-tailed 95\% CI of 30.9 — 98.5 m. From 1977 — 2006, the Deep Canyon Transect experienced a significant increase in mean annual temperature of 0.5 — 0.8\,\textdegree\,C. Variability in annual precipitation has also doubled over that time. Climate warming and increasing climate variability has been the primary driver of upward plant species shifts in Deep Canyon.

**Poster**

**Glacier Change in the Rwenzori Mountains, East Africa**

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In East Africa glaciers currently exist on Mt. Kilimanjaro and Mt. Kenya, and in the Rwenzori Mountains. While the Mt. Kilimanjaro and Mt. Kenya glaciers have been the subject of many recent studies, the glaciers in the Rwenzori Range are less thoroughly studied. This study reexamines the satellite record of retreat of these glaciers, as well as the climatic factors most responsible for the change. A recent study of the retreat of the Rwenzori glaciers using Landsat images acquired between 1987 and 2003 has been questioned. Using visual mapping and the Normalized Difference Snow Index (NDSI) to analyze Landsat, ASTER and SPOT images, we have re-evaluated the ice areas for the period 1987 to 2006. After identifying sources for possible error, our mapping indicates that the glaciers in the Rwenzori have shrunk from an area of 2.55 km\textsuperscript{2} in 1987 to 1.31 km\textsuperscript{2} in 2006. Glacier retreat in the Rwenzori from 1906 to 1990 showed a strong spatial correlation with potential increase in shortwave radiation due to decreased cloud cover as a consequence of a shift to drier conditions in the region. Whether or not recent glacier retreat shows a similar spatial correlation is under investigation.

**Poster**

**Toward Standardization in Methods and Techniques for Measuring and Monitoring Snowcover Albedo.**

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Global climate change portends increasing uncertainty regarding the reliability of mountain snow and ice fields as a source of fresh water for one-sixth of the world’s population. Standardization of system measurements is required to enhance our understanding of cryospheric responses and forcings. Irrespective of projected temperature trends, we have shown that interactions between deserts and downwind mountain ranges can and do result in significant advancements of snowmelt timing as well as increased snowmelt intensity, substantially altering regional hydrographs. We have developed and refined methods for monitoring enhanced radiative forcing of snowmelt caused by dust induced reductions in snowcover albedo. In-situ, continuous measurements of snowcover albedo and energy budget parameters are obtained in the Senator Beck Basin Study Area with two arrays of up- and down-looking pyranometers, pyrgeometers, and infrared snow surface temperature sensors. Air temperature, relative humidity, and wind speed are monitored at two heights above the snowcover. Measurements of short wave radiation reflected by the snowpack are corrected for surface geometry by monitoring an array of snow stakes referenced to a level plane. The efficiency of enhanced energy absorption by exposed and near-surface dust layers is monitored using a volumetric sampling design whereby ten snow samples are collected to a depth of 30 cm, near the limit of significant light penetration. Those samples are then processed to quantify the mass of absorbing material per unit of area at a
given depth, enabling the estimation of enhanced absorption throughout the near-surface and surface of the snowcover. These methods, in conjunction with traditional snowpack profiling techniques, have proven to be a reliable, practical, and repeatable approach to monitoring the influence of desert dust on mountain hydrology. The enhanced rigor with which these measurements are performed presents a platform upon which to build consensus protocols for adoption in other system monitoring applications and locales.

**Poster**

*A biophysical gradient analysis of climate for understanding conifer establishment in mountain ecosystems of the western U.S.*

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Establishment of conifer trees at upper treeline is controlled by both physical and ecological phenomena. The physical limitations on tree establishment and growth as well as the ecological and edaphic factors moderating climate vary significantly across western mountain ranges, from the more maritime Cascades through the basin-and-range to the heavily continental central Rockies. In order to understand the factors limiting tree establishment and estimate rates of ecosystem change under future climate change, it is critical to understand the climatic factors limiting tree establishment. We use a multiscale approach to identify climatic patterns associated with upper treeline in nine mountain ranges: the north Cascades, central Cascades, Eagle Cap, Beaverhead, Teton, Beartooth, Wind River, Snowy, and Zirkel mountain ranges. We examined NCDC divisional, SNOTEL, snowcourse, and DAYMET seasonal averages/totals for temperature and precipitation variables to compare the climates at treeline sites identified for conifer establishment research. Divisional data from 1948-2004 indicate a strong geographical gradient in winter precipitation/PDO correlations, but according to SNOTEL data from all mountain ranges, these differences are much weaker in the more recent past. Snow water equivalent at all the sites near the PDO dipole evident in the 1948-2004 correlations appears negatively correlated with PDO. We present DAYMET, SNOTEL, and snowcourse normals for the mountain environments near the treeline sites and relate them to species composition and the nature of recent establishment.

**Poster**

*Modeling the effects of topographic shading on snow-fed runoff with warmer temperatures*

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Discharge in small, tributary streams affects water table heights, riparian vegetation, and habitat in subalpine meadows. Because of this, meadows are very sensitive to the dates when the ephemeral streams go dry. The Distributed Hydrology Soil Vegetation Model (DHSVM) is used in conjunction with a high density hydroclimate monitoring network in the Tuolumne River basin of Yosemite National Park, California to investigate how high elevation sub-basins with different aspects and elevations respond to warmer temperatures. Specifically, this project investigates how topographic shading affects the advance of snowmelt onset and the date snow disappears as temperatures warm. Observations show that in years where the temperature warms earlier in the season, south-facing sub-basins start melting over a week earlier than north-facing basins. Thus, meadow areas fed by sub-basins with southern aspects are expected to be much more sensitive to warming temperatures than areas fed by sub-basins with northern aspects. Traditionally, most future hydrologic simulations are run for large basins and these effects would not be captured. DHSVM is used to test if high-resolution (150 m) modeling with a complete topographic shading component can represent these observed differences and be used to simulate how warmer temperatures will differentially affect various sub-basins and meadow regions.

**Talk**
Secondary Effects of Climate Change on Streamflow Through Wildfire: Compensating or Exacerbating?

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Changes to snow accumulation in mountains have yielded two noteworthy phenomena: A shift in the timing of snowmelt and streamflow and increased occurrence and severity of wildfires. Wildfire, in turn, produces feedbacks on the snow accumulation and melt process that further alters streamflow generation processes and future prospects for vegetation. An important question is whether increased wildfire will exacerbate or ameliorate climate related changes. Vegetation reduction experiments in small watersheds (0–1.5 km²) suggest we should expect greater snow accumulation and reduced evapotranspiration following wildfire, however they also show slight advances in the timing of snowmelt peaks. Recent large scale wildfires are providing an opportunity to see how the secondary effects of climate change through wildfire play out at scales comparable to those where direct changes have been assessed. In the Boise River basin, two mountain watersheds on the order of 2,000 km² each form a paired watershed experiment with approximately 45% of one basin burned and nearly no fire in the other. With sixty years of calibration, and twelve years post fire, significant increases in annual water yield on the order of 5% were found. Increases primarily occurred in winter and early spring, however, exacerbating the shift in flow timing for this high elevation basin. The tradeoff in timing and yield produced dramatically lower flows in early summer, but a slight increase in late summer, compensating for some climate change effects. Ecohydrologic theory predicts that vegetation changes accompanying increased evaporative demands should partition the losses between vegetation consumption and streamflow. The longer summer produced by these combined climate and land cover changes may yield less consumptive vegetation for the next generation.

