Snow Modeling and Observations at NOAA'S National Operational Hydrologic Remote Sensing Center

Thomas R. Carroll
National Operational Hydrologic Remote Sensing Center, National Weather Service,
National Oceanic and Atmospheric Administration
Chanhassen, Minnesota, USA

Abstract

The National Oceanic and Atmospheric Administration's (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC) routinely ingests all of the electronically available, real-time, ground-based, snow data; airborne snow water equivalent data; satellite areal extent of snow cover information; and numerical weather prediction (NWP) model forcings for the coterminous United States. The NWP model forcings are physically downscaled from their native 13 kilometer^2 (km) spatial resolution to a 1 km^2 resolution for the coterminous United States. The downscaled NWP forcings drive the NOHRSC Snow Model (NSM) that includes an energy-and-mass-balance snow accumulation and ablation model run at a 1 km^2 spatial resolution and at a 1 hour temporal resolution for the country. The ground-based, airborne, and satellite snow observations are assimilated into the model state variables simulated by the NSM using a Newtonian nudging technique. The principle advantages of the assimilation technique are: (1) approximate balance is maintained in the NSM, (2) physical processes are easily accommodated in the model, and (3) asynoptic data are incorporated at the appropriate times. The NSM is reinitialized with the assimilated snow observations to generate a variety of snow products that combine to form NOAA's NOHRSC National Snow Analyses (NSA). The NOHRSC NSA incorporate all of the information necessary and available to produce a "best estimate" of real-time snow cover conditions at 1 km^2 spatial resolution and 1 hour temporal resolution for the country.

The NOHRSC NSA consists of a variety of daily, operational products that characterize real-time snowpack conditions. The products are generated and distributed in a variety of formats including: interactive maps, time-series, alphanumeric products (e.g., mean areal snow water equivalent on a hydrologic basin-by-basin basis), text and map discussions, map animations, and quantitative gridded products. The NOHRSC NSA products are used operationally by NOAA's National Weather Service field offices when issuing hydrologic forecasts and warnings including river and flood forecasts, water supply forecasts, and spring flood outlooks for the nation. Additionally, the NOHRSC NSA products are used by a wide variety of federal, state, local, municipal, private-sector, and general-public end-users with a requirement for real-time snowpack information. This paper discusses, in detail, the techniques and procedures used to create the NOHRSC NSA products distributed over the NOHRSC Web site (www.nohrsc.noaa.gov).

Introduction

Snow has substantial impacts on human behavior and activity across the nation and, consequently, has important economic consequences. Generating, distributing, and using snowpack information in the decision making process has economic value, or benefits, because of the potential to increase positive impacts or decrease negative economic impacts associated with snow cover conditions. For example, in the western United States spring snowmelt provides over 70 percent of the water supply. It has been estimated that the water supply derived from spring snowmelt is worth in excess of $348 billion per year on average. Additionally, snow also plays a significant role in the U.S. tourism economy estimated to exceed $7.9 billion dollars per year. The average cost of snow removal for streets and highways in the United States exceeds $2 billion annually. In New York City alone, the cost of snow removal is estimated to be $1 million per inch of snow depth. The single 1997 snowmelt flood that impacted Grand Forks and the Red River of the North caused in excess of $5 billion dollars of damage. Enhanced, accurate, near real-time information on snowpack conditions across the country is critical for managers and others to make optimal decisions required to support river, flood, and water supply forecasting; agriculture and forest management; recreation and winter tourism; and the commerce, industry, and transportation sectors of the nation's economy. As a result of the critical importance of snow and snow information to the nation's economy, it has been estimated that improved information on snowpack conditions has "potential benefits greater than $1.3 billion annually" for the country (Adams, et al., 2004).

