MOUNTAIN VIEWS

The Newsletter of the Consortium for Integrated Climate Research in Western Mountains

CIRMOUNT

Informing the Mountain Research Community

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Mountain Views

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Graphic Designer: *Barbara DeLuisi, NOAA/ESRL, Boulder, CO*
Front Cover Photo: *Lightning from storms in late June sparked dozens of wildfires in California. This image by the MODIS on the Terra satellite shows the fires on July 8, 2008. The red dots show the location of the active fires. Many of the fires have visible gray plumes of smoke rising from them, and a great deal of smoke has drifted out over the Pacific Ocean. Credit: NASA GSFC MODIS Website.*
Back Cover Photos: *Mr. or Mrs. Pika, Sierra Nevada, California, Courtesy of Connie Millar and Gray Wolf, Courtesy, US Fish and Wildlife Service*

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The Mountain Views Newsletter

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The Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT) was formed to provide a unified voice for the climate science community to communicate concerns and promote public awareness of the serious problems arising from a changing climate and its interactions with human and natural systems in the region. Readers are encouraged to log-on to our website: http://www.fs.fed.us/psw/cirmount/.

We are pleased to report on our recently concluded Fourth Mountain Climate Conference that is part of our series of sponsored conferences, and which was held in Silverton, Colorado on June 9–12, 2008. These conferences focus on mountain climate sciences, including issues related to mitigation and adaptation activities related to global warming and other human activities impacting western North America. The meetings are interdisciplinary by design, and have attracted a wide spectrum of participants, as they provide ample opportunities for interaction among the attendees. Readers can get more information by login onto the CIRMOUNT website, or to the workshop site at http://www.fs.fed.us/psw/mtnclim/.

In this issue of the Newsletter, Diaz, Millar, and Woodhouse look back at the development of CIRMOUNT as an integrated bottom-up entity, and they reflect on whether—and how well—the goals of the Consortium have been met. We find that despite the fact that CIRMOUNT does not have a formal institutional framework, the contributions by the individuals involved, backed by their respective organizations have made tangible strides toward accomplishing the goals of the Consortium.

As noted above, CIRMOUNT's principal focus has been from the outset the changing climate of the western United States and emerging and future impacts. The region now finds itself in the midst of nearly a decade-long drought, as severe as any that has been experienced in the century long observational record. This fourth issue of Mountain Views highlights important activities related to climatic changes in the western United States. For example, Chris Landry reports on efforts to learn more about the challenges and threats posed by global climate change to mountain ecosystems in the San Juan Mountains of southwestern Colorado. In particular, Landry reports on the development of monitoring activities in an alpine region known as the Senator Beck Basin (SBB), Colorado. A variety of climate related measurements are being taken at SBB that are important for understanding the impact of climatic variability and change in the region.

Connie Woodhouse and Jeff Lukas report on their work using tree-ring records in the Colorado River Basin to infer longer-term changes in streamflow in order to inform water resources managers regarding how current climate conditions compare to changes reconstructed for the past several centuries, and to provide additional temporal context for ongoing and future anthropogenic climate changes. Marty Hoerling and Jon Eischeid report on ongoing efforts to develop a mechanistic understanding of recent climate variations, as well as on studies to develop robust climate attribution protocols regarding the origins of observed climate patterns of the last few decades. They also consider the impact of future global warming on the western United States.

In the context of multi-purpose monitoring of climate for activities such as climate change detection and attribution, and for developing appropriate mitigation and adaptation strategies, the article by Chris Daly is of particular importance to the mountain climate community. The PRISM data set (for Parameter-elevation Regressions on Independent Slopes Model) is one of the principal climate data sets in use today by the scientific community and a critical element of any future national climate service. Chris submitted this article at my request because of a shared concern that a lack of funding to maintain the PRISM database would have serious negative consequences on a broad range of climate analyses being carried out nationally and internationally. It is our hope that by disseminating the difficult circumstances faced by the PRISM group to continue their work, which we all view as a major piece of climate monitoring infrastructure that funding support will be found. Information about the PRISM work and products can be found at: http://www.prism.oregonstate.edu.

Finally, we note that we are planning special focus issues of MVN in the future, such as reporting on work on climate change adaptation by the U.S. Forest Service.

The Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT)—A Progress Report

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Introduction

CIRMOUNT is a collaborative, open, science consortium comprising agency and university scientists, natural-resource specialists, and program managers dedicated to improving understanding of climate variability and change, and to enhancing the capacity to sustain western North American society. CIRMOUNT goals are to 1) define regional vulnerabilities to climate variability and change in the unique landscapes that define western North American mountains; 2) measure and understand climate-driven changes in these regions; 3) develop information, products, and processes to assist natural resource decision-makers throughout the West; and 4) assist resource managers and others to respond to the scientific needs and challenges of western society for mountain resources.

CIRMOUNT's core topical scope and foci are the intersection of climate, water, society, ecosystems, and western North American mountains (Figure 1). CIRMOUNT has both disciplinary (monitoring; databases) and integrative (integrated research, decision-support) goals.

Background and Accomplishments

With the successful completion of the Mountain Climate Sciences Symposium (MCSS, Diaz and Millar, 2004), an ad hoc association of western United States climate science professionals established the Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT) in 2004. Our goal was to promote and integrate understanding of the physical and ecological processes relating to climate in western North American mountain environments, and to improve communication of scientific findings to decision-makers. An important outcome from the MCSS meeting was the identification of critical questions related to ongoing and future climatic changes in the US West. They include the following:

- How are the vertically stacked ecosystems in the West changing as a result of climate change and variability?
- How can we best link climate, ecosystem and human processes?
- How can we overcome insufficient integration of disciplinary research in the region?
- How can we enhance the delivery of information and effective communication of important scientific findings that are relevant to western mountains decision-makers?

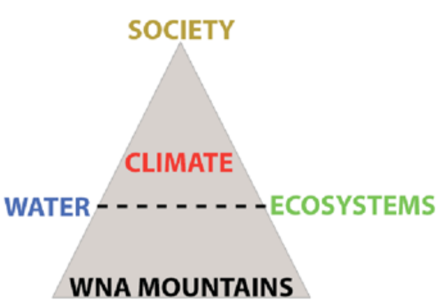

Figure 1. Key scope and foci of CIRMOUNT (WNA is western North America).

As a result of the MCSS and subsequent efforts by members of CIRMOUNT, a general audience publication highlighting key issues regarding climate change impacts on western United States (US) society was published and made available online (CIRMOUNT 2006). In this "Mapping New Terrain" publication, Consortium members reiterated the framework and motivation for their association: "*... the growing recognition that the climate of the West is changing, and that impacts are rapidly emerging in the form of changes in streamflow patterns, plant phenology, ecosystem structure, wildfire regimes, and the like ..." [by bringing together] "a group of scientists representing a wide range of disciplines ... crossing traditional disciplinary lines, exchanging ideas, and coordinating research efforts, Consortium participants seek to identify the greatest threats to western mountains arising from climate change and to develop priorities for a research strategy that addresses those concerns.*"

In March of 2005 CIRMOUNT launched the first of a series of mountain climate conferences (MTNCLIM) near Yellowstone National Park, Montana to further its goals to enhance communication of the available information about climate change science, climate impacts, and policy-related issues. A second MTNCLIM conference was held in Mount Hood, Oregon in September 2006, and a third conference will be held in June of 2008 in Silverton, Colorado. Abstracts and copies of the presentations given at these meetings, as well as for all other related meeting activity related to CIRMOUNT can be accessed via the Consortium's website: http://www.fs.fed.us/psw/cirmount/meetings/archives.shtml.

Oher activities of the Consortium designed to foster interactions between mountain science researchers and highlight mountain science research include the convening of annual disciplinary sessions at the Fall Meeting of the American Geophysical Union (AGU). The first of these was held in December 2004 with the theme of "Climate Challenges to Mountain Water Resources and Ecosystems". The topics for the other three AGU Fall sessions were: "Extreme Events in Western Mountain Climate, Resources, and Ecosystems" [2005]; "Elevational Gradients and Mountain Climates, Resources, and Ecosystems" [2006]; and "Climate Change in High-Elevation Mountain Environments" in 2007. Proposed for 2008 is, "Complexities in Mountain Climates, Ecosystem Response to Climate Change, and Resource Management."

With the launching of the Mountain Views Newsletter in 2007, CIRMOUNT took another tangible step toward the accomplishment of one its primary goals—to inform scientists, resource managers, and decision-makers of the latest developments regarding the dynamics of western climate, and the evolving natural and societal impacts associated with those changes. The newsletter is meant to be a clearinghouse for information about the state of regional and larger-scale climate patterns, and about climate- and related environmental and ecological-science activities bearing on western society. Current and past issues of the Newsletter can be downloaded from the CIRMOUNT website.

In addition to these communication activities CIRMOUNT has fostered, through focused working groups, interdisciplinary activities around a number of key climate issues. In 2004, CIRMOUNT launched the North American chapter of the international Global Research Initiative in Alpine Regions (GLORIA), a program that addresses responses of alpine flora to climate change. Nine multi-summit target regions are now installed, ranging from Alaska, through British Columbia, the Sierra Nevada, to the northern and central Rocky Mountains. An equal number of regions are planned for installation in 2008 and 2009. Similarly, the CIRMOUNT Mountain Climate Monitoring group has leveraged installation of long-term climate monitoring stations in several mountain ranges from Alaska to California. In addressing a CIRMOUNT goal to extend beyond its regional borders, an international effort resulted in the start-up of CONCORD, (Climate Change Science for the American Cordillera) and an initial meeting was held in Mendoza, Argentina in 2006—see Diaz et al., 2006). One result from this effort is the development of CORFOR, the Cordillera Forest Dynamics Network, which was established in association with the Western Mountain Initiative and international partners to establish and analyze standardized forest state measurements and trend information along the American Cordillera.

Future Directions

CIRMOUNT is organized as a grass-roots initiative, with no program staff or direct support; a 15-member scientific core team serves as the ad-hoc coordinating body, and supports a mailing list of over 700 interested participants. Even without a formal institutional framework, we have galvanized widespread interest and support for integration of climate and climate impacts work on western mountains. We have been seeking funding for a program base, and in the meantime continue to promote consortium goals of research, coordination, and communication through many existing and new venues and projects. A strategic plan developed by CIRMOUNT members outlines a program vision and set of primary goals linked to the critical questions facing mountain environments under the impacts of climate change (http://www.fs.fed.us/psw/cirmount/publications/pdf/strat_plan_0407.pdf).

Current high-priority and near-term goals include the establishment of at least five new GLORIA Target Regions, installation of long-term climate monitoring (including sampling through elevational gradients) in key mountain regions presently lacking coverage and filling in gaps in the CORFOR forest plot transect. Intermediate range goals are to produce comprehensive mountain-climate issue papers, and to promote a coordinated climate policy relationship for western North American mountain regions with other federal agency programs, such as the NOAA RISA (Regional Integrated Synthesis and Assessment) program. A long range "dream goal" is for CIRMOUNT to develop a unified interdisciplinary research program for Western mountains, envisioned as a "Climate Change Science Program for Western Mountains."