Poster

Evolution Of Quaternary Stream Fan Deposits At The Confluences Of Turung Khola And Bembung Khola Of Middle Teesta Basin In Sikkim-Darjeeling Himalaya,India: A Tectonic – Climate Response

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Tributary fan deposits are well preserved on either side of the Teesta river in the non-glaciated middle part of the Himalayan valley lying in a tectonic region bounded by the MCT and MBT. The lithofacies characteristics and assemblage patterns of these deposits bear testimony to the effects of tectonic and climatic activities on the sedimentation process in the basin. Two tributary streams, with small catchments namely Turung Khola and Bembung Khola are important in this context. Three major fan lobes (F2, F1, and F0) are preserved at Turung Khola. In contrast, two fan lobes (F1, F0) are preserved at the confluence of the Bembung Khola. Terraces, floodplains, channel bars, chute bars are associated geomorphic features in this part of the Teesta basin. Landslides cover an area of 7% and 15% in the catchment of Turung Khola and Bembung Khola, respectively. Dense forest covers 24% and 12%; open forest covers 30% and 29%; and scrubby vegetation covers 39% and 49% of the Turung Khola and Bembung Khola, respectively. The landslides mainly occur along the margins of the dense forest where they are active in every rainy season. Tributary longitudinal profiles and Hack profiles indicate a relationship between the knick points and high SL-Index values, where fault /thrust intersections are present. Active landslides and scarps are close to the major fault/thrust planes. Sediment characteristics of these fan deposits suggest that four types of depositional flows viz. debris flows, hyperconcentrated flows, sheet flows and channel flows laid down these sequences. The channel flow deposits are dominant (32%-54%) in the fan sequence of the Turung Khola followed by sheet flow deposits (28.5%), hyperconcentrated flow deposits (26%) and debris flow deposits (12%), respectively. Hyperconcentrated flow deposits are dominant (44%) in the F1 sequence, whereas the active channel fanlobe is dominant (80%) in the channel flow deposits. The rest of the active channel sequence is composed of sheet flow deposits (20%). On the other hand, the major part (52%) of the F1 fanlobe of Bembung Khola is built up of debris flow deposits and F0 fanlobe is composed of channel flow deposits and flood sediment. From the above analysis, an evolutionary model of the deposition and incision at the tributary stream fan confluence is proposed. The insetting of the younger fan lobes into older fan lobe surfaces is an evidence of tectonic uplift in the region. The landform and their depositional pattern are a responds to link tectonic- climatic process systems; some depositional lithofacies assemblages are responses to climatic events.
Runoff Efficiency of Sierra Snowmelt: Evaporative Water Losses in Wet vs. Dry Years

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High altitude Sierra basins have negligible summer precipitation and very little groundwater storage, which makes them ideal laboratories for indirectly monitoring changes in evaporative losses between wet and dry years. Dry years have greater potential evapotranspiration, due to warmer June and July air temperatures, warmer summer water temperatures, greater solar radiation exposure, and longer growing seasons. However, dry years also have limited saturated surface areas as compared to wetter years, and thus actual evapotranspiration is much less than the potential in dry years. Assessing the balance of these factors is important in estimating the effect of warming temperatures and shrinking snowpacks on Sierra ecosystems. When spring and summer rain events are excluded from the analysis, the annual sum of basin snowmelt (calculated from 119 CA DWR snow pillows) minus the sum of March to October streamflow (calculated from USGS records at 10 high-elevation California river basins) indicates water losses from the basin. Assuming negligible groundwater storage from one year to the next, these water losses are a measure of evaporation and evapotranspiration (ET). Records from 1968 to 2005 show that the least amount of water is lost to ET in the wettest years, but the story for dry to normal years is more complicated. Conceptual models are used to test the sensitivity of annual ET to snow cover extent, length of summer season, moisture availability, basin elevation distribution, and air and water temperatures. Results are compared with observations.

Deriving high resolution historical and future climate databases for mountainous environments

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General circulation model (GCM) and regional climate model (RCM) data are currently available in resolutions sufficient to conduct reasonable climate change studies for hydrologic systems on a scale of thousands of square kilometers and/or for terrains with minimal topographic variability. The Canadian Forest Service has created monthly climate datasets for North America at a 10 km resolution by interpolating climate station data (McKenney et al. Agric. For. Meteorol, 138, 69-81, 2006). However, much finer spatial resolutions are needed to investigate changes in watershed and ecosystem processes, particularly in regions of diverse topography. This work is building a series of interpolated high resolution hydro-meteorological surfaces for predicting hydrologic change in mountainous regions. Level A climate stations (with complete historical record 1961-2006) are interpolated using the ANUSPLIN thin plate smoothing spline technique to create historical daily climate field for the study region. Error surfaces from ANUSPLIN define regions within the study area where data availability limits confidence in the analysis. To minimize these errors we are synthesizing climate data using multiple regression infilling techniques for level B stations – with limited data records; and where needed, we use the SIMGRID alpine microclimate model to create level C climate stations with wholly synthetic data. SIMGRID has been used to successfully simulate snow pillow data and to provide high-resolution spatiotemporal climate data for hydrological simulations (Lapp et al., IJOC 25 (4), 521-526, 2005). The goals are two fold: first, to develop a technique for creating high resolution hydro-meteorological surfaces in mountainous regions; and second, a classified series of alpine climate response units for application in hydrologic and ecologic research.

Snow depth and snow water equivalent distribution in a high alpine basin: quantifying the length scales and magnitude of variation in Senator Beck Basin, Colorado

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Estimating the distribution of seasonal snow is important for water resource management, as one-sixth of the world’s population depends on snowmelt for their water supply. In addition, snow water equivalent (SWE) estimates are important for flood and hydropower forecasting, and are critical for understanding surface and groundwater systems. Because the snow cover has such a large effect on the global energy balance, accurate SWE estimates over large areas are necessary for evaluating future climate change scenarios. To adequately describe the correlation length scales of snow depth and SWE at the basin scale, however, measurements at 10 m resolution or less are required, which is impractical using traditional methods. Using an accurately calibrated, portable FMCW radar, coupled with a survey-grade kinematic GPS system, more than 700,000 independent radar measurements were made throughout Senator Beck Basin over a 3 day period in March 2007. These radar measurements are used to estimate snow depth and SWE, covering scales from 10 cm to several km. Due to the large number of estimates, the variogram of snow depth can be accurately calculated, and used to help interpolate between measurements. The length scales and magnitude of variation both above and below tree line are quantified, and uncertainties in the degree of variation are described. Due to the differences in environmental controls, optimum sampling and interpolation schemes vary with location in the basin.

Poster
Glacial Velocity Changes of Batura Glacier, Western Karakoram Himalaya

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Glacier fluctuations represent direct and indirect indicators of climate change. Many glaciers around the world are retreating and downwasting, thereby increasing glacial meltwater, as well as debris cover. These variations can cause variations in glacier-flow dynamics including changes in ice velocity and surging. Our objective was to evaluate ice-flow velocity variations on the Batura Glacier in the western Karakoram Himalaya by combining historical data and diagrams from the Chinese Batura Investigation Group of the early 1970s with information gathered from satellite image analysis (ASTER 29/Oct/2003, 13/Sep/2004). Modern ice-flow velocity estimates were generated utilizing ortho-rectified satellite imagery and feature tracking to produce ice-flow velocity fields. Feature tracking was accomplished using original spectral bands and texture images. We generated an average velocity gradient for the Chinese data (12m/yr/100m) and satellite-derived data (23m/yr/100m) using regression analysis. The Chinese mapping of Batura Glacier delineated the end of the lowermost (south-side) white ice stream at ~3.2 km from the Karakoram Highway in 1975. Due to down wasting and increasing supraglacial debris cover the white ice stream has retreated up-ice to ~5.9 km as of 2004. Comparison with historical data shows a possible increase in the annual-velocity gradient yet a decrease in the overall-velocity magnitude. Changes in meltwater at the base from warmer temperatures, or increased mass flux from increased precipitation at altitude, could both change the velocity gradient but not decrease the overall velocities. Downwasting and thinning ice could explain overall decrease in velocities and increased debris loads although attendant frictional increases on sides and base might have some influence.

