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Evaluation of SNODAS snow depth and snow water equivalent estimates for the Colorado Rocky Mountains, USA

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Abstract:

The National Weather Service's Snow Data Assimilation (SNODAS) program provides daily, gridded estimates of snow depth, snow water equivalent (SWE), and related snow parameters at a 1-km^2 resolution for the conterminous USA. In this study, SNODAS snow depth and SWE estimates were compared with independent, ground-based snow survey data in the Colorado Rocky Mountains to assess SNODAS accuracy at the 1-km^2 scale. Accuracy also was evaluated at the basin scale by comparing SNODAS model output to snowmelt runoff in 31 headwater basins with US Geological Survey stream gauges. Results from the snow surveys indicated that SNODAS performed well in forested areas, explaining 72% of the variance in snow depths and 77% of the variance in SWE. However, SNODAS showed poor agreement with measurements in alpine areas, explaining 16% of the variance in snow depth and 30% of the variance in SWE. At the basin scale, snowmelt runoff was moderately correlated ($R^2 = 0.52$) with SNODAS model estimates. A simple method for adjusting SNODAS SWE estimates in alpine areas was developed that uses relations between prevailing wind direction, terrain, and vegetation to account for wind redistribution of snow in alpine terrain. The adjustments substantially improved agreement between measurements and SNODAS estimates, with the R^2 of measured SWE values against SNODAS SWE estimates increasing from 0.42 to 0.63 and the root mean square error decreasing from 12 to 6 cm. Results from this study indicate that SNODAS can provide reliable data for input to moderate-scale to large-scale hydrologic models, which are essential for creating accurate runoff forecasts. Refinement of SNODAS SWE estimates for alpine areas to account for wind redistribution of snow could further improve model performance.

KEY WORDS SWE; snow depth; hydrological modeling; SNODAS; WEBB

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INTRODUCTION

Snow is an essential resource in the western USA, providing water for drinking, irrigation, industry, energy production, and ecosystems across much of the region. In the mountains of the western USA, most precipitation falls as snow, which accumulates in a seasonal snowpack that acts as a large natural reservoir. On average, 70 to 80% of the annual runoff in the western USA originates as mountain snowmelt (Doesken and Judson, 1996), and in the upper Colorado River basin, the percentage is even higher, with 85% of streamflow derived from melting snow (Edwards and Redmond, 2005).

The quantity of water stored in seasonal snowpacks is expressed as snow water equivalent (SWE). Springtime SWE is one of the most important inputs to hydrologic models used to forecast runoff in the western USA, because it is the main source of water to streams during late spring and early summer (Clark and Hay, 2004; Slater and Clark, 2006).

The National Weather Service (NWS) and the Natural Resource Conservation Service jointly develop runoff forecasts each spring to estimate flood potential and water availability for downstream users. The NWS River Forecast Centers have traditionally used a simple temperature-index model (SNOW-17) to make runoff forecasts, but they and others are moving toward using gridded input data sets and spatially distributed hydrologic models to improve runoff and flood forecasts (Franz *et al*., 2008; Hay *et al*., 2006; Kuchment *et al*., 2010).

Since 2004, the NWS National Operational Hydrologic Remote Sensing Center (NOHRSC) has provided daily, moderate-resolution (1 km^2), gridded estimates of SWE and related snow parameters (e.g. snow depth, sublimation, and snowmelt) for the conterminous USA through the Snow Data Assimilation (SNODAS) program (http://www.nohrsc.nws.gov/nsa/). SNODAS products have the potential to substantially improve the calibration and performance of spatially distributed hydrologic models in snow-dominated catchments of the western USA. It is the only nationwide, moderate-resolution, gridded SWE product available at a daily time step.

Development of SNODAS products follows several steps, as described by Carroll *et al*. (2006). First, the NOHRSC ingests data from the Rapid Update Cycle numerical weather prediction model and downscales it from 13 to 1 km^2. These data drive the NOHRSC Snow Model (NSM), which is a physically based, spatially distributed, energy-balance and mass-balance snow

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accumulation and ablation model run at a 1-km^2 resolution. All digitally available satellite, airborne, and ground-based snow observations are assimilated into the model and used to adjust model output by using a Newtonian nudging technique. The objective of using all of the available snow data is to produce a 'best estimate' of near real-time snow conditions for the conterminous USA.

Snow Data Assimilation products have been used in a range of applications. Barlage *et al.* (2010) compared modeled snowpack evolution in headwater areas of the Colorado Rocky Mountains from SNODAS with that from the Noah land surface model (LSM) to help validate the Noah LSM results. SNODAS SWE estimates have been used to validate SWE estimates derived from remotely sensed microwave brightness temperature data in the Great Lakes area (Azar *et al.*, 2008). SNODAS SWE data also have been used in regression models for predicting habitat suitability for coyotes in the eastern USA (Kays *et al.*, 2008), white-tailed deer density in the upper peninsula of Michigan (Millington *et al.*, 2010), and the presence/absence of fisher (*Martes pennanti*) in northern California forests (Zielinski *et al.*, 2010).

