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Mountain hydrology of the western United States

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[1] Climate change and climate variability, population growth, and land use change drive the need for new hydrologic knowledge and understanding. In the mountainous West and other similar areas worldwide, three pressing hydrologic needs stand out: first, to better understand the processes controlling the partitioning of energy and water fluxes within and out from these systems; second, to better understand feedbacks between hydrological fluxes and biogeochemical and ecological processes; and, third, to enhance our physical and empirical understanding with integrated measurement strategies and information systems. We envision an integrative approach to monitoring, modeling, and sensing the mountain environment that will improve understanding and prediction of hydrologic fluxes and processes. Here extensive monitoring of energy fluxes and hydrologic states are needed to supplement existing measurements, which are largely limited to streamflow and snow water equivalent. Ground-based observing systems must be explicitly designed for integration with remotely sensed data and for scaling up to basins and whole ranges.

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1. Introduction

[2] In the mountains of the western United States, sharp wet-dry seasonal transitions, complex topographic and landscape patterns, steep gradients in temperature and precipitation with elevation, and high interannual variability make hydrologic processes and variations significantly different from lower-elevation regions or those that are humid all year. Hydrologic feedbacks in mountainous regions control the availability of water, influence the distribution of vegetation, dominate biogeochemical fluxes, and contribute to global and regional climate variability. Improved knowledge of the processes controlling these feedbacks will promote clearer understanding of Earth's water, energy, and biogeochemical cycles, and enable sounder management of increasingly stressed natural resources. In the western mountain, our knowledge is particularly limited by problems of spatial scaling in complex topographic settings with strong climatic gradients and by lack of adequate understanding and monitoring of energy balance components in the seasonal snow.

[3] Making more informed decisions to manage water resources is a primary societal motivation for better hydrologic information. Mountain river basins, their associated reservoirs, and their underlying aquifers supply water demands of over 60 million people in the western United States. More than 1/6 of the world's population depends on snow covered glaciers and seasonal snow for water supplies, which may be at risk from a warming climate [*Barnett et al.*, 2005]. Water allocations in these supply limited systems rely on decision systems that also account for water laws and markets, interstate compacts, international treaties, flood control, and demands from agricultural, hydropower and municipalities, all of which eventually are based on interseasonal storage of most runoff in winter snow.

[4] Management of forest and other mountain resources also drives the need for new hydrologic knowledge. With their extensive forests and potentially large turnover of carbon on annual to decadal time frames, mountain regions in North America and elsewhere contribute significantly to continental carbon budgets. Montane forest dynamics are sensitive to the spatial and temporal variability of hydrologic variables, especially the variability in snow water equivalent and snowmelt [*Schimel et al.*, 2002].

[5] Snowmelt from mountains is the main source of many regional water supplies, with downstream processes, such as groundwater recharge and interactions with ecosystems, controlled by processes at higher elevations. A lack of process understanding and a reliance on sparsely distributed observation networks together limit our ability to simulate and predict hydrologic processes in mountainous regions, especially in a changing climate. Such change is likely to perturb the partitioning of energy and mass balances in ways that cannot be resolved by empirical approaches such as temperature index models. As examples, we lack an

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Table 1. Example Research Questions Related to the Three Overall Topics

Topic	Questions
Energy and water fluxes	How do we represent and scale basin-wide energy balance in complex, heterogeneous terrain from sparse point measurements? How do large-scale circulation and mesoscale forcing influence the distribution & timing of precipitation? What mechanisms generate interannual variability in precipitation and in the relationship between elevation and the amount of precipitation and snowmelt? Do subsurface flow paths and residence times increase with scale, from headwater catchment in a river basin? How does base flow respond to climate variability across the various geologic and vegetation regimes in a mountain range? How can we accurately estimate evapotranspiration and snowpack sublimation?
Hydrological fluxes, biogeochemistry, and ecology	How do physical and ecological factors and their perturbations determine the large variability in runoff versus infiltration across a mountain range? What principal geologic factors control groundwater storage, discharge to streams, and chemical composition in mountains? What role do snow lines play in the geomorphology, ecology, aqueous geochemistry, and hydrology of mountain catchments? What is the importance of seasonal transitions to carbon and nitrogen biogeochemistry at the scale of a mountain range, i.e., across elevational and longitudinal gradients? How do changing seasonal transitions affect carbon and nitrogen cycling in and export from aquatic ecosystems?
Integrated measurement strategies and data/information systems	How do we blend satellite, surface, and boundary layer measurements for scaling energy balance? How do we estimate the spatially integrated rainfall, snowfall, and snowmelt in the mountains? How do we economically extend stream gauging to higher elevations and lower-order watersheds? How do we estimate soil moisture? How do we integrate disjoint data acquisition and management institutions?

adequate description of factors controlling the partitioning of snowmelt into runoff versus infiltration and into evapotranspiration versus recharge, and we lack strategies to accurately measure the spatial variability of snow and soil moisture in the mountains. The volume of mountain block and mountain front recharge to groundwater and how recharge patterns respond to climate variability are poorly known in most mountain ranges.

[6] In the western United States and elsewhere, topographic variability, thin soils, varying bedrock permeability, heterogeneous forest cover, and a snowmelt-driven water cycle present unique challenges as well as opportunities for the study of hydrologic processes. A review covering all these topics in useful detail would be encyclopedic. However, among the many research needs stand three pressing hydrologic issues that integrate many subdisciplines of the hydrologic sciences and where the research questions have the highest priorities: First, despite the importance of mountain regions to the hydrologic cycle and regional water supplies, the processes controlling energy and water fluxes within and out from these systems are not well understood. Second, we poorly comprehend the feedbacks between hydrological fluxes and biogeochemical and ecological processes. Third, the lack of integrated measurement strategies and data/information systems for hydrologic data hamper improvements. In this paper we present a view (as distinct from an overview or review) of research needs and opportunities in these areas. We also offer examples of research questions that derive from these opportunities (Table 1).

2. Energy and Water Fluxes

[7] Complex distributions of energy and water fluxes dictate the flow of water to and from western mountains. The spatially fragmented and temporally varying distributions of climate, land cover, geology, and snow both characterize and complicate the hydrology of the region. Our vision is of a smooth integration of knowledge of energy and water fluxes into a more comprehensive understanding of range-scale processes.

2.1. Energy Fluxes

[8] Our understanding of energy exchange between the land and atmosphere in mountains is incomplete because of their physiographic heterogeneity and the relatively larger scales of the atmospheric variations that supply and receive those energy exchanges. This heterogeneity results in nonsystematic distributions of conditions that control the fluxes of latent heat, sensible heat, solar radiation, and terrestrial radiation at the surface. On the other hand, the atmospheric boundary layer that receives these fluxes mixes them over larger, topographically established scales.

[9] Perhaps the most important linkage of energy fluxes and the water cycle in the mountain west lies between snow accumulation and its melt. A simple example illustrates this linkage. Consider the possible impact of an increase in the average annual temperature of +3°C in the west, which is well within the range of possible increases for the year 2100 [*California Regional Assessment Group*, 2002]. During the past 50 years much of the precipitation in the coastal mountains fell when temperatures were in the $-3°$ to $0°C$ range (Figure 1a), suggesting that these areas are particularly vulnerable to a snow-to-rain transition. Moreover, across the mountain west much of the winter has average temperatures in the $-3°$ to $0°C$ range (Figure 1b), again with the Sierra Nevada and Cascades being particularly vulnerable to warming. Finally, a significant fraction of

