Meteorology and Hydrology in Yosemite National Park: A Sensor Network Application

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Abstract. Over half of California's water supply comes from high elevations in the snowmelt-dominated Sierra Nevada. Natural climate fluctuations, global warming, and the growing needs of water consumers demand intelligent management of this water resource. This requires a comprehensive monitoring system across and within the Sierra Nevada. Unfortunately, because of severe terrain and limited access, few measurements exist. Thus, meteorological and hydrologic processes are not well understood at high altitudes. However, new sensor and wireless communication technologies are beginning to provide sensor packages designed for low maintenance operation, low power consumption and unobtrusive footprints. A prototype network of meteorological and hydrological sensors has been deployed in Yosemite National Park, traversing elevation zones from 1,200 to 3,700 m. Communication techniques must be tailored to suit each location, resulting in a hybrid network of radio, cell-phone, land-line, and satellite transmissions. Results are showing how, in some years, snowmelt may occur quite uniformly over the Sierra, while in others it varies with elevation.

1 Introduction

California's water resources depend vitally upon runoff from its high elevations, particularly the snowmelt-dominated Sierra Nevada. In addition to providing over half of the state's water supply, rivers and river basins in the Sierra Nevada carry sediment, nutrients and pollutants and act as vital arteries in the regional airshed. Climate variability in the region is high, and annual precipitation and runoff fluctuate from under 50% to over 200% of climatological averages. In recent decades, streamflow records from watersheds in western North America, collected at relatively low elevation gages, suggest that an alarming change toward earlier snowmelt and snowmelt runoff has been occurring (Cayan et al 2001, Stewart et al 2002, Dettinger and Cayan 1995). Whether this reflects a natural climate variation or an early symptom of anthropogenic climate warming is not known. In the long run, it is estimated that, in response to projected global warming of 3 degrees C, the spring-summer snowmelt would be diminished by one third to one half (Roos 1987). Additionally, virtually all modern climate models suggest there will be higher annual

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evaporative demands as climate warming develops, and some models have predicted substantial changes in the State's precipitation. However, the data necessary to detect and understand these changes, and provide ground truth for numerical models is sparse, to the point that many of the variations and processes involved are ill-known and can only be inferred.

Much of the problem arises from our historic monitoring system. Currently, most meteorological observations are collected near highly populated, low elevation regions (Figure 1), while many of the important hydrologic processes occur in unpopulated wilderness areas, often in rugged terrain and high elevations. For example, snowmelt processes are spatially complex and thus difficult to forecast and incorporate in large-scale hydrologic and atmospheric models. Much of the difficulty arises because snow occurs in patches of nonuniform depth and density, particularly in mountainous regions. In situ measurements of the snowpack are both difficult to make and not necessarily representative of region-wide characteristics. Satellite images and geographical information systems have increased spatial coverage, but this data, which is often infrequent in time, is still difficult to relate to the actual river discharge originating from a basin. Apparently simple characteristics, such as the distribution and timing of snow accumulation, snowmelt, and runoff into rivers with elevation, are not routinely quantified.

