A High-Resolution Distributed Snowmelt Model in an Alpine Catchment

Michael T. Colee, Thomas Painter, Walter Rosenthal, Jeff C. Dozier

ABSTRACT

We run a physically based snowmelt model (SNTHERM.89) for each 30 m pixel in the Tokopah Valley, an alpine catchment in the Sierra Nevada of California. We use extensive field surveys to initialize and validate the distributed model (MrSNTHERM). We initialize with an April 1997 survey, as close to maximum snow accumulation as possible, and then compare the model results to a second survey in May 1997. Spatially distributed depth and density measurements were collected along a grid during these field surveys, and we use them to interpolate the initial snow surface. We derive initial snow-covered area (SCA) from Thematic Mapper (TM) data and albedo and surface grain size from Airborne Visible Infrared Imaging Spectrometer (AVIRIS) data. Meteorological data at hourly time steps from three stations within the basin are distributed over the basin based on observed lapse rates. Hourly solar radiation inputs to the model are calculated with the topographically corrected clear-sky radiation model TOPORAD and adjusted for cloud cover based on measured solar radiation from two sites in the basin. Hourly incoming longwave radiation is calculated from distributed temperature and relative humidity surfaces and is validated with measurements at two of the three meteorological stations. We evaluate model performance by comparing its outputs with the May field measurements of depth and density, AVIRIS derived snow cover and grain size, and TM-derived snow cover. To assess the accuracy of the model's snowmelt calculation, we compare them to measured basin hydrographs in two sub-basins as well as the entire basin.

1. INTRODUCTION

Although empirical snow melt runoff models are useful in predicting discharge from mountain snow packs they can not be used to predict the location, volume, and timing of melt or the snow pack properties of specific locations within the snow pack. The need for physically based spatially distributed tools to accomplish these tasks is becoming increasingly important. They will benefit environmental analysis of changes in snow-covered area (SCA) and patterns under potential climate change scenarios, water chemistry, soil erosion and geomorphology, and ecologically sensitive areas such as the alpine ecotone.

We describe preliminary results of a physically based one-dimensional mass and energy balance model applied to each 30 meter pixel of the Tokopah Valley, a 1900 hectare alpine basin within the Sierra Nevada of California. The basin is located at approximately 36° 36'N, 118°40'W in Sequoia National Park and ranges in altitude from 2622 to 3487 meters (Figure 1).

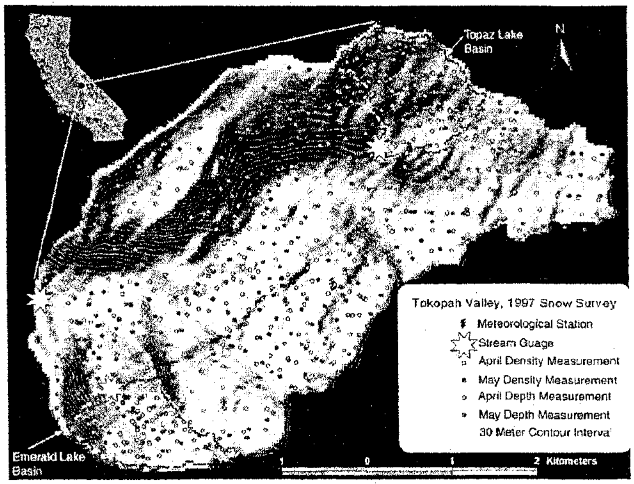

Figure 1. Map of study area.

Contact Information for first author: Michael T. Colee, Institute for Computational Earth System Science,University of California, Santa Barbara, CA 93106, mtc@icess.ucsb.edu

2. MODEL DESCRIPTION

SNTHERM.89 is a one-dimensional mass and energy balance model used here to model the temperature, density, depth, grain size, water content, and melt flux of the snow pack [Jordan, 1991] (Figure 2). We represent the basin snow pack with discrete 30m pixels, each having its own snowpack properties and time series of meteorology. We create a distributed version of SNTHERM by running the model separately on each of these points and assembling the output into images. This approach does not accommodate mass and energy fluxes between pixels. We scale modeled melt flux by SCA surfaces to derive discharge and we are currently exploring other models for use in routing within the basin.