To help capitalize on these potential benefits, the U.S. Department of Commerce's NOAA maintains the NWS NOHRSC site in Minneapolis, Minnesota. The NOHRSC uses advanced snow data collection and modeling technology to generate daily and hourly gridded NSAs at high spatial resolution (1 km^2) for the country. The NSA products and data sets use ground-based, airborne, and satellite snow observations coupled with numerical weather prediction model forcings to drive an energy-and-mass-balance snow model. In this way, all available snow information is used to generate the "best estimate" of snowpack characteristics across the country. The NOHRSC NSA products and data sets are used by the NWS, other government agencies, the private sector, and the public to support operational and research hydrology programs across the nation. The NSA products and data sets include estimates of: snow water equivalent, snow depth, snowpack temperatures, snow sublimation, snow evaporation, estimates of blowing snow, modeled and observed snow information, airborne snow data, satellite snow cover, historic snow data, and time-series for selected modeled snow products.

Operational Data Processing

The NOHRSC ingests daily ground-based, airborne, and satellite snow observations from all available electronic sources for the coterminous U.S. These data are used along with estimates of snowpack characteristics generated by a physically-based snow model. The NOHRSC Snow Model (NSM) is an energy-and-mass-balance, spatially-uncoupled, vertically-distributed, multi-layer snow model run operationally at 1 km^2 spatial resolution and hourly temporal resolution for the nation. The model has run continuously at hourly time steps since the 2001-2002 snow season ─ first in an experimental mode, and since the 2004-2005 snow season, in an NWS operational mode. Ground-based and remotely sensed snow observations are assimilated daily into the simulated snow-model state variables. NOHRSC NSA output products are distributed in a variety of interactive maps, text discussions, alphanumeric, time-series, and gridded formats. NSA product formats include: (1) daily national and regional maps for nine snowpack characteristics, (2) seasonal, 2-week, and 24-hour movie-loop animations for nine snowpack characteristics, (3) text summaries, (4) a suite of interactive maps, text, and time-series products, (5) selected hourly and daily gridded snow products for the continental United States excluding the states of Alaska and Hawaii (CONUS), and (6) 3-D visualization products suitable for viewing with KML interpreters (file format used to display geographic data in an Earth browser) such as Google Earth. The NSA provide information about snow water equivalent, snow depth, surface and profile snowpack temperatures, snowmelt, surface and blowing snow sublimation, snow-surface energy exchanges, precipitation, and weather forcings all in multiple formats.

A variety of data sets are ingested daily at the NOHRSC and include ground-based snow water equivalent and snow depth data from the Natural Resources Conservation Service (NRCS), the California Department of Water Resources, British Columbia Ministry of Environment, U.S. Army Corps of Engineers, NWS cooperative observers, and other mesonet sources. Each day, the office ingests, processes, and archives all snow data available from 25,000 reporting stations across the United States and southern Canada. Each snow season, the NOHRSC makes approximately 1,500 to 2,500 airborne snow water equivalent measurements that are assimilated into the NSA. Additionally, the office ingests the full spectral and spatial resolution Geostationary Operational Environmental Satellite (GOES) East and West image data four times each hour. Six passes of Advanced Very High Resolution Radiometer (AVHRR) data are ingested daily by the NOHRSC NOAA Polar Orbiting earth receive station. The GOES and AVHRR satellite data sets (and eventually, MODIS) are used to infer areal extent of snow cover over the coterminous United States. The AVHRR image data are used to generate daily fractional snow cover maps for the CONUS and Alaska. Numerical Weather Prediction (NWP) model data (i.e., Rapid Update Cycle [RUC2], Eta model, Mesocale Analysis and Prediction System [MAPS]) and Next Generation Radar (NEXRAD)-derived precipitation estimates for the coterminous United States are ingested daily and used to drive the physically based NSM (Carroll, et al., 2001).

Ground-based, airborne, satellite, numerical weather prediction (NWP) model, and radar data for the country are ingested daily at the NOHRSC (Figure 1). The data are pre-processed, quality controlled, archived, and used in the NOHRSC Snow Model. A variety of products are generated in multiple formats for distribution to end users.