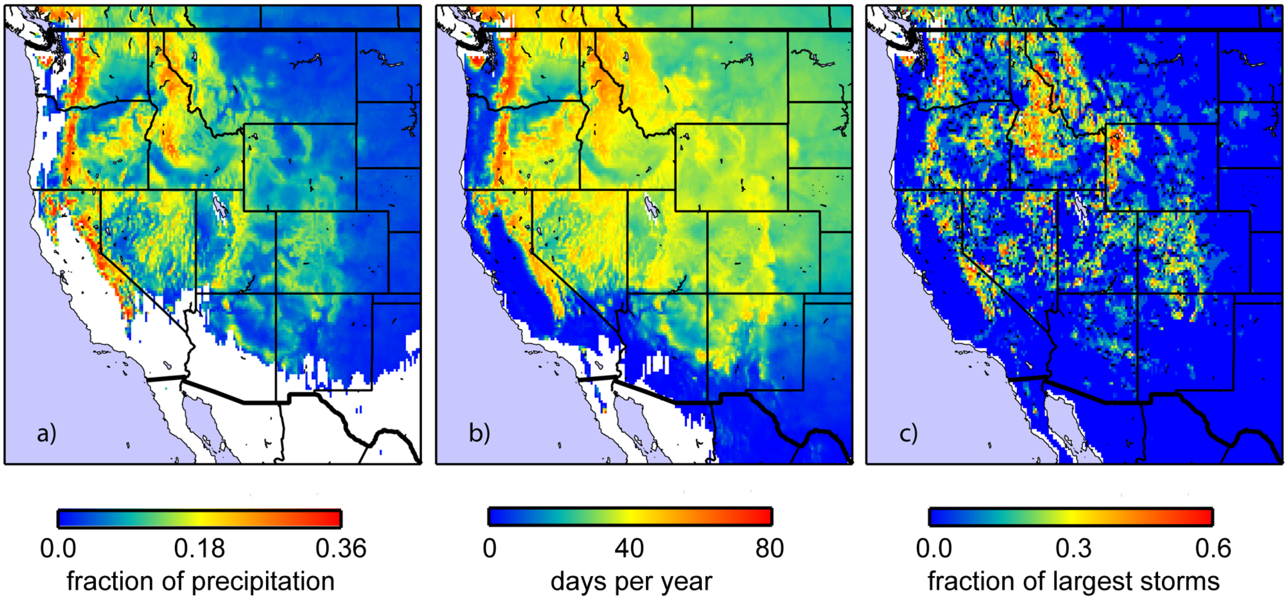

Figure 1. Illustration of the possible influence of a +3°C increase in average daily temperature on (a) snow versus rain, presented as the historical fraction of annual precipitation that fell in the temperature range −3°C to 0°C, (b) snow season length, presented as historical number of days per year with mean temperature in the −3°C to 0°C range, and (c) rain flood storms, presented as the fraction of 25 largest storms with temperatures in the −3°C to 0°C range [*Maurer et al.*, 2002].

large storms occur on days whose temperatures are between −3° and 0°C (Figure 1c), with the southern Sierra Nevada and northern Rocky Mountains being particularly vulnerable to changes in temperature and hence a greater chance that the largest storms will produce rain instead of snow.

[10] Further motivating the study of these processes is recent evidence that these energy fluxes respond to changes in the climate and landscape in unknown ways. For example, average temperature has increased in California over the past 50 years, and snow water equivalent (SWE) has decreased at lower elevations, especially at the more southern latitudes, with apparently no consistent trends at higher elevations [*Dozier*, 2004; *Howat and Tulaczyk*, 2005]. Recent studies have discovered that in the Rocky Mountains, desert dust deposition can increase absorption of solar radiation by as much as 50% during the ablation period [*Painter et al.*, 2005], suggesting that desiccation and land change that enhance dust emission could further affect snowmelt.

[11] Above timberline the spatial and temporal distribution of net solar radiation largely controls the timing and magnitude of snowmelt [*Marks and Dozier*, 1992], as Figure 2 illustrates for a typical high-elevation site when snow is present. In dense forests, longwave radiation represents the dominant energy source [*Link and Marks*, 1999] yet we usually lack the necessary observations to estimate the distribution of longwave radiation beneath the canopy. An understanding of these fluxes in the middle latitudes is critical for predicting hydrologic changes induced by natural and anthropogenic land cover alterations, as well as for predicting the fate of snow cover and associated soil moisture retreating to higher elevations as regional temperatures warm.

[12] Under warming scenarios, latent heat fluxes would potentially be altered by increased water vapor in the atmosphere associated with an intensification of the hydrologic cycle. The observed decrease in April 1 SWE at the lower elevations in the northwestern United States over the last 50 years [*Mote*, 2003; *Mote et al.*, 2005] possibly results from changes in precipitation phase (snow or rain) or warmer air temperatures enhancing radiative and turbulent fluxes, resulting in earlier snowmelt [*Hamlet et al.*, 2005]. Because soils and rocks lying within patchy snow cover can enhance turbulent and radiative fluxes, combined measures of fractional snow cover and energy exchange are necessary for understanding contributions to melt [*Dozier and Painter*, 2004]. Long-term observations of sensible and latent heat fluxes across gradients of elevation and latitude are needed for the identification of areas that are currently most sensitive to climate change.

[13] Therefore we recommend a spatially extensive, long-term investigation of the sensitivity of radiative fluxes and turbulent exchange to gradients of elevation, latitude, and vegetation density. Such an effort will require improving our distributed process modeling, extending the critically limited set of energy balance towers in mountains in the western United States (Figure 3) and coupling these with improvements in existing retrievals of snow albedo and longwave emission in heterogeneous terrain from remotely sensed data, mainly from the current NASA Moderate Resolution Imaging Spectroradiometers (MODIS) and the future Visible/Infrared Imager/Radiometer Suite (VIIRS) aboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS). Observations of canopy structures with airborne or future spaceborne LIDAR will help assess their relationship with radiative fluxes and snowmelt and the feedbacks associated with anthropogenic

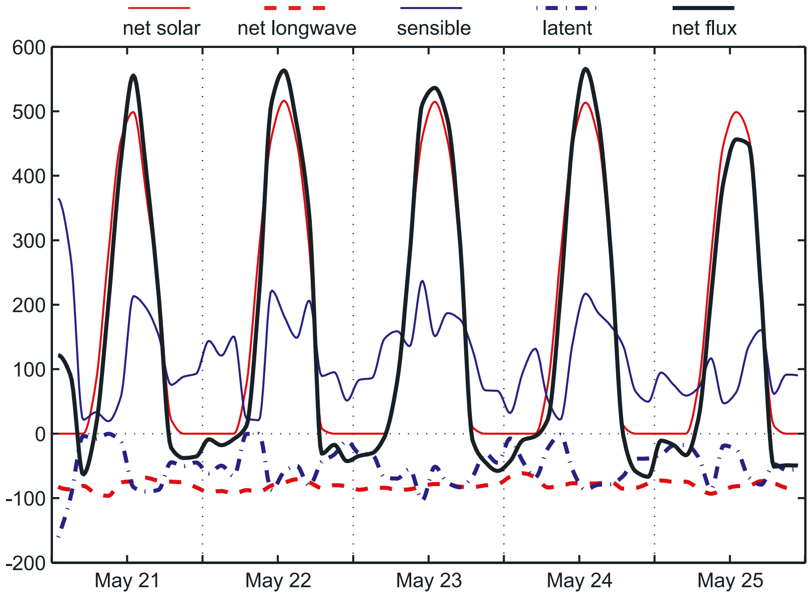

Figure 2. Energy balance components over alpine snow in the Senator Beck Basin, San Juan Mountains, Colorado, in spring 2005 during clear skies and emergence of dust layers from the snowpack.

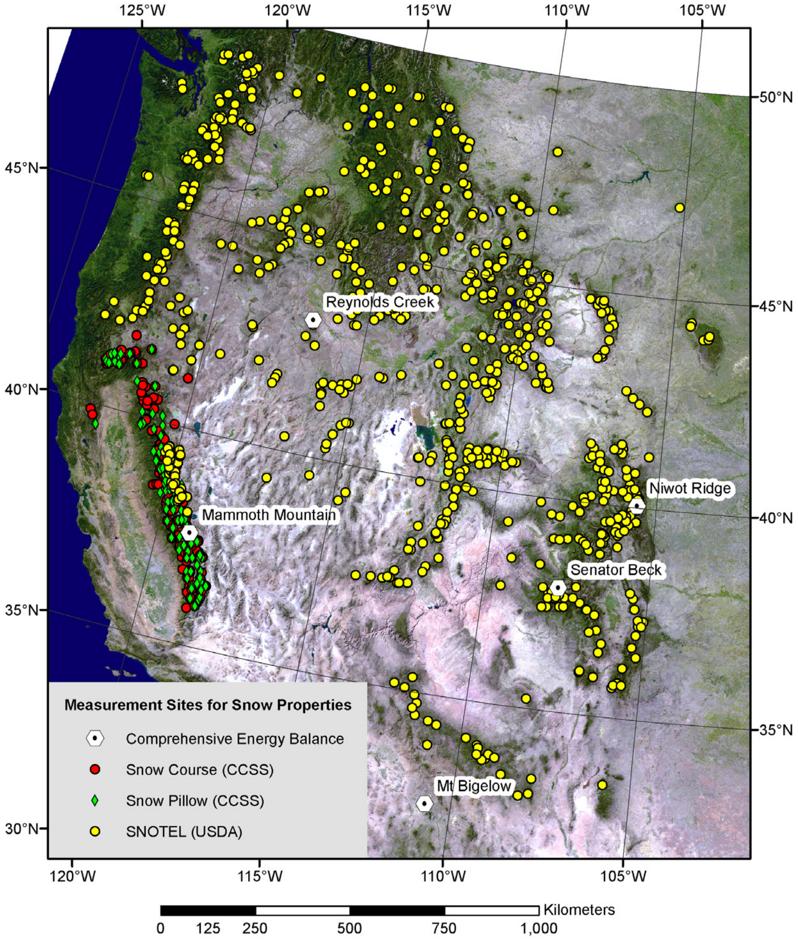

Figure 3. Composite MODIS image of the mountain west showing locations of long-term snowpack energy balance measurements, snow pillow and snow courses of the California Cooperative Snow Survey, and SNOTEL sites operated by the U.S. Department of Agriculture.

