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Spatial estimates of snow water equivalent from reconstruction

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ABSTRACT

Operational ground-based measurements of snow water equivalent (SWE) do not adequately explain spatial variability in mountainous terrain. To address this problem, we combine satellite-based retrievals of fractional snow cover for the period 2000 to 2011 with spatially distributed energy balance calculations to reconstruct SWE values throughout each melt season in the Sierra Nevada of California. Modeled solar radiation, longwave radiation, and air temperature from NLDAS drive the snowmelt model. The modeled solar radiation compares well to ground observations, but modeled longwave radiation is slightly lower than observations. Validation of reconstructed SWE with snow courses and our own snow surveys shows that the model can accurately estimate SWE at the sampled locations in a variety of topographic settings for a range of wet to dry years. The relationships of SWE with elevation and latitude are significantly different for wet, mean and dry years as well as between drainages. In all the basins studied, the relationship between remaining SWE and snow-covered area (SCA) becomes increasingly correlated from March to July as expected because SCA is an important model input. Though the SWE is calculated retrospectively SCA observations are available in near-real time and combined with historical reconstructions may be sufficient for estimating SWE with more confidence as the melt season progresses.

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1. Introduction

In the Sierra Nevada of California, most streamflow comes from snowmelt, and in most basins the reservoirs hold little more than average annual runoff, for example the Kings River basin with an April to July runoff volume of 1.3 km^3 and a total reservoir volume of 1.53 km^3. Point measurements of snow water equivalent (SWE) from snow pillows and transects from snow courses remain the primary source of data about the snow, but those data may not correctly represent the spatial and temporal variability in mountainous terrain. Significant areas lie above the highest snow pillows and courses, which monitor neither moderate nor steep slopes. Knowing the spatial distribution of SWE is necessary to reasonably estimate the partition of snowmelt between evapotranspiration, quickflow, percolation to the ground water, and streamflow. If water managers better understood the distribution of snow and its melt rate, they could better deal with the competing priorities for flood protection and resource provision for cities, industries, agriculture, hydropower and ecosystems.

Two separate entities, the NOAA/NWS California Nevada River Forecast Center (CNRFC) and the California Department of Water Resources (CADWR), work together but produce their own forecasts of seasonal runoff by multiple linear regression of streamflow against snow pillows and courses (NOAA/NWS 2016, California Department of Water Resources, 2016). In addition, NOAA/NWS uses the same information along with a numerical model to produce weekly ensemble forecasts. Historical predictions of seasonal runoff have been inaccurate in both wet and dry years (Dozier, 2011), partly because the measurement network provides few data about SWE at the highest elevations, and snow courses and pillows are all on nearly flat terrain. Decreasing snow accumulation and earlier snowmelt runoff (Mote et al., 2005, Maurer et al., 2007) make forecasting a challenging problem because the statistical environment is not stationary (Milly et al., 2008), so a more mechanistic way of estimating seasonal runoff is needed. Moreover, knowledge of the spatial distribution of snow will help inform the effects of snowmelt on soil moisture and vegetation. Projected changes in runoff during the lifetime of major water infrastructure are large enough to exceed the range of historical behavior (Seager et al., 2007).

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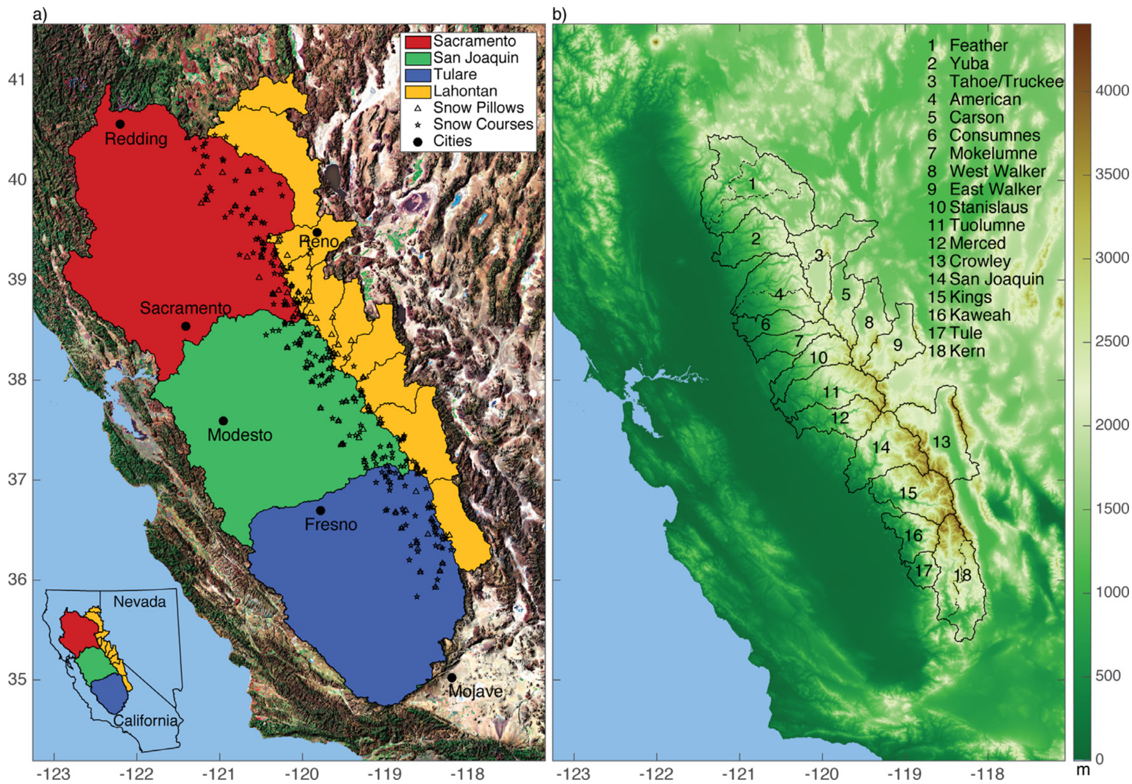

