

Sierra Nevada Snow Model, *Tamiasciurus*

The Sierra Nevada is a roughly linear mountain range trending north-northwest to south-southeast and lying between latitudes 35.7°N (Walker Pass) and 40.3°N (Fredonyer Summit) in eastern California. This semi-empirical model (*Tamiasciurus*^a) for snowpack and snowmelt in the Sierra Nevada mountains takes topography into account explicitly. The model calculates snowpack water content, temperature, insolation, and the date snow first disappears for any site that may be of interest in the deep snow belt.

Level-Site Snowpack

The calculation of snow deposition begins with a model of the snowpack on April first for level sites with no overstory cover. Snowpack is determined by elevation, latitude, and parameters describing critical aspects of the surrounding terrain; it is always measured as water content in mm. The date April first is the approximate date of maximum snowpack (DWR 1998) though this varies with elevation and terrain and from year to year. The model presumes a continuous snowpack through the winter months. In the Sierra Nevada this means that the model is generally valid only above elevations of about 1.8 km in the south or 1.5 km in the north and will give nonsensical negative results if used at lower elevations.

The snowpack model was fitted to data for 311 sites between 35.8°N in the south (Kern River watershed) and 39.8°N (Yuba and Truckee River watersheds), collected by the California Department of Water Resources, Cooperative Snow Surveys up to 1995, taken as a baseline year (Department of Water Resources, California Data Exchange Center, henceforth DWR, <http://cdec.water.ca.gov/> and DWR 1998). Sites were established in different years, the earliest being established in 1910 and the newest in 1986. The average duration of measurements over all 311 sites is 40 years. The DWR published average data for long-established sites is only over the previous 50 years. Included in the 311 are 71 sites where measurements were discontinued before 1995. The purpose of the DWR monitoring is primarily the prediction of water availability from snowmelt for beneficial uses, and these abandoned sites were generally where there was minimal snowpack; there should be no unusual errors in those data that would

a. Model named to honor the Douglas squirrel or chickaree, *Tamiasciurus douglasii*, found throughout the deep snow belt of the Sierra Nevada and a welcome companion to anyone working there.

prevent their use, however. The greatest average snowpack on April first in the data set is 1680 mm of water content, with 1400 mm recorded at several sites. The highest elevation site is at 3.4 km.

The model was fitted to the averaged April-first data, as provided by the DWR. April first is the date of the historical maximum snowpack. Snow measurements are of two kinds. The older sites consist of courses over which snow tube measurements are made on-site monthly. Newer sites are instrumented with snow sensors and transmit a continuous record of the weight of the snow pack for remote recording. Where snow courses and snow sensors are co-located, the average over the longer record, normally the snow course record, was used. Where snow sensors are not sited near snow courses the average of the snow sensor data was used. These 311 sites are approximately level and bare of trees, usually courses across meadows, and their slope and tree cover are taken as zero (DWR 1998 and personal communication with snow survey staff).

Topography enters the level-site snowpack model because of storm shadowing of rain and snow fall. South of latitude 40°N most winter storms approach the Sierra Nevada from the northwest with winds from the west-southwest (e.g. Dettinger et al. 2004; Daly et al. 2008). As a result sites to the east-northeast of terrain higher than the site will receive less snowfall than a site directly exposed. This effect of storm shadowing was quantified from a site-by site examination of the DWR data. The key element is the presence of a barrier to the west-southwest. (North of 40°N, the Feather River watershed (west side) and Susan River watershed, (east side) storms approach the mountains from several directions and the simple model described here is no longer applicable.)

The fitting of the data for the 311 DWR sites proceeded as follows. The first part of the snowpack model was fitted to 103 sites in the DWR data base that are not storm shadowed. April-first snowpack in mm of water content was fitted by a double Taylor expansion:

$$\sum_{i,j} A_{ij} \cdot ELEV^i \cdot LAT^j = A_{00} + A_{10} \cdot ELEV + A_{20} \cdot ELEV^2 + A_{02} \cdot LAT^2, \quad (S1)$$

where *ELEV* is the site elevation in km and *LAT* the site latitude in degrees. Fitting the data for the 103 sites yielded the result that only the terms shown were significant at $P < 0.01$ (RMS error = 145, mean response = 801, $R^2 = 0.81$, df = 99). Terms with *i* and/or *j* up to 3 were initially included in the model.

