PHOTOGRAMMETRICALLY DERIVED ESTIMATES OF SNOW DEPTH VARIABILITY IN COMPLEX TERRAIN

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ABSTRACT: Seasonal snow is a key cryospheric variable because of its influence on energy and water budgets, regional economies, and public safety. Quantitative information on the spatial distribution of snow depth and snow water equivalence (SWE) is central to numerous applications in cryospheric research. However, in complex terrain, strong orographic gradients and wind redistribution produce complicated accumulation patterns that are difficult to capture using traditional in situ and satellite-based approaches, and are challenging to model with acceptable levels of uncertainty. Here we present results from a pilot study where we apply a repeat airborne photogrammetric approach and employ a Structure from Motion (SfM) processing method to generate digital surface models (DSMs) of terrain during snow-free (fall 2014) and snow-covered (spring 2015) periods. Surface elevation differencing of these datasets produces continuous and accurate maps of end-of-winter snow depth variability over complex terrain in the maritime-continental transition zone of the eastern Chugach Mountains, Alaska, and provides valuable data for assessing avalanche susceptibility and modeling avalanche runout.

KEYWORDS: snow depth, spatial variability, photogrammetry, structure from motion, avalanche, Alaska

1. INTRODUCTION

Quantitative information on the spatiotemporal distribution of snow and water storage in complex terrain is important for understanding ecosystem health and function, water supply and resources, water management strategies, validation of model-derived products, climate change, and hazard forecasting and mitigation strategies for floods and avalanches, among many other important issues (Serreze et al., 1999, Jonas et al., 2009, Scalzitti et al., 2016). Many studies report exceptionally high spatial variability of snow depth over small distances in alpine terrain (Grünewald et al., 2010). Such high snow depth variability can complicate catchment and watershed scale mass storage and runoff simulations, and in avalanche starting zones it can have a strong influence on avalanche formation, character, and magnitude (Schweizer et al., 2003; 2008).

In Alaska, few direct measurements of catchment scale snow depth variability exist. In most cases snow depth distribution is assessed based on a small number of discrete (point) measurements determined by manual soundings, snow pit wall height, or automated stations (e.g. snow telemetry (SNOTEL) sites in the United States), leading to an inadequate characterization of the variability in snow accumulation.

In this paper, we present results from a pilot study where we employ modern airborne photogrammetric surveying methods to generate digital surface models (DSMs) from which we derive spatially continuous and accurate maps of the magnitude and variability of snow depth in the Thompson Pass area of the eastern Chugach Mountains, east of Valdez, Alaska (Fig. 1).

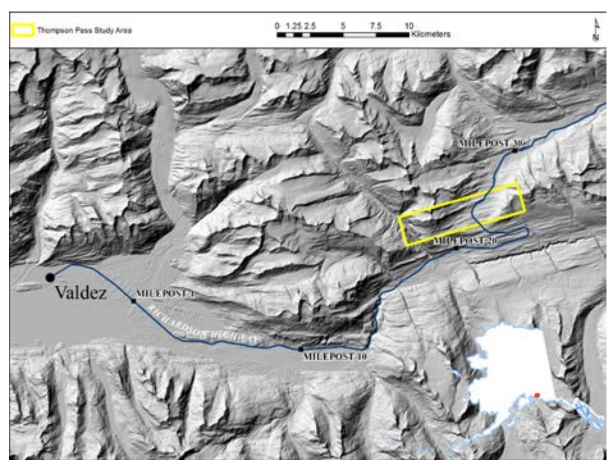

Fig. 1: Eastern Chugach Mountains, Alaska and Thompson Pass study area (yellow).

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2. METHODS

We conducted two airborne photogrammetric surveys from which we generated high resolution orthoimages and DSMs. Both surveys used a GNSS-linked Nikon D800 DSLR camera with a AF-Nikkor 28 mm lens. The first epoch of images was acquired in fall 2014 (snow-free) using a fixed-wing platform at a 1900 m mean flying height, yielding a 0.38 m ground sample distance (GSD). The second epoch of images was acquired in spring 2015 (snow-covered, end-of-winter) using a helicopter platform at a 1700 m mean flying height, producing a 0.30 m GSD.

Overlapping aerial photographs from each epoch were imported separately into the commercially available Agisoft Photoscan Professional software. This photogrammetric software uses a structure from motion algorithm to identify matching pixels in overlapping photographs and triangulate their common ground position to create a 3-dimensional point cloud (x, y, z coordinates) that defines the ground surface. The registered point clouds were used to orthorectify the image mosaics from each epoch (Fig. 2), and were interpolated to a 2.0 m grid to produce DSMs optimized both for processing efficiency and micro-topographic smoothing (Fig. 3).

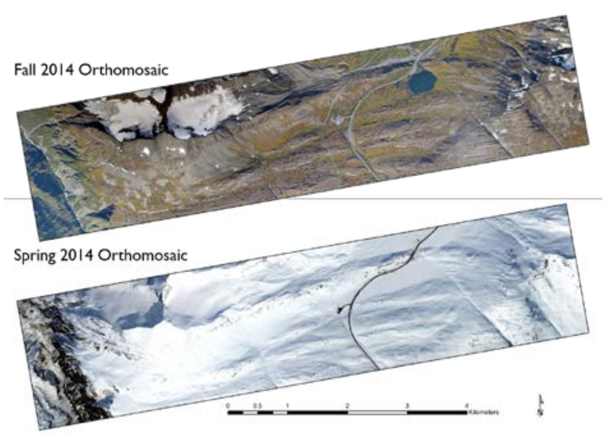

Fig. 2: Fall 2014 and spring 2015 orthoimage mosaics.

