LASER MAPPING OF MOUNTAIN SNOWPACKS: ENABLING RESILIENT MANAGEMENT OF WATER RESOURCES AND AVALANCHE HAZARD IN A CHANGING WORLD

Jeffrey S. Deems[1]

[1]*National Snow and Ice Data Center, University of Colorado, Boulder, CO USA*

ABSTRACT: Many resource and hazard management operations – from water supply to avalanche hazard mitigation – support decision-making by comparing present to past conditions. Index-based snowmelt runoff forecasting and nearest-neighbor avalanche models work this way, leveraging an observational period of record to predict the likely outcome of a specific storm or water year. Though this kind of methodology can be effective, current conditions are increasingly deviating from the historic record posing challenges to these approaches.

Part of adapting to this changing environment is to reduce reliance on our historically-based, index methods and improve our ability to observe the actual state of the snowpack. Two examples of high-resolution snow depth and SWE mapping exemplify efforts to add resilience to water management and avalanche control operations:

1) The NASA Airborne Snow Observatory operationally maps snow depth, SWE, and snow albedo across full mountain watersheds, supporting operational water management in California, and research efforts in California, Colorado, Switzerland, and elsewhere.

2) Repeat TLS snow depth mapping has supported planning and evaluation of active avalanche control measures, helping refine explosives tramway design and assess Gazex exploder placement.

These case studies and other efforts comprise a “spatial revolution” enabling distributed, physical monitoring and simulation of snow dynamics and hydrology in complex terrain.

KEYWORDS: remote sensing, spatial variability, snow depth mapping, forecast modeling

1. INTRODUCTION

Spatial variation in snow properties has long been recognized as a challenge to measurement and modeling. Variability at multiple scales affects the accuracy of water supply volume and streamflow forecasts as well as avalanche forecasting, control efforts, and stability assessments. Despite efforts to quantify and characterize this variability and its evolution over time, it is only recently that capabilities to measure these variations over wide areas at resolutions consistent with their native scales of action have matured to the point of operational relevance.

In particular, several methods of high-resolution snow depth mapping are seeing regular use in both research and applied or operational contexts. These data sources (and others) are ushering in a new era of spatial measurement, supporting forecasting, planning, decision-making, and physically-based modeling. This continued development has great importance for making operational models and forecasts robust to changing climate and precipitation patterns, forest cover, and societal demands.

1.1 Forecasting snowmelt runoff and avalanches: practice and challenges

**Corresponding author address:*
Jeffrey S. Deems, National Snow and Ice Data Center, University of Colorado, 449 UCB, Boulder, CO 80309;
tel: +1 303-492-4743
email: deems@nsidc.org

The volume and timing of snowmelt runoff is controlled by the distribution of SWE at the beginning of melt season, and surface energy balance inputs as the melt season progresses. It is rare, however, that full measurements of snow energy and mass balance are available to drive a model at anything but the point scale. Running such a fully-specified model over wider areas requires some parameterization of the variation of the mass and energy terms, or an assumption of homogenous conditions over wide areas.

Similarly, avalanche occurrence is a complex function of the spatial and temporal patterns of snow loading, weak layer distribution and properties, creep rates, and slab properties. Recent developments in dynamics modeling demonstrate an emerging capacity to incorporate these physical processes. Like the snow hydrology models, avalanche dynamics models require spatial inputs on appropriate scales.

As such, operational models have tended toward index or statistical approaches, with minimal data requirements and simplified physics. These types of models, e.g. temperature-index melt models, statistical seasonal runoff volume forecasts, or nearest-neighbor avalanche forecasting, leverage a set of historic observations to calibrate a relationship between measured variable(s) and the targeted response – snowmelt or avalanche occurrence (Magnusson et al., 2014; Buser et al., 1987).

1.2 Index forecasting methods: pros and cons

Limitations of data sources, model complexity, and computing power have posed a substantial challenge to purely process-based forecasting approaches to snowmelt runoff or avalanche occurrence, and therefore index or statistical methods have dominated the operational forecasting environment. Air temperature is more readily and commonly measured than any other surface energy balance component, making temperature-index snowmelt modeling an attractive option (Hock, 2003). Correlating snow/meteorological variables with avalanche occurrence or danger rating can be used to explore historic days with similar conditions and plan control operations or issue danger ratings.

