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An Assessment of Snowcover in Major River Basins of Sierra Nevada Network Parks and Potential Approaches for Long-term Monitoring

Natural Resource Technical Report NPS/SIEN/NRTR—2013/800

ON THE COVER
Upper Marble Fork of the Kaweah River, Sequoia National Park. Photograph by: Robert Rice

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Acronyms and Abbreviations

^{o}C	degrees Celsius
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
DEPO	Devils Postpile National Monument
DEM	Digital elevation model
ET	Evapotranspiration
fSCA	Fraction of snow-covered area
I&M	Inventory & Monitoring
km	kilometer
LIDAR	Light detection and ranging
m	meter
MODIS	Moderate resolution imaging spectroradiometer
MODSCAG	MODIS snow-covered area and grain size
NASA	National Aeronautics and Space Administration
NLCD	National Land Cover Data
NLDAS	National Land Data Assimilation System
NOHRSC	National Weather Service National Operational Hydrologic Regime Remote Sensing Center
NPS	National Park Service
NRCS	Natural Resource Conservation Service
NWIS	National Water Information System
PRISM	Precipitation-elevation Regressions on Independent Slopes Model
QA/QC	Quality assurance/quality control
RAWS	Remote automated weather station
SCA	Snow-covered area
SEKI	Sequoia and Kings Canyon National Parks
SIEN	Sierra Nevada Network
SWE	Snow water equivalent
WRCC	Western Regional Climate Center
YOSE	Yosemite National Park

Executive Summary

The Sierra Nevada Network Inventory & Monitoring Program (SIEN) performs long-term natural resource monitoring within four units of the National Park Service (Devils Postpile National Monument-DEPO, Sequoia and Kings Canyon National Parks-SEKI, and Yosemite National Park-YOSE). SIEN and park staff identified weather and climate as a high priority for monitoring because climatic forces are a major driver of Sierra Nevada ecosystems. Current patterns of vegetation, water dynamics, and animal distributions in the Sierra are determined largely by cumulative effects of past and present climates, in concert with geologic factors. Anthropogenic climate change is the stressor that is predicted to have the most pronounced effects on Sierra Nevada ecosystems. Since 85% and 91% of the elevations are above 1800 m in YOSE and SEKI respectively (i.e. above the rain/snow transition zone of 1500-1799 m), snow is the fundamental driver of hydrologic processes in these parks. Snowpack provides seasonal storage of water in the Sierra Nevada for soil moisture, lakes, and streams. This water storage is particularly important given the seasonal cycle of precipitation and the long summer-fall dry period in central and southern Sierra Nevada.

Due to its importance to park ecosystems and the Sierra Nevada region overall, snow was identified as a specific climatic indicator by the SIEN program. The goals of this project were to use existing data and techniques to assess the trends and current status of snowpack for six watersheds within SIEN parks and to recommend approaches for monitoring and modeling snowpack changes. To do so, we first retrieved, assembled, documented, and performed quality assurance and quality control of temperature and snow data for the six main river basins of the SIEN parks, including the Tuolumne, Merced, San Joaquin, Kings, Kern, and Kaweah River basins. Daily snow-covered area data were tabulated and snowmelt calculated for 300-m elevation bands over a ten-year period, 2000-2009, for each of the six basins. Daily snow-covered area estimates from satellite data were used to determine where snowmelt could occur. If an area was snow-covered on a day with an average temperature above $0^{o}C$, the amount of snowmelt was assumed to be proportional to the temperature above melting. The magnitude of snowmelt was estimated from average daily temperature for the elevation band and a melt factor (i.e., using a temperature-index/degree-day approach). Data from snow-measurement sites in each basin were used to estimate daily melt factors.

Evaluation of the satellite-derived snow-covered area (SCA) for the period 2000-2009 from MODIS (Moderate Resolution Imaging Spectroradiometer) showed that the average snowmelt progression, or the rate at which the snowline moves upslope during snowmelt, for the six basins is on average 17.0 m day^{-1}, and that each successively higher 300-m elevation band melts out about 20 days later than the elevation band below it. When the MODIS SCA was coupled with a temperature index model, the majority of the estimated snowmelt in the Tuolumne and Merced River basins was derived from mid-elevations between 2400-3000 m, and the majority of the estimated snowmelt in the San Joaquin, Kings, Kaweah, and Kern basins was derived from elevations above 3000 m.

Three climate change scenarios were considered: 2, 4, and 6 ^{o}C. Each $2^{o}C$ rise in temperature corresponded to the current average temperature about 300 m lower in elevation. Analysis showed that temperature increases will shift the amount of snow covered area as less precipitation falls as snow. To a first approximation, this can be viewed as a shift of 300 m in current SCA patterns. Currently across all six basins there is an elevation dependence of winter SCA, with each successive lower 300-m elevation band having greater inter-seasonal variability. That is, higher elevations, which are consistently below freezing much of the winter, have more consistent snowcover than lower elevations which in some winter months can melt out. The day of snowmelt was also projected, and achieved by imposing a temperature change on the basin and its snowpack by shifting the corrected SCA fractions up by 300 m per 2^{o}C change in temperature, which is consistent with the current observations that each 300 m corresponds to a 2^{o}C shift in temperature. Overall, the timing of snowmelt shifts toward earlier in the spring at a rate of -6 to -7 days per ^{o}C. That is, with a temperature increase of 2^{o}C, 50% of the seasonal snowmelt will be depleted about two weeks earlier than present

YOSE and SEKI have a fundamental gap in data and information about the water cycle, and how it affects water-dependent ecosystem services both in and downstream from the parks. This report focuses on one subset of the water cycle: snowpack and snowmelt. A more-extensive analysis of the water cycle, while clearly needed to assess critical park resources, would require modeling of additional parameters and is beyond the scope of the current analysis. Accurate knowledge of fine-scale temperature, precipitation, and snowpack patterns are fundamental to understanding water- and temperature-dependent resources. A current major gap is the lack of understanding of the amount of precipitation occurring across the landscape, and the partitioning of this precipitation between rain and snow. Other components of the hydrologic cycle have similar gaps. While improvements in modeling or gridding available data could help address these gaps, additional data for evaluation are also clearly needed. YOSE and SEKI have a fundamental need for a modern program of measurement of water-cycle attributes and analysis of water-cycle data to support management of other resources and assessment of ecosystem services provided within and outside their boundaries. A minimum protocol for continued assessment of snowpack resources should follow the approach used in this report.

Introduction

The National Park Service (NPS) has developed an Inventory & Monitoring (I&M) program to fill in knowledge gaps in baseline data about natural resources in parks and to design and implement long-term monitoring that will enable managers to develop broadly based, scientifically sound information on the current status and long-term trends in the composition, structure, and function of park ecosystems (Fancy et al. 2009). The Sierra Nevada Network (SIEN) is one of 32 I&M networks, or groups of parks, across the country. SIEN includes the following NPS administered units in California: Devils Postpile National Monument (DEPO), Sequoia and Kings Canyon National Parks (SEKI), and Yosemite National Park (YOSE).

SIEN and local park staff identified weather and climate as a high priority for monitoring through the NPS vital signs monitoring program (Mutch et al. 2008). Climatic forces are a major driver of Sierra Nevada ecosystems. Current patterns of vegetation, water dynamics, and animal distributions in the Sierra are determined largely by cumulative effects of past and present climates, in concert with geologic factors. Anthropogenic climate change is the stressor that is predicted to have the most pronounced effects on Sierra Nevada ecosystems. While weather and climate include multiple meteorological variables of interest for long-term monitoring, snowpack was singled out as a separate vital sign due to its importance in the Sierra Nevada and the entire region.

Snow is the dominant environmental factor in mountainous regions for more than half of the year (Mote et al. 2005). Sierra Nevada snowpack acts as a temporary reservoir, storing water until the spring snowmelt. It is then a primary source of water for the region, wherein reservoirs collect the snowmelt for gradual distribution to communities and for agricultural needs. In the semi-arid western United States, snowmelt runoff is thought to account for up to 80% of annual streamflow (Daly et al. 2000, Rice et al. 2011). In the alpine and subalpine, snowpack protects vegetation from the abrasive and dehydrating effects of wind and wind-driven snow, effectively limiting the height of most woody vegetation to that of the snowpack. Recent downscaled climate modeling results project that an increase in the average temperature in California of about 2°C would result in a loss of about half of the average April snowpack storage in the Sierra Nevada (Knowles and Cayan 2002, Mote et al. 2005).

Climate warming will affect ecosystem services through temperature-driven perturbations to the water cycle, manifest in effects including earlier runoff, lower late-season soil-moisture, lower stream baseflow, higher vapor-pressure deficits, and drought stress. Snowpack provides much of the seasonal water storage in SIEN parks, and replenishes soil-moisture storage late into spring and early summer. This soil-moisture storage provides for summer/fall baseflow and evapotranspiration. The amount and timing of snowmelt is thus critical for ecosystem health. Adaptation to that climate change involves managing the water cycle, through managing ecosystem services.

Our need to understand changes in snowpack across park landscapes requires us to use both ground-based and remotely sensed data. We have recently developed spatial distributions of snow water equivalent (SWE) in a subset of Sierra Nevada watersheds by combining remotely sensed snow-covered area products with point SWE measurements using a temperature-index/degree-day snowmelt calculation (Rice et al. 2011). This work provides an approach that can be applied to other watersheds in SIEN parks and offers a method that could be used for monitoring and estimating changes in snowcover and SWE from watershed to park and regional scales.

The goals of this project were to make use of existing data and methods to provide an assessment of the trends and current status of Sierra Nevada snowpack for the watersheds that are most important in or around SIEN parks, and to recommend approaches for monitoring and modeling snowpack changes. The area of interest includes the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins. The analysis focused on the main snow-producing parts of these watersheds, generally above 1500-1800 m elevation.

Product-oriented tasks outlined in the scope of work include:

1. Assemble and clean temperature and snow-pillow data for measurements in and around the six watersheds.
2. Prepare maps of fractional snow-covered area (fSCA) for the watersheds.
3. Conduct analyses of spatial and temporal trends in snowpack data for the six watersheds.
4. Make available the raw and/or derived snow and meteorological data available through the UC Merced Sierra Nevada Research Institute (SNRI) digital library.
5. Prepare a report that addresses the following for possible use by SIEN for developing long-term monitoring protocols for snowpack and weather/climate:
   - Includes detailed descriptions of tools and methods used for analyses of snow datasets.
   - Describes and interprets all analyses.
   - Recommends routine analytical methods, tools, and/or approaches to monitor changes in snowpack.
   - Identifies the most important gaps in ground-based snow measurements.
   - Prioritizes the most valuable areas to focus monitoring efforts, given limited resources and staff.
   - Assesses the current status of Sierra Nevada snowpack and highlights areas/watersheds that may be particularly sensitive to climate change.

This report addresses these required items and presents the findings, interpretation, and conclusions of our analysis. The core of the analysis involves assessing temporal and spatial trends in snowcover and snowmelt across the SIEN study area, both for current conditions and for warming of 2, 4, and 6^{o}C. Though the range of possible temperature scenarios covers several degrees, there is a strong consensus around these scenarios for northern California (e.g. Dettinger 2005; Hayhoe 2004; Cayan et al. 2008). Ground-based data are available in our digital library https://eng.ucmerced.edu/snsjho and satellite snowcover data at our *Center for Sierra Nevada Water Information Systems* http://zero.eng.ucmerced.edu/snow/csnwis.

Methods

Daily snow-covered area data were tabulated and snowmelt calculated for 300-m elevation bands over a ten-year period, 2000-2009, for each of the six main river basins that are partially within SIEN parks. Daily snow-covered area estimates from satellite data were used to determine where snowmelt could occur, and the magnitude of snowmelt was estimated from average daily temperature and a melt factor (i.e., using a temperature-index/degree-day approach). If an area was snow-covered on a day with an average temperature above $0^{o}C$, the amount of snowmelt was assumed to be proportional to the temperature above melting. Average temperatures for each elevation band were used in the calculations. Thus, results represent average conditions across aspects and forest cover at that elevation band. Data from operational snow-measurement sites in each basin were used to estimate daily melt factors.

The expected impact of climate warming on snow-covered area and snowmelt were then estimated by increasing temperatures under three scenarios: 2, 4, and 6 ^{o}C for snowmelt calculations; and also by shifting snowcover amounts at each elevation to values observed for the 2000-2009 period for a lower elevation that is presently 2, 4, or $6^{o}C$ warmer.

Study Area

The study area includes the six major watersheds within Yosemite National Park, Sequoia and Kings Canyon National Parks, and Devils Postpile National Monument: the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins (Table 1, Figure 1). The Tule River basin, which is also within the boundary of SEKI, was not included in the analysis due to the small area that is within the boundary of the park (20 km^2) and the similarities in topography to the Kaweah and Kern River basins. The Tuolumne, Merced, and San Joaquin basins drain into the San Joaquin River in the Central Valley, while the Kings, Kaweah, and Kern are endorheic basins (no outflow into other drainages). In the past, the Kings and Kaweah emptied into Tulare Lake and the Kern emptied into Buena Vista Lake.

Table 1. Basin areas and elevations.

	Above confluence		Within parks	
Basin	Area km^2	Elevation m	Area km^2	Elevation m
Tuolumne	4184	56-3980	1716	876-3980
Merced	2486	95-3969	1300	654-3969
San Joaquin	4418	92-4238	169	2447-4215
Kings	4789	110-4302	1641	1199-4302
Kaweah	2428	125-3814	907	414-3814
Kern	6142	154-4409	765	1929-4409
Total	24,447	56-4409	6509	414-4409

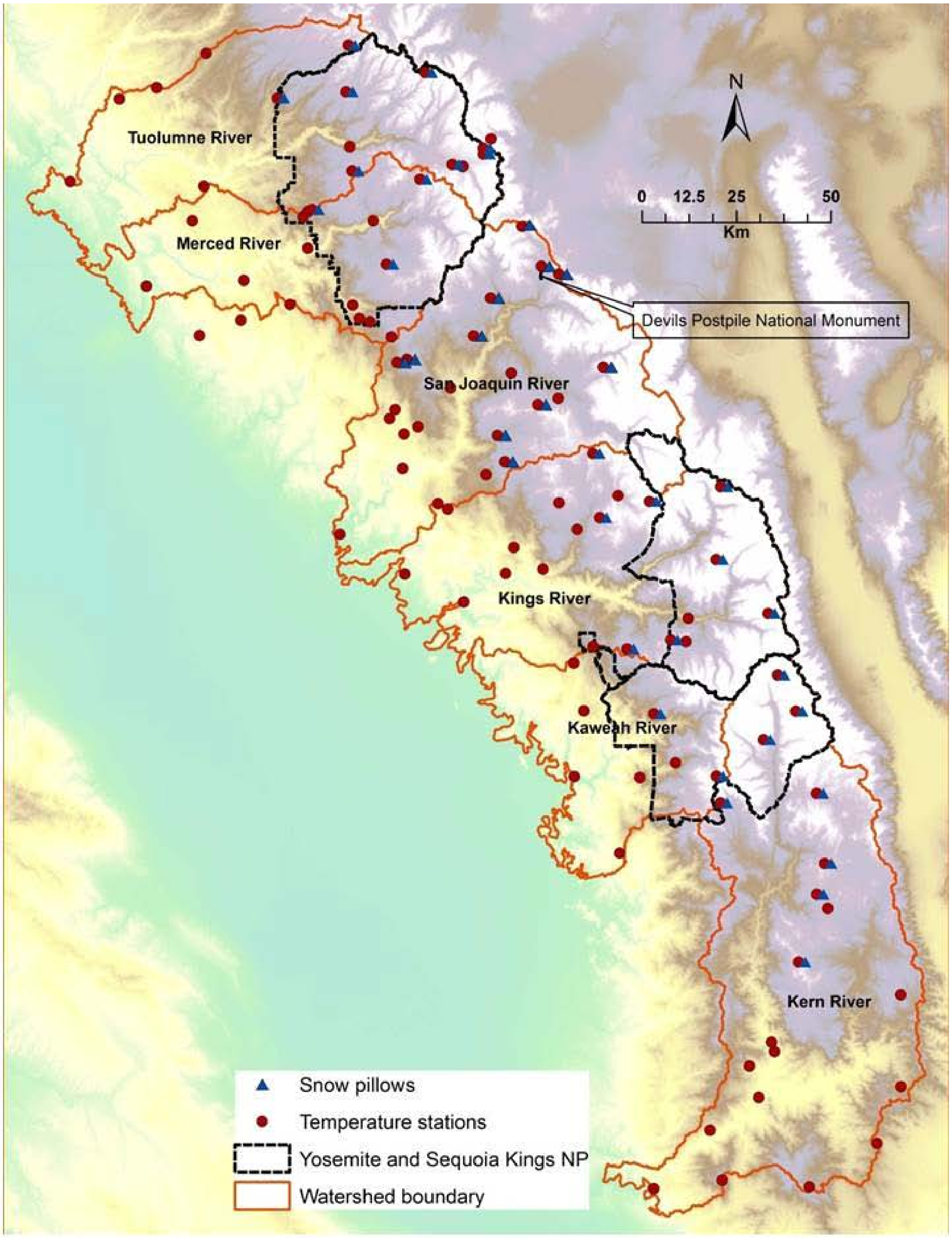

Figure 1. SIEN study area located in Yosemite and Sequoia and Kings Canyon National Parks, showing snow pillows and temperature stations in the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins.

The six river basins that overlay the parks extend down into the San Joaquin Valley, with areas of 2428-6142 km^2, and an average area of about 4000 km^2. The total area of YOSE is 3027 km^2; the area of SEKI is 3502 km^2; and the area of DEPO is 3.2 km^2. Since 85% and 91% of the elevations are above 1800 m in YOSE and SEKI respectively, with a snow/rain transition zone of 1500-1800 m, seasonal snow is the fundamental driver of the hydrologic processes. DEPO is at an elevation of 2188-2515 m.

The persistently seasonally snow-covered areas, which start at the rain/snow transition of 1500 m, represent 57% (2404 km^2) of the Tuolumne, 50% (1408 km^2) of the Merced, 72% (3199 km^2) of the San Joaquin, 66% (3172 km^2) of the Kings, 34% (835 km^2) of the Kaweah, and 75% (4628 km^2) of the Kern River basins. The study area was partitioned into eight (Tuolumne, Merced, Kaweah) or nine (San Joaquin, Kings, Kern) elevation bands of 300-m increments, beginning at 1500 m and extending to greater than 3900 m. Figure 2 illustrates that the southern Sierra Nevada basins, especially the Kings River basin, have the greatest proportion of high-elevation area. For example, about 20% of the Kings River basin is above 3000 m compared to only about 5% of the Merced and Tuolumne basins.

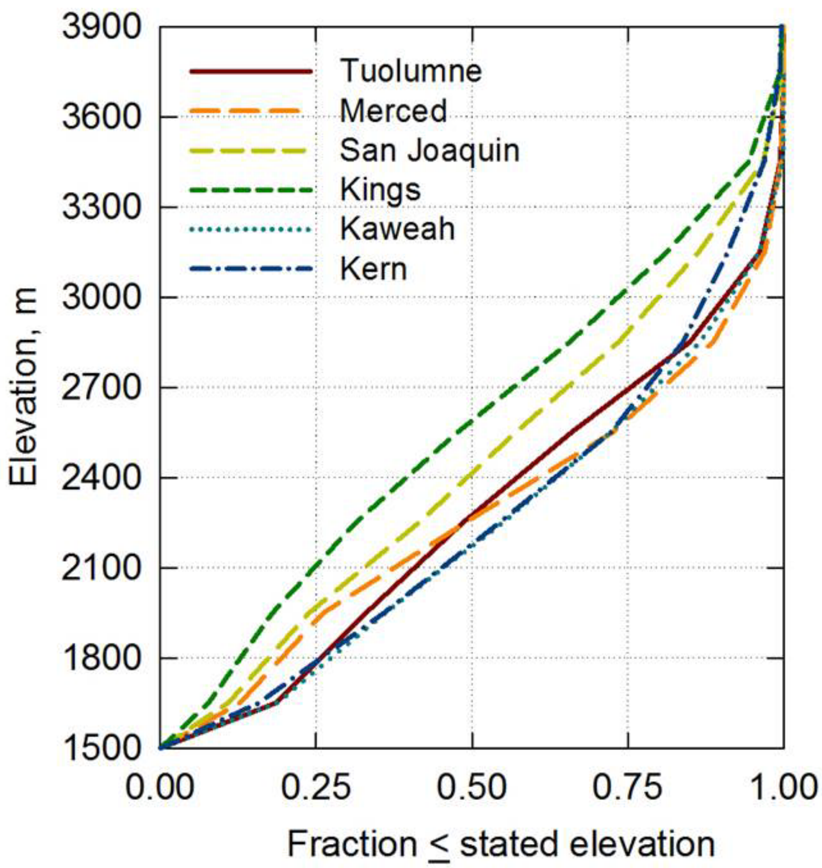

Figure 2. Elevation ranges of the portions of the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins above 1500 m.

Spatial Data

The Digital Elevation Model (DEM) used in these analyses was developed from topographic data from the Shuttle Radar Topography Mission at 30-m spatial sampling (Farr et al. 2007), and was resampled to 500 m for use with the MODIS products. This product was used instead of park-specific DEMs because it covers the full domain of the Sierra Nevada watersheds in the study area. Vegetation layers, including canopy closure values, were downloaded from the National Park Service website http://nrinfo.nps.gov/Geospatial.mvc/Welcome. These map layers were resampled and converted to a 500-m raster file using ArcGIS. Since the National Park Service maps only cover the area within the boundaries of Yosemite, Kings Canyon, and Sequoia National Parks, any missing tree-canopy densities were filled and extended across the 6 basins using National Land Cover Data (NLCD) (http://www.mrlc.gov/nlcd_multizone_map.php). The NLCD provides a 30-m resolution of tree-canopy densities derived from the Landsat Enhanced Thematic Mapper Plus, and was resampled to a 500-m resolution using ArcGIS.

Temperature and Snow Water Equivalent

Point temperature and snow-pillow data from operational agencies were downloaded from the California Data Exchange Center (CDEC) (http://cdec.water.ca.gov/) and from the Western Regional Climate Center (WRCC) (http://www.wrcc.dri.edu/) for water years 2000-2009. CDEC receives real-time data from over 180 federal, state, and local agencies that operate hydrometeorological measurement sites. CDEC then stores and serves these data and related information. All CDEC data are made available to the public in near-real time, with very limited data control. The result is that there is a range of data quality and reliability, with some data being excellent, and some data not adhering to strict data protocols that assure data quality. Therefore, all data downloaded from CDEC were checked for quality.

WRCC provides access to Remote Automated Weather Stations (RAWS), a network of stations that are not currently available on CDEC. Data from these stations undergo some degree of data processing prior to being made available to the public. These data were evaluated in the same manner as were the CDEC data, and used without modification unless there was an obvious problem.

Temperature is measured at 71 locations in the basins by a variety of operators and, with various levels of quality control, at elevations ranging from 174 m to 3477 m. Most stations report hourly temperature for the period of record and some report daily minimum, maximum, and average temperatures. Values were averaged to get daily average temperature, which was used for the current analysis. Examples of the data for seven stations along an elevation gradient in the San Joaquin basin are shown on Figure 3, with the complete daily average data in the Appendix. Spikes and spurious data were eliminated and gaps were filled by linear interpolation or correlation with nearby stations. The data used in this analysis are archived at the SNRI Digital Library (https://eng.ucmerced.edu/snsjho) and archived into three data levels: Level 0 is the raw data downloaded directly from CDEC and WRCC; Level 1 is the QA/QC data with gaps; and Level 2 is the gap-filled data.

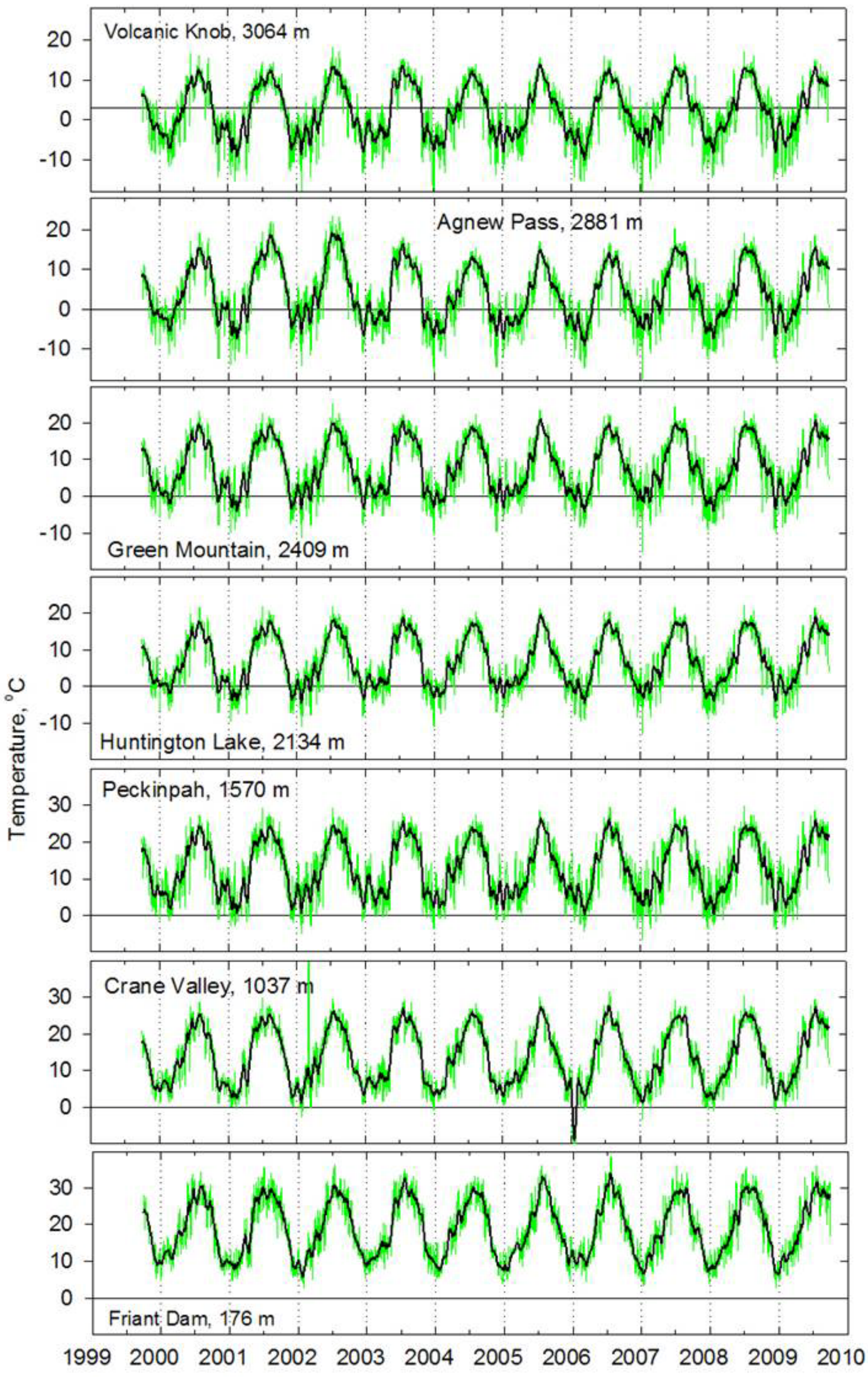

Figure 3. Daily average temperature for seven stations in the San Joaquin River basin. Green lines are daily means and black lines are 20-day running means.

Snow water equivalent (SWE) is measured continuously at 39 snow-pillow locations in the six basins: seven in the Tuolumne, three in the Merced, eleven in the San Joaquin, eight in the Kings, two in the Kaweah, and eight in the Kern (Figure 1). These operational sensors, operated mainly by the California Department of Water Resources (CDWR) and U.S. Natural Resource Conservation Service (NRCS), are primarily used for real-time statistical forecasts of seasonal runoff by data measured by the various water resources managers in the basins. Though these index sites (i.e. snow pillows) generally provide seasonal runoff forecasts of acceptable accuracy, they fail to provide spatially representative measures of SWE and do not capture the physiographic variability across a basin. Note also that while records were reasonably complete, about one-third of the stations had one or more years of missing SWE data during the 10-year period. Examples of the data for seven stations along an elevation gradient in the San Joaquin basin are shown on Figure 4, with the complete daily average data in the Appendix. Note that despite a 900-m elevation range for snow pillow in the San Joaquin, they do not show a consistent elevation difference in peak SWE, reflecting in part the wide spatial variability in SWE within all elevation ranges. Only the lower-elevation station shows less SWE in most years, likely due to a combination of less precipitation and some fraction of the precipitation falling as rain versus snow.

Data from longer-term snow courses are also available; however those measurements are only monthly snapshots of snowpack water equivalent at 86 index sites (17 Tuolumne, 5 Merced, 25 San Joaquin, 22 Kings, 5 Kaweah, and 17 Kern) in the six basins. The snow-course data were not used in the present analysis of daily snow cover and snowmelt.

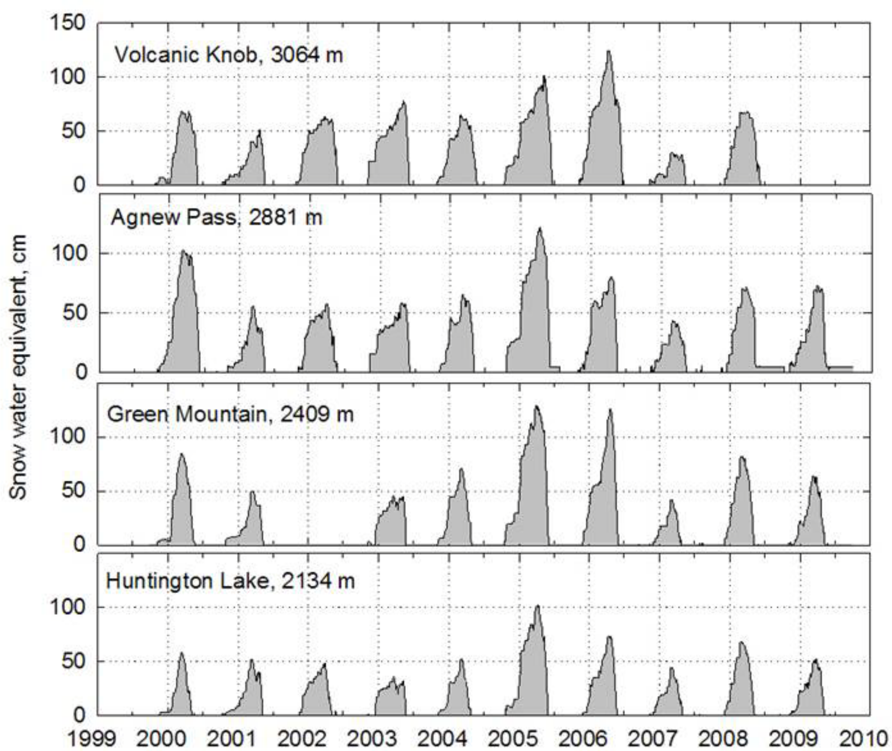

Figure 4. SWE for four pillows in the San Joaquin basin. Note that some years have missing data (not zero values).

Snow-Covered Area

Snow-covered area from MODIS provides the only basin-wide coverage of snow, shown on Figure 5 for one day in 2008. Daily fractional snow-covered area (fSCA) values for 2000-2009 were estimated from MODIS scenes using the MODSCAG algorithm (Painter et al. 2009). MODSCAG uses the MODIS surface-reflectance product (MOD09), sampled at a 500-m resolution in seven spectral bands and corrected for atmospheric scattering (Kotchenova et al. 2006). The MODSCAG product is retrieved from the satellite reflectances using a spectral-mixing model in which a set of end members (snow, rock, vegetation), present in different proportions in each pixel, is used to “unmix” a scene on a pixel-by-pixel basis. The algorithm uses the spectral information from MODIS to estimate subpixel snow properties: fSCA, grain size, and albedo (Painter et al. 2009). The daily snow-cover products were developed from the Terra satellite. It has previously been established that one must map snow-covered area at subpixel resolution in order to accurately represent its spatial distribution (Nolin et al. 1993). Otherwise, systematic errors result. While overestimates may balance underestimates for the basin average, distributed hydrologic applications in mountainous regions require the spatial distribution of snow cover.

Cloud-free days were selected from the daily time series by visual inspection of both the snow-cover product and the MODIS cloud products. This resulted in fSCA values being available for approximately half of the days of interest in any given year. These fSCA values were then averaged across all pixels in 300-m elevation bands from 1500 m to the highest elevation in each watershed. Raw data values for cloud-free days in 2008, an average accumulation year, are shown on Figure 6. Snow was only present below 1500 m in a few scenes, and values were generally near zero. The analysis used eight elevation bands for the Tuolumne, Merced, and Kaweah and nine for the San Joaquin, Kings, and Kern. The area above 3900 m in the San Joaquin, Kings, and Kern was still relatively small when compared to the total snow-producing area (Figure 2). Note that despite the day-to-day variability due in part to atmospheric conditions and noise in the viewing/retrieval system, fSCA shows a remarkable consistency between elevations and across the six basins (Figure 6).

Daily fSCA was then estimated by interpolation values from cloud-free days using a four-parameter sigmoidal curve fit. Figure 7 shows the four-parameter sigmoidal fits for a wet year (2005) and a dry year (2007) for the northern-most (Tuolumne), central (San Joaquin), and southern-most (Kern) basins.

One main factor limiting the accuracy of the satellite-derived fSCA values is forest canopy cover because tree canopies limit satellite observation of the ground. That is, satellites cannot detect snow under tree canopies. Thus corrections were made for snow obscured by canopy cover and were based on the range of fSCA and canopy cover across elevation bands for individual pixels in the elevation band. Another issue with the fSCA estimates is that the MODSCAG algorithm has a lower detection limit of 0.15, thus limiting detection of residual snow as pixels melt out. It should be noted that complex topography also limits full viewing of snow for off-nadir viewing angles.