Poster
Global Research Initiative in Alpine Environments: A New GLORIA Site in Southwestern Montana

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Global climate change is expected to have pronounced effects on the alpine environments and thus the alpine plants of western North America. Predicted responses include an upward migration of treelines, altered species compositions, changes in the percentage of land covered by vegetation, and a change in the phenology of alpine plants. To determine the effects of climate change on the alpine flora of southwestern Montana, we are installing a GLORIA (Global Research Initiative in Alpine Environments) site in order to monitor temperature, species composition, and percent cover of vascular plants, lichens, and mosses along an ascending altitudinal gradient. We are including lichens and mosses because of their importance as ecological indicator species. The abundance and spatial distribution of lichens and mosses provides essential baseline data for long-term monitoring of local and global impacts on the environment. Mt. Fleecer (9250 ft.), which is west of the continental divide and semi-isolated from other peaks in the Anaconda-Pintlar Range, is currently the most likely location for the southwestern Montana GLORIA site. Mt. Fleecer is accessible because it does not have the steep and hazardous glaciated talus cirques that characterize many of the neighboring, higher peaks. However, if an accessible and suitable higher summit is found, then it will be included as the highest summit in the GLORIA site. Interesting species at Mt. Fleecer include the whitebark pine, *Pinus albicaulis*, which is a keystone species in high mountain ecosystems of the western United States and Canada, the green gentian, *Frasera speciosa*, and the shooting star, *Dodecatheon pulchellum*. Data from this site will become part of a global network of GLORIA sites with which we will assess changes in alpine flora. Information gained from this GLORIA site can also be used as a link between studies of alpine climate change and related investigations on the timing of snowmelt and its influence on riparian ecosystems in western Montana.

Talk

**Sierra Nevada Rock Glaciers: Biodiversity Refugia in a Warming World?**

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Rock glaciers and related periglacial rock-ice features (RIFs) are common landforms in high, dry mountain ranges, and widely distributed throughout canyons of the Sierra Nevada, California, USA (Millar & Westfall, in press). Due to insulating rock carapaces, active rock glaciers (ice-cored) have been documented to maintain ice longer, and thus contribute to more enduring hydrologic output, under past warming climates than typical ice glaciers. This function has been suggested for the coming century. We propose a broader hydrologic and ecologic role for RIFs as temperatures rise in the future. For the Sierra Nevada, we suggest that canyons with either active or relict RIFs (Holocene and Pleistocene) maintain water longer and distribute water more broadly than canyons that were scoured by ice glaciers and are defined by primary river and lake systems. RIFs provide persistent, distributed water for extensive wetland habitat, rare in these otherwise barren, high, and dry locations. We mapped and assessed the area of wetlands surrounding active and relict RIFs from the central eastern Sierra Nevada; from these we delineated wetland vegetation community types and recorded plant species found in RIF-supported wetlands. Mid-elevation RIFs, likely inactive or with transient ice, develop soil patches on their rock matrix. At the Barney Rock Glacier (Duck Pass, Mammoth Crest), we inventoried plant species on all soil patches, and measured cover for each species per patch and total plant cover for the rock glacier. RIF landforms also appear to support high-elevation mammals. We show that American beaver (*Castor canadensis*) is associated with canyons dominated by active or relict RIFs and propose that the articulating, persistent, and distributed nature of streams makes dam-building easier than other canyons. Beavers further contribute to maintaining water and creating wetland habitat in upper watersheds by engineering ponds and marshes, and contributing to riparian extent. We also mapped 125 discrete locations of American pika (*Ochotona princeps*) and found a strong association of pika presence with active and relict RIFs, in particular cirque rock glaciers, valley rock glaciers, and boulder streams. Using the PRISM climate model and a small network of temperature dataloggers from RIF habitats, we present a climate envelope for the pika habitats we surveyed. We propose that the large area of RIFs in the Sierra Nevada over a range of elevations could provide extensive habitat for pika in the warming future. RIFs in general are a group of landforms little studied in high mountains of western North America but of potential increasing importance to hydrologic and ecologic function as climate warms in the future. Millar, C.I. and R.D. Westfall. In press. Rock glaciers and periglacial rock-ice features in the Sierra Nevada; Classification, distribution, and climate relationships. Quaternary International.

Talk

**Alpine Plant Monitoring for Global Climate Change; Analysis of the Four California GLORIA Target Regions**
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The Global Observation Research Initiative in Alpine Environments (GLORIA) is an international research project with the goal to assess climate-change impacts on vegetation in alpine environments worldwide. Standardized protocols direct selection of each node in the network, called a Target Region (TR), which consists of a set of four geographically proximal mountain summits at elevations extending from treeline to the nival zone. For each summit, GLORIA specifies a rigorous mapping and sampling design for data collection, with re-measurement intervals of five years. Whereas TRs have been installed in six continents, prior to 2004 none was completed in North America. In cooperation with the Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT), California Native Plant Society, and the White Mountain Research Station, four TRs have been installed in California: two in the Sierra Nevada and two in the White Mountains. We present comparative results from analyses of baseline data across these four TRs. The number of species occurring in the northern Sierra (Tahoe) TR was 35 (16 not found in other TRs); in the central Sierra (Dunderberg) TR 65 species were found. In the White Mountains, 54 species were found on the granitic/volcanic soils TR and 46 (19 not found in other TRs) on the dolomitic soils TR. In all, we observed 83 species in the Sierra Nevada range TRs and 75 in the White Mountain TRs. Using a mixed model ANOVA of percent cover from summit-area-sections and quadrat data, we found primary differences to be among mountain ranges. Major soil differences (dolomite versus non-dolomite) also contribute to floristic differentiation. Aspect did not seem to contribute significantly to diversity either among or within target regions. Summit floras in each target region comprised groups of two distinct types of species: those with notably broad elevational ranges and those with narrow elevational ranges. The former we propose to be species that retain importance in vegetation structure across elevation and the latter to be more sensitive to climate change. In general, we find common species in the Sierra Nevada to be rare in the White Mountains, that the northern Sierra Nevada TR (Tahoe area) to be distinct in many vegetation features, and that distinct substrate differences in the White Mountains delineate significant species diversities. With four target regions, we document patterns of species composition, distribution, and diversity with respect to elevation, aspect, and geographic distance. This provides new information about summit floras in the White Mountains and Sierra Nevada, and documents baseline conditions against which we will measure response to climate change.