Models of these types can perform well, when current conditions are well-represented in the period of record. When conditions deviate from 'normal', index and statistical models will perform poorly. Currently, dramatic changes in climate, forest cover, snow accumulation conditions, and human disturbances are adding uncertainty to forecasts when increasing societal demands require ever-better performance. Temperature-index melt models, relying on a calibrated air temperature/melt rate relationship, are vulnerable to changes in snow albedo (e.g. from dust or black carbon deposition) or changes in forest cover. Nearest-neighbor avalanche models may require new variable weights or a different set of snow-met variables to cope with changes in storm sequence, snow temperatures, or increases in mid-winder melt or rain-on-snow. The importance of specific variables, whether derived from an avalanche/meteorology database or expert knowledge, is likely to change as temperatures warm and as the character of storms and weather sequences change (e.g. Singh et al., 2014).

1.3 A way forward: Incorporating spatially-extensive measurements of snow depth

Recent efforts in measurement technologies and physical modeling capabilities are enabling greater degree of process representation in forecasting models. This better physical fidelityv will make these forecast models more responsive to changing conditions and thereby more robust to deviations from the historic record.

Advanced snow cover models – e.g. SNOWPACK (Lehning et al., 2002) or CROCUS (Durand et al., 1999) – are regularly used over wide areas forced by numerical weather model output, however quantification of mass and energy fluxes across mountain terrain remains challenging. Precipitation inputs are particularly critical, especially when redistribution processes are considered (Bellaire et al., 2011). Constraining the evolution of snow mass distribution in physical models is a crucial step for improving model accuracy.

Efforts to incorporate or assimilate spatial snow depth data are a promising approach to reducing snow state errors derived from precipitation uncertainty. For example, the operational snow-hydrological service (OHSD) at the Swiss SLF combines high-resolution weather forecasts and snow depth information from an extensive station network with index-based and energy-balance models to forecast snowmelt (Magnusson et al., 2014). The regular assimilation of widely-distributed snow depth data provides an important constraint on the snowpack state, greatly improving the fidelity of the simulated snow properties (Griessinger et al., 2016). However, station siting limitations constrain these measurements to flat, open sites; thus the majority of terrain and forest conditions are not represented in the assimilation, highlighting the need for comprehensive spatial data. New capacities for mapping snow depth at high resolution over wide areas represent an important advance to support physical models.

2. CASE STUDIES: SNOW DEPTH MAPPING

Two case studies exemplify the promise of new spatial data sources for operational support in water management and avalanche contexts. The NASA Airborne Snow Observatory (ASO) maps snow depth, SWE, and snow albedo over entire mountain basins, supporting research and operational water management in the Western US. Recent work mapping snow depth with terrestrial laser scanners (TLS) has supported planning and evaluation of active avalanche control measures, helping refine placement of explosives tramways and assess placement and operation of Gazex exploders.

2.1 The NASA Airborne Snow Observatory: enabling resilient water management through full basin snow mapping

Since 2013 the NASA ASO program has mapped snow depth over full mountain basins through differential lidar altimetry, incorporating observed and modeled density to map SWE, and mapping albedo with an imaging spectrometer (Painter et al., 2016). The resulting time series – weekly to bi-monthly, site-depending – provide an unprecedented view into snow cover evolution in accumulation and melt seasons. ASO works closely with operational water managers to provide SWE volume estimates in near-real time, either fully distributed or aggregated to a specific area.

