SNOW DENSITY OBSERVATIONS IN THE WASHINGTON CASCADES

J. E. Kay[1]

ABSTRACT

Density is a fundamental physical property of snow. Both the meteorological conditions during snowfall and snow pack processes affect snow density. As a result, field observations of snow density vary from 10 to 500 kgm^{-3}. Yet, conversion between snow water equivalence (SWE) and snow depth and modeling of snow processes is often accomplished using a fixed snow density of 100 kgm^{-3}. I use snow telemetry (SNOTEL) snow depth and snow water equivalent measurements to estimate snow density in the Washington Cascades, a "maritime", temperature-driven snow pack. Spot field measurements are used to validate the seasonal evolution of densities estimated from SNOTEL observations and to understand the vertical profile of snow density. Then, using visual inspection and principal components analysis (PCA), I document and compare the seasonal evolution and regional coherency of SWE and snow density. Specifically, I address: Can SNOTEL observations reveal seasonal and spatial patterns in snow density?, What is the regional coherency of SWE and snow density on seasonal timescales?, and How is snow density influenced by elevation and location in a cross barrier flow? .

INTRODUCTION

Alpine snow is of critical importance, especially when surface water runoff is dominated by snowmelt (e.g., Casola et al., 2005). Recently, observed reductions in alpine snow accumulation and earlier snow melt have been ascribed to increasing surface air temperature trends (Mote et al., 2003; Cayan et al., 2001). Surface air temperatures are projected to continue increasing throughout the Western USA (Coquard et al., 2004) and many researchers have suggested these temperature increases could reduce future snow accumulation (e.g., Leung et al. (2004)). Yet, quantitative prediction of seasonal snow evolution requires accurate representation of atmospheric circulation patterns, the precipitation processes producing snow in the atmosphere, and the seasonal evolution of snow on the ground. Our understanding snow processes both in the atmosphere and on the land surface is far from complete.

Snow density is a fundamental property of snow. A quantitative understanding of how and why new snow density varies should improve snow models and remote sensing observations of snow. In atmospheric models, snow density assumptions influence snow crystal sedimentation rates and can affect the quantity and spatial distribution of snow accumulation. Roebber et al. (2003) and Stoelinga et al. (2005) both suggest snowfall forecasting could be improved with a more detailed representation of snow density. Many atmospheric models only track snow mixing ratios and assume a fixed snow density. Xue et al. (2003) show that fixed snow density could produce as high as 100% error in estimating snow depth. Snow density affects snow stability, which is an

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[1] Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA, jenkay@u.washington.edu

important component of avalanche prediction models (Conway and Wilbur, 1999). Finally, snow density influences heat transfer in snow because snow thermal diffusivity depends on snow density. In snow models, fixed density assumptions can lead to significant SWE biases during the melting period (Xue et al., 2003). Thermal diffusivity, and therefore snow density, also affects passive microwave remote sensing of snow (Zwally, 1977).

Given these motivations to better understand and quantify snow evolution, I used field observations and snow telemetry (SNOTEL) observations to investigate variations in snow density and snow water equivalence in the Cascade Mountains of Washington State (USA). I focused on the following research questions:

1. Can SNOTEL observations reveal seasonal and spatial patterns in snow density?
2. What is the regional coherency of SWE and snow density on seasonal timescales?
3. How is snow density influenced by elevation and location in a cross barrier flow?

In this paper, I first describe the factors influencing snow density and introduce the Washington Cascades snow environment. Next, I discuss the methods I used to estimate snow density and evaluate spatial coherence in the Washington Cascades. Then, I present and discuss my snow density measurements and principal components analysis results. Finally, I state my conclusions and future work.

BACKGROUND

Factors Influencing Snow Density

Observed snow density reflects both processes occurring in the atmosphere and on the ground. Initially, snow density is determined by atmospheric processes. As snow remains on the ground, internal snow pack processes that are influenced by the atmosphere take control of snow density evolution.

Atmospheric temperature and water vapor super saturation affect snow density by controlling initial ice crystal habit, and processes such as riming, aggregation, melting, and sublimation (Wallace and Hobbs, 2006). For example, new snow density in the Central Rocky Mountains ranged from 10 to 257 kgm^{-3}; the smaller densities resulting from small unrimed stellar crystals and small clear plates, and larger densities corresponding with heavily rimed snow crystals and graupel (Judson and Doesken, 2000). In the Washington Olympic Mountains, LaChapelle (1969) found that heavily rimed needles only a few hours old had a density of 320 kgm^{-3}. Baxter et al. (2005) estimated snow density variations nationally using 30-year snow-to-liquid (SLR) ratios from the National Weather Service (NWS) Cooperative Summary of the Day (COOP) observations. They related regional variations in snow density to air mass moisture content.