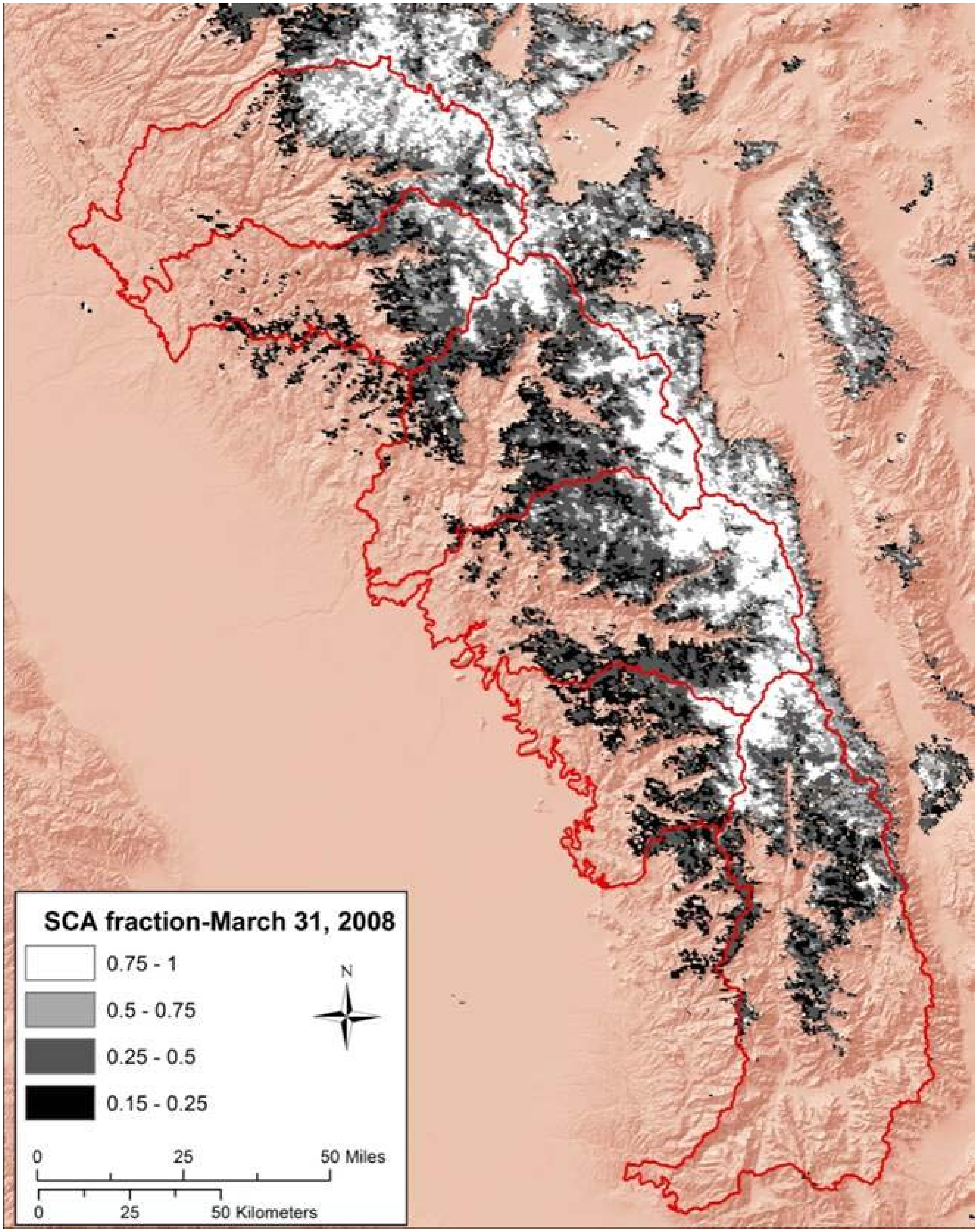

Figure 5. Fractional SCA across the six watersheds on March 31, 2008. fSCA values are binned into four fractions for ease of viewing (see legend). These values represent the fraction of the pixel that was detected by the satellite as being snow covered. Resolution of fSCA pixels is 500 m. Red polygons are hydrologic basin boundaries.

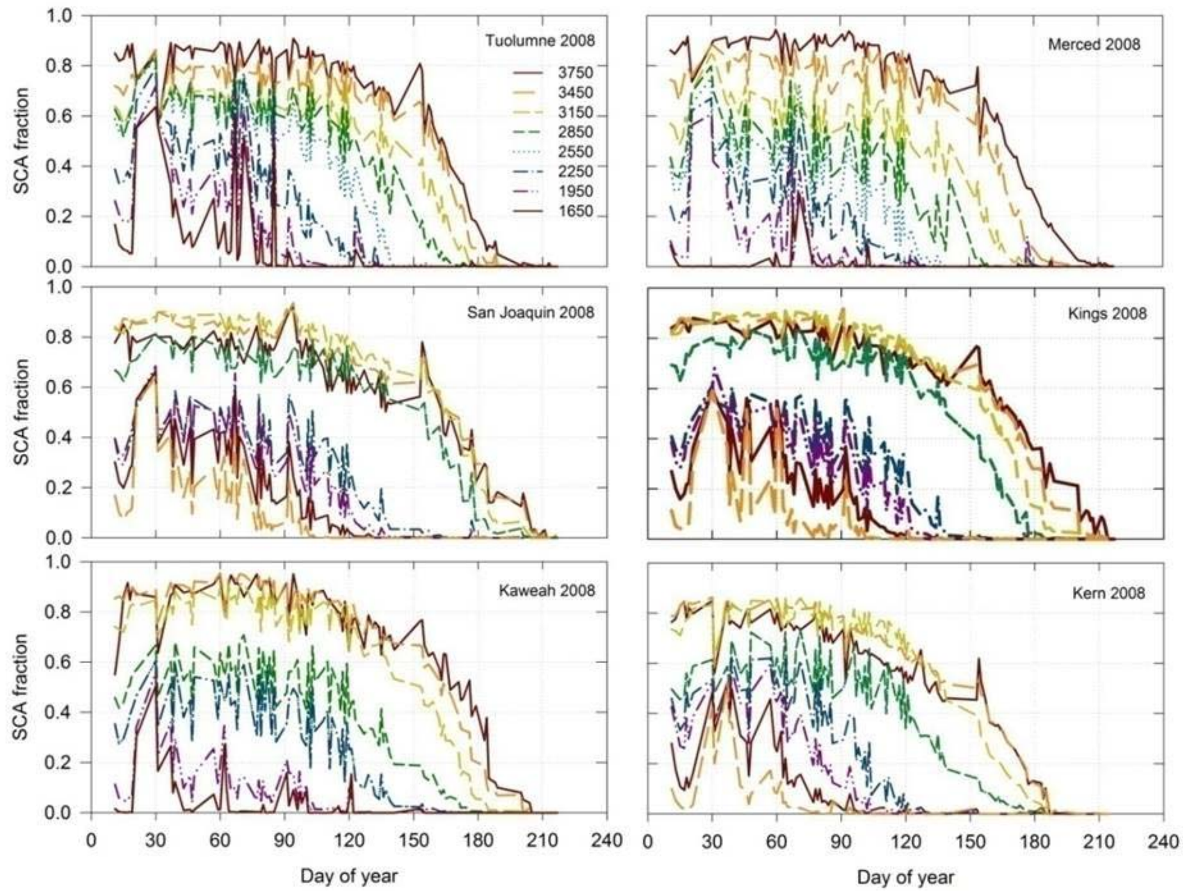

Figure 6. fSCA time series for 2008 for the six main watersheds draining from Yosemite and Sequoia and Kings Canyon National Parks.

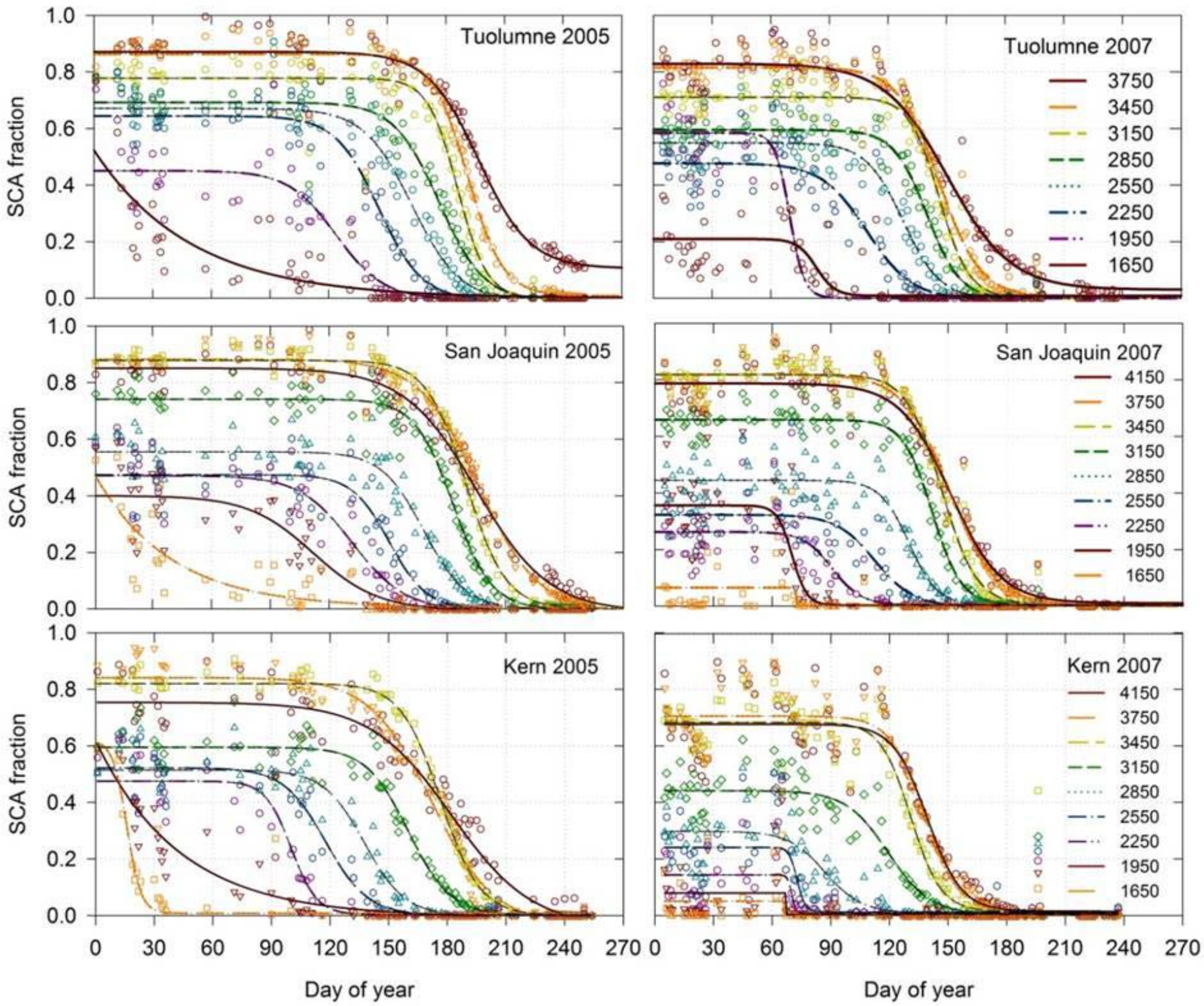

Figure 7. fSCA for Tuolumne, San Joaquin, and Kern River basins, with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for a wet (2005) and a dry (2007) year. Values not adjusted for canopy cover.

Canopy cover adjustments over the 2000-2009 period ranged from 0.10 to 0.45 for fSCA in each elevation band. Following adjustment, the resulting data were fit to a four-parameter sigmoidal curve, and the fits were used for subsequent analyses. Adjustments for 2008 for the nine elevation bands in the San Joaquin basin are shown on Figure 8. On this figure, the SCA values for each pixel and each day in 2008 are shown as a point; note that 2008 was about average SCA for the period of the analysis. The average line for the pixels is shown as a sigmoidal fit to the average fSCA, as well as the sigmoidal fit to the fSCA after adjustment. The magnitude of each adjustment was set to two standard deviations above the mean of the winter values for elevations between 1500 and 3600 m, prior to melt, and one standard deviation above the mean of the winter values, prior to melt, for elevations above 3600 m. The upper limit was a value of 1.0, with the adjustment also limited by the average canopy closure from the vegetation data. The same magnitude of vegetation and threshold corrections were applied to each year, up to a SCA fraction of 1.0.

Though ground snow-cover data for a formal evaluation of the correction were not available, estimates made when the higher elevations are essentially completely snow-covered suggest that uncertainty is on the order of 5%. That is, complete snow-cover represents coverage of 0.95-1.00, depending on the presence of slopes too steep to hold snow and trees. Corrections were larger in the mid elevations, which have greater canopy cover. Three years (2005, wet; 2007, dry; 2008, average) illustrate the magnitude of the corrected fSCA for the San Joaquin basin (Figure 9). Note that SCA in the San Joaquin River basin at highest elevation bands was corrected to near 100%, with values in lower elevation bands receiving adjustments of similar magnitude. Values before and after adjustment for two other basins, the Tuolumne and Kern, are shown in the Appendix.

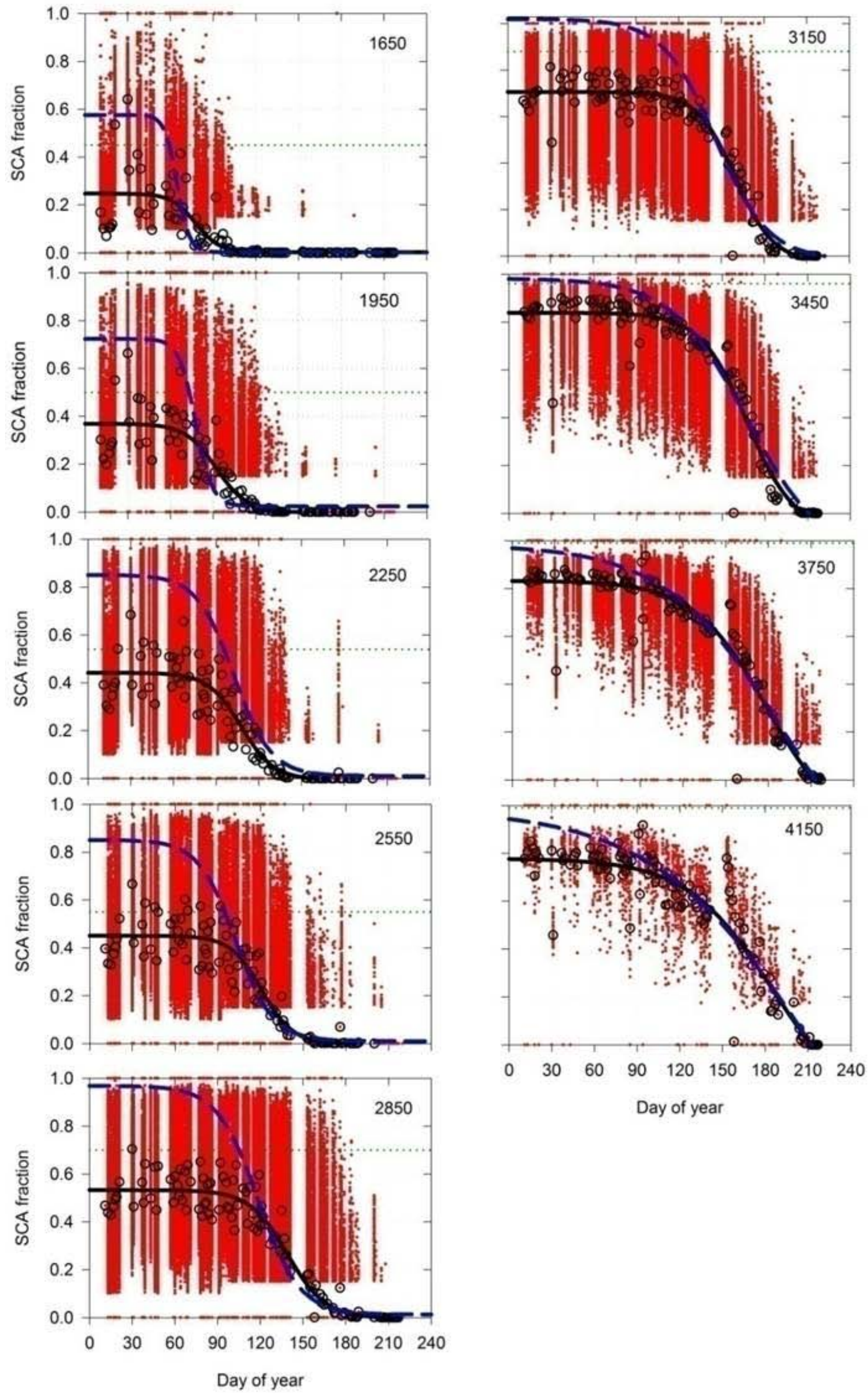

Figure 8. San Joaquin River basin fSCA for 2008, presented in 300-m elevation bands and centered on nine different elevations (indicated in the upper right corner of each panel). Each closed dot is the SCA for an individual pixel and each open circle is the daily average. The solid line is the fit to a four-parameter sigmoidal curve; the dashed line is the adjusted fit. The dotted line represents the mean canopy opening across the elevation band.

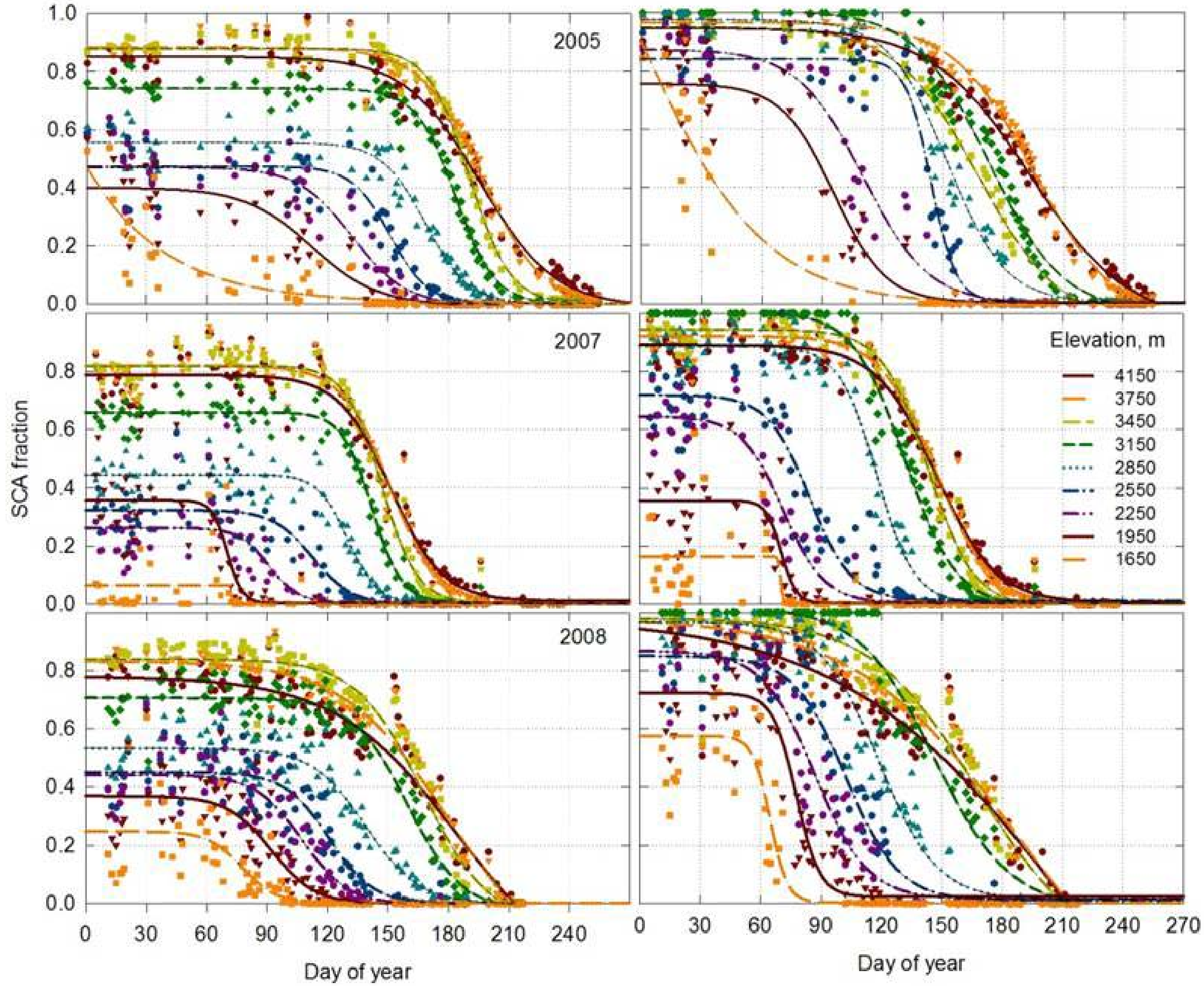

Figure 9. Comparison of the raw (left panels) and adjusted (right panels) fSCA for a wet (2005), dry (2007), and average (2008) year for the San Joaquin River basin.

Daily Snowmelt Volume

Daily snowmelt was estimated for each 300-m elevation band in each of the basins analyzed based on the snow-cover in that elevation range, and the daily temperature. The cumulative snowmelt was then summed back in time to get seasonal and annual totals (Cline et al. 1998, Liston 1999, Molotch et al. 2004). This "depletion" approach assumes that the amount of snow that melted in a given area on a given day is equivalent to the net energy available for snowmelt on that area multiplied by the fSCA value for that area. Daily snowmelt was back calculated using a temperature-index, degree-day equation rather than a full energy-balance model (Anderson 1968, Granger and Male 1978, Kuusisto 1980):

$$M = a(T_a - T_b) \quad (1)$$

where M is the daily snowmelt, a is a degree-day coefficient (m deg^{-1} day^{-1}), T_a is average daily temperature, $T_b = 0^{o}$C; when $T_a < T_b$, no melt occurs (Kustas et al. 1994). This depletion-method calculation was driven by daily average temperature, which was calculated across the elevation range of the study area using a ground-surface lapse rate that was estimated from stations in the study area. The approach provides an index of the average energy flux, but does not explicitly consider the individual fluxes and controlling factors that influence snowmelt (e.g. solar radiation, albedo, topography, turbulent energy exchanges).

Twenty-two stations in the Tuolumne, 27 in the Merced, 22 in the San Joaquin, 20 stations in the Kings, eight stations in the Kaweah, and 20 stations in the Kern (Table 1) were used to estimate, annual-average and monthly ground-level "lapse rates" for the ten-year period 2000-2009. In this analysis, lapse rate is defined based on near-ground-level stations at different locations and elevations. It does not refer to the vertical temperature profile in the atmosphere at one location, though the two quantities should be similar. Note that a continuous ten-year record is not always available for all the temperature stations, and in some years fewer stations were used. The lapse rates were determined by fitting a regression line to the daily, monthly, and annual-average temperatures reported for different elevations in each basin.

Daily data from snow-pillow sites were used to estimate coefficients for the degree-day calculation. Since temperature and SWE vary from year to year, producing different inter-annual daily melt rates, a daily degree-day coefficient for each year was calculated for the each river basin using the co-located snow-pillow and temperature measurements. Values of the degree-day coefficient (*a*) were estimated from data at each of the snow-pillow sites in the basins by dividing the amount of daily melt indicated by the snow pillow by the daily degree-day quantity.

Days with near-zero melt and days with very high melt (>0.045 m $^{o}C^{-1}$ day^{-1}) but near-zero degree days were not used. Note that snow-pillow response may on some days lag actual melt, and on other days show higher than actual melt, owing to creep, ice bridging, and the influence of ice lenses on meltwater flow.

This method of parameterizing the daily degree-day coefficient was similar to the methods developed by Martinec (1960) and Anderson (1968) and used in such semi-distributed runoff models as the Snowmelt Runoff Model (SRM) and Snow-17.

A second method for estimating daily snowmelt was performed for comparison with the back-calculation method. This method estimated snowmelt using fSCA and SWE interpolated from snow-pillows. The second method, which underestimated snowmelt from higher elevations relative to the back-calculation approach, is described briefly here. Further detail may be found in Rice et al. (2011). The method involved interpolation of point SWE measurements from snow pillows followed by masking with the MODIS fSCA product (Fassnacht et al. 2003, Bales et al. 2008). Masking involves multiplying the pixel-by-pixel MODIS fSCA product by the interpolated SWE product. In this method, SWE for each 500-m grid cell was interpolated using a linear regression between elevation and SWE for all snow pillows within a 200-km radius of that pixel, including those outside the basin. A residual was obtained at each grid cell where a snow pillow was located by removing the observed value from the analysis (i.e. jack-knifing) and subtracting the observed SWE from the computed SWE. Elevation-dependent biases in the residuals were removed by regressing residuals to a fixed datum of 5000 m using a lapse rate. Once regressed to the common datum, the lapsed residuals were spatially distributed using inverse distance squared weighting. The gridded residual surface was then regressed back to the basin surface using the same lapse rate and subtracted from the hypsometrically derived SWE grid in order to derive the SWE surface, thus preserving the SWE observation at each station.

Daly et al. (2000) used a similar approach but computed one hypsometric relationship for each sub-basin instead of using a moving search radius to compute the hypsometric relationship at each pixel. Daily snowmelt was calculated by the daily grid cell differences in SWE.

Results

Snow-Covered Area

The fSCA results for the six basins are shown for a relatively wet year (2005) and a relatively dry year (2007) on Figure 10. Patterns in fSCA were remarkably consistent across the watersheds, with winter values near 1.0 at the highest elevations, and lower fSCA values in successively lower elevation bands.

In the Tuolumne River basin, which is representative of the northern portion of the SIEN study area and of Yosemite National Park, winter fSCA values in 2005 reached 0.80 to 0.90 in the winter for the highest elevations (3150, 3450, and 3750 m), dropping off slightly to 0.65 to 0.70 over the next 900 m (2250, 2550, and 2850 m), and dropping off steeply over the next 300 m. In 2007, which was 46% of the historical April 1 SWE from snow courses, fSCA shows a similar trend, but less snow, with fSCA values reaching 0.80 at the highest two elevations (3450 and 3750 m), and dropping off to 0.70 over the next 300 m (3150 m), and again dropping off steeper at elevations below 3000 m.

In the San Joaquin River basin for 2005, fSCA values reach 0.85-0.90 in winter at the highest elevations (3450, 3750, and 4150 m elevation bands), drop slightly in the next 300 m (3150 m elevation band), and then drop off more steeply over the next 300 m. The drier year, 2007, shows a similar trend, but with less snow, with SCA values reaching 0.80 at the highest elevations, dropping slightly to 0.75 over the next 300 m (3150 m), and again dropping off steeply at the lower elevations (<3000 m).

In the Kern River basin, representing part of the southern part of SEKI, fSCA values in 2005 reached 0.75-0.85 in winter at the highest three elevations (3450, 3750, and 4150 m), drop to 0.48-0.6 in the next four elevations (2250, 2550, 2850, and 3150 m), and drop off more steeply over the next 900 m. In 2007 the highest three elevations have a lower SCA value (0.70) across all three bands, with significantly lower SCA at the mid- to lower- elevations. Both 2005 and 2007 exhibit one main spring melt, with snowcover declining from relatively constant winter values to zero over a period of 2-3 months, except at the lowest elevations were melt was over a period of 1-2 months. In the analysis that follows, 2005 and 2007 are used as indicative of the snow-producing elevations during a wet and dry year, respectively.

Note that in the lowest elevation bands, snowmelt occurs relatively quickly in winter. fSCA in the more-southern Kern River basin is lower than that in the more-northern Tuolumne River basin, and snowmelt was earlier. Only in the wet year (2005) was there significant snow-covered area in the lowest elevation band, 1650 m. In the dry year (2007) there was also little snow-covered area in the 1950 and 2250 m elevation bands. Note that the six river basins have similar elevation distributions in their main snow-producing elevations, with 60-70% of each basin being in the 1800-3000 m elevation range (Figure 2).

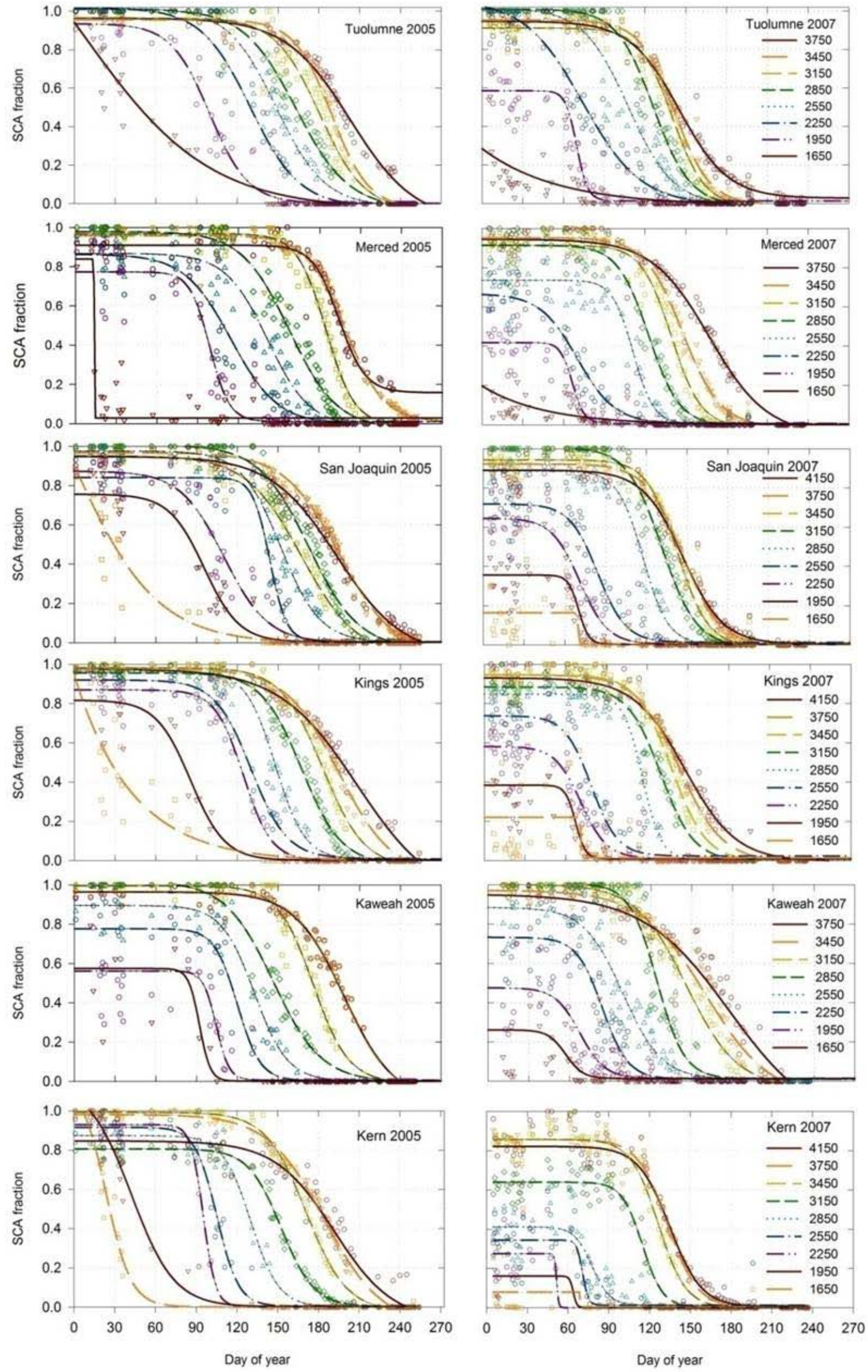

Figure 10. fSCA for the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins, with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for a wet (2005) and dry (2007) year. Values are adjusted for canopy cover

The average snowmelt progression, indicated by the day at which fSCA in a given elevation band drops below 0.2, over the period 2000-2009 for the six basins is on average 17.0 m day^{-1}. However, the snowmelt progression in the Tuolumne and Merced is slightly lower, with an average of 15.5 m day^{-1}, and an average of 17.7 m day^{-1} in the San Joaquin, Kings, Kaweah, and Kern (Figure 11). Note that each successively higher 300-m elevation band melts out about 20 days later than the elevation band below it, in warm and cool springs, deep or shallow snow, high or low elevations. Though there was some inter-annual variability in these values, it was not systematically different between wet versus dry years.

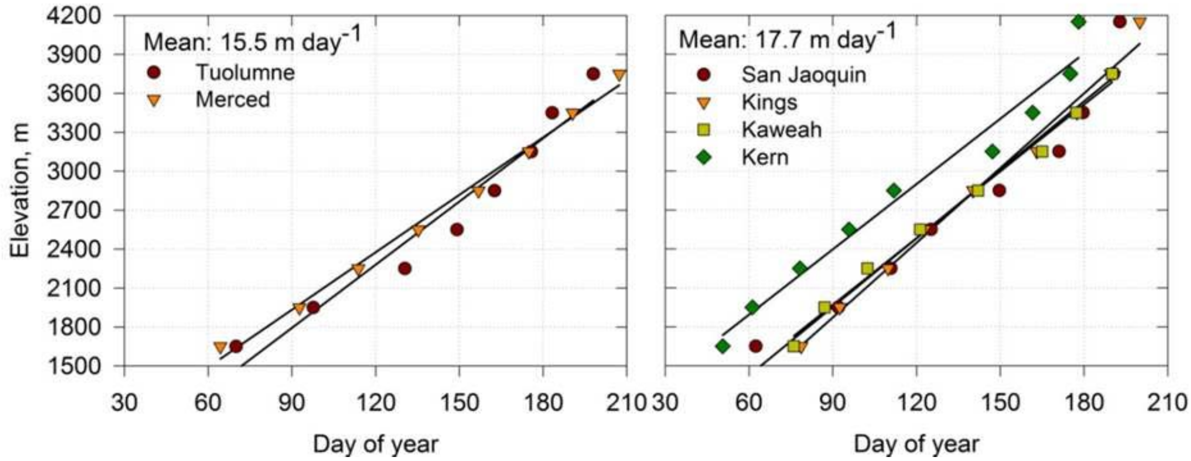

Figure 11. Average snowmelt progression for 2000-2009, indicated by increase in elevation of average snowline during melt season. Values on this graph are indexed at 20% SCA rather than zero.

Back-Calculated Snowmelt Volume

Temperature Lapse Rates

Average monthly and average annual ground-level temperatures and associated lapse rates for the two YOSE basins (Merced and Tuolumne) are shown on Figure 12a. Monthly lapse rates (see figure legend) ranged from -5.1 to -6.3 ^{o}C per 1000 m elevation, with an annual average of -5.9 and –5.6 ^{o}C per 1000 m for the Tuolumne and Merced, respectively. Values are lowest in winter and highest in summer. For the main snow-accumulation season, December through March, the averages range from -4.6 to -5.9 ^{o}C per 1000 m; for the main snowmelt season, April through June, the average ranges from -5.9 to -6.3 ^{o}C per 1000 m, corresponding to approximately a 1.8 to 2 ^{o}C change in average temperature for each 300-m elevation change.

Monthly lapse rates for the four SEKI basins, shown on Figure 12b, ranged -4.6 to -7.3 ^{o}C per 1000 m elevation; with an annual average of -5.6, -5.9, 5.8, and -6.7 ^{o}C per 1000 m for San Joaquin, Kings, Kaweah and Kern River basins, respectively. Values are lowest in winter and highest in summer. For the main snow-accumulation season, December through March, the average ranges from -5.1 to -6.2 ^{o}C per 1000 m, i.e. slightly higher than in the Tuolumne and Merced basins. For the main snowmelt season, April through June, the average ranges from -5.8 to -7.2 ^{o}C per 1000 m, corresponding to approximately a 1.7 to 2.2 ^{o}C change in average temperature for each 300-m elevation change.

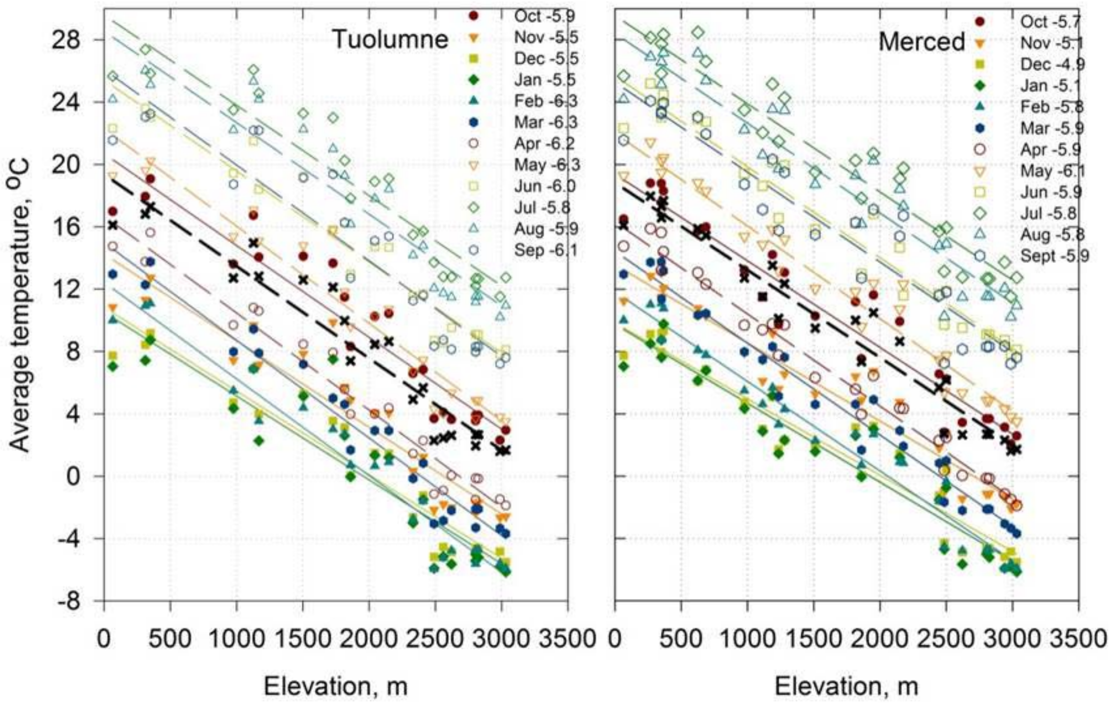

Figure 12a. Average monthly and average annual ground-level temperatures and calculated lapse rates for the two basins in YOSE. Average annual temperatures are marked by × and fit by heavy dashed line. Monthly lapse rates (i.e., slopes of the individual monthly fitted lines) are in the legend.