Shadowed sites are characterized by a barrier elevation, *BARELEV*, which is the average elevation of a continuous barrier to the west-southwest subtending at least 90° from the site of interest, and by a barrier distance, *BARDIST*, which is the distance from the barrier to the site of interest, both in km. The

barrier height *BARHT* is usually the difference between *BARELEV* and *ELEV*. Equation (S1) is then multiplied by a shadowing factor to take into account the reduction of snowpack caused by storm shadowing. For sites west of the Sierra crest and with *BARDIST* between about 3 to 8 km, the simple expression $(1 - 0.74 \cdot \bar{BARHT})$ can be used as this shadowing factor. However, this expression overestimates snowpack on sites downwind of several long barriers, such as the Sierra crest itself as it shadows sites on the east side of the range, and on sites more distant than about 10 km from the barrier. It also underestimates snowpack for sites closer to the barrier than about 2 km.

An improved and generally applicable shadowing factor was developed by a detailed study of sites in or adjacent to the Lake Tahoe basin, which lies east of the Sierra crest and is the largest collection of sites east of the crest. The Tahoe basin and nearby watersheds of the Walker, Carson, and Truckee Rivers include sites both near the Sierra crest (the barrier) and sites at considerable distance from the crest. Snowpack appears to fall off more or less exponentially with distance from the barrier, and the following expression was found to be a useful shadowing factor.

$$B_1 \cdot \bar{BARHT} \cdot [\exp (- B_2 \cdot \bar{BARDIST}) / \bar{BARHT}) - 1] + 1 . \quad (S2)$$

Here, the barrier height takes two forms: Where terrain generally slopes down monotonically from the barrier to the site of interest, *BARHT* is just the difference between *BARELEV* and *ELEV*, as in the simple model. However, if there is extensive low terrain between the barrier and the site of interest, such as a valley or lake, *BARHT* is the difference between *BARELEV* and the elevation of this low terrain. This is the case particularly for sites on the east side of Lake Tahoe. Where *BARHT* and *BARDIST* are both large, equation S2 overpredicts shadowing and eventually gives a nonsensical negative result. To eliminate this problem, *BARHT* is limited to a fitted value *M*, a value that governs the shadowing at large distances from the barrier. Parameter values resulting from simultaneously fitting 311 sites in the DWR data base with the use of a non-linear least square fitting routine (SAS Institute 1995) are in Table S1. The model RMS error is 153 mm in an average value of 650 mm (*n* = 311).

Temperature Models

Daily temperature—A temperature model for daily maximum and minimum temperatures was developed from monthly temperature normals published by the National Oceanic and Atmospheric Administration (NOAA 1982) for 12 sites within the Sierra Nevada snow belt and 10 sites in the Central Valley of the Sacramento and San Joaquin Rivers to the west of the range. Six of the mountain sites were

on the west side of the range and six on the east side. Elevations for the mountain sites ranged from 1.5 km to 2.4 km, and latitudes from 36.7°N to 39.5°N. The Central Valley is a major low-elevation valley paralleling the Sierra Nevada to its immediate west. The 10 valley sites are roughly in a line along the Valley between latitudes 35.4°N and 38.5°N and at elevations below 0.14 km. In all cases the tabulated monthly normal data were assigned to the monthly midpoint date. The following form was fitted to this data in °C using the non-linear least square fitting program,

$$\begin{aligned} & (C_0 + E \cdot ELEV + L \cdot LAT + S \cdot EAST) + (C + C_E \cdot ELEV + C_L \cdot LAT + C_S \cdot EAST) \cdot \\ & \{ \cos [(2 \pi / 365) \cdot (DATE + D + D_E \cdot ELEV + D_L \cdot LAT + D_S \cdot EAST)] + \\ & F_0 \cdot \cos [(4 \pi / 365) \cdot (DATE + F + F_E \cdot ELEV + F_L \cdot LAT + F_S \cdot EAST)] \} , \end{aligned} \quad (S3)$$

where variables are as defined above, *EAST* equals zero west of the Sierra crest and one east of the crest, and *DATE* is the date number (counted from January first).