Although the major components of SNODAS, such as the NSM, have been extensively tested (e.g. Frankenstein *et al.*, 2008; Pomeroy *et al.*, 1993; Rutter *et al.*, 2008), several studies have suggested that the accuracy of SNODAS gridded SWE estimates has not been well evaluated or is uncertain (Azar *et al.*, 2008; Hay *et al.*, 2006). This is, in part, because SNODAS assimilates virtually all readily available ground-based and airborne SWE data, leaving little or no data for validation.

The objective of this study was to evaluate the accuracy of SNODAS snow depth and SWE estimates in the Colorado Rocky Mountains by using two independent methods including (1) ground-based snow surveys and (2) water-balance calculations on headwater basins. The snow surveys provided information on model performance at the 1-km^2 scale, whereas the water-balance calculations provided information at the basin scale. To gain a better understanding of issues of scale and processes affecting snow distributions, SNODAS model results were compared with those from a fine-scale (30-m^2 resolution) model of snow depth in Loch Vale, a US Geological Survey (USGS) research watershed in Colorado. Lastly, effects of wind redistribution of snow on SNODAS model results were evaluated, and a simple method for adjusting SNODAS snow depths in alpine/subalpine terrain was developed. Assessment of SNODAS accuracy in the Colorado Rocky Mountains should provide a rigorous test of the model owing to the complexity of terrain in the study area.

STUDY AREA

The study area was the Colorado Rocky Mountains in the western USA (Figure 1). It is an area of high relief, with elevation ranging from approximately 2000 m on the eastern and western boundaries to 4400 m along the Continental Divide, which trends roughly north–south. Much of the terrain is steep, particularly in high-elevation areas that were glaciated during the Pleistocene. Vegetation consists mostly of conifer and aspen forests at low elevations, shifting to krummholz (dwarf conifers) in the subalpine, and forbs and grasses in the alpine zone (Peet, 1988). Treeline varies with latitude, ranging from about 3200 m in the north to 3700 m in the southern part of the state (Weber, 1961).

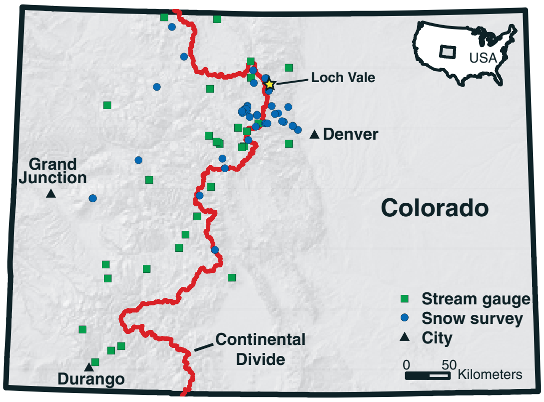

Figure 1. Map showing locations of snow survey sites and stream gauges used in the study

Snow is the dominant form of precipitation at high elevations. Winters are cold, and snow usually accumulates in the mountains from November through March or April, with minimal mid-winter melt. Snowmelt usually begins in April or May and lasts through June or July. Westerly winds are common, causing substantial redistribution of snow in the alpine zone, with scouring on the windward side of peaks and ridges, and deposition on the leeward side. Wind redistribution of snow is responsible for the continuing presence of most of the remaining glaciers in Colorado, which tend to be small, 'wind drift' glaciers on the leeward (east) side of the Continental Divide (Outcalt and MacPhail, 1980).

Snow Data Assimilation model results were compared with a fine-scale model of snow depths for the Loch Vale watershed, in the northern part of the study area. Loch Vale is a 6.6-km^2 alpine/subalpine (hereafter, alpine) basin where the USGS has been investigating hydroclimatic and biogeochemical processes since the early 1990s through the Water, Energy, and Biogeochemical Budgets (WEBB) program (http://co.water.usgs.gov/lochvale/). The USGS operates three weather stations in Loch Vale, including a 10-m tower at a 3100 m elevation, which provided wind vector data for this study.

METHODS

Gridded SNODAS data from January 2007 through July 2007 were obtained from the National Snow and Ice Data Center (http://nsidc.org/data/docs/noaa/g02158_snodas_snow_cover_model/). Data were processed using Geographic Information System (GIS) software to extract snow depth and SWE for grid cells and dates corresponding to each of the snow surveys. For the water-balance calculations, basin boundaries were overlain on the SNODAS SWE, precipitation (snow and non-snow), and sublimation (surface and blowing snow) grids to calculate basin-wide estimates for each of the snowpack water-balance components (see section on Water-Balance Calculations for more details). For each basin, SNODAS grid cells that intersected the basin boundary were clipped to include only the portions of the grid cells that were within the basin.