The NOHRSC Snow Model (NSM)

Because snow water equivalent observations are not sufficient in time or space across the coterminous United States to infer reasonably the distribution of snow water equivalent, it is helpful to model the snowpack using available NWP model output data sets as input to a fully distributed, energy-and-mass-balance snow model (Cline, 1997a, 1997b). Consequently, the NOHRSC developed the NSM to simulate, in near real-time, snow water equivalent and other snowpack properties, for the coterminous United States. The NSM consists, essentially, of three components: 1) data ingest, quality control, and downscaling procedures, 2) a snow accumulation and ablation model, and 3) snow model data assimilation and updating procedures.

Hydrometeorological observations and NWP output are used to force the NSM, run at 1 km^2 resolution, for the country (Figure 2). Furthermore, after the model is initialized, periodic (or sometimes daily) observations of snow water equivalent, snow depth, and areal extent of snow cover are assimilated into the modeled snow states at the appropriate time step.

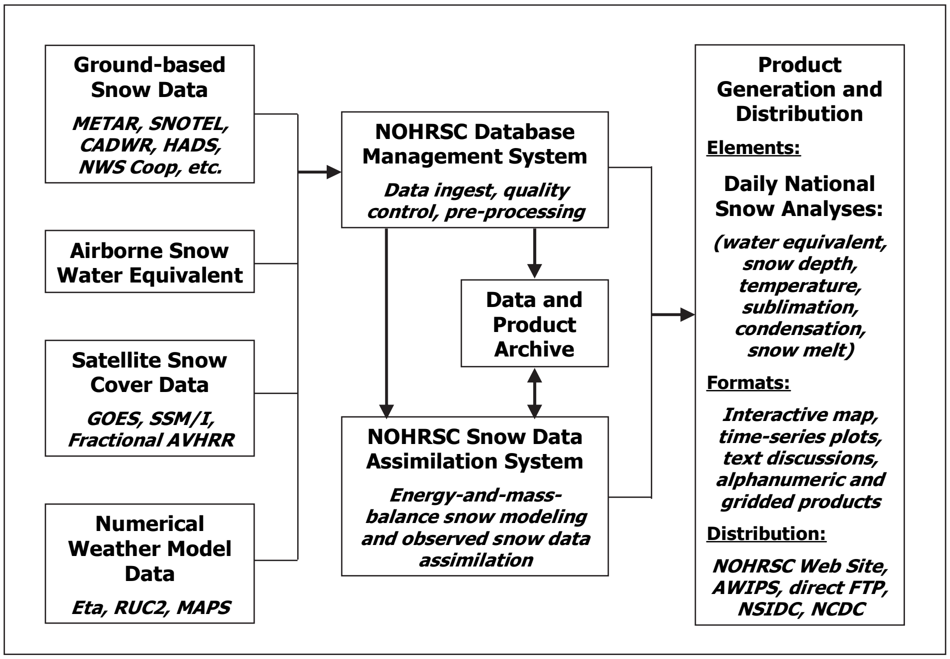

Figure 1. National Operational Hydrologic Remote Sensing Center Operations.