The Tuolumne River Basin in California has been a primary test basin for the ASO program, in close collaboration with basin water managers

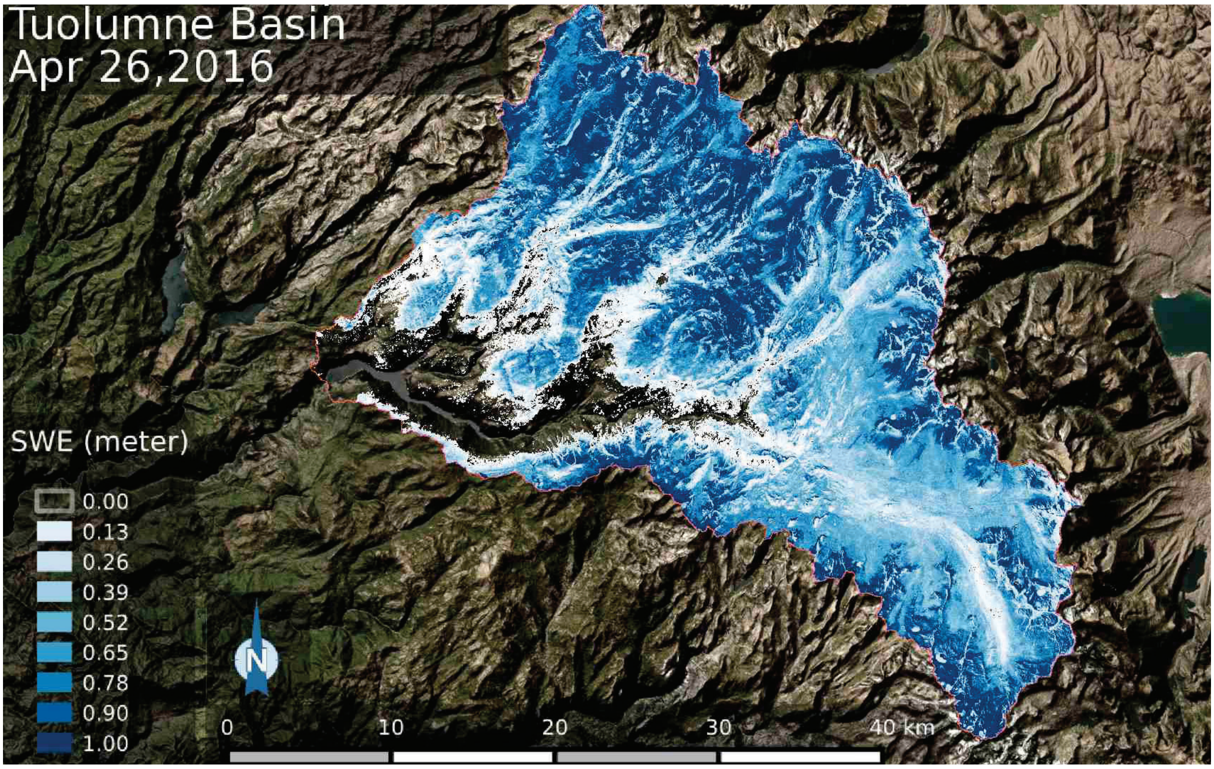

Figure 1: 26 April, 2016 50m resolution ASO SWE map for the Tuolumne River, California.

(Fig 1). Over the 6 year period of record, including extreme drought and high runoff years, ASO SWE volumes predict total reservoir inflow with an R^2 of 0.98. Compared to prior runoff forecast errors often exceeding 40% in the region (Dozier, 2011), this predictive capacity is transformational, enabling reservoir management to much tighter tolerances. In addition to this strong predictive relationship, assimilation of ASO data into a physically-based snow model illustrates the value of regular state variable updates as opposed to forcing with interpolated precipitation measurements or mesoscale model outputs, especially in simulating SWE variation across complex terrain (Hedrick et al., 2018).

2.2 Snow depth mapping in avalanche starting zones: supporting operations and planning

Pilot projects with the Arapahoe Basin Ski Area (A-Basin) and the Transportation Avalanche Research Pool/Colorado Department of Transportation (TARP/CDOT) employed TLS snow depth mapping to support explosives targeting, explosives tramway planning, and Gazex effectiveness assessment (Deems et al., 2015; 2016). These projects highlighted several operational use cases, and identified future applications for snow depth mapping.