After snow accumulates on the ground, snow density increases with time. This increase in density reflects snow settling and metamorphism (grain rounding), additional snow accumulation, and snow melting. The first stages of snow densification occur quickly, with the dominant mechanism being grain settling and packing (Herron and Langway, 1980). Destructive or equi-temperature metamorphism is complete when snow crystals have been reduced to rounded grains of ice with a density around 500-600 kg m^{-3} (LaChapelle, 1969). Destructive metamorphism rates are faster when snow temperatures are close to zero because even though temperature gradients are small, large vapor pressure gradients exist (due to exponential increases in the saturation vapor pressure with temperature). When water is present in the snow pack as melt or rain, metamorphism and densification rates increase.

Washington Cascades Snow Environment and Densities

The Washington Cascades are a North-South mountain range located 145-200 km inland from the Pacific Ocean. They range in elevation from 1220 to 3050 m and their presence induces strong zonal gradients in precipitation and temperature. In the winter, orographic lifting of moisture-laden marine air results in heavy rain and snowfall on the windward west-facing slopes. On the west-facing slopes, seasonally-averaged freezing levels are typically around 900 m and much of the snow falls at relatively warm temperatures. Riming of snow is common, especially during post-frontal showers (personal communication, John Locatelli). Isolated volcanic peaks including Mt. Rainier, Mt. Adams and Mt. Baker have extreme snowfall amounts. Mt. Baker set a world record for snowfall in 1998. East of the Cascade crest, the winter climate is more continental with colder temperatures and less snowfall.

Snow densities in the Cascades reflect the snow environment. Baxter et al. (2005) found a E-W gradient in density with larger densities West of the Cascade crest (mean ~100 kgm^{-3}) and smaller densities in the lee of the Cascades (mean ~77 kgm^{-3}). Although they are not common, new snow densities up to 300 kgm^{-3} have been observed at Steven's Pass, WA (LaChapelle, unpublished data). Once snow is on the ground, mild temperatures favor rapid densification through destructive metamorphism, settling, rain-on-snow events, and melting. Large snow amounts result in significant compaction and further snow densification. Rapid densification of snow has been observed after rainfall events in the Washington Cascades (Marshall et al., 1999). Due to these factors, measured snow densities are significantly larger than mean reported new snow density observations. For example, I measured average snow densities of 335-106 kgm^{-3} (mean-standard deviation), which are significantly larger than new snow densities (e.g., Baxter et al. (2005); median snow density 80 kgm^{-3} at Stevens Pass, WA (LaChapelle, unpublished data)).

FIELD AND ANALYSIS METHODS

Measurement Techniques

I used both field measurements and automated station data to estimate snow density in the Washington Cascades. I made field measurements of snow density in the vicinity of Snoqualmie Pass, WA (Figure 1). To derive the snow density profile, I measured the weight of a fixed snow volume (250 or 1000 cm^{-3}) throughout the vertical column of snow pits. Automated SNOTEL data provide a distributed measurements of both snow water equivalence (SWE) and snow depth throughout the Washington Cascades (Figure 1). To estimate the bulk snow density, I divided SNOTEL SWE by SNOTEL snow depth. As bulk snow density is a ratio, large variance in snow density results with small values of snow depths and SWE. Therefore, I only calculated snow density during the heart of the snow season (December 15 – March 31) and only when snow depths exceeded 10 cm and SWE exceeded 0.5 cm.

