

SNOWCOVER ALONG ELEVATION GRADIENTS IN THE UPPER MERCED AND TUOLUMNE RIVER BASINS OF THE SIERRA NEVADA OF CALIFORNIA FROM MODIS AND BLENDED GROUND DATA

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ABSTRACT

Accurate, frequent satellite-derived snow covered area (SCA) products provide the opportunity to explore the spatial patterns of snow, as well as the impact of snow accumulation and ablation on snow distribution along elevation gradients. Blending a MODIS fractional snow cover product with interpolated point snow water equivalent (SWE) measurements and energy balance calculations yields composite maps of the spatial distribution of SWE. Results from the 2004 and 2005 water years show the utility of the MODIS fractional SCA product to estimate snow accumulation and melt along 300-meter elevation gradients in the Upper Merced and Tuolumne River Basins of the Sierra Nevada of California. The analysis considers the elevation bands from 1,500 to 3,900 m with 40% of the elevation between 2,100-2,700 m, while the 1,500 m elevation band is considered the transitional rain/snow zone. Spatial maps of SWE highlight elevational bands that contribute significantly to snowmelt across the basin, as well as those elevational bands that are susceptible to warming and thus rapid depletion of the snowcover. The results of the 2004 ablation season demonstrate the implications along the elevation gradients of an above normal mid-season snowcover of 120% impacted by an unseasonable warm and dry air mass that rapidly depleted the snowcover across all elevation gradients, leading to a below average snowpack of 84% by April 1. These results highlight the critical elevation zones in which the snowpack is susceptible to climate variations, while underscoring deficiencies in the current measurement network which provide the impetus for designing of an adequate measurement network along elevational gradients.

INTRODUCTION

In many mid-latitude montane regions, seasonal snow cover stores significant amount of water, much of which is released into streams. In the semi-arid western United States, the ratio of snowmelt runoff to the total stream runoff increases during spring due to the seasonality of precipitation. It has been reported that in the western United States, snowmelt runoff accounts for up to 80 percent of the annual streamflow (Palmer, 1988; Daly et al., 2000). Therefore, the bulk of the western United States surface water resources are derived from the melt of the winter snowpack (Serreze et al., 1999). Acknowledging the importance of the hydrologic role of snow, hydrologists are interested in monitoring and estimating the spatial and temporal variations in snowpack conditions in the mountains, focusing on forecasting volume and timing of snowmelt runoff.

Hydrologic forecasts in the western U.S. are generated from snow water equivalent (SWE) measurement at manual snow courses and automatically telemetered sites. However, precipitation in the western U.S. varies spatial and temporally because of topography, vegetation and larger-scale synoptic or meso-scale processes. Therefore, substantial variations exist between snow measurements, even from sites close together (Carroll, et al., 1999) and the monthly ground-based and hourly telemetered SWE measurements that supply the bulk of the data used in the Sierra Nevada Mountains of California and other areas, which provide inadequate temporal resolution to diagnose the spatial and temporal distribution patterns. McGurk et al. (1993) analyzed relationships between low- and high-elevation snow courses and found the correlations unreliable because the early disappearance of snow at the lower elevations gives no further information about snow at the higher elevations.

Currently the most widely used ground-based observations for evaluating, initializing, and updating grid-element snowpack estimates come from the real-time snow sensor stations and manual snow courses. Snow courses and automated snow stations were not designed to provide SWE values that are representative of the

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average values within a grid element, because the spacing of automated and manual snow measurement stations is too coarse to resolve this small-scale variability. Therefore, the small-scale variability in snow distribution cannot be resolved if the distance between observations is greater than the correlation length (Bloschl, 1999). Nevertheless, the network has been used to estimate the spatial distribution of SWE (Carroll and Cressie, 1996; Carroll and Carroll, 1993; Daly et al., 2000; Fassnacht et al., 2003; Ling et al., 1995; Molotch et al., 2005) and to update snowpack model state variables within data assimilation schemes (Brubaker and Menoes, 2001; Carroll et al., 2001). Current research on the spatially distributed snowmelt models require field based measurements and remotely sensed data on snow surface parameters (e.g. albedo) and snow covered area (SCA) which enhance the reliability of the models providing the ability to initialize and reinitialize parameters, as well as for validation.