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Integrative Mountain System Monitoring and Snow System Research at the Senator Beck Basin Study Area, Red Mountain Pass, San Juan Mountains, CO

Chris Landry

Center for Snow and Avalanche Studies, Silverton, CO

Introduction

Mountain systems are often described as sensitive bellwethers of global change, where climate-driven system forcings and disturbances are quickly manifested yet insufficiently monitored. Further, the predicted ramifications of global change for mountains systems, for their residents, and for the ecosystem services that mountains provide has stimulated calls for an integrative approach to investigations of those complex process interactions.

As the challenges and threats posed by global climate change to mountain ecosystem services become increasingly apparent, the need for and value of place-based observation and monitoring has gained urgency, right alongside opportunities for new, integrative, process-focused research. To those ends, the Senator Beck Basin Study Area was established in 2003 in an alpine catchment near Red Mountain Pass, in the San Juan Mountains of Southwest Colorado, to enhance American snow-driven mountain system science capacity with a synergistic new venue for both research and monitoring.

A Study Area With History

The proverbial, "This is the place!" moment came in April 2002 when, during a scouting trip looking for a suitable alpine study area, all the right ingredients were revealed in a 290 ha (720 acre) headwater catchment near Red Mountain Pass in the western San Juan Mountains of Southwest Colorado. Soon thereafter the newly formed, not-for-profit, and independent Center for Snow and Avalanche Studies opened an office in the nearby historic mining town of Silverton and a proposal to establish the Senator Beck Basin Study Area (SBBSA) was submitted to the US Forest Service. In the absence of any US Geological Survey place name for the proposed study area catchment, the CSAS adopted the only named feature within the basin as a descriptor for the study area, the long-since abandoned Senator Beck mine, a small vestige of the historic gold and silver mining boom in the region.

A year later, aided by the unusually dry and mild fall of 2003, and with a freshly minted Special Use Permit from the Uncompahgre National Forest in hand, development of three new sites and refurbishing of a fourth site nearby was underway, initiating the Senator Beck Basin Study Area (SBBSA) research and monitoring infrastructure. Sensors were programmed and activated by headlamp on Halloween night, as the first winter storm of the 2003/2004 roared in from the west, and the Basin began producing data.

Thus began a 2nd phase of rigorous snow and mountain system research at Red Mountain Pass, after a long interlude. In 1971 the Bureau of Reclamation awarded the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado a two-pronged research contract designed to assess the potential impacts of intensive cloud seeding and enhanced winter precipitation on the San Juan Mountains and its communities. Soon the resulting San Juan Avalanche Project developed weather and avalanche monitoring infrastructure at several locations near Red Mountain Pass while their sister San Juan Ecology Project began investigating potential ecosystem responses to enhanced snowpack. While much of that infrastructure was dismantled at the conclusion of the 5-year field campaign, the CSAS did restore instrumentation to one of their sites and used salvaged materials from others.

Geography

The Senator Beck Basin Study Area (SBBSA) is located at the headwaters of Red Mountain Creek, a tributary of the Uncompahgre River, itself a tributary of the Gunnison River. SBBSA is centered at 37° 54' 30" N x 107° 43' 30" W, immediately west of US Highway 550 and northwest of Red Mountain Pass in the western San Juan Mountains, a range approximately equivalent in area, but certainly not in population or human infrastructure, to the Swiss Alps (Fig. 1). No other research infrastructure or study area comparable to the SBBSA currently exists in the San Juan Mountains, and its nearest counterpart is the venerable Niwot Ridge Long-Term Ecological Research (LTER) site west of Boulder, Colorado, operated by INSTAAR and the University of Colorado.

The 290 ha (719 acre) SBBSA exhibits physical and climatological attributes that reflect its continental position, high elevation, and comparatively southerly latitude within the American Rocky Mountain cordillera. Elevations in SBBSA drop from the un-named Point 4,118m (13,510') to 3,353m (11,000') at the catchment pour point. Trico Peak, at 4,060m (13,321'), sits at the

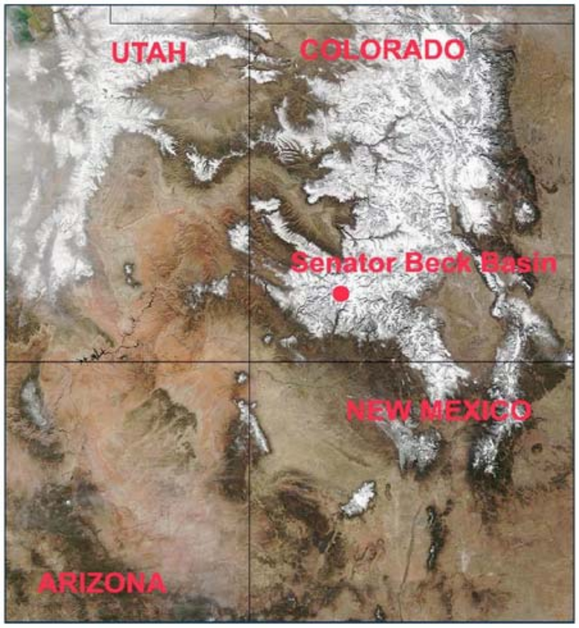

Figure 1. The Four Corners region showing the Senator Beck Basin Study Area location in the San Juan Mountains of Southwestern Colorado, with early winter snowcover. Photo courtesy of NASA.

southwest corner of the basin and marks the intersections of San Juan, San Miguel, and Ouray Counties; Senator Beck Basin lies within Ouray County.

The San Juan Mountains have been described as a "[continental] radiation snow climate", where particularly dynamic radiative energy balance fluctuations drive the 'kinetic' snow metamorphism processes typical of continental snow climates and make the San Juan Mountains notorious for a weak, avalanche-prone snowpack. A 30-year period of record at the nearby Red Mountain Pass Snotel site, at an elevation comparable to the lower end of Senator Beck Basin, puts mean Water Year (October-September) precipitation at 1,092 mm. In comparison, over Water Years 2004, 2005, 2006, and 2007 the Red Mountain Pass Snotel site averaged 1,120 mm total annual precipitation while the Swamp Angel Study Plot in Senator Beck Basin, located 1.6 km to the north of that Snotel site and 1 km north of Red Mountain Pass, averaged 1,181 mm annually, or 5.5% more precipitation. Monsoonal rains contribute approximately 25-35% of annual precipitation, with the balance delivered as seasonal winter snowpack. No permanent snowfields exist in the basin, but a small, lobate rock glacier beneath the north face of Trico Peak may contain an ice core.

SBBSA land cover is typical of alpine basins throughout the San Juan Mountains, with some ¾ of the basin comprised of tundra and bare rock and the remainder in sub-alpine forest and krumholz stands. Unlike many adjoining basins, no active roads are present in SBBSA and late 19th and early 20th Century mining activity resulted in only minor disturbances to the land surface, principally at the Senator Beck and Swamp Angel lodes. Much of the basin was recently returned to the public domain thanks to the tireless efforts of the Red Mountain Task Force and Trust for Public Lands to acquire inactive mining claims and return them to the US Forest Service, and no active mining is taking place in the basin or in the vicinity. Current US Forest Service management policy for the basin prohibits the use of motorized vehicles during summer and winter, but the basin is open to other public use; domestic sheep have historically been permitted to graze the basin, generally for only 1-2 days per summer season.

Observatory Instrumentation and Parameters

Mountain systems are both driven by, and driving, complex and often non-linear process interactions across an enormous range of spatial and temporal scales. Measuring, or observing, or monitoring 'everything' in these systems is simply infeasible. Nonetheless, within the inherent limitations of 'place-based' observation, a mountain system observatory, or monitoring program, can aspire to capturing sufficiently integrative information to enable the characterization of system forcings and disturbances through an ensemble of 'proxy' measurements—'representative' snapshots of system behavior at appropriate spatio/temporal scales. While no consensus, detailed blueprint for integrative mountain system observation and long-term monitoring presently exist, recent efforts have begun to identify critical indicators of global change in mountain systems and particular research strategies aimed at those behaviors (GLOCHAMORE, 2005). Consistent with many of those strategies, the Senator Beck Basin Study Area has begun capturing a suite of measurements and observations that are supporting interdisciplinary process investigations and laying the foundation of a long-term record of weather, energy budget, snowcover, plant community, soils, and hydrologic conditions for the catchment.

Two micro-met stations with adjoining snow study plots have been developed in Senator Beck Basin—the Senator Beck Study Plot (SBSP – Fig. 2) at 3,719 m (12,200 ft) and the Swamp Angel Study Plot (SASP – Fig. 3) at 3,368 m (11,050 ft), also named after a small abandoned mine. A broad-crested, notched concrete weir has been installed at the basin "pour-point"—the Senator Beck Stream Gauge (SBSG – Fig. 4) at 3,362 m (11,030 ft). A third, 'free air' micro-met station, the Putney Study Plot (PTSP – Fig. 5) at 3,757 m (12,325 ft), has been restored on private land on a ridgeline 3 km SE and within line-of-sight of SBSP and SASP, immediately east of Red Mountain Pass. The Putney site was first established by INSTAAR during the San Juan Avalanche Project in 1972. All four CSAS sites are linked in a radio-telemetry network enabling remote data acquisition and programming. Weather, snowpack, and hydrologic data collection began during the winter of 2003/2004. A comprehensive baseline inventory of the SBBSA vascular plant community was then performed in summer 2004 by Colorado Natural Heritage Program and National Park Service botanists. The design of that inventory captured the diversity of the basin's alpine, treeline, and subalpine zones in three separate transects totaling 230 separate 0.1 m2 samples, and field monuments were installed to enable 5-year repeat studies. The complete species list obtained in 2004 is available at http://www.snowstudies.org/beckbaselinestudy.html.

Figure 2. Senator Beck Study Plot (SBSP) at 3,719m (12,200'), May 5, 2008.

Considerable enhancement of the original sensor arrays has followed through the CSAS's first National Science Foundation award (ATM-0431955, for dust-in-snow research) and other local grants, adding radiation and albedo monitoring arrays, soil sensor arrays, and snowmelt monitoring equipment. In October 2005 an automated sun-tracking photometer was installed at SASP, becoming the second-highest elevation site in the NASA AERONET global network of such sensors. Table 1 presents the current configuration of instrumentation at each of the four sites in the SBBSA.

At every step in the development of SBBSA, the US Forest Service's Ouray Ranger District and their Grand Mesa, Uncompahgre, and Gunnison National Forest Supervisor's Office have been diligent in their oversight yet supportive of the outcome—creating a unique new national asset for the study of the mountain realm. In due time, the CSAS hopes to extend this infrastructure across a larger elevation gradient in an "Alpine to Arid" monitoring network extending downstream from the snow-dominated Senator Beck Basin headwater catchment into the arid pinõn/juniper landscape some 30 km to the north.