Poster
Climate Change in Tropical East Africa: Combining High-Altitude Measurements, Proxy Records and Numerical Modeling

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Several types of proxy data indicate a rapid climate change in tropical East Africa around 1880, leading from wet to relatively dry conditions. The change manifested itself in the drop of lake levels, alteration of limnological sediment composition, and - at high altitude - glacier recession. To understand these changes, we run an extensive field program on the glaciers in the vicinity of Kilimanjaro summit (5895 m a.s.l.). Application of the field data to a glacier mass balance model, which resolves the physics of the glacier-climate interaction, allows the derivation of former glacier extents and thus local climate conditions of the pre-1880 wet period. From the latter we can deduce the magnitude of changes in precipitation, air temperature, air humidity, and solar radiation in the mid-troposphere. To explore the potential value of upscaling from regional to large-scale tropical climate change, a 200-year paleoclimate simulation with the Community Climate System Model (CCSM 3.0) is analyzed. Results suggest that changes in Indian Ocean dynamics (atmosphere-ocean interactions), and related moisture transport into East Africa, most likely contributed to this rapid regional climate change.
Poster

An Investigation of the Impacts of Climate and Environmental Change on Alpine Lakes in the Uinta Mountains, Utah

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Aquatic systems in alpine and sub-alpine areas of the western United States are potentially impacted by atmospheric pollution and climate change. Because these mountainous regions are an important water resource for the western United States, it is critical to monitor and protect these systems. The Uinta Mountains are an east-west trending mountain range located on the border between Utah, Wyoming and Colorado and downwind of the Wasatch Front, Utah, which is characterized by a rapidly expanding population, as well as mining and industry. This alpine area provides water to many areas in Utah, and contributes approximately nine percent of the water supply to the Upper Colorado River. Our research is focused on determining the impacts of climate change and pollution on alpine lakes in the Uinta Mountains. The results presented here are based on limnological measurements made at 64 Uinta Mountain lakes spanning a longitude gradient of one degree and an elevation gradient of 3000 feet. At each lake maximum depth, conductivity, salinity, pH, Secchi depth, temperature, alkalinity, and concentrations of major anions, cations and trace metals were measured. Principal Components Analysis (PCA) was performed to determine relationships between these variables and to examine the variability of the values of these variables. Our results indicate that steep climate gradients related to elevation and longitude result in clear differences in limnological properties of the study sites, with high elevation lakes characterized by greater amounts of nitrate and nitrite compared to low elevation sites. As well, diatoms in these lakes indicate that many high elevation sites are mesotrophic to eutrophic, which is unexpected for such remote aquatic ecosystems. We hypothesize that elevated nitrate and nitrite levels at high elevation sites are related to atmospherically derived nitrogen, but are being exacerbated relative to lower elevation sites by greater snow cover and reduced plant cover. Paleolimnological analyses of well dated sediments from selected lakes indicate that some of these high elevation sites have undergone rapid and dramatic change beginning in the late 1800s to early 1900s. Many of these lakes have become more productive as indicated by loss-on-ignition and diatom analyses. Although the exact mechanism of these changes is uncertain, the timing closely follows recent increases in air and chironomid-inferred surface water temperatures, and increased fossil fuel burning in the region. Regardless of the exact mechanism, our results clearly indicate dramatic changes at these high elevation sites, which threaten critical water resources.

Talk

Glacier Retreat in the Southern Peruvian Andes: Climate Change, Environmental Impacts, Human Perception and Social Response

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This paper presents results from recent environmental and anthropological research near glacierized areas in the department of Cusco, Peru, home to the well-known Quelccaya Ice Cap and to the peak of Ausangate (6384 m). Glaciers in the region are in negative mass balance, losing volume and area, with upslope movement of the glacier fronts. Somewhat paradoxically, flows in many streams close to the glaciers are reduced, particularly in the dry season, due to a shift in the seasonal distribution of melting, to increased evaporation and to increased percolation into newly-exposed sands and gravels. Associated with this reduction in flow is a desiccation of some anthropogenic and natural wetlands, reducing the availability of dry season forage to wild (vicuna) and domesticated (alpaca, llama) ruminants. Interviews and ethnographic observations with local populations of Quechua-speaking herders at elevations of 4500-5200 meters provide detailed comments on these changes. They have an extensive vocabulary of terms for glacial features associated with retreat. They link this treat with environmental factors (higher temperatures, greater winds that deposit dust on lower portions of glaciers) and with religious factors (divine punishment for human wrong-doing, failure of humans to respect mountain spirits). They describe a variety of economic and
extra-economic impacts of this retreat on different spatial, social and temporal scales. Though they face other issues as well (threats of pollution from new mining projects, inadequacy of government services), glacier retreat is their principal concern. Many herders express extreme distress over this unprecedented threat to their livelihoods and communities, though a few propose responses—out-migration, the formation of an association of neighboring communities, development of irrigation works—that could serve as adaptations.

Talk

Neoglacial fluctuations of Deming Glacier, Mt. Baker, Washington USA.

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Deming Glacier flows from the upper west slopes of Mt. Baker, a stratovolcano in the Cascade Range of Washington, USA. The north and south lateral moraines of Deming Glacier are composed of at least four tills separated by layers of detrital wood and sheared stumps in growth position. The stratigraphy records fluctuations of the glacier during the Holocene. The outer ten rings of an in situ stump from the middle wood layer, which is about 40 m below the north lateral moraine crest and 1.2 km downvalley from the present glacier terminus, yielded an age of 1750 ± 50 $^{14}C$ yr BP [1810-1550 cal yr BP]. The stump revealed at least 300 rings and thus records a period of landscape stability and relatively restricted glaciation for several hundred years prior to ca. 1750 $^{14}C$ yr BP. Samples from the lowest wood layer also have been submitted for radiocarbon dating. Outer rings of detrital wood samples collected from two wood mats exposed in the south lateral moraine, 2.3 km downvalley of the glacier terminus, returned radiocarbon ages of 1600 ± 30 $^{14}C$ yr BP [1550-1410 cal yr BP] and 430 ± 30 $^{14}C$ yr BP [AD 1420-1620]. These data indicate that Deming Glacier advanced over a vegetated moraine sometime after 1810 cal yr BP to a position less extensive that it achieved at the peak of the Little Ice Age. The glacier then receded before it began its final and most extensive Holocene advance after AD 1420. The older advance is correlative with the ‘First Millennium AD’ advance, recently recognized throughout western North America. The younger advance coincides with an advance of Mt. Baker’s Easton Glacier [AD 1430-1630], and advances of many alpine glaciers elsewhere in western North America. Our data suggest that glaciers on Mt. Baker fluctuated in a similar manner to alpine glaciers in the Coast Mountains of British Columbia and in other mountain ranges of northwest North America during Neoglaciation.

Talk

Influence of NRCS snowcourse measurement date on data accuracy and climatic trends

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The Natural Resources Conservation Service measures high elevation snowpack manually at snowcourses across the western US. The date of the measurement is nominally the first and fifteenth of the month although in recent years it averages approximately two days earlier to support timely operational water supply forecasts whose production begins on the first. This study found that the primary factors influencing measurement dates are, 1) the epoch of the measurement, 2) the day of the week of the nominal measurement date, 3) the presence or absence of snow at the site and 4) if the measurement is for the first or the fifteenth of the month. Specifically, the measurement date is less variable if snow is absent from the site. Mid-month data are collected closer to the nominal measurement date and first of month data have a bias towards being several days early.
Since 1957, there has been a stronger aversion to collecting data on Fridays and weekends whereas before 1957 snow surveyors mostly avoided measuring on Sunday. Further, measurements are taken today, on average, 1.34 days earlier than before. These factors were modeled and the effect on climate trends was found to be small, on the order of less than 5% although in individual circumstances the effect can be significant.