The coupling of ground-based measurements with space-borne satellite imagery provides a viable way to examine the critical physical processes controlling spatial and temporal distribution of seasonal snow in the mountains. The objectives of this paper are to (1) show the importance and utility of snow covered area (SCA) depletion maps to examine the accumulation and melt along 300 meter elevation gradients in the Tuolumne and Merced River Basins; (2) explore the use of SWE spatial maps and highlight the elevational bands that contribute significantly to snowmelt across the basin, as well as those elevational bands that are susceptible to warming and thus rapid depletion of the snowcover; and (3) illustrate the deficiencies in the existing SWE measurement network.

METHODS

Study Area

The Upper Tuolumne and Merced River basins are located in the Sierra Nevada Mountains of California, and located above the Sierra foothill reservoirs of Don Pedro (Tuolumne) and Lake McClure (Merced). The Upper Tuolumne River Basin is 4,184 km² with elevations ranging from 58 to 3980 meters, while the Upper Merced River Basin is 2,812 Km² with elevations ranging from 95 to 3929 meters. Both the Tuolumne and Merced Rivers drain into the San Joaquin River in the Central Valley of California with 73% of the streamflow runoff resulting from the seasonal snowpack. Therefore, the analysis is restricted to the seasonal snow-covered areas that are above 1500 meters, which represents 58% (2,420 km²) and 62% (1,755 km²) of the Tuolumne and Merced River Basins, respectively (Figure 1). In the Tuolumne River Basin Snow Water Equivalent (SWE) is measured hourly at 7 snow pillows and monthly at 17 snow courses, while in the Merced River Basin SWE is measured hourly at 2 snow pillows and monthly at 5 snow courses.

Using the 30-meter topographic data obtained from the Shuttle Radar Topographic Mission (SRTM), the study area was partitioned into 300-meter elevation bands beginning at 1500 meters and extending to 4000 meters. The SRTM was re-sampled from a 30 meter to a 500-meter resolution in order to correspond pixel-by-pixel with the MODIS fractional SCA product.

Snow Covered Area

Daily fractional SCA maps at a 500-meter resolution from 2004 and 2005 for the Sierra Nevada were obtained through the Multi-Resolution Snow Products for the Hydrological Sciences (NASA/REASoN) from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS SCA product was processed using a spectral mixing model using techniques developed by Rosenthal and Dozier (1996). The spectral mixing algorithm is based on a Multiple end member snow covered area and grain size model (MEMSCAG) (Painter et al., 2003) in which the set of end members (e.g. snow, rock, vegetation) may vary pixel by pixel allowing heterogeneous distribution of SCA (Roberts et al., 1998; Painter and Dozier, 2004).

Interpolated Snow Water Equivalent

Spatially distributed SWE was interpolated (Fassnacht et al., 2003) using point SWE measurements from telemetered snow stations from 2004 and 2005, obtained from the California Data Exchange Center (CDEC) (<http://cdec.water.ca.gov/snow/current/snow/>). For each 500-meter grid cell in the basin, all snow telemetry sites within a fixed radius, including those outside of the basin, were identified. A linear regression was computed between elevation and SWE for all of the sites within the search radius. The hypsometric relationship was used to estimate SWE for each grid cell using the SRTM. A residual was obtained at each grid cell where an observing snow telemetry station was located by removing the observed value from the analysis (i.e. jack-knifing) and