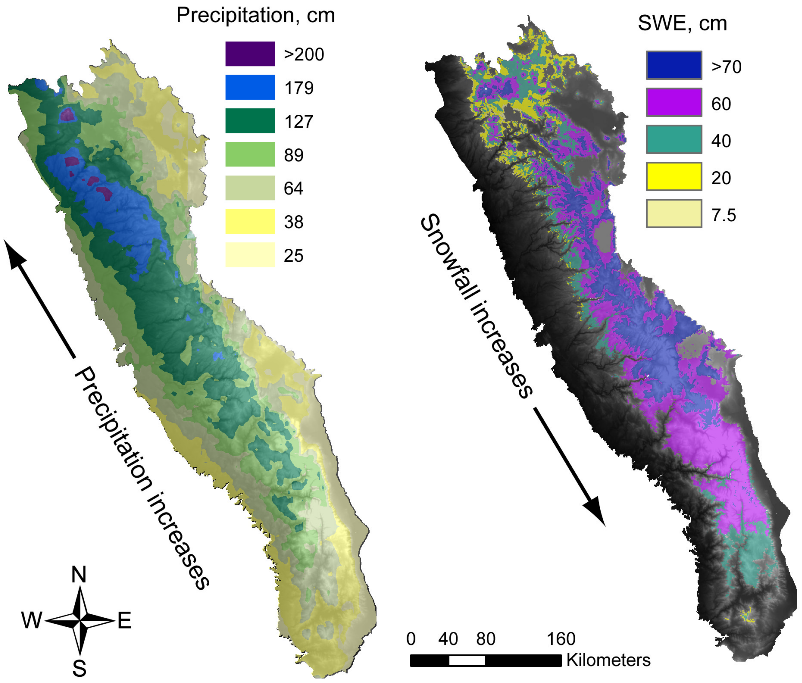

Figure 4. Annual average precipitation and snow water equivalent gradients related to latitude and elevation in the Sierra Nevada. Precipitation data from 1961 to 1990 and SWE data from 1951 to 2003 snow courses are interpolated by the method of *Fassnacht et al.* [2003].

and natural disturbance, including fire and its suppression, forest thinning, and logging.

2.2. Water Fluxes Into and out of the Mountain System

[14] The partitioning of precipitation and snowmelt into various hydrologic pathways (surface runoff, infiltration, potential recharge, and evapotranspiration) are particularly sensitive to climate variability. While groundwater recharge is an important component of the water balance, we focus our vision on fluxes occurring above the vadose zone, where climate variability has a direct influence on hydrologic processes. In particular, understanding the processes that control partitioning into the hydrologic pathways is critical for linking the energy fluxes to resultant water fluxes, and for assessing the links between hydrological, biogeochemical, and ecological functions and their sensitivity to climate change.

[15] Hydrologic processes, including partitioning, that are important at one scale may be less important at other scales. At the point scale, surface energy exchange, storage, and movement of meltwater within the snowpack dominate snowmelt and runoff. At coarser scales, lateral movements of water through soil, snow, and stream networks affect timing and amounts of runoff. At longer temporal scales, storage and routing integrate short-term variations in runoff caused by variations in melt rates. Models and inferences based on snowpack processes at the point scale allow point-scale processes to dominate when integrated to the basin scale. Each of the water fluxes through mountain systems needs to be measured and understood with the larger integrated scales as the ultimate targets.

2.2.1. Precipitation

[16] Direct measurements of precipitation in mountain environments are particularly challenging, because of the need to cover a large range of elevations and orographic positions. Moreover, much of the precipitation falls as snow, and precipitation gauges catch too little of the snowfall. Although it is possible to infer precipitation rates from snowpack observations, direct observations of precipitation are needed to explore changes in precipitation type associated with climate variability and change. Time-resolved observations of precipitation type and intensity, as well as the environmental conditions controlling them, are needed across latitudes, vegetation zones and climate regimes. We need to study elevation gradients in precipitation independently of latitudinal gradients. That is, rain-snow regimes vary along both gradients, giving different patterns of the ratio of snow to total precipitation. For example, annual precipitation in the Sierra Nevada decreases from north to south, but annual snow accumulation is greater in the higher elevations in the south (Figure 4). The elevation at which precipitation falls as snow varies from storm to storm and often varies during an individual storm. The elevation of this snow line can be critical when rain-on-snow events result in catastrophic floods and dramatically reduce snowpack water storage for spring and summer runoff.

2.2.2. Snow Distribution

[17] Research grade hydrologic and land surface models increasingly include mass balance and physically based snowmelt models [e.g., *Cline et al.*, 1998]. Improvements in the treatment of snowmelt as well as other model components depend on data. For snowmelt, data needs include spatially distributed components of the surface energy balance as well as snow properties (Figure 5).

[18] A pragmatic approach to estimating snow distribution is needed at resolutions that reduce subgrid heterogeneity to a level where most of the variability in the system can be modeled explicitly [*Blöschl*, 1999]. Ground obser-

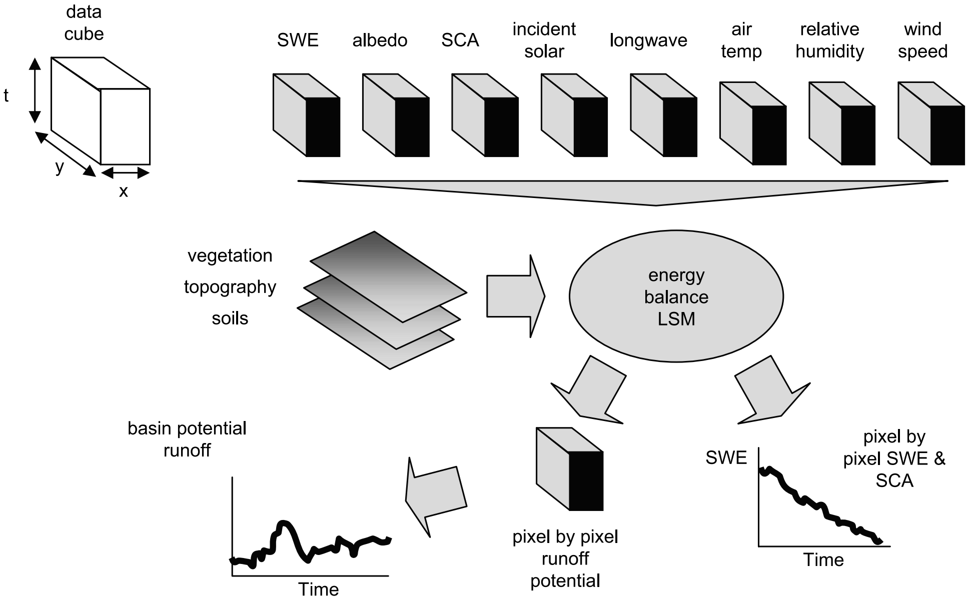

Figure 5. Energy balance modeling scheme for snowmelt. Because snowmelt is sensitive to the input variables and because these have considerable topographic and temporal variability, spatially distributed time series data are necessary for accurate, physically based snowmelt models.

vations of SWE have been used in conjunction with remotely sensed snow covered area data to estimate the spatial distribution of snow across mountainous water sheds [*Fassnacht et al.*, 2003]. However, such efforts do not yield representative measures of snow distribution across a basin owing to the nonrepresentative location of snow courses and snow pillows, which may give different values than the immediately surrounding terrain (Figure 6). Important challenges include systematic, accurate estimation of snow under clouds, canopy corrections for satellite snow covered area measurement, the design of adequate ground networks to merge with remotely sensed information, and the merging of energy balance and snow cover information to estimate the rate at which the snowmelts.

2.2.3. Evapotranspiration

[19] In many mountainous regions, the greatest flux of water out of the system is evapotranspiration [*Dressler et al.*, 2004]. We need to understand the physiographic controls on how vegetation responds to energy fluxes and water stress across a range of vegetation types and climate regimes. Some variables measurable by remote sensing (vegetation properties, surface temperature, and soil moisture) affect evapotranspiration, but integrating them into a method for estimating evapotranspiration at the regional scale has proven one of the most challenging problems in remote sensing [*Entekhabi*, 2005]. An effective method requires independent measurement of the evaporative fraction of a grid cell, the surface temperature, and soil moisture. Current methods of observing changes in soil moisture from passive microwave data [*Njoku et al.*, 2003] have a spatial resolution that is too coarse for use in the mountains. Moreover, a scarcity of ground-based observations of water vapor flux across vegetation transitions prevents the linkage of scales between point and remotely sensed observations. Observational clusters must be designed to characterize the continuum of evapotranspiration across the landscape.