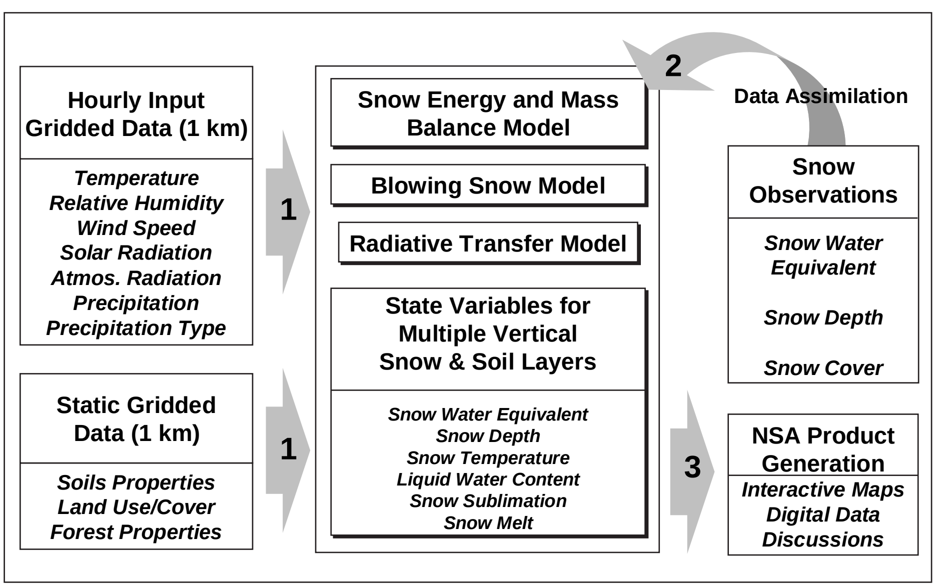

Figure 2. The NOHRSC snow model.

The NOHRSC snow model uses hourly NWP model output products and static data sets as input. The model includes an energy-and-mass-balance snow model, a blowing snow model, and a radiative transfer model. Unadulterated model output (i.e, snow water equivalent and snow depth) are compared to available snow observations, differences are calculated, the model is reinitialized to include information from snow observations, and final products are generated.

The NSM is an energy-and-mass-balance, spatially-uncoupled, vertically-distributed, multi-layer snow model. The NSM incorporates the mathematical approach of Tarboton and Luce (1996) to address the snow surface temperature solution and that of Jordan (1990) to address the snow thermal dynamics for energy and mass fluxes as represented in SNTHERM.89 (a one-dimensional mass and energy balance model of snow and frozen soil). It accounts for the net mass transport from the snow surface to the atmosphere by sublimation of the saltation-transported and suspension-transported snow as developed by Pomeroy, et al. (1993).

The NSM is forced by hourly, 1 km^2, gridded, meteorological input data downscaled from mesoscale NWP Rapid Update Cycle (RUC2) model analyses with the three major-layer state variables of water content, internal energy, and thickness. It generates total snow water equivalent, snowpack thickness, and energy content of the pack along with a number of energy and mass fluxes at the snow surface and between the snow and soil layers.

Development of the NSM was motivated by the need for moderate spatial resolution (~1 km) commensurate with operational, optical, remote sensing data sets (i.e., GOES and AVHRR) used to update the model. Additionally, high temporal resolution (hourly) is required to provide adequate representation of the physical processes in shallow snowpacks. These spatial and temporal resolution requirements for the coterminous United States demand computational efficiency by the model. The current multi-layer snow model is moderately comprehensive with a strong physical basis. It requires only a few input state variables, is parsimonious and efficient in computation, and is appropriate for representing most prevailing snowpack conditions.

Snow Model Data Input

The NSM is driven with gridded estimates of air temperature, relative humidity, wind speed, precipitation, incident solar radiation, and incident longwave radiation (Figure 3). Surface meteorological data are acquired by the NOHRSC from manual and automatic weather stations. Most of these data are in METAR format (international standard format for hourly surface weather observations) and are decoded, quality controlled, and inserted into the NOHRSC Informix database. Additional surface meteorological data are acquired from sources such as the NRCS Snow Telemetry (SNOTEL) system and from NWS cooperative observers. The meteorological driving data for the NSM are generated by downscaling gridded NWP model analysis products from the RUC2 developed and supported by the NOAA Forecast Systems Laboratory (FSL) in Boulder, Colorado (Miller and Benjamin, 1992). If, for some reason, the RUC2 data are temporarily unavailable, the system is capable of ingesting automatically the companion FSL Mesoscale Analysis and Prediction System (MAPS) data sets. The National Environmental Satellite, Data, and Information Service, NOAA, currently produces solar radiation products derived from the GOES imager and sounder data (Tarpley, et al., 1997) that are used by the NSM. The NSM also uses "static" gridded data such as digital elevation data and associated derivatives of slope and aspect, forest cover, and forest type information derived from remotely sensed data, and soils information (Figure 3).