Separate fits were made for the monthly normal maximum and minimum temperatures. For the maximum temperatures, only the mountain sites were used in the fitting. This fitting adequately separated the effects of elevation and latitude, even though the site locations were such as to result in substantial colinearity between these two variables, correlation coefficient equal to -0.40 . The RMS error of the fit was 1.1°C ($n = 144$). However, for the minimum temperatures the mountain data alone were inadequate to separate the effects of elevation and latitude unambiguously. In this case the 10 valley sites were used to determine the latitude dependence. This is equivalent to assuming that with prevailing winds from the west, air masses will be minimally mixed as they move from the valley into the mountains. The full expression was then fitted to the mountain data with the latitude dependence fixed to the results of the valley fit. The RMS error of the fit constructed in this way was 2.2°C ($n = 144$).

The effect of differing insolation at inclined sites on temperature was explored by monitoring maximum and minimum air temperatures at three pairs of sites located near latitude 36°N and near elevation 2.5 km. Max-min thermometers were placed in shaded louvered enclosures (Royce 1997; additional data, Royce unpublished). Statistically significant differences of up to 3°C in (mid-day) maximum summer temperatures were sometimes observed between north- vs. south-facing sites. For one of the pair of sites with a separating ridge between the sites and for the pair with a separating valley between the sites, the south-facing site was the warmer site. Unfortunately, for the other pair with a

separating ridge, the north-facing site was the warmer. Differences in (near-dawn) minimum summer temperatures were not significant, as one might expect in view of the absence of night-time insolation. In view of the inconsistent maximum temperature results, no correction for site inclination was included in the temperature model. The results suggest that winds are generally adequate to move air masses between sites at the same elevation without air temperature change, even though insolation differences probably make ground and vegetation temperatures differ between sites. Consistent with this conclusion, Piche evaporimeter tubes were included in the shelters housing the max-min thermometers. These tubes showed no significant differences in daily evaporation between north- vs. south-facing sites.

Diurnal temperatures—A double sinusoid model was used to represent the diurnal variation of temperature. One sinusoid describes the daytime temperature rise above the minimum temperature, occurring at sunrise, and its progression through the day, and one describes the nighttime temperature decline back to the minimum temperature. The switch between sinusoids occurs at sunrise and sunset, times $Time1$ and $Time2$ calculated in the isolation model described below. The daytime sinusoid, characterized by the frequency $F2'$, has its origin at sunrise at the daily minimum temperature and is given by

$$(TMax - TMin) \cdot \sin (F2' \cdot \pi \cdot (Time - Time1)) + TMin. \quad (S4)$$

where $TMax$ and $TMin$ are calculated from the daily temperature model described above, and where $F2'$ is given by $F2' = F2 + F3 \cdot \cos ((2 \cdot \pi / 365) \cdot (DATE - 172))$. Typically it peaks somewhat after noon and falls at sunset to a value roughly midway between the daily maximum and minimum temperatures, $TMax$ and $TMin$. The nighttime sinusoid, characterized by the frequency $F1$, has its origin at sunset and describes a monotonic decline to the minimum temperature at sunrise. From midnight to sunrise it is given by

$$X \cdot (\sin (F1 \cdot \pi \cdot (Time + Time2)) - \sin (F1 \cdot \pi \cdot (Time1 + Time2))) + TMin, \quad (S5)$$

while from sunset to midnight the nighttime sinusoid is given by

$$X \cdot \sin (F1 \cdot \pi \cdot (Time + Time2 - 1)) + (TMax - TMin) \cdot \sin (F2 \cdot \pi \cdot (1 - Time1 - Time2)) + TMin. \quad (S6)$$

In both (S5) and (S6),

$$X = - (TMax - TMin) \cdot \sin (F2 \cdot \pi \cdot (1 - Time1 - Time2)) / \sin (F2 \cdot \pi \cdot (Time1 + Time2)). \quad (S7)$$

Times are measured from midnight and are normalized to go from zero to one over the 24-hour day. The times *Time1* and *Time2* are calculated in the insolation model as τ'_1 and τ'_2 , respectively. The model was fitted to temperature data from two Sierra sites at differing elevations with the use of the non-linear least squares routine. Results of this fitting are in Table 1, and produce an RMS error of 2.3°C (df = 14625 and 8242 for the two sites, respectively).