2.2.4. Runoff

[20] Empirical seasonal runoff forecasts in snow-dominated systems, normally presented as outlooks for operational water supply, are based on historical relationships between point observations of snow and observed runoff. These empirical models perform best near mean conditions but poorly during conditions that are not well represented in the historical record. For improved hydrograph forecasts, which are critical for flood control, hydropower operation and resource management, the movement with the research community toward more physically based models with greater data needs is a strong driver for both process understanding and new observational networks [*Burges*, 1998].

3. Ecological and Biogeochemical Feedbacks

[21] Ecological and biogeochemical feedbacks play crucial but poorly understood roles in the function of mountain hydrologic systems. At the same time, fluxes of carbon and nitrogen in mountain systems are important to both the local and global biogeochemical cycles. For example, modeling suggests that in the western United States, net ecosystem exchange (NEE) is greatest in the mountains (Figure 7) and observations indicate that influxes of nitrogen and other pollutants are increasing. Most of the carbon exchange (60%) occurs between 700 m and 2000 m elevation, related to a combination of warmer temperatures than those at higher elevations and more water than at lower elevations [*Schimel et al.*, 2002; *Gordon et al.*, 2004]. However, very few data are available to evaluate fluxes at these and higher elevations, owing to there being few short- or long-term meteorological stations and almost no flux towers. Flux towers, the most widely used method for estimating net ecosystem exchange, are generally in flatter lowland areas because of access requirements and to ensure long, uniform fetches and land cover. There are snow pillows and snow

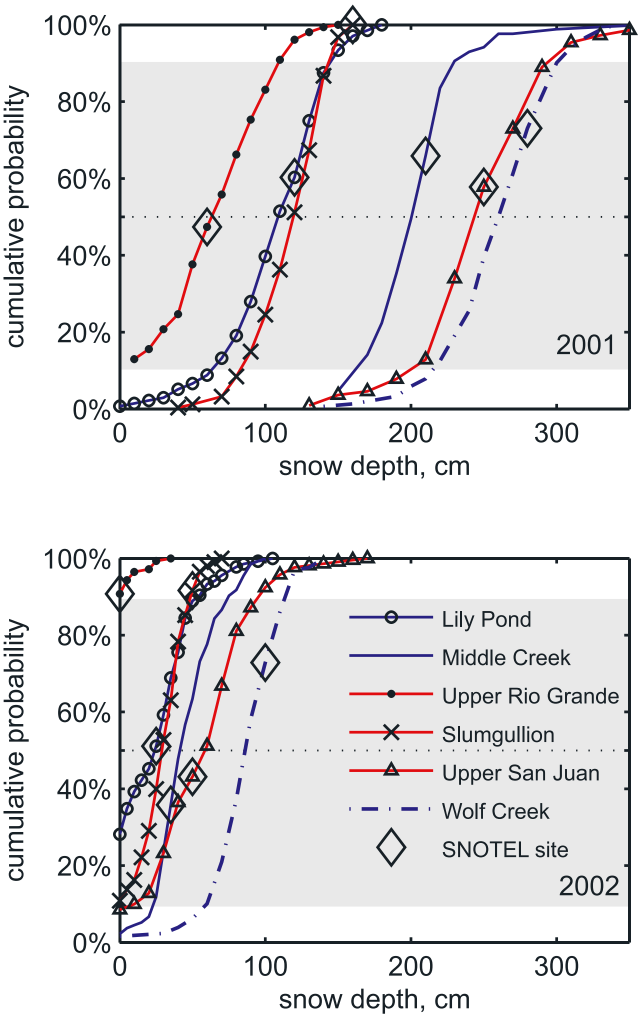

Figure 6. Statistical distribution of snow depth measurements made in (top) April 2001 and (bottom) April 2002 surrounding six SNOTEL sites in the Rio Grande headwaters [*Molotch and Bales*, 2005]. The dashed lines represent the median, and 80% of the observations occur within the shaded regions.

courses at the high elevations (Figure 3), but their locations on flat or gently sloping areas fail to capture the variability of snow accumulation and ablation in complex mountain topography. Our vision includes much more complete integration of biological processes and responses into our understanding and inferences about spatial and temporal hydrologic variations in the western mountains.

3.1. Ecosystem Response to Hydrologic Perturbations

[22] The variable frequency and magnitude of extreme events like droughts, flooding and severe storms, plus possible future shifts, will alter biogeochemical cycles and the responses of ecosystems. In addition, possible changes in seasonal precipitation patterns coupled with these hydrologic perturbations may alter the landscape as terrestrial and aquatic systems adapt or change. Expected upward movement of the snow line makes this zone particularly vulnerable.

[23] Improving climate models' predictive capabilities of hydrologic perturbations and the response of ecosystems to abrupt changes in the hydrologic cycle can only be accomplished by better parameterization and calibration of existing models, supported by new measurements and expanded knowledge of physical processes in mountain landscapes. Long-term observations of the hydrologic cycle are critical, including remote sensing of land processes, installation of flux towers for monitoring energy and mass exchange, and the development of additional paleoclimate and geochemical observations such as sediment cores from alpine lakes and reservoirs [*Melack et al.*, 1997]. Of importance is the ability to scale up from point measurements along transects to provide detailed observations on the spatial and temporal characteristics of the hydrologic cycle.

3.2. Hydrologic and Biogeochemical Response to Ecological Perturbations

[24] Major ecological issues remain unresolved when considering the impacts of climate, fire, land use, and vegetation changes on the water and biogeochemical cycles in meadows, streams, and forests of the mountainous west. Forest managers are evaluating how to best develop and maintain healthy forests, while still meeting legal constraints and public opinion. For example, greater carbon sequestration occurs as logged forests regrow, but logging can increase the release of CO_2 to the atmosphere [*Schimel et al.*, 2002]. Changes in the water cycles in forests will have important secondary effects on terrestrial and aquatic flora and fauna, and on the water resource serving downstream users. Forest studies indicate that the timing and volume of streamflow and recharge are altered with a decrease in forest canopy density [*Ffolliott et al.*, 1989]. Knowledge of postfire hydrology is critical, including the effect of fire on infiltration rates, erosion and water quality.

[25] Revegetation of forested areas that have burned depends on the availability of water, with nutrient limitations less important [*Clow et al.*, 2003]. Thus any changes in the terrestrial water cycle, particularly soil moisture, provide important feedback to planning and management of forest treatment. More widespread measurements of soil moisture, along with measurements of evapotranspiration, will help to further diagnose changes and responses of vegetation to hydrologic perturbations.

[26] Many meadows across the west are being restored. Fire in surrounding forested areas can have both beneficial and deleterious effects on meadows. For example, debris flows during postfire rain events can fill in eroded channels; they can also perturb sensitive ecosystems. Groundwater levels and soil moisture will be good indicators of water cycle perturbations in meadow settings. Water levels respond to surface water-groundwater interactions, and indicate an integrated meadow system response. Away from meadows in the forest, changes at ephemeral springs should be good indicators of basin- to range-scale water cycle change.

[27] The aquatic ecosystems of streams and lakes are perhaps the most sensitive to forest treatments, though there is evidence that some streams recover to near preburn conditions within a few years after a fire [*Clow et al.*, 2003]. Stream stage and discharge are the basic indicators of water yield, and integrate responses throughout a catchment. Temperature and electrical conductivity are simple yet good diagnostic measures of water quality, with nitrate concentration being a good indicator of nutrient response.