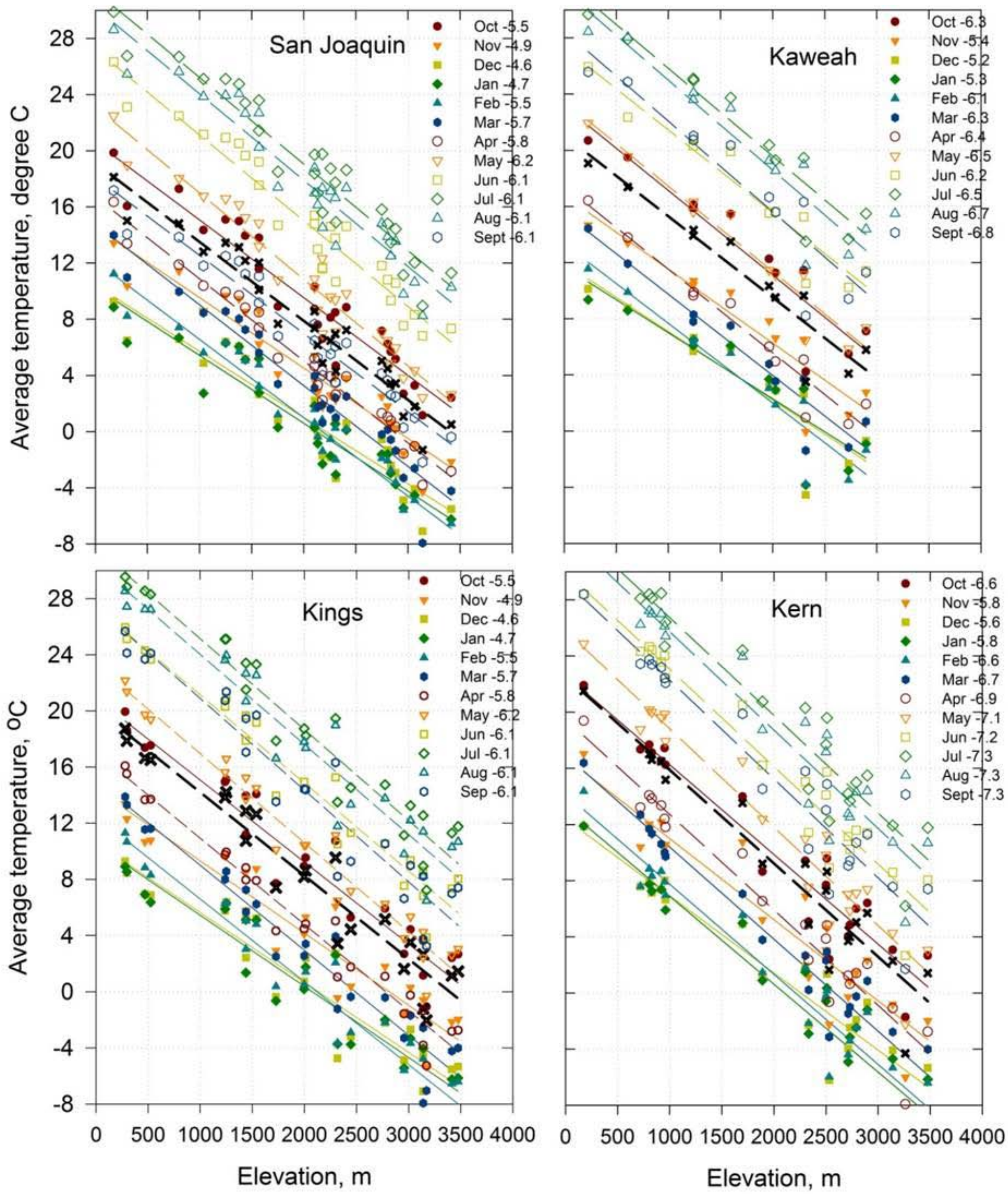

Figure 12b. Average monthly and average annual ground-level temperatures and calculated lapse rates for the four basins in SEKI. Average annual temperatures are marked by × and fit by heavy dashed line. Monthly lapse rates (i.e., slopes of the individual monthly fitted lines) are in the legend.

In the calculations that follow, values of -5.8°C per 1000 m were used over the year for the Tuolumne, Merced, San Joaquin, Kings, and Kaweah River basins, while -6.7°C per 1000 m was used for the Kern River basin.

Degree-Day Coefficient
There was no consistent or statistically significant seasonal trend to the degree-day coefficient for any of the sites. Some sites had a large degree of inter-annual and intra-annual variability, with others showing much less scatter, but values did increase over the ablation season (Figure 13). Each of the basins had different degree-day coefficients, possibly reflecting differences across latitude, e.g., (north versus south), and possibly just reflecting different placements.

In part because there were multiple snow-pillow and co-located temperature stations in each basin we used different degree-day coefficients for the northern, central, and southern basins (Figure 14). Since the Tuolumne and Merced River basins are adjacent and have similar physiographic characteristics, the same set of daily values was used for both. Snow pillows and temperature stations were located in four of the eight elevation bands between 1800-3000 m in the Tuolumne and Merced River basins, four of the nine elevations bands between 2100-3300 m for the San Joaquin River basin, five of the nine elevations bands between 2100-3600 m in the Kings and Kern River basins, and three of the eight elevations bands between 2100-3000 m in the Kaweah River basin. Stations were grouped by elevation band and a linear trend fit to the values. In addition, in order to reduce the effects of possible site-specific differences (i.e. local shading, vegetation) snow pillow stations within $\pm$80 m of an elevation band were included to increase the sample size and reduce the bias. It should be noted that no station data were available above the 2700-3000 m elevation band in the Tuolumne and Merced, 3000-3300 m elevation band in the San Joaquin, 3300-3600 m elevation band in the Kings and Kern, and 2700-3000 m elevation band in the Kaweah River basins. Where station data above and below elevation bands are available, daily coefficients from the adjacent elevation band were applied. Note that not all sites had usable data for estimating the coefficients for each year, and that the slopes to the fitted lines for the individual years were not statistically significant (Figure 14).

Snowmelt Volume
Back-calculated, snowmelt estimates from the depletion method are shown for the six basins for 2005, 2007, and 2008 on Figures 15a and 15b. Recall that in this analysis, daily snowmelt is summed back in time beginning with the day that fSCA reaches zero. The summation is done back to the day that snowmelt is zero, i.e. when daily average temperatures are constantly below zero. This cumulative snowmelt is expressed as SWE, or water depth. Because precipitation was small during snowmelt, the product is indicative of SWE on the ground for that period. Over the full snowmelt period, mid and higher elevations contributed a greater depth of snowmelt than lower elevations; although the relative ranking of different elevation bands changed from year to year.

Snowmelt contributions from each elevation band for the full ten-year period are summarized on Figure 16, which shows the mean and standard deviation for the period. Note that seasonal snowmelt increases a similar amount with elevation in all basins, despite the approximately 20-50% more snowmelt in the Tuolumne, Merced, and San Joaquin versus the Kings, Kaweah, and Kern. The drop-off at the highest elevation in the Tuolumne and Kaweah is due in part to the very small fraction of the basin in that elevation band and thus limited range of physiographic variability within that fraction. Note also the steep gradient in snowmelt with elevation, with mainly elevations at 2400 m and above for the San Joaquin and Kings and above 2700 m for the Kaweah and Kern having the most snowmelt. Results are qualitatively similar for the six basins,

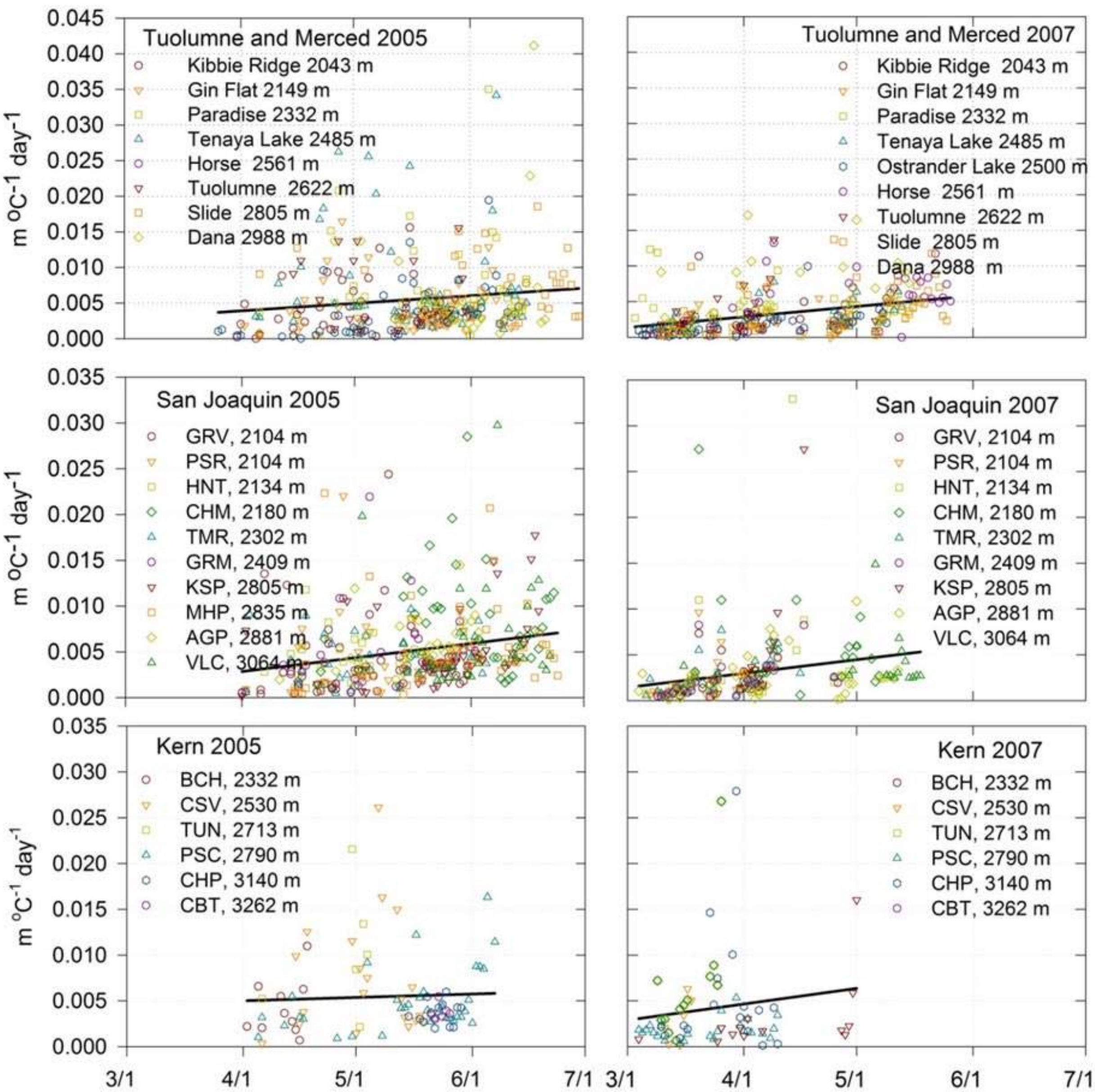

Figure 13. Degree-day coefficients for snow-pillow sites in the Tuolumne, Merced, San Joaquin, and Kern River basins for a wet (2005) and dry (2007) year.

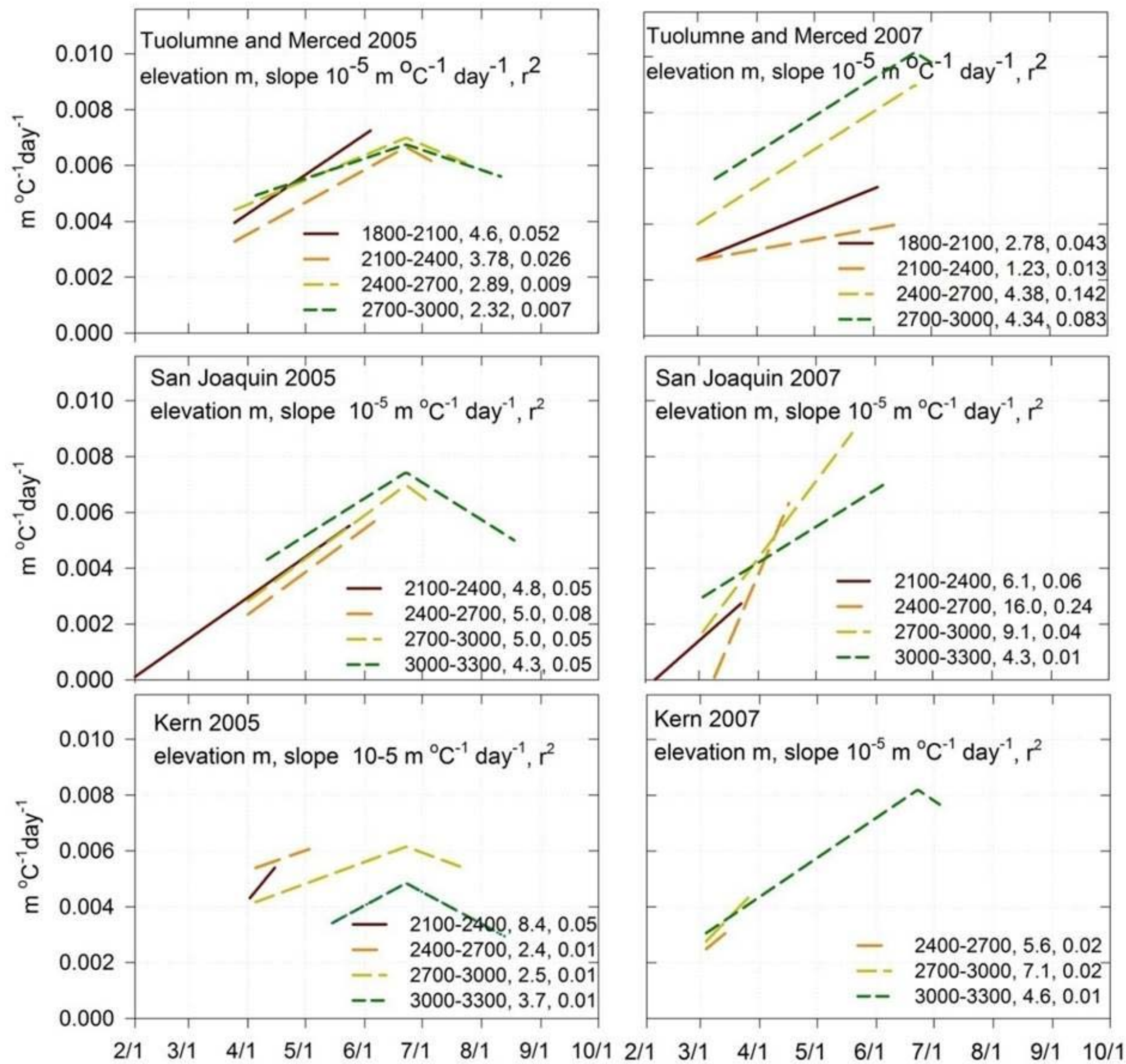

Figure 14. Elevation-dependent degree-day coefficients across four of nine elevation bands in a wet (2005) and a dry (2007) year. Note that only three elevation bands are shown in the Kern River basin for 2007 due to insignificant snowmelt at elevations below the 2400-2700 m elevation band. Values are shown for period of snowmelt at each elevation.

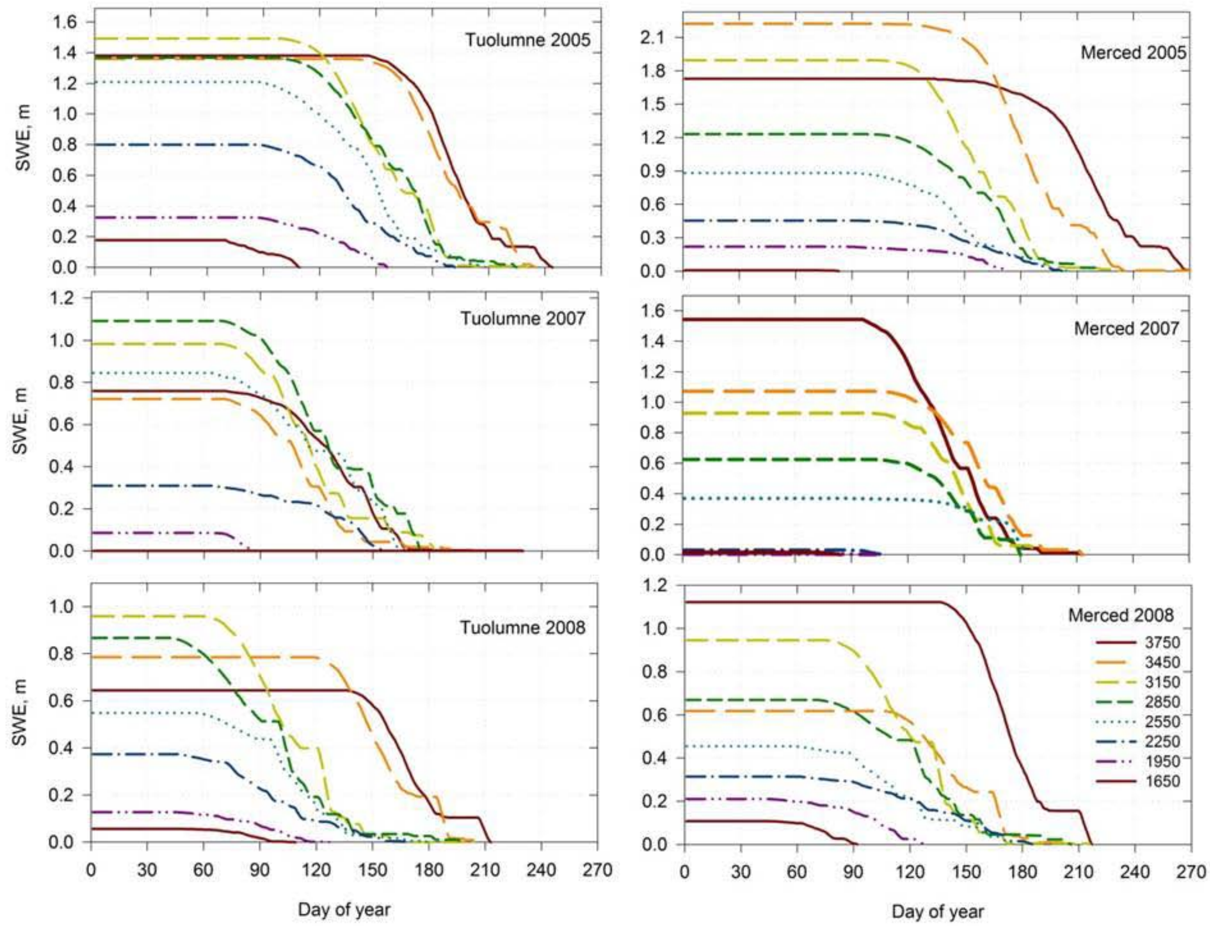

Figure 15a. Snowmelt (expressed as SWE) by elevation band based on snow-depletion calculations using degree-day and satellite fSCA for the Tuolumne and Merced River basins.

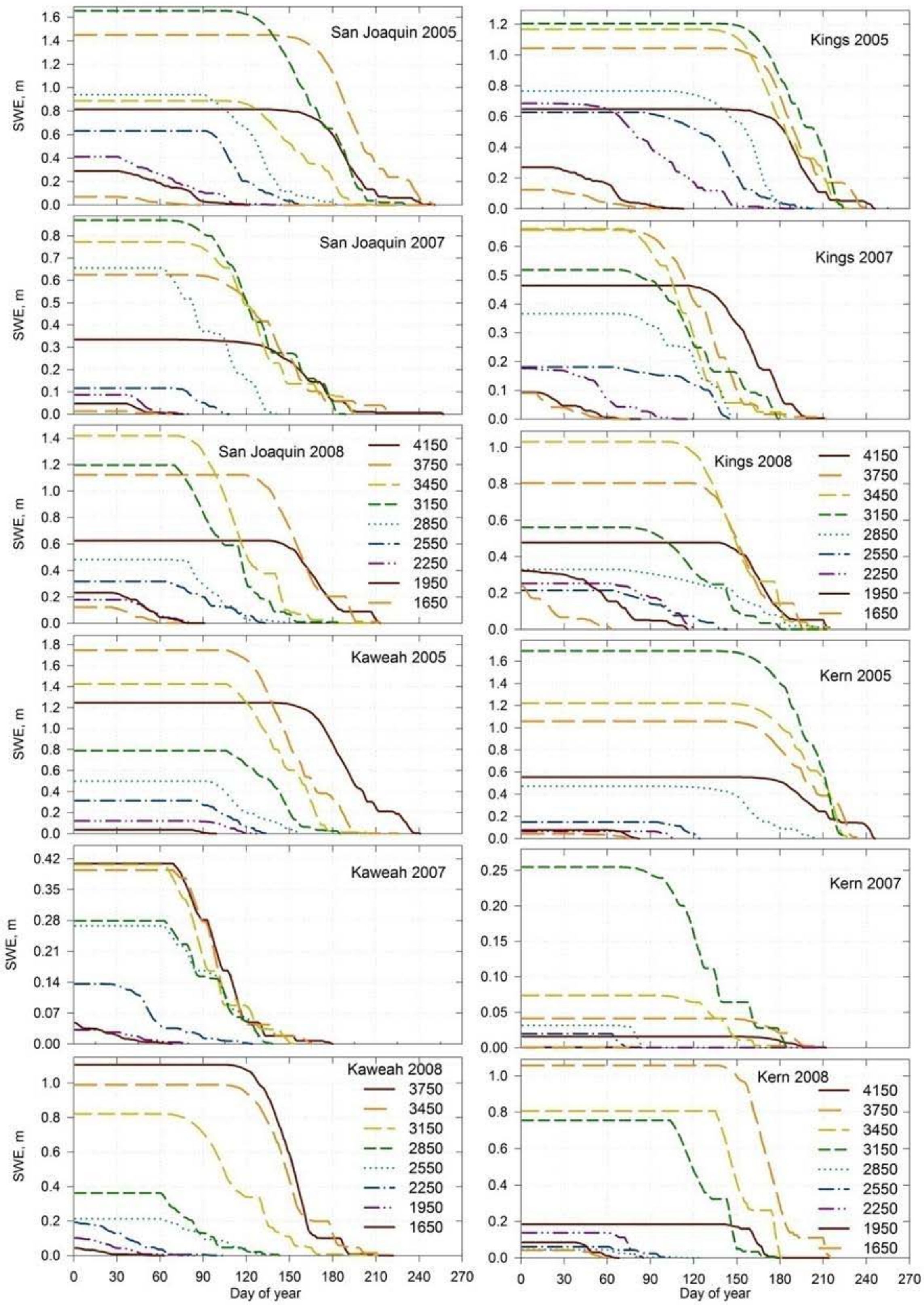

Figure 15b. Snowmelt (expressed as SWE) by elevation band based on snow-depletion calculations using degree-day and satellite SCA for the San Joaquin, Kings, Kaweah, and Kern River basins.

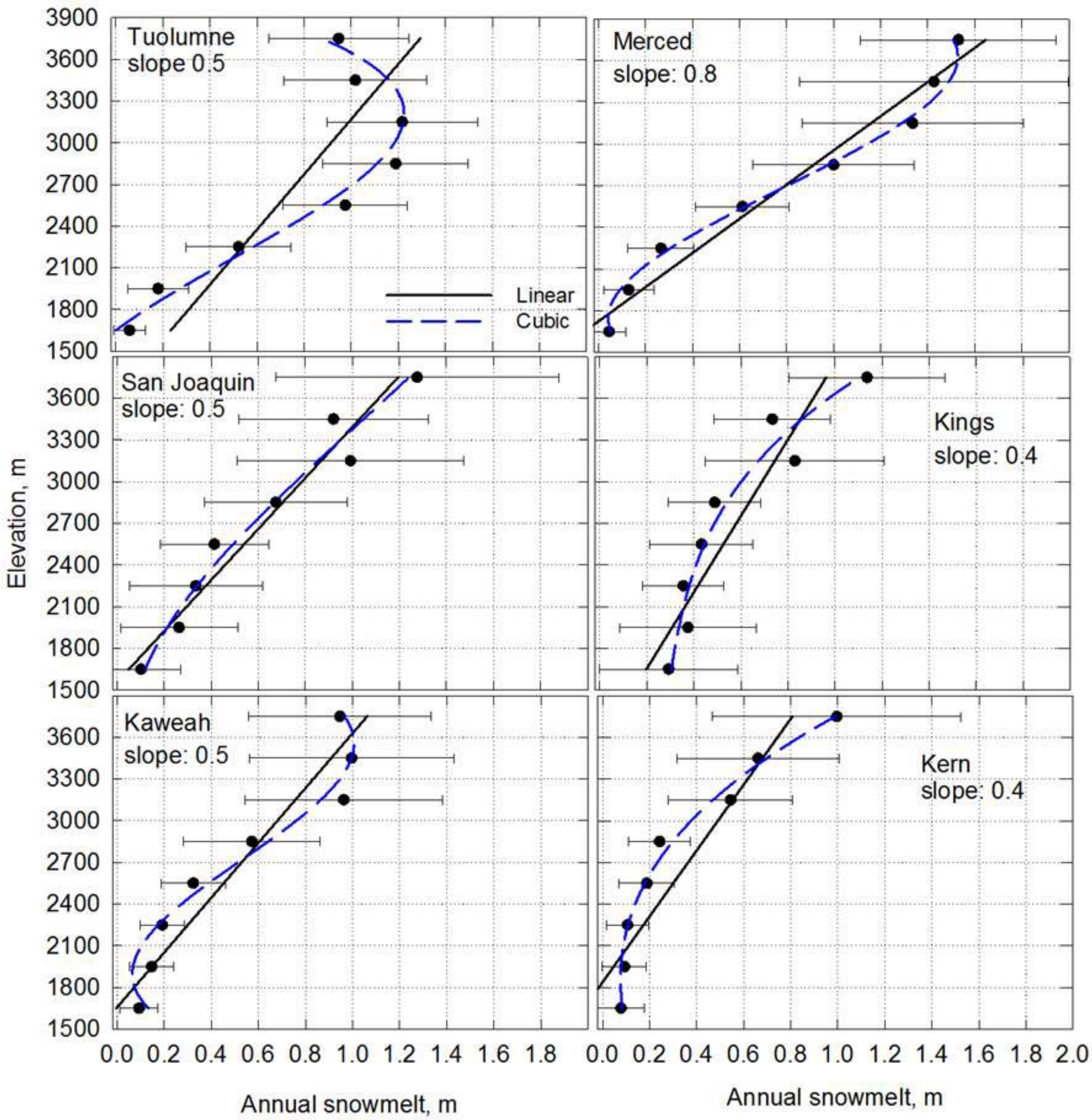

Figure 16. Snowmelt contributions from each elevation band based on depletion calculations for each of the six basins (Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River). Shown are ten-year means (circles), standard deviations and best-fit to means (solid and dashed lines represent linear and cubic).

though snowmelt in the lower elevations shows up more in the Tuolumne, Merced, San Joaquin, and Kings River basins.

The majority of the snowmelt in the Tuolumne and Merced River basins was derived from mid to upper elevations, between 2400-3300 m (Figure 17). In 2005 when the snowpack in Tuolumne and Merced were 163% of the historical April 1 snow course average, 25-29% of the total snowmelt volume was derived from the area above 3000 m. The area above 3000 m accounts for 23% and 11% of the total area in Tuolumne and Merced, respectively. The mid-elevations, 2400-3000 m, contributed 53% of the total snowmelt volume. These mid-elevations were 40% of the total area in the Tuolumne and Merced. Below 2400 m, 23% and 18% of the total snowmelt volume were derived in the Tuolumne and Merced, respectively. In 2007, when snow-course-derived SWE values in the Tuolumne and Merced basins were 46% and 45% of the historical April 1 average, respectively, trends were similar. A smaller fraction of the total snowmelt volume, however, was derived from the lowest elevations, while the mid to high elevations above 2400 m accounted for much of the difference in snowmelt volume in the wetter (2005) versus drier (2007) year. In the Tuolumne and Merced 11% and 5% of the total snowmelt volume were derived from below 2400 m. The importance of mid-elevations (2400-3000 m) increased with the Tuolumne and Merced, contributing to 64% and 60% of their respective snowmelt volumes. Elevations above 3000 m remained relatively stable in the Tuolumne as 25% of the snowmelt volume was derived from the highest elevations, while the Merced increased to 35% of the total snowmelt volume. Elevations below 2400 m contributed 100% of the March 2005 snowmelt in the Tuolumne and 82% in the Merced, declining to 70% (Tuolumne) to 52% (Merced) in April and 11% June (Figure 18). Mid elevations (2400-3000 m) in the Tuolumne contributed no snowmelt in March, with 18% in the Merced, increasing to 30% (Tuolumne) to 46% (Merced) in April, 58% (Tuolumne) to 65% (Merced) in May, and dropping to 51% (Tuolumne) to 58% (Merced) in July and nearly disappearing by August. Elevations above 3000 m contributed no snowmelt to the monthly total in March, increasing to 17% (Tuolumne) to 18% (Merced) in May, and 63% (Tuolumne) to 91% (Merced) in August.

In 2007, the snowmelt pattern was similar, but the relative snowmelt contributions were one month earlier due to the smaller snowpack, which was about 45% of the historical snow course averages in the Tuolumne and Merced River basins. The lower elevations (<2400 m) contributed 31% (Tuolumne) and 52% (Merced) of the snowmelt during March declining to near 13% and 6% by April 30. The mid elevations were contributing 61% (Tuolumne) and 47% (Merced) of the March snowmelt, increasing to 73-81% for April, and declining to 63% (Tuolumne) and 53% (Merced) in June, with a steady decline to zero in July. Elevations above 3000 m contributed 0-7% of the March snowmelt increasing to 47% (Tuolumne) and 68% (Merced) for June, with a steady decline to zero by the end of July.

In 2008, which is considered an average year, based on the MODIS period of record analyzed here (2000-2009), the snowmelt patterns were similar to 2005 and 2007. The lower- and mid-elevations began contributing to snowmelt in March, with no contributions from elevations above 3000 m. By May 1 all elevations were contributing to snowmelt, from 31% (Tuolumne) and 22% (Merced) below 2400 and 60% (Tuolumne) and 67% (Merced) for elevations 2400-3000 m, and 9% and 11% in the Tuolumne and Merced, respectively. In May snowmelt contributions shifted, with 62% of the snowmelt deriving from the mid elevations and 27% from

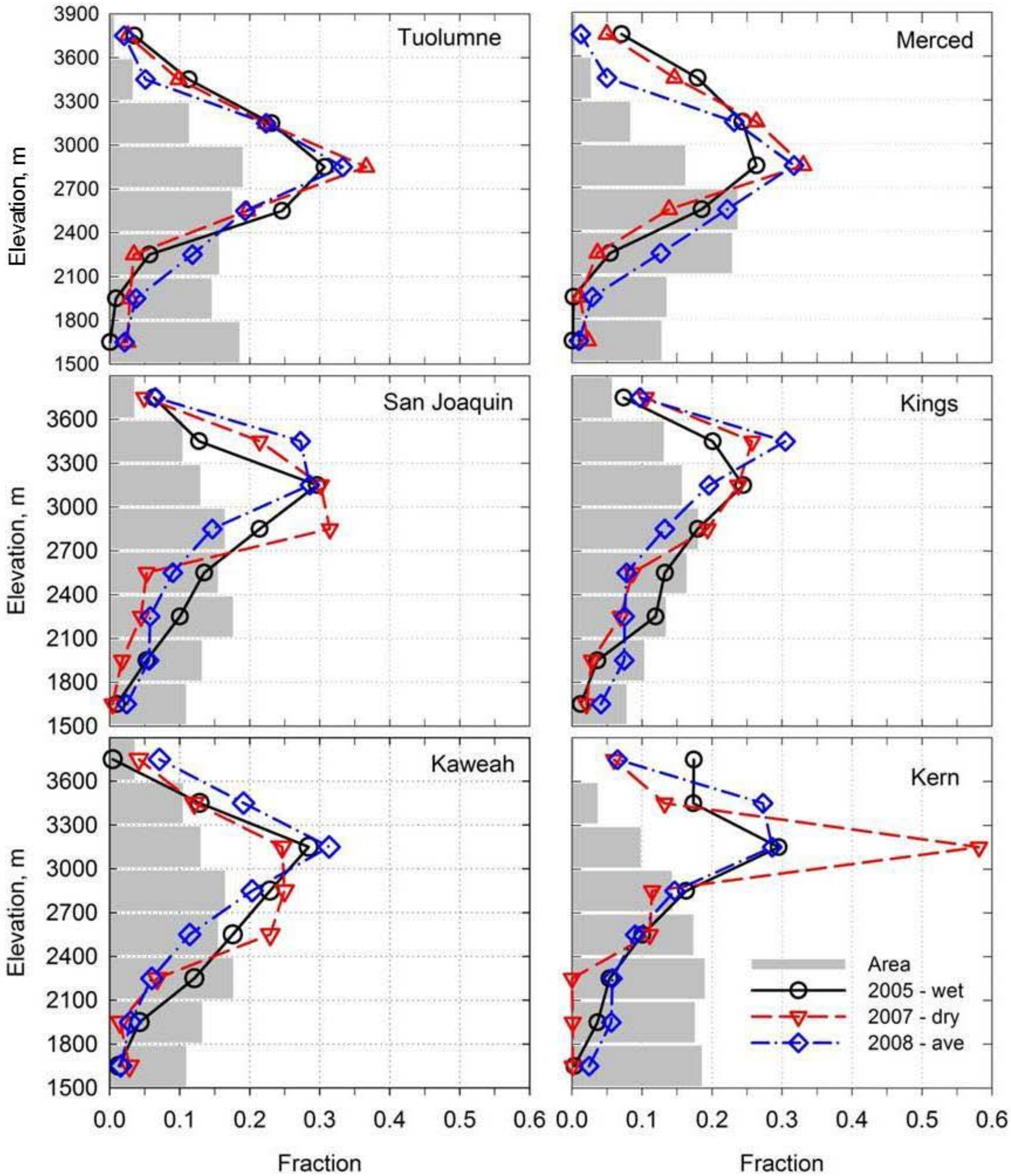

Figure 17. Fraction of annual snowmelt by elevation band for the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River basins in 2005, 2007, and 2008. The sum of fractions for all elevation bands for a given year is 1.0. Values for 2005, 2007, and 2008 are averages.