Insolation model

An insolation model was developed following formulae provided by Kaufmann and Wetherred (1982), Swift (1976), and Lee (1964, see also Frank and Lee 1966 and Lee and Baumgartner 1966). Instantaneous direct beam insolation on a level surface is given by equation (S8),

$$R = (R_0 / r^2) \cdot (\sin \theta \cdot \sin \delta + \cos \theta \cdot \cos \delta \cdot \cos \omega t), \quad (\text{S8})$$

where θ is the site latitude, ω is the earth's rotation rate ($= 2\pi/365$ radians per day) and time t is measured from solar noon. All angles are in radians. R_0 is the insolation on a surface perpendicular to the direction to the sun. The normalized distance between the earth and the sun, r , is given by $r^2 = 0.999847 + 0.001406 \cdot \delta$. The solar declination δ is given by $\delta = (23.5 \pi / 180) \cdot \cos (2\pi d / 365)$, where d is the number of days from the summer solstice. The limits of the integration of equation (S8) to yield daily insolation are $\pm \tau$, where $\cos \omega \tau = -\tan \theta \cdot \tan \delta$ (τ always > 0).

Insolation on an inclined surface is addressed in terms of an equivalent surface, parallel to the surface of interest but displaced in latitude and longitude so that the equivalent surface is level with the ground. Equation (S8) then becomes

$$R = (R_0 / r^2) \cdot (\sin \theta' \cdot \sin \delta + \cos \theta' \cdot \cos \delta \cdot \cos \omega t'). \quad (\text{S9})$$

Here θ' is the latitude of the equivalent surface, $\sin \theta' = \sin i \cdot \cos a \cdot \cos \theta + \cos i \cdot \sin \theta$. The change in longitude α is given by $\tan \alpha = \sin a \cdot \sin i / (\cos i \cdot \cos \theta - \cos a \cdot \sin i \cdot \sin \theta)$, where a is the azimuth angle of the inclined surface, measured toward the east from north, and i is the angle of inclination (slope). As before $\cos \omega \tau' = -\tan \theta' \cdot \tan \delta$. Daily insolation is given by the integration of equation (S9). The limits of the integration are $\omega \tau_{\text{sunrise}} = \max(-\omega \tau + \alpha, -\omega \tau')$ and $\omega \tau_{\text{sunset}} = \min(\omega \tau + \alpha, \omega \tau')$, after shadowing at sunrise and sunset at the actual site is taken into account. The result is just

$$R = (R_0 / r^2) \cdot [\sin \theta' \cdot \sin \delta \cdot (\omega \tau_{\text{sunset}} - \omega \tau_{\text{sunrise}}) -$$

$$- \cos \theta' \cdot \cos \delta \cdot (\cos \omega \tau_{\text{sunset}} - \cos \omega \tau_{\text{sunrise}})]. \quad (\text{S10})$$

Clear-sky atmospheric attenuation— Solar beam attenuation due to scattering and absorption in a clear sky is assumed to follow Beer's Law, $dI/ds = -I \beta(s)$, where I is the beam intensity and $\beta(s)$ is the density of scattering and absorption centers along the optical path s . For simplicity, a clear-air value of β is assumed to be proportional to air density ρ and is a function only of elevation. The intensity of insolation is then given by

$$\int (1/I) dI = -G \int \rho(s) ds = -G \int \rho(z) dz / \cos \phi, \quad (\text{S11})$$

where z is a vertical distance and ϕ is the polar angle of the incident radiation on a level surface, given by

$$\cos \phi = \sin \theta \cdot \sin \delta + \cos \theta \cdot \cos \delta \cdot \cos \omega t. \quad (\text{S12})$$

Integration of (S11) yields

$$I/I_0 = \exp \left[-G \int \rho(z) dz / \cos \phi \right] \quad (\text{S13})$$

where limits of the integration over z are the site elevation, $ELEV$, and the top of the atmosphere. Air density is assumed to fall off rapidly enough that the value of the integral at the top of the atmosphere is negligible, in which case the integral is just evaluated at $ELEV$. The parameter I_0 is the unattenuated beam intensity on level ground.