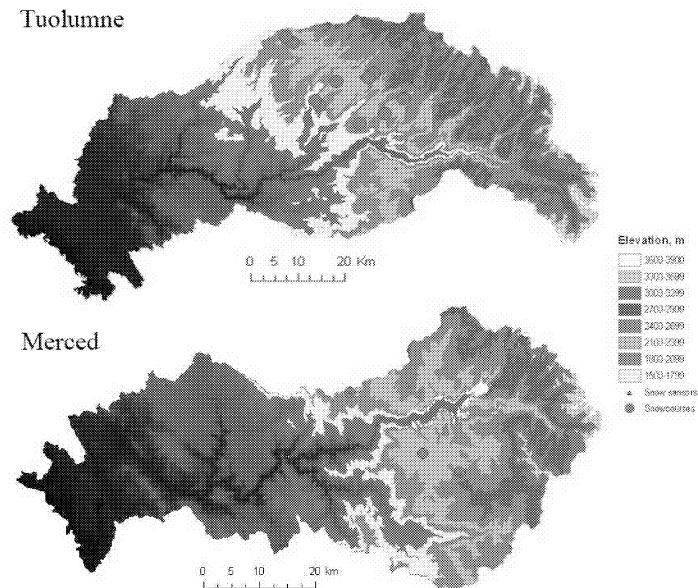


Figure 1. The Upper Tuolumne and Merced River Basins are located in the central Sierra Nevada Mountains of California. Analysis is restricted to those elevations above 1500 meters, which represents 58% (2,420 km²) and 62% (1,755 km²) of the Tuolumne and Merced River Basins. In the Tuolumne River Basin Snow Water Equivalent (SWE) is measured daily at 7 snow pillows and monthly at 17 snow courses, while in the Merced River Basin SWE is measured daily at 2 snow pillows and monthly at 5 snow courses.

subtracting the observed SWE from the computed SWE. Elevation dependent bias in the residuals was removed by regressing residuals to a fixed datum. Once regressed to the common datum, the lapsed residuals were spatially distributed using inverse distance weighting with a power of 2. The gridded residual surface was then regressed back to the basin surface and subtracted from the hypsometrically derived SWE grid in order to derive the SWE surface. The final SWE surface was generated by coupling the MODIS fractional SCA with the interpolated SWE surface (Figure 2). The blended SWE surfaces were generated daily for 2004 and 2005. Snowmelt was complete or snow free for a grid cell when either the interpolated SWE or SCA value was 0.

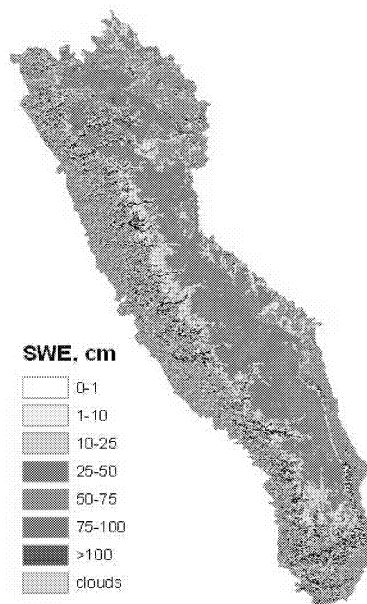


Figure 2. Blended SWE product coupling MODIS fractional SCA and interpolated SWE at a 500 meter grid resolution across the Sierra Nevada.

Temperature-index Model

A temperature index model (Martinec, 1960) was applied to calculate the snowmelt (M , centimeters per day) along each of the eight elevation bands:

$$M = a(T_a - T_b)$$

where a is a degree-day factor (centimeters per degrees per day), T_a is average daily temperature, $T_b = 0^\circ\text{C}$, and when $T_a < T_b$ then $M = 0$ (Kustas et al., 1994). A degree-day factor, a , was calculated for each day starting at the onset of snowmelt for each year, 2004 and 2005, for the Tuolumne River Basin and Merced River Basin using the historical daily snow pillow and temperature data.

Hourly temperature data from 2004 and 2005 were obtained from telemetered sites through CDEC, and average daily temperature (T_a) was computed for each elevation band that was available. When average daily temperature was not available for an elevation band, a simple lapse rate was calculated from historical data and interpolated. The calculated lapse rate for 2004 and 2005 was $0.3^\circ\text{C}/100$ meters and $0.5^\circ\text{C}/100$ meters, respectively. Recent work by Lundquist and Cayan, (2007) in Yosemite National Park indicate that a simple lapse rate is often a poor description of the spatial structure of temperature across complex terrain, but for this specific initial study this simple lapse rate method is sufficient.