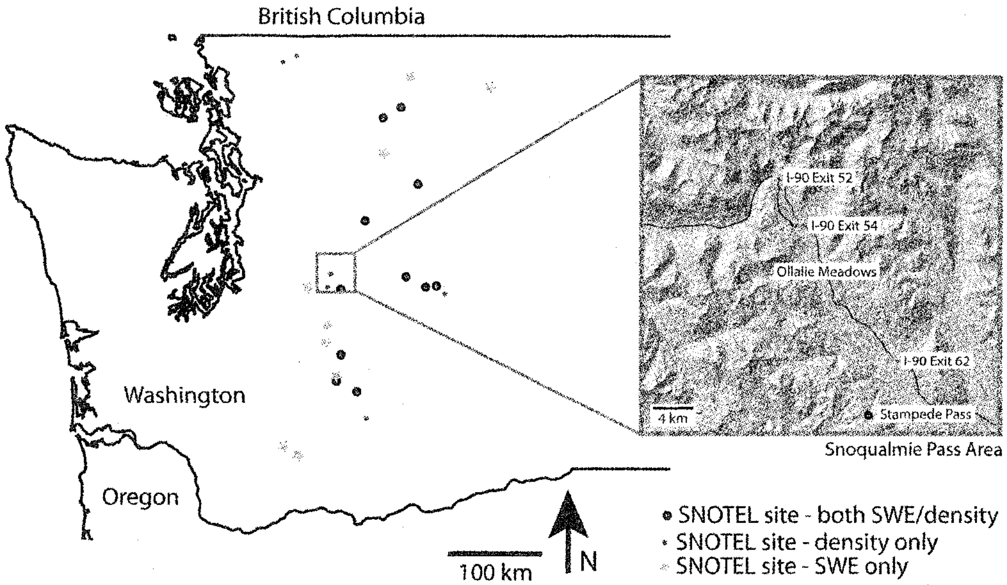

Figure 1. Location map showing SNOTEL sites and field sites

Analysis Techniques

Using visual inspection and statistical techniques, I documented the seasonal evolution and regional coherency of snow water equivalence (SWE) and snow density in the Washington Cascades. With the calculated field snow densities, I evaluated the seasonal variation in vertical snow density profiles. I attempted to validate densities estimated from SNOTEL observations in the Snoqualmie Pass area. However, easily accessed field areas were located close to the highway (I-90 Exit 54 and I-90 Exit 62), complicating direct quantitative comparisons with higher elevation SNOTEL sites (Figure 1).

With the SNOTEL SWE and density, I used Principal Components Analysis (PCA) to objectively find the dominant spatial and temporal patterns in Washington Cascade SWE and density. The outputs of a PCA include empirical orthogonal functions (EOF), which represent variations in space, and principal components (PC), which represent variations in time. The results of PCA are mathematical constructs that don't necessarily have physical meaning. Therefore, testing against an a priori hypothesis and ensuring the robustness of structures using sub-setting techniques is required for confidence in PCA. In my analysis, I evaluated the statistical significance of my PCA results by testing against a red noise null hypothesis with confidence intervals derived by North et al. (1982). Whenever possible, I also completed PCA on subsets of the dataset to ensure the robustness and physical meaning of the returned mathematical structures.

For SWE, I completed PCA on both the midnight values and the midnight values with the daily mean at each site removed. For density, I only completed PCA using two years of data: water year 04 and water year 06 due to data availability and data quality issues. The SNOTEL-derived density data often had missing and/or unreasonable values. For example, when the depth sensor measured falling snow instead of the snow on the ground, the depth value was anomalously high and the density was correspondingly too low. I established simple data quality rules to address obvious data quality concerns, but missing data values resulted. PCA requires a temporally continuous dataset. Therefore, if a station had a lot of missing data, I could not use it for PCA. As a result of these pragmatic data quality and data continuity concerns, I experienced an inherent trade-off between number of sites and length of record. I chose to optimize the number of data sites, thus reducing the number of years over which the analysis was completed, but retaining enough sites to obtain a robust spatial pattern.

RESULTS

Seasonal Snow Density Evolution

At two SNOTEL sites near Snoqualmie Pass with continuous data records for water year 2004, the seasonal snow density evolution was visually coherent (Figure 2). Through the season, bulk snow density increased monotonically with deviations for new snowfall events and subsequent densification. Ollalie Meadows received more snow than Stampede Pass and had a correspondingly higher mean snow density (Table 1). The higher mean snow density at Ollalie Meadows probably resulted from increased compaction and densification from a heavier overlying snow pack. In addition to receiving more snow than Stampede Pass, Ollalie Meadows had a higher density than Stampede Pass for a given SWE (Table 1). Therefore, the larger density at Ollalie Meadows may also be partially explained by factors such as denser new snow or slightly warmer temperatures (Figure 3).