Snow survey methods

Snow surveys (depth and SWE) were conducted in 45 SNODAS grid cells in Colorado during late January 2007 through early April 2007 (Figure 1). Each grid cell was surveyed once by a two-person crew. Survey sites were selected to span a range of elevation, slope, aspect, and vegetation characteristics, except that slopes greater than 30° were avoided because of avalanche hazard. Within each grid cell, snow depths were measured every 60 m along a predefined, square route by using a graduated probe. This resulted in 33 measurements within each grid cell on the day that it was surveyed; these data were used to calculate an average snow depth for that grid cell and day. Snow survey routes were approximately 0.5 km on each side and were centered within the SNODAS grids, which are 30 arc sec in size (nominally 1 km; Carroll *et al*., 2006). Routes were followed using a high-precision global positioning system connected to a field computer running topographic map software; this allowed field personnel to follow routes with high accuracy and record their locations and measurements digitally.

Snow density, which tends to vary much less than snow depth (Sturm *et al*., 2010), was measured along each snow survey route in one to three locations, depending on the uniformity of slope, aspect, vegetation, and snow depths. At each density measurement location, a snow pit was dug to the ground, and the north-facing wall was shaved back to provide a smooth face. Snow density was measured using standard methods, and average SWE for each grid cell was calculated as the product of average snow depth and average snow density in the cell (Ingersoll *et al*., 2002). These data were compared with snow depth and SWE extracted from SNODAS raster data sets for the dates and locations corresponding to each snow survey using simple linear regression.

To help identify reasons for possible discrepancies between SNODAS model results and ground-based surveys, a GIS analysis was performed to obtain topographic and vegetation characteristics of each snow survey grid cell and its adjacent neighbors. Input data sets included a 1-km resolution digital elevation model (DEM; http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info) and the 30-m resolution 2001 National Land Cover Dataset (NLCD; http://www.mrlc.gov/). The DEM was used to calculate slope and curvature (convexity and concavity) relative to each grid cell's neighbors in the upwind direction. NLCD vegetation data were used to classify grid cells and their neighbors as montane or alpine; results were checked against high-resolution (15 m) aerial photography, which indicated misclassification of approximately 10% of the grid cells. The misclassified grid cells were reclassified on the basis of aerial photograph interpretation.

Water-balance calculations

To evaluate the accuracy of SNODAS SWE estimates at the basin scale, water-balance calculations were performed for the 2007 snowmelt period on 31 gauged headwater basins in Colorado with minimal or no diversions (Figure 1; Clow, 2010). A simple water-balance equation for snowmelt-dominated basins may be expressed as follows:

$$\text{Runoff} = \text{SWE}_{\text{April 1}} + \text{precipitation} - \text{sublimation} \\ - \text{evapotranspiration} \pm \text{groundwater storage}$$

where all components, except $\text{SWE}_{\text{April 1}}$, pertain to basin-wide totals for the snowmelt period (April 1 to July 31). $\text{SWE}_{\text{April 1}}$ refers to the average basin-wide SWE on April 1.

Runoff was calculated from stream-gauge records for each basin, which were obtained from the USGS National Water Information System database (http://waterdata.usgs.gov/nwis). All other fluxes, except evapotranspiration (ET) and groundwater storage, were derived from SNODAS. The SNODAS model, which focuses on snowpack processes, does not estimate ET and groundwater storage; thus, ET and groundwater storage are unresolved errors in the equation. In the study basins, both terms are likely to be sinks during the snowmelt period (Clow *et al*., 2003).

Fine-scale variations in snow distributions

Fine-scale variations in snow depth were modeled for Loch Vale as part of this study by using binary regression tree analysis, as described by Elder *et al*. (1998). Input data included snow depth measurements at 328 locations from a snow survey conducted in the basin during mid-April 2003, wind direction data from the 10-m meteorological tower in Loch Vale, and basin characteristics from a GIS analysis. Basin characteristics that were tested as explanatory variables included elevation, aspect, and mean incoming solar radiation for each 30-m^2 grid cell (Clow *et al*., 2003; Clow and Sueker, 2000), and the mean slope and percentage of alpine terrain within a wedge-shaped area 100 m in the upwind direction (±18°) from each measurement location. This approach is similar to that used by Winstral *et al*. (2002). Optimal regression model selection was based on the combination of explanatory variables that maximized the coefficient of determination (R^2) and minimized the root mean square error (RMSE) during cross-validation testing (Helsel and Hirsch, 1992).

RESULTS AND DISCUSSION

Ground-based surveys

The average measured snow depth in forest grid cells was 81 ± 29 cm (average ± 1 standard deviation; $n = 26$). In alpine areas, measured snow depths were more variable, averaging 100 ± 60 cm (Table I; $n = 19$).