The temperature index model determines the potential snowmelt. This method was applied to all areas within the Tuolumne and Merced River Basins that were snow covered and the fractional MODIS SCA product was applied as a correction to potential snowmelt. In other words, if an area has snow cover, then it is assumed to contribute melt at an equal rate to the potential snowmelt times SCA. The degree-day calculation was complete when the snowmelt calculated up to day when SCA is depleted equals beginning SWE.

RESULTS AND DISCUSSION

Snow Covered Area

The daily 500-meter fractional SCA for 2004 and 2005 was partitioned into the eight elevation bands ranging between 1500-4000 meters at 300 meter intervals and daily fractional SCA was averaged across each of these bands. Figure 3 shows the daily average SCA depletion across each of the eight elevation bands for the Tuolumne River Basin from March 1 to October 1, 2004. On April 1, 2004 basin-wide SWE was 84% of the April 1 historical average (based on basin-wide snow course data). The SCA depletion shows the onset of snowmelt began on or before March 1, 2004, which is consistent with the automated snow pillows in the Tuolumne, with the ground becoming snow free at the lower elevations by June, the mid-elevations by July, and the upper-elevations by August. In addition, each higher elevation band required one month longer to become snow free.

In 2005, significant snowfall created an above average snowpack on April 1, 2005; both the Tuolumne and Merced were 163% of the April 1 historical average (based on basin wide snow course data). This is evident in Figure 4 as the onset of snowmelt occurred 1 month later for each of the eight elevation bands, as well as the ground becoming snow-free one month later than in 2004.

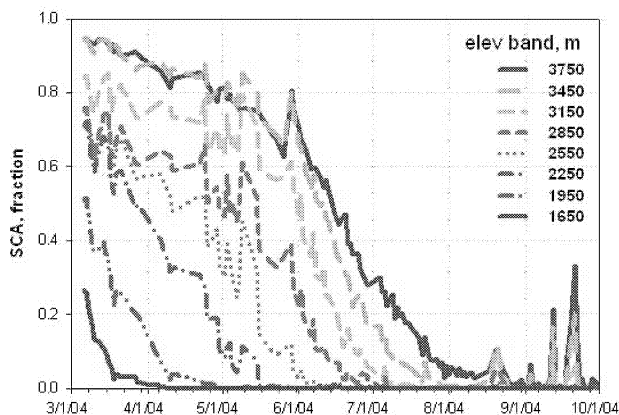


Figure 3. 2004 SCA depletion in the Tuolumne Basin across eight elevation bands. The onset of snowmelt began on or before March 1 with the ground becoming snow free one month later for each successive elevation band.

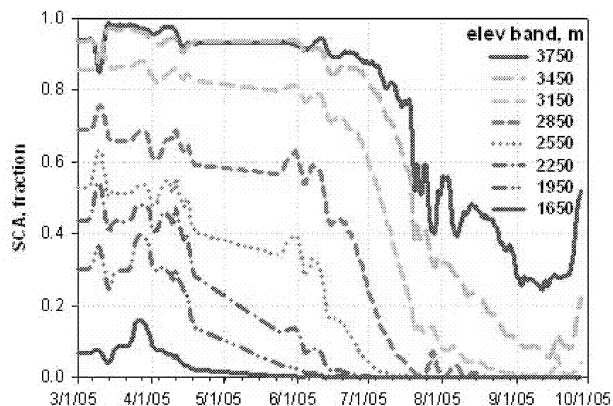


Figure 4. 2005 SCA depletion in the Merced River Basin across the eight elevation bands. The onset of snowmelt occurred one month latter for each elevation band and the ground became snow free one month later than in 2004.

Interpolated Snow Water Equivalent

The daily interpolated SWE was partitioned and averaged across the eight distinct elevation bands for both the Tuolumne and Merced River Basins in 2004 and 2005, respectively (Figure 5A and 5B). There is little difference in the interpolated SWE at the onset of snowmelt in both the Tuolumne and Merced, this is especially apparent in 2005 in the Merced River Basin (Figure 5B), when 1.2 meters of SWE is being reported at each of the eight elevation bands at peak accumulation.

