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Snow cover variability in a forest ecotone of the Oregon Cascades via MODIS Terra products

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ABSTRACT

Snow cover pattern and persistence have important implications for planetary energy balance, climate sensitivity to forcings, and vegetation structure, function, and composition. Variability in snow cover within mountainous regions of the Pacific Northwest, USA is attributable to a combination of anthropogenic climate change and climate oscillations. However, snow covered areas can be heterogeneous and patchy, requiring more detailed mapping of snow trends to understand their potential influences on montane forests. We used standard daily MODIS snow products (MOD10A1.5) to investigate the 15-year record (2000–2014) of snow cover in the predominant forest ecotone of the Oregon Western Cascades. We modeled the ecotone using field data from the H.J. Andrews Experimental Forest, and only considered forested MODIS Terra pixels located within the mapped ecotone of a five-county region. Three snow cover metrics were developed using both binary and fractional snow cover data: mean ecotone snow cover percent, number of snow covered days during the melt season, and day of snow disappearance. Snow cover and depletion dates exhibited large interannual variability and no significant linear trends. This variability is likely influenced by the preceding wintertime states of the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation (ENSO), which tend to covary. We improve and generalize existing methods for power analysis of trend estimation and quantify the number of uninterrupted observations of the snow metrics that would be needed to distinguish trends of different magnitudes from noise variance, taking possible autocorrelation into account. Sensitivity analyses of the results to some of our heuristic choices are conducted, and challenges associated with optical remote sensing of snow in a dense montane forest are discussed.

1. Introduction and background

Global increases in surface temperature have direct and indirect implications for the hydrological cycle. Anthropogenic changes in radiative forcing affect precipitation (including changes in amount, frequency, timing, and type), evaporation, and sensible heat transfer at the Earth's surface (IPCC, 2013). Even relatively small changes in temperatures can have large effects on the hydrologic cycle including alterations to soil moisture, drought, and flooding regimes (Barnett, Adam, & Lettenmaier, 2005; USGCRP, 2000). More than one-sixth of the world's population depends on glaciers or seasonal snow for their available water, and these supplies are at significant risk as a consequence of a warming climate (Barnett et al., 2005). Snowmelt runoff dominates the hydrologic cycle in mountainous regions of the western USA, where significant portions of annual precipitation fall as snow (Serreze, Clark, Armstrong, McGinnis, & Pulwarty, 1999). Although snow telemetry (SNOTEL) data provide empirical evidence for decreasing trends in snow water equivalent (SWE) within the Pacific Northwest in recent decades (Mote, 2003; Mote, Hamlet, Clark, & Lettenmaier, 2005), model projections for future changes in winter precipitation as a consequence of anthropogenic warming are more equivocal (Mote & Salathé, 2010).

Annual variability in snow can also be influenced by climate oscillation modes associated with ocean–atmosphere couplings such as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Hamlet & Lettenmaier, 2007). In the Pacific Northwest, variability in ocean circulation patterns over the last 25,000 years can explain significant variation in coastal fog and sediment transport (Briles, Whitlock, Bartlein, & Higuera, 2008; Long & Whitlock, 2002; Van Laningham, Duncan, Pisias, & Graham, 2008). Over the past two centuries, streamflow in the Columbia River has been as sensitive to these teleconnections as to the considerable water withdrawal for irrigation in the basin (Naik & Jay, 2011), and the strength of these linkages has increased in the 20th century (Gedalof, Peterson, & Mantua, 2004). The PDO and ENSO are an important source of decadal-scale climate variability throughout the Pacific Northwest (Abatzoglou, Rupp, & Mote,

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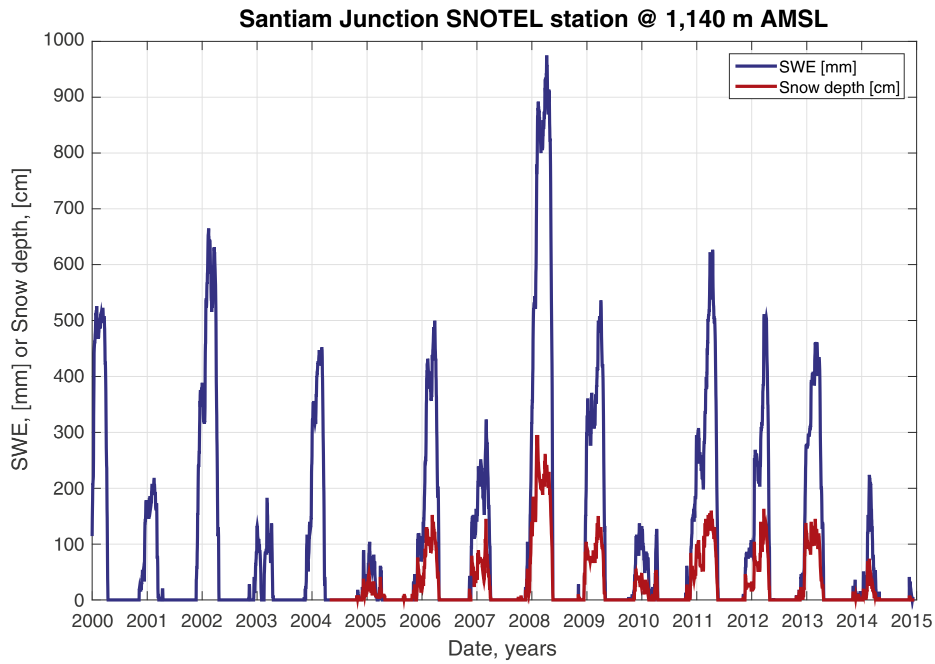