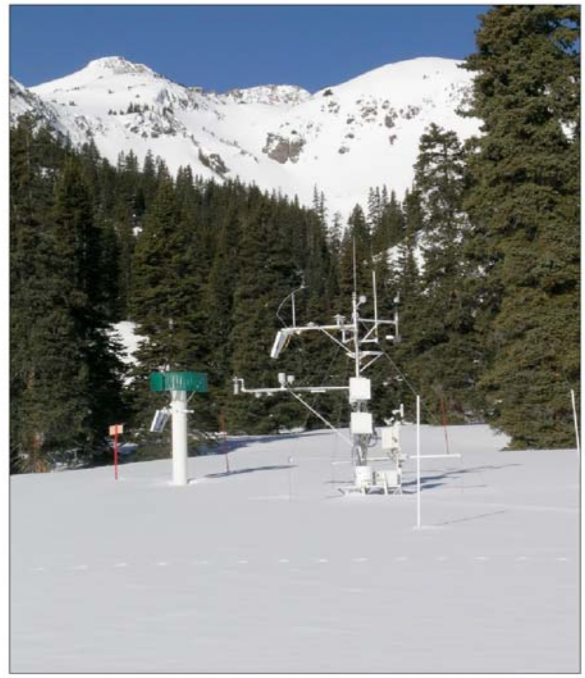

Figure 3. Swamp Angel Study Plot (SASP) at 3,368m (11,050'), March 24, 2008.

Figure 4. Senator Beck Stream Gauge (SBSG) at 3,362m (11,030'), August 1, 2007.

The spatial configuration of these instrumentation arrays yields complimentary measurements of challenging parameters in mountain environments. The well-sheltered SASP site, located in a large 'hollow' within the sub-alpine forest, is especially well-suited for measurement of precipitation and for snowpack properties monitoring, given minimal wind effects on precipitation gauge capture rates and an absence of snowpack redistribution by wind. Conversely, the SBSP site was selected to reflect weather and snowcover conditions in an exposed, heavily wind-effected alpine tundra site. The PTSP site captures 'free air' measurements of wind direction and speed, and of air temperatures and relative humidity, that are minimally influenced by adjoining terrain, and those measurements offer insights into the same measurements at SASP and SBSP, where terrain significantly influences wind behavior, air temperatures, and humidity. SASP and SBSP also 'bracket' the ecotone from sub-alpine forest to tundra. Particularly fortuitously, the hydrologic pour point of Senator Beck Basin is located in a channel confined by bedrock, thereby enhancing the capture of the basin's discharge at the SBSG structure.

Measurements from the network are processed in, dependent on the parameter and site, 1-hour arrays (all), 3-hour arrays (some), and 24-hour (calendar day) arrays (all); diffuse SW radiation data from a shadow array are collected in 2-minute arrays surrounding solar noon. Most measurements are executed at 5 second intervals, then summarized for the given array period (1-hour, 3-hour, or 24-hour). All three micro-met sites are now

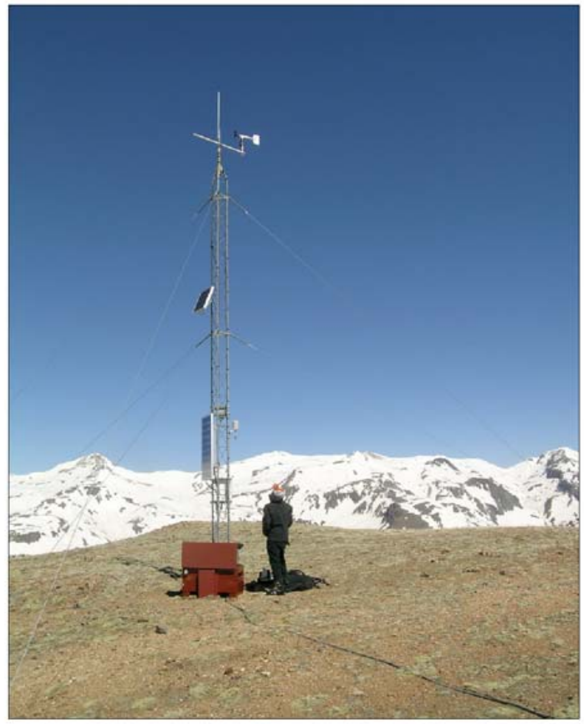

Figure 5. Putney Study Plot (PTSP) at 3,757m (12,325'), May 31, 2008, with Senator Beck Basin in the distance.

Table 1. Sensor configuration at Senator Beck Basin Study Area study plots. (CS = Campbell Scientific; K&Z = Kipp and Zonen; ETI = ETI Instrument Systems).

Parameter	Sensor(s)	SASP	SBSP	PTSP	SBSG
Air temperature	CS 500, HMP50, HMP35-C (not aspir)	X (2)	X (2)	X	
Relative humidity	CS 500 (not aspirated)	X (2)	X (2)	X	
Wind speed & dir	RM Young Wind Monitor	X (2)	X (2)	X	
Snow depth	CS SR50 Ultrasonic	X	X		
Incoming SW radiation	K&Z CM21 Pyranometer	X	X		
Diffuse SW radiation	K&Z CM21 Pyra & Swiss ASRB array	X	X		
Incoming NIR/SWIR	K&Z CM21 Pyranom filtered	X	X		
Incoming LW radiation	K&Z CG4	X	X		
Reflected SW radiation	K&Z CM21 Pyranometer	X	X		
Reflected NIR/SWIR	K&Z CM21 Pyranom filtered	X	X		
Emitted LW radiation	AlpuG GmbH SnowSurf IR	X	X		
Snow temperatures	CS 107 probes (5 in array)	X	X		
Soil heat flux	CS/Rebs HFT-3.1	X	X		
Soil temperatures	CS 107 probes (4 in array)	X	X		
Soil volumetric H_20	CS 616 probe	X	X		
Snow moisture content	CS 616 probe (2 in array)	X	X		
Barometer	CS/Vaisala 105	X			
Precipitation	ETI Noah II	X			
Atmospheric particulates	AERONET Cimel photometer	X			
Stream stage	Druck CS420 transducer				X
Stream stage	Staff gauge				X
Stream stage	Hobo Water Level Logger (2)				X
Stream water temperature	CS 547A probe				X
Stream elect. conductivity	CS 547A probe				X
Dataloggers	CS CR10x	X (2)	X (2)	X	X
Multiplexers	CS AM16/32	X	X		
Power supply	Solar charged battery banks	X	X	X	X

operated year-round, but the stream gauge is shut down each fall when base flows are reached, to prevent instrumentation damage, and then reactivated in late winter before snowmelt flux begins. Seasonal, winter and summer datasets from each site are posted, as Excel spreadsheets, on the CSAS website at http://www.snowstudies.org/data.html; metadata for each seasonal data set are also available at that site. Data from the Swamp Angel and Putney study plots are also used by the Colorado Department of Transportation's Highway 550 avalanche mitigation program and the Colorado Avalanche Information Center.

Snow System Research Synergies

Mountain System Monitoring is a compelling, long-term mission unto itself, and the CSAS is fully committed to sustaining this program, in part, through fundraising approaches that engage "Citizen Funders" (see http://www.snowstudies.org/programpages/monitoring.html). The same infrastructure, however, is also supporting a group of inter-related, integrative snow system research programs and demonstrating the synergistic results of combining process studies and long-term monitoring in the same study area, just as occurs at other mountain research venues such as the Niwot Ridge LTER site. The first hosted snow system research project hosted in Senator Beck Basin began in winter 2003/2004, initiated by geographer Tom Painter (then at the National Snow and Ice Data Center, now at the Univ. of Utah), and illustrates the evolution of an integrative, multi-scale, and highly interdisciplinary set of snow system science research themes. Born of the large-scale, atmospherically driven interaction between the Colorado Plateau and the Colorado mountains (and akin to desert/mountain system interactions throughout the globe), Painter had observed dramatic desert dust layers within and on top of the Colorado snowpack – research questions emerged quickly and after a year of pilot study with the CSAS, an NSF-funded collaborative project was underway in Senator Beck Basin. The Painter project's findings about the significant effects of dust-in-snow on snowmelt timing and intensity (Painter et al., 2007) have led to the direct engagement and support of the water resource management community, anxious to apply those research results and ongoing dust-on-snow observations throughout the Colorado mountains into their snowmelt management practices.

Meanwhile, a parallel effort led by Painter's colleague Jason Neff, from the Terrestrial Biogeochemistry Laboratory at the University of Colorado, began assessing the biogeochemical affects and paleoclimatology of this desert/mountain relationship. Neff's team has found compelling evidence of anthropogenic disturbances to soils in the Colorado Plateau within core samples of alpine tarn sediments in and near Senator Beck Basin (Neff et al. 2008), complimenting the research of Painter et al. Neff's students, Corey Lawrence and Sarah Castle, hosted by the CSAS and Mountain Studies Institute, have focused on the biogeochemical contributions of that snow-borne dust to local ecosystem process. Just recently, a pilot project by Heidi Steltzer of the Natural Resource Ecology Laboratory at Colorado State University has begun investigating potential impacts of dust-in-snow on the alpine plant community of Senator Beck Basin caused by the dust-in-snow induced advancement of the date of "snow all gone" in the alpine tundra. And, while the impetus for his research was independent of the dust-in-snow theme per se, INSTAAR scientist's Hans Peter Marshall's ongoing development of highly portable FMCW radar technology, using Senator Beck Basin as his 'test bed', has contributed an exciting new tool for measuring and modeling the spatial variation of snowcover and SWE in mountain terrain, a long-standing challenge for modelers of basin-scale snowmelt processes, thereby contributing to the development of a catchment scale distributed snowmelt model by the original dust-in-snow team of Painter, Barrett, and Landry.

Each of these process studies has synergistically benefitted the others, and each has contributed to development and operation of the high quality infrastructure simultaneously supporting research and our long-term Mountain System Monitoring program. The CSAS invites all students of the mountains—undergraduate, graduate, staff scientists, agency scientists, and practitioners—to consider the Senator Beck Basin Study Area and/or its data as a resource for your mountain research career, and to join this growing community of mountain system scientists.

Connecting RCMs, Remote Sensing Platforms, and the SBBSA Observatory

The automated environmental monitoring infrastructure already developed in Senator Beck Basin, combined with the frequency of field observations, may offer an unique opportunity for verification of climate and weather modeling at a variety of spatio/temporal scales, and for calibration and verification of remote sensing data, all in a mountain (i.e., "rough") setting. While the SBBSA constitutes a mere 'point' at the scale of regional climate models and many remote sensing platforms, it is nonetheless a very well instrumented point capturing an integrated suite of weather, snowpack, albedo, vegetation, soil conditions, and other data. The location of the SBBSA at the western end of the San

Juan Mountains, in close proximity to the Colorado Plateau and arid Southwest, may also effectively link the climate of SBBSA with climate forcings in the larger region, and clearly does link the deserts to the downwind mountains of Colorado in processes such as dust emission and deposition. The June 2008 MTNCLIM conference held in Silverton featured frequent statements by the modeling and remote sensing community regarding their need for rigorous, long-term observation and monitoring, as essential data for their climate modeling and remote sensing communities. Senator Beck Basin offers a new resource, in that regard, and the CSAS seeks to serve established and new members of the climate modeling and remote sensing community in developing data and observational support services tailored to their programs.

For Additional Details

Additional descriptions, maps, and numerous photographs of the Senator Beck Basin Study Area infrastructure are presented at the CSAS website at: http://www.snowstudies.org/infrastr.html. CSAS Executive Director Chris Landry can be reached at clandry@snowstudies.org, or by telephone at (970) 387-5080.

