NOHRSC OPERATIONS AND THE SIMULATION OF SNOW COVER PROPERTIES FOR THE COTERMINOUS U.S.

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ABSTRACT

The National Weather Service (NWS) provides timely and accurate hydrologic warnings, forecasts, and planning information to ensure the safety of the population, mitigate property losses, and improve the economic efficiency of the Nation. To that end, the National Operational Hydrologic Remote Sensing Center (NOHRSC), NWS, National Oceanic and Atmospheric Administration (NOAA), provides remotely sensed and modeled products and data sets to support the NWS Hydrologic Services Program for the country. The NOHRSC generates satellite-derived areal extent of snow cover observations and makes airborne snow water equivalent measurements over large regions of the country. Additionally, the office ingests a wide variety of near real-time, ground-based hydrometeorological data sets along with real-time, numerical weather prediction (NWP) model data sets for the country. NWP model output data sets are used to force a physically-based, snow-modeling, and snow-data-assimilation system. The ground-based, airborne, and satellite snow cover observations will soon be assimilated, in near real-time, into the gridded fields generated by the snow accumulation and ablation model. Snow model products include a variety of alphanumeric and gridded representations of the snow pack state variables.

A distributed, energy-and-mass-balance snow model and data assimilation system has been developed and implemented at the NOHRSC to augment basic hydrologic analysis. The purpose of the Snow Data Assimilation System (SNODAS) is to provide a physically consistent framework for integrating the wide variety of snow data that is available at various times. SNODAS includes: (1) data ingest and downscaling procedures, (2) a spatially distributed energy-and-mass-balance snow model that is run once each day, for the previous 24-hour period and for a 12-hour forecast period, at high spatial (1 km) and temporal (1 hr) resolutions, and (3) data assimilation and updating procedures. The snow model is driven by downscaled analysis and forecast fields from a mesoscale, NWP model, surface weather observations, satellite-derived solar radiation data, and radar-derived precipitation data. The snow model states can be updated using satellite, airborne, and ground-based snow observations. The model is cast in an assimilation framework and serves to organize various snow observations and to track the evolution of the snow pack between observations. SNODAS permits more frequent and timely product generation—near real-time model analyses and forecasts—and provides several new products, including maps of modeled snow characteristics such as snow ripeness, melt rates, and sublimation losses. Preliminary simulations for test periods during the 2001 snow season give encouraging results.

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INTRODUCTION

Background

The National Operational Hydrologic Remote Sensing Center (NOHRSC), National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), generates satellite-derived areal extent of snow cover observations and makes airborne snow water equivalent measurements over large regions of the country. Additionally, the NOHRSC ingests a wide variety of real-time, ground-based hydrometeorological data sets along with real-time, numerical weather prediction (NWP) model data sets for the country. These data sets are used at the NOHRSC to generate near real-time operational products, in raster and alphanumeric format, of snow water equivalent, satellite-derived areal extent of snow cover, surface temperature, and cumulative freezing and thawing degree days for the country. The NOHRSC products are used by the NWS River Forecast Centers (RFC) in their mission to issue river and flood forecasts, water supply forecasts in the West, and spring snow-melt flood forecasts for the country to save lives and property. Additionally, the NOHRSC products are used by other Federal, state, and local agencies and by the private sector to support a variety of operational and research hydrology programs.

The Problem

Unfortunately, the available ground-based, airborne, and satellite snow cover data sets are not sufficient to satisfy the NWS RFC hydrologic modeling and forecasting requirements for the country. There are simply not enough snow observations to provide hydrologic forecasters with a near real-time, reliable, high resolution (1 km), gridded snow water equivalent product for the country required to support NWS operational hydrologic forecasting. Never has been; probably never will be. Consequently, a promising solution to the problem is to capitalize on the more widely available, near real-time, meteorological observations and NWP model output to model snow water equivalent and other snow pack properties. Observed snow water equivalent, snow depth, and satellite-derived areal extent of snow cover data can, in turn, be used to update the appropriate snow model states when the data are available. In this way, it is possible to use *all* of the available data, (i.e., NWP model output coupled with meteorological and snow observations) to generate a “best estimate” of gridded snow water equivalent for the country in near real-time.