Table I. Statistical summary for snow depth and SWE from snow surveys and SNODAS

Parameter	Measured (cm)*	SNODAS (cm)*	R^2**	RMSE (cm)***
Snow depth, forested	81 ± 29	80 ± 40	0.72	15
Snow depth, alpine	100 ± 60	83 ± 49	0.16	55
Snow depth, all	89 ± 45	82 ± 43	0.31	37
Adjusted snow depth, all (calibration)		83 ± 34	0.75	23
Adjusted snow depth, all (validation)		92 ± 26	0.68	24
SWE, forested	22 ± 10	23 ± 13	0.77	5
SWE, alpine	30 ± 20	24 ± 16	0.30	17
SWE, all	25 ± 15	24 ± 14	0.42	12
Adjusted SWE, all (calibration)		24 ± 12	0.75	6
Adjusted SWE, all (validation)		28 ± 10	0.63	6

SWE, snow water equivalent; SNODAS, Snow Data Assimilation; RMSE, root mean square error.
*Average ± 1 standard deviation.
**R^2 for regression of measurements against SNODAS estimates.
***RMSE for regression.

A comparison of measured snow depths against SNODAS snow depths for forested areas indicated good agreement, with an R^2 of 0.72 and an RMSE of 15 cm (Figure 2a; Table I). These results indicate that SNODAS was able to explain most (72%) of the variability in snow depths in the forest with an accuracy of 15 cm or better.

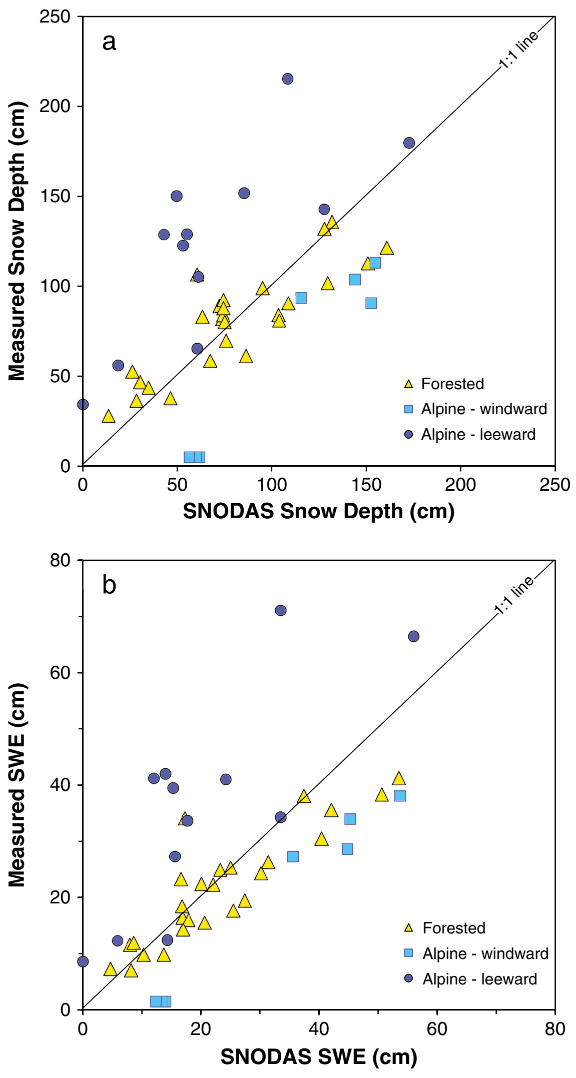

Figure 2. Comparison of measured and Snow Data Assimilation (SNODAS) (a) snow depth and (b) snow water equivalent (SWE)

In alpine areas, agreement between measured snow depths and SNODAS snow depths was relatively poor, having an R^2 of 0.16 and an RMSE of 55 cm (Figure 2a; Table I). This indicates that the processes that are captured in the SNODAS model may not be the most important ones driving spatial variations in snow depth in the alpine zone. Sturm and Wagner (2010) noted that in tundra areas, wind is the dominant control on spatial variations in snow depth, and other studies have documented similar results for prairie and alpine landscapes (Pomeroy *et al*., 1993; Winstral *et al*., 2002).

Variations in density were relatively small compared with variations in snow depth. Considering all sites (forest and alpine), the relative standard error (RSE; RSE = RMSE/ estimate) for measured densities was 17%, whereas the RSE for measured snow depths was 51%. Thus, variations in SWE (which are the product of density and depth) were driven mainly by variations in snow depth (Figure 2b; Table I). SNODAS explained 77% of the variation in SWE in the forest and 30% of the variance in SWE in the alpine zone (Table I).

Water-balance calculations

Runoff during the 2007 snowmelt period in the 31 headwater basins analyzed in this study averaged 25 cm, and sublimation accounted for 2.4 cm of water loss (Figure 3a). April 1 SWE in the headwater basins averaged 24 cm, similar in magnitude to runoff and to April–July precipitation (22 cm; Figure 3a). Most of the April–July precipitation was snow during April, but the form of precipitation shifted primarily to rain by June–July; May was a transition month.