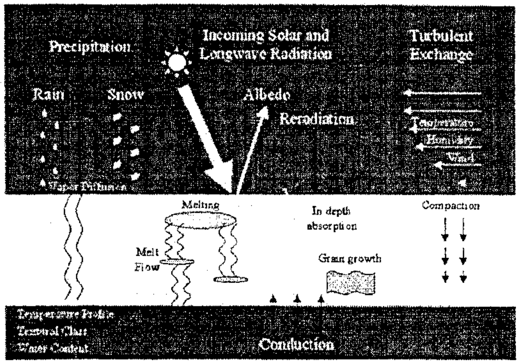

Figure 2. Model dynamics.

The input variables necessary to drive the SNTHERM model can be separated into two categories, meteorological fields and snow pack parameters. Meteorological fields include wind speed, air temperature, relative humidity, incoming long wave radiation, and incoming solar radiation. We model only snow melt in this exercise and assume precipitation to be zero. Snowpack parameters include snow-covered area, snow depth, snow density profile, snow temperature profile, snow grain size, and albedo. We derive the meteorological fields from three meteorological stations distributed in the Tokopah Valley and the snow pack parameters from a combination of remotely sensed data and field surveys. We run the model on an hourly time step, the smallest time step common to all three meteorological stations.

3. METHODS AND ANALYSIS

Rather than assuming a constant environmental lapse rate (ELR), for each hour we calculate an ELR based on a least squares fit to the spatial locations and measurements of each of the three stations. We then apply the ELR for a given hour to the DEM of the area to create a temperature surface for the entire basin. This method has the benefit of more realistically capturing current environmental conditions such as inversions. We use the same methodology to create relative humidity and wind speed surfaces.

We model incident longwave radiation similar to the method of *Cline* [1998] with the addition of unique environmental lapse rates calculated for each hour as described above and accuracy assessment at two points within the basin. In this approach we apply the equations of *Idso* [1981] to each pixel of the temperature and RH surfaces calculated earlier to derive incident longwave radiation at each pixel. This results in a modeling period RMSE of 34 W/m^2 for Emerald Lake and 40 W/m^2 for Topaz Lake.

We use TOPORAD [Dozier, 1980] to model incoming solar radiation at the Emerald Lake and Topaz Lake met towers under 5 different atmospheric conditions. We model 5 different sets of atmospheric parameters with LOWTRAN7 [Kneizys et al., 1988]. We use the measured incoming solar radiation values at the Topaz and Emerald meteorological stations to select the modeled surface closest to the measured.

We derive initial surface grain size from AVIRIS. The closest AVIRIS scene to the model start date is April 23rd and the study area is obscured by cloud in this scene. We therefore used snow grain size measurements surrounding the basin to develop a relationship of grain size with respect to elevation, slope, and aspect and apply this regression to the DEM of the study basin. We compare measured snow surface grain size from a May 5th AVIRIS image with modeled for the same day by subtracting the modeled surface from the measured surface, which gives a mean error of –0.15 mm with a standard deviation of 0.21mm.

We interpolate 415 April depth measurements and 316 May measurements to depth surfaces for initialization and comparison respectively. Mean modeled depth is 30 cm greater than measured at the end of the run with a standard deviation of 35 cm.

For initial snow density profiles we stratified ten measured density profiles from snow pits across the basin into bottom, middle, and top thirds. We then interpolate each of these layers across the basin to derive three density surfaces for the basin. In this effort we only compare bulk density of the snow pack as opposed to density within the pack. Snow pack conditions during the May survey permitted the use of a Federal Sampler and 66 measurements were taken which we interpolate with 11 snow pit density profiles across the basin to derive measured density. Modeled density is 147 kg/m^2 greater than measured with a standard deviation of 171 kg/m^2.

Modeled Snow Water Equivalence (SWE) is 544 kg/m^2 greater on average than measured with a standard deviation of 214 kg/m^2 (Figure 3).

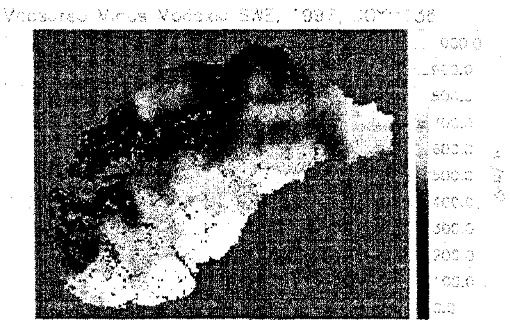

Figure 3. Measured minus modeled SWE for day of year 136, 1997.