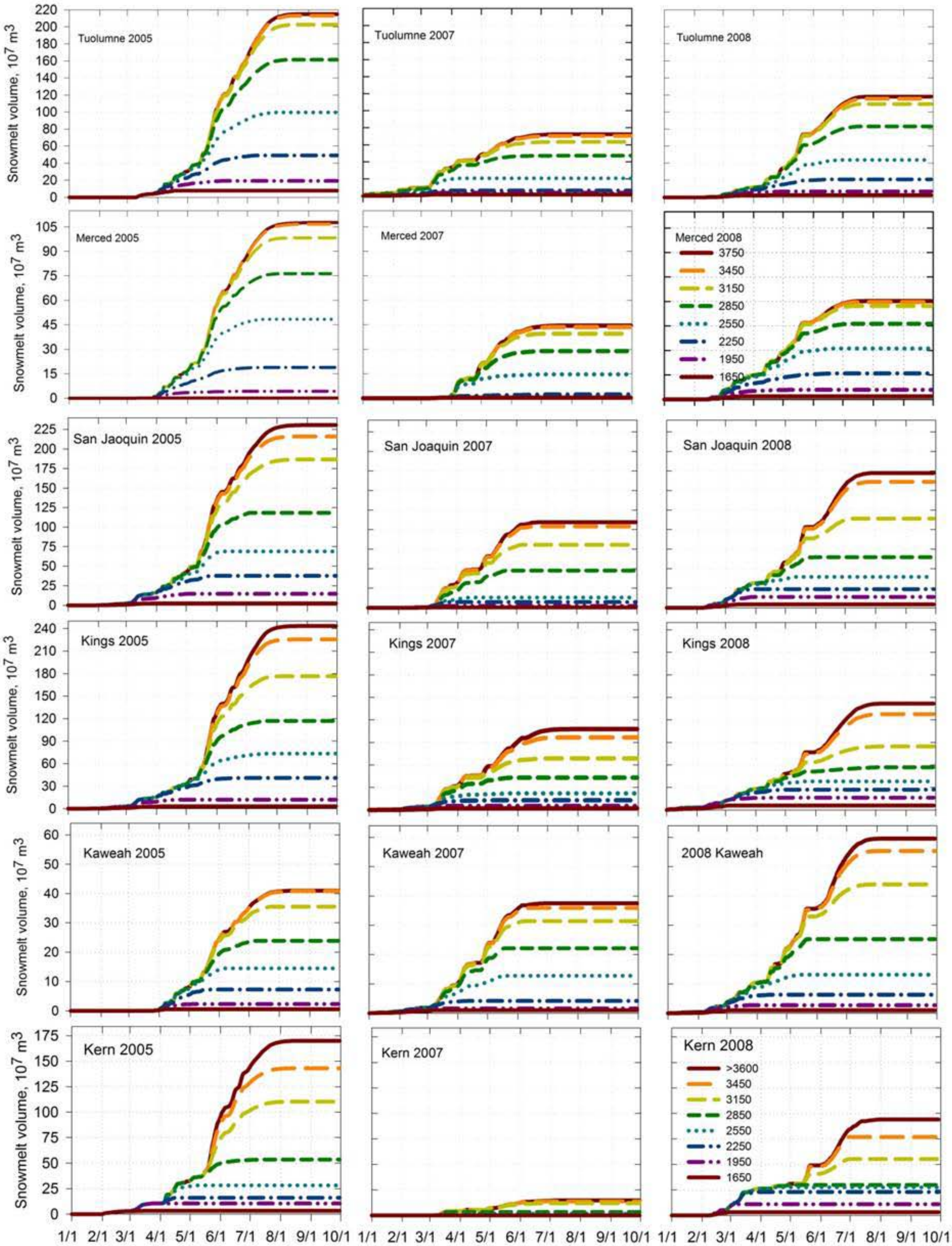

Figure 18. Cumulative snowmelt for each of the 6 basins (Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern River) in 2005, 2007, and 2008.

above 3000 m, with elevations below 2400 m declining to near zero by July, and the upper elevations declining to zero in August.

Over half of the snowmelt in the San Joaquin, Kings, Kaweah, and Kern was derived from elevations above 3000 m (Figure 17). In 2005, when the snowpack volumes in the San Joaquin, Kings, Kaweah, and Kern were 167%, 163%, 159%, and 184%, respectively, of the historical April 1 snow course average, 50-65% of the total snowmelt volume was derived from the area above 3000 m. The area above 3000 m accounts for 26%, 35%, 23%, and 20% of the total area in the San Joaquin, Kings, Kaweah, and Kern, respectively. The mid-elevations, 2400-3000 m, contributed similar amounts, 26-40%, of the total snowmelt volume. These mid-elevations were 32%, 34%, 41%, and 28% of the total area of the San Joaquin, Kings, Kaweah, and Kern, respectively. Below 2400 m only 17% of the total snowmelt was derived from these elevations below 2400 m in the San Joaquin, Kings, and Kaweah; while in the Kern only 7% of the total snowmelt volume was derived below 2400. The lower snowmelt volume in the Kern is likely a result of the basin being the furthest south in latitude, and the south orientation of the basin, which is unique to the either a west or east orientation of river basins throughout the Sierra Nevada. In 2007, when the San Joaquin, Kings, Kaweah, and Kern were 43%, 40%, 40%, and 21% of the historical April 1 average, trends were similar, but a smaller fraction of the total snowmelt volume was derived from the lowest elevations, while elevations above 3000 m accounted for much of the difference in snowmelt volume in the wetter (2005) versus drier (2007) year. In 2007, In the San Joaquin, Kings, Kaweah, and Kern, 7%, 12%, 11%, and 1% of the total snowmelt volume were derived from below 2400 m. The mid-elevations, (2400-3000 m) remained relatively constant, with the San Joaquin and Kings, contributing 37% and 28% of the respective snowmelt volumes, while the Kaweah increased to 48% of the total snowmelt volume, and the Kern declined to 22% of the total snowmelt volume. Elevations above 3000 m contributed 56%, 60%, 41%, and 77% of the total snowpack volume in the San Joaquin, Kings, Kaweah, and Kern.

Elevations below 2400 m contributed 100% of the March 2005 snowmelt in all four basins, declining to 30% (Kern) to 75% (Kings) in April and 0-10% May (Figure 18). Mid elevations (2400-3000 m) contributed no snowmelt in March, increasing to 26% (Kings) to 70% (Kern) in April, 36% (Kern) to 59% (Kaweah) in May, and dropping to 10% (Kern) to 40% (Kaweah) by June and nearly disappearing by August. Elevations above 3000 m contributed no snowmelt to the monthly total in March, increasing to 30% (Kaweah) to 39% (Kings) in May, and 89% (Kaweah) to 100% (Kern) in July.

In 2007, the snowmelt pattern was similar, but the relative snowmelt contributions were one month earlier due to the smaller snowpack, which was 43% of the historical snow course averages. In the San Joaquin, Kings and Kaweah basins the lower elevations (<2400 m) contributed 100% of the snowmelt during February declining to near zero by April 30. In the Kern contributions from the lower elevations were insignificant through all months. The mid elevations were contributing 45-60% of the March snowmelt, increasing to 50-65% for April, and declining to zero in June. Elevations above 3000 m contributed 15-35% of the March snowmelt increasing to 100% for June, with a steady decline to zero in July.

In 2008, which is considered an average year based on the MODIS period of record analyzed here (2000-2009), the snowmelt patterns were similar to 2005 and 2007. The lower elevations below 2400 m began contributing to snowmelt in February, with no contributions from elevations above 2400 m. By April 1, all elevations were contributing to snowmelt, from 40% (Kaweah) to 89% (Kern) below 2400 and 19% (Kern) to 59% (Kaweah) for elevations 2400-3000 m. In April, snowmelt contributions shifted, with 55-75 of the snowmelt deriving from the mid elevations and 25-35 from above 3000 m, with elevations below 2400 m declining to zero by July, and the upper elevations declining to zero in August.

Snow-Covered Area and Snowmelt Projections for Climate Change Scenarios

Three climate change scenarios are considered: +2, +4 and +6 ^{o}C. Using an average ground-based lapse rate of -6.8^{o}C per 1000 m, each 2 ^{o}C rise in temperature corresponds to the current temperature patterns about 300 m lower in elevation. Substituting space for time, current snowpack conditions at some elevations can be expected to indicate snowpack conditions at an elevation that is 300 m higher under a 2 ^{o}C warmer climate; e.g., conditions at 2400 m today are what conditions would be like at 2700 m under a 2 ^{o}C warmer climate, or 3000 m under a 4 ^{o}C warmer climate. That is, with a warmer climate the rain-snow transition elevation is projected to move upslope about 300 m for each 2 ^{o}C warmer climate. Note also that each successively higher 300-m elevation band melts out about 20 days later than the elevation band below it, in warm and cool springs, deep or shallow snow, high or low elevations (Figure 11). Thus to a first approximation, this rate of snowmelt should continue in a warmer climate. However, melting will be earlier.

Figures 19a and 19b represent an average record of temperatures across the park when temperatures from all stations have been indexed to a common elevation. For this figure, we used an elevation of 3000 m, but any index elevation could be used and the variability in temperature across stations would be the same. Using this average record (Figures 19a, 19b) and the average lapse rates (Figures 12a, 12b), the current distribution of temperatures by elevation band shows that, at elevation 3000-3300 m, about half of the year has a daily average temperature below zero across the study area (Figure 20). At 2100-2400 m, about 27% (Tuolumne and Merced) and 20% (San Joaquin, Kings, Kaweah, Kern) of the year has a temperature below zero. With temperature increases of 2, 4 and 6 ^{o}C, at 3000-3300 m elevation in the Tuolumne and Merced, only 45%, 34%, and 27%, respectively of the days will have average daily temperatures below zero, with a similar change in the San Joaquin, Kings, Kaweah, and Kern of 43%, 33% and 20% respectively. In terms of number of days, at 3000-3300 m this represents a change from 180 to 150, 110 and 75 days, respectively across both regions within the study area (Figure 21).

In terms of snowmelt, the current calculation is based on degree days, projecting future snowmelt based on temperature. Using variability in current temperatures for individual years for one elevation (3000 m), expressed as cumulative degree days (Figure 22), shows that in a warmer year (2001), a given value of cumulative degree-day is reached about 20 days before the same level is reached in a colder year (2005) across the study area. That is, the potential for snowmelt occurring by a given date varies nearly as much as is the expected change in mean of a 2 ^{o}C warming. So, even though both warm and cold months occur in most years, cumulative degree days clearly show warm and cold years for snowmelt.

This same 20-day or 2-3 week advance in snowmelt per 2 ^{o}C of warming noted above also shows up in an examination of the projected cumulative degree days for the 3000-m elevation (Figure 23). Other elevations show a similar pattern (data not shown). Cumulative degree days are an index of the cumulative potential for snow to melt. This 14-20 day change in the date that a given level of cumulative degree day is reached per 2 ^oC change in temperature represents a real advance in snowmelt. As noted above, since the lapse rate is 5.8 and 6.0 ^oC, each 2 ^oC higher temperature change also represents a 300-m lower elevation under present temperatures.

Temperature increases will shift the amount of snow covered-area as less precipitation falls as snow. To a first approximation, this can be viewed as a shift of 300 m in current fSCA patterns as being equivalent to 2 ^oC (Figure 24). Currently across all six basins there is an elevation dependence of winter fSCA with each successive lower 300 m elevation band having greater inter-seasonal variability. That is, higher elevations, which are consistently below freezing much of the winter, have more consistent snowcover than do lower elevations.

The timing of snowmelt can also be projected (Figures 25a and 25b) by imposing a temperature change on the basin and its snowpack and shifting the corrected SCA fractions (Figure 16) up by 300 m per 2 ^oC change in temperature, which is consistent with the current observations that each 300 m corresponds to a 2 ^oC shift in temperature (Figures 12a and 12b). A 2 ^oC shift in temperature also results in a 300-m upward shift in the degree days (Figure 21). The effect is that with an increase in temperature, there is less snow and it melts faster. The magnitude of change in a given year depends on the patterns of fSCA and snowcover depletion that were observed. The effects are similar in the Tuolumne and Merced and the four basins in and around SEKI (San Joaquin, Kings, Kaweah, Kern) (Figures 25a and 25b). Overall, the timing of snowmelt shifts toward earlier in the spring at a rate of 5-6 days per ^oC in the Tuolumne and Merced and 6-7 days per ^oC in the San Joaquin, Kings, and Kaweah. That is, with a temperature increase of 2 ^oC, 50% of the seasonal snowmelt is projected to be depleted about two weeks earlier than present, and the effect is slightly greater in the southern basins. Of interest is that the imposed 6 ^oC increase in temperature in 2005 and 2006 (wet year) results in similar conditions experienced in 2004 and 2007 (dry years). For example, in 2004 and 2007, 50% of the seasonal snow-cover was depleted by day 120 in the Merced and Kings River basins. With an imposed temperature shift of 6 ^oC for the wet years 2005 and 2006, the date that snow-cover was 50% depleted shifted from day 148 and 155, respectively, to about day 130 in the Merced, and shifted from day 150 and 145, respectively, to about day 120 in the Kings.

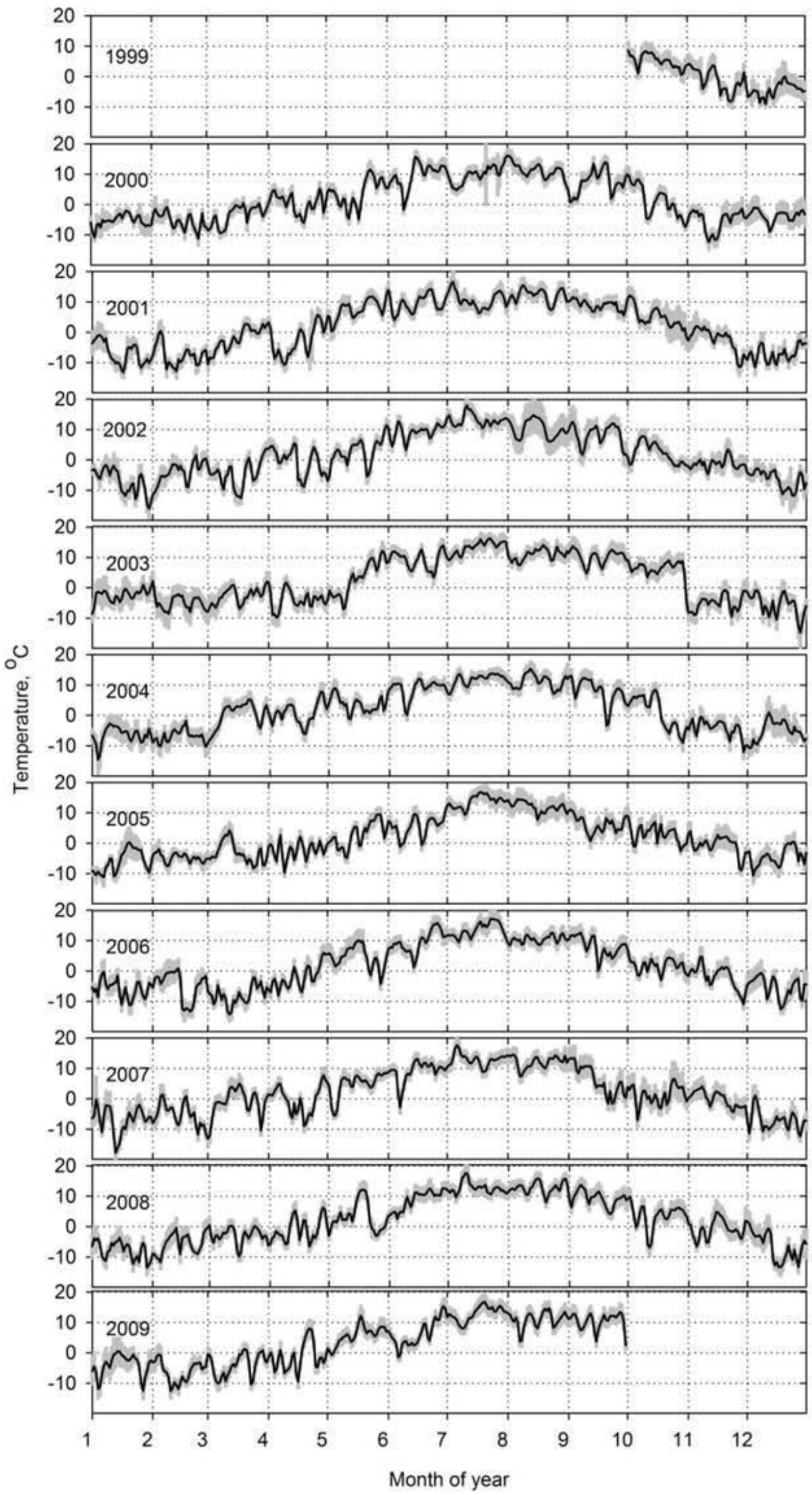

Figure 19a. Average daily temperature (^{o}C) for all 30 stations in the two YOSE basins for each year from 1999-2009. Temperatures at each station were indexed to 3000m elevation using a ground-based lapse rate of 5.8 ^{o}C per 1000m. Black line represents the average, and shaded area represents standard deviation.

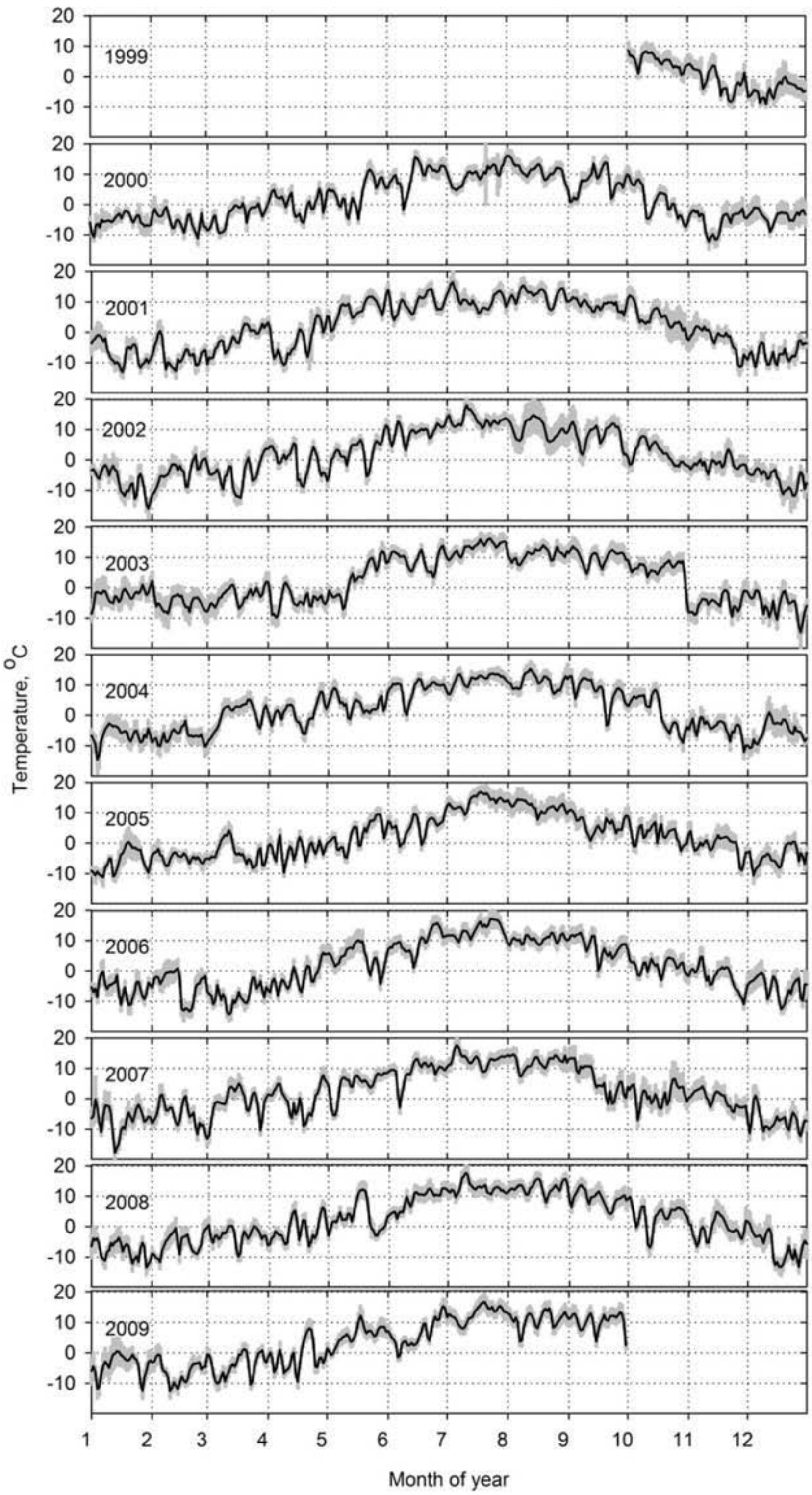

Figure 19b. Average daily temperature (^{o}C) for all 51 stations in the four SEKI basins for each year from 1999-2009. Temperatures at each station were indexed to 3000m elevation using a ground-based lapse rate of 6.0^{o}C per 1000m. Black line represents the average, and shaded area represents standard deviation.

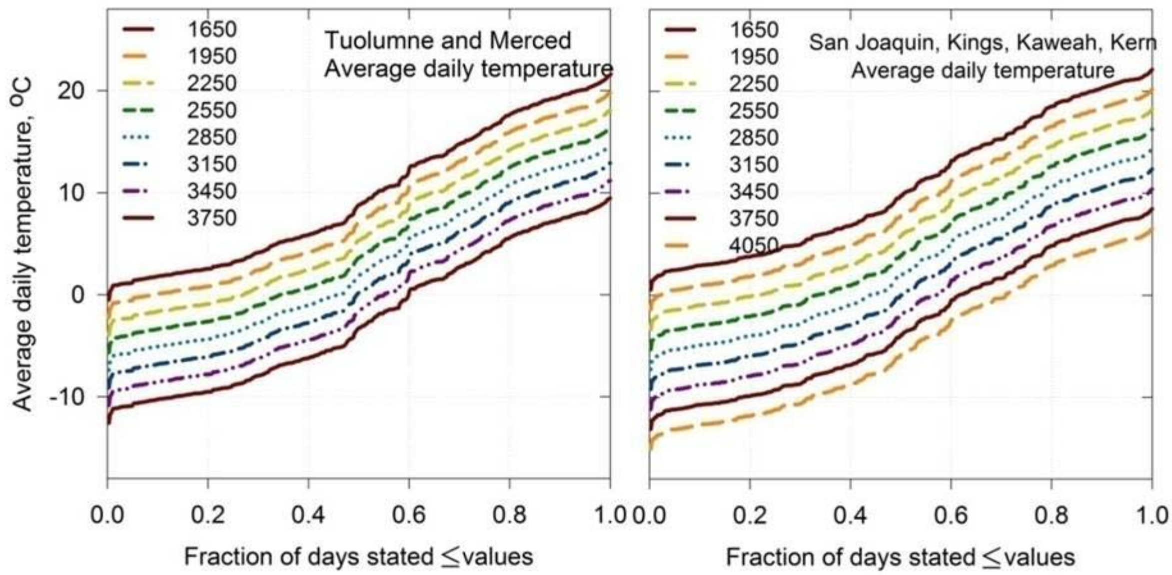

Figure 20. Distribution of daily average temperature for each 300-m elevation band based on mean values from Figure 19a and 19b, averaged over 2000-2009 for the six river basins.

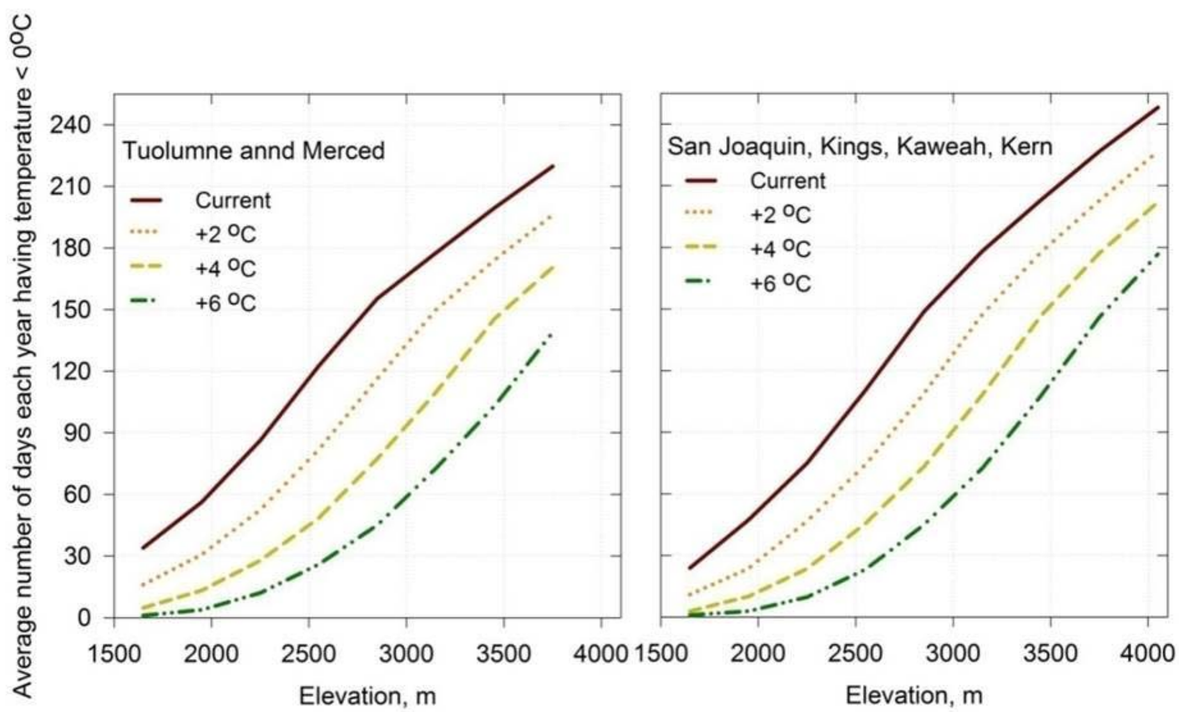

Figure 21. Mean number of days temperature is below zero currently (solid line) and with 2-6 ^{o}C increases in average temperature (broken lines).

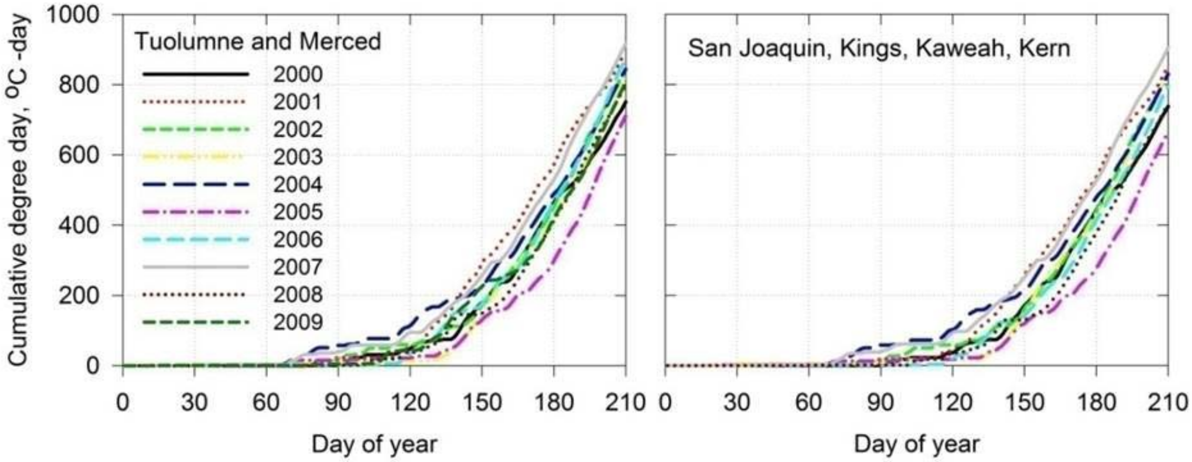

Figure 22. Cumulative degree days for 2000-2009, based on Figure 21, for 3000 m elevation.

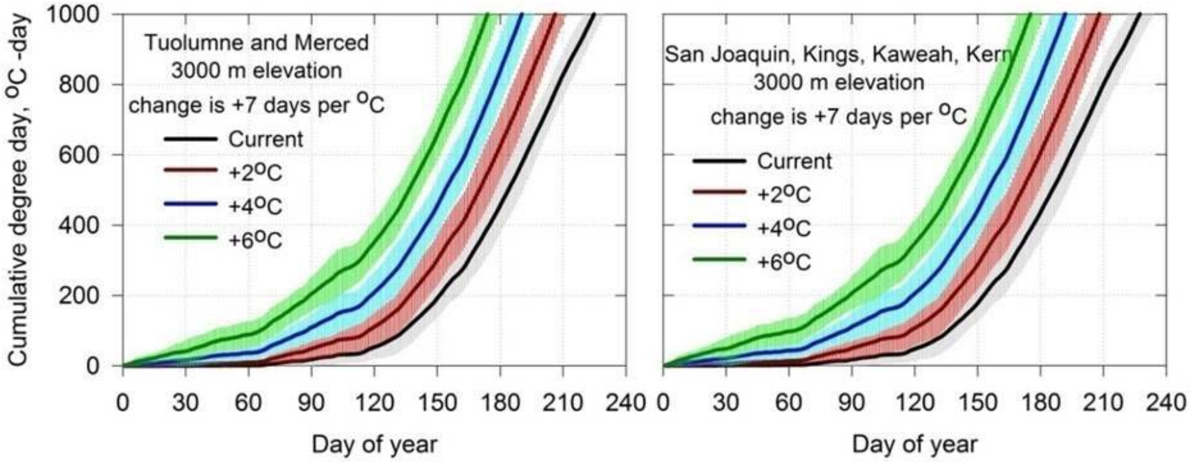

Figure 23. Cumulative degree days for current (2000-2009) conditions, based on Figure 22; and cumulative degree days with temperature increases of 2-6 °C. Lines represent means and shaded areas are standard deviations based on inter-annual variability.

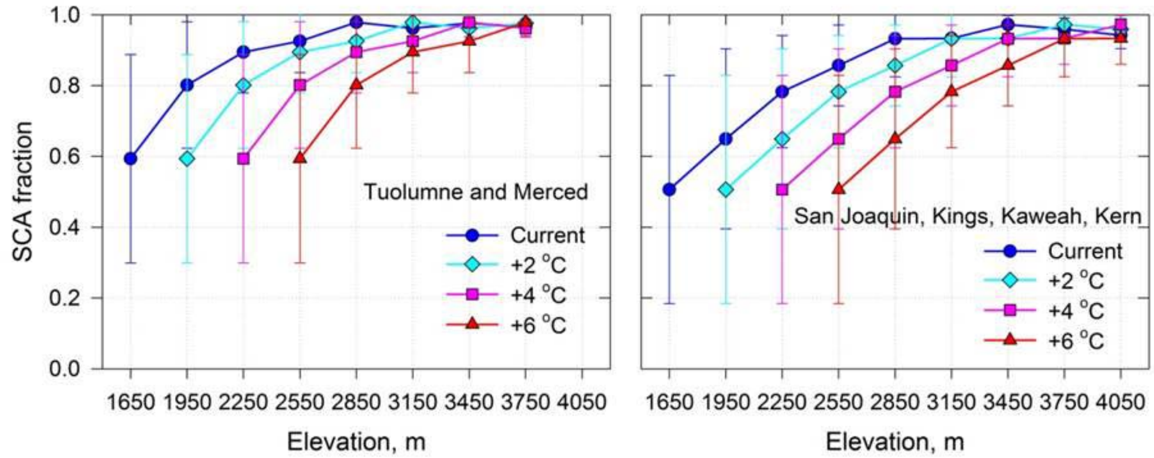

Figure 24. Winter snow-covered area fraction by elevation under current (2000-2009) conditions and projected temperature increases. Error bars indicate inter-annual variability for ten years.

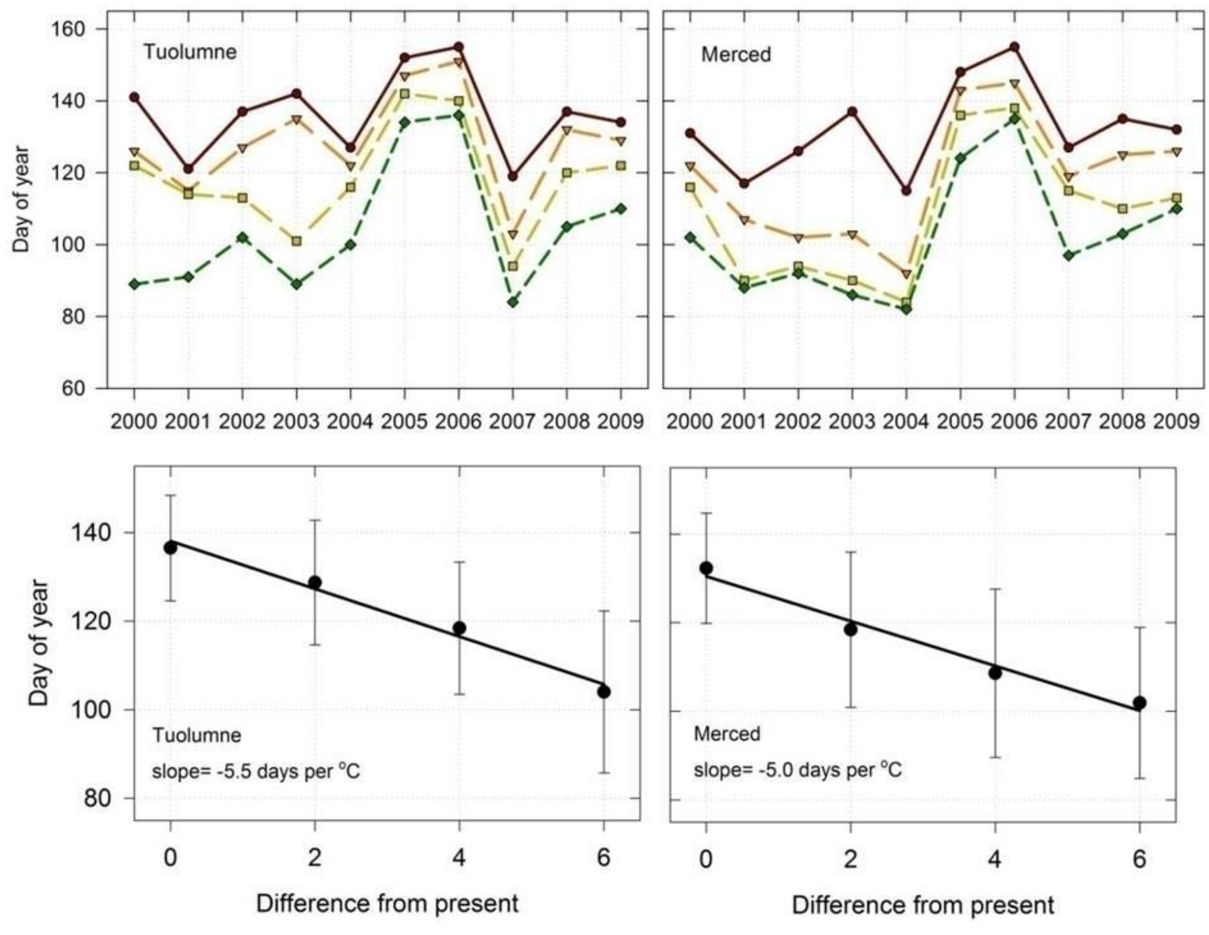

Figure 25a. Snowmelt timing based on depletion method for current (2000-2009) conditions and with a 2, 4 and 6 °C increase in average temperature in the Tuolumne and Merced. Upper panels show day of year that 50% of seasonal snowmelt occurred; solid circles, triangles, squares, and diamonds indicate current, +2 °C, +4 °C, and +6 °C scenarios. Lower panels show mean, best fit, and standard deviation of the nine years.