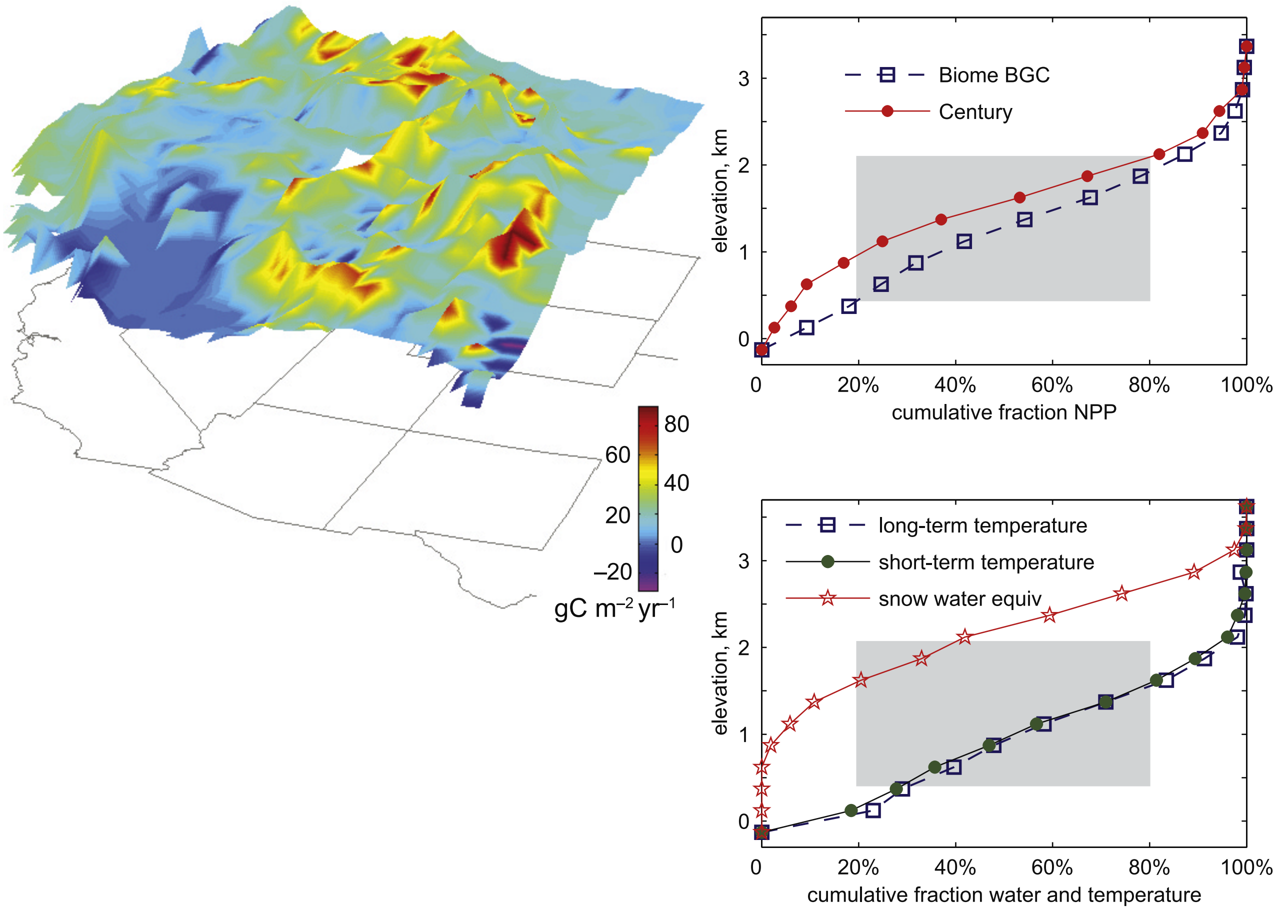

Figure 7. Two models (Century [*Parton et al.*, 1988] and Biome BGC [*Running and Hunt*, 1993]) showing that net ecosystem exchange (NEE) in the western United States is highest in the mountains. Most of the carbon exchange occurs between 700 and 2000 m elevation (shaded area in the graphs), related to a combination of warmer temperatures than those at higher elevations and more water than at lower elevations [adapted from *Schimel et al.*, 2002].

Physical and chemical measures alone may not suffice to characterize stream response. Benthic macroinvertebrates provide a simple yet potentially sensitive biological indicator that integrates several unmeasured physical/chemical changes.

3.3. Ecological Response to Biogeochemical Perturbations

[28] High-elevation ecosystems in the western United States have seen increases in the atmospheric deposition of nitrogen from the transport of nitrogen and carbon from lower to higher elevations resulting from fires [*Takemoto et al.*, 2001]. The alpine ecosystems' transition from nitrogen limited to saturated has changed water chemistry [*Baron and Campbell*, 1997]. With this evidence of increasing nitrogen influxes to the system, knowledge of the hydrological and biological processes controlling the fluxes of nitrogen through the system is relatively unknown. The cycling of nutrients into the system is strongly linked to the hydrologic cycle, creating a strong seasonality (e.g., wet to dry) to the influx of carbon. An earlier spring as the climate warms, as indicated by both models and observations [*Cayan et al.*, 2001], would result in changes to the biogeochemical cycle, with longer growing seasons, species shifts and creation of conditions favorable for invasive species.

[29] Recent studies indicate that nitrate concentrations are controlled by the seasonal snow cover and its effect on soil respiration, and suggest that climate perturbations may directly control the availability of nitrogen [*Brooks and Williams*, 1999; *Sickman et al.*, 2003; *Meixner et al.*, 2004]. Possible effects to the terrestrial ecosystem include longer growing seasons in alpine terrain, thus allowing and supporting higher rates of nitrogen retention as well as decreasing the aquatic export and redistribution of nutrients. As the temperatures warm, the coupling of the carbon, nitrogen, and hydrologic cycles is likely to be affected as the historical cold to warm seasonal transitions are replaced with seasonal transitions that are characterized more as wet to dry.

[30] Innovative measurements at the process level are needed to understand the biogeochemical evolution of snowmelt and surface waters in seasonally snow covered catchments and at the snow line. Research at the catchment scale in the last decade shows that our understanding of the biogeochemical processes that determine surface water quality in alpine basins is not sufficiently mature to model and predict responses of biogeochemical transformations

and surface water quality changes in response to climatic and anthropogenic changes in energy, water, and chemicals [*Sickman et al.*, 2003; *Meixner et al.*, 2004].

[31] Reliable long-term measurements are essential to examine and evaluate environmental changes and impacts to the system where residence times range from days to decades. By measuring residence times on a broad basis throughout several basins, geochemical compositions may be linked to the ages of the water. In addition, biogeochemistry can provide insight into events on short and long temporal scales. At the short temporal scale, carbon, nitrogen, phosphorous, and sulfur may be measured in fine resolution during short-lived, high-impact events (e.g., floods). Longer timescales can be addressed by paleolimnological investigation in low-elevation reservoirs and high-elevation lakes and coupled with tree ring studies that document fire frequency, drought, and flooding.

4. Integrated Measurement Strategies

[32] Independent ground-based observations have long supported operational water resource management, yet they leave much of the hydrologic cycle undersampled in space and time. Streamflow is accurately measured at the base of many basins and on some lower-order streams within mountain catchments, but many gauges are being taken out of service [*Maidment et al.*, 2004b] and most tributary streams have never been gauged. Soil moisture and evapotranspiration remain poorly and infrequently measured, and prototype network designs are lacking. Owing to complex topography and heterogeneous cover, research is clearly needed to develop hydrologic network designs that, together with advances in modeling and remote sensing, would better characterize the fluxes and reservoirs in the mountains, and provide necessary information on large-scale partitioning of snowmelt between runoff, infiltration, sublimation, and evapotranspiration. Such new integrated observations would enhance decision support systems by more densely sampling the range of changes and responses considered and by reducing prediction uncertainties.

[33] Transfer of knowledge of physical processes, rescaling climate model outputs, and validating remotely sensed data are subject to greater uncertainty in mountainous regions because of greater subgrid heterogeneity. Advances in ground observations have not matched those in remote sensing and modeling, and few ground observation networks in mountainous regions have been implemented with an integrative water balance focus. As discussed above, our vision of a comprehensive understanding of energy and water fluxes (section 2) and ecological and biogeochemical feedbacks (section 3) in western mountains necessarily requires carefully planned integrated measurement strategies and systems.

4.1. Energy Fluxes

[34] Figure 3 demonstrates that we have essentially ignored the long-term measurement of the radiative fluxes and turbulent fluxes in mountain regions. Only a handful of sites in the western United States measure snow albedo with coupled incident and reflected broadband pyranometers, and only one watershed, Reynolds Creek in Idaho, has several long-term measurement sites that cover a range of elevations in the basin [*Marks et al.*, 2001]. Possible anthropogenic effects on snow albedo include synoptic scale warming that coarsens grain size and deposition of light-absorbing impurities such as dust and soot [*Hansen and Nazarenko*, 2004; *Painter et al.*, 2005]. Efforts to measure other components of the energy balance (sensible and latent heat exchange)are equally sparse. We believe the most cost-effective approach to improving knowledge is to make detailed energy balance estimates at strategically placed instrument clusters along gradients of latitude and elevation, linked with satellite and existing operational data.