NOHRSC Current Operations

The NOHRSC satellite remote sensing program focuses on NOAA GOES and AVHRR data. Data ingest and pre-processing steps are performed automatically, including data calibration and orbital navigation, image alignment with surface features, solar normalization of visible data, and cloud detection (Carroll, *et al*., 2000). Manual image analysis is used to classify snow cover from image data. The image processing environment incorporates a variety of geospatial data sets to facilitate the image classification process. The principal product is a daily map of areal extent of snow and cloud cover for the continental U.S.

Additionally, the NOHRSC maintains an Airborne Gamma Radiation Snow Survey Program to make near real-time snow water equivalent measurements over a network of 1,900 flight lines covering portions of 29 states and 7 Canadian provinces (Carroll, 1985). The ability to make reliable airborne gamma radiation snow water equivalent measurements is based on the fact that natural terrestrial gamma radiation is emitted from the potassium, uranium, and thorium radioisotopes in the upper 20 cm of soil. The radiation is sensed from a low-flying aircraft flying 150 m above the ground. Water mass in the snow cover attenuates, or blocks, the terrestrial radiation signal. Consequently, the difference between terrestrial radiation measurements made over bare ground and over snow-covered ground can be used to estimate a mean areal snow water equivalent over the approximately 2-3 km^2 flight line with a root mean square error of less than one cm.

Satellite-derived snow- and cloud-cover products are used in conjunction with airborne and ground-based observations of snow water equivalent to perform analyses of the spatial distribution of snow water equivalent. Daily maps of snow water equivalent are generated using available ground-based and airborne snow water equivalent data sets. Additionally, regional snow water equivalent maps for the central and eastern U.S. are produced following each NOHRSC airborne snow survey mission. Alphanumeric summaries of these maps are provided, in near real-time, to operational hydrologic forecasters in NWS field offices to support river, flood, and water supply forecasting.

Lastly, the NOHRSC routinely generates daily surface temperature, cumulative freezing and thawing degree-day, and snow depth (from cooperative observer data) products for the coterminous U.S. Temporal composites of satellite-derived areal extent of snow cover and cooperative observer snow depth products are generated each week.

NOHRSC DATA INGEST, DATA PROCESSING, AND OPERATIONAL PRODUCT GENERATION

The NOHRSC ingests a large amount of data each day to generate the operational snow cover products described above. Included are ground-based and airborne snow water equivalent and snow depth data and satellite data used to derive areal extent of snow cover products. Because the available snow water equivalent data are not sufficient to generate reliable snow water equivalent estimates at sufficient resolution (1 km), the NOHRSC ingests mesoscale, NWP model data sets that are used to drive the physically-based snow model (Figure 1).

NOHRSC Satellite and Hydrometeorological Data Ingest

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, BC Ministry of Environment, U.S. Army Corps of Engineers, NWS cooperative observers, and other sources. Each day, the office ingests, processes, and archives all snow data available from about half of the 11,000 NWS cooperative observers, from 1,100 automated snow water equivalent sensors, from 1,600 snow courses, and from about 800 snow-spotters across the U.S. and Canada. Approximately 1,000 to 1,500 airborne snow water equivalent measurements are made each snow season and ingested by the NOHRSC. Additionally, the office ingests the full spectral and spatial resolution GOES East and West satellite data four times each hour. Six passes of 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 U.S. The AVHRR data are used also to map areal extent of snow cover in Alaska each spring. NWP hourly model data (i.e., Rapid Update Cycle 2) and NEXRAD-derived precipitation estimates for the coterminous U.S. are ingested daily and used to drive the physically-based snow model.