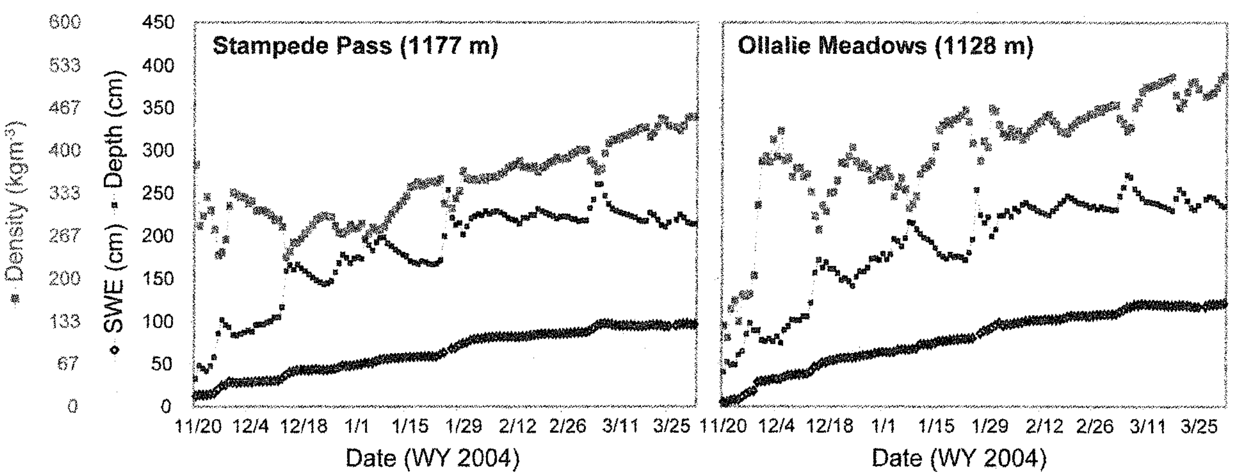

Figure 2. Seasonal evolution of snow water equivalence, snow depth, and snow density at two SNOTEL sites near Snoqualmie Pass, WA.

Table 1. Comparison of snow density at two SNOTEL sites near Snoqualmie Pass, WA.

Stampede Pass 1177 m			*Ollalie Meadows 1128 m*		
Date (wy04)	**SWE (cm)**	**Density (kgm^{-3})**	**Date (wy04)**	**SWE (cm)**	**Density (kgm^{-3})**
Dec. 1-Mar. 31	68	350	Dec. 1-Mar. 31	85	421
Dec.15	40	242	Dec.13	41	335
Jan.24	61	355	Dec.28	60	372

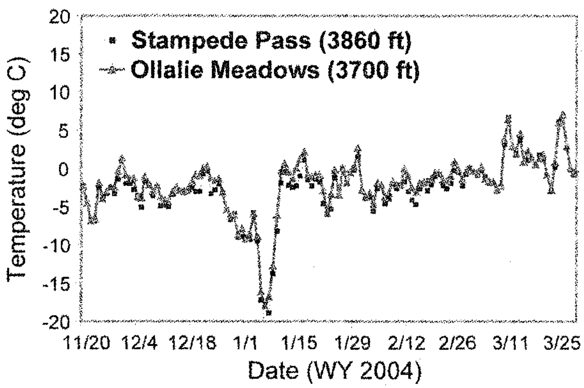

Figure 3. Seasonal evolution of temperature at two SNOTEL sites near Snoqualmie Pass, WA.

Nearby field measurements demonstrate the influence of atmospheric conditions on the vertical profile of snow density and affirm the seasonal evolution observed at Ollalie Meadows and Stampede Pass SNOTEL sites. At the beginning of the snow season, new snowfall events resulted in low density snow at the top of the pit and compaction of the underlying snow (Figure 4a). Fresh snow densities measured at the snow surface only hours after they fell resulted in the lowest density observed by this study: 59 kgm^{-3} (Table 2). Within 24 hours, snow densities had increased dramatically under the weight of subsequent snowfall. Another important factor was riming. The largest fresh snow densities corresponded with heavily rimed snow crystals (Table 2). During the middle of the snow season, new snow fall and melting events cause significant variation in the density near the top of the pit. The largest vertical gradients in snow density with depth occurred when relatively fresh snow overlaid older compacted snow (Figure 4b). When temperatures exceeded freezing, surface melting lead to rapid densification of the surface snow (Figure 4c). Using midnight SNOTEL observations, I found densification rates of up to 35 kgm^{-3} per day when daily mean temperatures approached 2 °C (see January 15-16, 2004 in Figure 2 and 3). At the end of the snow season, I observed a homogeneous isothermal snow pack with large snow densities (Figure 4d).