Water-balance calculations for individual sites indicated that runoff during the snowmelt period correlated moderately well with the sum of SNODAS components of the water balance (April 1 SWE and precipitation minus sublimation; $R^2 = 0.52$; Figure 3b). Runoff usually was less than the sum of SWE, precipitation, and sublimation, reflecting loss of water to ET and groundwater recharge, or

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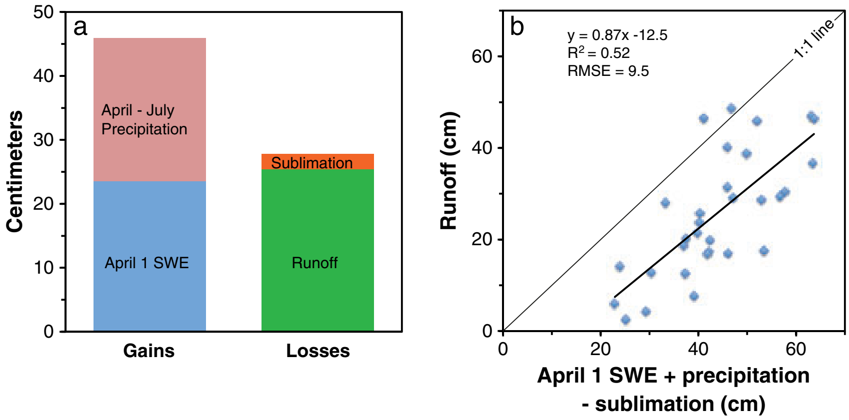

Figure 3. Comparison of April–July water-balance components for (a) averages of all study basins and (b) individual basins. RMSE, root mean square error; SWE, snow water equivalent

bias in some or all of the water-balance components. If, for simplicity, it is assumed that all of the bias in the runoff–SNODAS regression is due to ET and groundwater recharge losses, then it may be inferred that the magnitude of those losses was typically approximately 20 cm, which is a reasonable value for these basins (Carey *et al.*, 2010). Under the same assumption, the RMSE of the regression (9.5 cm) gives an approximation of error in SNODAS estimates, runoff estimates, or a combination thereof.

Fine-scale variability

The optimal fine-scale binary regression tree model for snow depths in Loch Vale included elevation, aspect, mean radiation, and mean slope in the upwind direction. The model had an R^2 of 0.60 and an RMSE of 82 cm, which was 30% of the average modeled snow depth (272 cm). Results indicated substantial spatial heterogeneity in snow depth, largely reflecting topographically controlled wind redistribution of snow (Figure 4a).

In Loch Vale, and most of western Colorado, prevailing winds during winter and spring are from the west and the southwest (Figure 5). Typically, snow from the alpine zone on the west side of the Continental Divide is transported over the Continental Divide by accelerating winds and is deposited on the leeward side as winds decelerate, creating large snow drifts. West-facing slopes tend to be scour zones, and east-facing slopes tend to be drift accumulation zones (Figure 4a). This spatial pattern of scour on the western slope and accumulation on the east side of the Continental Divide is common in the alpine zone of western Colorado (Figure 6).

Snow Data Assimilation snow depth estimates for Loch Vale were of similar magnitude to those from the fine-scale model (Figure 4b). SNODAS grid cells covering the Loch Vale basin had estimated snow depths of 100 to 250 cm, whereas the average basin-wide snow depth calculated from the fine-scale model was 272 cm. However, SNODAS did not accurately predict snow depths near the marginal, higher elevations of the basin, where wind redistribution is important (Figure 4). The large area of shallow snow depths predicted by the fine-scale model for the southeastern part of Loch Vale (Figure 4a), for example, was not resolved by the SNODAS model, nor were the areas of deep snow depths in sheltered parts of the basin.

Accounting for wind redistribution of snow

The NSM, which forms the core of SNODAS, is ‘an energy-and-mass-balance, spatially uncoupled, vertically distributed, multilayer snow model’ (Carroll *et al.*, 2006). Because it is spatially uncoupled, it does not account for redistribution of snow from one grid cell to another by wind.

The good agreement between snow depths from SNODAS and from snow survey measurements in forested areas indicates that the lack of a wind redistribution component in SNODAS is not a major problem there (Figure 2a). However, it is an important issue in the alpine zone, where snow depth measurements and SNODAS did not agree well (Figure 2a; Table I). These results are consistent with previous studies in tundra and alpine landscapes, which have noted that snow distribution in these areas is largely controlled by interactions between wind, terrain, and vegetation (Pomeroy *et al.*, 1993; Sturm and Wagner, 2010; Winstral *et al.*, 2002).

Sturm and Wagner (2010) noted that, because terrain and vegetation usually change slowly, snow distribution patterns generally are persistent from year to year. They used snow survey data to calibrate an empirical model that used wind direction, topography, and vegetation information as explanatory variables to predict spatial patterns in snow depths at a tundra site in Alaska (Sturm and Wagner, 2010).