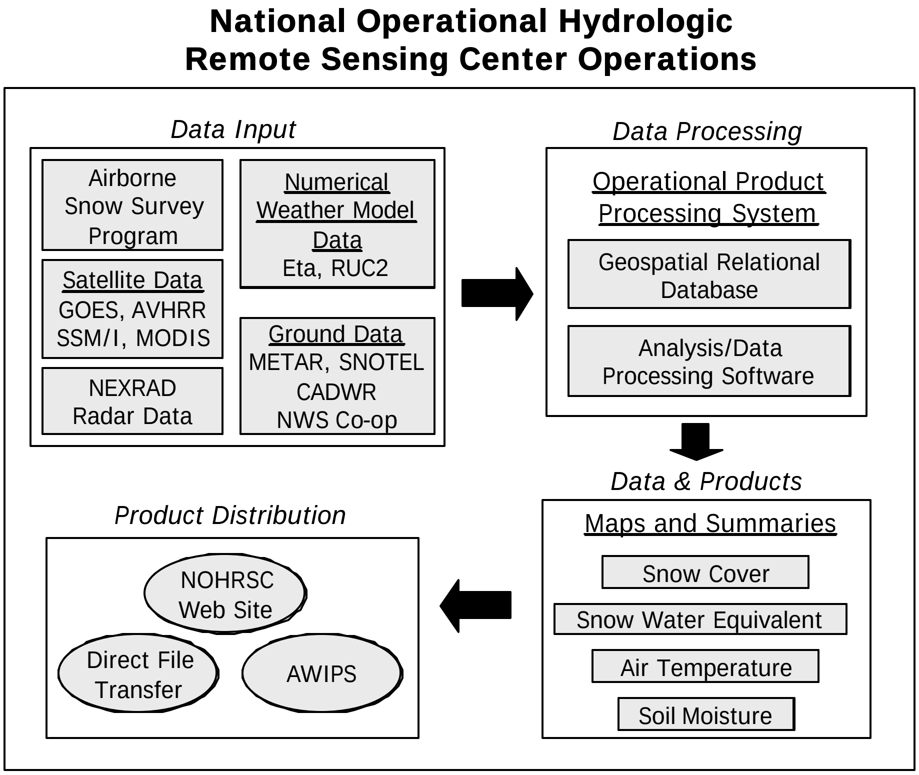

Figure 1. Ground-based, airborne, satellite, numerical weather prediction (NWP) model, and radar data for the country are ingested daily at the NOHRSC. The input data are processed and archived by the Operational Products Processing System (OPPS). OPPS generates a variety of products in map and alphanumeric format that are distributed in near real-time to NWS and non-NWS users.

Product Generation and Data Processing: the Operational Products Processing System

Data processing and product generation is accomplished by a software suite referred to as the NOHRSC Operational Products Processing System (OPPS) (Hartman, *et al*., 1995). OPPS was designed and developed in-house to meet the following design objectives:

1. To streamline, to the greatest extent possible, the production of snow estimation products in an operational environment,
2. To integrate, in an automated and objective manner, a wide variety of input data sources used to produce snow estimation products,
3. To develop and employ state-of-the-art spatial data processing algorithms tailored to the task of producing snow estimation products from integrated input data sources, and
4. To automate the dissemination of generated products.

OPPS is designed to automate data integration. Primarily through the use of spatial interpolation techniques and polygon membership modeling, OPPS is capable of integrating raster data with point, line, and areal vector data. The integration of variable-resolution raster data is supported by run-time data sub- and super-sampling functions allowing OPPS to define a range of output product resolutions without regard to the resolution of the input data.

The spatial integration of raster and vector data is supported by automated procedures that exploit the temporal distribution of the input data. Many OPPS processes are designed to evaluate data within windows of opportunity centered on a target date and time. Because OPPS is designed to address snow estimation on a continental scale, there is a strong possibility that suitable input data are not available for a given instant in time. For example, processes that require satellite-derived areal extent of snow cover maps are often hampered by cloud cover. By integrating the cloud-free portions of multiple snow cover maps acquired during a window of opportunity, OPPS can minimize the impact that cloud cover has on the snow estimation process. Similar mechanisms were designed into OPPS for the treatment of each input data source.