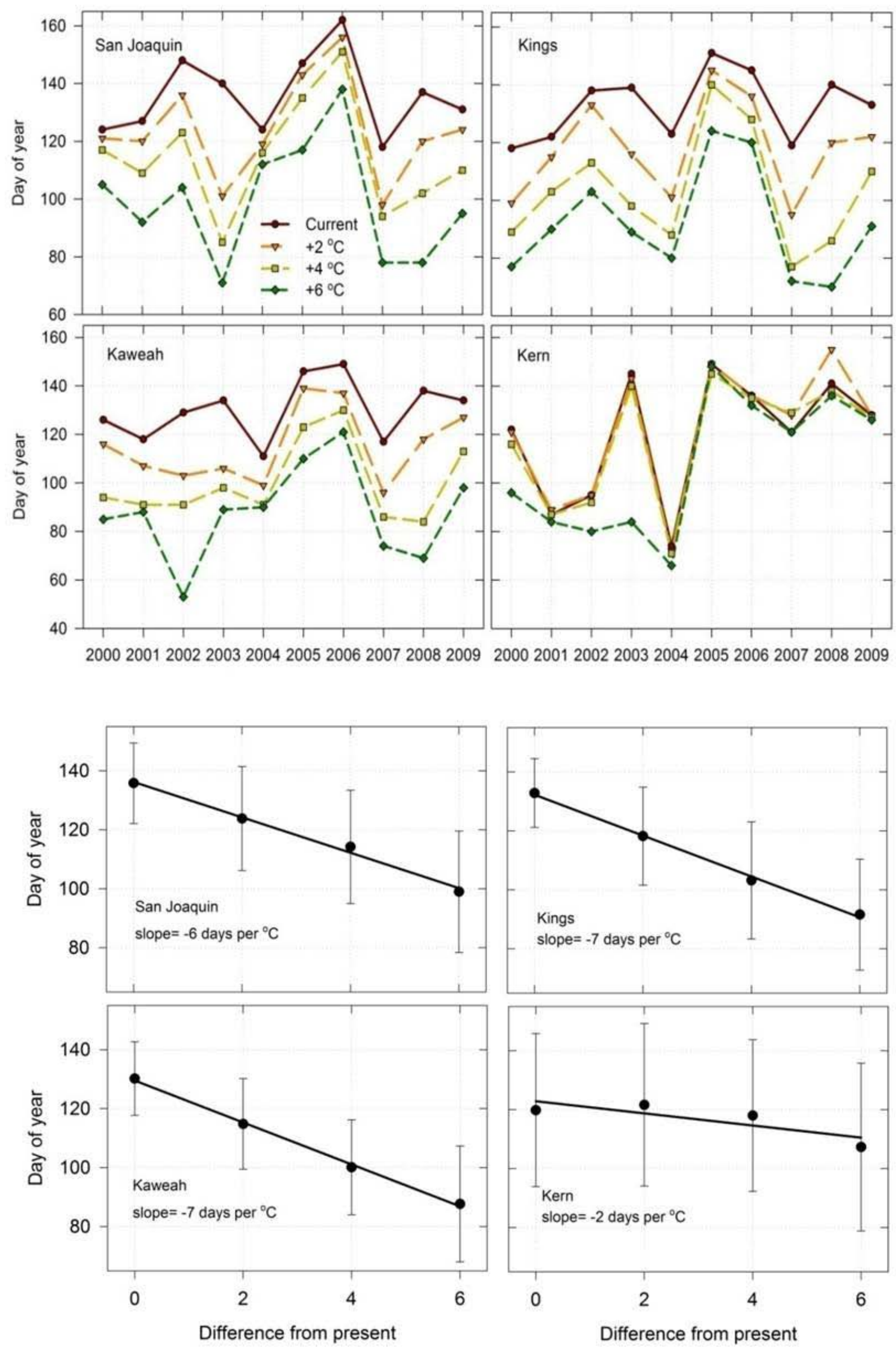

Figure 25b. Snowmelt timing based on depletion method for current (2000-2009) conditions and with a 2, 4 and 6 °C increase in average temperature in the San Joaquin, Kings, Kaweah, and Kern. Upper panels show day of year that 50% of seasonal snowmelt occurred; lower panels show mean, best fit, and standard deviation of the nine years.

Discussion

Snow and Temperature Patterns

Broad temperature patterns are known with some confidence across the parks, such as the near-linear relationship between temperature and elevation that is illustrated by Figures 12a and 12b. These figures show that most points fall close to a regression line with elevation. Another view of the variability is to index all temperatures to a common elevation (Figures 19a and 19b), in this case 3000 m. Any index elevation could be used, with the same resulting variability in temperature. In Figures 19a and 19b, the standard deviation for indexed temperatures from stations across all six basins ranged from 1-3 ^{o}C and largely reflects the physiographic variation at a common elevation. At a 6.8 ^{o}C per 1000 m ground-based lapse rate, the 1-3 ^{o}C standard deviation among stations is equivalent to about 150-450 m variability in elevation. Cold-air drainage at night may be partly responsible for variability in average daily temperature between stations at comparable elevations. For example, comparing Lodgepole (Kaweah basin) and Grant Grove (Kings basin) on Figure 26, it is apparent that the two sites, which are at comparable elevations, have a similar mean daily maximum temperature but a daily minimum that differs by about 4.5 ^{o}C. Some of the uncertainty may also be in the temperature records themselves. Several manual corrections were made to the data, but it is apparent that several records have received little calibration and quality control over the years, and further analysis will be needed to examine sub-daily temperatures in any detail.

Thus while the general temperature relationships on Figures 12 and 19 are applicable for broad, basin-scale analyses, assessments in smaller areas and in narrow elevation bands could benefit from finer-resolution measurements. Temperature patterns have a relatively high level of confidence at the broad landscape scale in part because elevation is a main determinant of temperature. However, the available data do not capture more-local variability, and current modeling approaches are much too coarse to provide accurate estimates of the effects of local topography, e.g. valleys and ridges. Thus while available temperature data do indicate the general snowpack accumulation and melt patterns, they are not at a level of detail that permits predicting or downscaling snow patterns at the scale of tens to hundreds of meters.

Snowcover Persistence

Areas with persistent snowcover are areas that are reliably covered in snow from year to year Areas with persistent snowcover are potentially less vulnerable to small temperature changes than areas that have less consistent snowcover from year to year. Maps in figures 27a-d and 28a-d depict areas with different degrees of snowcover persistence in the YOSE and SEKI basins. Different colors represent areas that were snowcovered for different proportions of the 12 year period from 2000-2011, specifically during the months of March through June. Note that much of the area in the parks consistently had some snow March 1, with the exception of the lower elevations of Sequoia and Yosemite, and the lower part of the Kings River Canyon in Kings Canyon NP. On April 1, all of the main river canyons show intermittent snowcover, with the higher elevations consistently being snow-covered.

On May 1 about half of the area inside the parks had consistent snowcover, with much of the rest having intermittent snowcover. Lower elevations currently have no snowcover on May 1. By June 1 only the higher elevations are consistently snow-covered in all parks and river basins, and much of the remaining area has few years with any snowcover on this date.

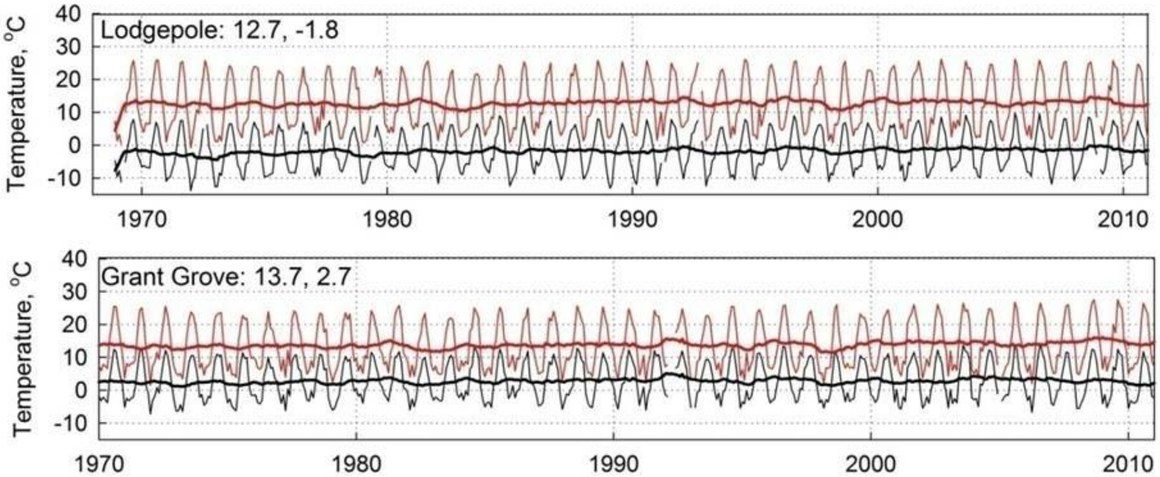

Figure 26. Monthly averages of daily minimum and maximum temperatures for Lodgepole and Grant Grove in the Kaweah River basin (Sequoia National Park) with longer records. Also shown is a 12-point running mean of the monthly values. Number after the station name is the average minimum and maximum temperature for the period of record.

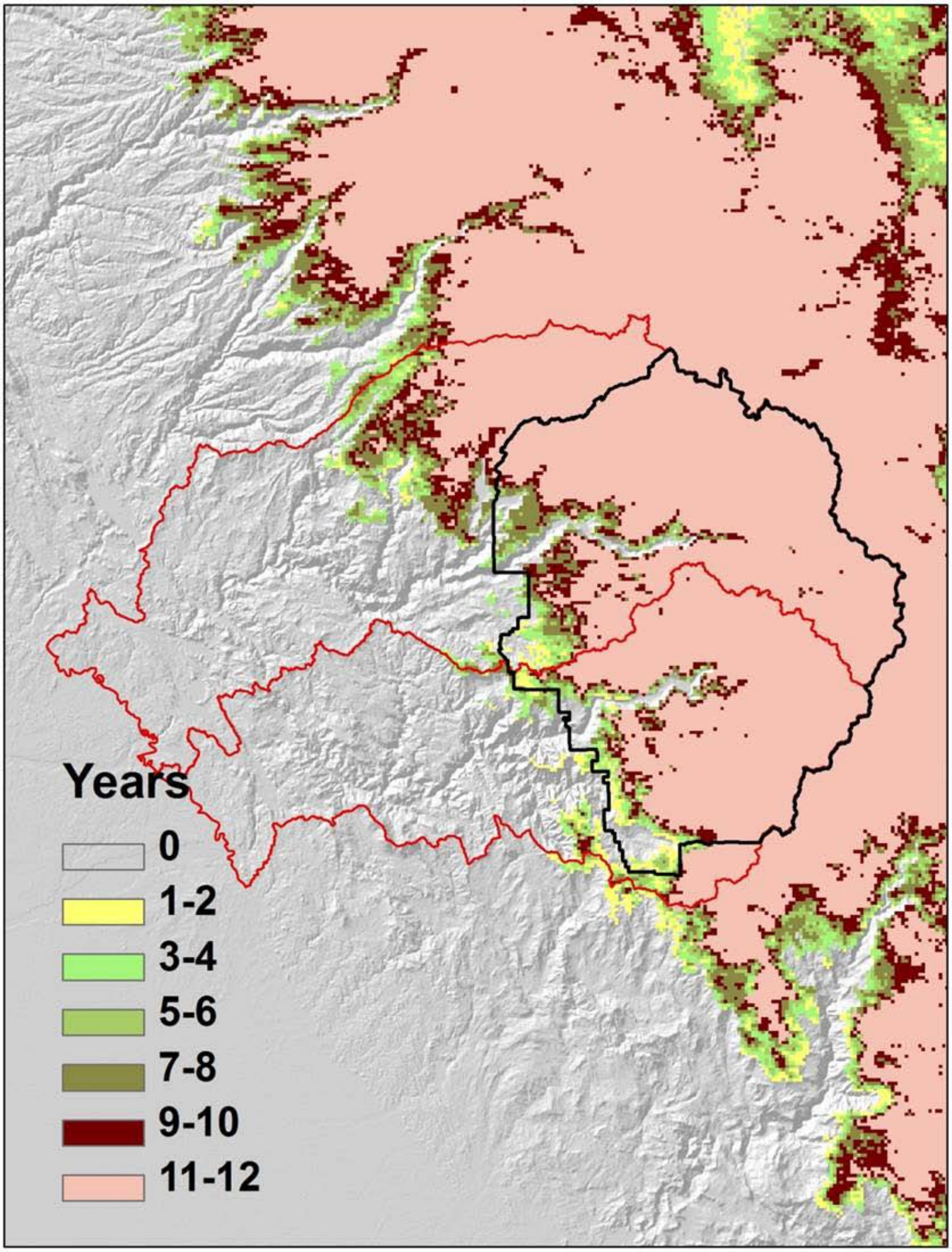

Figure 27a. Snowcover persistence across the Tuolumne and Merced River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on March 1.

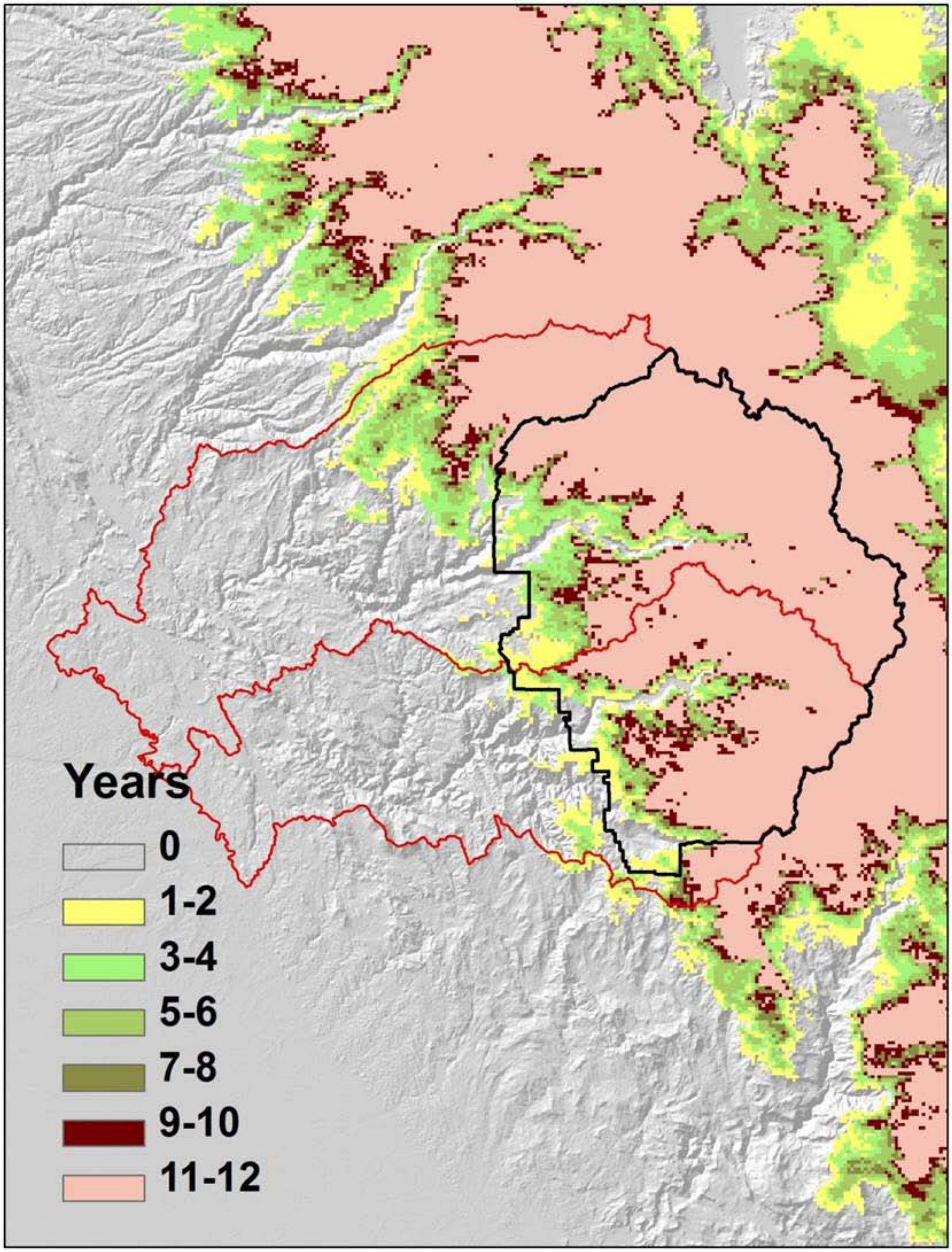

Figure 27b. Snowcover persistence across the Tuolumne and Merced River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on April 1.

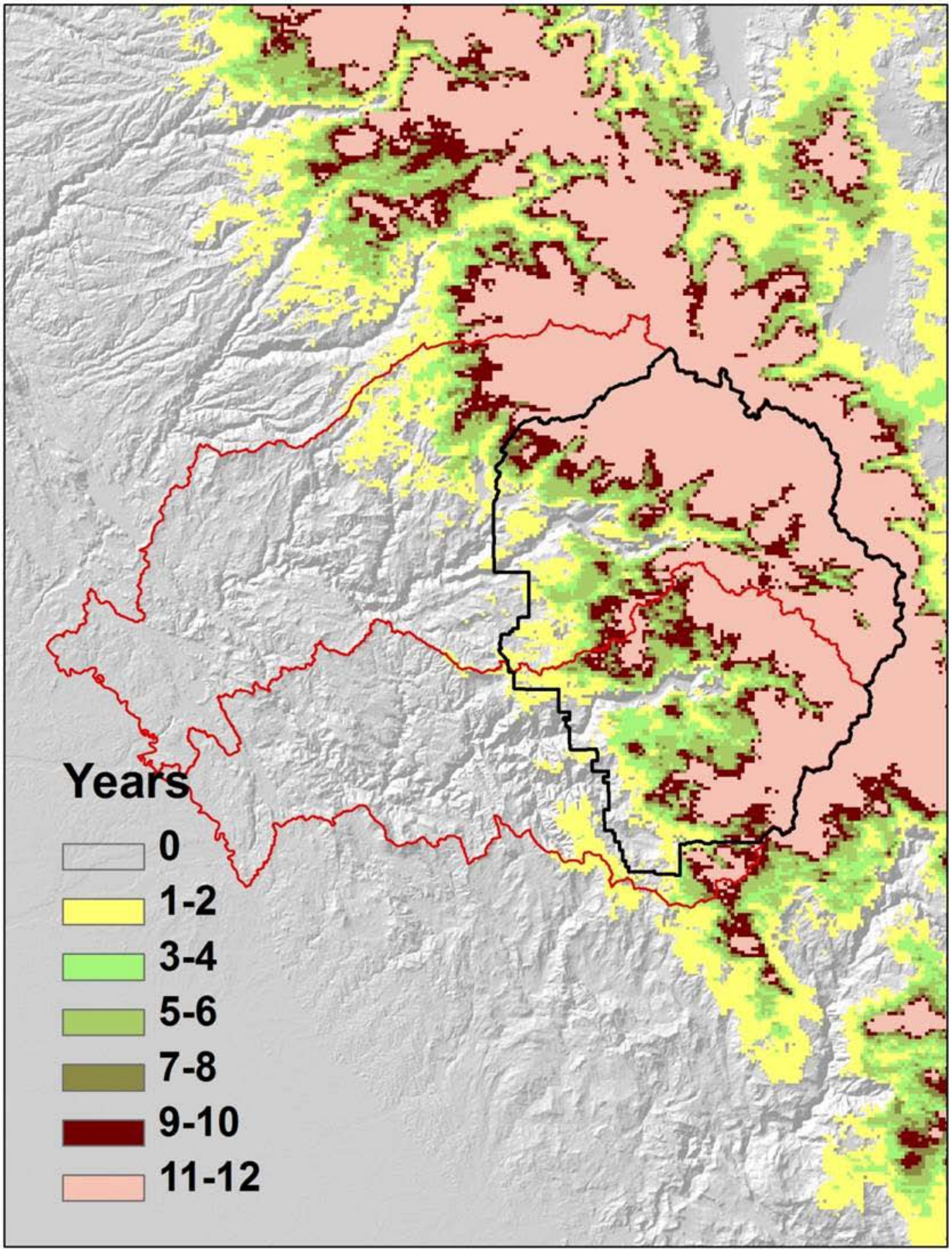

Figure 27c. Snowcover persistence across the Tuolumne and Merced River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on May 1.

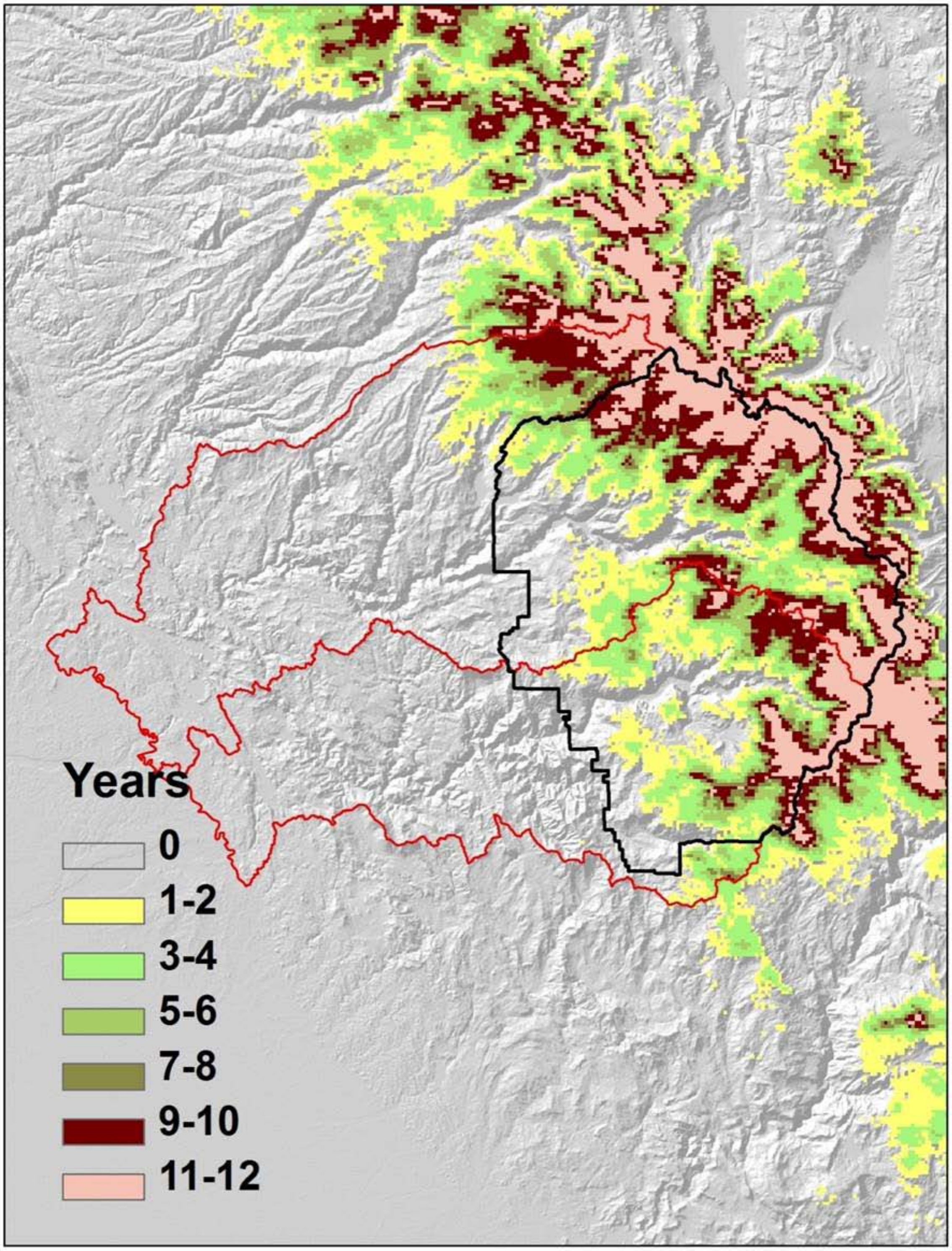

Figure 27d. Snowcover persistence across the Tuolumne and Merced River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on June 1.

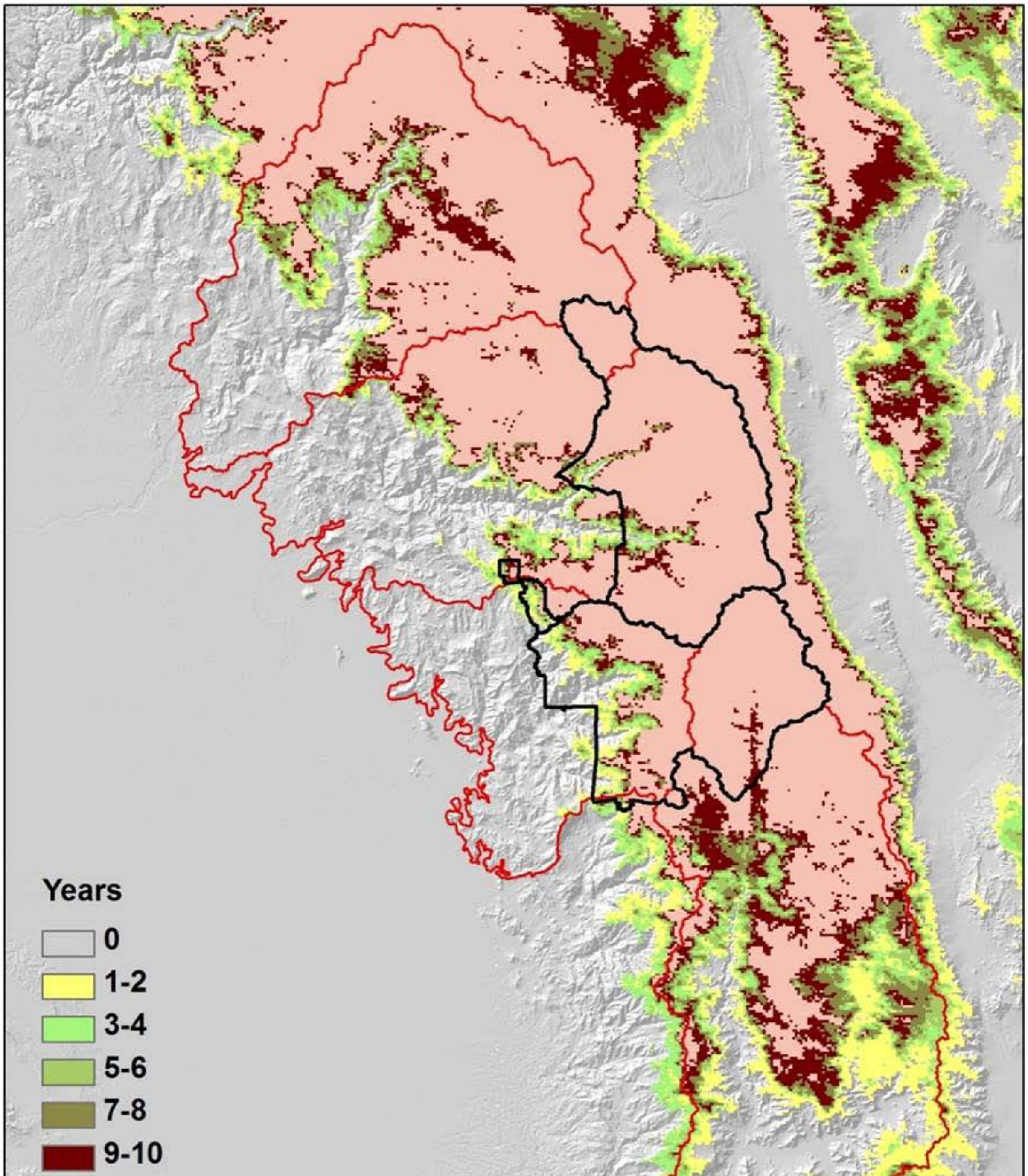

Figure 28a. Snowcover persistence across the San Joaquin, Kings, Kaweah, and Kern River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on March 1.

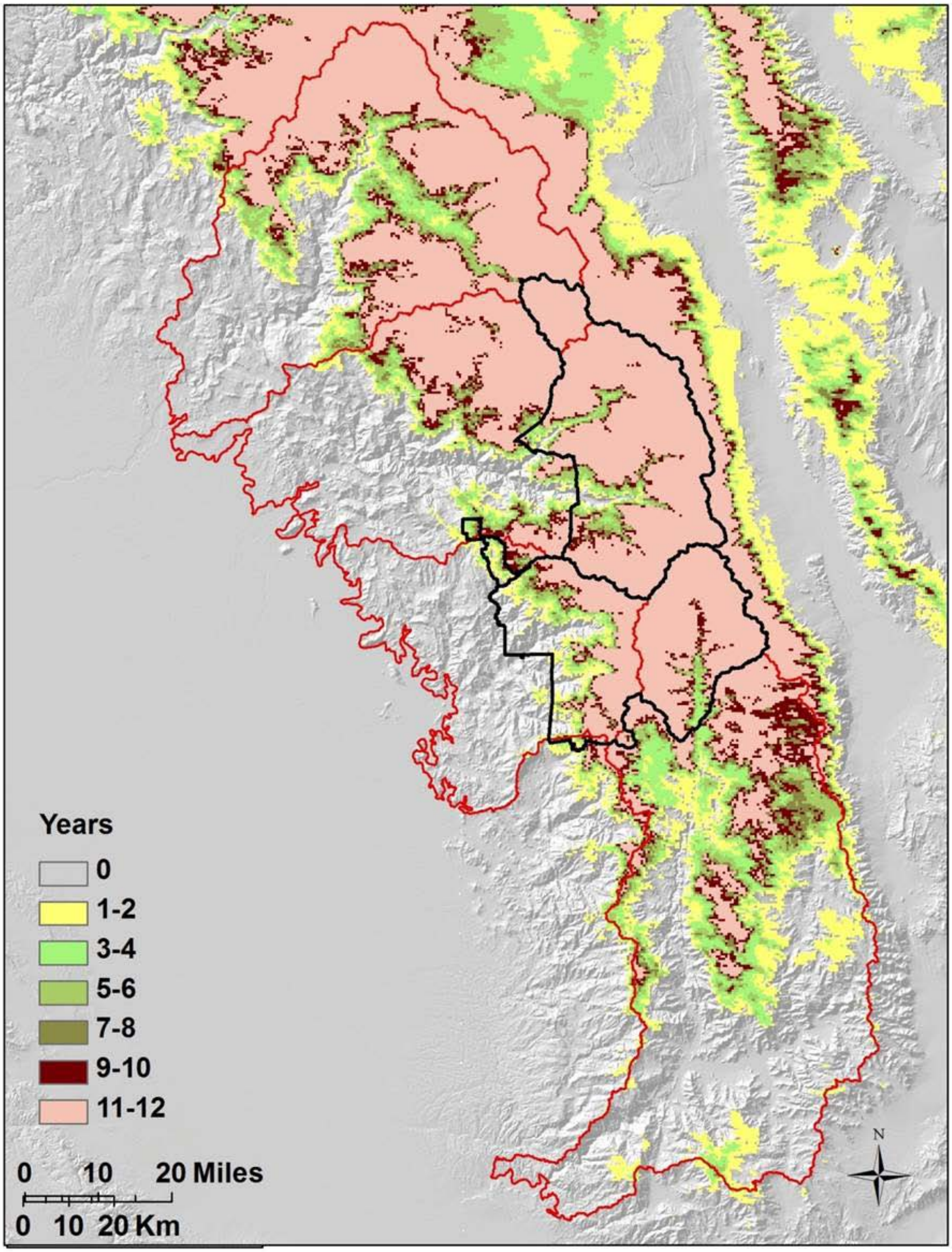

Figure 28b. Snowcover persistence across the San Joaquin, Kings, Kaweah, and Kern River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on April 1.

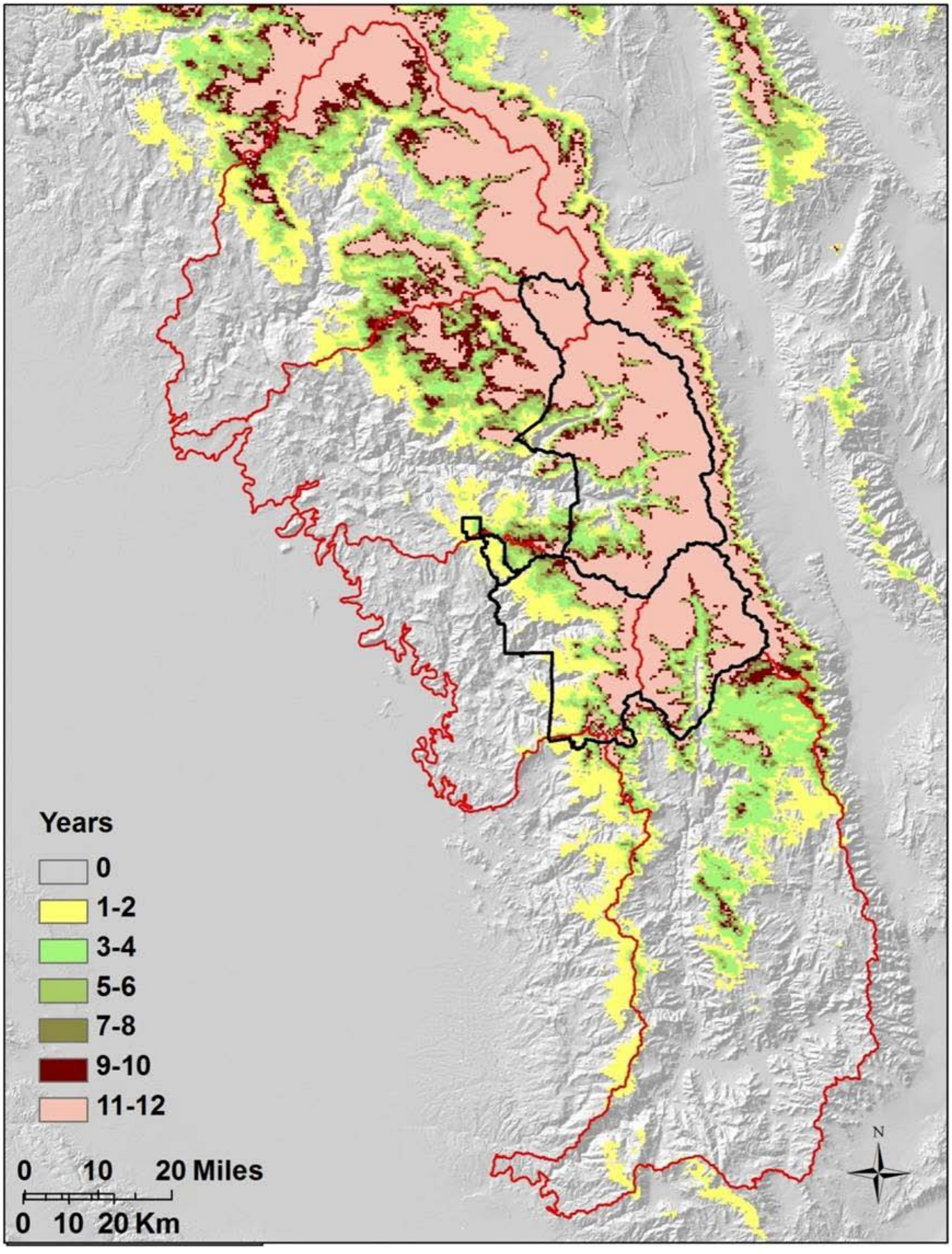

Figure 28c. Snowcover persistence across the San Joaquin, Kings, Kaweah, and Kern River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on May 1.