Fig. 1. (a) Sierra Nevada study area and its four major drainages with snow pillows and snow courses; (b) Elevation and HUC8 basins that have full natural flow data. The Feather, Tahoe/Truckee, American, and Kern have multiple forks represented with dotted lines.

We address the following questions: (1) How well can the spatial distribution of SWE in the mountains be estimated using space-based remote sensing to reconstruct the post-peak snow accumulation? (2) How strong is the seasonal relationship of SWE to elevation in the Sierra Nevada? (3) How does this relationship differ between basins and among years? (4) What is the relationship between snow-covered area (SCA) and SWE and can SCA be used to estimate basin wide SWE?

Section 2 describes the characteristics of the Sierra Nevada and its basins. Section 3 describes the reconstruction model, the data used to drive the model, and downscaling methods used to distribute the energy balance. In the absence of any method to directly measure SWE over large mountain ranges, reconstruction appears to be the most reliable way to estimate its spatial distribution (Lettenmaier et al., 2015). Section 4 assesses error and uncertainty in energy balance components, using ground observations where available and a model that couples energy and water balances where observations are not available. Section 5 compares SWE from the reconstruction model with snow courses and snow surveys. Section 6 explores the relationship of SWE with elevation, latitude, and snow covered area.

2. Study area

The Sierra Nevada maritime snowpack lies primarily in California and encompasses four major drainages (Fig. 1(a)) within which full natural flow calculations are available in 18 smaller hydrologic unit code 8 (HUC8) basins (Fig. 1(b)). Those in the Sacramento and San Joaquin drainages cover 17,560 km^2 and 17,710 km^2, while those in the Tulare and Lahontan cover 12,590 km^2 and 5730 km^2. Table 1 shows areas and minimum, mean, and maximum elevations for each HUC8 basin. Basins in the Tulare drainage generally have higher elevations than those in the Sacramento or San Joaquin, while Lahontan basins have the highest elevations but lie on the lee side of the Sierra Nevada. HUC8 basins in the Sacramento, San Joaquin and Tulare drainages drain toward the southwest, with the exception of the Kern that flows southward, while the Lahontan basins drain northeast except for the Owens, which drains toward the south.

Table 2 summarizes the primary forms of vegetation in the Sierra Nevada derived from the LANDFIRE dataset's existing vegetation type (Rollins, 2009). Coniferous forest is the primary form of vegetation for every basin except the East Walker in the Lahontan, which has more shrubs than trees. In general, the basin forest cover fraction decreases from north to south, as bare soils, rock outcrops and shrubs are more common at the highest elevations more prevalent in the south.

There is extensive monitoring of snow through snow pillows and courses, as Fig. 1(a) shows. The Sacramento drainage is the most highly instrumented, while the Lahontan is the least instrumented. Even with extensive monitoring, there is a lack of information about the highest elevations throughout the season.

Fig. 2 illustrates the consequences of this lack of information. It shows fractional snow covered area from the Landsat Thematic Mapper (TM) on July 2nd and July 18th, 2011 in the Tuolumne and Merced River basins. On these days significant snow existed at the high elevations, and between the two dates the snow covered area decreased, producing significant melt. Fig. 2(c) shows the snow pillow observations throughout the season. On July 2nd, only two snow pillows, STR (8200 m) and VRG (9300 m) registered any snow and on the July 18th all snow pillows were bare including the two other moderately high elevation snow pillows, SLI (9200 m) and (DAN 9800 m). A forecast of streamflow that relied on these observations would likely underestimate the likely amount of snow still to melt without the areal information shown in Fig. 2(a,b). This lack of information is problematic for the late melt season shown here. At maximum accumulation, the same problem exists and the volume of SWE stored above the snow pillows is an unknown.

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