OPPS consists of a series synchronized programs communicating with one another through an Informix database server and system calls. The OPPS programs fall into three classes: Database, Analysis, and Product Development. The OPPS programs are supported by the OPPS database consisting of static and dynamic tabular and graphic data. The dynamic portion of the OPPS database is constantly updated by a wide variety of inputs. OPPS is designed to integrate data from a variety of sources, data-types, structures and formats. OPPS can handle both raster and vector data types. Raster data can be variable in resolution. Vector data may be either point, line, or area structures.

To minimize distortions associated with map-projected coordinates, OPPS requires that all of its inputs be in geodetic (longitude and latitude or Earth) coordinate pairs. All calculations are performed in the geodetic coordinate system. The World Geodetic System 1984 (WGS 84) horizontal datum and the National Geodetic Vertical Datum of 1929 (NGVD 29) were selected for OPPS on the basis of the availability of digital elevation model (DEM) data. Many of the analysis programs in OPPS model orographic processes and, as such, are highly dependent upon DEM data. The highest quality of DEM Data available in national coverage are in the WGS 84 and NGVD 29 datums. The system is designed to ingest raster data in GRASS, ARC/INFO, and Global Imaging formats. It can be easily modified to ingest raster data conforming to the Spatial Data Transfer Standard raster profile upon significant demand.

Point observation data are registered and stored as Informix database records. OPPS is capable of ingesting flat files into the Informix database. All line and areal vector structures are stored in OPPS as individual binary flat files whose headers are stored in the Informix database. Since many spatial data analysis systems (i.e., GIS) are capable of exporting flat files, the OPPS approach for dealing with these types of data allows a great deal of flexibility. OPPS is designed to generate composites from existing rasters in the OPPS database and to:

1. Produce a single raster mosaic of a larger area from multiple rasters of smaller geographically distributed areas; and
2. Produce a single raster composite from temporally-distributed rasters occupying the same geographic area. As rasters are composited, unknown and cloudy pixels are replaced by pixels of known value.

Both functions can operate simultaneously and there is full control of how multiple rasters are integrated. Composite control is facilitated by prioritizing raster file attributes. Raster compositing may be constrained by vector feature outlines.

OPPS Product Generation and Distribution

OPPS is designed to generate final map products at four different scales: NWS County Warning Area scale (112 in the coterminous U.S.), RFC scale (12 in the coterminous U.S.), East/West scale, and the full U.S. scale. Image products and rasters are distributed in gif, Arc/Info, Grid-in-Binary (GRIB), and PostScript formats. Additionally, alphanumeric summaries of each map product are automatically generated and distributed in Standard Hydrologic Exchange Format (SHEF). The SHEF messages give airborne snow water equivalent by individual flight line. Also, OPPS generates and automatically distributes SHEF messages that give a mean areal estimate of the map element for each RFC hydrologic forecast basin. The maps and SHEF products are distributed, in near real-time, over the NWS Advanced Weather Interactive Processing System (AWIPS), by direct file transfer, and are posted to the NOHRSC web site: (www.nohrsc.noaa.gov) (Figure 1).

NOHRSC SNOW DATA ASSIMILATION SYSTEM

The SNODAS Snow Model

Because snow water equivalent observations are not sufficient in time or space across the coterminous U.S. to infer reasonably the distribution of snow water equivalent, it is helpful to model the snow pack 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 has developed a Snow Data Assimilation System (SNODAS) to model the snow water equivalent, and other snow pack properties, for the coterminous U.S.

SNODAS 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 snow model, run at 1 km 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 will be assimilated into the modeled snow states at the appropriate time step. This paper focuses on the development, implementation, and preliminary results of a real-time, energy-and-mass-balance snow model for the coterminous U.S.