4.2. Precipitation

[35] The spatial distribution of precipitation in mountainous terrain is nearly impossible to measure at the resolution of basin-scale hydrologic models (e.g., ~1 km). The primary resources available to estimate these patterns are several existing, overlapping networks, including NWS cooperative stations, USDA SNOTEL (Snowpack Telemetry) stations, and some smaller networks. Most of these stations lack the capacity to differentiate snow from rain. The National Weather Service installed the Next Generation Weather Radar system (NEXRAD) in 1994 to improve operational measurements of precipitation around the country. However, NEXRAD signals are occluded by mountains and thus are less reliable in the complex terrain where snowfall occurs. Traditional precipitation gauges catch too little snow and cannot discriminate solid from liquid precipitation, and the measurement typically registers when the snow caught by the gauge melts, not necessarily when it falls, causing a temporal lag. Both heated plate [*Lundberg and Halldin*, 2001] and optical sensors [*Löffler-Mang and Joss*, 2000] have been developed to estimate snowfall more accurately, but challenges in deploying them in remote locations away from reliable power sources restrict their use in mountains.

[36] Techniques to estimate precipitation using a combination of ground-based and remotely sensed observations are being developed, albeit still at coarse resolutions and with poor abilities to distinguish rain from snow. A key research question remains: Can a coupled satellite and ground-based precipitation estimation system be designed to meet the requirements for hydrologic applications in mountain regions?

4.3. Snow Properties

[37] Several sources of seasonal snow cover data exist, ranging from information collected as part of weather monitoring to sites dedicated to snow data collection, and more recently to remotely sensed products from polar orbiting and geostationary satellites. The research value of these time series data mandates their inclusion in future snow data archives. However, none of these data sets effectively sample the topographic variability of snow properties.

[38] Satellite remote sensing is the only practical way to measure the spatial extent and variability of snow cover and albedo, and, during the past decade, methods for mapping snow covered area from visible and infrared instruments on satellites have become well developed [*König et al.*, 2001; *Dozier and Painter*, 2004]. Snow covered area in alpine terrain often varies at a spatial scale finer than that of the ground instantaneous field of view of the remote sensing instrument. This spatial heterogeneity poses a ‘‘mixed

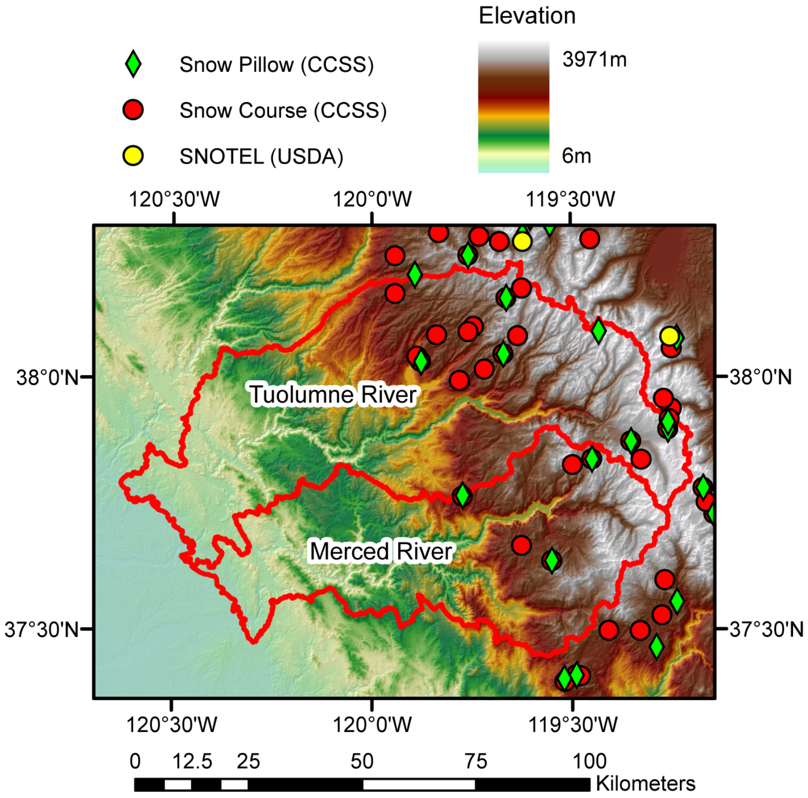

Figure 8. A subset of Figure 3 showing the snow courses and snow pillow in the Tuolumne and Merced river basins of the Sierra Nevada, along with elevations. The higher elevations are poorly represented by the sensors.

pixel" problem in that the sensor may simultaneously receive radiance reflected from snow, rock, soil, and vegetation. To use the snow characteristics in distributed physical models, we must therefore map snow covered area at subpixel resolution in order to accurately represent its spatial distribution. Otherwise, systematic errors may result. While overestimates may balance underestimates for the basin average, distributed hydrologic applications in mountainous regions require the spatial distribution of snow cover. As mentioned in section 2, significant improvements are needed in remote sensing of the spatial distribution of snow albedo in alpine and relatively sparse vegetation canopies where the net shortwave flux is still a significant component of the energy balance.

[39] Snow water equivalent is measured at over 1,700 points in the western United States, from a combination of manual snow surveys and transmitting snow pillows (Figure 3). While these many samples provide regional knowledge of the spatial distribution of snow, they are insufficient to resolve the variability of SWE at the basin scale (Figure 8). Most snow courses and automated stations are situated below timberline on flat or nearly flat terrain, and are preferentially placed high enough that they stay covered with snow most winters (to justify the expenditures), leaving us largely blind to elevations where snow is more ephemeral. The existing snow measurements are used as indices of streamflow, rather than direct measurements of basin-scale snow volumes. The locations were chosen to be characterized by homogenous snow cover and snowpack conditions specific to that elevation in that basin. In years of heavy snowfall, the lack of sampling of alpine snow manifests itself as a significant underestimate of late spring runoff. Therefore the distribution of snow courses and automated stations undersamples the low-altitude ephemeral cover and the high-altitude persistent cover, and inadequately samples the middle elevations for basin distributions.

[40] We recommend extending the network of in situ SWE sampling for more spatially dense sampling with strategic deployment in targeted basins that may be leveraged for high-resolution distributions through spatial modeling and remotely sensed products. Basin-scale prototypes that examine how snow depth and density vary with terrain are critically needed. There is a pressing research need to develop strategies to blend remotely sensed and ground-based data, including measurement network design, to accurately estimate SWE. Maps such as those produced by the NWS National Operational Hydrologic Remote Sensing Center [*Carroll et al.*, 2001] come from a spatially distributed energy and mass balance model forced with precipitation, snow telemetry, and snow course measurements coupled with coarse-scale remote sensing of snow cover. Yet the location and paucity of these sites necessarily provides poor information on model performance.

[41] Multifrequency/multipolarization radar has promise for mapping SWE globally at adequate resolutions for basin-scale hydrology [*Shi and Dozier*, 2000a, 2000b], but progress in instrumentation and algorithm development has been slow. As radar retrievals of SWE advance, they will be integrated into the spatial interpolation schemes developed around the in situ network; simultaneously, new additions to

the network should be located to best fill gaps in radar retrievals. However, for the foreseeable future, we have no operational radar satellites with sufficient spectral and polarization capabilities to infer snow water equivalent in the mountains.

[42] A ground-based observational network remains an important component of the snow observing system that will not be replaced by the satellite system because of inherent uncertainties in retrievals. Satellite-based snow cover/depth observations might cover the future needs of some users of snow data, but economics and scientific objectives now require a merging of all available snow information in an enhanced data set. Judicious and strategic extensification of in situ measurements to lower- and higher-elevation sites coupled with advancements in remote sensing acquisitions will provide the means to a long-term, high-resolution monitoring of snow water equivalent.

4.4. Soil Moisture

[43] Soil moisture is measured at some RAWS and SNOTEL sites, but these generally do not lie in alpine settings. As in the case of SWE, passive microwave retrievals of soil moisture are too coarse for the spatial variability and rugged terrain in mountain regions. Radar retrievals of soil moisture are in research mode now but again the lack of an operational radar satellite presents a significant obstacle to the implementation of these retrievals [*Zehe and Blöschl*, 2004]. Moreover, rugged terrain and vegetation cover can confound retrievals. While the technical difficulties are great, definition of the spatial variability of soil moisture is critical in modeling hydrologic response in mountain catchments. Therefore we strongly recommend extension of the network of soil moisture samples for more spatially dense sampling covering a range of altitudes and a multiyear field campaign to address soil moisture in rugged terrain. As radar retrievals of soil moisture advance, they should be integrated into the spatial interpolation schemes developed around the in situ network. As with SWE, proper network design for soil moisture measurement remains a critical research issue.