Talk
Climate response in the western United States to dust-shortened snow cover duration since late 1800s soil disturbance

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Dust emitted from the deserts of the western US is currently shortening snow cover duration in the Rocky Mountains by 20-35 days and affecting a Spring radiative forcing of 25 Â­ Ä Â­ Ä Â­ Ä Â­ Ä Ä Â­ Ä Â­ Ä Â­ Ä 50 W m-2 through snow albedo reduction. With the injection of railroads and infrastructure into the interior of the western US in the mid 1800s came substantial increases in grazing, farming, and mining, and in turn a disturbance of 70% of natural ecosystems resulting in losses of soil stability and increased dust emission. Recent geochemical analysis of alpine lake sediments in southwest Colorado shows that since the 1800s settlement of the western US, dust loading to mountain environments abruptly increased by a factor of ~5 above average rates of the last 5000 years. Given present dust loading to the Rocky Mountains and its associated forcing of snowmelt and reduction of snow cover duration, it is evident that snow cover endured significantly longer prior to the mid 1800s disturbance. In this work, we assess the climate response in the western US to the perturbed duration of mountain snow cover affected by the dramatic increase in dust loading using the NCAR Community Atmosphere Model (CAM). We drive the CAM with snow cover duration scenarios consistent with the snow albedo reductions associated with pre-1850 and post-1850 dust loadings. The 2nd indirect effect of dust loading to snow is given by the enhanced absorption of shortwave radiation by a darker substrate emerging from the early ablation of snow cover. In this region, 30 days of reduced snow cover results in mean daily 2nd indirect effect of ~ 150 W m-2. Therefore, we hypothesize that reduced snow cover duration results in significant regional tropospheric warming, a perturbed monsoon in the southwest US, and reduced cloud cover. In turn, the historical record of hydrologic observations in these regions has likely been entirely disturbed by anthropogenic forcing.

Invited Talk
Critical Hydrologic and Atmospheric Measurements in Complex Alpine Regions

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The Alps are often referred to as the « Water Towers of Europe » and as such play an essential role in European water resources. The impact of climatic change is expected to be particularly pronounced in the Alps and the lack of detailed hydrologic field observations is problematic for predictions of hydrologic and hazard assessment. Advances in information technology and communications provide important possibilities to improve the situation with relatively few measurements. We will present sensorscope technology (arrays of wireless weather stations including soil moisture, pressure, and temperature) that has now been deployed at the Le Genepi and Grand St. Bernard pass. In addition, a Distributed Temperature Sensor array on the stream beds has been deployed and stream discharge monitored. The high spatial resolution data collected in these previously “ungaged” regions are used in conjunction with new generation hydrologic models. The framework as to what is possible today with sensor arrays and modeling in extreme mountain environments is discussed.

**Poster**

**Comparison of Surface Mountain Climate With Equivalent Free Air Parameters Extracted From NCEP/NCAR Reanalysis: Kilimanjaro, Tanzania.**

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It is difficult to predict future climate changes in areas of complex relief, since mountains generate their own climates distinct from the free atmosphere. Thus trends in climate at the mountain surface are different from those in the free air. We compare surface climate (temperature and vapour pressure) measured at seven elevations on the south-western slope of Kilimanjaro, the tallest free standing mountain in Africa, with equivalent observations in the free atmosphere from NCEP/NCAR reanalysis data for September 2004 to January 2006. Correlations between daily surface and free air temperature anomalies are greatest at low elevations below 2500 metres, meaning that synoptic (inter-diurnal) variability is the major control here. However, temperatures and moisture on the higher slopes above the treeline (3000 m) are decoupled from the free atmosphere, showing intense heating/cooling by day/night and import of moisture from lower elevations during the day. The lower forested slopes thus act as a moisture source, with large vapour pressure excesses reported in comparison with the free atmosphere ($>$5 hPa) which move upslope during daylight and subside downslope at night. Strong seasonal contrasts are shown in the vigour of the montane thermal circulation, but interactions with free air circulation (as represented by flow indices developed from reanalysis wind components) are complex. Upper air flow strength and direction (at 500 mb) have limited influence on surface heating and upslope moisture advection, which are dominated by the diurnal cycle rather than inter-diurnal synoptic controls. Thus local changes in surface characteristics (e.g. deforestation) could have a direct influence on the mountain climate of Kilimanjaro, making the upper slopes somewhat divorced from larger scale advective changes associated with global warming.

**Talk**

**Evidence of Regional Warming during the 20$^\text{th}$ Century in Alpine and Subalpine Lakes in the Western United States**

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Subfossil midge analyses have been used to develop high-resolution (sub-decadal) reconstructions of 20th century temperature change in the Sierra Nevada, CA with success. Expansion of this earlier work to additional sites in the western United States suggests that a widespread increase in lake water temperatures has occurred in this region during the late 20th and early 21st centuries. Inference models for summer surface water temperature (SSWT) were developed combining midge abundance data from 56 lakes in the eastern Sierra Nevada, California, with subfossil midge remains from the Uinta Mountains, UT. The newly merged Sierra Nevada–Uinta Mountains calibration set contains a greater diversity of chironomid assemblages and spans a wider SSWT range than the previously published Sierra Nevada calibration set. The lakes in the merged calibration set spanned elevation, depth, and SSWT temperature ranges of 900 m, 12.7 m, and 11.3 °C, respectively. A robust inference model for SSWT (3-component WA-PLS), based on 90 lakes, had a high coefficient of determination (r²jack = 0.66) and a low RMSEP (1.4 °C). The midge-based SSWT inference model was applied to subfossil chironomid remains extracted from well-dated sediment sequences recovered from alpine and subalpine lakes in the Sierra Nevada, CA, Snake Range, NV and Uinta Mountains, UT. A close correspondence exists between the chironomid-inferred temperature profiles for the 20th and 21st centuries and mean July or summer temperatures measured at nearby meteorological stations. Application of this midge-based SSWT inference model to other intact, late Quaternary sedimentary sequences found in subalpine and alpine lakes in the Great Basin will help resolve the impact of late Quaternary and recent climate change in this region, improve our understanding of regional climate and aquatic ecosystem variability, and can be used to monitor the effects of climate change on aquatic ecosystems and establish ‘baseline’ conditions against which future biotic changes can be compared.

Poster

Providing more informative projections of climate change impact on plant distribution in a mountain environment

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Due to their conic shape and the reduction of area with increasing elevation, mountain ecosystems were early identified as potentially very sensitive to global warming. Moreover, mountain systems may experience unprecedented rates of warming during the next century, two or three times higher than that records of the 20th century. In this context, species distribution models (SDM) have become important tools for rapid assessment of the impact of accelerated land use and climate change on the distribution plant species. In this study, we developed and tested new predictor variables for species distribution models (SDM), specific to current and future geographic projections of plant species in a mountain system, using the Western Swiss Alps as model region. Since meso- and micro-topography are relevant to explain geographic patterns of plant species in mountain environments, we assessed the effect of scale on predictor variables and geographic projections of SDM. We also developed a methodological framework of space-for-time evaluation to test the robustness of SDM when projected in a future changing climate. Finally, we used a cellular automaton to run dynamic simulations of plant migration under climate change in a mountain landscape, including realistic distance of seed dispersal. Results of future projections for the 21st century were also discussed in perspective of vegetation changes monitored during the 20th century. Overall, we showed in this study that, based on the most severe A1 climate change scenario and realistic dispersal simulations of plant dispersal, species extinctions in the
Western Swiss Alps could affect nearly one third (28.5%) of the 284 species modeled by 2100. With the less severe B1 scenario, only 4.6% of species are predicted to become extinct. However, even with B1, 54% (153 species) may still lose more than 80% of their initial surface. Results of monitoring of past vegetation changes suggested that plant species can react quickly to the warmer conditions as far as competition is low. However, in subalpine grasslands, competition of already present species is probably important and limit establishment of newly arrived species. Results from future simulations also showed that heavy extinctions of alpine plants may start already in 2040, but the latest in 2080. Our study also highlighted the importance of fine scale and regional assessments of climate change impact on mountain vegetation, using more direct predictor variables. Indeed, predictions at the continental scale may fail to predict local refugees or local extinctions, as well as loss of connectivity between local populations. On the other hand, migrations of low-elevation species to higher altitude may be difficult to predict at the local scale.