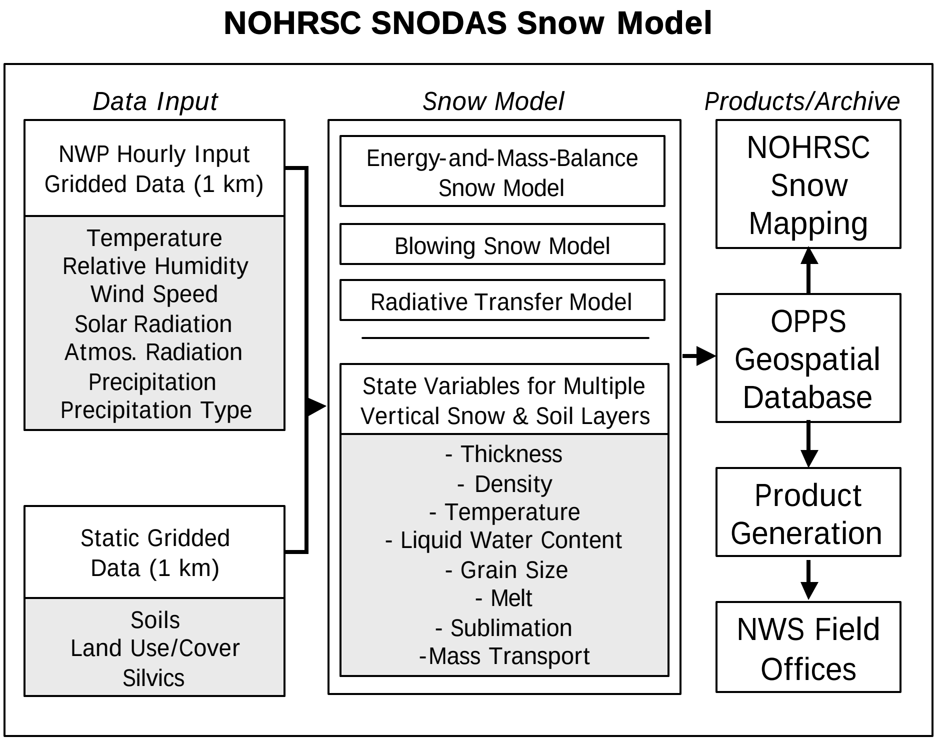

Figure 2. The NOHRSC SNODAS snow model uses hourly NWP model output products and static data sets as input. The model includes an energy-and-mass-balance snow model, a blowing snow model, and a radiative transfer model. Model output is sent to OPPS and used in NOHRSC snow mapping and product generation.

The model is an energy-and-mass-balance, spatially-uncoupled, vertically-distributed, multi-layer snow model. The model 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. 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 model is forced by hourly, 1 km, gridded, meteorological input data downscaled from mesoscale NWP model (RUC2) analyses with the three major-layer state variables of water content, internal energy, and thickness. It generates total snow water equivalent, snow pack 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 snow model 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 packs. These spatial and temporal resolution requirements for the coterminous U.S. demand computational efficiency by the model. The current multi-layer snow model is moderately comprehensive with a strong physical bases. It requires only a few input state variables, is parsimonious and efficient in computation, and is appropriate for representing most prevailing snow pack conditions.

Snow Model Data Input

SNODAS 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 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 pillow sites and from NWS cooperative observers. The meteorological driving data for the SNODAS snow model are generated by downscaling gridded NWP model analysis products from the Rapid Update Cycle (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 snow model (Figure 3).

SNODAS 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). Numerical weather model data (scaled and unscaled) used to drive the snow model are also used with satellite observations to automatically detect clouds, providing a first-guess of cloud cover for the manual snow cover classification process. Similarly, the forecast snow water equivalent from SNODAS can provide a first-guess of snow cover for the next manual snow mapping session. These *a prioi* estimates of snow and cloud cover are intended to improve both the accuracy and speed of manual classification (Figure 2), and most importantly, enable the estimation of snow cover beneath clouds.