Fig. 1. Santiam Junction SNOTEL site snow water equivalent (SWE) in mm (blue curve) and snow depth in cm (red curve). See Fig. 2B or Fig. 3 for the SNOTEL station location (red diamond). AMSL = above mean sea level.

2014; Cayan, Dettinger, Diaz, & Graham, 1998; Dettinger, Cayan, Diaz, & Meko, 1998; Wise, 2010), with warm-phase PDO and El-Niño years tending to be warmer and drier than average and cold-phase PDO and La-Niña years tending to be colder and wetter than average; these effects are generally additive and get amplified when PDO and ENSO are in phase (Climate Impacts Group, 2014a; Hamlet & Lettenmaier, 1999).

Several studies have examined the relative contributions of global climate change trends and PDO/ENSO climate oscillations to snow dynamics in the mountains of the western US and determined that both have detectable signals (Moore, Holdsworth, & Alverson, 2002; Mote, 2006; Peng, Zhongbo, & Gautam, 2013). However, these studies typically provide inferences over large regions (Trujillo & Molotch, 2014) or use changes in streamflow as the response variable of interest, which aggregates snowmelt over entire basins (e.g., Stewart, Cayan, & Dettinger, 2005). Snow covered areas can be heterogeneous and patchy, varying over very small spatial scales, especially in forested and/or complex terrain (Lundquist & Lott, 2008; Raleigh et al., 2013). Many forest processes that are dependent on snow hydrology, such as seedling recruitment and mortality, operate at these finer functional scales (Dingman et al., 2013; Mori, Mizumachi, & Sprugel, 2008). For example, snow dynamics may be a key factor influencing the specifics of forest composition change within forest community ecotones of the Pacific Northwest (Lookingbill, Rocca, & Urban, 2011; Mori et al., 2008); however, snow variability has been poorly quantified at these local scales. Existing ground-based sensor networks such as SNOTEL (Serreze et al., 1999) indicate the high annual variability of snow cover (Fig. 1), but are generally too sparsely distributed to capture the fine spatial scales required for ecotone-level studies. No studies have been published in the region using remotely sensed snow products to evaluate snow trends within a specific forest community ecotone.

Remotely sensed data can provide the daily synoptic world-wide sampling at high spatial resolution required to track seasonal changes in forest snow cover (Nolin, 2010). Standard operational snow cover algorithms for the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors retrieve snow presence or absence (binary product) or fractional snow covered area (fSCA) using the visible and near-infrared (NIR) bands (Riggs, Hall, & Salomonson, 2006). Hall, Foster, DiGirolamo, and Riggs (2012) derived metrics of snow cover amount and timing of melt from ten years of MODIS data for the Wind River Range in Wyoming, USA and found a significant correlation with spring discharge in the basin. A similar approach could be used to develop ecologically relevant metrics for evaluating potential changes in snow condition at a forest community ecotone. Useful metrics would consider the relationship between the phenology of snow-tolerant species and the timing of melt (Mori et al., 2008). These metrics would allow the assessment of overall trends in snow cover and duration and the influence of PDO/ENSO climate oscillations on these trends. In addition, quantification of the inter-annual variance in snow cover metrics would allow the estimation of the record length required to distinguish statistically significant trends from noise.

Here, we use standard daily MODIS Terra binary and fSCA snow products for the 2000–2014 period to investigate snow cover variability in the western hemlock-true fir ecotone of the Oregon Western Cascades. We develop and compare three ecologically meaningful snow metrics using both data sets and map these metrics for MODIS Terra pixels located within the ecotone. We hypothesize that the annual variability in the metrics is associated with the state of the PDO and ENSO. To test this hypothesis, we divide the time series into wintertime warm, cold and neutral PDO/ENSO years and compare the snow metrics for the cold vs. the warm years using Wilcoxon rank-sum tests. We also investigate the linear correlation of PDO/ENSO indices with our metrics. We test for the presence of linear trends for the fifteen years of data and quantify noise variance in the data; we then generalize existing power analysis of trend estimation methods and use them to forecast the minimum length of record that would be required to detect long-term changes in snow cover for this ecotone.

2. Study area

2.1. Geographic setting

The study area comprises the Oregon Western Cascades within Clackamas, Marion, Linn, Lane and Douglas counties, eastwards of 123°7′40″W (Fig. 2). These counties were chosen because their