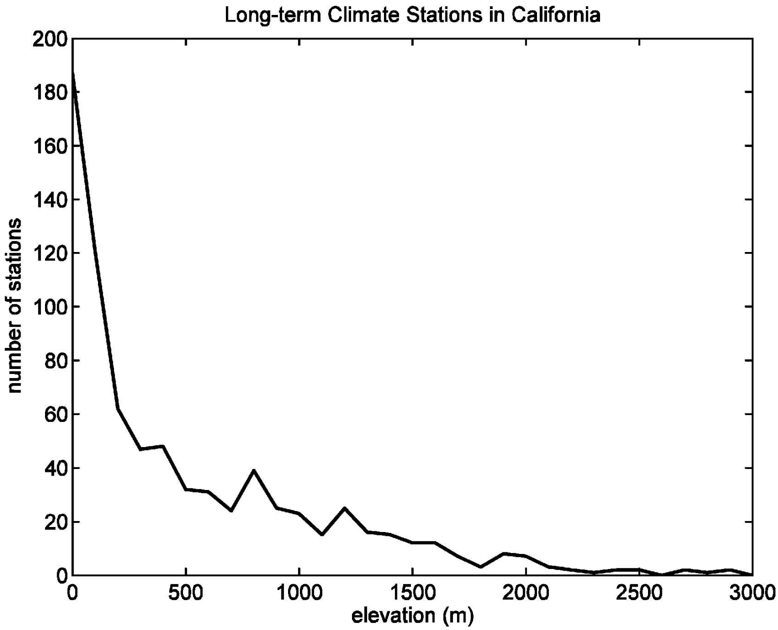

Fig. 1. Number of long-term climate stations in each 100 m elevation band in California. Only two stations, operated by the White Mountain Research Center, exist above 3000 m

Data collection in high elevation wilderness areas historically has been difficult and expensive because of the extra costs and logistics required to visit snowy sites and preserve their undisturbed character. Many such regions are designated as

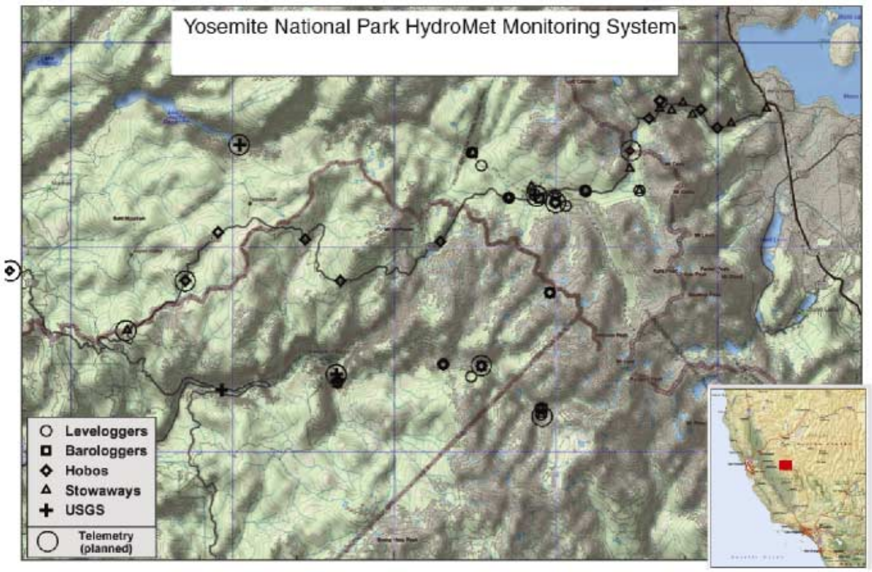

Fig. 2. Map of sensor locations in Yosemite National Park, as of September 2002. Sensors include water level and temperature (*circles*), stream chemistry (*crosses*), air pressure (*squares*), air temperature and humidity (*diamonds*), and air temperature alone (*triangles*). Circled stations have been approved by the National Park Service for telemetry

national parks and wilderness, requiring special permission for instrument installation and access. However, new sensor and wireless communication technologies designed for low maintenance operation, low power consumption and small, unobtrusive footprints are providing new opportunities to monitor mountainous watersheds. Such technologies will allow a significant expansion of data collection vital for understanding, predicting and informing about the variability of climate and water resources in the State and the Nation.