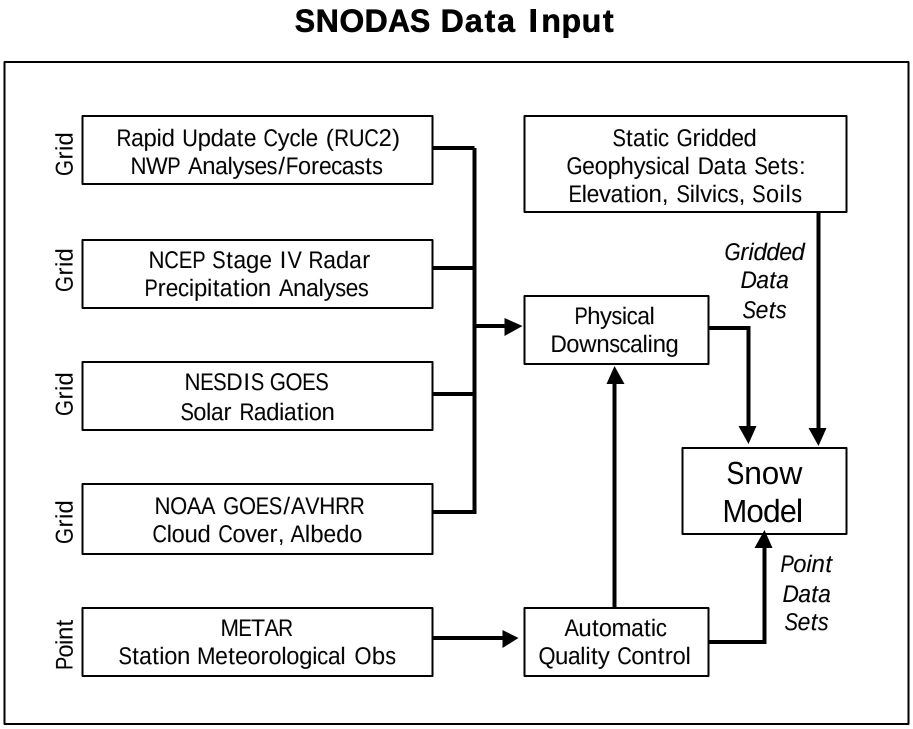

Figure 3. The gridded data input are physically downscaled from the 40 km NWP model resolution to 1 km required by the snow model. Ground-based point observations are automatically quality controlled, used in downscaling, and ingested by the snow model.

Physical Downscaling

The mesoscale RUC2 atmospheric model output variables are downscaled, using a 1 km DEM, from the native 40 km resolution to the 1 km resolution required by the snow model. The NOHRSC downscaling procedures are currently capable of processing higher resolution NWP model output fields as they become available. The RUC2 model profile variables (i.e., winds, pressure, temperature, and relative humidity), model precipitation, and the half-degree GOES-derived solar radiation product are downscaled to 1 km and used to force the snow model. The algorithm to downscale the GOES solar radiation product defines incoming solar radiation as the sum of direct, diffuse, and reflected radiation components and uses TOPORAD coupled to the 1 km DEM data to downscale the satellite product (Dozier and Frew, 1990). Precipitation is extracted from the RUC2 data and separated into snow and non-snow and interpolated over the 1 km DEM. The RUC2 wind data are scaled using a procedure after Liston and Sturm (1998) where the effect of wind downscaling is to increase the wind speed near windward slopes and to decrease the wind speed near leeward slopes.

The thermodynamic profile variables used to drive the snow model (pressure, temperature, and relative humidity) are downscaled to 1 km using the DEM and observed lapse rates (Figure 3). Unscaled variables at all levels in the vertical profile, as well as model level geopotential heights♠, are first smoothed to a 1 km grid using a two-dimensional bilinear interpolation. The scaling then proceeds along one of two paths: when the 1 km grid elevation exceeds the model elevation, linear interpolation between profile levels is used (Figure 4). When the 1 km grid elevation is below the model elevation, the model profile is extrapolated to the 1 km grid elevation. This extrapolation of temperatures and virtual temperatures♣ to the 1 km grid elevation, when required, is based upon the model lapse rate calculated from smoothed quantities at the second and fifth model profile levels.

For positive lapse rates, the temperature or virtual temperature is extrapolated linearly from the model elevation to the 1 km grid elevation. The lapse rate is not allowed to exceed the dry adiabatic lapse rate of about 9.75 K/km, and the lapse rate in virtual temperature is further limited by the constraint that the virtual temperature cannot fall below the temperature at the 1 km grid elevation. For negative lapse rates (inversion layers), the temperature or virtual temperature at the first model profile level is attributed to the 1 km grid elevation.

