ELEVATING SNOW RESEARCH AT THE US ARMY CORPS OF ENGINEERS

Shad O'Neel[1,2]*, Naheem Adebisi[2], Tate Meehan[1,2], Zach Hoppinen[1,2], Elias Deeb[1], HP Marshall[2]

[1] *Cold Regions Research and Engineering Laboratory, Hanover, NH, USA*
[2] *Boise State University, Boise, ID, USA*

ABSTRACT: In the U.S. Mountain West, climate change is increasing the duration and severity of drought, as well as the frequency of extreme weather events. Although snow forms a primary water source for the region, broad, distributed estimates of snow water equivalent remain out of reach, negatively impacting water forecasting and supply. The US Army Corps of Engineers manages a network of reservoirs in the US for flood risk reduction and drought resiliency. Through the new strategic Research and Development (R&D) program, the agency will be improving consistency and accuracy of how snow is included in reservoir operations. Initial efforts will focus on both data collection and assimilation in models. Here we will give an overarching view of the R&D program as well as our pilot study using lidar, radar and machine learning to understand snowpack distributions at the watershed scale.

KEYWORDS: Snow properties, lidar, complex terrain.

1. INTRODUCTION

The US Army Corps of Engineers (USACE) mission is to build and maintain infrastructure with environmental sustainability. The Civil Works Research and Development Area concentrates on water-resource development including flood control, navigation, recreation, environmental stewardship and coastal storm processes and protection. USACE research is growing, especially long-range strategic efforts, adding breadth to more tactical, short-term programs that exist today. The strategic R&D program contains six focus areas including: ecosystems, infrastructure, sediment management, water modeling, crises mitigation and data analytics. Each focus area takes a different approach to developing long-lasting solutions to today's biggest problems including climate change resilience, infrastructure modernization and accelerated decision-making. For example, can coupled physical and economic models provide better predictions of hurricane damage and increase efficiency and effectiveness of a post-storm response?

Proposals to incorporate snow science in the strategic R&D program include a rain-on-snow effort within crises response and better understanding of snow property distributions for water resource planning and execution within the water modeling focus area. The intent of the Water Modeling focus area is to build an integrated Earth observations platform that leads to an improved inter-agency national simulation framework. Each intention helps to inform support risk-informed decision making while considering social and environmental justice aspects of decision making. Snow is an important flood driver, and knowledge gaps surrounding widescale snow property estimates in a non-stationary climate (e.g., Lundquist et al., 2021) must be resolved to optimize water storage during potential flood events.

Today's floods are complex with compound drivers. Climate warming and the associated increase in precipitation variability challenge traditional methods of predicting the magnitude and extent of flood events (e.g., Pirani and Najafi, 2020; Zscheischler et al., 2020; Brunner and Fischer, 2022). In coastal regions, sea level rise further limits predictions during storm surges, which may be compounded by inland forcing (e.g., snow melt). Finally, the expanded built environment and flood feedbacks (e.g., poorly mapped storm drain systems) increase uncertainty in flood prediction. Of particular interest to USACE are flood-drought linkages, including the interaction between soil properties and snow melt following wildfire. Better understanding the interactions among fire, forests, soil and snow are needed to predict when and where flood hazards are most likely.

2. INFORMING SNOW-WATER STORAGE

Snow forms the largest seasonal reservoir in the western US (e.g., Siirila-Woodburn et al., 2021), strongly motivating snow water equivalent (SWE) estimates for operational water resources (e.g., Painter et al., 2016). When calculating SWE in complex mountains terrain, multiscale variability of both snow depth and density necessitate assumptions that remain challenging to quantitatively assess (Seyfried and Wilcox, 1995; Meyer et al., 2022). To date, the large variability of snow properties prevents extrapolation of point or sparse measurements, requiring logistically-expensive continuous, fine-resolution observations to accurately estimate SWE (Hedrick et al., 2018).