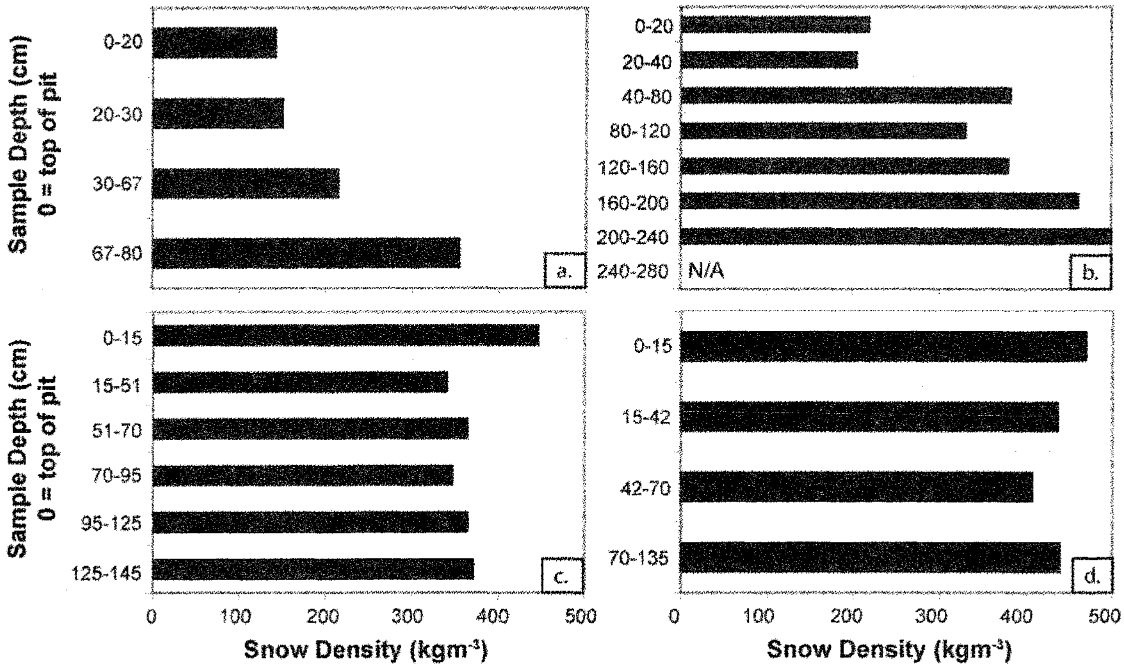

Figure 4. Snoqualmie Pass snow pits showing the seasonal evolution of vertical snow density profiles.
a. November 26, 2003 above I-90 Exit 62 (838 m) b. February 25, 2006 above I-90 Exit 54 (975 m) c. January 17, 2004 at I-90 Exit 54 (780 m) d. March 26, 2004 above I-90 Exit 54 (1006 m)

Table 2. Fresh snow density measurements from Snoqualmie Pass, WA

Location	Sampling Time	Estimated age	Fresh Snow Density
I-90 Exit 54 (780 m)	March 9, 2006 2:00 pm PDT	< 3 hrs < 24 hours	57 ± 4 kg m^{-3} 201 ± 10 kg m^{-3} (heavily rimed crystals)
I-90 Exit 62 (732 m)	March 9, 2006 4:00 pm PDT	< 24 hours < 24 hours	79 ± 6 kg m^{-3} 129 ± 14 kg m^{-3} (rimed crystals)

Principal Components Analysis (PCA)

For both SWE and density PCA, the first principal component/empirical orthogonal function pattern explained the majority of the variance (Table 3). For all PCA I completed, only the first EOF/PC pattern was statistically different from my null hypothesis of red noise (Figure 5a, Figure 6a). Together, these analysis suggest that snow water equivalence and snow density has strong coherence on seasonal timescales.