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Tree-Rings and Reconstructed Streamflow: Information from the Past to Plan for the Future

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Introduction

Tree rings have long proven to be an excellent proxy for annual streamflow over past centuries in many parts of the western U.S. One of the earliest studies targeted the Truckee River, investigating the relationship between tree growth and streamflow and implications for the agricultural sector (Hardman and Reil 1936). In the 1940s and 1950s, the potential of tree rings as a proxy for streamflow for regions that included the Colorado and Missouri River basins and several southern California rivers was explored by Schulman (1945, 1947, 1951, 1956). The first statistical reconstruction of streamflow was developed for the Colorado River at Lees Ferry by Stockton and Jacoby (1976), and since then, a number of streamflow reconstructions have been generated for rivers that range from Colorado River upper and lower basin tributaries (e.g., Smith and Stockton 1981, Meko and Graybill 1995, Woodhouse et al, 2006) to the Sacramento (Earle and Fritts 1986, Meko et al. 2001), Yellowstone (Graumlich et al. 2003), and Columbia Rivers (Gedalof et al. 2004). For a more complete review of the history of streamflow reconstructions, see Meko and Woodhouse (in press).

These reconstructions provide centuries-long records of the natural variability in streamflow, including periods of sustained droughts, and document the richer variety of sequences of flow that occurred over past centuries compared to the modern gage records, which are usually less than 100 years in length. While the development of some of the earliest reconstructions was motivated by potential applications to resource management, until recently, the reconstructions have not been widely recognized as a management and planning tool. Recent droughts throughout the western U.S., however, have drawn new attention to the usefulness and relevance of these data to resource management.

Physical Basis for the Reconstructions

The arid and semi-arid regions of the western U.S. contain conifer species that are exceptionally sensitive to variations in moisture. Species such as Pinus ponderosa, Pinus edulis, Juniperus occidentalis, and Pseudotsuga menziesii growing in relatively low-elevation forests and at sites where moisture is limiting are typically best suited to reconstructions of annual streamflow (but see Gedalof et al. 2004 for exceptions). The most moisture-sensitive trees are located on steep, often south-facing slopes, where the soil is rocky and poorly developed (Meko et al. 2005). The annual growth of these trees is strongly related to the soil moisture at the beginning of the growing season, which has been preconditioned by precipitation in the prior fall, winter, and spring (Fritts 1976). Conversely, trees growing in flood plains in direct contact with rivers, or in the high-elevation snowpack accumulation regions, are generally not useful for reconstructing streamflow because their growth is not moisture-limited. Annual streamflow (most often water year, October-September) and annual increments of tree growth are linked by the integration of precipitation and evapotransporation over the course of the year, mediated by the soil (Meko et al. 1995). These factors reflect the regional climate that influences both annual tree growth and water year streamflow, with winter snowpack often the main influence on both. Thus, the link between annual tree growth and water year streamflow is indirect, but quite robust.

It is important to note that since it is the regional climate that provides the association between tree growth and streamflow, changes in land use and disturbances that may influence runoff are not reflected in the reconstructions. If land use or disturbances have greatly impacted runoff, this may cause a departure in the relationship between the gage record and the reconstruction. For example, Gedalof et al. (2004) suggest that a trend in the residuals in the Columbia River reconstruction model may be due to 20th century land cover changes impacting runoff in the basin. This type of departure has not been observed in streamflow reconstructions for other western U.S. river basins.

How Streamflow Reconstructions are Being Applied to Water Resource Management

Reconstructions of annual streamflow are developed by calibrating moisture-sensitive tree-ring chronologies with a gage record of interest, typically using some form of multiple linear regression. The reconstruction models do not provide perfect estimates of streamflow, but can explain up to 80% of the variance in the gage record (e.g., Meko et al. 2001, Woodhouse et al. 2006). Reconstructions in the western U.S. extend from several hundred to over 1000 years into the past. The long-term context that these extended records of streamflow provide for assessing the shorter gage records has proven to be quite useful and relevant to water resource planning and management in recent years, particularly as water resources in many areas of the western U.S. have become stressed by greater demand and changing uses (e.g., instream flows for ecosystems and recreation) along with natural variability which includes droughts that may now be exacerbated by warming climate conditions (Breshears et al. 2005).

The first set of multi-disciplinary studies to address management and decision-making issues using streamflow reconstructions examined potential impacts of severe sustained drought in the Colorado River basin using the 16th century drought revealed in Stockton and Jacoby's Lees Ferry reconstruction as a basis for a worst case scenario drought (Young 1995 and references within). This set of studies was largely ignored by the water resources community in part because water supplies in the basin at that time were sufficient to meet demands. Interest in reconstructed flows and their applications to water resource management emerged in California partly in response to the severe drought of 1987–92 in the Sierra Nevada. The California Department of Water Resources commissioned an updated tree-ring study of the Sacramento River to estimate long-term probabilities of low flows (Meko et al. 2001). In the Colorado River basin, the drought, which began at the end of the 1990s and peaked in 2002 was a key motivating factor among a large number of water providers and agencies throughout the Colorado River and other western U.S. river basins to consider the usefulness of tree-ring based streamflow reconstructions. Agencies that have since used information from reconstructed streamflow in some way include federal (e.g., Bureau of Reclamation), and state agencies (e.g., New Mexico Interstate Stream Commission), urban water providers (e.g., Salt River Project, Denver Water Board), municipalities, (e.g., Boulder, Santa Fe, and Phoenix), and a host of local and regional water providers, conservation districts and other water administration units.

As more water managers begin to employ these data in planning, it has become evident that there is a range of levels of use of these data. The ways the information is used depends on the specific needs of the agency, and the type of water system that is being administered. We have found that the range of uses can be considered within a conceptual framework proposed by Ray (2004) in her study of the use of climate information by resource managers in the Gunnison River basin in Colorado (Woodhouse and Lukas 2006). Ray (2004) defines four types of use of climatic information: consulted, when information is received or looked up; considered, when information is potentially influential to decisions; incorporated, when information is actually used in an operational model for decision-making; and communication of risk, when the information and its implications are conveyed to others to prompt or justify action. We have found that these levels of use may be incremental, one level leading to the next, or each may be an end point for a particular user.

In the case of the streamflow reconstructions, information on reconstructed streamflow is being introduced to water managers through a number of venues, including a series of technical workshops for water managers as well as through numerous other types of workshops and conferences (http://wwa.colorado.edu/resources/paleo/workshops.html). Within the intermediate levels of use described above, there are two broad categories of technical application of the tree-ring data: (1) as the basis for analyses and visualizations that provide quantitative or qualitative context for evaluating characteristics of the gage record, and (2) as direct input to a water system model or other model to assess management and/or policy options. Applications in the second category, when information is incorporated into operational or planning models, usually necessitate additional processing of the annual reconstructed flows, to make them ingestible by models which require monthly or daily input at multiple nodes. One example of how this is being accomplished is described in the recent Bureau of Reclamation Environmental Impact Statement for managing shortages in the Lower Basin of the Colorado River (U.S. Bureau of Reclamation, 2007), with further details in Prairie et al. (2008). A few early adopters such as Denver Water and the Salt River Project have helped pave the way for the acceptance of this type of information in water resource management. In some regions, such as the Colorado Front Range and Phoenix metropolitan areas, there is now a critical mass of users who can act as resources for new users of this information. A recent survey of water managers and consultants in Colorado, Wyoming, Arizona, and New Mexico who have been introduced reconstructions of streamflow through the series of workshops mentioned above indicated that over half of the 28 respondents are using this information to inform planning and decision making (Rice 2008).

How Reconstructions Of Past Streamflow are Relevant in a Changing Climate

One of the main reasons that the tree-ring based reconstructions of past streamflow are being increasingly incorporated into water resource planning is somewhat ironically due to the now broadly accepted reality of anthropogenic climate change. Major uncertainties in general circulation model (GCM) projections of precipitation at regional and watershed scales have prompted water managers to instead consider records of the past as a basis for long-term planning. Although this may seem like a contradiction, it is actually a logical step for management that has for decades considered only the gage record in planning. The need for planning scenarios, or "alternative hydrologies" (Prairie et al. 2008) that reflect a broader range of conditions than in the gage records has motivated many of the recent applications of the tree-ring reconstructions to water resource management. Natural hydroclimatic variability and the controls on variability at decadal and longer time scales are likely to continue to operate in the future. For at least the next several decades, this natural variability may well swamp the changes due to anthropogenic climate change, and after that, will both underlie and shape the variability and trends caused by climate change. GCMs and downscaled model projections of precipitation will certainly continue to improve, but for now, there is broad agreement among many water managers that the tree-ring reconstructions are a more credible source for scenarios which reflect plausible future conditions than model projections.

A newly emerging direction for plausible future scenarios is combining the best features of backward-looking data (from tree-rings) with forward-looking projections. Since the different GCMs assessed for the 4th IPCC report consistently project warmer temperatures, but disagree regarding projected precipitation in the western U.S., it makes sense to derive alternative hydrologies to take advantage of both the robust temperature projections from models and the range of natural hydrologic variability from the centuries-long tree-ring reconstructions. Several efforts have been recently completed or are now underway to develop planning scenarios based on this blend of information (e.g., Smith et al. 2007, McCabe and Wolock 2007, Gray and McCabe 2008)

Acknowledgements

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Attribution of Colorado Climate Variations and Change

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Introduction

This section addresses the scientific understanding of climate variations and change over Colorado during the past half-century, including an assessment of the recent state of temperature, precipitation, and water resources. The cause for the recent drought that has plagued the western U.S. as a whole since the late 1990s is also addressed, including the possible role of increasing greenhouse gases.

The Evidence for a Warming Climate

a. A Global View

The evidence that Earth's climate has changed during the last century is clear. Comprehensive observations of snow cover, glacial extent, sea level, ice sheets, sea ice, surface temperature, atmospheric temperature permit an accurate monitoring of the state of the Earth system. As reported by the Intergovernmental Panel on Climate Change (IPCC, 2007) Fourth Assessment Report, "warming of the climate system is unequivocal", and is evidenced by rising terrestrial temperatures, rising ocean temperatures to depths of several hundred meters, melting snow cover and sea ice, and rising global sea level. For global average temperatures, eleven of the last twelve years (1995–2006) rank among the 12 warmest since 1850.

b. A North American View

Significant anthropogenic warming over the past half-century has likely occurred (>66% chance) over each continent except Antarctica (IPCC 2007). Over North America, the recent U.S. Climate Change Science Program's (CCSP) Synthesis and Assessement Report (SAP 1.3; 2008) states that the largest annual-mean temperature increases since the middle of the 20th Century have occurred over northern and western North America. Figure 1 presents the trend in surface temperature during 1950–2007, which illustrates this western focus. The time series of annual North American-averaged temperatures is striking in that every year since 1997 has been warmer than the 30-yr climatological reference of 1971–2000. The rise in temperature has not been steady, however, with large year-to-year fluctuations superimposed on this overall upward trend.