Following Monteith and Unsworth (1990), manipulation of the ideal gas law under adiabatic expansion yields the result

$$\rho / \rho_0 = [1 - \Gamma \cdot z / T_0]^{5/2}, \quad (\text{S14})$$

where ρ_0 and T_0 are values at ground level. Integration of equation (S14) yields

$$I/I_0 = \exp \{ -G_0 \cdot [1 - (\Gamma / T_0) \cdot ELEV]^{7/2} / \cos \phi \}. \quad (\text{S15})$$

Here $T_0 = 300^\circ\text{K}$, Γ is the dry adiabatic lapse rate $= 10^\circ\text{C/km}$, and $G_0 = 0.24$, a typical value to yield observed clear-sky atmospheric attenuation near sea level (Oke 1978, Monteith and Unsworth 1990).

Atmospheric attenuation due to clouds — The attenuation effect of clouds was modeled from DWR snow-sensor data on daily precipitation by ignoring insolation on days where there was rain or snow with more than 2.5 mm of water content. Six sites on the west side of the range with long high-quality records of daily precipitation were selected for detailed study. The six sites were distributed along the Sierra in latitude and were at elevations between 2.0 km and 3.2 km; all were unshadowed in

the sense described under snowpack, above. The average number of days with precipitation was calculated for each site in 15-day intervals. No systematic dependence of this data on elevation or latitude was identifiable. Apparently other factors produced greater variations between sites than these parameters. The average values over the six sites were fitted with a quartic polynomial in the date as measured from January first,

$$H = \sum_{i=0}^{i=4} H_i \cdot DATE^i, \quad (S16)$$

where H is the fraction of the days with cloud attenuation (RMS error = 0.063, mean = 0.34, $R^2 = 0.88$, all $P < 0.05$, $df = 13$). Total insolation is then given by the product of the expressions in equations (S10) and (S15), and $(1 - H)$.

Inclined sites — snow melt

A model for snowpack on inclined sites takes into account the fact that snow melting occurs during the winter months simultaneously with snowfall, and that this snow melting will be different on a level vs. an inclined site. Energy fluxes affecting melting include direct solar beam radiation, re-radiation from trees and exposed rock outcrops, energy exchange with moving air, and re-radiation from the snow surface. In the model site inclination is taken into account by correcting insolation falling on the site with the slope and aspect of the site. It is assumed that melting occurs only when the local ambient temperature, as calculated in the diurnal temperature model described above, is above freezing and that the melt rate is linearly dependent on direct solar beam radiation. Such radiant energy may be directly absorbed by a snow field or may be absorbed by surrounding exposed rocks or vegetation, then further transferred to the snow field by re-radiation or convection. The critical quantity is the difference between insolation on a hypothetical level site and the inclined site at the same location. Numerical integration of this difference is carried out over the portion of the daylight hours where the temperature is above freezing and over days from mid-November to whatever date may be of interest. Mid-November is the approximate date when snowpack becomes continuous in the deep snow belt. When multiplied by an effective absorption coefficient and divided by the latent heat of melting, this integration is the difference in snow melting over the period from mid November to April first and is added to the April first snowpack predicted on a hypothetical level site at the same location.