4.5. Discharge

[44] Stage and discharge measurements in streams and springs integrate catchment response to upstream fluxes and remain the firmest component in most water balance estimates. While expansion of accurate gauging, such as that provided by the USGS network, power companies, various other agencies and long-term research sites, provides clear benefits to the research and operations communities, lower-cost and lower-impact stream stage sensors that use pressure transducers also can provide valuable information to augment traditional networks, particularly in a basin's lower-order streams.

[45] Standard discharge measurement gauges can be difficult and logistically expensive to establish and maintain in remote and seasonally inaccessible watersheds. For some investigations, inexpensive, self-logging stage recorders provide significant insights into locations, timing, and relative contributions of key watershed events, even though they do not quantify discharge. Thus far greater spatial coverage can be obtained using the stage recorders, to augment and inform interpretations of the quantitative and detailed discharge information from standard discharge measurement networks [*Lundquist et al.*, 2005]. Being considerably more economical, they allow a greater presence to be established in high-altitude watersheds at realistic funding levels.

[46] Thus a mixed strategy combining minor extensions of accurate discharge gauging on major tributaries and some headwater streams, with considerable extension of lower-cost stage measurements on more numerous ungauged catchments should be pursued to serve multiple communities and interests.

4.6. Evapotranspiration

[47] Remote sensing of the spatial distribution of evapotranspiration is one of the outstanding problems in hydrology, not just in mountainous areas. Flux towers remain the method of choice for accurately estimating land surface-atmosphere exchange at a point. Strategies for extending estimates across mountain ranges, with their strong gradients of precipitation and temperature, mixes of vegetation types, and varying management practices, combine transects of flux towers with remotely sensed data on vegetation water content and soil moisture, along with surface energy balance models designed to use remotely sensed parameters [*Ogunjemiyo et al.*, 2002; *Margulis and Entekhabi*, 2003].

4.7. Biogeochemistry

[48] Biogeochemical research begins first and foremost with information about water balances and flow paths and residence times. Research in hillslope hydrology in selected systems needs expansion in spatial extent and across spatial scales [*Meixner and Bales*, 2003; *Meixner et al.*, 2004]. Biogeochemical measurements need to be integrated into water balance instrument clusters and opportunities for automatic, remote measurements expanded. At a minimum, electrical conductivity measurements should be colocated with those for stream stage, with other measurements added as opportunities arise. Still, there is much to be learned from discrete sampling, particularly focusing on isotopic tracers integrated with nutrients and other solutes.

4.8. Data and Information Systems

[49] Current computing environments, investigator-specific research practices, and agency data distributions are too disjoint to facilitate system/data integration. Typically, these systems use ad hoc scripts to perform the required processing and idiosyncratic naming conventions for the files that hold the products. Data extraction from a variety of systems is therefore time-consuming and subject to error proliferation, especially when assembling a synoptic view or parsing the data according to a suite of criteria (e.g., data from all snow courses above some particular elevation in a particular basin with more than some threshold length of record). Our current modes of analysis usually require reorganization of data and creation or rediscovery of metadata values for each product. Dissemination, especially where custom processing such as subsetting, reprojection, or reformatting is required, is often treated in a similarly ad hoc fashion. Even the Distributed Active Archive Centers (DAACs) of the NASA EOSDIS implement colloquial data processing codes that are largely incompatible. The technologies to solve most of these problems are at hand already, but implementation will require a concerted collective commitment by users and providers.

[50] Cyber infrastructure advances can overcome these problems by making data and information available in ways that are convenient for users. That does not necessarily mean that data are made available to users in the same way that they access data now. Rather, technologic advances that are tailored to be responsive to community needs can both make users more cyber savvy and information more accessible. For example, community based development of the basic structures for a digital library and digital watershed [*Maidment et al.*, 2004a] offer much promise. The digital watershed represents a powerful tool to assist in analysis and modeling of hydrologic data. Advances in the infrastructure for both digital libraries and digital watersheds are critical to the success of future hydrologic science observation strategies.

5. Concluding Thoughts

[51] The economic value of and societal demand for new knowledge and tools for mountain hydrology is very large. Public agencies, private companies, watershed councils, and other nongovernmental organizations, and a myriad of other stakeholders need and want new information with which to make water-sensitive decisions. Climate change, the high degree of climate variability, population growth, and land cover change experienced in the west are important drivers of this demand for new and expanded knowledge.

[52] Advances will require sustained investments in new measurements and infrastructure to enable the research described above. The proposed NSF-supported hydrologic observatories will be an important component of this investment, but the need is broader. Adequate data and information systems to support research are a necessary complement to the research and infrastructure, as are satellite systems designed to examine specific components of the hydrologic cycle.

[53] We envision approaches to monitoring and understanding the hydrology of western mountains that is as energy and water centric, and that explicitly addresses and incorporates ecological and biogeochemical feedbacks. The approach recognizes that measurements and models at one scale will not often be germane at others; our vision is of amalgamated on-site monitoring, remote sensing, and modeling, all designed, prioritized, and implemented with basin-scale water balance processes at their primary focuses. Our current ability to quantitatively estimate water and chemical fluxes and reservoirs in mountains is inadequate. While there are numerous accurate streamflow measurements, many rivers are ungauged except for far from where the key processes are at work, or have only short records. Precipitation and snowpack are measured relatively accurately at points, but the accuracy of range-scale estimates is unknown. One of the more sensitive indicators of water cycle change, soil moisture, has rarely been monitored in mountain settings. There are also large knowledge gaps in other components of the water cycle, biogeochemical fluxes, and ecological linkages.

[54] Historical monitoring of watershed processes, beyond the basic measurements of river discharge and snow water equivalent, in the seasonally snow covered mountains has too often been project driven or too narrowly tuned to an agency's needs. The most pressing requirement is for much more communication, site-to-site synthesis, and network integration across mountain ranges and regions of their runoff, if the science is to move forward.

[55] Measurement strategies for mountain systems will rely heavily on satellite remote sensing coupled with in situ measurements. In most cases the needed complementary ground-based systems are not adequate to fill the temporal and spatial gaps and integrative uncertainty of remotely sensed products. Thus network design encompassing all of the modern options for improved hydrologic monitoring and study of the mountains is itself a research need.

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References

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*, 303–309, doi:10.1038/nature04141.

Baron, J. S., and D. H. Campbell (1997), Nitrogen fluxes in a high elevation Rocky Mountain basin, *Hydrol. Processes*, *11*(7), 783–799, doi:10.1002/(SICI)1099-1085(199706)11:7<783::AID-HYP519>3.0.CO;2-U.

Blöschl, G. (1999), Scaling issues in snow hydrology, *Hydrol. Processes*, *13*(14–15), 2149–2175, doi:10.1002/(SICI)1099-1085(199910)13:14/15<2149::AID-HYP847>3.0.CO;2-8.

Brooks, P. D., and M. W. Williams (1999), Snowpack controls on nitrogen cycling and export in seasonally snow-covered catchments, *Hydrol. Processes*, *13*(14–15), 2177–2190, doi:10.1002/(SICI)1099-1085(199910)13:14/15<2177::AID-HYP850>3.0.CO;2-V.

Burges, S. J. (1998), Streamflow prediction: Capabilities, opportunities, and challenges, in *Hydrologic Sciences: Taking Stock and Looking Ahead*, pp. 101–134, Natl. Acad. Press, Washington, D. C.

California Regional Assessment Group (2002), *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change—California*, 432 pp., U.S. Global Change Res. Program, Washington, D. C.

Carroll, T., D. Cline, G. Fall, A. Nilsson, L. Li, and A. Rost (2001), NOHRSC operations and the simulation of snow cover properties for the coterminous U.S., *Proc. West. Snow Conf.*, *69*, 1–14.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001), Changes in the onset of spring in the western United States, *Bull. Am. Meteorol. Soc.*, *82*(3), 399–415.

Cline, D. W., R. C. Bales, and J. Dozier (1998), Estimating the spatial distribution of snow in mountain basins using remote sensing and energy balance modeling, *Water Resour. Res.*, *34*(5), 1275–1285.

Clow, D. W., J. O. Sickman, R. G. Striegl, D. P. Krabbenhoft, J. G. Elliott, M. Dornblaser, D. A. Roth, and D. H. Campbell (2003), Changes in the chemistry of lakes and precipitation in high-elevation national parks in the western United States, 1985–1999, *Water Resour. Res.*, *39*(6), 1171, doi:10.1029/2002WR001533.

Dozier, J. (2004), The Sierra Nevada snowpack: Do the snow course data show historical trends?, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract C31A-0275.

Dozier, J., and T. H. Painter (2004), Multispectral and hyperspectral remote sensing of alpine snow properties, *Annu. Rev. Earth Planet. Sci.*, *32*, 465–494, doi:10.1146/annurev.earth.32.101802.120404.