2 Sensor Network: Yosemite National Park

For high altitude monitoring, the most immediate concerns are access – both in terms of transportation to the monitoring sites and in terms of permission to use the given sites – and scientific merit. With these factors in mind, the Merced and Tuolumne Rivers in Yosemite National Park, which drain the western slope of the Southern Sierra from a range of snowmelt-contributing elevations from 1,200 to 3,700 m, have been chosen as test basins. One of the greatest assets of this region is the Tioga Road (Highway 120), which crosses the range at elevations from 1,200 to 3,050 m. This is one of only five highways transecting the Sierra Nevada, and of the five, it has the highest summit. The river basins have been protected by the National Park Service for over 100 years. Not only does this make the region an excellent laboratory for

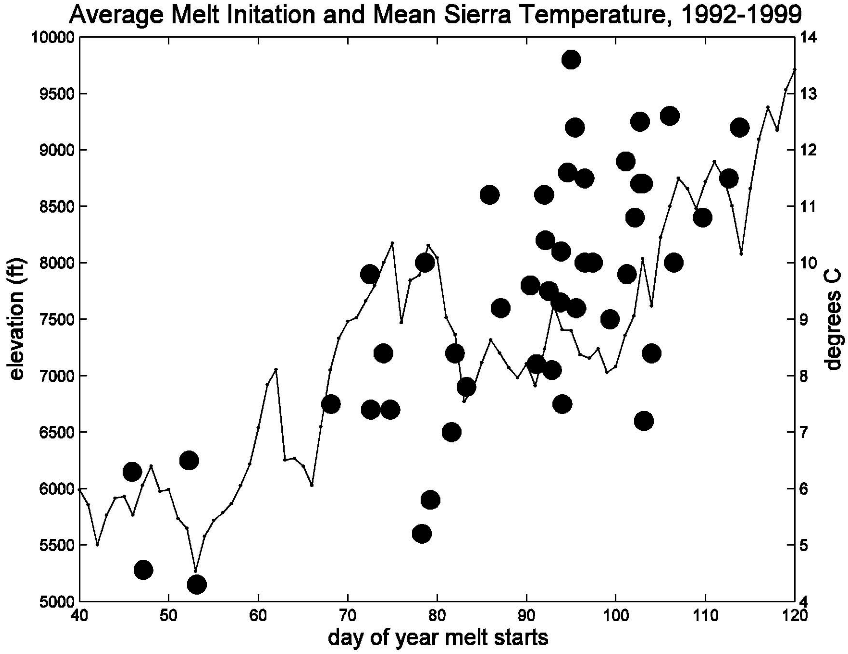

Fig. 3. A weighted average of mean temperatures at Nevada City, Tahoe City, Sacramento, and Hetch Hetchy (*line, right axis*) from 1992 to 1999 shows that, on average, temperature increases smoothly through the spring. Average days of maximum snow accumulation (*circles, left axis*) at 44 CDWR snowpillows over the same period show that higher elevations start melting later in the season, on average

natural, unimpaired processes, but it provides an important opportunity for designing instruments for wilderness areas.

Scientifically, the Merced River gage at Happy Isles has a long daily record (1916-present) of unimpaired flows, and a spatially-distributed USGS watershed model is available for testing hypotheses. Several studies (Cayan et al 2001, Peterson et al 2000) have shown that the Merced's flow characteristics are representative of basins throughout the Western United States. Since 1999, instruments measuring hourly water levels, conductivities, and temperatures have been installed at Pohono Bridge, on Tenaya Creek, and at Happy Isles on the Merced River. Starting in summer 2000, hourly measurements of snow depth and downward shortwave radiation have been added to augment measurements of air temperature, humidity, precipitation, and snow liquid water content measurements at five California Department of Water Resources (CDWR) telemetered snow pillow stations at elevations ranging from 2,000 to 3,000 m.