Table 3. PCA set-up and total variance explained by the first EOF/PC

Variable	Time period	Number of SNOTEL Stations	Total Variance Explained by EOF1/PC1
SWE	wy84-wy06	22	85%
SWE anomaly	wy84-wy06	22	66%
Density	wy04, wy06 – (Dec. 15-Mar. 31 only)	37	84%

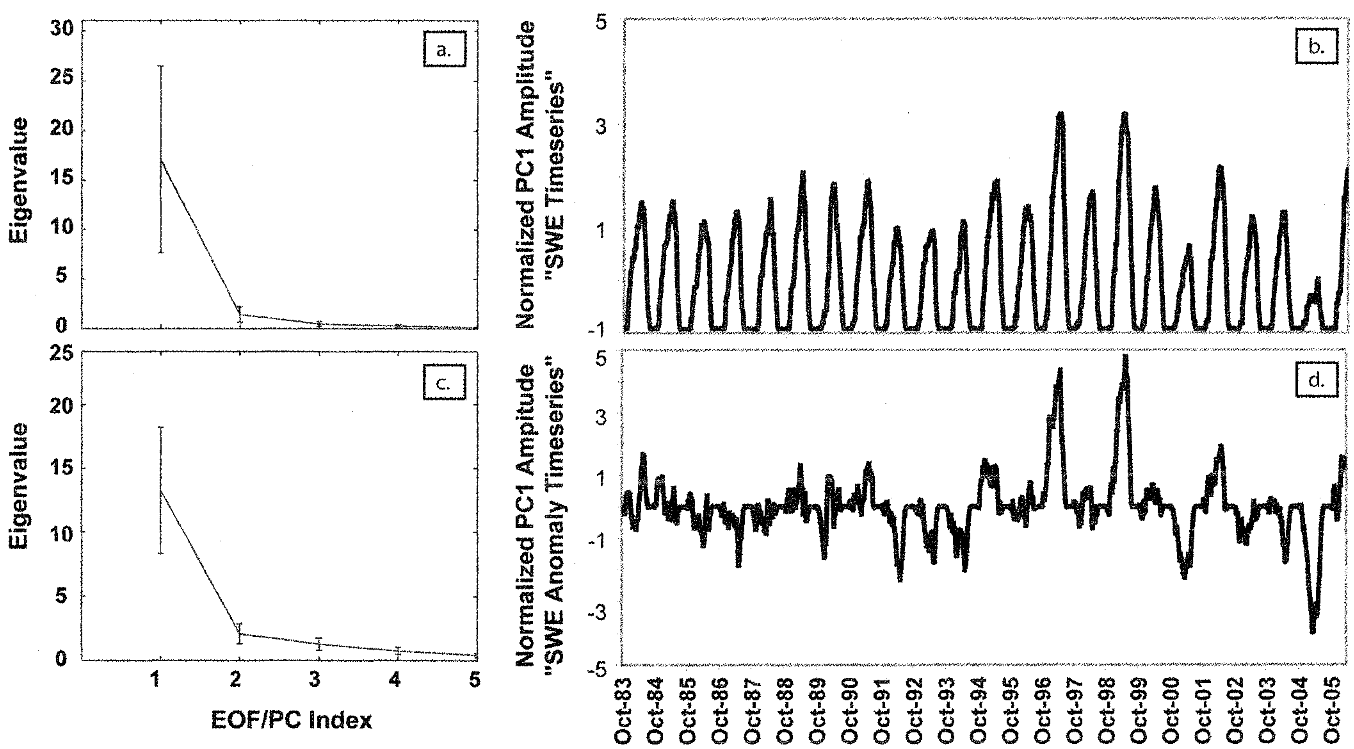

Figure 5. Eigenvalues and first principal components from SNOTEL SWE PCA and SWE Anomaly (daily mean at each site removed) PCA.

The retrieved spatial and temporal patterns suggested PCA was an effective way to reduce the dimensionality of the SNOTEL SWE dataset. The 1st EOF of the SWE analyses was highly correlated with average April 1 SWE (R^2=0.99). Essentially, the first PC represents a statistically averaged Washington Cascades SNOTEL SWE time series. The EOF pattern reveals the spatial distribution of snow accumulation throughout the Washington Cascades (not shown).