In carrying out details of this calculation it is useful to define two variables: *INSOL* and *INSOL_L*, conveniently referred to as "melt insolation." These variables are the insolation on a site integrated over that part of a day where the temperature is above zero. Corrections for atmospheric attenuation and shading due to clouds are applied, and the integral is divided by the latent heat of melting. *INSOL* applies to inclined sites (or level sites), and the slope and aspect parameters are set to the measured slope and aspect. *INSOL_L* refers to what would occur on hypothetical (or real) level bare sites, and slope and aspect are set to zero. The snow melt rate, *MR* or *MR_L*, was modeled as the simple relation

$$(J_1 \cdot (INSOL \text{ or } INSOL_L) \cdot (1 - J_2 \cdot COVER / 100) + J_3, \quad (S17)$$

where *COVER* is the overstory cover in percent. Total snowfall at a hypothetical level site at the location of interest is then the snowpack calculated for level sites on April first (equations (S1) and (S2)) plus *MR_L* integrated from date number -45 (mid November) to 91 (April first). Under the assumption that snowfall is not influenced by site inclination, snowpack on any date on an inclined site (or level site) is then this snowfall minus the integral of *MR* integrated from -45 to any date of interest.

The parameters in equation (S17) were determined from two data sets. Snowpack in 1998 was measured several times during snow melt on ten sites in three clusters, for a total of 23 site-days. Each cluster was at a different elevation, but all were near latitude 36°N. Sites were north- or south-facing, or level in each cluster, and had varying amounts of overstory cover. Equation (S17) was fitted to this snowpack data, and the parameters J_1 and J_2 were determined from this fit (RMS error = 92 mm, mean value = 519 mm, $R^2 = 0.88$, $df = 13$). Since these measurements were made in only a single year, melting was not uniform in either time nor between clusters. For this reason it was necessary to add a series of cluster- and date-dependent constants to the regression. This prevented a determination of the parameter J_3 from this data.

A second data set was prepared from 29 years of snowpack data from 36 snow sensors in the DWR data system, a total of 751 data points, not all records being complete. Data were the April first snowpack and the no-snow date for each site and year, from which an effective melt rate was calculated. Equation S17 was fitted to these rates. Since the DWR sites are all essentially level and bare of trees it was not possible to get a value of the parameter J_2 , but values for J_1 and J_3 were obtained ($R^2 = 0.44$, $df = 720$, RMS error = 3.4 mm/d, mean value = 14.3 mm/d). The values of J_1 from these two determinations (two data sets, different sites, different latitudes covered, different years covered, different variables

fitted, snowpack vs. melt rate) were within the standard deviations of each other, so the average was used. The fit of the DWR data set also yielded a useful value of J_3 .

The coefficient of the insolation term, J_1 , may be regarded as just a total absorption coefficient. Its value of 0.153 (effective albedo 0.847) appears to be reasonable for a relatively reflective snow surface. One might have expected the value of J_2 to be unity, if overstory cover effectively shaded the ground. The fitted value of 0.58 suggests that some of the energy reaching the snow surface is not direct solar beam, though it still depends on insolation.

The no-snow date was simply calculated from the snowpack value with the use of the melt rate, equation (S17).

Climate change

Changes associated with increased temperature, but with snowfall remaining unaffected, were evaluated by simply adding the temperature change to both maximum and minimum temperatures in the daily temperature model. This affects melt insolation, hence all melt rates, and the snowpack on April first. The change in snowpack, it turn affects the no-snow date because of the need to melt the extra (+ or –) snowpack. There is also a small effect on melt rate, since melting takes place at somewhat different dates. Changes associated with reduced snowfall, but with temperatures remaining unaffected, were evaluated by adding the change to snowfall.

References

- Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., and Pasteris, P.P. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* **28**: 2031-2064.
- Dettinger, M., Redmond, K., and Cayan, D. 2004. Winter orographic precipitation ratios in the Sierra Nevada—large-scale atmospheric circulations and hydrologic consequences. *Journal of Hydrometeorology* **5**: 1102-1116.
- DWR 1998. 1998 California snow survey measurement schedule. California Cooperative Snow Surveys, Department of Water Resources (DWR).