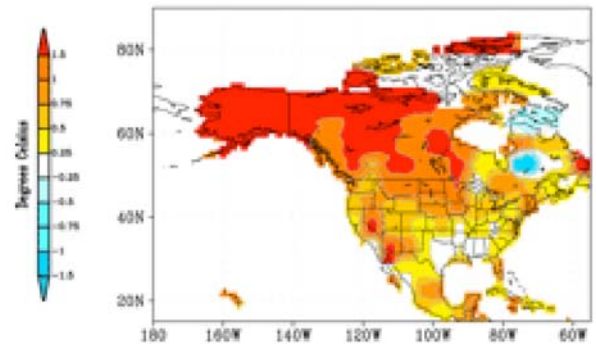

Figure 1. The 1950 to 2007 trend in observed annual averaged North American surface temperature (left). Time series of the annual values of surface temperature averaged over the whole of North America (right). Curve highlights the lower frequency variations after applying a 9-point Gaussian filter to the annual values. Data is the UK Hadley Center's CRUv3 global monthly gridded values. Annual departures are with respect to a 1971-2000 reference.

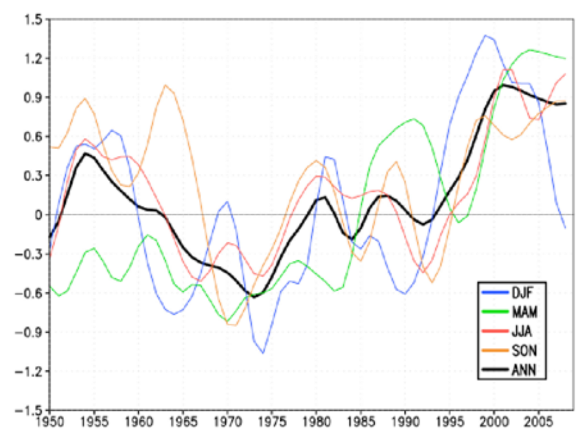

Figure 2. Time series of the annual (black curve) and seasonal (colored curves) values of surface temperature anomalies averaged over the State of Colorado for 1950–2007. Curves are of the 9-point Gaussian filter applied to the raw values in order to highlight lower frequency variations. Data is from the U.S. National Climate Data Center. Departures are relative to a 1971–2000 reference.

c. A Colorado View

Colorado's annually averaged temperature climbed +1°C between 1950 and 2007 (Fig. 2), similar to the warming rate averaged for all of North America. Much higher rates of warming have occurred to the north and west of Colorado, whereas no significant increase in temperature has occurred along the Gulf Coast.

Strong seasonal dependency of the Colorado statewide temperature trends have occurred. Figure 2 compares the time series of annual averages (black) with those for each of the four cardinal seasons. Spring (green) and summer (red) have exhibited the most significant warming since 1950, whereas the recent fall (orange) and winter temperatures (blue) have not greatly exceeded those experienced during the 1950s.

The Cause for a Warming Climate

The consensus statement of the IPCC Fourth Assessment Report (2007) is that most of the observed increase in global average temperatures since the mid-20th Century is very likely (>90% chance) due to increased concentrations of greenhouse gases, especially carbon dioxide and methane. It is very likely that the observed warming of land and oceans, together with the loss in ice mass, is not due to natural causes alone. It is likely that the increases in greenhouse gas concentrations alone would have produced even greater warming than what has actually been observed because volcanic and human-induced aerosols have offset some warming that would otherwise have occurred.

More than half of the North American warming since the middle of the 20th Century likely resulted from increases in greenhouse gases (CCSP 2008). Figure 3 shows the 1950–2007 trend in annually averaged North American surface temperature derived from the IPCC model simulations. These were forced with the observed changes in greenhouse gases, volcanic aerosols, and solar forcing during 1950-1999, and subsequently with a business-as-usual scenario (A1B) of greenhouse gas changes. This is the best estimate available today for the impact of external climate forcing on surface temperature change. There are several agreements between the simulations and observations that argue for an anthropogenic cause. First, the time series of both indicates the bulk of the warming to have occurred after about 1970. Second, the externally forced warming of +1°C since 1950 is close to the observed warming rate. Some inconsistencies between the two are also apparent. For instance, there is greater year-to-year variability in observed North American averaged temperatures than can be explained by fluctuations in external forcing. Also, the IPCC simulated pattern of warming is more spatially uniform across the continent compared to what has been observed. Such regional differences in observed surface temperature trends across the continent are unlikely the result of anthropogenic forcing alone (CCSP 2008).

Drought Over the Western U.S.

Meteorological drought occurs when a region's normal surface water balance is disrupted, typically due to a lack of precipitation. High surface temperatures aggravate water imbalances via increased evapotranspiration. In the West, drought can also result from a deficiency in remote mountain snowpack that is the principal downstream water resource for numerous urban, industrial, and agricultural interests.

It is therefore useful to focus on two measures of drought in order to highlight recent conditions in the West as a whole, and Colorado in particular. One indicator, derived from the monthly

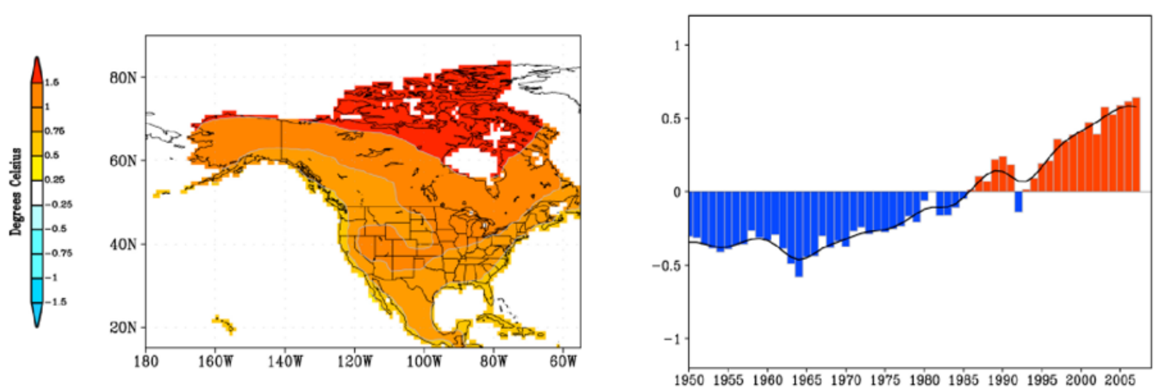

Figure 3. The 1950 to 2007 trend in annual averaged North American surface temperature from 22 IPCC model simulations forced with the estimated greenhouse gas, aerosol, solar and volcanic forcing from 1950–1999, and the business-as-usual emissions scenario (A1B) afterwards. Time series (right) shows the annual values of surface temperature averaged over the whole of North America. Curve highlights the lower frequency variations after applying a 9-point Gaussian filter to the annual values. Annual departures are with respect to a 1971–2000 reference.

records of precipitation and temperature, is referred to as the Palmer Drought Severity Index (PDSI; Palmer 1965), which estimates the state of surface water balance (excluding reservoir storage). The other drought indicator is the annual flow in the Colorado River measured at Lee Ferry at a location beneath Lake Powell. This is a useful index for the annual water supply stored in the State's snowpack that replensishes the downstream storage of Lake's Powell and Mead. In order to highlight the climatic effects on flow, the Lee Ferry time series has been adjusted to reflect the "natural flows" after accounting for consumption and diversions.

Figure 4 presents two time series of the year-to year fluctuations in drought severity over the 11 western states during 1895–2007, the area-averaged PDSI (top) and the % area covered by severe drought (PDSI below –3; bottom). Wet conditions prevailed at the turn of the 20th Century with the West virtually devoid of severe drought during 1905–1920. Dry periods emerged during the 1930s and 1950s with severe social and economic consequences, but these were eventually replaced by another wet epoch from the 1960s till the end of the 20th Century.
The current dry period began in late 1998. The West has recently encountered one the most severe droughts during the 113-year instrumental record, with the % area covered by severe drought during 2002 being the greatest since at least 1895. Nonetheless, consistent with the overwhelming decadal fluctuations in drought, the current view of the scientific community is that it is unlikely

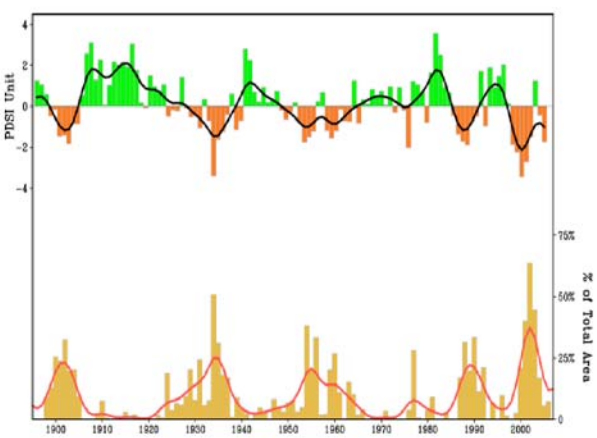

Figure 4. Time series of estimated drought conditions during 1895-2007 averaged over the 11 western states. Top panel is the area-averaged Palmer Drought Severity Index (PDSI), with negative departures indicating dry conditions compared to the region's normal moisture balance. Bottom panel is the % area of the 11 western states experiencing severe drought (PDSI <–3). Smooth curves are 9-point Gaussian filters applied to the raw annual values. Data from the National Climate Data Center.

that a systematic change has occurred in either the frequency or in area coverage of severe drought over the contiguous U.S. during the past half-century (CCSP 2008). This view is consistent with the paleo-hydroclimate evidence indicating some droughts prior to 1600 were more severe and longer in duration than those of recent history (Woodhouse and Overpeck 1998; Meko et al. 2007).

Low Colorado River Flow and the Drought's Causes

Lake Powell-Lake Mead storage was near full capacity as recently as 1998. Storage levels have consistently declined since, standing at only 50% capacity in late 2007. The principal reason for this decline has been a reduction in Colorado River inflow (Figure 5, bottom). Consistently low flows occurred from 2000 to 2004 with annual unregulated inflows of 62, 59, 25, 51, and 49% of average. A near normal inflow in 2005 has since been followed by 71% and 68% of average inflows in 2006 and 2007, respectively.

It is very unlikely that climate change has played a material role in this recently low Colorado River flow and depleted reservoir storage. The principal cause for recent reduced Colorado River flow has primarily been the reduction in precipitation deposited over the Upper Colorado River basin (Fig. 5, top panel). Results from IPCC model simulations indicate that it is very unlikely that greenhouse gas increases played a role in such low precipitation. Further, as will be shown subsequently, no significant change in annual average precipitation due to greenhouse gas emissions is forseen thru the mid-21st Century in the headwaters region. Instead, the recent drought is very likely the consequence of natural climate variability, related in part to the natural fluctuations of the El Niño/La Niña cycle of ocean surface temperature variations in the tropical Pacific. These events affect the movement of moisture bearing storms in winter and spring that are the principal moisture sources supplying the region's montane snowpack and eastern Plain's soil moisture.

However, the current drought has been accompanied by unusually high surface temperatures. Research published in the Proceedings of the National Academy of Sciences (Breshears et al. 2005) comparing the 1950s drought to the current drought indicates that greater warmth has been a material factor in the current drought's greater impacts. The consensus view of the CCSP SAP 1.3 is that "Greenhouse gas forcing may be creating conditions more favorable for drought over the Southwestern U.S., and that increasing land surface temperatures are adding to water stress during droughts".