When MODIS fractional SCA product is coupled with interpolated SWE (Figure 6A and 6B), distinct elevation gradients become apparent, as the satellite coverage maps provide details on snow distribution patterns along elevation gradients. This blended interpolated SWE and SCA product, provide daily information on the contribution of snowmelt from each elevation band within the basin, as well as the daily amount of potential SWE available for melt. Figure 7A and 7B shows the contribution of snowmelt in June and July for 2004 and 2005, respectively, in the Tuolumne and Merced River Basins. Both the Tuolumne and Merced have a similar response, with the major contribution of snowmelt resulting from 2400 and 3300 meters, when the lower elevations, below 2400 meters have melted or when little snow is left to significantly contribute to snowmelt. Further, there are insignificant contributions to snowmelt from the upper elevations above 3300 meters.

Upon further examination, SCA depletion maps (Figure 3 and 4) are not snow free, especially at the upper elevations until August 2004 and never fully depleted in 2005, while the interpolated SWE (Figure 5A and 5B) shows that all or most of the SWE is completely depleted by June 2004 and July 2005. Once the lower elevations snow pillows melt-out, no SWE can be interpolated to the upper elevations, and therefore these upper elevations are now snow-free, even though the SCA maps have not depleted. Therefore, a discrepancy begins to develop between the SCA and interpolated SWE depletion curves, as interpolated SWE develops a faster depletion rate. The results indicate that snow pillows will melt out 1.5 to 2 months prior to SCA depletion. These faster SWE depletion rates are due in large part to the sparse network of upper elevation telemetered snow pillow sites in the Sierra Nevada.

Temperature Index Model

The calculated degree-day factor, a , estimated from the daily telemetered snow pillow sites and average daily temperature ranged linearly from 0.1 to 0.35 $\text{cm } ^\circ\text{C}^{-1} \text{ d}^{-1}$ for the Tuolumne and 0.1 to 0.30 $\text{cm } ^\circ\text{C}^{-1} \text{ d}^{-1}$ for the Merced in 2004 and 2005. The degree-day factor showed no systemic variation by elevation for 2004 and 2005, but suggests a strong seasonal change.

The temperature index model coupled with the fractional SCA depletion maps shows that 36% of the Tuolumne (Figure 8A and 8B) (34%-Merced) snowmelt resulted from elevations above 3000 meters and provided the main source of August and September snowmelt, in addition to contributing significantly to the snowmelt in June and July 2004. Below 2100 meters, 13% of the Tuolumne (5% -Merced) of the snowmelt is derived and impacting the watershed in March 2004 and 2005 and April 2005. The majority of the snowmelt in the Tuolumne (50%) (60%-Merced) occurs within the 2100-3000 meter elevation bands, with snowmelt depletion occurring over a 2 month period at 2100-2400 meters and 4 months at 2700-3000 meters.

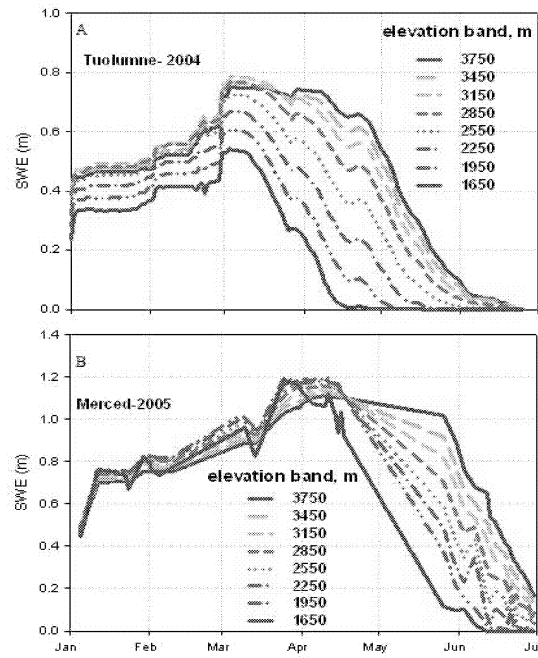


Figure 5. (A) Interpolated SWE in the Tuolumne River and (B) in the Merced River Basins across the eight elevation bands. For both the Tuolumne and Merced, there is little elevation difference in the interpolated SWE at the onset of snowmelt.