* *Corresponding author address:*
Shad O'Neel, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory Boise, ID 83703;
tel: +1 907-529-4010 email: shad.r.oneel@erdc.dren.mil

Ongoing and proposed snow research at USACE focuses on improving confidence in snow property estimates at the basin scale for operational resilience. We began producing time-series airborne lidar observations of snow depth at the basin scale during 2021. Figure 1 shows our study domain in the Mores Creek headwaters of Idaho's Boise Mountains. This area has been surveyed 7 times during snow on conditions and once under snow free conditions. Surveys cover approximately 30 km^2 of the Mores Creek headwaters area that feeds into the USACE-managed Lucky Peak Reservoir. The domain spans roughly 600 m in elevation, with steep, dissected terrain. Conifer forest covers a majority of the landscape, and about half of the domain burned during summer 2016. We target 30-40 points m^{-2} with the lidar, and collect RGB imagery with some flights. Ground-based radar data collection has occurred twice, and validation (depth probe) measurements occur to the extent possible with each flight.

To date, we have focused on automated data processing and uncertainty assessment alongside first order analyses of snow pack distribution and post-fire impacts on the snowpack. Snow depth maps from three of the lidar acquisitions are shown in Figure 2, with a broad view of the domain at peak snow shown in Figure 3. We developed a co-registration approach that leverages the plowed highway that runs through the domain (Figure 2). Surveys of control surfaces within the domain are repeatable at sub-decimeter levels after iterative closest point co-registration (Zhang et al., 2015). Even though the validation approach samples a much smaller ground footprint (1 cm2 vs >1m2), snow depths using the two approaches correlate with r values greater than 0.8 and average root mean squared error of 18cm (Figure 4).

Snow depth varies as a function of elevation, aspect and wildfire occurrence. During mid-winter when solar radiation is low and temperatures tend to stay below freezing, elevation and burn exhibit the strongest controls on snow depth. Because the fire occurred more than 5 years ago, surface soot is minimal, and fire impacts appear to be more related to loss of the canopy than albedo. Less snow is intercepted by the canopy and snow depths in burned areas tend to be 10% or more deeper than in unburned areas (Figure 5). As the days lengthen and temperatures warm, aspect dependencies increase, and in areas of thin snow, depths in unburned areas exceed those in burned zones. This is likely due to canopy shading preventing melting and slowing compaction.

Our ongoing work emphasizes data stream integration for both optical imagery and GPR. Imagery processed using Structure from Motion (Westoby et al., 2012; Meyer et al., 2022) can be used to gap fill point clouds. Addition of color can improve ground classification and control. When combined with a snow surface constraint from Lidar, radar profiles provide information related to density variability. Both of these techniques are being used to inform extrapolation of sparse data in complex topography. These data allow us to constrain and inform runoff models using snow properties. Planned model comparison experiments will inform sampling requirements in the intermountain snow climate.

3. SUMMARY

USACE snow research efforts are beginning to expand through the initiation of a Civil Works Strategic R&D program. This program will foster applied water-resources research with 3- to 10-year lifecycles. Proposed snow research will expand on pilot time-series studies of snow depth distributions in Idaho's Boise Mountains. Analyses seek to better understand lidar uncertainty in complex topography, integrate sensors to resolve snow density and ultimately to constrain runoff models used to predict reservoir infilling.

REFERENCES

Brunner, M. I. and Fischer, S.: Snow-influenced floods are more strongly connected in space than purely rainfall-driven floods, Environ. Res. Lett., 17, 104038, https://doi.org/10.1088/1748-9326/ac948f, 2022.

Hedrick, A. R., Marks, D., Havens, S., Robertson, M., Johnson, M., Sandusky, M., Marshall, H., Kormos, P. R., Bormann, K. J., and Painter, T. H.: Direct Insertion of NASA Airborne Snow Observatory-Derived Snow Depth Time Series Into the *iSnobal* Energy Balance Snow Model, Water Resources Research, 54, 8045–8063, https://doi.org/10.1029/2018WR023190, 2018.

Jalili Pirani, F. and Najafi, M. R.: Recent Trends in Individual and Multivariate Compound Flood Drivers in Canada's Coasts, Water Resour. Res., 56, https://doi.org/10.1029/2020WR027785, 2020.

Lundquist, J. D., Dickerson-Lange, S., Gutmann, E., Jonas, T., Lumbrazo, C., and Reynolds, D.: Snow interception modelling: Isolated observations have led to many land surface models lacking appropriate temperature sensitivities, Hydrological Processes, 35, e14274, https://doi.org/10.1002/hyp.14274, 2021.