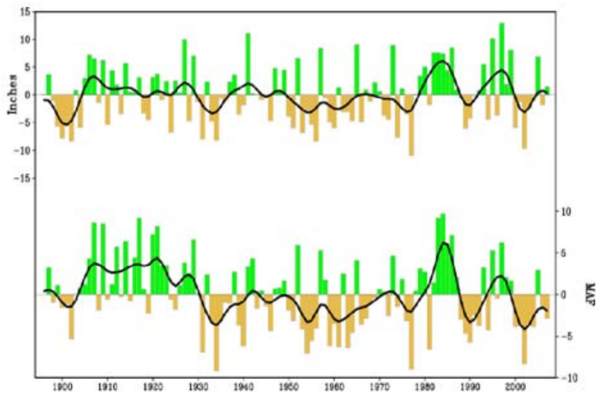

Figure 5. Observed time series of annually averaged precipitation departures during 1895–2007 area-averaged over the Upper Colorado drainage basin (top) and annually averaged Colorado streamflow departures measured at Lee Ferry (bottom). The precipitation data is based on 4-km gridded PRISM data, and the streamflow data is of the "natural" unregulated flows provided by the U.S. Bureau of Reclamation. Smooth curves are 9-point Gaussian filters applied to the raw annual values.

Future Change in Colorado's Climate

According to the climate change projections contained in the IPCC (2007) report, a further warming of global average surface temperatures is expected for the next two decades—even if the concentrations of greenhouse gases and aerosols were kept constant at their 2000 level. Further increases in the atmospheric concentration of greenhouse gases can be expected to lead to even larger increases in temperature. As has already been the case in recent decades, land temperatures will continue to warm more rapidly than ocean temperatures. Colorado's annual surface temperatures would be expected to increase an additional +2°C to +3°C by about 2050, relative to a 20th Century climatology (Figure 6, top panel). Further warming is expected during the latter half of the 21st Century, although the intensity of that additional warming bears greater uncertainty owing to sensitivity to different greenhouse gas emission scenarios in the late 21st Century. Considerable uncertainty exists regarding the projections for precipitation change, especially at regional scales. On a global scale, it is expected that storm tracks of the winter and spring seasons will shift poleward. This shift could cause a wintertime reduction in precipitation in the U.S. Southwest (Seager et al. 2007). At this time, climate models are inadequate to address the impact of greenhouse increases on regional precipitation patterns. In particular, simulations of climate that incorporate realistic topographic complexity are needed to provide more meaningful projections for Colorado precipitation change. The current estimate of the most probable change in precipitation by 2050 under a business-as-usual emissions scenario shows a pattern of northern U.S. increases and southwestern U.S. decreases (Figure 6, bottom), with Colorado in the transition between these. Given the small amplitude of the precipitation change signal due to greenhouse gases, it is very likely that natural variability in precipitation will continue to be the dominate driver for the region.

Implications of a Warmer Climate for Colorado Water Supplies

Notwithstanding the uncertainity in Colorado precipitation changes due to the greenhouse gas effect, the high confidence in projections for a substantial temperature increase over Colorado has numerous implications for Colorado water supply. These involve changes in the quantity and quality of water, and are likely to occur even in the absence of precipitation change. The 2007 National Academy of Science Report "Colorado River Basin

Projected Climate Change at 2050

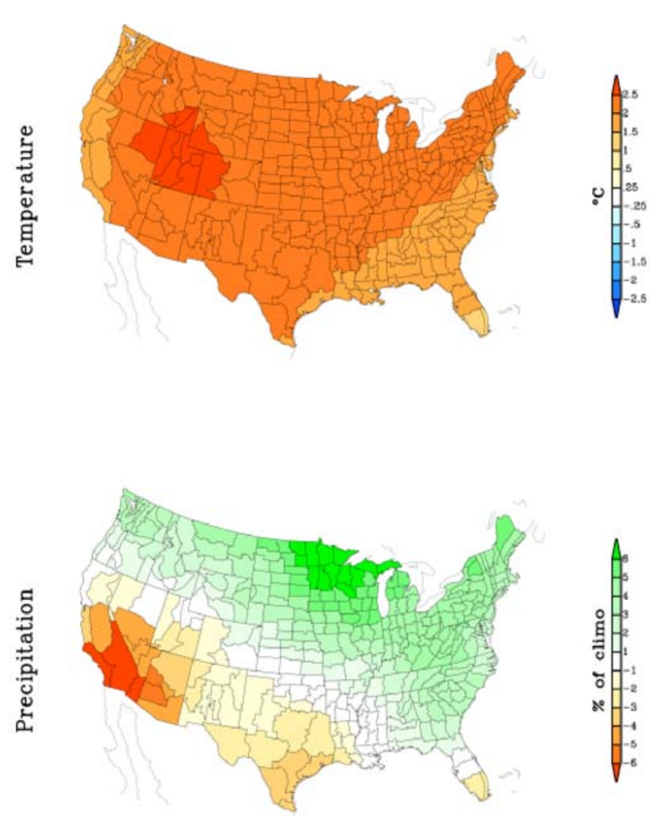

Figure 6. The projected North American surface temperature and precipitation responses at 2050 to business-as-usual emissions scenarios of greenhouse gases and aerosols. Data are from the average of 22 IPCC model simulations forced with the business-as-usual emissions scenario. The anomalies are compared relative to a 1971–2000 reference.

Water Management" summarizes an extensive body of scientific literature on this subject, and highlights the following likely consequences of warming for Colorado water supplies:

- more winter precipitation to fall as rain compared to snow
- shorter snow accumulation season at high elevations
- earlier melting of snowpack
- more runoff and increased streamflow in early spring
- less runoff and reduced streamflow in summer and fall
- greater loss of water due to increased evapotranspiration
- increased water demand by vegetation.

The combination of reduced volume streamflow during summer and increased surface temperature is expected to increase the temperature of in-stream flow. This would negatively impact aquatic ecosystems and fish. A recent example is the widespread fish kill during the summer of 2007 in several western rivers, including the Firehole River near Yellowstone where in-stream temperatures of 82°F killed hundreds of rainbow and brown trout. These river conditions were attributed to the heat wave and drought plaguing the West last year. A similar combination of low summer streamflows and high ambient air and water temperatures had severe impacts on electricity production throughout the Rhone River Valley of France and Switzerland in 2003. These impacts were triggered by an unprecedented summer heat wave over Europe in 2003. Regarding the European heat wave, a scientific paper in Nature by P. Stott and colleagues (2004) found that increased greenhouse gases doubled the risk of a severe heat wave during the summer of 2003. The IPCC (2007) report states that it is very likely that heat waves will increase in frequency over most land areas based on climate projections for the 21st Century.

Hydroclimatic projections for runoff into Colorado rivers and reservoirs indicate significant reductions for the 21st Century. While there exists uncertainty regarding precisely how low streamflow could become as a result of climate change, virtually all methods that have been applied to the problem indicate reduced water supply. A recent comprehensive study by US Geological Survey scientists indicate the Southwest U.S. is likely to experience the most severe reduction in runoff, with about 20% diminished annual runoff in the Colorado River Basin by 2050 (Milly et al. 2005). Indications are that runoff would be more severely curtailed in the southern portions compared to the northern portions of the State. In all cases, owing to increased temperatures, rivers including the Colorado, the South Platte, Clear Creek, Arkansas, Yampa, and Boulder Creek will see peak flow occurring earlier in the year, increased winter flow, and decreased summer flow. The combination of low summer flows and greatly elevated air temperatures is expected to cause in-stream temperatures to increase. The greater frequency of heat waves due to climate change is likely to further aggravate the occurrence of unusually warm water drawn from the State's rivers.

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Estimating Mountain Climate in Space and Time—the PRISM Climate Mapping Program

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Mountain research has always been a spatial pursuit. We revel in the topographic complexity of our study areas, and often use this complexity as an organizing principle for our work. In the last decade, however, new developments in computer technology have enabled a variety of hydrologic, ecological, natural resource, and other models and decision support tools to be linked to geographic information systems (GIS) in new and exciting ways. Mountain science has embraced these developments, and it is now commonplace for us to extrapolate data and ideas across the landscape.

GIS has an insatiable thirst for spatial data sets, and it is not surprising that the advent of GIS technology has produced a dramatic increase in the demand for spatial climate data sets. Spatial climate data are often key drivers of computer models and statistical analyses, which form the basis for scientific conclusions, management decisions, and other important outcomes. Basic climate elements provided by these gridded data sets typically include minimum and maximum temperature and precipitation, and sometimes humidity or dew point, given over a monthly or smaller time step.

The most widely used spatial climate data sets are those developed by Oregon State University's PRISM Group, named for the PRISM climate mapping system. The PRISM Group website receives thousands of GIS data downloads per month, and hundreds of published studies have used PRISM data sets. According to Google Scholar, the paper describing the first version of PRISM (Daly et al., 1994) has been cited in over 700 published articles. At the recent MTCLIM 2008 symposium in Silverton, a startling number of presenters used PRISM data sets to drive their analyses. Yet there is a surprising lack of knowledge about the program. I am often asked: "How did the PRISM model come to be and how does it work? Who pays for these PRISM data sets? Will we continue to see new data sets on your web site?" I hope this article will help shed light on some of these questions.

How did the PRISM model come to be and how does it work?

I coded the first version of PRISM in 1991 as a second-year biogeography doctoral student working for Ron Neilson at Oregon State University. Ron was testing a model he and his team had developed for assessing how vegetation patterns might change across the United States under future climate scenarios. He was able to run his model at climate station locations only, however, because there were no comprehensive spatial climate data sets available. This meant that his assessment left out many ecologically important areas, including most mountainous areas of the West. Precipitation was particularly difficult to map, because of myriad rain shadow effects. Knowing my background as a meteorologist, Ron set me to the task of producing wall-to-wall mean monthly and annual precipitation maps for the lower 48 states.

The two methods in use at that time for climate mapping were unsuitable. Manually hand-drawing a map was a lengthy, costly, and non-repeatable process. Computerized statistical methods such as inverse-distance weighting, simple kriging, and spline fitting algorithms were fast and repeatable, but were generalized functions that were "climate challenged;" they produced inferior maps because they lacked information on the physiographic forcing factors that produce climatic patterns. Given recent advances in GIS, the timing was right for a new method of creating climate maps that would bring meteorological intelligence and geographical analysis to the statistical interpolation of climate.

From my background in forecast meteorology, forest geography, and mountain climatology, it was clear that elevation was the primary determinant of climatic conditions. However, the climate-elevation relationship varied across the landscape, and sometimes quite sharply, and could be confounded by other factors. In a previous job as a meteorologist with an air pollution consulting firm, I had developed a method called "Sub-regional Interpolation (SI)" for temperature mapping in coastal areas. If you could manually divide the region into relatively homogeneous sub-regions, such as coastal and interior, within which the relationship between temperature and elevation was relatively constant, the SI model would develop temperature-elevation regressions within each sub-region, apply those to estimate temperature on sub-grids, and knit the resulting sub-grids together to form a complete map. This worked well for small areas, but dividing the US into sub-regions was a horse of a different color; it would have taken me months, and probably would have driven me crazy, to try to attempt such a feat. I was desperate!