In summer 2001, in consultation with Park planners and scientists, the USGS, and the CDWR, we obtained necessary research permits and began installing a river monitoring network in the high country of Yosemite National Park. As a result,

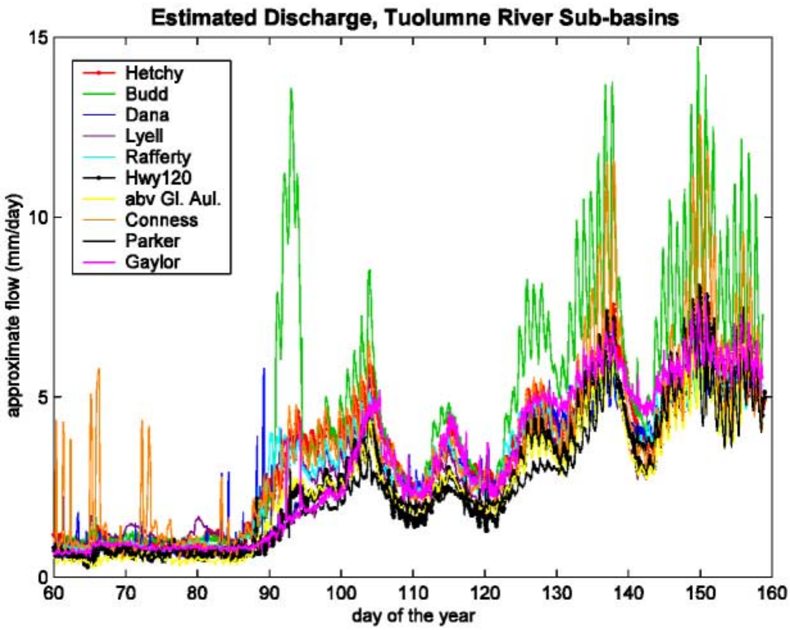

Fig. 4. Spring runoff began simultaneously in ten instrumented sub-basins of the Tuolumne River in Yosemite Natrional Park in spring 2002

twenty instruments recording hourly water level and temperature were installed in the upper reaches of the Merced and Tuolumne Rivers (Figure 2) to provide information about how and when different subbasins contribute to the river's flow. Sensor locations were selected to monitor subbasins with a variety of topographic characteristics. For example, some drain primarily north-facing slopes, and some drain primarily south-facing slopes. These measurements will be combined with remote-sensing and models to understand where and when snowmelt occurs and how it moves through these basins. Four water conductivity sensors were also deployed to make hourly measurements in the Merced and Tuolumne Basins. In summer 2002, stream chemistry measurements were made by NPS personnel at various points along both watersheds to measure water quality and composition throughout the summer. At the same time, discharge measurements were made at each station to establish curves relating discharge rates to water levels.

Along Highway 120, during Summer 2002, we also began to establish a set of meteorological stations (Figure 2) that augment the snow/meteorological stations operated by the CDWR Snow Surveys. Presently, our stations consist of approximately 25 internally-recording temperature/relative humidity sensors, stationed along Highway 120, along the west slope of the Sierra up to the crest of Tioga Pass, and down to the Mono Basin at Lee Vining. This array will monitor weather systems and air masses as they sweep across the Sierra from the Pacific, or occasionally, from the Western Great Basin. We have plans to expand the sensor suite at several of these stations to include other elements such as wind and solar radiation. We also expect to install a webcam at Tioga Pass to view snow in surrounding alpine areas. In addition to our stream and atmospheric temperature/humidity gages, we are collaborating with Frank Gehrke of CDWR to install a full snow/meteorological station at Merced Lake, in the Upper Merced River drainage, complete with GOES satellite telemetry.