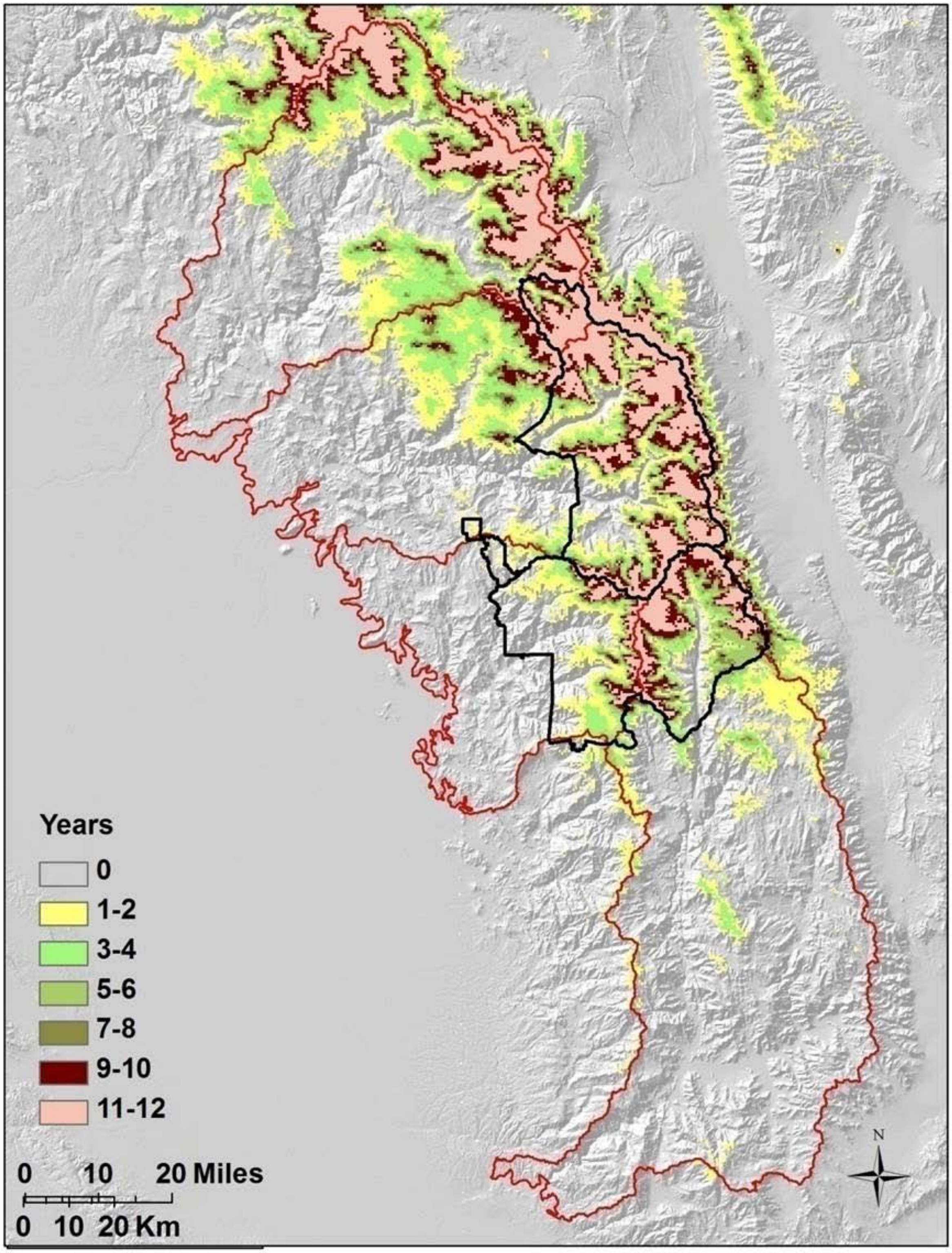

Figure 28d. Snowcover persistence across the San Joaquin, Kings, Kaweah, and Kern River basins, or number of years out of a 12-year period (2000-2011) that each pixel had >20% snowcover on June 1.

Uncertainty

There is uncertainty in both the fSCA values and the calculated snowmelt amounts. The fSCA values show some day-to-day variability, owing in part to changing atmospheric conditions and satellite viewing angle. To some extent these are addressed by multi-day smoothing of the data. In comparison, canopy adjustments are thought to be a larger factor affecting fSCA values. Though ground data for a formal evaluation of the canopy adjustment are not available, estimates made when the higher elevations are essentially completely snow covered suggest that uncertainty is on the order of 5%. That is, complete snowcover represents coverage of 95-100%, depending on the presence of slopes too steep to hold snow and trees. The same magnitude of vegetation and threshold corrections were applied to each year, up to a SCA fraction of 1.0. Corrections were larger in the mid elevations, which have greater canopy cover. Note that while canopy effects will be larger at low satellite viewing angles, that angle effect was not accounted for in the analysis.

There is also uncertainty in the calculated snowmelt (Figures 15a and 15b), whether by pixel or by elevation band. The current analysis used a temperature-index approach, calibrated to data within the watershed, and is appropriate for the data available. It is judged to be a better estimate of snowpack than those developed from climate models, which are generally indexed with the long-term PRISM (Parameter-elevation Regressions on Independent Slopes Model) (http://www.prism.oregonstate.edu/). Improvements in the snowmelt estimates should come from refinement of the snowmelt energy balance, which should be based on improved vegetation data for the basins of interest.

The temperature-index equation was formulated based on snow-surface-energy balance under a clear-sky condition as expressed below:

$$Q = (1 - r)Q_{sr} + Q_{lr} + Q_s + Q_l \qquad (2)$$

where Q is the net energy flux into the snowpack, Q_{sr} is the incident solar radiation including both direct and diffuse components on the snow surface, Q_{lr} is net longwave radiation, Q_s is sensible heat transfer, Q_l is latent heat transfer, and r is the snow surface albedo. In this energy-balance equation, two other heat components - heat advection of rain and heat conduction from ground are neglected because of the focus on the snow surface melt under a non-rain condition, and the negligible contribution of heat flux from the ground.

For a given net energy flux Q, the snowmelt rate M (melt rate per hour: mm hr^{-1}) can be estimated from:

$$M = \frac{10^3}{\rho \cdot L_f} Q \qquad (3)$$

where ρ is the water density, L_f is the latent heat of fusion, and 10^3 is unit conversion factor from meter to millimeter.

In order to calculate the snowmelt, and hence snowmelt volume, detailed meteorological forcing data are required (i.e. shortwave radiation, longwave radiation, wind speed, humidity, and temperature), and modeled across a gridded surface. However, temperature is the only reliable and extensively available historical data set available. The National Weather Service National Operational Hydrologic Remote Sensing Center (NOHRSC) provides an energy-based snow model, Snow Data Assimilation System (SNODAS) that provides snowpack estimates at a 1-km resolution (Rutter et al. 2008; Barrett 2003). Questions about such models arise given the uncertainty in the meteorological forcing, (e.g. radiation, wind speed, humidity), as results of energy-balance models are sensitive to errors in the meteorological forcing data, especially radiative energy. High-quality forcing data for snowmelt are available for the full MODIS time period at a limited number of sites (e.g. Mammoth Mountain and Central Sierra Snow Lab). More recently, additional sites closer to the parks have the needed data (e.g. Southern Sierra Critical Zone Observatory). With detailed analysis of data and terrain/canopy adjustments, energy-balance forcing data could be developed for at least part of the MODIS period.

Recommendations

Planning infrastructure and operations for climate change needs to be a process and not just an event (Bales et al. 2004), and should involve a continuing program of measurement, modeling and assessment. Going forward, management of water-dependent resources should consider an adaptive-management approach, involving a continual cycle of investigation and synthesis to inform decision-making. We recommend developing more-definite scenarios for temperature, precipitation, snowpack, snowmelt and streamflow that are specific to the relatively small sub-basins and complex topography of the SIEN watersheds and should consider the following elements:

1. An expanded and enhanced measurement program of mountain temperature, precipitation, snowpack, soil moisture and selected other energy-balance components to augment the current system, which was put in place over the past several decades and is largely based on technology developed over 50 years ago. Technological advances of the past decade have resulted in many low-power, low-cost, robust sensors and networks that can provide real-time data to inform operations, as well as longer-term information to inform planning and policies. A program involving at least hundreds of sensors distributed across the main snow- and runoff-producing sub-basins should have a very fast payback in terms of the value of the information to the aggregate of ecosystem services that serves stakeholders both in and outside the park that depend on snow. These data will require integration into energy balance models of snowmelt covering all areas of the parks. Because of the large number of stakeholders who benefit, there should be opportunities for cost-sharing on such a program.
2. Improved characterization of forest vegetation from satellite and aircraft data in support of hydrologic data analysis and modeling. Use of LIDAR data is especially promising.
3. An ongoing program of assessment of hydrologic conditions, trends, forecasts, and outlooks, with particular emphasis on extreme events and years; integrating this program with decision support.
4. A rigorous, focused analysis of temperature and precipitation, and regridding to produce a PRISM-like data set would provide greater confidence. Additional quality control of data, plus a focused regional analysis is recommended.

Accurate fine-scale temperature, precipitation, and snowpack patterns all affect understanding of rain, snow and temperature resources. While improvements in modeling or gridding available data could help address these gaps, additional data for evaluation are also a clear need. The degree-day method of estimating snowmelt is used throughout the world, because the temperature data needed to drive such a model are perhaps the most easily available meteorological data. However, the degree-day method does not truly represent the processes that drive snowmelt. Kumar et al. (2013) show that degree-day coefficients derived from a specific snow pillow can drive a snowmelt model for that pillow, but the coefficients differ for different pillows and they cannot reliably drive a distributed snowmelt model. In addition, possibilities of driving energy balance models from assimilated satellite data and model result, specifically from NLDAS (the National Land Data Assimilation System) and current work at NASA 's Jet Propulsion Lab show very promising results (Rittger et al. 2011; Rittger 2012).

A minimum protocol for continued assessment of snowpack resources should follow the approach used in this report. Table 2 provides an estimate of the effort required to carry this out. An additional 60 hours of time for a Scientist/Analyst were added to enable integration of data into an energy balance model.

Table 2. Tasks, processing time, equipment/software, and personnel required to develop the data necessary for analysis of the snowcover for the six major river basins for Yosemite, Kings Canyon, and Sequoia National Parks.

Tasks	Processing Time, *hrs.*	Equipment/Software	Personnel
Data Acquisition	40	Unix/linux shell scripts	Computer specialist
Quality Control/ Quality Assurance	140	Programming Language (i.e. Python/Matlab)	Computer specialist
Temperature Lapse Rates	70	Programming Language (i.e. Python/Matlab)	Computer specialist
Degree day factors	30	MS Excel/ Sigmaplot/Matlab/Python	Scientist/Analyst
MODIS SCA by elevation band	30	Programming language (i.e. Python/Matlab)	Computer/GIS specialist
MODIS corrections	60	Programming language (i.e. MS Excel/Matlab/ Sigmaplot)	Scientist/Analyst
Temperature Index Model	30	MS Excel	Scientist/Analyst
Integrate assimilated data into energy balance model	60	Programming Language (i.e. Python/Matlab)	Scientist/Analyst

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Appendix

This appendix includes additional graphics not included in the main body of the report. These include the following:

1. Average daily temperature from 2000-2009 for meteorological stations in the Tuolumne, Merced, San Joaquin, Kings, Kaweah, and Kern river basins (Figures A-1 to A-6).

2. Snow water equivalent from 2000-2009 for snow pillows in these six river basins (Figures A-7 to A-12).

3. Raw and adjusted snow-covered area for a wet, a dry, and an average year in the Tuolumne and Kern river basins (Figures A-13 to A-14).

4. River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the period 2000-2009 for all six river basins (Figures A-15 to A-20).

Figures

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Figures (continued)

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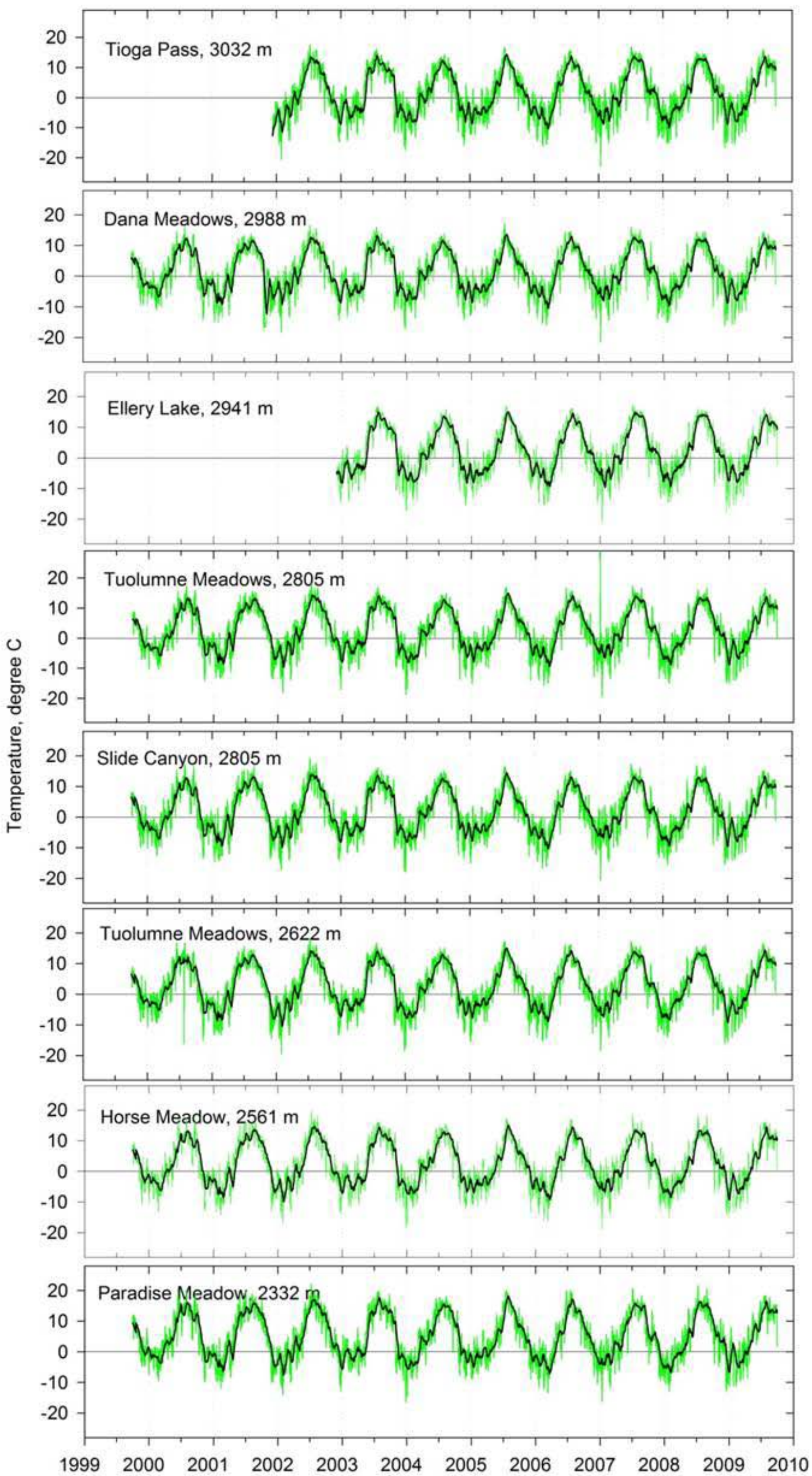

Figure A- 1. Daily average temperature for 15 stations in the Tuolumne River basin. Green lines are daily means and black lines are 20-day running means.

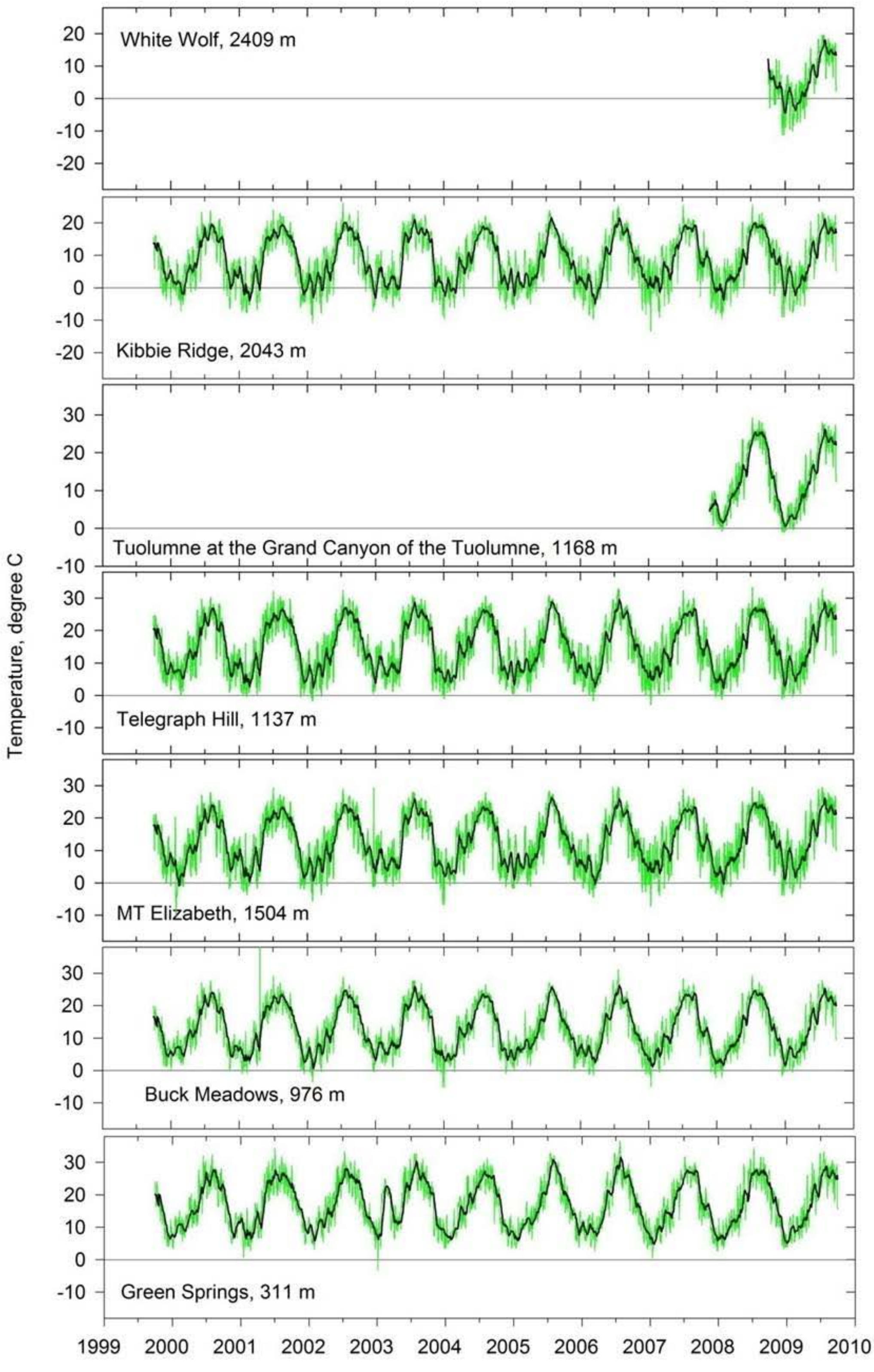

Figure A- 1 (continued). Daily average temperature for 15 stations in the Tuolumne River basin. Green lines are daily means and black lines are 20-day running means.

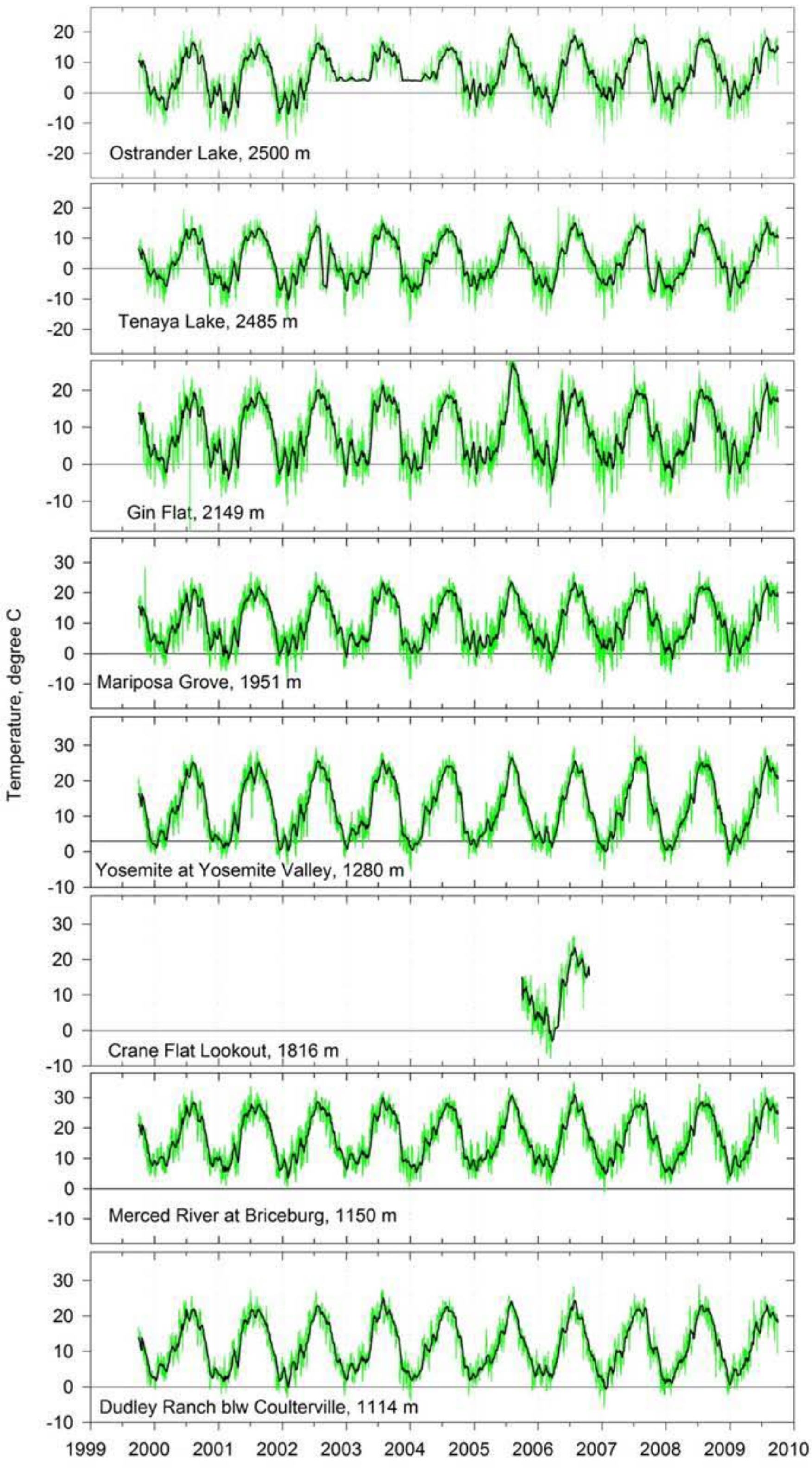

Figure A- 2. Daily average temperature for 14 stations in the Merced River basin. Green lines are daily and black lines are 20-day running means.

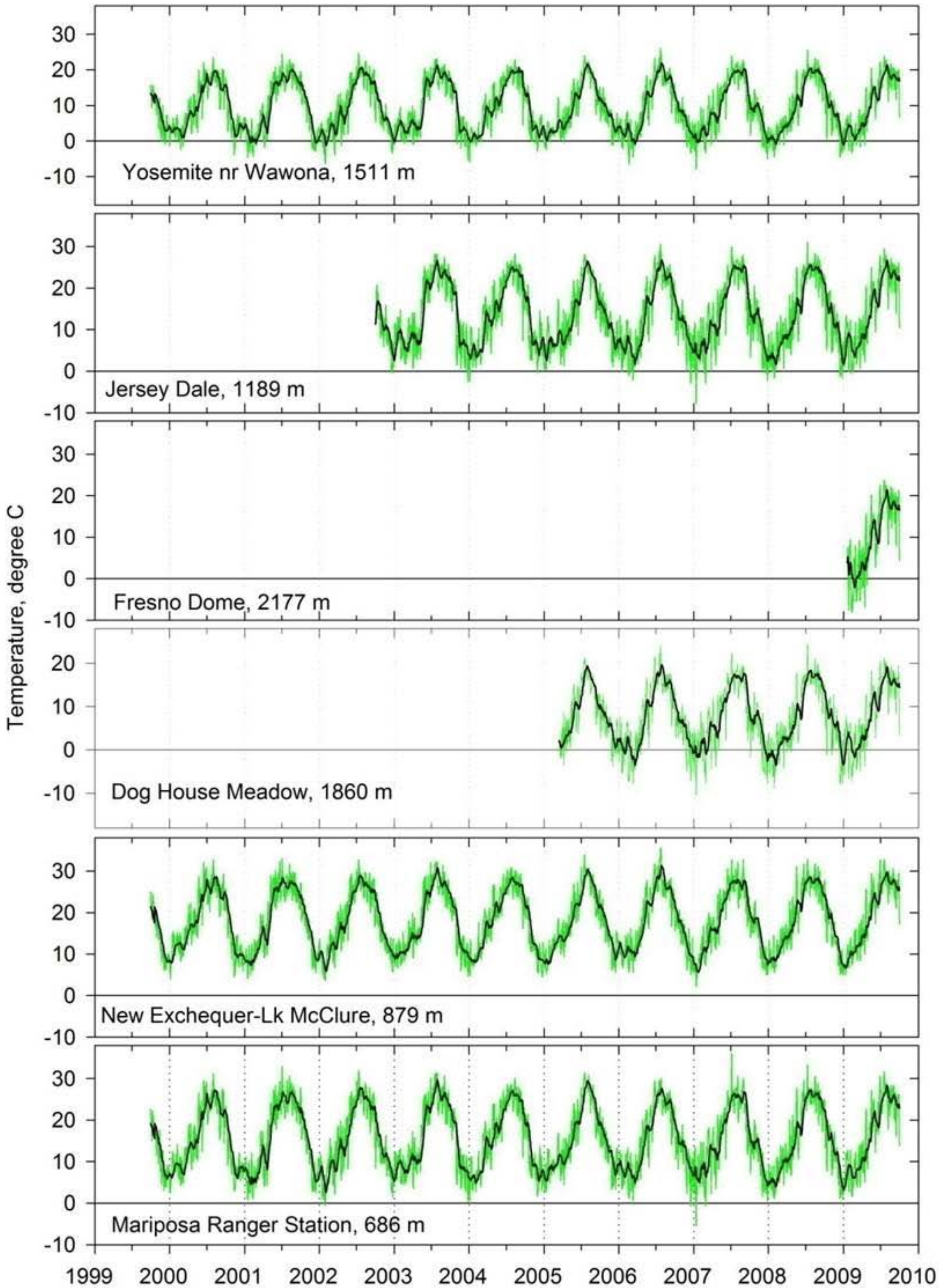

Figure A- 2 (continued). Daily average temperature for 14 stations in the Merced River basin. Green lines are daily and black lines are 20-day running means.

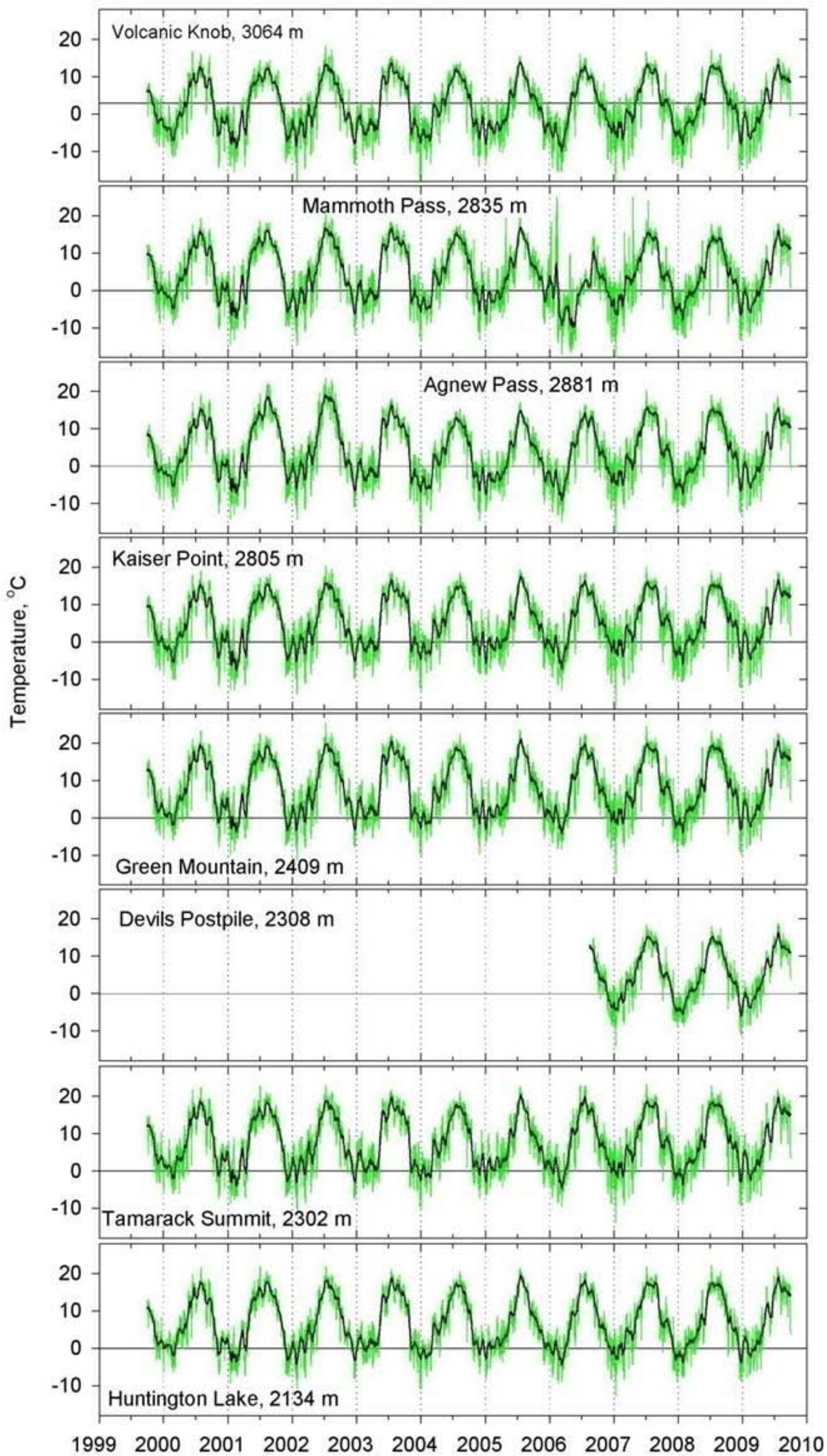

Figure A- 3. Daily average temperature for 16 stations in the San Joaquin River basin. Green lines are daily and black lines are 20-day running means.

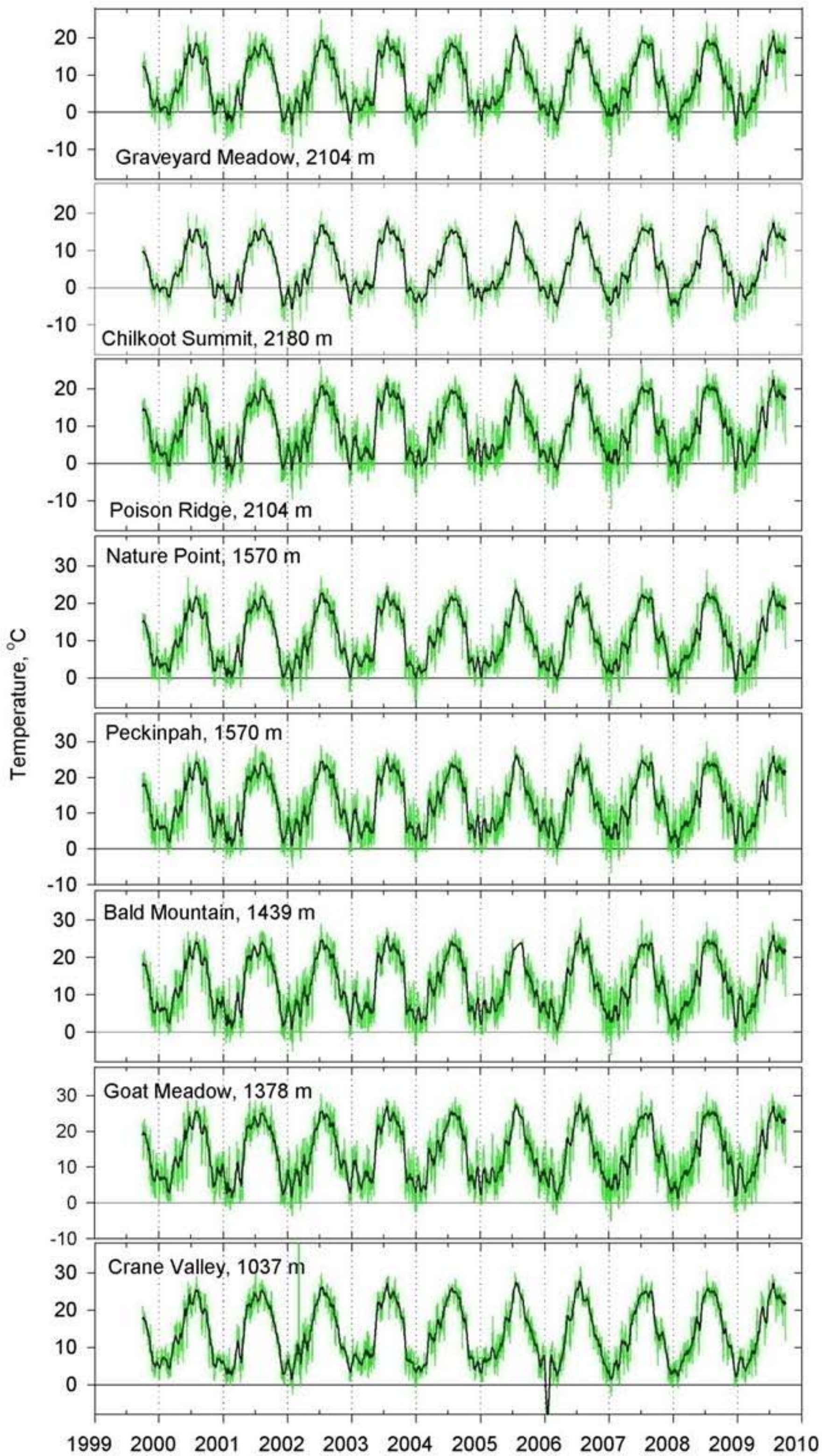

Figure A- 3 (continued): Daily average temperature for 16 stations in the San Joaquin River basin. Green lines are daily and black lines are 20-day running means.

