CLASSIFYING FOREST-EDGE SNOW DEPTH VARIABILITY IN MULTIPLE CLIMATES

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EXTENDED ABSTRACT

Forest shading, scour, and wind related deposition result in significant snow depth variability between different sides of the forest edge (Broxton et al., 2015; Church, 1933; Geddes et al., 2005; Hiemstra et al., 2002, 2006; Marr, 1977; Musselman et al., 2008). The net effect of these physical snow processes is greater snow accumulation and longer snow retention on either leeward or north-facing forest edges (Golding & Swanson, 1978; Hiemstra et al., 2002, 2006; Lawler & Link, 2011; Tabler, 2003). Understanding the dominant modes of snow depth variability between forest-edges as a result of these physical processes is valuable when predicting watershed scale processes including streamflow magnitude, timing, and temperature, particularly during late summer flows (Clark et al., 2011; Leach & Moore, 2014; Luce et al., 1998, 1999; Lundquist et al., 2005; Lundquist & Dettinger, 2005; Sun et al., 2018).

Due to the unique physical interactions between the forest, atmosphere, and snowpack at forest-edges, snow depth differences between different sides of the forest edge were analyzed in Olympic National Park, WA; Tuolumne River Watershed, CA; Jemez Caldera, NM; and the Boulder Creek Watershed, CO. Within each location, canopy height models (CHM), digital elevation models (DEM), and wind direction data were used to classify four 1000-m by 1000-m snow depth domains into areas that are either forested (CHM > 2 m), along the forest edge, or in exposed areas. Forest edges and exposed classifications were sub-classified based on wind and solar direction to provide six different classifications (Figure 1). Differences between median snow depth values from different forest-edge classifications were then compared to differences between median snow depth values for different slope classifications and between exposed and forested areas (Table 1).

Forest-edge classifications were classified as either north-facing edge or leeward facing edge and as south-facing edge or windward facing edge of the forest depending on whether the classifications were based on the solar exposure or most frequent wind direction. Forest-edge classifications based on solar direction searched out north and south of the forest. The search distance was based on both the tree height (H) from an individual grid cell within the canopy height model and literature values that showed a range in the expected extent of forest shading (Golding & Swanson, 1978; Lawler & Link, 2011; Musselman et al., 2015; Seyednasrollah & Kumar, 2014). North and south-facing forest edges were thus classified using forest-edge search distances of 0.5, 1, 2, and 3 H. Similarly, a range of values based on the literature were used to classify leeward and windward classifications: 1, 3, 6, and 10 H (Brandle, J.R., Finch, 1991; Hiemstra et al., 2002, 2006; Tabler, 2003). Areas where the two-opposite forest edges overlapped (e.g. north and south-facing forest edges) were classified as overlapping forest edges. Lastly, exposed areas (areas not beneath the canopy or along the forest edges) were sub-classified as either north-facing slopes or leeward slopes, and these were compared to south-facing or windward slope classifications, respectively.

In Olympic National Park, WA, the Northwest Modeling Consortium (Mass et al., 2003) provided wind speed and wind direction data from the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) at a spatial resolution of 1.33 km. In Tuolumne, CA wind speed and wind direction was simulated using WRF at a 4-km spatial resolution by Mimi Hughes (Hughes et al., 2017). The 4-km WRF wind direction and wind speed data were downscaled using Micromet (Liston & Elder, 2006) with a 250-m DEM. Wind data at Jemez, NM were provided by the Valles Caldera Mixed Conifer eddy covariance tower (Ameriflux US-Vcm), while at Boulder Creek, CO wind data were provided from the Niwot eddy covariance tower (Ameriflux site NR1).

At Boulder Creek, CO, we found that there were statistically significant snow depth differences between leeward and windward forest edges but not between north and south-facing forest edges. On average, across the four sites, the difference between the median snow depth value for leeward forest edges differed the most from windward forest edges when the forest-edge search distance was 6H. At this search distance, the median snow depth value for leeward forest-edges was 38% higher than the median snow depth value for windward forest edges (Table 1).

Paper presented Western Snow Conference 2018

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Snow depth differences at Boulder Creek, CO were likely the result of cold mean winter temperatures (-5 – -10°C), significant wind speeds (>10-12 m s^{-1}), and the forest distribution. The four Boulder Creek sites were located in a krummholz environment that contained ribbon forest (Billings, 1969; Hiemstra et al., 2002, 2006; Liston, 1999), which served as wind breaks (Brandle, J.R., Finch, 1991), and therefore caused the preferential deposition of snow on leeward forest edges. We hypothesize that the preferential deposition of snow on leeward forest edges was from both freshly falling snow and from upwind scouring. We note that the difference between median snow depth values for leeward and windward forest edges was greater than the difference between exposed and forested classifications (Table 1). This implies that within these areas, wind related deposition influenced by the forest causes greater snow depth variability than forest-snow interception and subsequent sublimation. Furthermore, these results suggest that in forested areas with similar meteorology to Boulder Creek, forest managers could maximize snow retention by altering the forest to serve as windbreaks (Brandle, J.R., Finch, 1991; Brandle & Nickerson, n.d.; Tabler, 2003).