A similar approach was used in the present study to develop a simple empirical model to adjust SNODAS snow depths for alpine areas. Prevailing wind direction was calculated on the basis of data from Loch Vale and from Niwot Ridge, an alpine site approximately 50 km to the south; at both sites, prevailing winds were from the west–southwest (Figure 5; Winstral *et al.*, 2002). Differences between measured snow depths and SNODAS snow depths were compared with slope, aspect, and curvature of terrain in the upwind direction from the snow survey grid cells. Of these parameters, slope in the upwind direction was the most reliable predictor of errors in SNODAS

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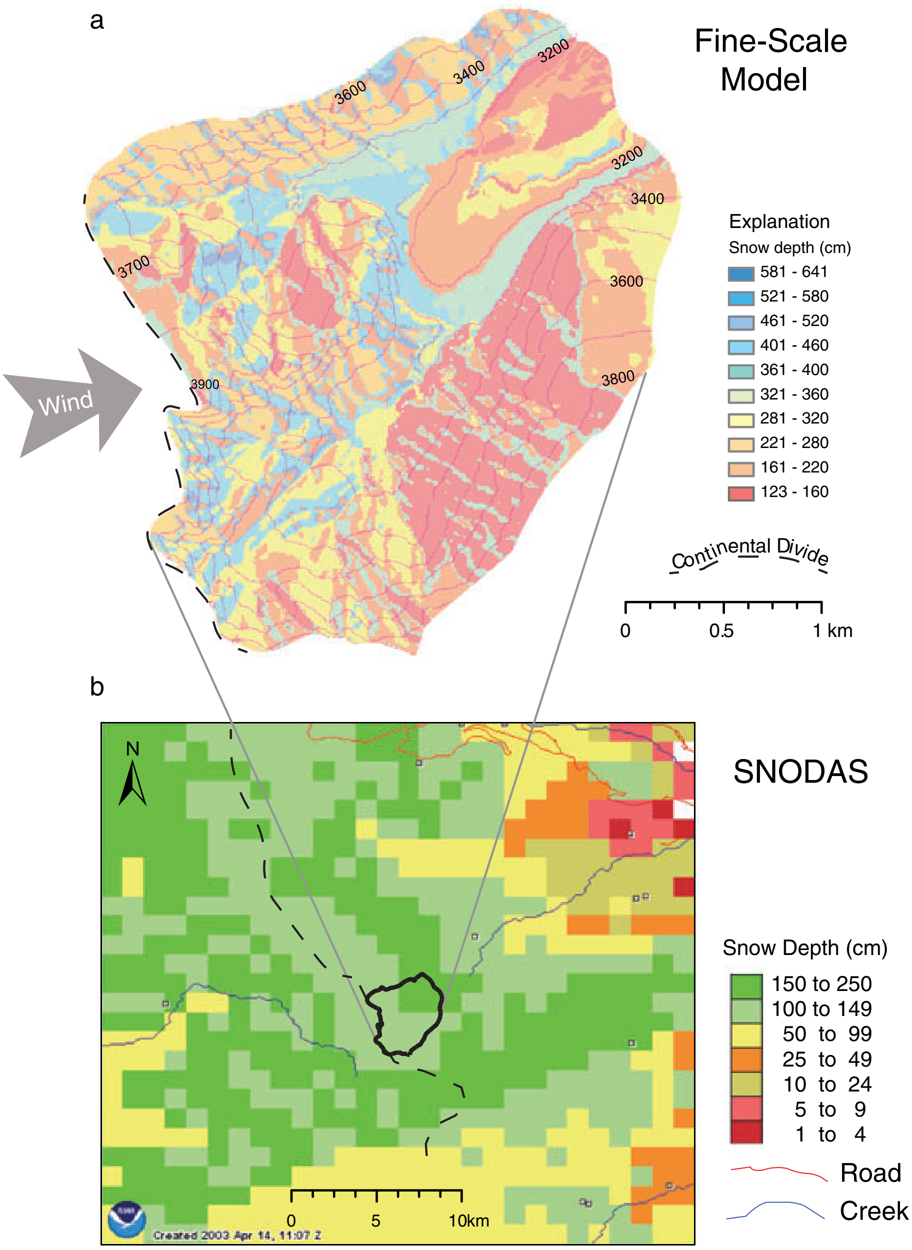

Figure 4. Modeled snow depths in Loch Vale during mid-April 2003 from (a) binary regression tree analysis and (b) Snow Data Assimilation (SNODAS). SNODAS grid cells are 1 km^2

estimates. This variable is similar to the 'wind shelter index' of Winstral *et al*. (2002). Negative slopes (indicating terrain sloped downward in the upwind direction, to the west–southwest) were associated with positive bias (SNODAS over-predicted). Positive slopes (indicating terrain sloped downward to the east–northeast) were associated with negative bias (SNODAS under-predicted). However, bias was only present when snow survey sites were within approximately 1 km from a major ridge, such as the Continental Divide. The aerial photograph of the area near Berthoud Pass, Colorado, shows that preferential deposition declines with distance from the Continental Divide, consistent with reduced wind effects as distance from terrain features increases (Figure 6).