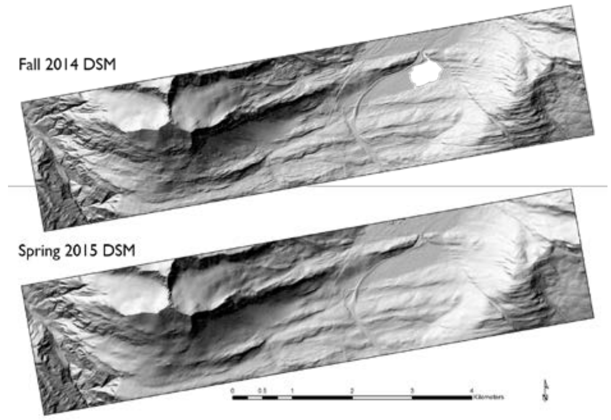

Fig. 3: Fall 2014 and spring 2015 DSMs.

End-of-winter snow depths (HS) were determined by subtracting the fall 2014 DSM (snow-free) from the spring 2015 DSM (snow-covered; Fig. 4). The resultant raw difference DSM (dDSM) was then masked to exclude trees and shrubs, resulting in a map of snow depths in the alpine sector of the 20 km^2 study area (Fig. 5).

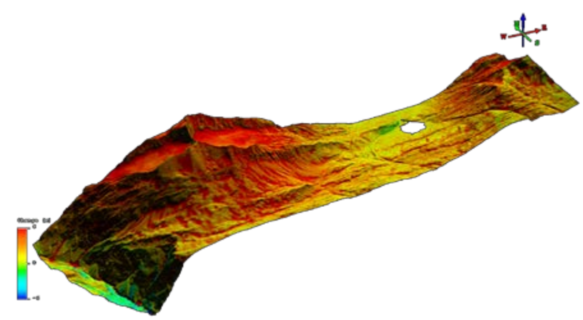

Fig. 4: Oblique view of raw dDSM, determined by subtracting the fall 2014 DSM (snow-free) from the spring 2015 DSM (snow-covered). Color gradient scale saturates at +6 m and -6 m to better illustrate HS variability. Negative values correspond to subalpine and montane trees and shrubs.

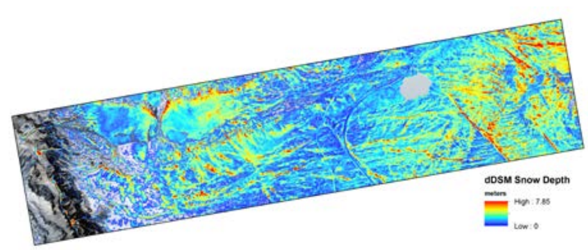

Fig. 5: End-of-winter snow depths (HS) in alpine terrain. Color gradient scale saturates at 7.85 m (2 standard deviations) to better illustrate HS variability.

Snow depth validation measurements were carried out concurrently with airborne photogrammetry. We compared more than 176 citizen-scientist and research personnel observations with the photogrammetrically derived maps, providing crucial validation information which we used to constrain uncertainties in the airborne product (RMSE = 0.18 m).

3. RESULTS AND DISCUSSION

The photogrammetry-derived products reveal the high spatial variability of HS in the study area (Fig. 4 and 5). End-of-winter snow depths in the study area range from zero over wind-scoured areas to nearly 10.0 m in the wind-loaded, lee-side of arêtes. In some avalanche runout debris cones, snow depths exceeded 12.0 m.

Topography appears to be a major influence on snow depth variability at multiple scales. At the study area scale, orographic effects dominate HS distribution, while at the catchment and local scales this signal is modulated strongly by topography-enhanced wind redistribution effects.

The spatially continuous HS maps provide a unique dataset for assessing avalanche distribution, behavior, and susceptibility. Mass transfer, through the process of avalanching, is visible on many slopes throughout the study area, and recent avalanches are particularly apparent on south-facing slopes (Fig. 4). Equally apparent are significant avalanche hazards, i.e. pockets of high snow accumulation perched on steep, south-facing slopes that had not released at the time of the photogrammetric survey.

4. CONCLUSIONS AND FUTURE WORK

In this pilot study we assess the variability of snow depth over complex terrain in the maritime-continental transition zone of the eastern Chugach Mountains, Alaska. We use repeat airborne surveying techniques and structure from motion photogrammetric methods to produce DSMs of snow-free and snow-covered land surfaces. By differencing these surfaces we generate spatially continuous maps of snow depth over 20 km^2.

Our results show snow depth in the Thompson Pass study area is highly variable (0 to >12 m), and is controlled by orographic gradients and wind redistribution patterns that are strongly dependent on topographic complexity at multiple scales.

This study provides valuable information for assessing avalanche susceptibility and modeling avalanche runout in areas that are challenging to access and have limited data. Future work is focusing on resolution-accuracy improvements, economy of scale analyses for future operational acquisitions, and utilizing photogrammetrically derived datasets to improve avalanche modeling in Alaska.

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