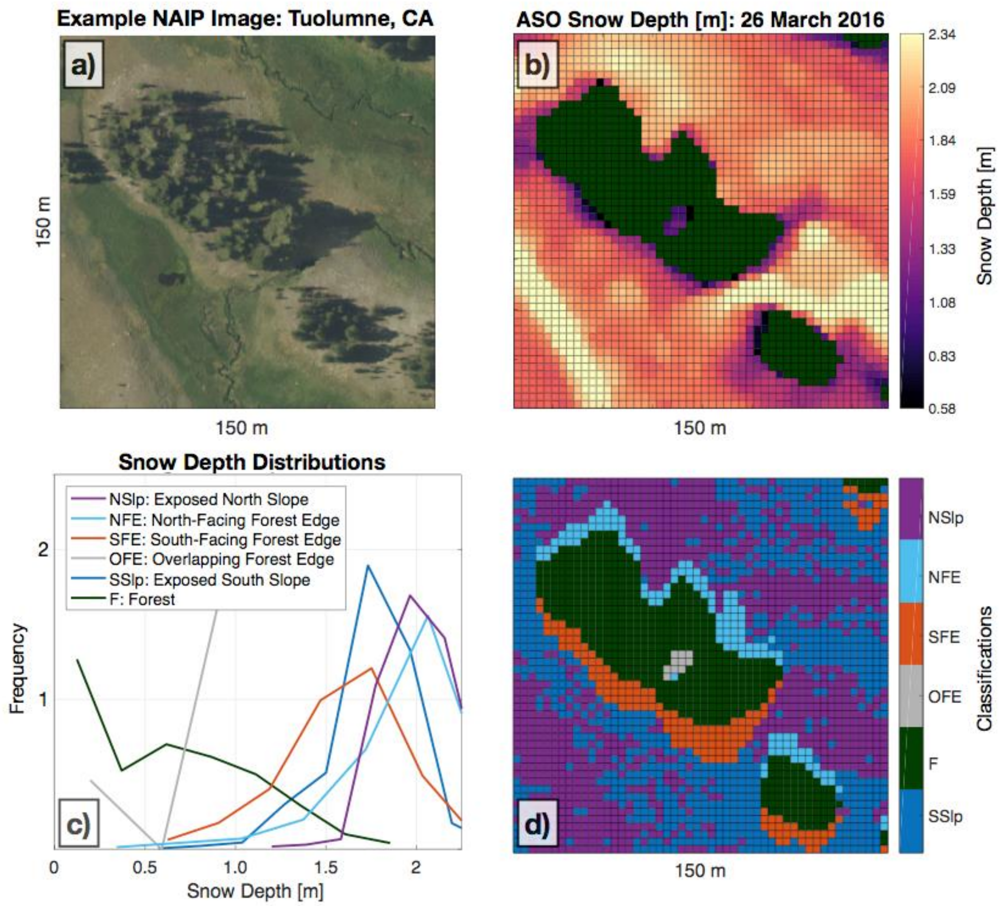

Figure 1. Conceptual diagram showing the six different classifications for a 150-m domain in Tuolumne CA. a.) National Agriculture Imagery Program (NAIP) aerial image from 25 June 2016 in Dana Meadows, Tuolumne, CA. b.) Airborne Snow Observatory (ASO) gridded snow depth (3 m) data (Painter et al., 2016). Dark green shading represents forested areas. c.) Snow depth distributions for the six classifications. d.) Classification of regions within a 150-m domain based on the CHM and DEM. In this example, the length of the forest edge was at 2 H. Acronyms are defined within the snow depth distributions legend. Figure is adapted from Currier and Lundquist 2018.

In the Olympic Mountains, wind speeds were similar to Boulder Creek, but snow depth differences between forest edges were not significantly different between north and south-facing forest edges or leeward and windward forest edges. This was likely due to mean winter temperatures near 0°C, which resulted in a relatively wet and dense snowpack that could generally resist scour (LaChapelle, 1958; Li & Pomeroy, 1997). Furthermore, the four sites in the Olympic Mountains did not contain ribbon forests. The greatest variability in the Olympic

Mountains was between exposed and forested areas and between different slopes aspects (Table 1). Therefore, in the Olympic Mountains, snow depth variability was likely the result of forest-snow interception and subsequent melt (Dickerson-Lange et al., 2017; Martin et al., 2013; Storck et al., 2002) as well as preferential deposition of freshly fallen snow across topographic ridges.