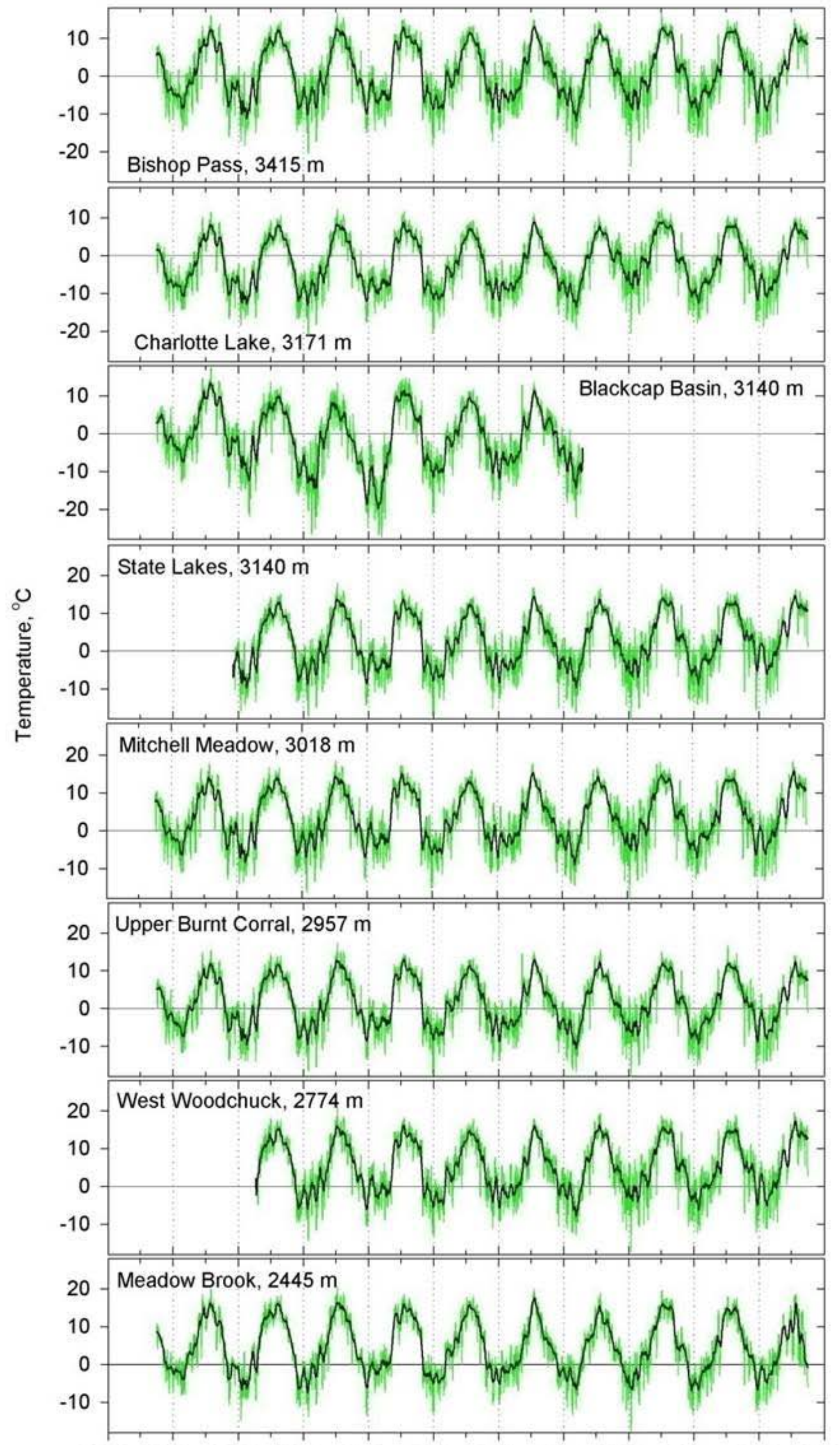

Figure A- 4. Daily average temperature for 16 stations in the Kings River basin. Green lines are daily and black lines are 20-day running means.

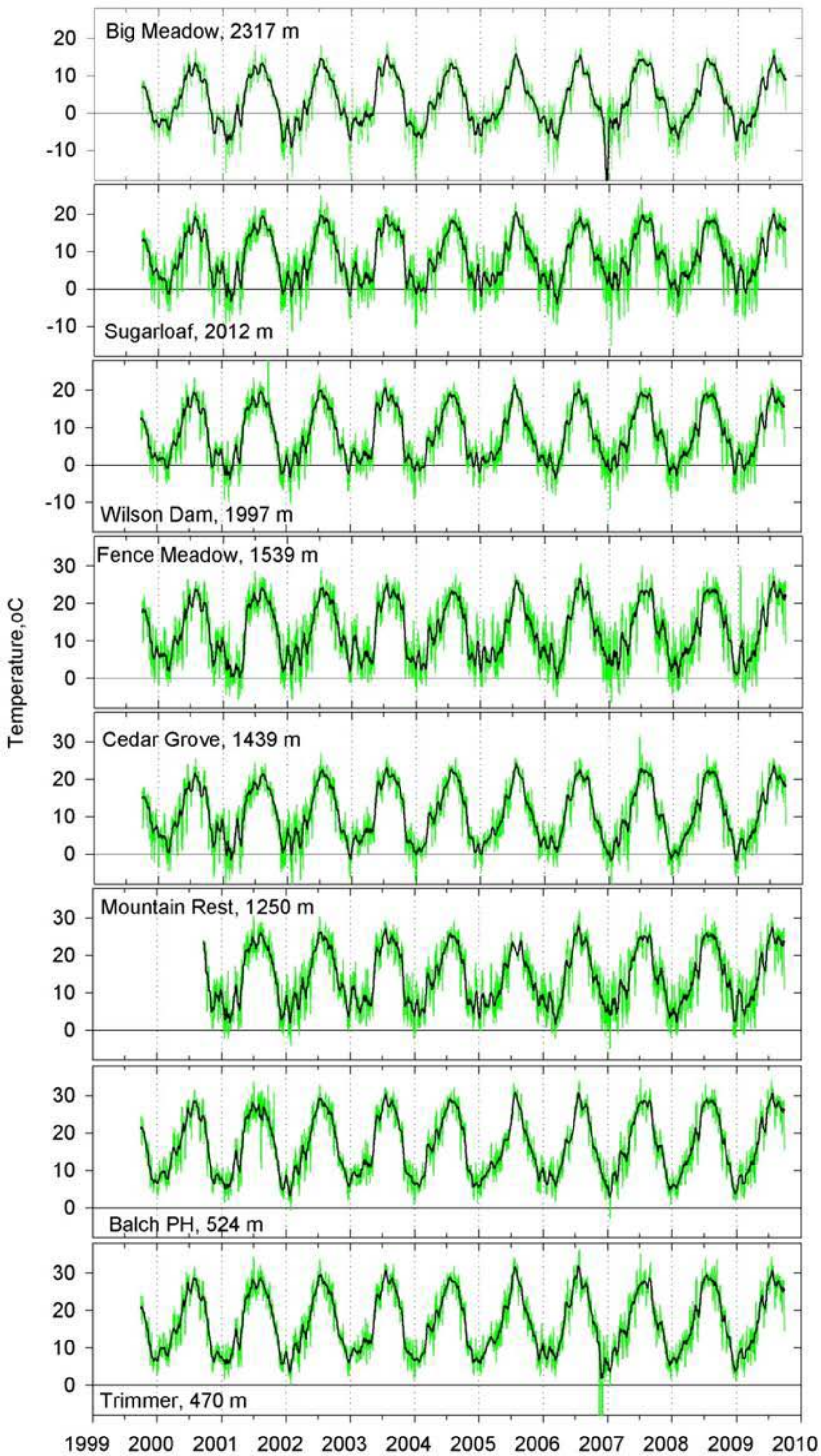

Figure A- 4 (continued). Daily average temperature for 16 stations in the Kings River basin. Green lines are daily and black lines are 20-day running means.

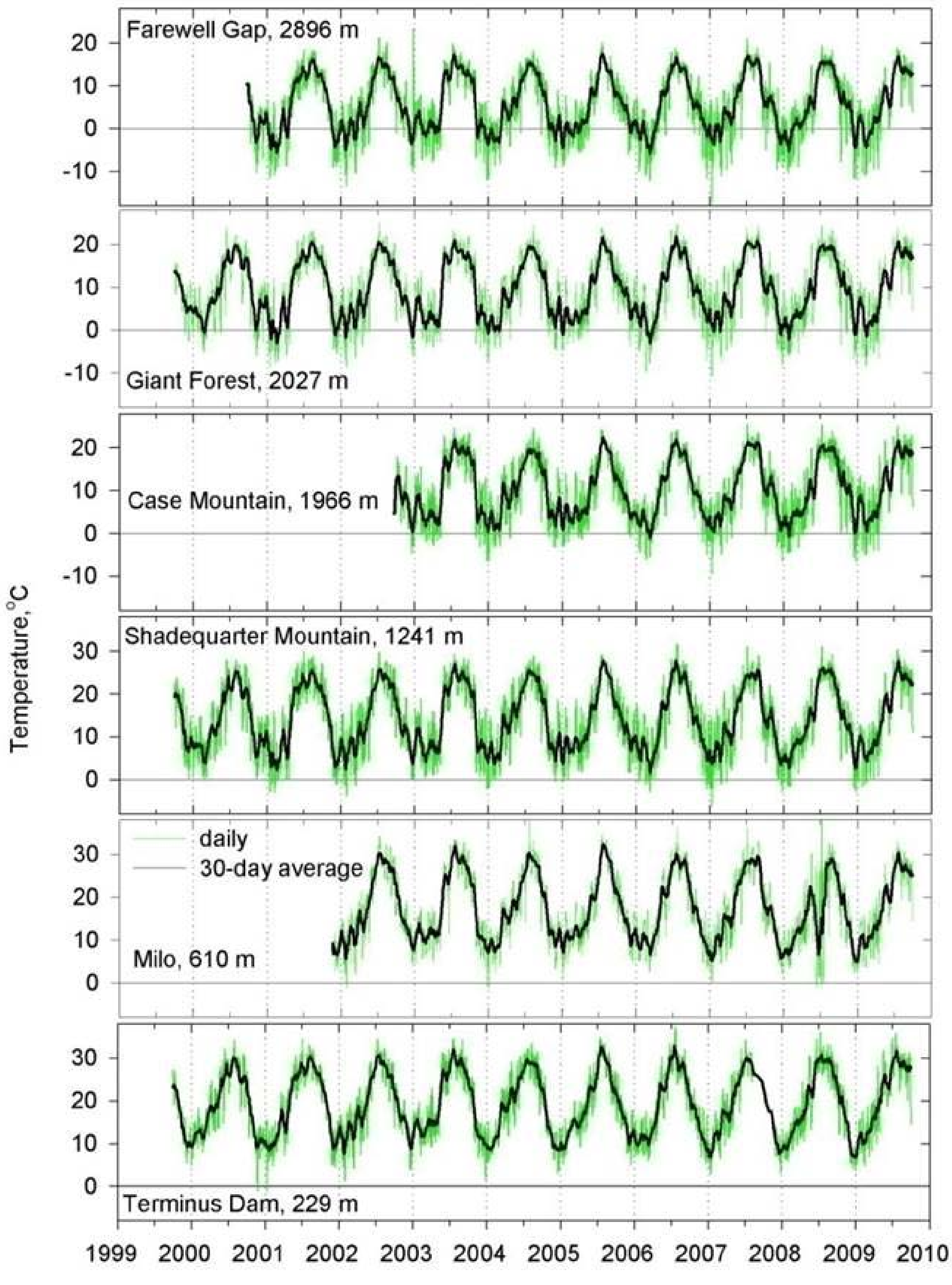

Figure A- 5. Daily average temperature for six stations in the Kaweah River basin. Green lines are daily and black lines are 20-day running means.

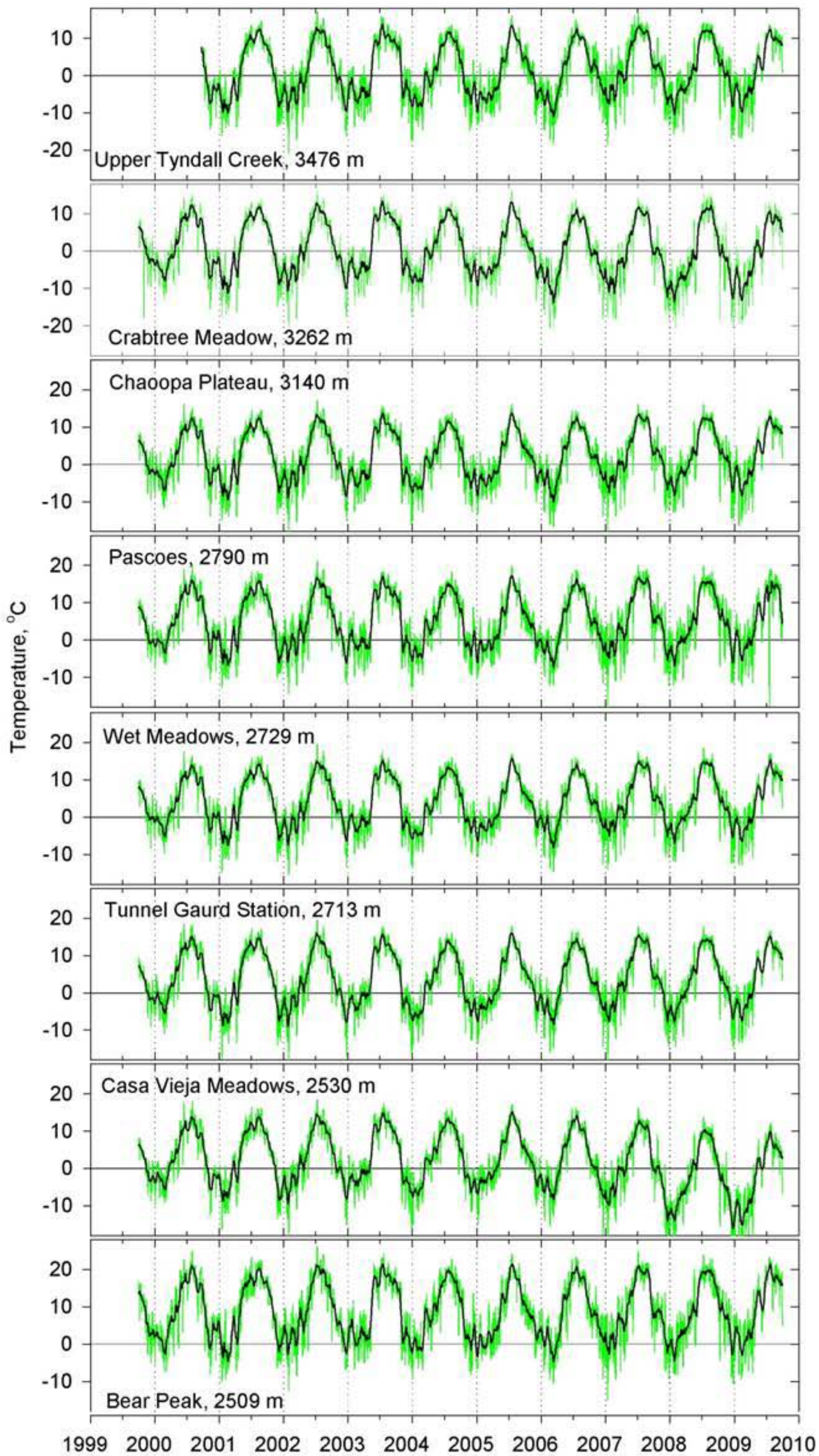

Figure A- 6. Daily average temperature for 13 stations in the Kern River basin. Green lines are daily and black lines are 20-day running means.

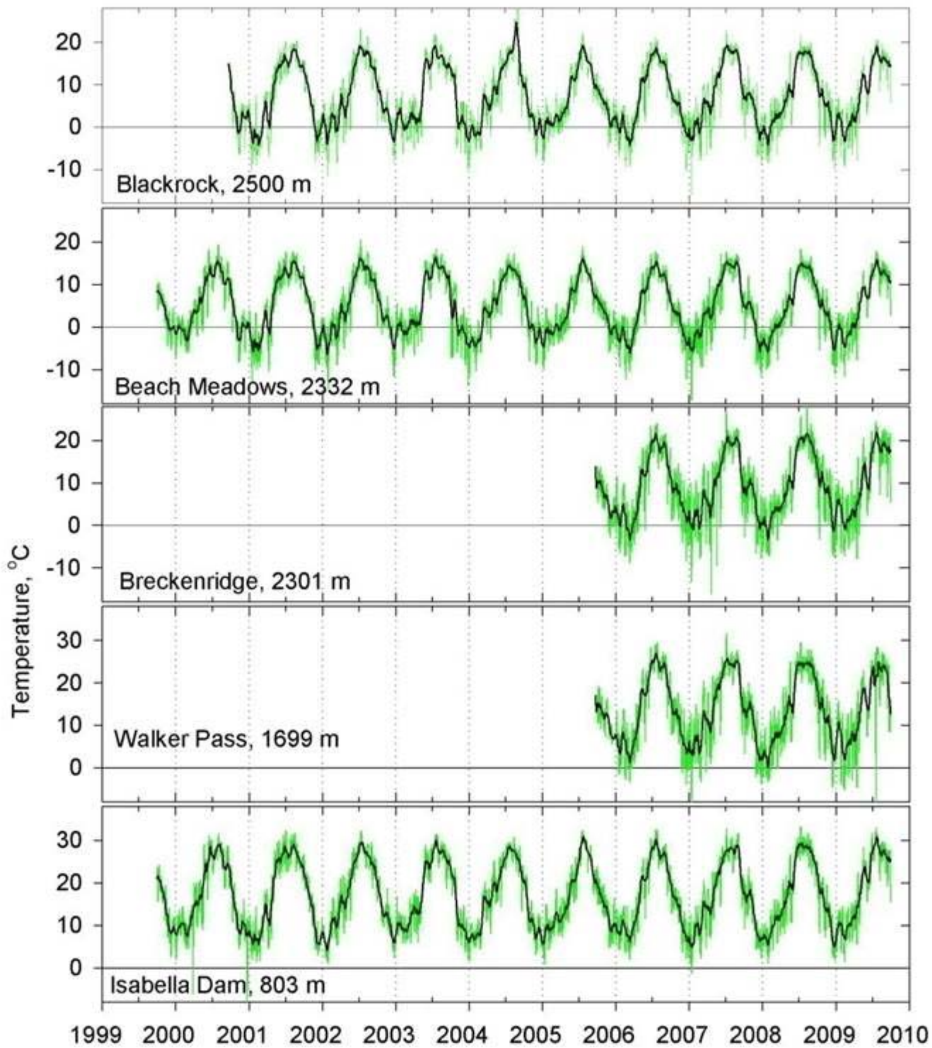

Figure A- 6 (continued). Daily average temperature for 13 stations in the Kern River basin. Green lines are daily and black lines are 20-day running means.

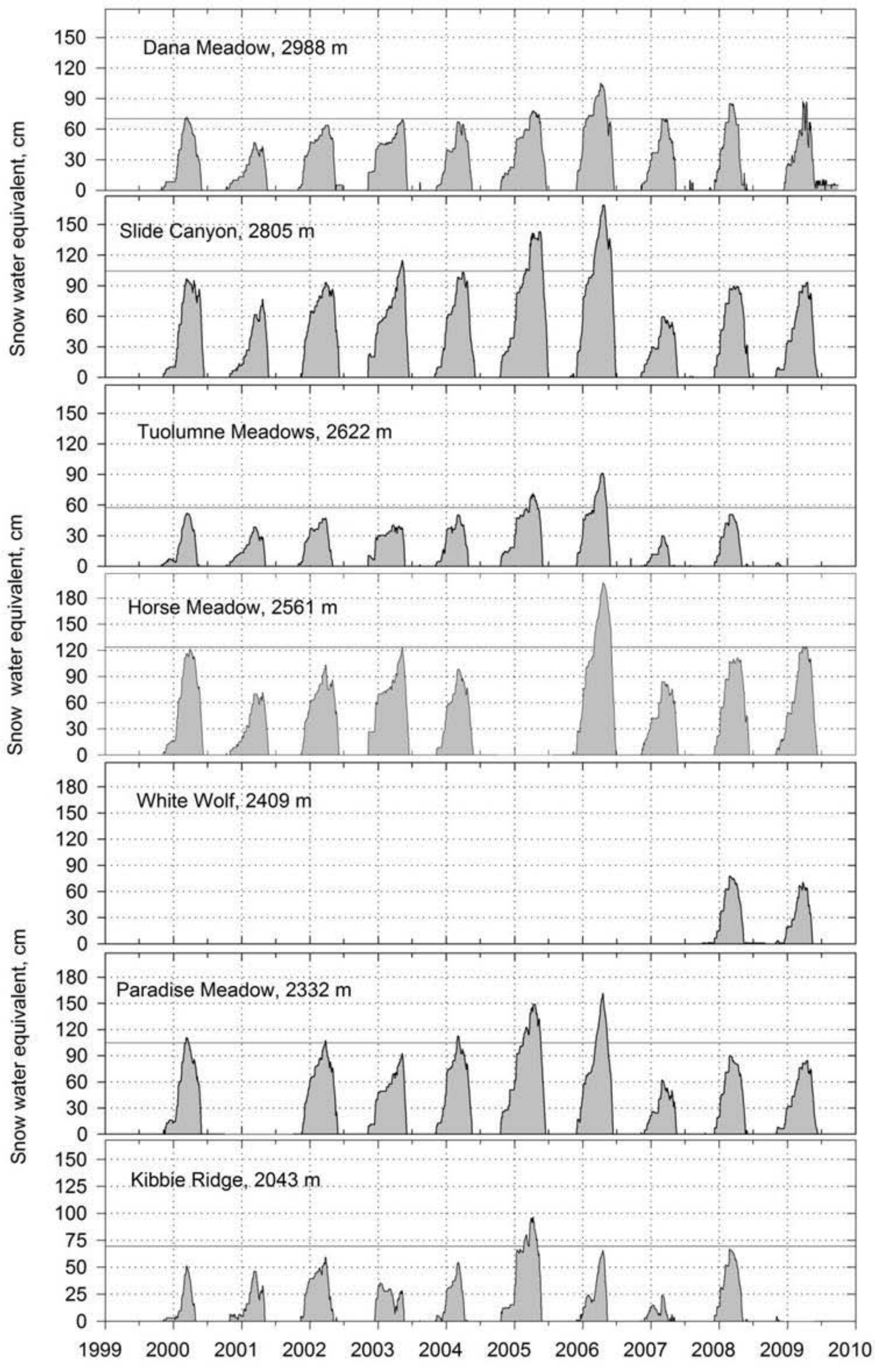

Figure A- 7. SWE for seven pillows in the Tuolumne basin. Note that some years have missing data (not zero values).

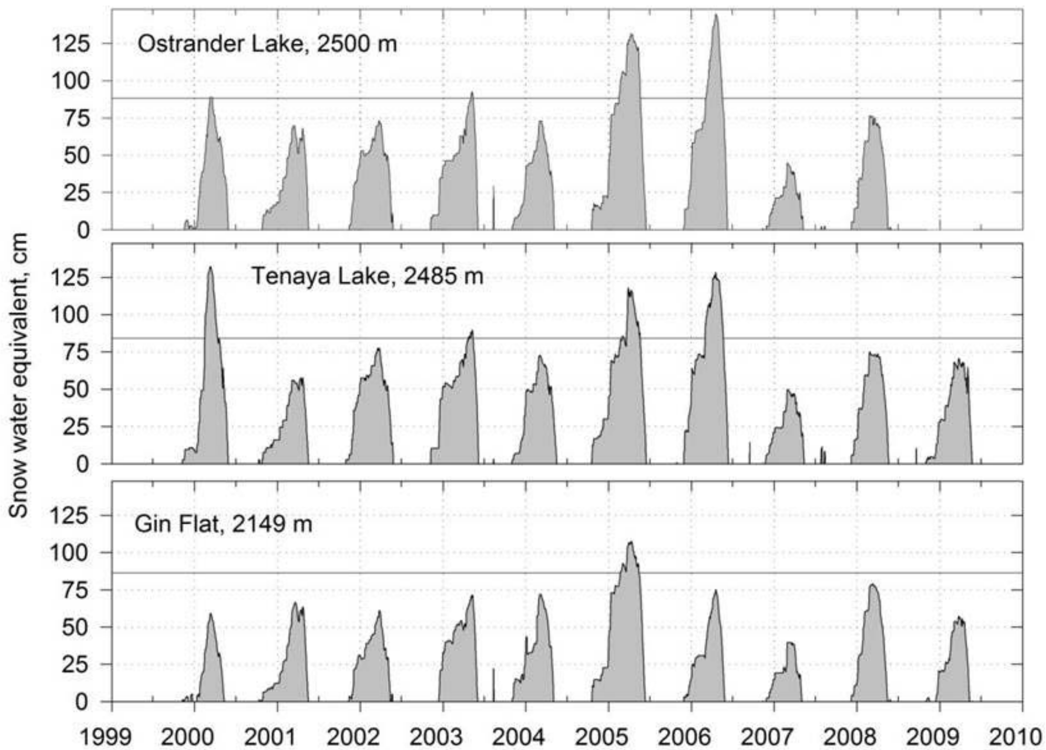

Figure A- 8. SWE for three pillows in the Merced basin. Note that some years have missing data (not zero values).

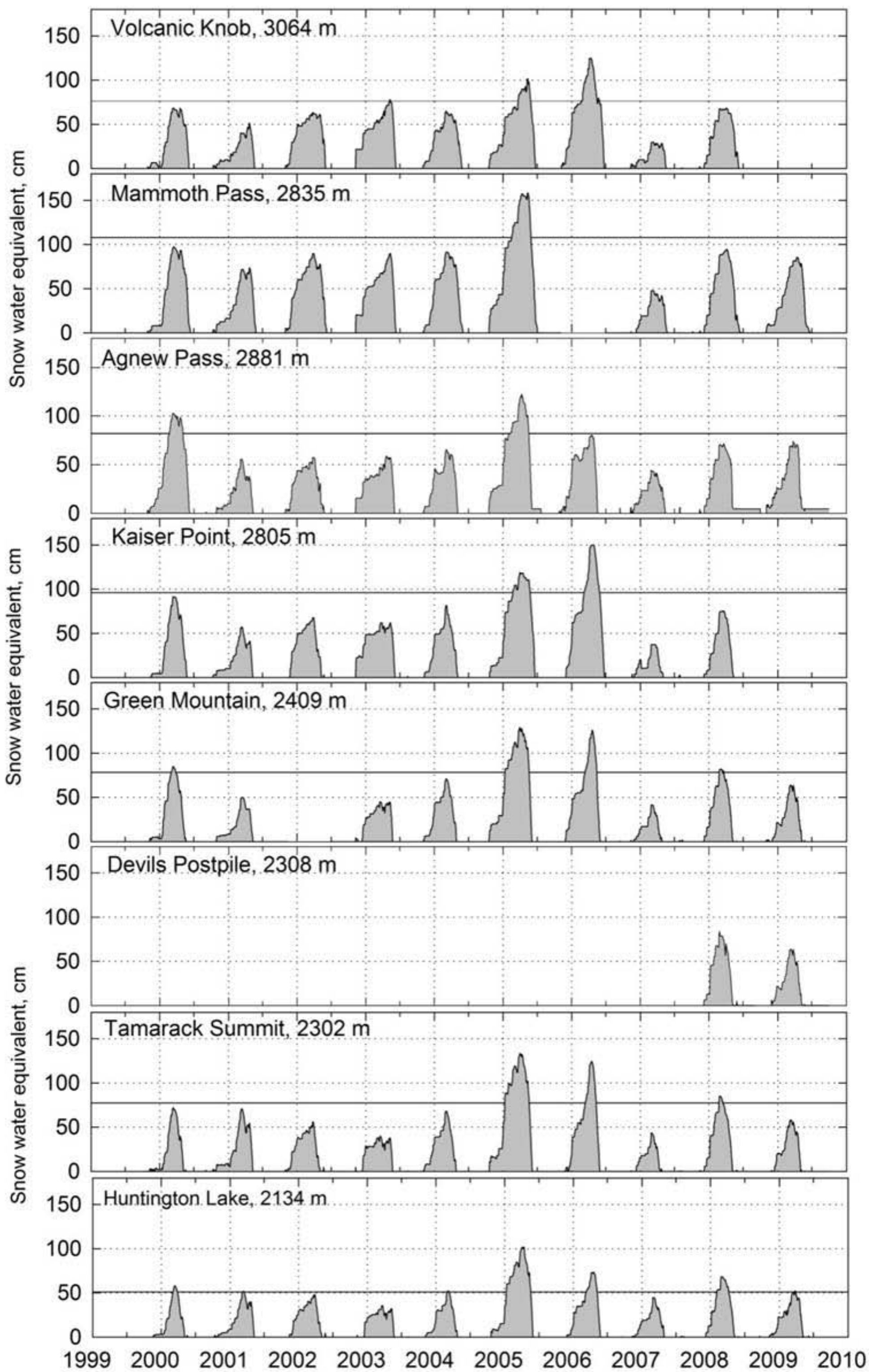

Figure A- 9. SWE for 11 pillows in the San Joaquin basin. Note that some years have missing data (not zero values).

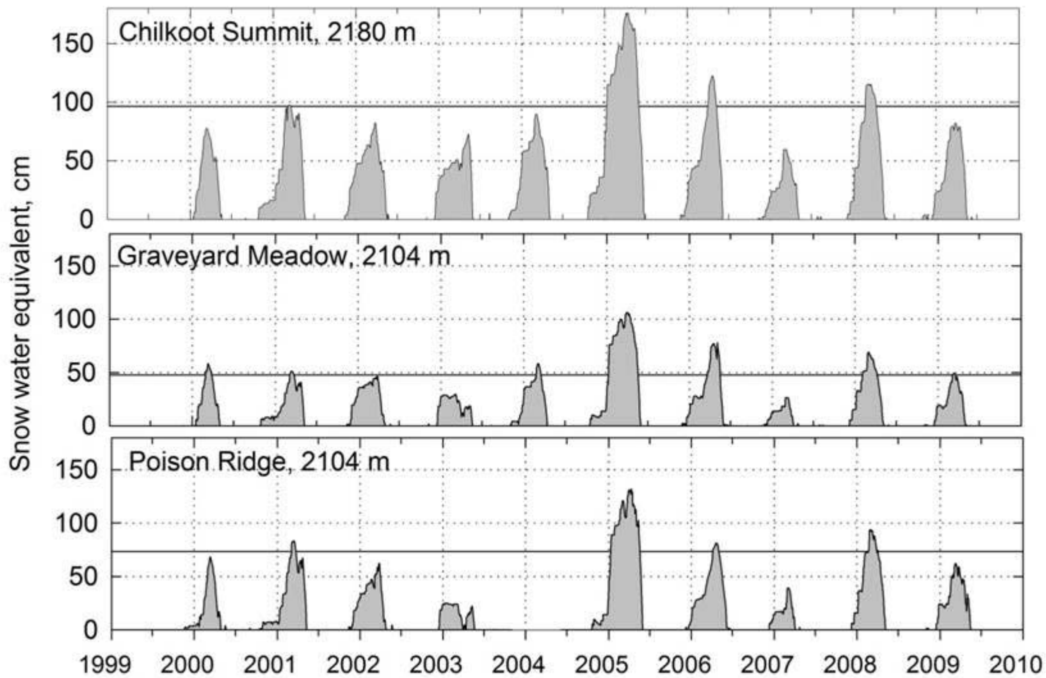

Figure A- 9 (continued). SWE for 11 pillows in the San Joaquin basin. Note that some years have missing data (not zero values).

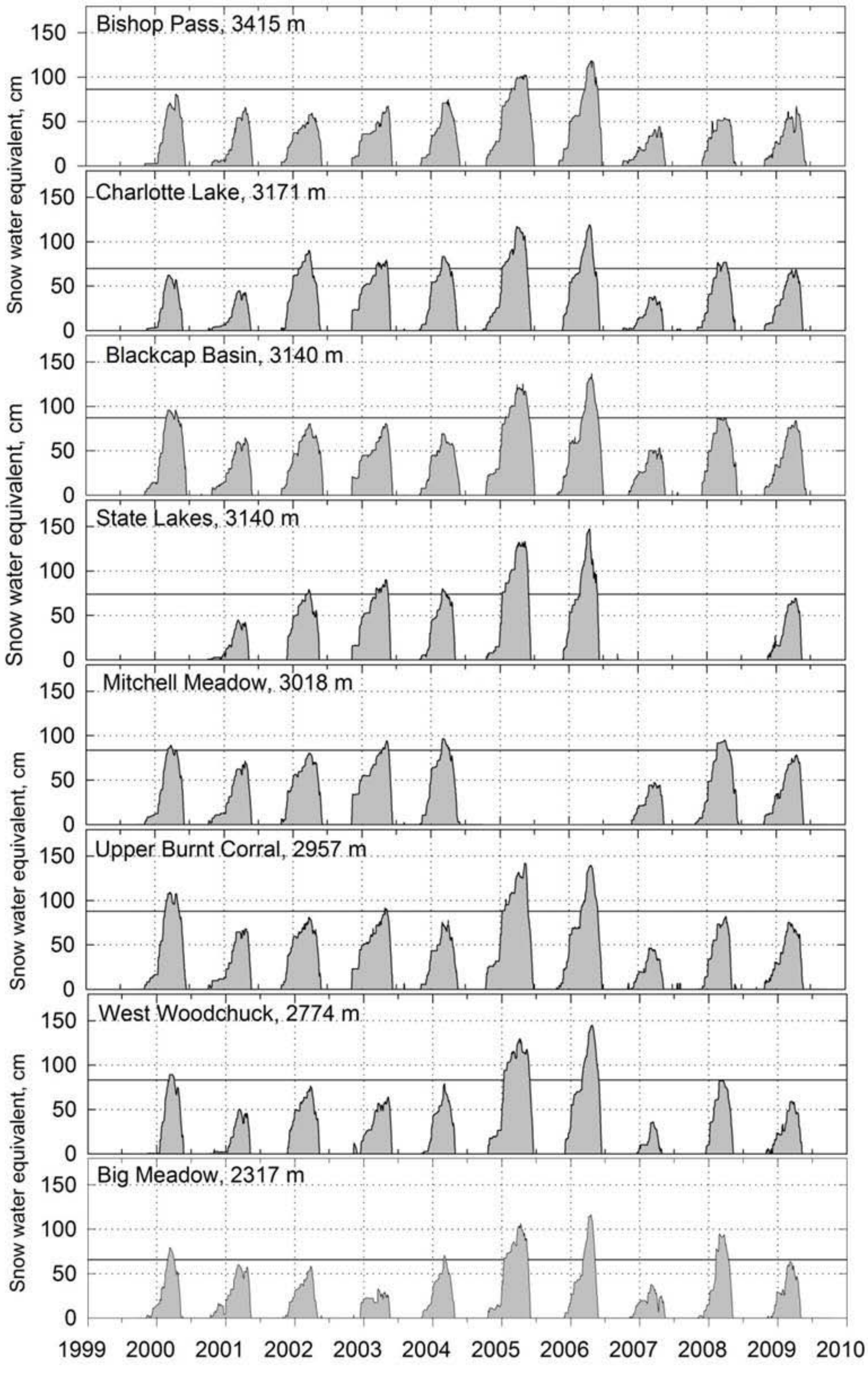

Figure A- 10. SWE for eight pillows in the Kings basin. Note that some years have missing data (not zero values).