Integrating near-real time snow mapping at A-Basin supported active avalanche control efforts. In one instance specific snow drift features were targeted for avalauncher control, with a control result that would not have occurred without the lidar map availability. In another instance, the lidar depth change map showed that starting zone snow accumulations were smaller than study plot data indicated, and a decision not to shoot the avalauncher was made, saving money and worker exposure.

In support of ongoing operating area expansion work at A-Basin, lidar snow depth maps were used to adjust planned explosives tramway network alignment, resulting in a plan that allows greater flexibility in targeting specific accumulation targets (Fig 2). Initial results from the first year of explosives control following the tram network installation are very encouraging with a high fraction of successful control missions.

A TLS mapping project assisted with assessing the effectiveness of a new Gazex array installed along US Highway 6 near Loveland Pass, CO. Repeat scans illustrated the diversity of avalanche behavior within the set of paths. Two paths regularly released the entire start zone due to their concave geometry. Other exploders showed evidence of work-hardening, suggesting changes in operation frequency or timing. One exploder in particular was completely buried in both years of the lidar study. Time series of snow depth cross-sections through this exploder show that its placement is likely suboptimal and that burial can be expected regardless of operation frequency (Fig 3).

These cases illustrate the strong potential for lidar snow depth mapping to support operational

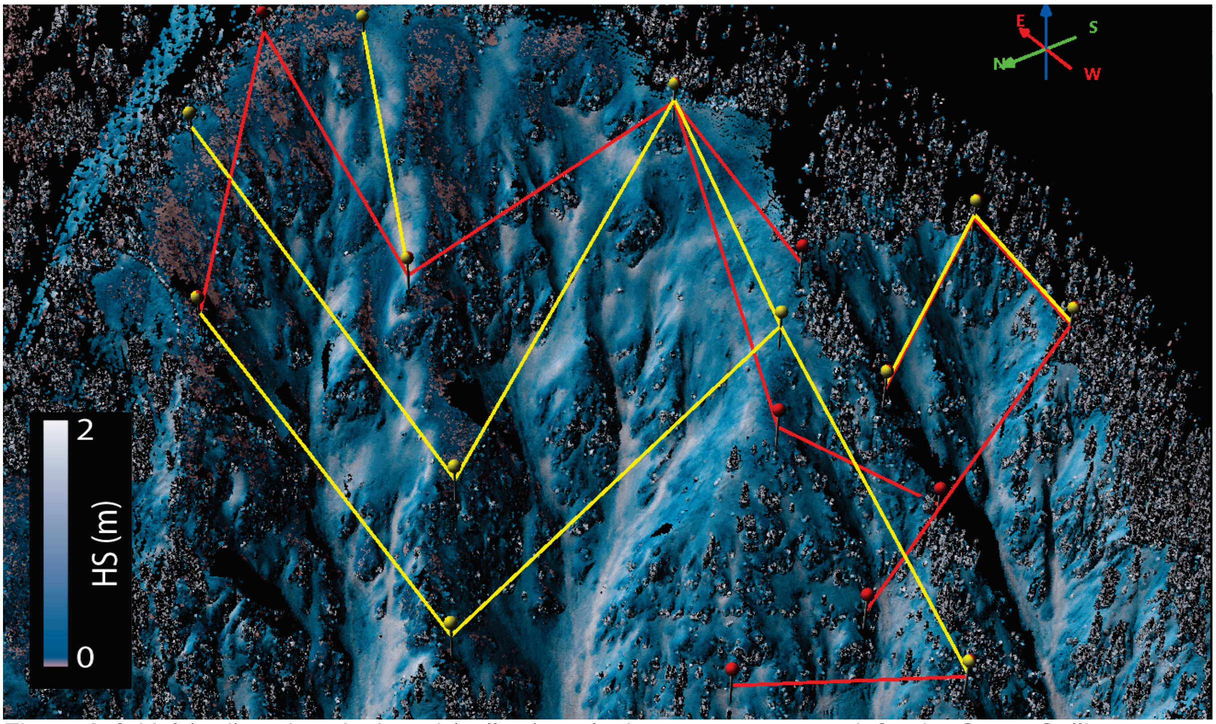

Figure 2: Initial (red) and re-designed (yellow) explosive tramway network for the Steep Gullies expansion area at A-Basin, overlaid on a TLS snow depth map (from Deems et al., 2016).

water management or avalanche control, both for real-time data needs and future planning.