Meyer, J., Deems, J. S., Bormann, K. J., Shean, D. E., and Skiles, S. M.: Mapping snow depth and volume at the alpine watershed scale from aerial imagery using Structure from Motion, Front. Earth Sci., 10, 989792, https://doi.org/10.3389/feart.2022.989792, 2022.

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., and Winstral, A.: The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo, Remote Sensing of Environment, 184, 139–152, https://doi.org/10.1016/j.rse.2016.06.018, 2016.

Seyfried, M. S. and Wilcox, B. P.: Scale and the Nature of Spatial Variability: Field Examples Having Implications for Hydrologic Modeling, Water Resour. Res., 31, 173–184, https://doi.org/10.1029/94WR02025, 1995.

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., Nico, P. S., Feldman, D. R., Jones, A. D., Collins, W. D., and Kaatz, L.: A low-to-no snow future and its impacts on water resources in the western United States, Nat Rev Earth Environ, 2, 800–819, https://doi.org/10.1038/s43017-021-00219-y, 2021.

Westoby, M., Brasington, J., Glasser, N., Hambrey, M., and Reynolds, J.: ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology, 179, 300–314, https://doi.org/10.1016/j.geomorph.2012.08.021, 2012.

Zhang, X., Glennie, C., and Kusari, A.: Change Detection From Differential Airborne LiDAR Using a Weighted Anisotropic Iterative Closest Point Algorithm, IEEE J. Sel. Top. Appl. Earth Observations Remote Sensing, 8, 3338–3346, https://doi.org/10.1109/JSTARS.2015.2398317, 2015.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., Van Den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N., Thiery, W., and Vignotto, E.: A typology of compound weather and climate events, Nat Rev Earth Environ, 1, 333–347, https://doi.org/10.1038/s43017-020-0060-z, 2020.

4. FIGURES

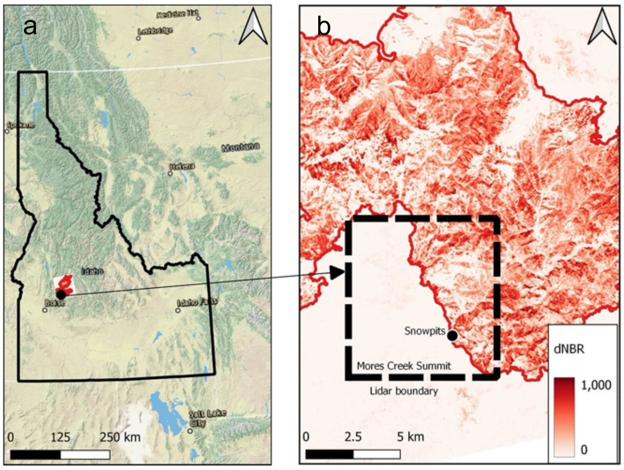

Figure 1: Location of Mores Creek Headwaters relative to the state of Idaho (a), and expanded in (b), where red indicates wildfire severity using Difference in Normalized Burn Ratio (dNBR;) available from Monitoring Trends and Burn Severity (mtbs.gov) for the 2016 Pioneer Fire that impacted the study site. The black dot marks the location of the Mores Creek Summit Snotel.

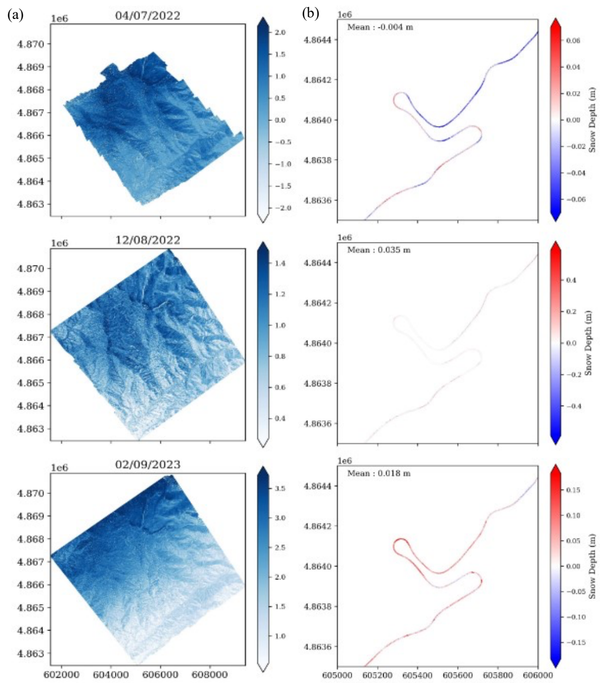

Figure 2. Timeseries of LiDAR derived snow depth maps. (a): Snow depth maps for the domain outlined in Figure 1. (b): Snow depth clipped to the highway. Near-zero differences along Highway 21 in the lower region of the domain indicate a successful co-registration with the snow-free reference map.