For initial snow temperature profiles we stratified seven measured temperature profiles from snow pits across the basin into bottom, middle, and top thirds and interpolated each across the basin. We thus have three temperature layers that we map to each pixel's depth value. Based on survey data and measured discharge we assume the May snow pack to be isothermal. The snowpack was actively melting and all temperature readings were 0 °C.

Modeled SCA does not change and measured SCA decreases only 5% during the period of the run. Five pixels within the basin change from snow-covered to snow-free. Because SNTHERM.89 is a point model, its interpretation of SCA is binary and each pixel is 100% snow covered until it completely melts. Modeled depth does, however, change from a minimum of 132 cm in the initialization surface to 40 cm in the May 16th modeled surface with an average decrease in depth of 57 cm over the basin.

Instead of scaling the time series of melt flux surfaces by a constant SCA image, we created a time series of SCA images, one corresponding to each time step of model output. These images are linearly scaled from the initial April 6th image to the May 8th image. When multiplied by the melt flux images we obtain 3,643,874 m^3 of modeled melt water versus 2,693,196 m^3 measured for the entire basin. At Emerald Lake we model 41,952 m^3 versus 403,977 m^3 melt discharge and at Topaz we model 441,358 m^3 versus 388,919 m^3 measured.

4. CONCLUSION

The preliminary results shown here are largely exploratory and reveal significant errors. Even so, they will help direct future efforts and resources by lending insight into where the largest improvements can be made. Based on the delay of onset of modeled melt it may be useful to give the model a longer period to equilibrate. Errors in modeling the measured hydrographs reinforce the need for a snowmelt routing model and indicate a need for improved modeled longwave irradiance.

In the future we plan to incorporate advection models for energy and mass fluxes between pixels to more accurately model the distributed snowpack. We will also improve our modeling of incoming long wave irradiance by adapting TOPORAD. We plan to integrate real-time updates of grain size and SCA surfaces. We will be implementing the use of area depletion curves for adjusting SCA between scenes and as well as using snow cover products from MODIS when it becomes available. We are currently exploring other models to more accurately route melt water within the basin.

ACKNOWLEDGMENTS

This research was supported by the following NASA programs: IDS 'Hydrology, Hydrochemical Modeling, and Remote Sensing in Seasonally Snow-Covered Alpine Drainage Basins' and cooperative agreement NCC5-302, the "Earth System Science Workbench". We would like to thank Bert Davis and Ceretha McKenzie for the use of and help with the distributed version of SNTHERM.89. We are especially indebted to all the field grunts responsible for collecting the data that made this research possible.

REFERENCES

Cline, D., R. Bales, and J. Dozier, Estimating the spatial distribution of snow in mountain basins using remote sensing and energy balance modeling, *Water Resour. Res., 34*(5), 1275-1285, 1998.

Dozier, J., A clear-sky spectral solar radiation model for snow-covered mountainous terrain, *Water Resour. Res., 16*, 709-718,1980.

Idso, S. B., A set of equations for full spectrum and 8-14 μm and 10.5-12.5 μm thermal radiation from cloudless skies, *Water Resour. Res., 17*,295-304, 1981.

Jordan, R., A one-dimensional temperature model for a snow cover, *Spec. Rep. 91-6,* U.S. Army Cold Reg. Res. And Eng. Lab., Hanover, N. H., 1991.

Kneizys, F. X., E. P. Shettle, L. W. Abreu, J. H. Chetwynd, G. P. Anderson, W. O. Gallery, J. E. A. Selby, and S. A. Clough, User's guide to LOWTRAN7, *Rep. AFGL-TR-88-0177,* Air Force Geophys. Lab., Bedford, Mass., 1988.

Painter, T.H., D.A. Roberts, R.O. Green, and J. Dozier, 1998, Automated subpixel snow parameter mapping of imaging spectrometer data, *SPIE '98*, September, 1998, Beijing, China.

Rosenthal, W., and J. Dozier, Automated mapping of montane snow cover at subpixel resolution from the Landsat Thematic Mapper, *Water Resour. Res., 32*(1), 115-130, 1996.