Consistent with previous studies, forest shading likely caused statistically significant differences between north and south-facing forest edges at Jemez, NM (Musselman et al., 2008; Veatch et al., 2009). At Jemez, NM, the greatest difference between north and south-facing forest edges was when the forest-edge search distance was at 1H. At this forest-edge search distance, the difference between median snow depth values for north-facing forest edge classifications and south-facing forest edge classifications was 32% on average across all four sites (Table 1). When Jemez forest edges were based on the most frequent wind direction, the snow depth differences were less than or equal to 2%, which was likely the result of relatively low wind speeds (< 8 m s^{-1}). The difference between the median snow depth values for north and south-facing forest edges was similar to the differences between north and south-facing slopes, as well as between exposed and forest classifications (Table 1). This implies that at Jemez, NM, forest shading has a similar degree of influence on snow depth variability than forest-snow processes, which affect snow depth underneath the forest or radiative differences that affect the snow depth differences between slope aspects.

Table 1. Median Snow Depth Differences: The snow depth difference or percent difference between median values for different forest-edge classifications, slope classifications, and between exposed and forested areas. The mean difference from the four domains within each different location was reported. Percent differences were normalized by the median snow depth value for the entire domain. This table has been adapted from Currier and Lundquist 2018.

Location	**North vs. South[a] Forest-Edge Difference [cm/%]**	**Leeward vs. Windward[b] Forest-Edge Difference [cm/%]**	**Exposed vs. Forested Difference [cm/%]**	**North vs. South Slope Difference [cm/%]**	**Leeward vs. Windward Slope Difference [cm/%]**
Boulder Creek, CO *(0.5 H[a] and 6 H[b])*	18 13%	57 38%[+]	32 17%[+]	26 17%	87 53%[+]
Olympic Mountains, WA *(0.5 H[a] and 3 H[b])*	22 11%	29 13%	126 55%[+]	93 48%[+]	148 81%[+]
Jemez, NM *1 H[a] and 1 H[b])*	31 32%[+]	1 2%	19 29%[+]	19 28%[+]	6 8%
Tuolumne, CA* *(2 H[a] and 1 H[b])*	21 14%*	13 8%	25 16%	32 19%[+]	19 12%[+]

* Results between north and south-facing forest edges were statistically significant at two of the four locations where the area was not shaded from the surrounding topography.

[+] The snow depth differences between classifications were statistically significant. See Currier and Lundquist for more details.

[a] North and south-facing forest-edge search distances that provided the greatest difference in median snow depth values.

[b] Leeward and windward forest-edge search distances that provided the greatest difference in median snow depth values.

Tuolumne, CA differed by about two degrees of latitude and had similar incoming solar radiation magnitudes as Jemez, NM, but only two of the four sites contained significant snow depth differences between north and south-facing forest edges. The two Tuolumne sites without significant snow depth differences at the forest edge received less direct solar radiation due to topographic shading from mountains outside the examined 1000-m domain. For instance, on 1 February, at two of the Tuolumne sites, the sun was beneath the horizon angle 30% and 40% of the daylight hours, while at the two other sites in Tuolumne and at all the sites in Jemez, NM, the sun was beneath the horizon angle less than 10% of the daylight hours. We note that at the two sites in Tuolumne without significant topographic shading from areas outside the domain, the difference between median snow depth values for north and south-facing forest edge classifications was 14% and 31%, which is similar to results found at Jemez. Here, the difference between median snow depth values for north and south-facing forest edges were greater than or equal to snow depth differences between slopes and between exposed and forested areas. Therefore, results in regions with significant amounts of direct solar radiation suggest that the forest could be managed to maximize forest-shading, which had its most significant effect on snow retention between 1-2 H.

Snow depth variability between forest edges was likely a result of a combination between the area's mean winter temperature, incoming solar radiation, wind speed, forest architecture and nearby topography, all of which change within a watershed. At Jemez, Boulder Creek, and Tuolumne, snow depth differences between forest edges were statistically significant and greater than or equal to differences between exposed and forested areas. This implies that snow depth variability between forest edge classifications was similar to snow depth variability between classifications used in hydrologic models that capture sub-element snow depth variability (e.g. exposed and forested areas).

This extended abstract is a modified and shortened version of Currier and Lundquist (2018). We gratefully acknowledge funding support from a NASA Earth and Space Sciences Fellowship, Grant NNX16AO02H. Jessica D. Lundquist was supported by NSF Grant CBET-1703663. We would also like to thank Tom Painter and Kathryn Bormann for providing ASO data in the Olympic Mountains, WA and the Tuolumne River Watershed, CA. Furthermore, we want to thank NCALM for the airborne lidar data at Jemez Caldera, NM and the Boulder Creek Watershed, CO. (KEYWORDS: forest edges, forest, snow depth variability).

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