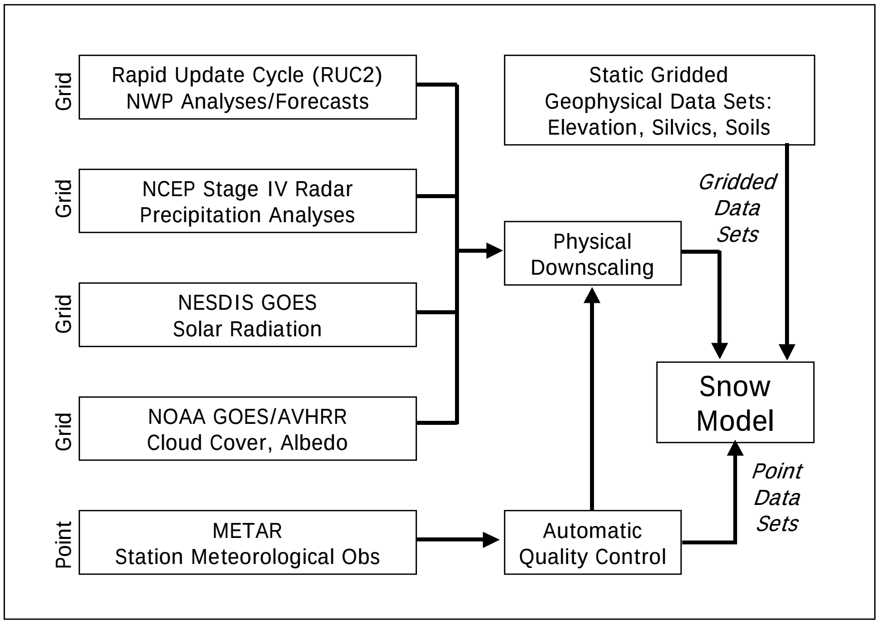

Figure 3. NOHRSC snow model data input. The gridded data input are physically downscaled from the 40 km NWP model resolution to 1 km^2 required by the NSM. Ground-based point observations are automatically quality controlled, used in downscaling, and ingested by the NSM.

The mesoscale RUC2 atmospheric model output variables are downscaled, using a 1 km^2 digital elevation model (DEM), from the native 13 km resolution to the 1 km^2 resolution required by the NSM. The NOHRSC downscaling procedures are currently capable of processing higher resolution NWP model output fields as they become available (Carroll, et al., 2000).

NOHRSC Snow Model Updating

Observations of snowpack properties (e.g., snow water equivalent and snow depth) are used to update the NSM state variables. The NOHRSC ingests point data from over 25,000 reporting stations in the coterminous United States. Of those 25,000 stations, approximately 10,000 report snow data during the course of the season. Table 1 provides the complete summary of the NSM input and output variables. A clear advantage to the NSM modeling approach is that all of the available data — ground-based, airborne, satellite, and NWP model data sets — are used to generate the “best estimate” of a gridded snow water equivalent field at 1 km^2 resolution for the country. Consequently, this approach provides the opportunity to capitalize on the comparatively plentiful ground-based snow depth data heretofore of limited use in NWS operational hydrologic modeling.

Ground-based and airborne observations of snow water equivalent are used to update the NSM water equivalent state variable. Additionally, the comparatively plentiful snow depth observations made by cooperative observers are used to update the snowpack thickness state variable. Satellite areal extent of snow cover is used to update the presence or absence of snow cover.