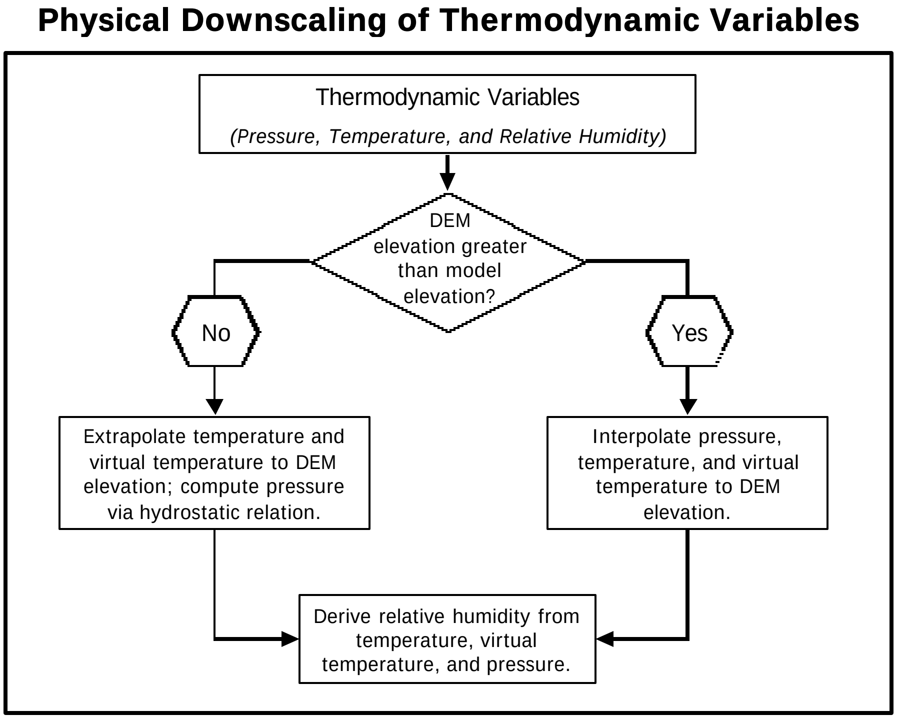

Figure 4. Observed lapse rates derived from station meteorological data are used to downscale the RUC2-generated pressure, temperature, and relative humidity data from 40 km to 1 km using DEM data.

♠ **Geopotential height** is the height of a given point in the atmosphere in units proportional to the potential energy of unit mass (geopotential) at this height, relative to sea level.

♣ **Virtual temperature** is the temperature that dry air must have in order to have the same density as moist air at the same pressure.

For pressure extrapolation, the hydrostatic pressure relation is integrated to the 1 km grid elevation, accounting for the lapse rate in virtual temperature. Finally, the temperature, virtual temperature, and pressure that have been extrapolated to the 1 km grid elevation are used to calculate the scaled relative humidity.

Snow Model Updating

Observations of snow pack properties (e.g., snow water equivalent or snow pack thickness) can be used to update the snow model state variables. Table 1 provides the complete summary of the snow model input and output variables. Once fully implemented, the snow model will be updated with satellite snow cover and with a variety of airborne and ground-based snow water equivalent and snow depth observations (Figure 5). A clear advantage to the SNODAS 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 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.

Table 1
Snow 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	Snow pack sublimation rate
Snow water equivalent	Snow pack surface temperature
Snow pack internal energy	Vapor diffusion flux
Snow pack thickness	
Snow pack average temperature	
Snow pack unfrozen fraction	

Table 1. Ground-based and airborne observations of snow water equivalent are used to update the snow model water equivalent state variable. Additionally, the comparatively plentiful snow depth observations made by cooperative observers are used to update the snow pack thickness state variable. Satellite areal extent of snow cover is used to update the presence or absence of snow cover.