Dressler, K. A., G. Leavesley, R. C. Bales, and S. Fassnacht (2004), Streamflow estimation from hydrologic model assimilation of remotely sensed snow information in snowmelt dominated basins, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract C31A-0288.

Entekhabi, D. (2005), Estimation of land surface latent heat flux and its determinants based on remotely sensed measurements, *Eos Trans. AGU*, *86*(52), Fall Meet. Suppl., Abstract H14B-01.

Fassnacht, S. R., K. A. Dressler, and R. C. Bales (2003), Snow water equivalent interpolation for the Colorado River Basin from snow telemetry (SNOTEL) data, *Water Resour. Res.*, *39*(8), 1208, doi:10.1029/2002WR001512.

Ffolliott, P. F., G. J. Gottfried, and M. B. Baker (1989), Water yield from forest snowpack management: Research findings in Arizona and New Mexico, *Water Resour. Res.*, *25*(9), 1999–2007.

Gordon, W. S., J. S. Famiglietti, N. L. Fowler, T. G. F. Kittel, and K. A. Hibbard (2004), Validation of simulated runoff from six terrestrial ecosystem models: Results from VEMAP, *Ecol. Appl.*, *14*(2), 527–545.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier (2005), Effects of temperature and precipitation variability on snowpack trends in the western United States, *J. Clim.*, *18*(21), 4545–4561, doi:10.1175/JCLI3538.1.

Hansen, J., and L. Nazarenko (2004), Soot climate forcing via snow and ice albedos, *Proc. Natl. Acad. Sci. U. S. A.*, *101*(2), 423–428, doi:10.1073/pnas.2237157100.

Howat, I. M., and S. Tulaczyk (2005), Climate sensitivity of spring snowpack in the Sierra Nevada, *J. Geophys. Res.*, *110*, F04021, doi:10.1029/2005JF000356.

König, M., J.-G. Winther, and E. Isaksson (2001), Measuring snow and glacier ice properties from satellite, *Rev. Geophys.*, *39*(1), 1–28.

Link, T. E., and D. Marks (1999), Point simulation of seasonal snow cover dynamics beneath boreal forest canopies, *J. Geophys. Res.*, *104*(D22), 27,841–27,858.

Löffler-Mang, M., and J. Joss (2000), An optical disdrometer for measuring size and velocity of hydrometeors, *J. Atmos. Oceanic Technol.*, *17*(2), 130–139, doi:10.1175/1520-0426(2000)017<0130:AODFMS>2.0.CO;2.

Lundberg, A., and S. Halldin (2001), Snow measurement techniques for land-surface-atmosphere exchange studies in boreal landscapes, *Theor. Appl. Climatol.*, *70*(1–4), 215–230, doi:10.1007/s007040170016.

Lundquist, J. D., M. D. Dettinger, and D. R. Cayan (2005), Snow-fed streamflow timing at different basin scales: Case study of the Tuolumne River above Hetch Hetchy, Yosemite, California, *Water Resour. Res.*, *41*, W07005, doi:10.1029/2004WR003933.

Maidment, D. R., J. Helly, P. Kumar, M. Piasecki, and R. Hooper (2004a), CUAHSI hydrologic information system, *Eos Trans. AGU*, *85*(45), Fall Meet. Suppl., Abstract SF11A-01.

Maidment, D. R., et al. (2004b), *Assessing the National Streamflow Information Program*, 164 pp., Natl. Acad. Press, Washington, D. C.

Margulis, S. A., and D. Entekhabi (2003), Variational assimilation of radiometric surface temperature and reference-level micrometeorology into a model of the atmospheric boundary layer and land surface, *Mon. Weather Rev.*, *131*(7), 1272–1288, doi:10.1175/1520-0493(2003)131<1272:VAORST>2.0.CO;2.

Marks, D., and J. Dozier (1992), Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance, *Water Resour. Res.*, *28*(11), 3043–3054.

Marks, D., K. R. Cooley, D. C. Robertson, and A. Winstral (2001), Long-term snow database, Reynolds Creek Experimental Watershed, Idaho, United States, *Water Resour. Res.*, *37*(11), 2835–2838.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States, *J. Clim.*, *15*(22), 3237–3251, doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2.

Meixner, T., and R. C. Bales (2003), Hydrochemical modeling of coupled C and N cycling in high-elevation catchments: Importance of snow cover, *Biogeochemistry*, *62*(3), 289–308, doi:10.1023/A:1021118922787.

Meixner, T., C. Gutmann, R. Bales, A. Leydecker, J. Sickman, J. Melack, and J. McConnell (2004), Multidecadal hydrochemical response of a Sierra Nevada watershed: Sensitivity to weathering rate and changes in deposition, *J. Hydrol.*, *285*(1–4), 272–285, doi:10.1016/j.jhydrol.2003.09.005.

Melack, J. M., J. Dozier, C. R. Goldman, D. Greenland, A. M. Milner, and R. J. Naiman (1997), Effects of climate change on inland waters of the Pacific Coastal Mountains and Western Great Basin of North America, *Hydrol. Processes*, *11*(8), 971–992, doi:10.1002/(SICI)1099-1085(19970630)11:8<971::AID-HYP514>3.0.CO;2-Y.

Molotch, N. P., and R. C. Bales (2005), Scaling snow observations from the point to the grid element: Implications for observation network design, *Water Resour. Res.*, *41*, W11421, doi:10.1029/2005WR004229.

Mote, P. W. (2003), Trends in snow water equivalent in the Pacific Northwest and their climatic causes, *Geophys. Res. Lett.*, *30*(12), 1601, doi:10.1029/2003GL017258.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier (2005), Declining mountain snowpack in western North America, *Bull. Am. Meteorol. Soc.*, *86*(1), 39–49, doi:10.1175/BAMS-86-1-39.

Njoku, E. G., T. J. Jackson, V. Lakshmi, T. K. Chan, and S. V. Nghiem (2003), Soil moisture retrieval from AMSR-E, *IEEE Trans. Geosci. Remote Sens.*, *41*(2), 215–229, doi:10.1109/TGRS.2002.808243.

Ogunjemiyo, S., D. A. Roberts, K. Keightley, S. L. Ustin, T. Hinckley, and B. Lamb (2002), Evaluating the relationship between AVIRIS water vapor and poplar plantation evapotranspiration, *J. Geophys. Res.*, *107*(D23), 4719, doi:10.1029/2001JD001194.

Painter, T. H., A. P. Barrett, C. Landry, and J. C. Neff (2005), Radiative effects of desert dust deposits to alpine snow, *Eos Trans. AGU*, *86*(52), Fall Meet. Suppl., Abstract B34B-05.

Parton, W. J., J. W. B. Stewart, and C. V. Cole (1988), Dynamics of C, N, P and S in grassland soils: A model, *Biogeochemistry*, *5*, 109–131.

Running, S. W., and E. R. Hunt (1993), Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models, in *Scaling Physiological Processes: Leaf to Globe*, edited by J. R. Ehleringer and C. B. Field, pp. 141–158, Elsevier, New York.

Schimel, D. S., T. G. F. Kittel, S. Running, R. Monson, A. Turnipseed, and D. Anderson (2002), Carbon sequestration studied in western U.S. mountains, *Eos Trans. AGU*, *83*(40), 445, 449.

Shi, J., and J. Dozier (2000a), Estimation of snow water equivalence using SIR-C/X-SAR, part I: Inferring snow density and subsurface properties, *IEEE Trans. Geosci. Remote Sens.*, *38*(6), 2465–2474, doi:10.1109/36.885195.

Shi, J., and J. Dozier (2000b), Estimation of snow water equivalence using SIR-C/X-SAR, part II: Inferring snow depth and grain size, *IEEE Trans. Geosci. Remote Sens.*, *38*(6), 2475–2488, doi:10.1109/36.885196.

Sickman, J. O., A. Leydecker, C. C. Y. Chang, C. Kendall, J. M. Melack, D. M. Lucero, and J. Schimel (2003), Mechanisms underlying export of N from high-elevation catchments during seasonal transition, *Biogeochemistry*, *64*(1), 1–24, doi:10.1023/A:1024928317057.

Takemoto, B. K., A. Bytnerowicz, and M. E. Fenn (2001), Current and future effects of ozone and atmospheric nitrogen deposition on California's mixed conifer forests, *For. Ecol. Manage.*, *144*(1–3), 159–173, doi:10.1016/S0378-1127(00)00368-6.

Zehe, E., and G. Blöschl (2004), Predictability of hydrologic response at the plot and catchment scales: Role of initial conditions, *Water Resour. Res.*, *40*, W10202, doi:10.1029/2003WR002869.

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