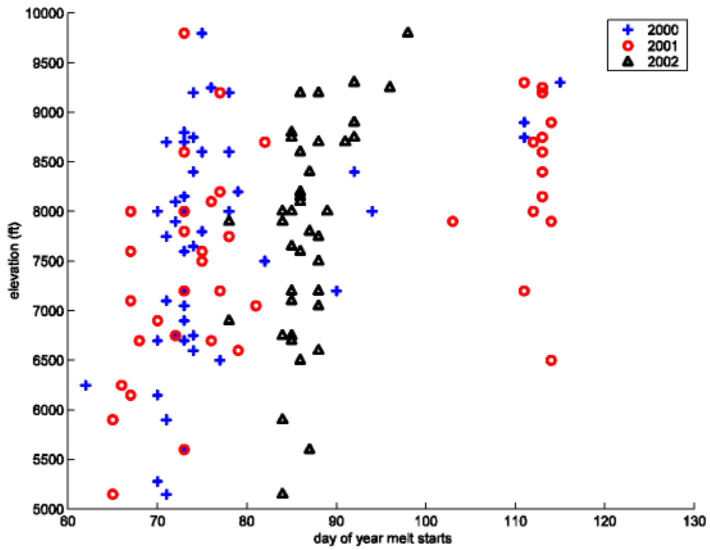

Fig. 5. The dates of maximum snow accumulation (shown here) and snowmelt initiation at 44 snow pillows in the Central Sierra were remarkably similar from elevation to elevation in spring 2002 (*triangles*). Similarly, in 2000 (*crosses*) and 2001 (*circles*), snow at most elevations began melting at the same time (before day 80, March 21st), but several stations at higher altitudes waited until weeks later

3 Preliminary Results

Because of the scarcity of high elevation data, our first year's measurements already provide interesting new insights into how snow melts and spring runoff begins at different altitudes in the Sierra. Common experience and intuition suggest that snow at lower elevations melts first. The standard atmospheric lapse rate describes a decrease in temperature of 6.5°C per 1000 m elevation gain. Reece and Aguado (1992) studied snow pillow stations in the Truckee River Basin and found an approximate 4-day delay in the start of the snowmelt season for each 100 m increase in altitude. Averaged over many years (Figure 3), these results are typical. Sierra Nevada temperature (Figure 3, right axis) increases steadily through the spring.

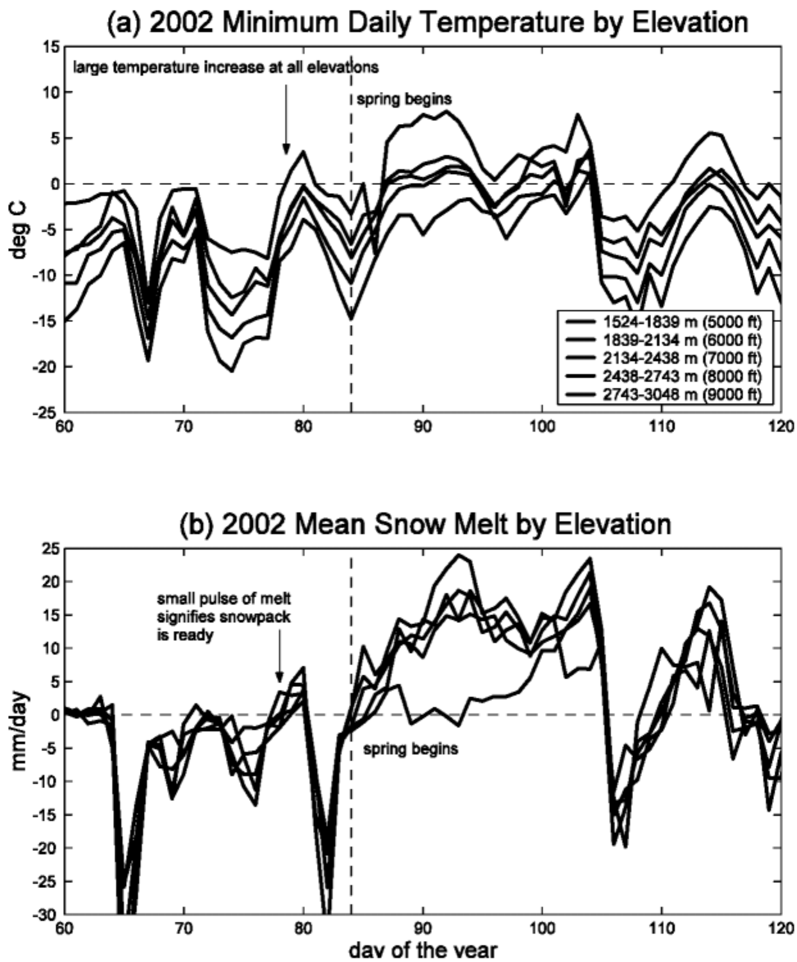

Fig. 6. Average temperatures (*a*) and snowmelt rates (*b*) by elevation for 44 snow pillows in the Central Sierra. In each graph, the top curve is the lowest elevation bin (1524–1839 m, 5000–6000 ft) and the lowest curve is the highest elevation bin (2743–3048 m, 9000–10000 ft)