With these observations, an objective classification procedure was developed to categorize alpine snow survey sites as being in a 'windward zone' or a 'leeward zone', depending on slope and vegetation in the upwind direction and distance from a major drainage divide. A wind-effect variable was created in which each alpine snow survey grid cell was assigned a -1 if it was in a windward zone, a $+1$ if it was in a leeward zone, and a 0 if it was in a 'no-effect zone'. Forested sites were categorized as being in a no-effect zone, and snow depths at those sites were not adjusted. Sites were randomly split into a calibration data set ($n = 23$) and a validation data set ($n = 22$). A multiple linear regression model was created using the calibration data to adjust SNODAS snow depths:

$$\text{Adjusted snow depth} = 22.8 + 0.69(\text{SNODAS snow depth}) + 42.4(\text{wind effect})$$

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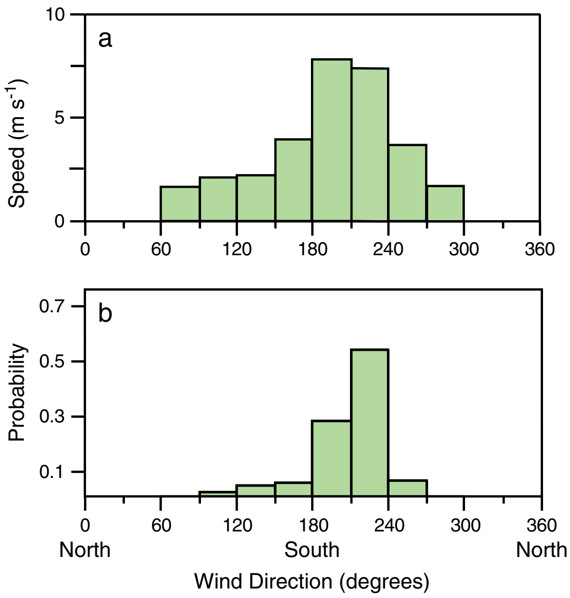

Figure 5. Daily mean (a) wind speed and (b) wind direction at main Loch Vale weather station during 1 November 2006 to 15 April 2007

Model coefficients were estimated using the least squares method (units are in centimeters). Identical procedures were used to develop a model for adjusted SNODAS SWE values:

$$\text{Adjusted SWE} = 3.0 + 0.82(\text{SNODAS SWE}) + 11.0(\text{wind effect})$$

The adjustment procedure substantially improved agreement between SNODAS estimates and measured values of snow depth and SWE (compare Figures 2 and 7). With the use of just the validation data, the R^2 for the regression of measured snow depths against adjusted SNODAS snow depths was 0.68, and the RMSE was 24 cm (Table I). These values indicate substantially better agreement to measured

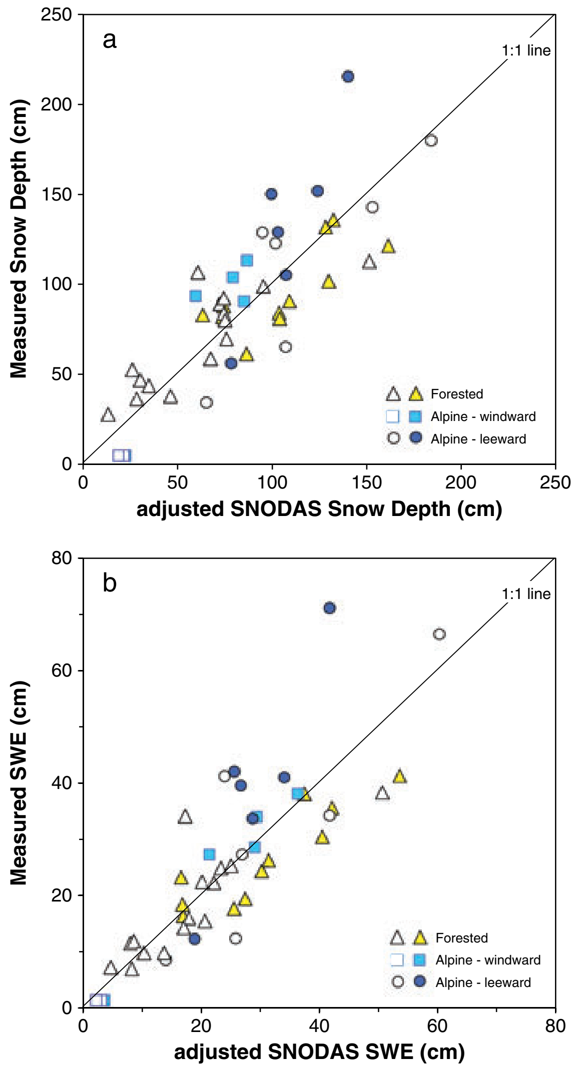

Figure 7. Comparison of measured and adjusted Snow Data Assimilation (SNODAS) (a) snow depth and (b) snow water equivalent (SWE). Filled symbols represent data used for model calibration. Open symbols represent data used for model validation.