Desperation breeds many of our best ideas, and in this case produced the concept of "topographic facets," which I defined as contiguous areas of constant orientation. Most rain shadows occurred as a result of large-scale terrain barriers, over which the terrain orientation changed markedly. A leeward slope would have a very different precipitation-elevation relationship than a windward slope, for example. I built a simple algorithm that automatically divided the terrain given by a DEM (digital elevation model) into topographic facets with several slope orientation categories. After playing around with the resulting facet grids, it became clear that no one spatial scale produced facet patterns that made sense for all situations; thus, I ended up modifying the algorithm to produce facet grids at six spatial scales. I then set my SI model to start with the smallest-scale facet grid, search around to see if sufficient climate stations were available with which an elevation regression function could be developed, and if not, would move up in scale until either there were sufficient stations, or the largest facet scale was reached. The devil was in the details, and it took a lot of experimentation to determine how many stations were needed to establish to good regression function, how to define and place bounds on the slope of the regression to keep unusual stations from spinning the model off in the wrong direction, how to quality control the station data effectively, and to handle the many, many other situations that threatened to ruin the map's quality. This resulted in the development of an elaborate decision-making system that could recognize and troubleshoot problems as they arose.

In the 17 years since its inception, PRISM has undergone nearly constant development. It is now a large model with about 17,000 lines of code (Daly et al., 1994, 2001, 2002, 2003, 2008; Daly, 2006). Some things have remained essentially the same; PRISM still adopts the assumption that for a localized region, elevation is the most important factor in the distribution of climate variables. PRISM still calculates a local climate-elevation relationship for each grid cell on a DEM, and uses nearby station data to populate the regression function. I have remained with a simple, rather than multiple, regression model because controlling and interpreting the complex relationships between several independent variables and climate can be difficult and unstable. Instead, PRISM weights the data points to control for the effects of physiographic variables other than elevation.

The list of station weighting variables has increased dramatically over time. Currently, the list includes clustering, distance, elevation, coastal proximity, topographic facet, vertical layer, topographic position, and effective terrain height (Daly et al., 2008). I pick and choose which weighting functions to use, depending on the application. Overall, the farther away a station, both horizontally and vertically, the less weight is given. Stations clustered with each other are down-weighted so as to not over-sample a given location. Stations on the same side of a terrain feature as the target grid cell are weighted more highly than others. Depending if the target cell is within the boundary layer or the free atmosphere, stations in the same atmospheric layer are weighted more highly than those in a different layer. Stations with similar proximity to coastal influences are weighted more highly than those that are not. Stations on terrain features with similar effectiveness in enhancing precipitation are weighted more highly, as are stations in similar topographical positions, (i.e., valley bottoms, hillslopes, and ridgetops).

In order to be useful in PRISM, a station weighting function must be general enough to work properly over large areas, and in a variety of climatic situations. It usually takes years of modification and many different applications before a weighting function stabilizes into something I am happy with. Many of the weighting functions require input grids that describe the spatial patterns of these physiographic features. This has led me to write pre-processing algorithms such as a coastal proximity model that brings marine air parcels onshore in complex terrain and finds the least-cost path to an inland location (Daly et al., 2003), and a straight-line trajectory model that moves moist air parcels up and over terrain features to identify relatively wet and dry zones (Daly et al., 2003).

Throughout the development process, I have known in my mind's eye what the finished maps should generally look like, based on my experience, and it is my job to create a model that is "smart" enough to produce maps of acceptable quality to an expert climatologist. I cannot underestimate the advantage of knowing more than the model that you are developing. This may sound like a small point, but if you do not have the experience to seriously critique your own model for reasonableness, your model will not be the best it can be. (Statistical comparisons with observations only take you so far, and say nothing about where there are no stations, which seem to be most everywhere in the mountains.) I was constantly asking myself: "If you think PRISM did the wrong thing, what information did you access that it did

not have? What decisions did you make that it did not?"
As it turns out, our mental computers access and process a huge array of information in various forms, all leading to what appears to be a relatively simple decision. Much of the development of PRISM is based on trying to mimic the decisions an expert climatologist would make when making a climate map (Daly et al., 2002). An overview presentation on PRISM can be downloaded at: http://prism.oregonstate.edu/pub/prism/docs/PRISM_overview_050808.ppt.

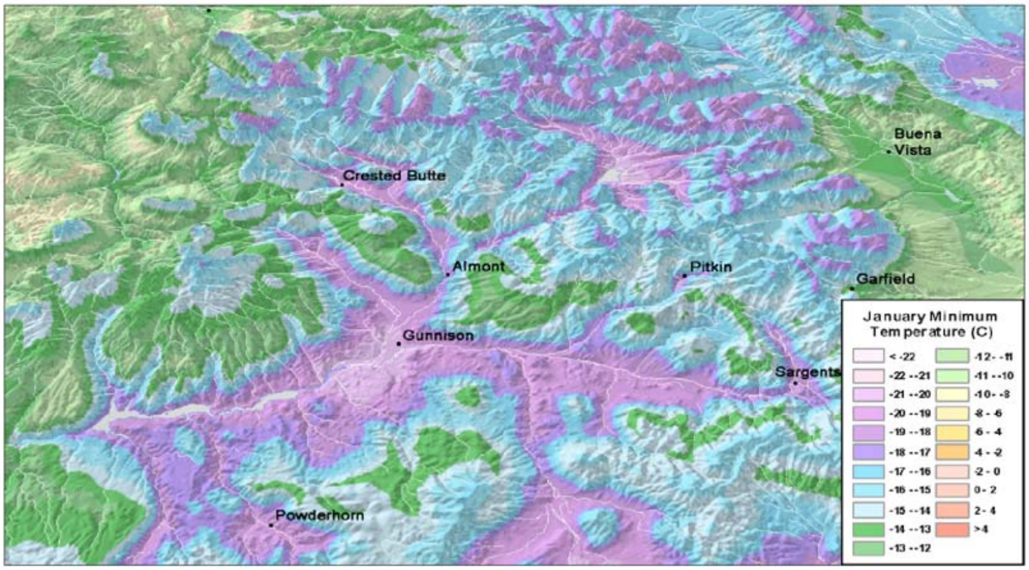
Who has been paying for these PRISM data sets?

The first major funding for PRISM came in 1993 from the USDA Natural Resources Conservation Service (USDA-NRCS, formerly USDA Soil Conservation Service) National Water and Climate Center in Portland, Oregon. Phil Pasteris, a hard-working visionary despite his self-described title of "Federal Slug," foresaw that the agency would need to become GIS-capable, and end its reliance on hard copy products and hand drawn maps. Some of the most important maps in need of updating were state hand-drawn precipitation maps last prepared in the 1960's. (It may come as a surprise to many, but the official precipitation maps for the US have historically originated from the USDA, not NOAA). Phil became aware of the PRISM technology when he saw a presentation given by George Taylor, then the Oregon State Climatologist, on a new Oregon precipitation map he had commissioned me to develop. The first NRCS project resulted in new official USDA 1961-1990 mean precipitation maps for every state in the country. The process included repeatedly putting me in the "hot seat" before the PRISM Evaluation Group, a committee designed to rake me over the coals on every aspect of the model and the maps (and which included our own Kelly Redmond). I ended up making some pretty substantial changes to the model and the maps as a result of these repeated "grillings".

The success of the NRCS project opened the door to dozens of other spatial analysis projects worldwide. Our work expanded into Canada, China, Mongolia, Taiwan, SE Asia, and Europe. Project funding has come from a wide variety of sources, including many agencies within the USDA and NOAA, NASA, NPS, USFS, USEPA, NSF, The Nature Conservancy, and others. Many of our analyses and data sets undergo rigorous peer review, sometimes involving dozens of reviewers. Below are just a few highlights of current and past PRISM Group projects, some of which are better known than others.

USDA Agricultural Research Service: A new official US Plant Hardiness Zone Map for the United States. This map is by far the most used climate map in the world, and is the key plant selection guide for horticulturalists, the nursery industry, and backyard gardeners everywhere. It is anticipated that the new map will be accessed over 100 million times within the first week of release. We are pleased to say that mountainous areas will be depicted in a realistic way for the first time.

- USDA Foreign Agriculture Service: The first-ever detailed maps of climate and soils for the People's Republic of China. This allowed Oregon grass seed growers to create a multi-million dollar market for their seeds in regions of China where conditions were well suited to their grass species, avoiding areas where they were poorly suited (Daly 2007; Daly and Hannaway 2005; Hannaway et al., 2005).
- National Weather Service: Major updates to official extreme precipitation maps last created in the 1960's and 70's. These maps provide the basic climatological guidance used by states, counties, and municipalities to determine building codes and regulations.
- NOAA Office of Global Change: Monthly time series of climate grids for the lower 48 states at 4-km resolution that started in 1895 and ended in 1997. US Forest Service supported us to extend this time series to the present (Daly et al. 2000). The Nature Conservancy recently commissioned an 800-m version of this time series.
- USDA-NRCS: 800-m update of the 1961-1990 climatologies to 1971-2000 for the lower 48 (Daly et al. 2008). NPS and USFS funding added US possessions in the Caribbean and Pacific; Alaska is currently being updated.
- USDA-NRCS: An automated quality-control system for SNOTEL temperature and precipitation data (Daly et al. 2005).
- NWS and NASA: "Targeted" PRISM precipitation climatologies classified by storm direction, and temperature climatologies classified by syntopic flow pattern (ridge, trough, zonal), to provide forecasting guidance.
- NSF: Principal Investigator for climate at the HJ Andrews Long-Term Ecological Research site in the Oregon Cascades, studying climatic spatio-temporal relationships and global change at the landscape scale (Daly and Conklin, in prep.).
- USDA National Research Initiative: PRISM-based weather forecast system for agricultural applications. The system uses PRISM maps as the first-guess of today's weather, then



PRISM January 1971–2000 mean minimum temperature in the Gunnison, Colorado area, showing complex relationships between elevation and temperature due to cold air pooling.

modifies it with station data and forecast model output to produce current and forecast weather maps.

Additional information about these projects can be found at: http://prism.oregonstate.edu/projects/nri.

An overview presentation of PRISM Group activities can be downloaded at: http://prism.oregonstate.edu/pub/prism/docs/prism_group_activities_0608.ppt.

Will we continue to see new data sets on your web site?

The PRISM program has come a long way from its inception, and has advanced the discipline of geospatial climatology to the benefit of all. PRISM products have been woven deeply into the research and government infrastructure of this country. Our web site is one of the busiest at OSU, and we field calls and emails every day from users taking advantage of our freely available data sets, without charge to them.