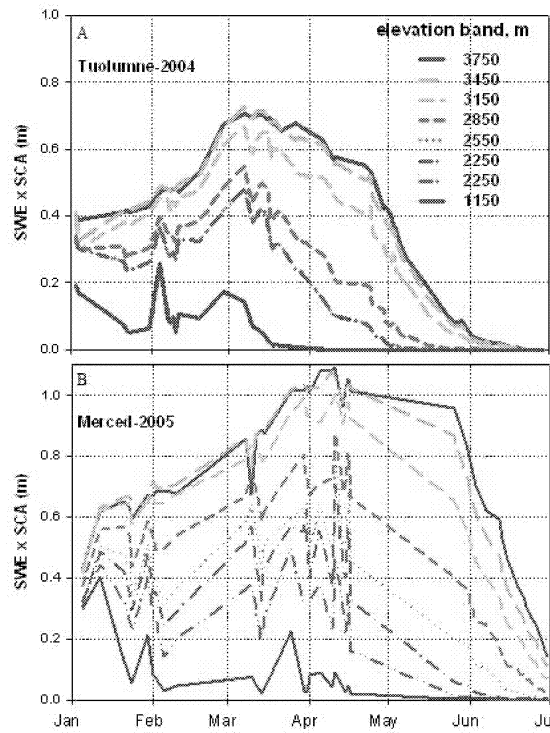


Figure 6. Blended interpolated SWE X SCA for the Tuolumne (A) and Merced (B) River Basins in 2004 and 2005, respectively, showing the distinct elevation bands and the apparent impact of the spatial distribution patterns of the fractional SCA product.

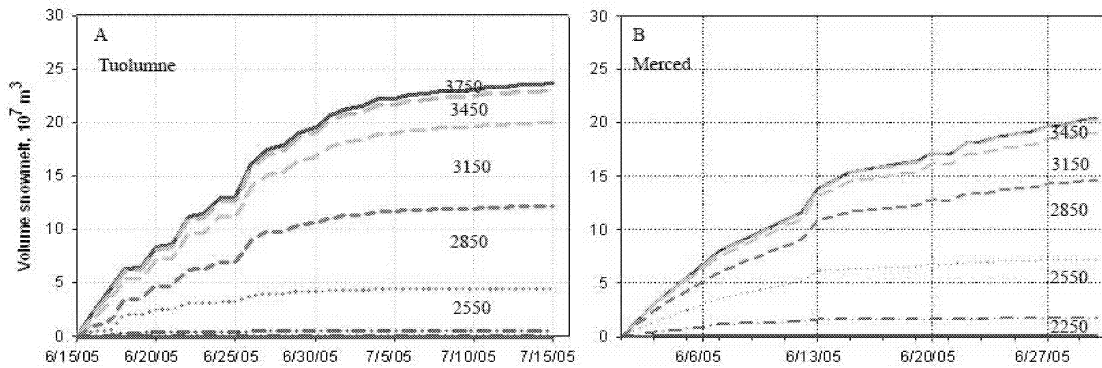


Figure 7. Contributions to snowmelt by elevation bands from June and July 2005 in the Tuolumne (A) and Merced (B) River Basins using interpolated SWE and SCA depletion, with progressive contributions from higher elevations, while the lower elevations and upper elevations do not contribute to the overall volume of snowmelt.