Rasters for each of the model state variables (Figure 4 and Table 1) snow water equivalent, snow depth, snow temperature (both internal and snow surface), and change in snowpack heat content, etc., and the relevant meteorological driving data can be made available to end users upon request. The most appropriate and effective methods for the four-level discrete dipole approximation (4DDA) system, an atmospheric model, remain to be determined and are the subject of current research activities at the NOHRSC.

NOHRSC Snow Model Results and Conclusion

NOHRSC NSA products are generated daily and distributed over the NOHRSC Web site (www.nohrsc.noaa.gov). The gridded products are shipped in near real-time to the National Snow and Ice Data Center in Boulder, Colorado, and to the NOAA National Climatic Data Center in Asheville, North Carolina, where they are archived and distributed to end users upon request. NSA products include information in multiple formats on snow water equivalent, snow depth, surface and vertical average snowpack temperature, snowpack surface condensation and sublimation, blowing snow sublimation, and snow melt.

The NOHRSC snow model is a physically-based, energy-and-mass-balance snow model for a three-layer snowpack with two layers of soil below. It is run with a horizontal resolution of 1 km. Input data are primarily outputs from the RUC2 model, scaled from the model's intrinsic 13 km resolution to the required 1 km^2 resolution. The primary driving (input) variables for the model are surface air temperature, relative humidity, vector winds, precipitation (snow and non-

Table 1. NOHRSC sow model input and output variables.

Static Data	**Diagnostic Variables**
Forest cover fraction	Blowing snow sublimation rate
Soil bulk density	Compaction rate
Soil plasticity	Conductive heat flux
Driving Data	Convective water flux
Surface zonal wind	Latent heat flux
Surface meridional wind	Melt rate
Surface air temperature	Net convection water flux
Surface relative humidity	Net convection water heat flux
Snow precipitation	Net long wave radiation flux
Non-snow precipitation	Net solar radiation flux
Solar radiation	Sensible heat flux
State Variables	Snowpack sublimation rate
Snow water equivalent	Snowpack surface temperature
Snowpack internal energy	Vapor diffusion flux
Snowpack thickness	
Snowpack average temperature	
Snowpack unfrozen fraction	

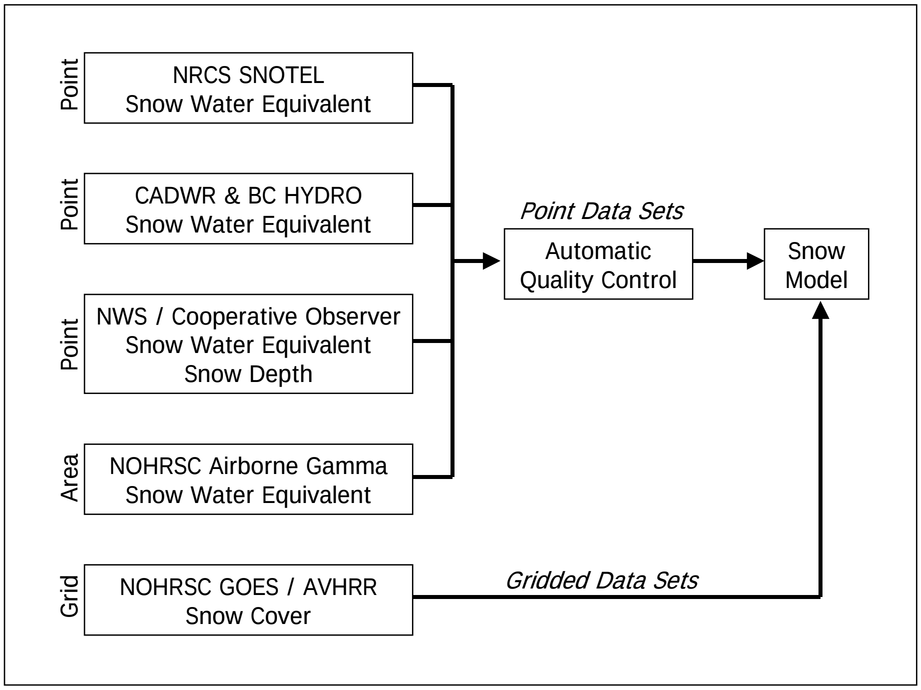

Figure 4. NOHRSC snow model update data sets. Ground-based and airborne snow water equivalent data are used to update the NSM. Snow depth and satellite-derived areal extent of snow cover observations are also used to update the model.