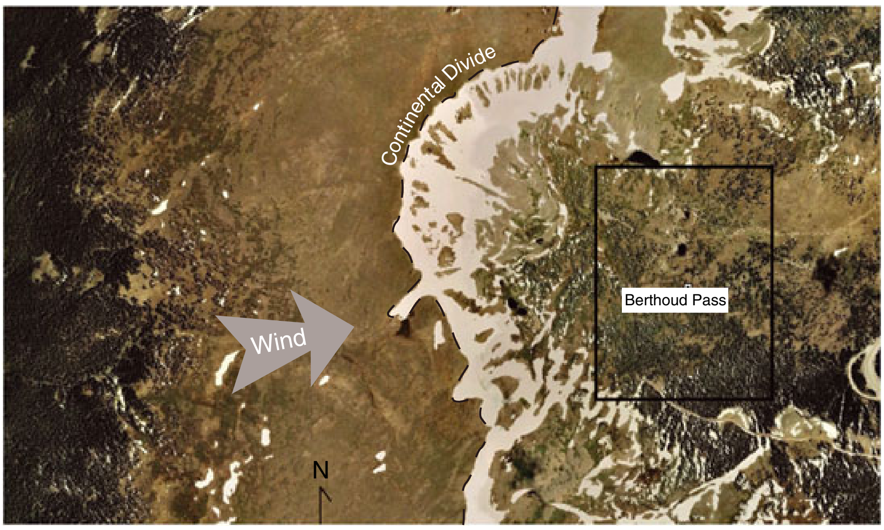

Figure 6. Aerial photograph showing areas of wind-induced scour and deposition of snow along the Continental Divide near Berthoud Pass, Colorado, during late spring 2008. Snow Data Assimilation (SNODAS) grid surrounding Berthoud Pass snow survey site outlined in black for reference. SNODAS grid is 30 arc sec (nominally 1 km). Photo credit: US Geological Survey, EarthExplorer (http://earthexplorer.usgs.gov/; photo ID 1656267_13SDE3050702008030X600)

snow depths than the unadjusted SNODAS values (Table I). SWE showed a similar improvement, with the R^2 increasing from 0.42 to 0.63 and RMSE decreasing from 12 to 6 cm (Table I).

These results need to be independently verified, and the model coefficients are likely to vary by region. However, when combined with observations in previous studies that spatial patterns in snow distribution are persistent and controlled largely by interactions between wind, terrain, and vegetation, they suggest that it is possible to develop a method to adjust SNODAS snow depth and SWE estimates in alpine terrain to account for wind redistribution of snow (Pomeroy *et al.*, 1993; Sturm and Wagner, 2010; Winstral *et al.*, 2002). SNODAS already uses static data layers, including a DEM and a forest cover map, that would be needed to calculate slope and forest cover in the upwind direction of SNODAS grid cells. Prevailing wind directions could be determined from meteorological data that SNODAS currently assimilates on a daily basis. In the present study, distance to major drainage divides was determined on a site-by-site basis using topographic software; however, the calculation for each SNODAS grid cell could be automated in a GIS framework. It is likely that the simple approach that was used in this study could be refined and improved upon. A continuous upwind slope variable, for example, might be a more appropriate and powerful predictor of wind effects than the simple 'leeward/windward' binary classification scheme used here.

CONCLUSIONS

This study demonstrated that SNODAS provides reasonably accurate estimates of snow depth and SWE in forested areas; SNODAS was able to account for 72% of the variance in snow depth and 77% of the variance in SWE in the forest. However, SNODAS showed poor agreement with measurements in alpine areas, explaining 16% of the variance in snow depth and 30% of the variance in SWE. The lack of a wind redistribution scheme in SNODAS appears to limit its accuracy in the alpine zone.

A simple method for adjusting SNODAS snow depth and SWE estimates for alpine areas based on relations between prevailing wind direction, terrain, and vegetation was developed; it provided substantially improved estimates of snow depth and SWE. Although further testing and development are required, results indicate that it might be possible to increase the accuracy of SNODAS by including a wind redistribution subroutine that takes advantage of persistent patterns in snow distribution caused by interactions between wind, vegetation, and terrain.

Results from this study indicate that SNODAS can provide reliable data for input to moderate-scale to large-scale hydrologic models, which are essential for creating accurate runoff forecasts. Refinement of SNODAS SWE estimates for alpine areas to account for wind redistribution of snow could further improve model performance.

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