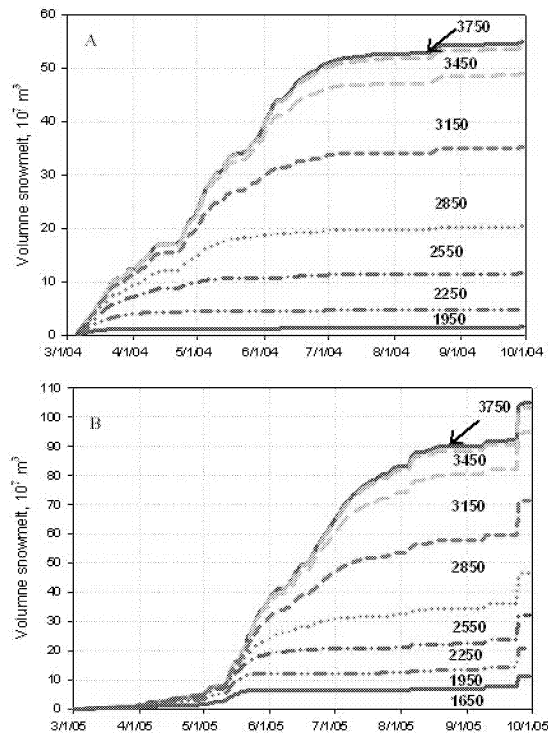


Figure 8. Snowmelt contribution using the temperature index model in the Tuolumne Basin for 2004 (A) and 2005 (B) by elevation band. The majority of the snowmelt in the Tuolumne occurs within the 2100-3000 meter bands, with snowmelt depletion occurring over a 2-month period at 2100-2400 meters and 4 months at 2700-3000 meters.

SWE Interpolation Versus Temperature Index Model

Given the complexity of snow distribution patterns, SCA depletion maps provide a better quantitative basis for estimating basin-scale SWE, when coupled with an energy balance/temperature index model than when coupled with interpolated SWE. Differences between the two methods arise when comparing the timing and rate of snowmelt.

In the Tuolumne River Basin for 2004, Figure 9A shows the rapid depletion of snowmelt along elevation bands by June using the interpolated SWE method, while with the temperature index/degree-day calculation (Figure 9B), snowmelt is still occurring in the upper elevations in July. In addition, the SWE interpolation method provides large contributions of snowmelt below 2100 meters, while over-estimating below 3000 meters and underestimating above 3000 meters. Similar results in the Merced River Basin from 2005 are evident when the interpolated SWE (Figure 10A) is compared with the temperature index model (Figure 10B). In the Merced, all lower elevations were snow-free prior to June using the interpolated SWE method, as well as rapid depletion at the mid-elevations. In addition, the total volume of snowmelt is lower using the interpolated SWE method, since telemetered snow data

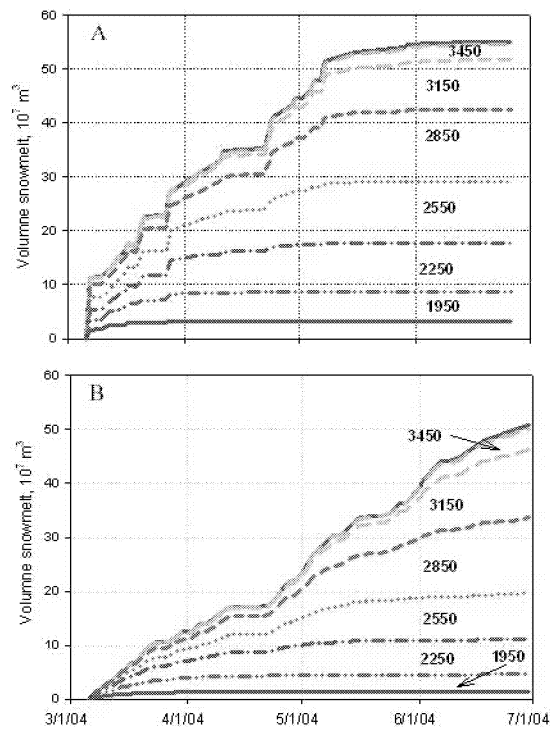


Figure 9. Contributions of snowmelt in the Tuolumne River Basin from 2004 using the (A) temperature index/degree-day method and (B) interpolated SWE. Rapid snowmelt across all elevations is apparent using interpolated SWE, as well as large contributions of snowmelt below 2100 meters, while over-estimating below 3000 meters and underestimating above 3000 meters. By July the degree-day method still has considerable snowmelt above 2700 meters.