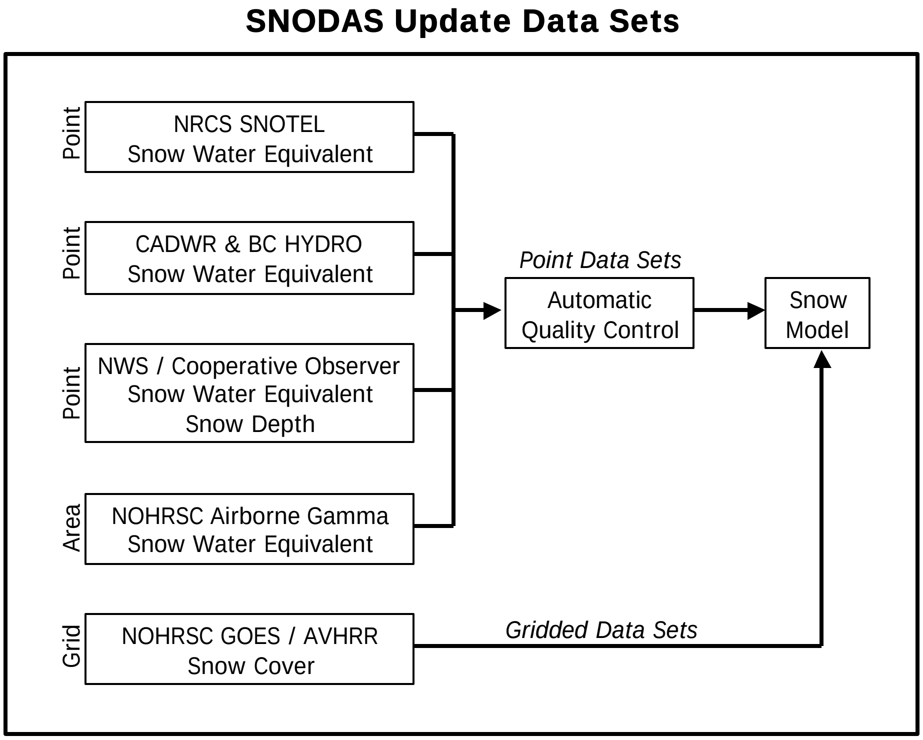

Figure 5. Ground-based and airborne snow water equivalent data are used to update the snow model. Snow depth and satellite-derived areal extent of snow cover observations are also used to update the model.

Rasters for each of the model state variables (Figure 2 and Table 1: snow water equivalent, snow depth, snow temperature (both internal and snow surface), and change in snow pack heat content) and the relevant meteorological driving data will be made available to end-user over the Internet and over AWIPS. The most appropriate and effective methods for the 4DDA system remain to be determined and are the subject of current research activities at the NOHRSC.

SNOW MODEL RESULTS AND CONCLUSION

The NOHRSC snow model is a physically-based, energy-and-mass-balance snow model for a three-layer snow pack 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 40-km resolution to the required 1 km resolution. The primary driving (input) variables for the model are surface air temperature, relative humidity, vector winds, precipitation (snow and non-snow), and solar radiation. The primary state variables (input/output) of the model are snow water equivalent, snow pack thickness, and snow pack 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 SNODAS snow model is not yet operational; there are a number of data ingest, processing, data transfer, and other mechanical software issues to be resolved. Nonetheless, the initial model runs are quite promising. The SNODAS snow model was initialized and run, for the first time, during the winter 2001 for the central and eastern portions of the U.S. The model was able to successfully simulate snow accumulation, ablation, and melt from South Dakota to New England. Because 2001 constituted such an exciting snow year in the Upper Midwest and in the East, the model was run for the region, using hourly time steps, for a two-day period (February 20-21) and for a five-day period (March 7-12). The results are best viewed, in animated-gif form, on the Bulletin Board page of the NOHRSC web site (www.nohrsc.noaa.gov). The web site shows average surface air temperature, total snow fall, total snow melt, snow water equivalent, and snow depth animated at hourly time steps for each of the two periods. Next year, we plan to run the model continuously, starting on October 1, for the conterminous U.S. Real-time model states will be posted to the web. Automated data assimilation and updating procedures will be developed and incorporated into future versions of the NOHRSC SNODAS snow model. Additionally, snow model verification will be addressed at a future date. It's all so much easier said than done.

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