- Frank, C.F., and Lee, R. 1966. Potential solar beam irradiation on slopes. U.S. Forest Service Research Paper RM-18.
- Kaufmann, M.R., and Weatherred, J.D. 1982. Determination of potential direct beam solar irradiance. U.S. Forest Service Research Paper RM-242.
- Lee, R. 1964. Potential insolation as a topoclimatic characteristic of drainage basins. Bull. Int. Assoc. Sci. Hydro. **9**(1): 27-41.
- Lee, R., and Baumgaratner, A. 1966. The topography and insolation climate of a mountain forest area. For. Sci **12**(3): 258-267.
- Monteith, J.L., and Unsworth, M.H. 1990. Principles of environmental physics, 2nd ed. Edward Arnold, London, New York, Melbourne, Aukland.
- NOAA 1982. Monthly normals of temperature, precipitation, and heating and cooling degree days 1951–1980. National Climate Center, National Oceanic and Atmospheric Administration.
- Oke, T.R. 1978. Boundary layer climates, 2nd ed. Menthuen, London and New York.
- Royce, E.B., 1997. Xeric effects on the distribution of conifer species in a southern Sierra Nevada ecotone. Ph.D. dissertation, University of California, Davis, California, USA.
- SAS Institute 1995. JMP statistics and graphics guide. SAS Institute Inc., SAS Campus Drive, Cary, NC, USA 27513.
- Swift, L. W., Jr. 1976. Algorithm for solar raiation on mountain slopes. Water Resource Research **12**(1): 108-112.

Table S1. Model Parameter Values	
Snowpack Model	
$A_{00} = -8800$, sd = 410	
$A_{10} = 3600$, sd = 220	
$A_{02} = 3.3$, sd = 0.17	
$A_{20} = -630$, sd = 45	
$B_1 = 1.31$, sd = 0.06	
$B_2 = 0.14$, sd = 0.02	
$M = 0.75$, sd = 0.08	
Daily Temperature Model	
Maximum Temperatures	Minimum Temperatures
$C_0 = 70$, sd = 5	$C_0 = 37.8$, sd = 1.4
$E = -9.0$, sd = 0.5	$E = -4.1$, sd = 0.8
$L = -1.0$, sd = 0.1	$L = -0.74$, sd = 0.17
$S = 1.6$, sd = 0.2	$S = -2.6$, sd = 0.4
$C = -14.6$, sd = 1.0	$C = -7.4$, sd = 0.3
$C_E = 2.9$, sd = 0.6	$C_E = 0$
$C_L = 0$	$C_L = 0$
$C_S = -2.0$, sd = 0.3	$C_S = 0$
$D = 0$	$D = 0$
$D_E = -8$, sd = 3	$D_E = -8.9$, sd = 1.6
$D_L = -0.44$, sd = 0.14	$D_L = -0.47$, sd = 0.09
$D_S = 5.6$, sd = 1.5	$D_S = 9$, sd = 4
$F_0 = 0.132$, sd = 0.012	$F_0 = 0.12$, sd = 0.04
$F = 48$, sd = 3	$F = 58$, sd = 8
$F_E = 0$	$F_E = 0$
$F_L = 0$	$F_L = 0$
$F_S = 0$	$F_S = 0$

Table S1. Model Parameter Values (continued)	
Diurnal Temperature Model	
$F_1 = 0.56$, sd = 0.06	
$F_2 = 1.75$, sd = 0.06	
$F_3 = -0.36$, sd = 0.01	
Insolation Model	
$I_0 = 1.37 \text{ kW/m}^2 = 1.37 \text{ kJ/m}^2 \text{ sec}$ $= 1.96 \text{ Langley (cal/cm}^2 \text{ min)}$	
Clear-Air Attenuation	
$G_0 = 0.24$	
Cloud Attenuation	
$H_0 = 0.45$, sd = 0.03	
$H_1 = 1.6 \text{ e-3}$, sd = 0.7 e-3	
$H_2 = -40 \text{ e-6}$, sd = 8 e-6	
$H_3 = 0.35 \text{ e-6}$, sd = 0.14 e-6	
$H_4 = -1.3 \text{ e-9}$, sd = 0.6 e-9	
Melt Rate	
Latent heat of melting = 79.7 cal/gm	
$J_1 = 0.15$, sd = 0.02	
$J_2 = 0.58$, sd = 0.27	
$J_3 = 7.0$, sd = 0.8	