3. THE SPATIAL REVOLUTION: THE EMERGING FUTURE OF APPLIED SNOW SCIENCE

The examples above highlight ongoing operational and applied science efforts to leverage and incorporate high-resolution spatial snow depth data for water resources and avalanche hazard management. The availability and use of this type of data source will expand as tools and techniques proliferate and decrease in cost.

The ASO program is expanding with investment from state water resource agencies in the Western US. Other efforts involving federal forecast systems and the NASA SnowEx campaigns seek to improve snow density measurement, enable spaceborne observations, and catalyze data assimilation into operational forecasts.

The National Oceanic and Atmospheric Administration (NOAA) in the US is implementing a new, physically-based National Water Model (WRF-Hydro) to replace the existing index model. Recent collaborations have demonstrated WRF-Hydro performance improvement from assimilating multiple ASO data sets.

An ongoing project is testing lidar snow depth assimilation into the Swiss OSHD model system (see above; Jonas et al., 2016). The ASO-European Alps project aims to test the value of ASO snow depth data from a wide variety of terrain and forest components relative to the existing station-based snow depth data assimilation.

Previous efforts have explored infrastructure planning using snow depth maps. Prokop et al. (2016) used a time series of lidar-derived snow depth maps to design a snow drift fence array. Margreth et al. (2016) demonstrated the utility of TLS snow depth maps for planning the size of supporting structures, and advocated for adoption of this technique. The Gazex and A-Basin results suggest that snow depth mapping prior to site selection could improve exploder siting help optimize design of control infrastructure. The spatial perspective provided by lidar snow depth mapping is a valuable planning resource, and can also provide high-resolution terrain maps for

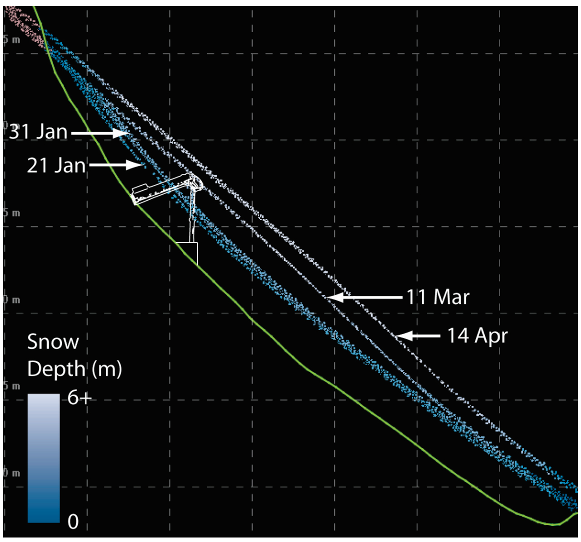

Figure 3: Time series cross-section of snow depth through the 1Low Gazex exploder, Loveland Pass, CO.

use in engineering and construction phases.

Other techniques for mapping snow depth or other snow properties are in use or development. Photogrammetric tools such as Structure-from-Motion (SfM) are used to build point clouds and elevation models from RGB imagery.

Radar remote sensing techniques offer the potential to map snow density and SWE (e.g. L-band interferometry), surface elevations for differential mapping (e.g. Ka-band altimetry), or roughness mapping for avalanche debris detection (e.g. Eckerstorfer and Malnes, 2015).

Drone-based remote sensing using optical or lidar sensors is increasing in use, and offers a cost-effective means to map snow depth or surface properties over moderate extents (e.g. Bühler et al., 2015). The drone perspective can combine the high point density of a TLS survey with a view geometry for optimal laser incidence angle and subcanopy mapping.

4. SUMMARY

Regular production and operational use of spatially extensive, high resolution snow mass and volume data sets is on the cusp of widespread adoption. This ‘spatial revolution’ has the potential to greatly improve the skill of hydrologic and avalanche forecasts, while making them more robust to changing conditions.