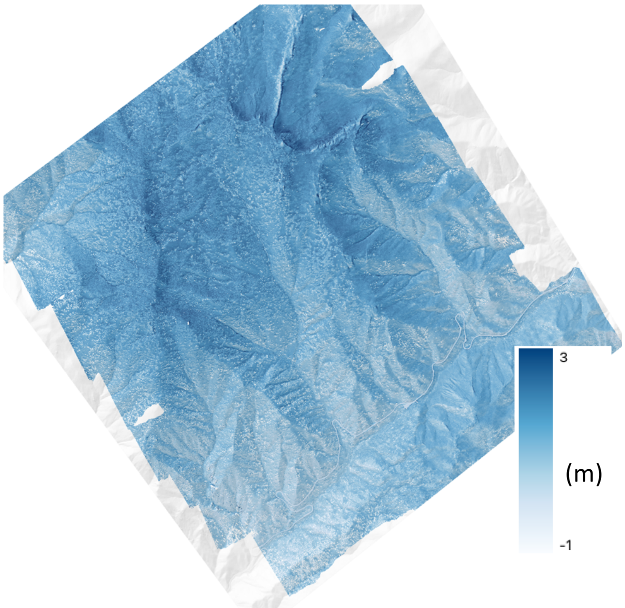

Figure 3. Snow depth (7 April 2022) in meters draped over topography revealing elevation and aspect dependencies.

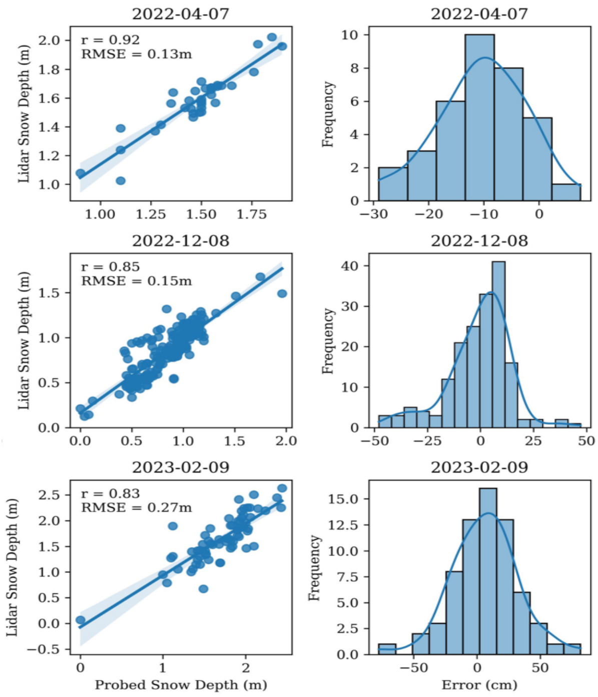

Figure 4. Scatter plots of lidar and probed snow depths (left panels) for the same flights as shown in Figure 2. The right panels show histograms of the same validation data.

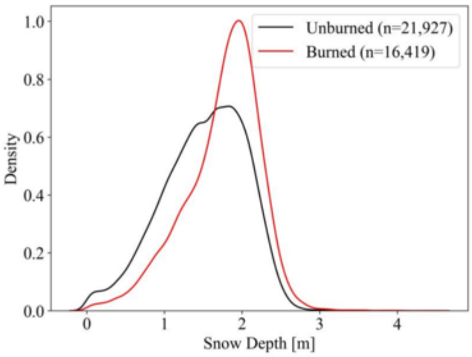

Figure 5. Probability density function of snow depths partitioned into burned and unburned pixels on 16 March, 2023 showing that depths in burned areas exceed those in unburned areas in deep snow locations. Where snow cover is thin the opposite is true, with unburned forest exhibiting deeper snow.

ACKNOWLEDGEMENT

Thank you to all the volunteers contributing to make the validation efforts for this project successful.