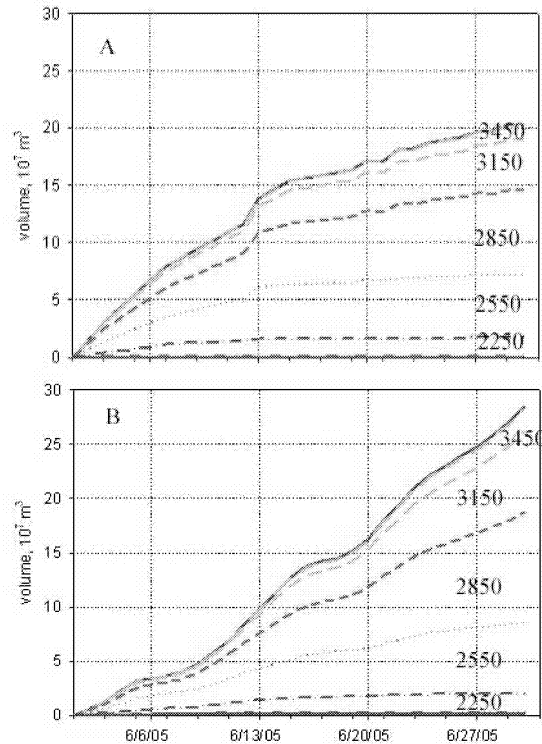


Figure 10. Contributions of snowmelt in the Merced River Basin from June 2005 using the (A) interpolated SWE and (B) temperature index/degree-day method. Prior to June 2005, all snow below 2250 meters has been depleted, but the interpolated SWE method (A) shows more rapid depletion at mid-elevations. The temperature index/degree-day method (B) shows continued snowmelt beyond June in elevations above 2700 meters. above 3000 meters is not available for SWE interpolation. The temperature index model shows continued snowmelt into July for elevations above 2700 meters, which is consistent with SCA depletion maps.

Source of Error

Errors arise in SCA resulting from the influence in vegetation especially below 2100 meters in the Merced River Basin. A discrepancy develops between SCA and canopy openings and the ability of the satellite to determine the amount of snow underneath the canopy, especially in highly forested areas, such as the lower elevations of the Merced (Rice et al., 2006; Liu et al., 2004). During the accumulation season of 2004, vegetation may have caused an under-estimation of SWE by 20-50% at elevations below 2400 meters, but when considering the Tuolumne and Merced River Basins it only accounted for and under-estimation of 5%.

CONCLUSIONS

Much of the snow that falls throughout mountainous regions is spatially distributed in complex patterns influenced by topography and vegetation. The MODIS fractional SCA product at a 500-meter resolution provides a robust and reliable product to discern complex snow distribution patterns over mountainous terrain. SCA maps provide a daily record of snow cover and can effectively track the depletion of snow through ablation and when coupled with ground based measurement networks provide more reasonable estimates of basin-wide SWE.

The construction of the SWE spatial maps for Tuolumne and Merced River basins highlighted those elevation bands that contributed significantly to snowmelt. In both the Tuolumne and Merced the most significant contribution to snowmelt resulted from 2100-3000 meter elevation bands where 50-60% of the snowmelt was derived in 2004 and 2005. Further, 34-36% of the snowmelt is derived from elevations above 3000 meters and contributes significantly to late season streamflow and basin recharge. Of interest is the snowmelt at elevations below 2100 meters and the potential response due to climate warming. At elevations below 2100 meters 5-13% of the snowmelt is attributable to this region and if 2004 is any indication, then this elevation band is susceptible to warming, as well as the impact of increasing rain on snow events. In the Tuolumne and Merced at 2100 meters and below, the timing and magnitude of snowmelt will be concentrated to March and possibly earlier.

The SCA depletion maps highlighted deficiencies in the existing SWE measurement network when considering the basin-wide interpolated SWE. The interpolation scheme demonstrates coarse spacing of automated and manual snow measurement stations and the inability to resolve small-scale variability. This scaling issue is emphasized as a discrepancy develops from the SCA depletion and interpolated SWE, and therefore highlights the weakness in the SWE measurement network above 3000 meters, in which significant contributions of snowmelt are derived. These elevations will become more important as the bulk of the seasonal snowmelt is derived from these elevations, and therefore necessary to measure.

SCA depletion maps when coupled with a temperature index model can provide a more accurate record of potential snowmelt than when coupled with interpolated SWE during ablation. However, the development of a spatial and temporal measurement array will improve remotely sensed and modeled SWE estimates by defining the subgrid variability at a scale smaller than an instrument's pixel size.

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