Because temperatures decrease with increasing elevation, the average day of maximum snow accumulation, which we are using as an index of snowmelt initiation (Figure 3, dots, left axis), is later in the season for higher elevation snow pillow stations. However, what happens in a given year, as exemplified by spring 2002, may vary widely from the average values.

In Spring 2002, ten water-pressure sensors measured the onset of spring runoff in subbasins of the Tuolumne River in Yosemite National Park, California. Subbasin areas ranged from 6 km^2 to 775 km^2, and measurement elevations ranged from 1200 m (3,800 ft) at Hetch Hetchy to 2900 m (9,600 ft) at Gaylor Creek. Some were

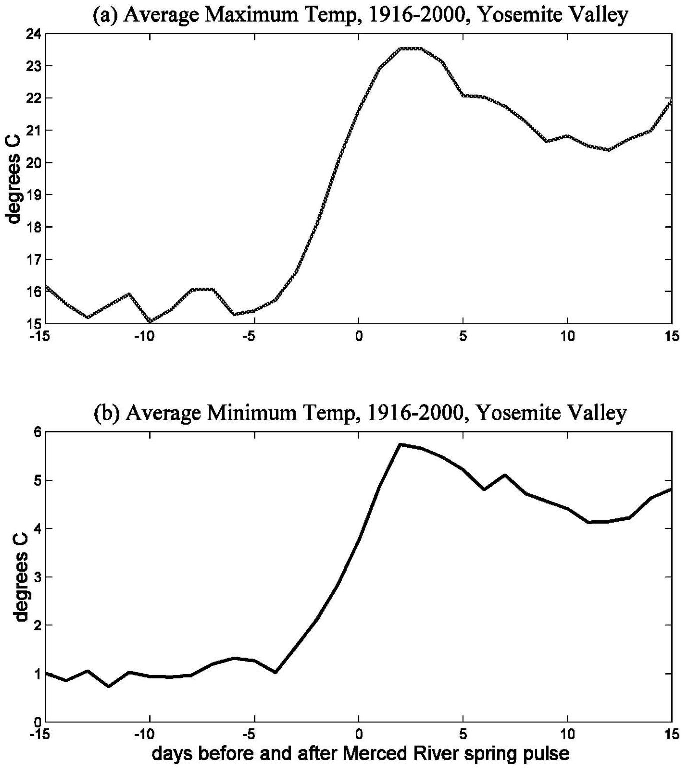

Fig. 7. Average maximum temperatures (*a*) and minimum temperatures (*b*) in Yosemite Valley, 1916-2000, for the 15 days before and after the start of spring runoff in the Merced River at Happy Isles

northfacing and some were south-facing. Estimated mean April radiation varied from 552 W/m^2 in Budd Creek Basin to 635 W/m^2 in Gaylor Creek Basin. Despite these differences, streamflow rose simultaneously, just before April 1st, at all gages (Figure 4). The date of maximum snow accumulation and initiation of spring melt also was remarkably uniform from elevation to elevation (Figure 5). Using the same stations, mean temperature and melt rates were calculated in five elevation bands. In 2002, two large increases in temperature preceded spring snowmelt (Figure 6a). After the first, a small amount of melting occurred at all elevations (Figure 6b) so that, during the second temperature increase, melting began in earnest everywhere. Notice that stream runoff only began in earnest after minimum temperatures exceeded 0°C at most elevations.