Ironically, it appears that our strong commitment to public service might have backfired on us when it comes to continued funding. People are dumbfounded when they hear that the PRISM Group (currently at five members) has never had anything resembling "line-item" funding or an operating budget. "But your products are so useful, you must have lots of agencies funding you all the time, right?" Well, not exactly. We derive 100% of our funding (including my salary) from external contracts and grants, the dreaded "soft money," from a handful of agencies. These projects come sporadically, many times skipping one or several years, as the discretionary funding budgets of these agencies come and go. There is often little rhyme or reason to the requirements of these grants, which severely limits our ability to update and improve our products on a regular basis. There has never been funding for the PRISM model itself, only products resulting from the model; and many of those products never make it to our web site due to insufficient resources. It is a case of a square sporadic funding mechanism trying to fit into the round hole of the ongoing, operational process of researching, creating, improving, and updated spatial climate data sets.

The Federal fiscal year 2008 has been particularly difficult for the PRISM Group, as I suspect it has been for many research groups. Elimination of extramural research dollars, pull backs of existing money, and long delays of committed funds all have contributed to a financial crisis for the group that has nearly eliminated my job and the entire program. I have placed a message on our web site announcing that our popular monthly update mapping is slated to cease in mid-2008 because of funding cuts, and now is the time for users to provide support to continue the program. This has elicited a few well-meaning responses, but typically once I tell them that we need at least $75,000/yr to keep this particular product afloat, the conversation ceases. Despite the seeming universal agreement that the value of the program is very high, and that our products save users an inestimable amount of resources, there is no organized commitment to supporting them.

Why is this? In some ways, I think that spatial climate data sets are too useful for their own good. The range of applications cuts across too many disciplines for one agency to feel that supporting them is solely within their purview, so each agency stands back and hopes that the other will do the funding. The USDA-NRCS was the best example of an agency that was altruistic enough to step forward, but we cannot count on their help anymore. The other problem is that people are used to getting "weather data" for free. Don't our tax dollars pay for the collection of weather data, and aren't PRISM data sets just a compilation of those numbers? Clearly, a lack of education on the research and effort that goes into these data sets, and their resulting value, plays a part.

Climate is arguably the single most powerful driver of natural (and many societal) functions in the mountains and worldwide. Spatial climate data sets provide estimates of this basic environmental driver where there are no observations available. The old adage applies: You get what you pay for. Errors in these data sets translate into errors in every analysis that uses them (Daly 2006). Those performing those analyses recognize that grappling with problems caused by these errors consumes far more time and effort than just supporting high-quality spatial climate data sets in the first place. The challenge is communicating this fact to decision-makers who can make a difference.

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Announcements

CIRMOUNT Session at AGU 2008 Fall Meeting

Once again CIRMOUNT will host a session at the Fall meeting of the American Geophysical Union in San Francisco, CA. The 2008 session, organized under the Global Environmental Change section is entitled "Complex Mountain Climates Create Complex Ecosystem Responses and Require Complex Management Strategies". The theme of the session follows in recognition that mountain ranges of western North America are by nature heterogeneous physical environments, defined by great topographic, altitudinal, and substrate variations. These qualities contribute to meteorological and climatic complexity that is increasingly recognized as distinct from lowland counterparts. In paleohistoric contexts as well as under current global change, mountain systems show unique responses to global as well as regional and local climate perturbations. Complex as mountain climate variability is, it creates and catalyzes equally or more complex responses in mountain landscape systems, including hydrologic, atmospheric, soil, and ecologic structure, composition, and functioning.

Under the influence of even minor changes in climate, landscape elements can exhibit episodic, reversible, opposing, threshold, gradual, or non-equilibrium responses. Completing a triad of associations, complexities in climate change and landscape response require sophisticated, case-by-case strategic and tactical approaches to resource management. The relationships of climatic, landscape, and resource-management complexities in mountain systems are not yet well understood or characterized.

To the contrary, many model projections and scenario exercises assume gradual and linear changes with directional shifts in management: e.g., warming temperatures are often assumed to translate directly into upward migration of species and a shift in management frameworks. While linear responses may (or may not) result in the long term, in the short (decadal) term, highly non-linear responses are likely to occur. In this session, we invite studies that investigate complexities in modern as well as paleohistoric mountain climates and landscapes, and/or that expand the toolbox of management strategies used to address mountain landscape management in the climate-change context.

Fifth WMRS Regional Research Symposium: "Climate, Ecosystems, & Resources in Eastern California"

Increases in greenhouse emissions and other factors are bringing about climate change on a scale unknown in recorded human history. Wildland ecosystems are being directly and indirectly affected, and changes seem to be accelerating. Mountain environments of the Sierra Nevada and western Great Basin ranges serve as key but threatened water towers that provide resources for downhill uses near and far. Because ecosystem services are necessary for activities such as tourism, outdoor recreation, water export and agriculture, the human economy of montane Eastern California will probably be profoundly affected. What form will climate change take in this region? What will be the nature of ecosystem responses to climate change? How will particular plant and animal species respond? How will ecosystem changes affect services on which the human economy depends? How can resource managers and local governments deal with these changes?

These and related topics will be the subject of a three-day symposium to be held November 5-8, 2008 in Bishop, California. We hope to share current research and thinking, so that scientists, resource managers, and the public will gain a better understanding of what is happening, and why. The symposium will include three broadly defined plenary sessions: climate and water, ecosystem responses, and adaptation & mitigation (management & policy). The morning plenary sessions will be followed by 10-15 concurrent sessions organized around themes relating to the central topics. There will be an opportunity for contributed talks as well as a poster session. Field trips may be offered, either before or after the symposium, and a keynote address will be open to the public free of charge. Please consult the following website for details and registration information: http://www.wmrs.edu/projects/CEREC/announcement.htm

For more information, contact: John Smiley, UCSD/WMRS, jsmiley@ucsd.edu or Connie Millar, USFS, CIRMOUNT, cmillar@fs.fed.us

News from the Mountain Research Initiative

Geo-Referenced Biological Databases—A Tool for Understanding Mountain Biodiversity

The Mountain Research Initiative has invited Dr. Eva Spehn, Director of the Global Mountain Biodiversity Assessment (GMBA) and Dr. Antoine Guisan, head of the Spatial Ecology Group at the University of Lausanne, to introduce the reader to their coordinated efforts in advancing the understanding and prediction of mountain biodiversity. Antoine Guisan's EUROMONT project is one of the many scientific projects that may potentially provide data for the new GMBA initiative for a GIS mountain biodiversity database.

The Global Mountain Biodiversity Assessment (GMBA) GMBA, a cross-cutting network of DIVERSITAS, aims at encouraging and synthesising research on high elevation organismic diversity, its regional and global patterns, its causes and functions (Spehn, Liberman, and Körner 2005). Existing and emerging databases are promising tools to achieve these goals. Many research projects generate data sets that are relevant for the scientific community, government natural resource managers, policy makers, and the public. The Global Biodiversity Information Facility (GBIF) has the mission to make the world's primary data on biodiversity freely and universally available via the Internet. In cooperation with GBIF, GMBA encourages a global effort to mine geo-referenced archive databases on mountain organisms, to build new biodiversity databases, and to link them with geophysical databases.

When building or analysing database information it is essential to include geographical coordinates and altitude specifications (geo-referencing) of observed or collected biological species, as it allows to link biological with geophysical information, particularly climate data. Given the amplitude of climatic conditions and topographies across the world's mountains, they offer unbeaten test conditions for biodiversity theory. The high diversity and endemism of mountains may take its origin in past climatic events, by having allowed faster altitudinal than latitudinal migrations of species, as cooling and warming succeeded during the quaternary or through survival of some species in high-elevation refugia (nunataks). But the great richness and originality of their flora and fauna may also simply result from the higher habitat diversity and climatic turnover over short distances or the (possibly) long isolation of mountain tops from each other (alpine species cannot migrate through low-elevation areas) favouring speciation (Chapin & Körner 1995). Furthermore, the usual decrease of species richness observed toward higher elevations may result from the conic shape of mountains and the shorter growing seasons restricting both time and space for evolution (Körner 2000, 2004). Yet, these theories of biodiversity are usually assessed locally, in a single mountain range (e.g. in Chapin & Körner 19953), while a wider view is often required to identify the real proximal causes of biodiversity patterns (e.g. for treeline, Körner 1998).

A first GMBA workshop in the Central Caucasus in July 2006 developed a Research Agenda on the potential of geo-referenced biodiversity databases for understanding mountain biodiversity and predicting its changes. GMBA will follow up on these issues in a SCOPE Rapid Assessment synthesis project in order to reach a synthesis of regional mountain biotic richness from various parts of the world.

The EUROMONT Initiative: An Example of Potential Data for GMBA

The idea of the EUROMONT workshops—which aim to assess climate threat to alpine plant diversity in Europe - started from a recent paper by Thuiller et al. (2005) predicting species loss up to 60% for mountain plant species in Europe in response to climate change. These coarse-resolution (10'x10') projections provide valuable scenarios for anticipating risks that climate change exerts on overall biodiversity in Europe. But their accuracy may not be sufficient to assess ecological impact in complex high-elevation mountain landscapes, where the rugged topography requires high resolution mapping (e.g. 25x25m; Guisan & Theurillat 2000). As these predictions are then used to address management issues, such as the role of parks and natural reserves as reservoirs of future biodiversity (Araujo et al. 2004), it has become urgent to assess whether reliable local trends can be predicted from these global projections. This is the main aim of the EUROMONT initiative, supported by MRI and the University of Lausanne. A first workshop brought together 19 scientists from 11 countries, bringing together 11 data sets from 6 mountain ranges (Alps, Apennines, Pyrenees, Scandes, Scottish highlands, Carpathians). Local climate change impact scenarios were derived for mountain floras, using the same tool and IPCC projections as used by Thuiller et al. (2005). Preliminary results suggest lower extinction rates on average at the local scale, but higher extinction rates where also predicted for some study areas under severe climate change scenarios (Fig.1). The different study areas clearly show distinct sensitivities to climate change (Fig.1). Nonetheless, all extinction rates remain important (above 10%) and show that all mountain floras are vulnerable, especially when considering the highest climate change scenario (A1; up to >60% extinctions). A second workshop in December 2006 will allow a finer interpretation of these results per study area, per species type and per climate change scenario.

New Sources of Georeferenced Biodiversity Data for the SCOPE/GMBA Initiative

The EUROMONT initiative is one of many scientific projects that collect and use large geo-referenced mountain biodiversity data sets to answer specific questions in ecology, biogeography and conservation biology. The GLORIA project on monitoring global change effects on alpine plants or the MIREN network on invasive species in mountains are other examples. A thorough testing of biodiversity theories with comprehensive data at the global scale, as obtained through EUROMONT, GLORIA or MIREN, would constitute a significant step in our understanding of mountain diversity patterns. Many data sets are associated with short-term projects and thus threatened of destruction at the end of the project. The new GMBA initiative for a GIS mountain biodiversity database precisely aims at gathering them to prevent their destruction and allow a first global assessment of primary causes of mountain biodiversity patterns.[1]

Internet

EUROMONT: see http://ecospat.unil.ch

DIVERSITAS: http://www.diversitas-international.org/

GBIF (Global Biodiversity Information Facility): http://www.gbif.org

GLORIA (Global Observation Research Initiative in Alpine Environments): http://www.gloria.ac.at/

GMBA (Global Mountain Biodiversity Assessment): http://www.gmba.unibas.ch

MIREN (Mountain Invasion Research Network): http://www.miren.ethz.ch

SCOPE: http://www.icsu-scope.org

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