REFERENCES

Bellaire, S., Jamieson, J.B., Fierz, C., 2011. Forcing the snow-cover model SNOWPACK with forecasted weather data. Cryosph. 5, 1115–1125. doi:10.5194/tc-5-1115-2011

Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P., Ginzler, C., 2015. Snow depth mapping in high-alpine catchments using digital photogrammetry. Cryosph. 9, 229–243. doi:10.5194/tc-9-229-2015

Deems, J.S., Gadomski, P.J., Vellone, D., Evanczyk, R., LeWinter, A.L., Birkeland, K.W., Finnegan, D.C., 2015. Mapping starting zone snow depth with a ground-based lidar to assist avalanche control and forecasting. Cold Reg. Sci. Technol. 120, 197–204. doi:10.1016/j.coldregions.2015.09.002

Deems, J.S., R. Evanczyk, D. Vellone, E. Greene, T. Weldon, D.C. Finnegan, P.J. Gadomski, A. LeWinter, 2016. Supporting, Evaluating, and Planning Avalanche Control Efforts with Lidar-Derived Snow Depth Maps, in: Proc. of the International Snow Science Workshop. Breckenridge, CO, pp. 205–212.

Durand, Y., Giraud, G., Brun, E., Mérindol, L., Martin, E., 1999. A computer-based system simulating snowpack structures as a tool for regional avalanche forecasting. J. Glaciol. 45, 469–484. doi:10.1017/S0022143000001337

Eckerstorfer, M., Malnes, E., 2015. Manual detection of snow avalanche debris using high-resolution Radarsat-2 SAR images. Cold Reg. Sci. Technol. 120, 1–14. doi:10.1016/j.coldregions.2015.08.016

Gassner, M., Brabec, B., 2002. Nearest neighbour models for local and regional avalanche forecasting. Nat. Hazards Earth Syst. Sci. 2, 247–253. doi:10.5194/nhess-2-247-2002

Griessinger, N., Seibert, J., Magnusson, J., Jonas, T., 2016. Assessing the benefit of snow data assimilation for runoff modeling in Alpine catchments. Hydrol. Earth Syst. Sci. 20, 3895–3905. doi:10.5194/hess-20-3895-2016

Hock, R., 2003. Temperature index melt modelling in mountain areas. J. Hydrol. 282, 104–115. doi:10.1016/S0022-1694(03)00257-9

Jonas, T., Winstral, A. H., Magnusson, J., & Deems, J. S., 2016. Snow water resources monitoring using ASO data-fusing and leveraging three national approaches. AGU Fall Meeting Abstracts.

Lehning, M., Bartelt, P., Brown, B., Fierz, C., 2002. A physical SNOWPACK model for the Swiss avalanche warning Part III: meteorological forcing, thin layer formation and evaluation. Cold Reg. Sci. Technol. 35, 169–184.

Magnusson, J., Gustafsson, D., Hüsler, F., Jonas, T., 2014. Assimilation of point SWE data into a distributed snow cover model comparing two contrasting methods. Water Resour. Res. 50, 7816–7835. doi:10.1002/2014WR015302

Margreth, Stefan, Jóhannesson, Tómas, Már Stefánsson, H., 2014. Avalanche Mitigation Measures for Siglufjörður – Realization of the Largest Project with Snow Supporting Structures in Iceland, in: Proc. International Snow Science Workshop, Banff, Canada. pp. 263–269.

Painter, T.H., Berisford, D.F., Boardman, J.W., Bormann, K.J., Deems, J.S., Gehrke, F., Hedrick, A., Joyce, M., Laidlaw, R., Marks, D., Mattmann, C., McGurk, B., Ramirez, P., Richardson, M., Skiles, S.M., Seidel, F.C., Winstral, A., 2016. The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. Rem. Sens. Environ. 184, 139–152. doi:10.1016/j.rse.2016.06.018

Prokop, A., Procter, E.S., 2016. A new methodology for planning snow drift fences in alpine terrain. Cold Reg. Sci. Technol. 132, 33–43. doi:10.1016/j.coldregions.2016.09.010