**Talk**

**Recent Accelerated Warming in Western United States Mountains**

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The mountainous western portion of the United States and North America have been warming since the mid 1970s, by a total of about 1 degree C. This warming has been most pronounced in spring, present but less obvious in winter, and nearly absent in autumn. In summer, a slow rise in temperature was under way until the late 1990s. Over the past 8 years a succession of very warm summers has occurred, with multi-year temperatures well above all similar past multi-year averages. Of further interest is that the major Colorado River drought now underway also began about this time. Contributing to that drought were several springs that featured a month with much above normal temperatures that greatly hastened snow melt at a time of year when snow pack is usually still accumulating. These warming effects have been seen in lower elevation and higher elevation monitoring networks. They do not appear to be a product of observational methodologies. There is some evidence that other parts of the global climate system have behaved somewhat differently over those years. Potential relationships or causes for this apparent acceleration in warming will be discussed.

**Talk**

**A dynamic species modeling approach to assess climate change impacts on California tree species**

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Global climate change during the 21st century is anticipated to have consequences on potential niche viability for woody plant species. Previous research on modeling bioclimatic envelopes has allowed us to predict where to find species assemblages under future climate scenarios and hence predict loss or gain of specific habitats. However, species may not identically respond to climate change. This could result in species disassembling and disagreement between predicted potential niches and realized niches. Therefore, it is critical to examine potential niche shifts at the species level. We used a spatially explicit demographic model to predict shifts in tree species of the northern Sierra Nevada mountains in the context of competition with neighboring plant functional types as well as disturbance (i.e. fire) under various climate change scenarios. Additionally, we incorporated a dispersal model to account for intermediary dispersal strategies. In particular, we were interested in modeling Pinus species found in the checkerboard region of the northern Sierra Nevada. These populations are of novel interest due to their disparate management strategies (private vs. public landownership). Our findings have important implications for the assessment of the impact of climate change on these high elevation Montane species.
Talk
The Relation Between Climate Variability and Glacier Morphometry: A Space-for-Time Substitution Analysis for Glaciers in British Columbia, Canada

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We explore the relation between spatial climate variability and glacier morphometry for British Columbia using gridded temperature and precipitation normal data and a comprehensive glacier inventory obtained from aerial photography. The altitudinal range of over 10,000 glaciers, distributed across 10$\deg$ of latitude (49 to 60$\deg$N) and 23$\deg$ of longitude (115 to 139$\deg$W), was related to principal components of local climate and extracted morphometric variables. Derived climatic indices represent maritime-continental, latitudinal, and seasonal variability gradients, whereas the morphometric parameters represent measures of glacier slope, aspect, shape, and flow network order. For glaciers exceeding 6 km$^2$ in area (n=561), over 70\% of the altitude range variability can be explained using optimized regression models that incorporate both climatic and morphometric predictor variables. We use the multivariate models to quantify the degree to which spatial patterns of climate can be inferred from glacier altitude data and investigate the degree to which morphometric controls moderate these relations. Applications of the developed models include the reconstruction of past climate patterns from historical glacier extents and the prediction of future altitudinal limits for glaciers given projected climate change scenarios.

Poster
1935-2006 Duration of Snowcover and Growing Degree Trends from the Summit and Base of Mount Washington, NH

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Start and end dates of continuous snowcover, growing degree days and thawing degree days were calculated using the 71-year climate record from the summit of Mount Washington (1914m ASL), NH. Preliminary results show the start of continuous snowcover (defined as $\geq 2.54$cm of snow on ground) on the summit of Mount Washington occurs later in the autumn by 2.1 days decade $^{-1}$ and ends slightly later in the spring by 0.3 days decade $^{-1}$, a net decrease in continuous snowcover of 1.8 days decade $^{-1}$. The trend of a shorter snow season is more pronounced for the date of first and last observed snow on the ground; the first snow occurring 6.7 days decade $^{-1}$ later in the autumn and last snow 3.3 days decade $^{-1}$ earlier in the spring. Similarly, using hourly values, cumulative thawing degree days ($>0$deg C) and growing degree days ($>5$deg C) exhibit spring warming; for example the date at which the cumulative thawing degree days = 50 is occurring earlier by 1.1 days decade $^{-1}$. There is a slight discrepancy between the later continuous snowcover persistence in the spring and the other metrics that we are examining. The above metrics will also be presented from for the eastern base of the mountain, Pinkham Notch, New Hampshire (619m ASL), and compared with these summit data. These results provide insight into how the remnant islands of Arctic flora surviving on the Northeast's higher peaks are now and will be challenged in the future.
Space-Based Observations of Batura Glacier Fluctuations, Western Karakoram Himalaya

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Monitoring glacier variations by our GLIMS (Global Land Ice Measurements from Space) Regional Center for Southwest Asia (Afghanistan and Pakistan) shows unusual fluctuations over a 40 year period for Batura Glacier. We use multiple field measurements (1984, 1991, 1992, 1993), maps and the work of others (1966, 1974, 1975, 1978, 1980), and satellite imagery (KH-9 Lower Resolution Mapping Camera 4/Aug/1973; Landsat MSS 15/Jul/1979; SPOT 20/Jul/1990; Landsat 5 TM 15/Oct/1992; Landsat 7 ETM 29/Oct/2000 & 30/Sep/2001; ASTER 29/Oct/2003 & 13/Sep/2004). The terminus was at the Hunza River in late 19th and first half of 20th century and then retreated rapidly ~800 m by 1966, leaving behind prominent end moraines on the north terminus. Declassified KH-9 imagery of 1973 shows Batura Glacier width, due south of Shanoz midway between the Chinese cross sections VI and VII, was only ~1523 m wide, whereas after Chinese mapping of 1974-75, and in all imagery thereafter, width there increased to >2 km. Batura does not surge and kinematic waves have not been detected. An ice cliff had formed at the terminus in 1966, advanced forward 100 m and thickened by 15 m by 1975, and advanced another 33 m by 1978, perhaps from this heretofore undetected, probable kinematic wave. Then instead of advancing as predicted by Chinese scientists, by 1984 the frontal ice cliff had retreated 50-100 m, declined in slope angle, and was covered with debris and vegetation, which makes the slope still visible on recent imagery. Our orthorectified imagery shows that from 1973 – 2004 the front of the white ice stream from the first ice fall on the right (south) side underwent retreat of ~2846 m, (retreat rate of 92m yr-1), mainly through down-wasting increase of debris cover and new melt-water lakes. Similarly the terminus underwent ~392 m of retreat from 1973 – 1990 (~23 m yr-1 annual retreat rate), ~36 m retreat from 1990-1992, (~18 m yr-1 annual retreat rate), and a ~37 m advance (~3 m yr-1 annual advance rate) from 1992-2004. High-resolution imagery on Google Earth™ acquired in 2005 or thereafter shows an exposed-ice terminus that has advanced ~50 m from 2004 on. A large new ice cliff has emerged on the southeast side ~ 275 m behind the present ice terminus, even while the parent south white-ice-stream source continued to retreat up-ice. The Chinese Batura Glacier Investigation Group used mass balance and tree-ring data in the 1970s to predict glacier advance from the 1970s, cessation in 1991 – 1997, and retreat for 20 – 30 years thereafter. Global cooling was hypothesized with advances again by 2060, but the actual situations have been otherwise.