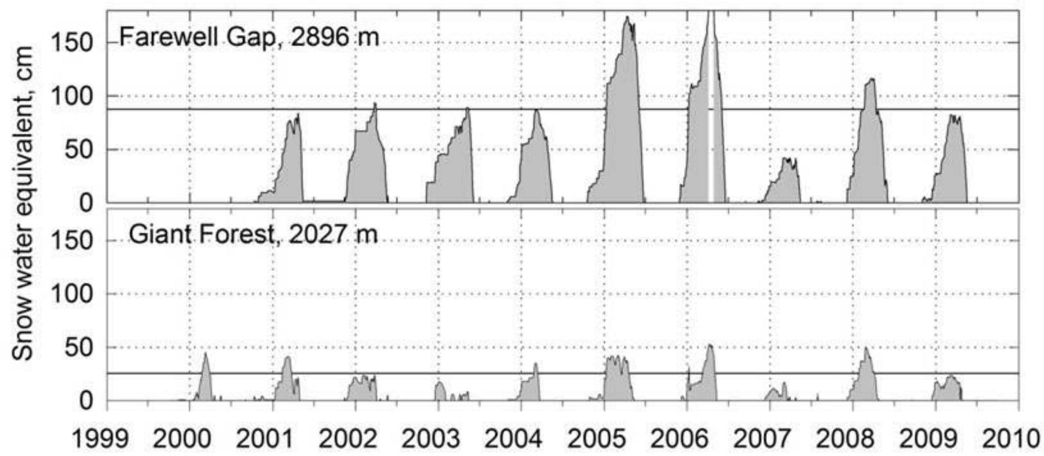

Figure A- 11. SWE for two pillows in the Kaweah basin. Note that some years have missing data (not zero values).

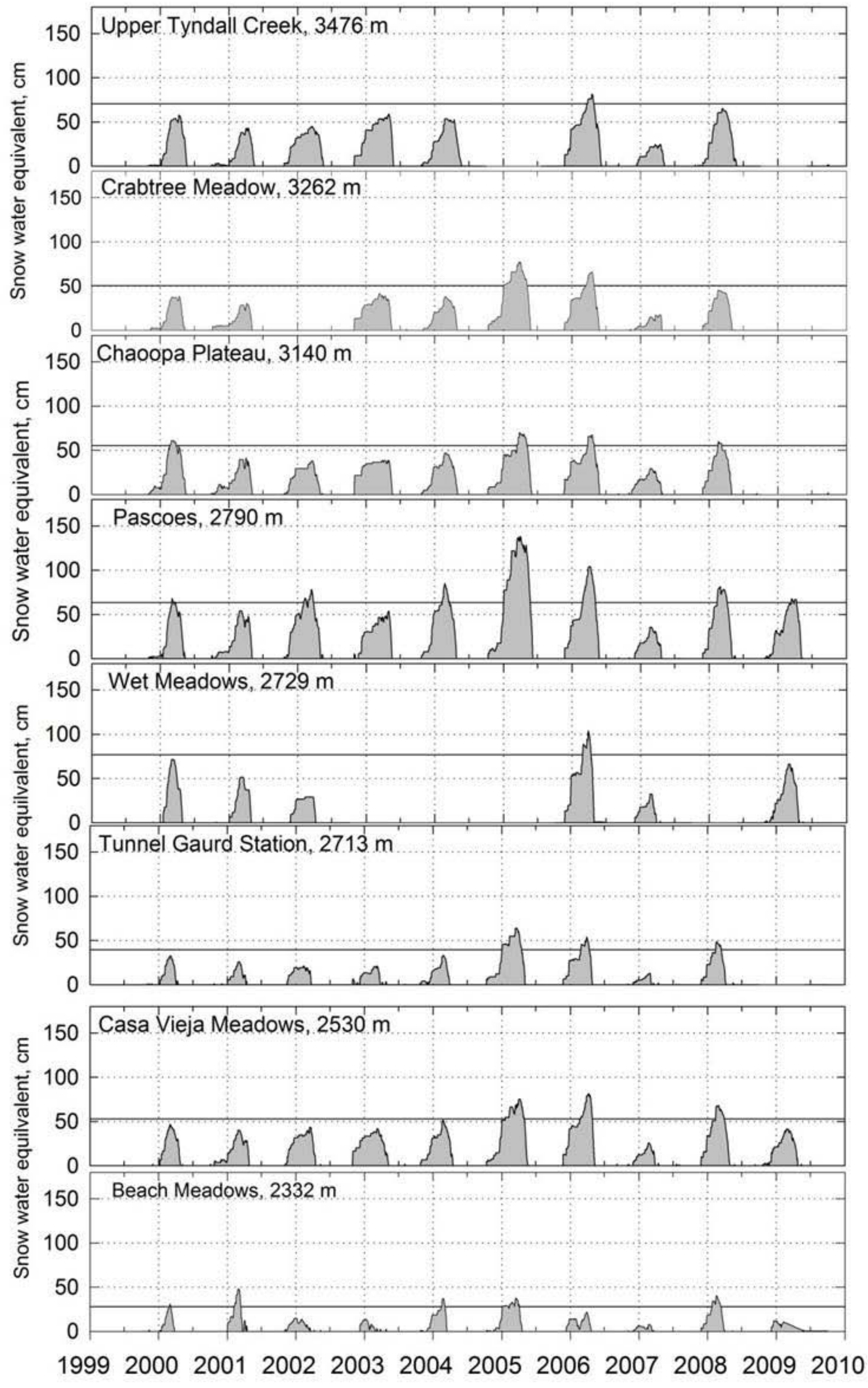

Figure A- 12. SWE for two pillows in the Kern basin. Note that some years have missing data (not zero values).

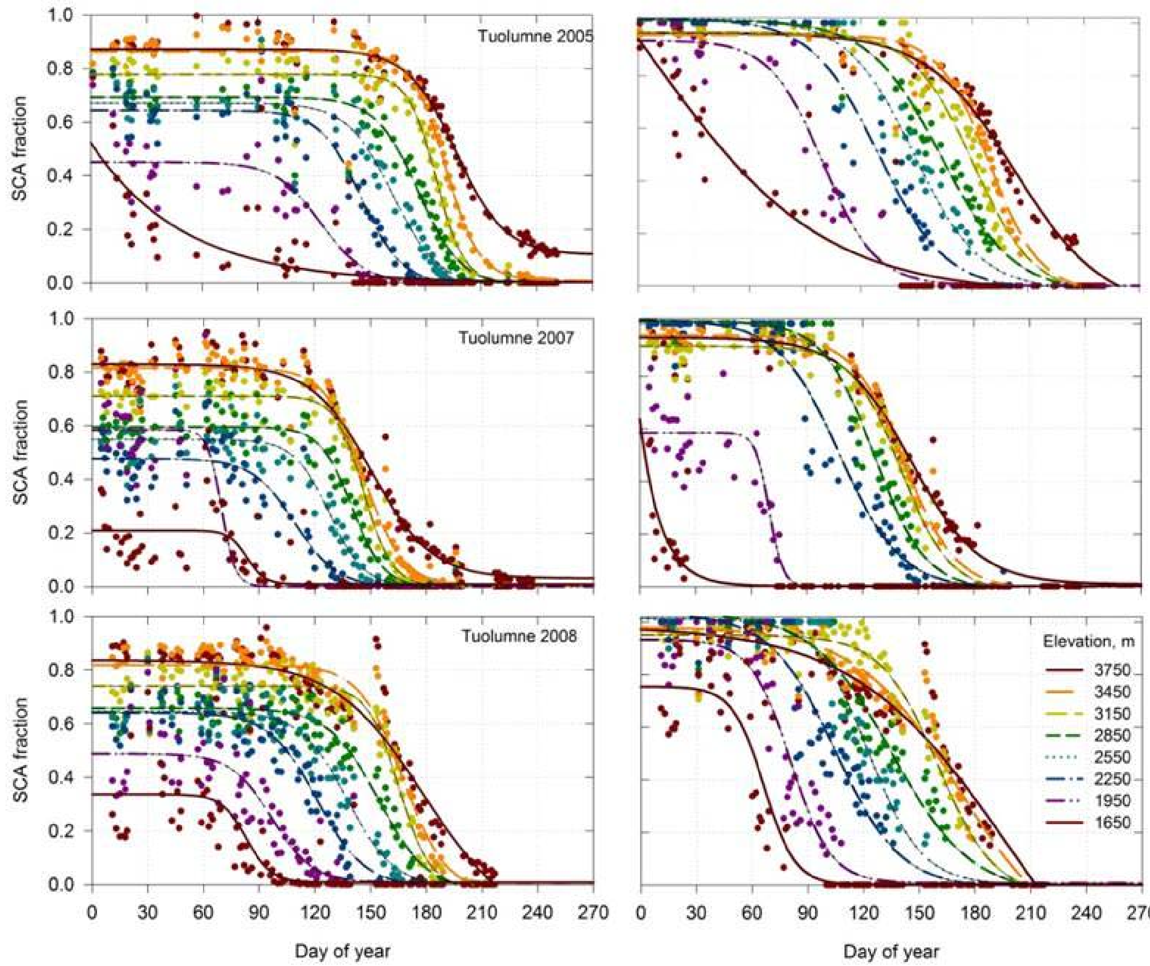

Figure A- 13. Comparison of the raw (left panels) and adjusted (right panels) SCA for a wet (2005), dry (2007), and average (2008) year for the Tuolumne River basin.

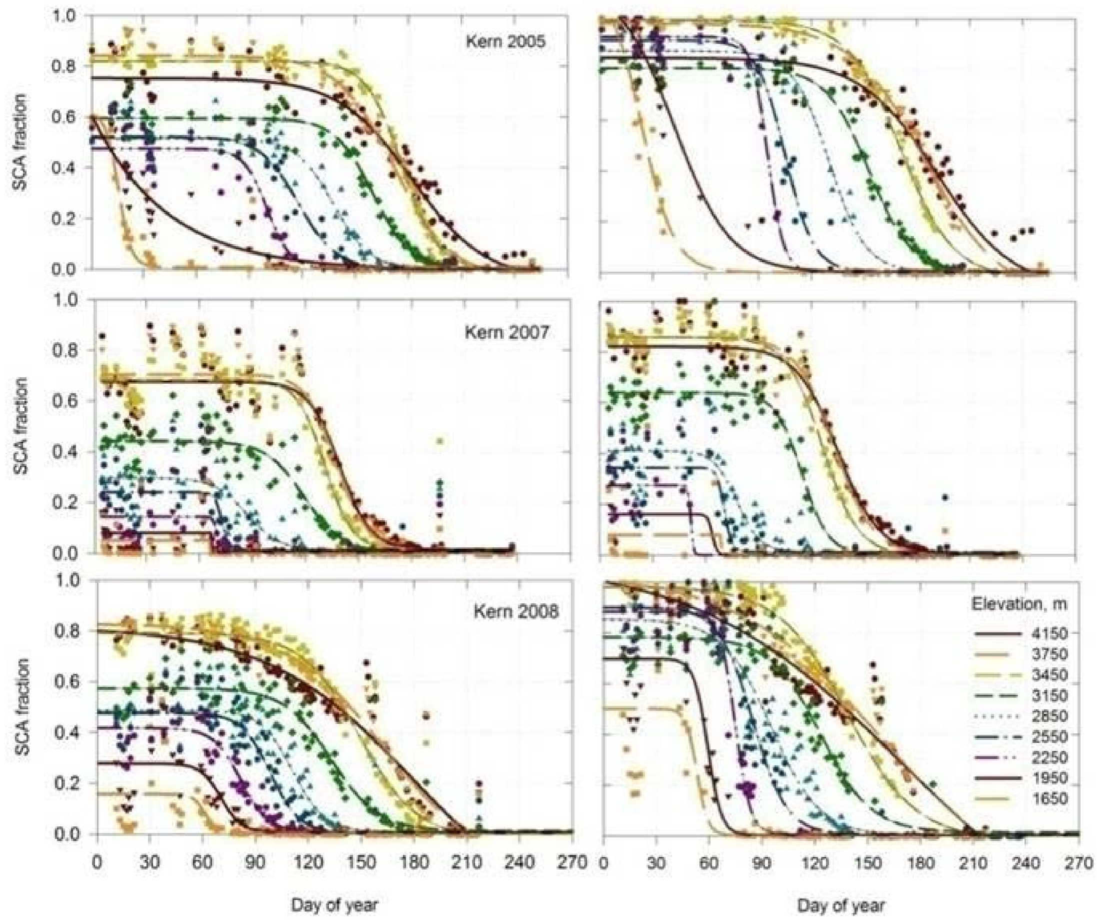

Figure A- 14. Comparison of the raw (left panels) and adjusted (right panels) SCA for a wet (2005), dry (2007), and average (2008) year for the Kern River basin.

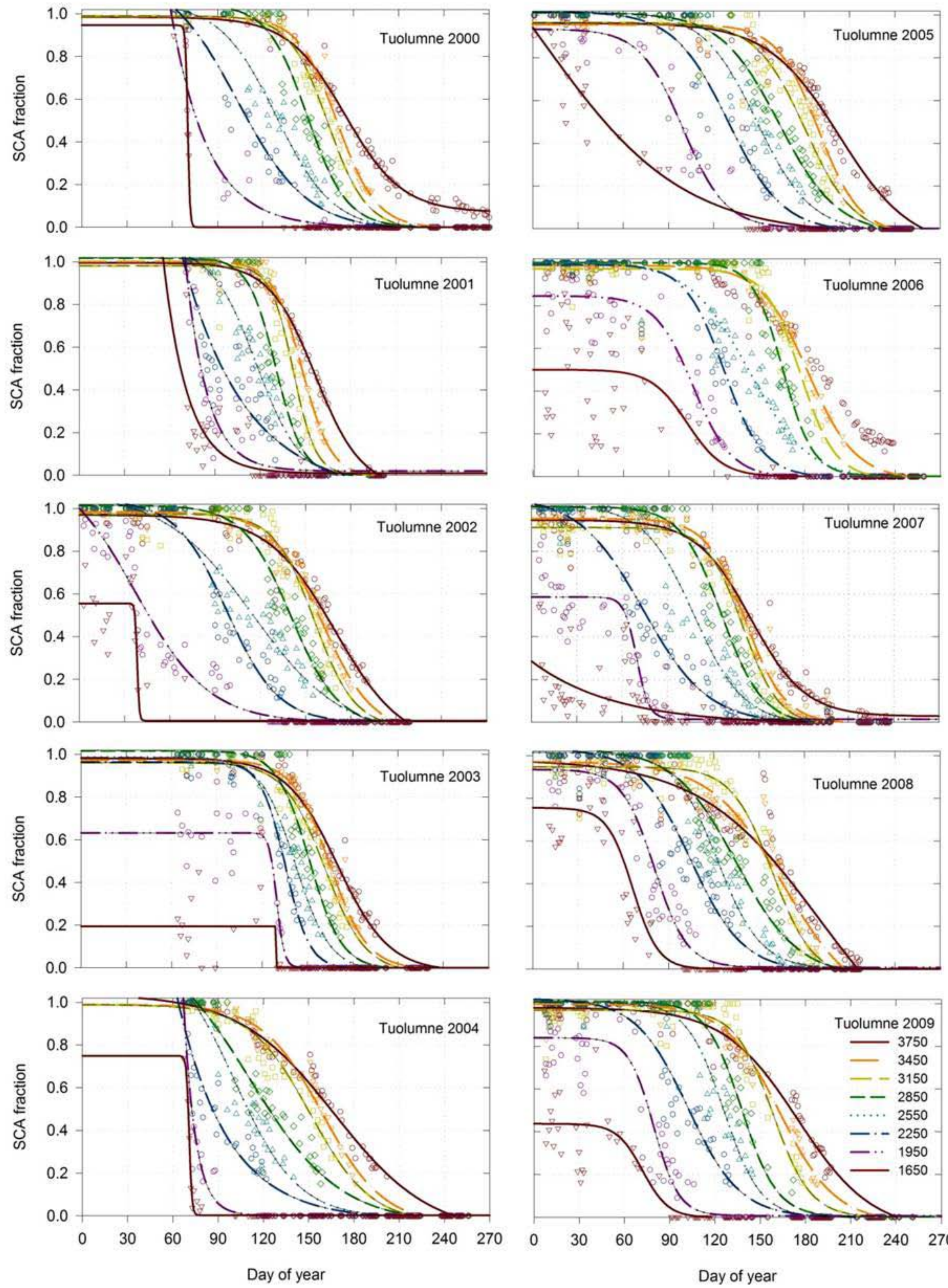

Figure A- 15. Tuolumne River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the 10 year period 2000-2009. Values are adjusted for canopy cover.

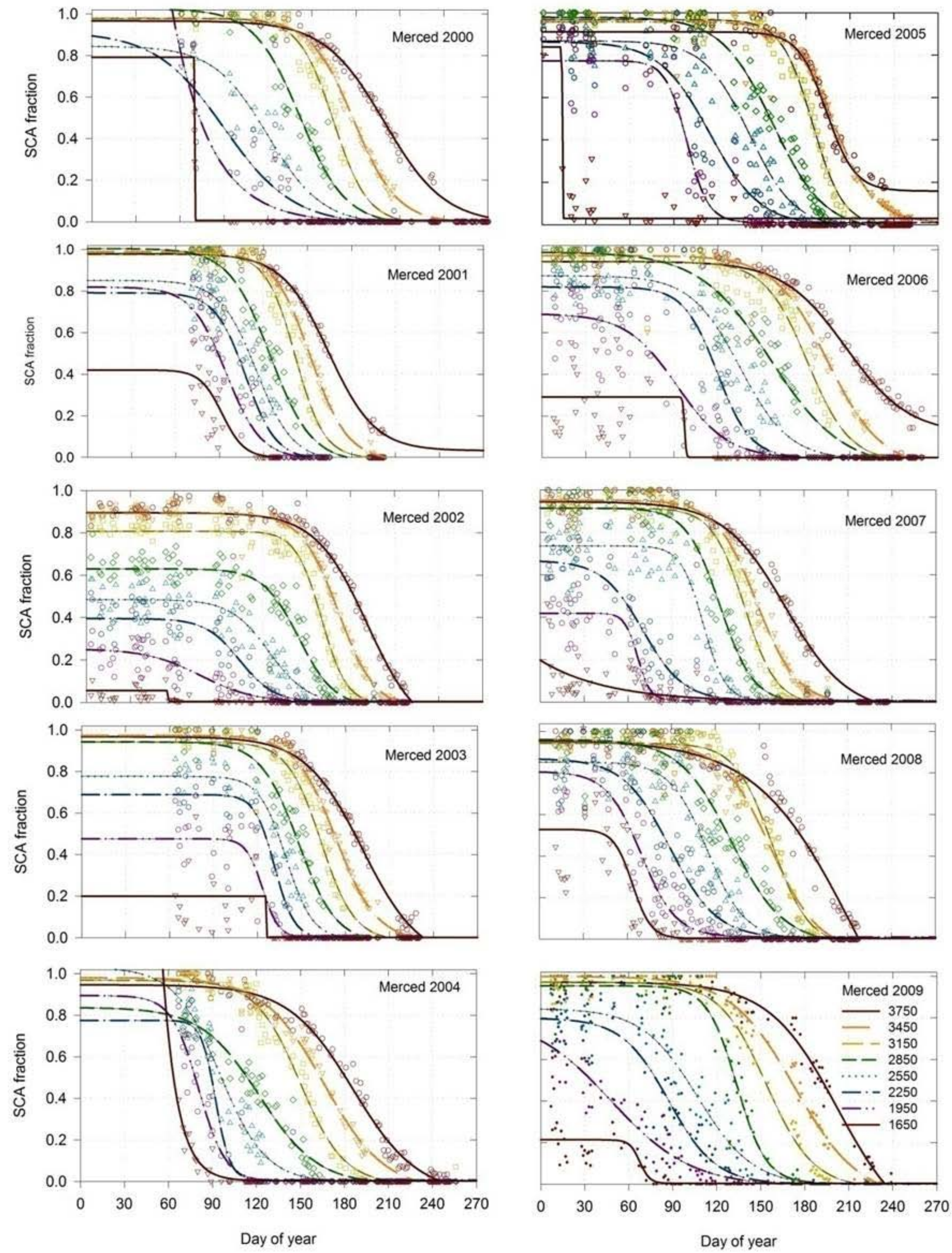

Figure A- 16. Merced River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the ten-year period 2000-2009. Values are adjusted for canopy cover.

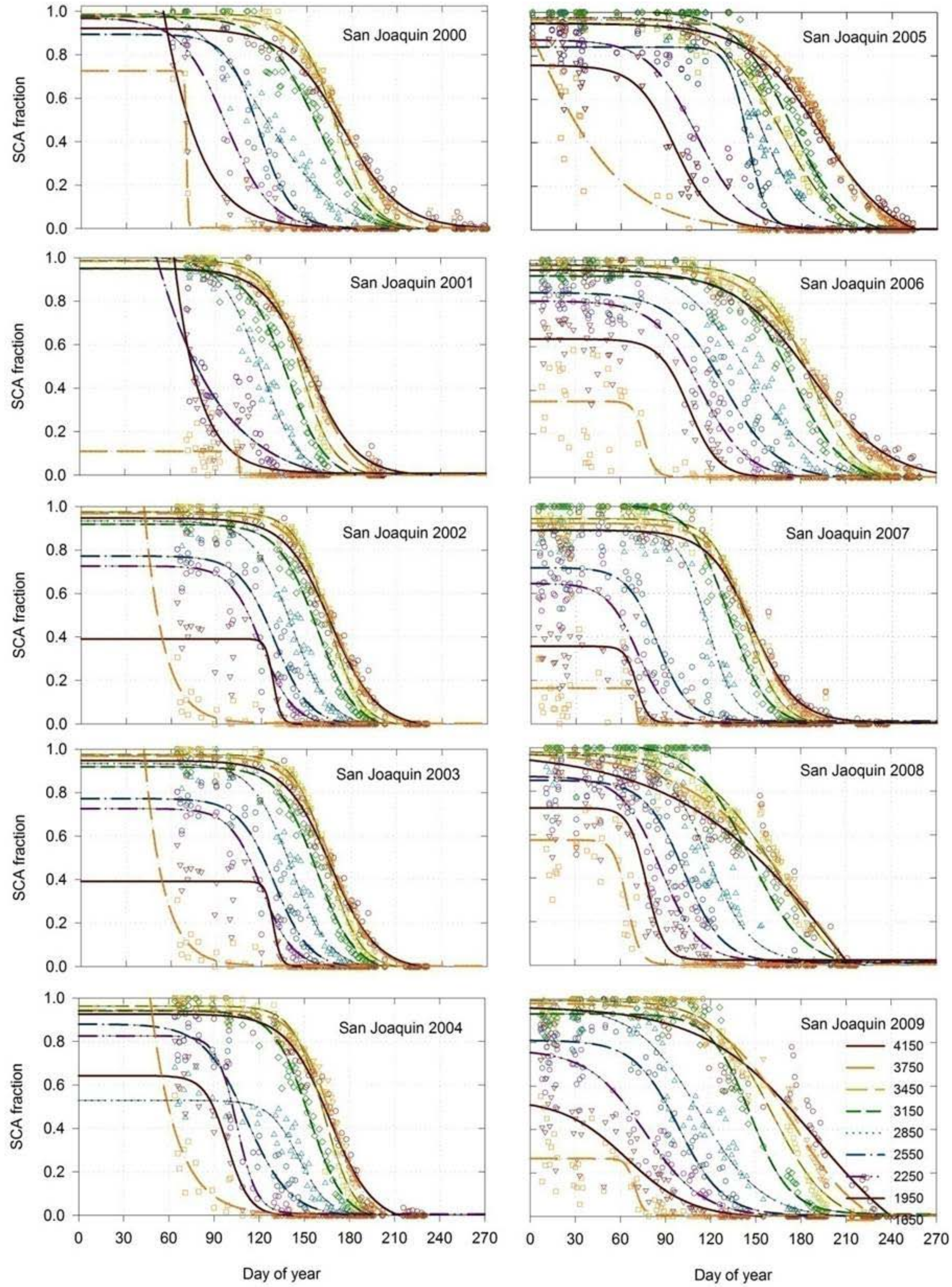

Figure A- 17. San Joaquin River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the ten-year period 2000-2009. Values are adjusted for canopy cover.

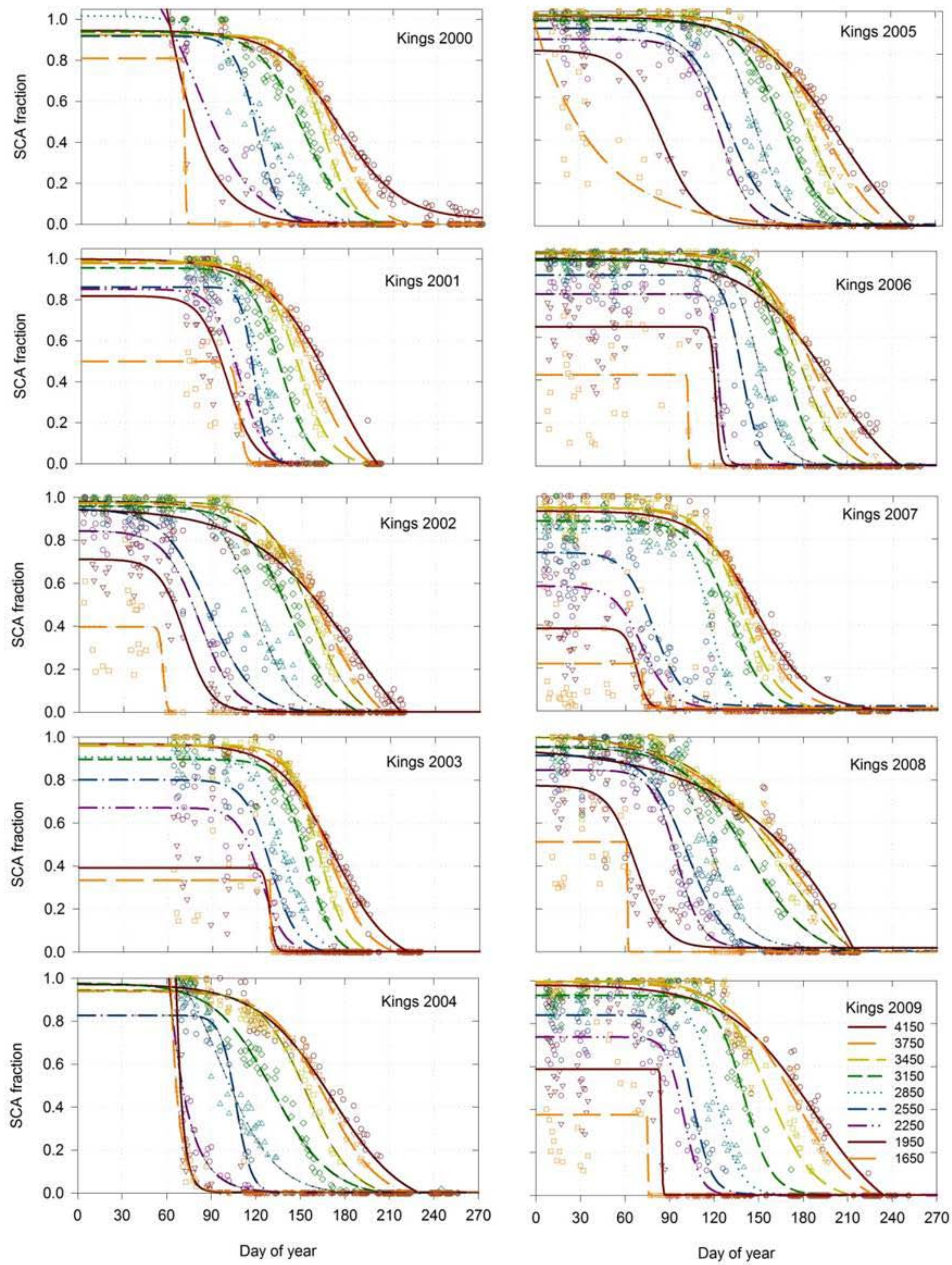

Figure A- 18. Kings River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the ten-year period 2000-2009. Values are adjusted for canopy cover.

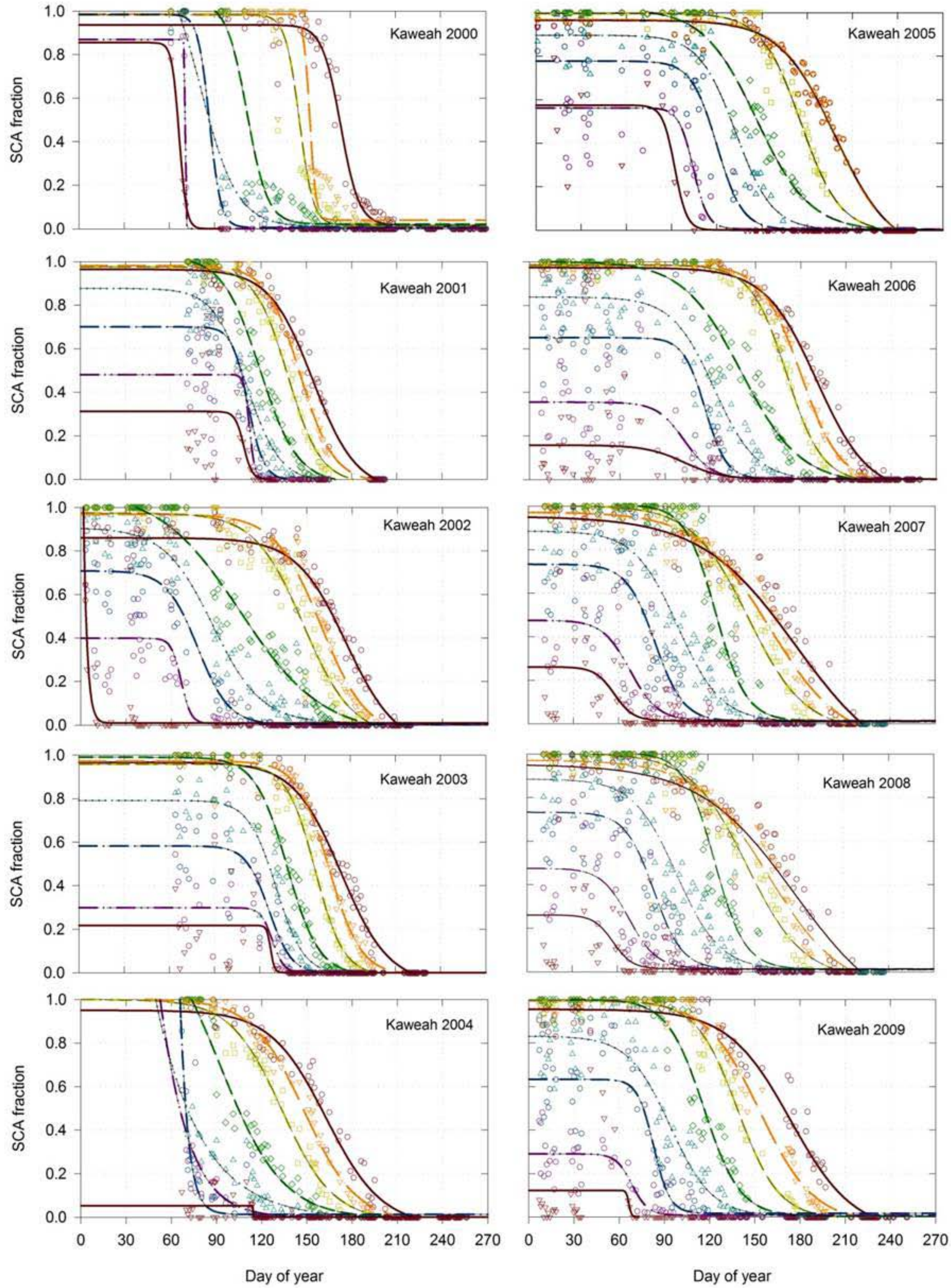

Figure A- 19. Kaweah River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the ten-year period 2000-2009. Values are adjusted for canopy cover.

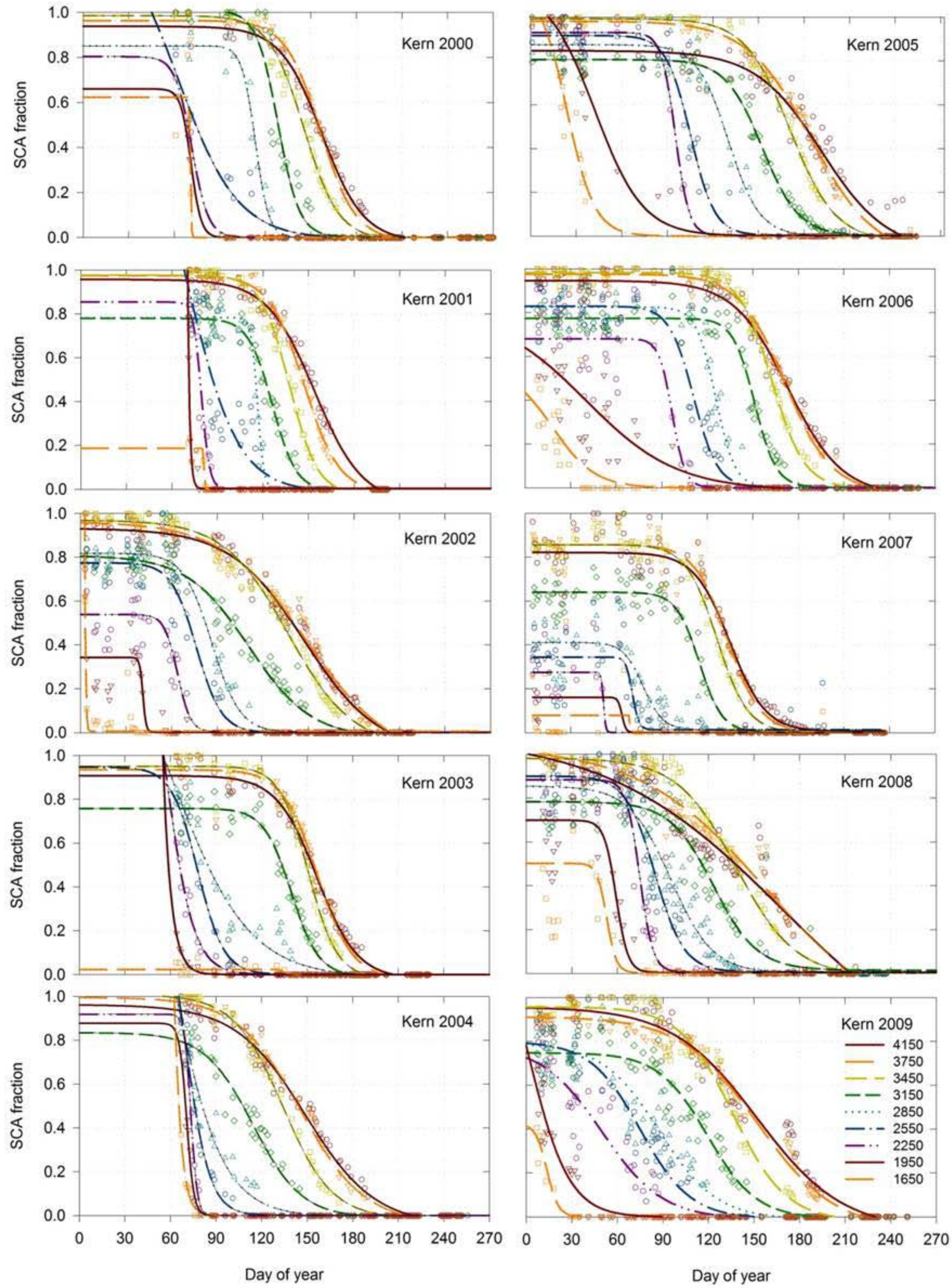

Figure A- 20. Kern River basin fSCA with a four-parameter sigmoidal fit of the daily mean fSCA across 300-m elevation bands for the ten-year period 2000-2009. Values are adjusted for canopy cover.

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