snow), and solar radiation. The primary state variables (input/output) of the model are snow water equivalent, snowpack thickness, and snowpack internal energy. The initial snow water equivalent required by the model (when initialized in the middle of the snow season) is generated by interpolating point observations of snow water equivalent and snow depth. The initial internal energy is inferred from daily temperature data.

The snow modeling and observed snow data assimilation approach adopted by the NOHRSC has the advantage of maximizing all of the information provided by near real-time NWP model forcings as well as all electronically available snow observations. In this way it is possible to generate a “best estimate” of snowpack characteristics using: (1) state-of-the-art snow model physics, (2) NWP model forcings, and (3) all available ground-based, airborne, and satellite snow observations. Resulting NOHRSC NSA products are generated in a variety of formats including: interactive map, animation, time series, gridded, text discussions, flat file, and 3-D visualization. The NOHRSC NSA products are used by a wide variety of federal, state, local, municipal, private-sector, academic, and general public end users. The critical nature and importance of the NOHRSC NSA products is reflected in the fact that after a major snow storm, the NOHRSC Web site can receive over 1 million hits in a single day.

Author E-mail contact: tom.carroll@noaa.gov

References

Adams, R.M., Houston, L.L, and Weiher, R.F. 2004. The Value of Snow and Snow Information Services. Report prepared for NOAA's Office of Program, Planning and Integration under contract DG1330-03-SE-1097 p.

Carroll, T., Cline, D., Fall, G., Nilsson, A., Li, L., and Rost, A. 2001. NOHRSC operations and the simulation of snow cover properties for the coterminous U.S. Proceedings of the 69th Annual Western Snow Conference; Sun Valley, Idaho; 2001 April 16-19. pp 1-10.

Carroll, T.R., D.W. Cline, and L. Li. 2000. Applications of remotely sensed data at the National Operational Hydrologic Remote Sensing Center. Presented at the IAHS, Remote Sensing and Hydrology 2000; Santa Fe, New Mexico; 2000 April 2-7.

Cline, D. 1997a. Snow surface energy exchanges and snowmelt at a continental, mid-latitude Alpine site, *Water Resources Research.* 33(4), 689-701 pp.

Cline, D. 1997b. Sub-resolution energy exchanges and snowmelt in a distributed SWE and snowmelt model for mountain basins, *EOS, Transactions, American Geophysical Union.* 78(46) Supplement, p. 210.

Jordan, R. 1990. *User's Guide for USACRREL One-Dimensional Snow Temperature Model (SNTHERM.89).* U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Miller, P.A. and S.G. Benjamin. 1992. A system for the hourly assimilation of surface observations in mountainous and flat terrain, *Monthly Weather Review.* 120(10), 2342-2359 pp.

Pomeroy, J.W., D.M. Gray and P.G. Landine. 1993. The prairie blowing snow model: characteristics, validation, operation. *Journal of Hydrology.* 144, 165-192 pp.

Tarboton, D. G. and C. H. Luce. 1996. Utah Energy Balance Snow Accumulation and Melt Model (UEB). Utah Water Research Laboratory, Utah University and USDA Forest Service, Intermountain Research Station. 41 p.

Tarpley, D., R. Pinker, I. Laszlo, and K. Mitchell.1997. Surface and cloud products for validation of regional NWP models, *GEWEX Continental-Scale International Project (GCIP) Meeting Abstracts*, University Consortium for Atmospheric Research/National Center for Atmospheric Research, November 5, Boulder, Colorado. 39 p.