Poster

Stream Water Temperature and Climate Variability along Two Elevational Gradients in the Sierra Nevada Mountains, California, U.S.A.

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Water temperature plays an important role in life cycles and species interactions of aquatic biota in alpine streams. Climatic variability and global change affect the landscape characteristics, flow regime and air-surface water energy balance that collectively determine stream water temperature. Our high frequency measurements of stream temperatures over space and time along two elevational gradients in the Sierra Nevada mountains give insight into the effects of climate variability and change on water temperatures of snowmelt dominated upland streams. ‘Cumulative degree days’ is an ecologically relevant metric that integrates the effects of differences in precipitation, snowmelt timing, and air temperature. We present our initial analyses of stream temperature data collected from two study sites in the Sierra Nevada: Sagehen Creek and the Kings River Experimental Watershed. These range in elevation from 1800-2600 m and represent a range of runoff regimes.
Poster
Late-Quaternary Environmental Change in the Sierra Nevada: A 19,000-Year Sedimentary Organic Matter Record From Swamp Lake, Yosemite National Park, California

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Paleoclimate and environmental change in California over the last several millennia have received intensive study, in part because future climate warming in this drought-vulnerable region is likely to be expressed most acutely through rearrangements in the hydrological cycle (e.g., changes in the amount and timing of precipitation, snowmelt, and runoff). The 19,000-year sedimentary record from Swamp Lake, a small mid-elevation (1554 m) lake in the central Sierra Nevada, provides a rare opportunity to examine the relationships among climate variability, drought, and ecosystem response over a longer timeframe, spanning deglaciation and the Holocene, including several periods in which the Sierra Nevada is thought to have been warmer and drier than the present. Lake sedimentary organic matter (SOM) preserves paleoenvironmental information in a variety of elemental, isotopic, molecular, and microfossil indicators. In this study we utilize carbon and nitrogen elemental abundances and isotopic compositions ($\delta^{13}$C, $\delta^{15}$N) of bulk organic matter, along with measurements of biogenic silica (BSi), diatom and pollen assemblages, and magnetic susceptibility to reconstruct changes in lake productivity, organic matter sources, and plant and algal community composition in relation to climatic variables. We will also present preliminary measurements of the hydrogen isotope ratios ($\delta$D) of specific biomarker compounds extracted from the sediment, providing more direct information about the hydrologic status of the lake and watershed. In addition to tracing the post-glacial recovery and Holocene evolution of Sierra Nevada ecosystems, the Swamp Lake SOM record contains significant millennial- and century-scale variability that may correspond to periods of enhanced/suppressed ENSO activity.

Talk
Hydrological implications of glacial recession in the Rwenzori Mountains of Uganda

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The areal extent of tropical icefields in the Rwenzori Mountains of East Africa has reduced steadily over the last century from 7.5 km$^2$ in 1906 to <1 km$^2$ in 2003. Considerable debate persists, however, regarding the impact of observed deglaciation on alpine riverflow and the precise climate signals indicated by glacial recession in the Rwenzori Mountains and other areas of the East African Highlands including Kilimanjaro and Mount Kenya. We present the first measurements of alpine riverflow in the Rwenzori Mountains to show that the contribution of meltwater flows from dwindling icefields to local freshwater resources is negligible, <1% of the mean annual river discharge recorded at the base of the mountains. Stable isotope ratios ($\delta^{18}$O:$\delta^{16}$O, $\delta$D:$\delta^{1}$H) in streamflow trace the contemporary origin of precipitation in the Rwenzori Mountains to the same source (Indian Ocean) as other alpine icefields in East Africa. Hydrometeorological trends, indicated by observational datasets (precipitation, lake levels) over the 20th century and palaeoenvironmental and anecdotal evidence over the 19th century, are inconsistent with an abrupt reduction in humidity that has been proposed to account for observed deglaciation in the East African Highlands.
**Assessment of 21st Century Climate Change Projections in the Tropical Andes**

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The tropical Andes are one of the regions of the globe where climate change has been most evident. This is consistent with the notion that tropical high-elevation mountains extending into the mid-troposphere will be more affected by warming. One of the main impacts of this warming is the rapid retreat of glaciers; a process that could have severe consequences, affecting the availability of water for human consumption, irrigation, mining, and hydroelectric power production. This study presents some results related to the most important changes in climate that might be expected in the tropical Andes, at the end of the 21st century. Results are provided by the comparison of two Regional Climate Model (RCM) simulations based on the Hadley Center Regional Climate Modeling System, PRECIS. A medium-high CO$_2$ emission scenario simulation for the period 2071-2100 (Intergovernmental Panel on Climate Change, IPCC-SRES scenario A2) is compared to a base-line mean climate state simulation for the 1961-1990 period. In addition, some results using a low-medium CO$_2$ emission scenario (IPCC-SRES scenario B2) are also presented for comparison. Preliminary results show a generalized warming over the region with values reaching up to approximately 7 degrees C in some places in the Andes in the A2 scenario. Precipitation presents a mixed pattern of increases and decreases across the region, and a decrease in relative humidity is expected for most of the highlands at the end of the century. Both scenarios (B2 and A2) show an increased warming of the free troposphere at higher altitudes (up to 200 hPa). The obtained results reveal that anthropogenic climate change, as predicted with the A2 scenario, may constitute a serious threat to the survival of tropical glaciers along the Andes Cordillera.

**Talk**

**A Model of Temperature Inversion Across the White Mountains, California to Explain Downslope Migration of Trees**

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Shifting species distributions in montane ecosystems under a warming climate are generally assumed to be toward higher elevations, but the possibilities of lateral and downward shifts in complex terrain have received less attention. We modeled nighttime minimum temperatures across the White Mountains, eastern California based on hourly temperature recorded by inexpensive temperature loggers, a 10m Digital Elevation Model (DEM), and long-term weather station data. Thirty-five iButton Thermochrons recorded hourly temperatures from July 23 to October 6, 2006, and were distributed along elevation gradients on all aspects around a valley with strong night-time temperature inversions and a weather station. The overall lapse rate was calculated from three local weather stations: Bishop WSO Airport (1253m; 4110ft), White Mountain 1 (at 3094m; 10,151ft), and White Mountain 2 (at 3800m; 12,470ft). Using multiple least-squares regression, deviations from the local weather station were predicted by topographic position (the average elevation within 500m subtracted from the cell elevation), slope, and the absolute value of topographic position ($r^2 = 0.92$). The results were extrapolated across the rest of the range using the same parameters embedded in the overall lapse rate. The models predict strong night-time temperature inversions (up to 7 degrees C) in valleys and canyons across the range. Field observations and airphoto analysis show limber pine (Pinus flexilis) and bristlecone pine (P. longaeva) population migrating downward into the inversions. The temperature measurements and models explain this downslope migration as low temperature limitations in the cold valley bottoms are relieved under a generally warming climate. Range-wide maps provide testable hypotheses of minimum night-time temperatures.
The Influence of Climate Change on Headwater Stream Discharge in the Southern Sierra Nevada (1957-2007)