The rapid and simultaneous initiation of snowmelt and runoff at all elevations in 2002 shows that the onset of spring can differ greatly from the long-term average conditions. How common are sudden springs compared to gradual ones? The 85 years of Yosemite Valley temperature and Merced River discharge data suggest that spring

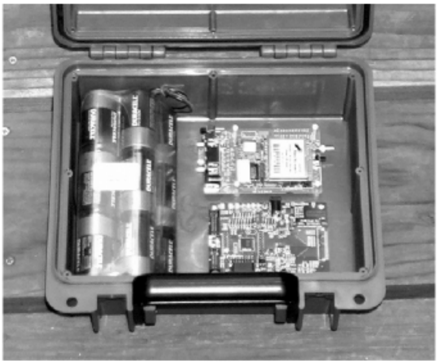

Fig. 8. View of interior of data logger being developed by Douglas Alden. Battery pack (to the left) provides power for data storage and transmission (electronics on right)

most often occurs suddenly. Averaging the temperatures before and after the day the river started rising (spring pulse days, as described in Cayan et al. 2001) reveals that maximum temperatures (Figure 7a) rise about 8°C and minimum temperatures (Figure 7b) rise about 5°C during the weeks surrounding the spring pulse. Out of 85 years, only 8 years had rapid flow increases that were not accompanied by dramatic temperature rises. This suggests that spring runoff is closely tied to large-scale atmospheric circulation patterns, and further study may reveal ways to use this link to improve forecasts of water supply and timing. However, before forecasts can improve, real-time data is essential.

4 Communications Issues

Communications in the Park are difficult because of the high relief. Conditions are especially challenging in river valleys, which are crucial to our study but are typically isolated by surrounding topography. We are exploring potential wireless communications options that include digital cellular, satellite, and land line (phone line) links to the Internet. At several sites (circled sites on map, Figure 2), we have obtained or requested Park approval to install communications equipment. There is tension between the resource-management interests of the Park, which seek more environmental information, and the wilderness-preservation interests, which seek to protect wilderness values from instrument installations. Seeking to balance these interests, our communications will depend on site location and will likely include radio, cell phone and satellite transmissions. The equipment will need to interface with the variety of existing and new sensors and data loggers used by the agencies working in this area. Implementing workable communications solutions in Yosemite will serve as a prototype for other instrumental nodes and networks that will need to be developed to serve California's increasingly multifaceted environmental monitoring needs.

Because access is often difficult in these remote and snowy settings, power consumption and long-term backups of data collected are important design considerations. Thus, SIO Development Engineer Douglas Alden is building a low cost, low power data logger (Figure 8) that will log, record and wirelessly transmit data from several meteorological and hydrological sensors. The logger is designed for wilderness applications and will accommodate several standard meteorological and hydrological sensors. The current version will be powered by a small battery pack, and its 32MB of memory is adequate to store several months of data (while logging measurements at three-minute intervals).

Installing and monitoring a high density of sensors in Yosemite will reveal the spatial variability of meteorological properties at high altitudes. Data intercomparison within the region will also help identify sensors that may not be properly calibrated or indicative of region characteristics, prompting timely repairs and replacements. Connecting the instruments to the internet will eliminate the limitations of data storage and will minimize the travel costs involved in data retrieval. However, battery power will continue to be a limiting factor. Solar panels, in conjunction with 12-volt batteries, are currently used at the CDWR snow pillows, but the large visible panels are not unobtrusive enough for protected wilderness areas. Further technological advances in power generation and consumption are desirable.

5 Future Directions

High altitude observations are necessary to improve understanding of mountain snowpacks, a crucial resource that provides over half of California's water supply. Because the settings are in remote, protected areas, instruments must be designed for low maintenance operation, low power consumption and small, unobtrusive packaging. The technology also must perform despite the lack of traditional cell phone coverage in these regions and the isolated nature of river valleys surrounded by steep terrain. Fortunately, the demand for these measurements is such that any communications advances will be quickly incorporated, and more real-time highaltitude measurements will become available online in the future.

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