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The Sierra Nevada Mountains are of critical importance to water availability for the State of California. Historically, the winter snowpack has acted as a natural reservoir of fresh water throughout the winter months when a majority of the precipitation falls in the state. With the onset of spring snow melt, the water in the snowpack is released and made available to the remainder of California over the dry summer months. As a result of global climate change, warmer temperatures on the order of 2-5 ºC are predicted for California over the next century. This will lead to diminished winter snow cover and the onset of an earlier release of the snowpack making significantly less water available during the summer period. We use the long-term historical discharge and precipitation records (1957-2007) from the Teakettle Experimental Forest (Teakettle) to evaluate whether the hydrological effects of climate change are already evident on small, headwater systems in the southern Sierra Nevada. Additionally, the long-term pattern from Teakettle is compared to the past five-year record from 10 recently instrumented headwater systems in the Kings River Experimental Watershed (KREW). Teakettle is an unmanaged old-growth forest while the other watersheds are actively managed. At an elevation of 2050 m to 2450 m, winter precipitation on Teakettle is snow dominated. However, winter rain events at this elevation do occur in the southern Sierra Nevada. The KREW watersheds, including Teakettle, extend across the rain-snow interface boundary (1485 m to 2500 m) where winter precipitation may fall as either rain or snow. This provides a good opportunity to observe whether the number of winter rain events on the Teakettle watershed is increasing and what role this may play in the distribution of annual runoff. The historical record also allows us to evaluate any potential changes in the timing of spring snow melt and the effects climate change may have on annual discharge totals.

Talk
Climate change and Elevation Dependence at a Mid-Latitude Mountain System, Niwot Ridge, Colorado Rocky Mountains

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Mid-latitude mountain systems are critically sensitive to recent and projected climate change under an elevated greenhouse gas world. It is often taken that climatic change at high elevation sites will reflect those at lower sites. There are several reasons why this might not be the case, or at least considerably delayed Climate change at high elevation sites may be buffered from regional lowland trends or if they are decoupled from them as a result of mountain climatic processes. We evaluated standard climatological variables (minimum & maximum temperature, precipitation) and derived variables [diurnal temperature range, growing season length (using both 0º & –3ºC thresholds), and growing degree days (0ºC base)] from subalpine (C1, 3048m) and high alpine (D1, 3749m) sites from 1953 to 2006 at Niwot Ridge in Colorado, the longest high-elevation climate record in the US. Over the last 54 years, mean maximum temperature (Tmax) increased through much of the year in the subalpine (trend in annual Tmax=+0.4ºC/decade), but in the alpine decreased in early winter (A/ 0.4 to A/ 0.6ºC/decade). These patterns resulted in altered seasonal cycles for the two sites, but in different ways: a positive offset in the subalpine (C1) and amplification in the alpine. Precipitation increased at the alpine site from October through April (trend in annual ppt=+100mm/decade), but not during any season in the subalpine. At both sites, summer onset is later and termination earlier, so that the 0º growing season has shortened at the subalpine site; this reflects long-term tendencies in minimum temperatures. An apparent contradiction is that growing degree-days have gone up at the subalpine site; this due to the positive
trend in maximum temperatures. The alpine showed no corresponding trend. An integrated view of these trends infer synoptic
dynamics and surface energy processes that act differently in the high alpine near the Continental Divide vs. in the subalpine
dominated by closed conifer forest. At the same time, these climates are affected by multidecadal hemispheric circulation
changes. Nearly all temperature-related timeseries for both sites show a period of cooling until around 1980, followed by
warming. Precipitation series show corresponding periods of increasing then decreasing precipitation. On the face of it, this
pattern resembles that of the Pacific Decadal Oscillation (PDO). This suggests that alpine and subalpine climate signals are not
as decoupled as they appear, but rather that across a relatively short elevational gradient (Δf Å/Δe Å, -4 to 700m) synoptic and
landscape-scale processes react differently to and differentially modify a prevailing hemispheric signal.

Poster
Alpine Meadows Vegetation Monitoring

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East Shield (3658 m) and Barcroft Gate (3697 m) Meadows in the White Mountains of California on the Inyo National Forest
were selected for a pilot study to provide quantitative descriptions of vegetation associations as a baseline for monitoring
vegetation change over time. The study is part of the Global Observation Research Initiative in Alpine Environments Project
(GLORIA) hosted by the University of California White Mountain Research Station. Separating the effect of climate change
from anthropogenic disturbance is an integral step towards quantifying vegetation change in alpine meadows under current
scenarios of future increases in global temperature and atmospheric carbon dioxide. In this study we compare the vegetation of
East Shield Meadow, which is undisturbed, and Barcroft Gate Meadow, which is disturbed. Both are sedge-rush-grass wet
meadows which are sustained by surface water in the form of streams and springs. The objective is to monitor fluctuations in
vegetation, especially changes in species diversity and composition over five year time increments, along with tracking annual
variations in precipitation. A comprehensive plant list was compiled and the dense vegetation of each meadow was sampled
with a point intercept method along north-south and east-west randomly placed transects. The occurrence of all species at
predetermined one-meter interval sample points along the transect were recorded, and percent occurrence was calculated.
Twenty seven species of plants in Barcroft Gate Meadow and twenty four in East Shield Meadow were recorded, and sixteen
species in Barcroft Gate Meadow and eight in East Shield Meadow were sampled. The 2007 IPCC report estimates that a
doubling of atmospheric CO2 will increase global temperature within a possible range from 2.0 Å/ÅÅÅÅ, Å°C to 4.5
Å/ÅÅÅÅ, Å°C, with a best estimate of 3.0 Å/ÅÅÅÅ, Å°C. Assuming that the present general lapse rate of -6.32 Å/ÅÅÅÅ, Å°C per
kilometer for the White Mountains will persist, a 3.0 Å/ÅÅÅÅ, Å°C increase may result in an equivalent elevation of about +475
m. Plots of elevation ranges of recorded species indicate that it is not likely that the projected temperature increase will affect
the present distribution of the meadow plants. Species composition may change to an unknown degree, however, due to the
possible increase in the abundance of those plants now at their upper elevation range limits in the meadows and to the upslope
migration of plants whose upper ranges are now at lower elevations. Uncertainties in this projection include the behavior of
meadow plants, adequate sampling of their species ranges, and future distribution of precipitation. Monitoring will reduce the
uncertainties and confirm or correct the expected consequences of temperature change.

Talk
Alpine Treeline Changes in the Central Rocky Mountains: A Progress Report

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Changes in the elevation, composition, and structure of alpine treeline can reflect climate variability and change, as well as
patterns of disturbance which themselves may be mediated by climate variability. Information about past treelines may provide
insight into the likely character of future changes. We have recently begun a new project to investigate changes in past treeline
and determine the status of the current treeline in the central Rocky Mountains of Colorado, documenting the past and present
treeline and their relationships to climate and fire using dendrochronological techniques. In summer 2007, we sampled three
sites near Monarch Pass, Cottonwood Pass, and on Sheep Mountain, west of Fairplay, CO. The Monarch site shows evidence of a relict treeline of mixed Pinus flexilis and Pinus aristata above the current treeline, while the current treeline composition is predominantly Picea engelmannii. Dating, when completed, will reveal whether this relict treeline is evidence of a Medieval-era warm period in Colorado or an older period of warmth. At Sheep Mountain, remnant material above a stand of living Pinus flexilis and Pinus aristata trees of 800 years old or more was sampled. The remnant collections include samples with up to 700-1000 rings, and if they overlap in time with the living trees, will provide an extended chronology of climate variability, as well as information on the timing of tree establishment. At both of these sites, the presence of seedlings above the current tree line may be evidence of a rising treeline and warming temperatures, although this study may not be sufficient to confirm this. Evidence of fire at two of the three study sites may also shed light on the role of fire in shaping treeline in this region.