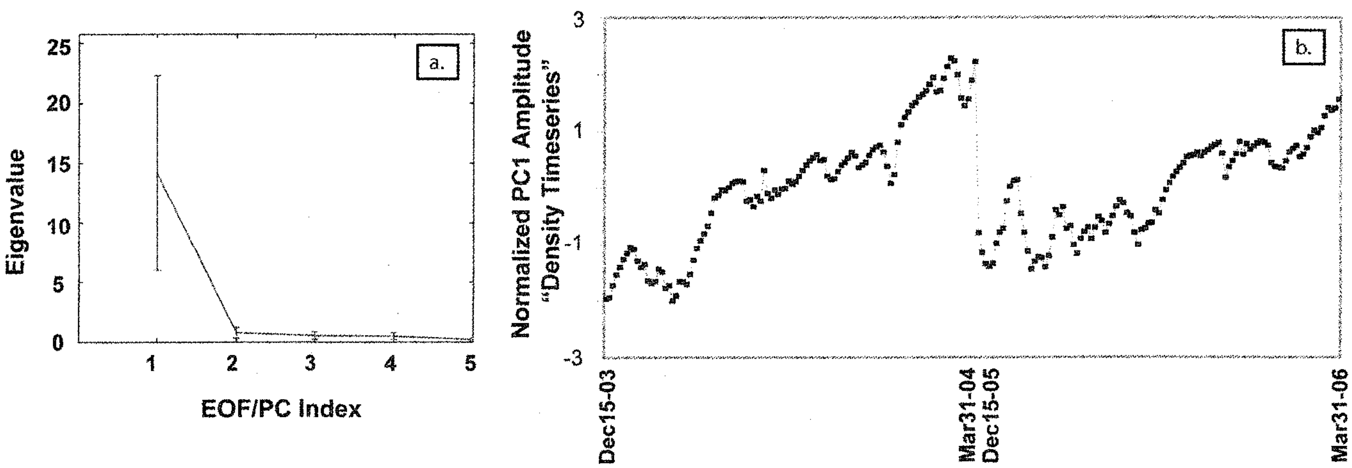

Figure 6. Density eigenvalues and first principal component

Unlike the first SWE EOF pattern, the first density EOF pattern was not correlated to the mean seasonal density (R^2=0.01). However, the first EOF/PC pattern did explain a large amount of the total variance and individual site variance (Table 3, Figure 7). A convenient plotting method for PCA is to scale EOF1 so that it reflects the change in density associated with a unit change in PC1. This "scaled" EOF shows density variability throughout the Washington Cascades (Figure 7). An interesting E-W gradient is noted in the Central Cascades, with smaller scaled EOF1 amplitudes in the East and larger scaled EOF1 amplitudes in the West. The spatial patterns are intriguing, but do not always have any obvious physical interpretation. For example, why do the sites closest to British Columbia show a 10 unit change in scaled EOF over a small distance? Density variations are not easily explained by total SWE or elevation. For example, simple regressions of the mean seasonal snow density demonstrates a correlation with mean seasonal SWE (R^2=0.56), but not with elevation (R^2=0.051) (Figure 8). Clearly, additional factors beyond those considered in this study are required to explain these apparent snow density patterns.

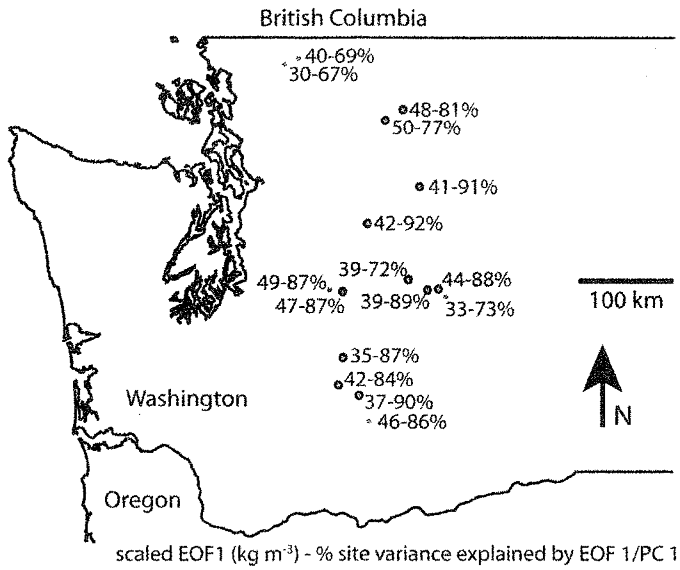

Figure 7. Change in density associated with a unit change in PC1 (kgm^{-3}) and site variance explained by EOF1/PC1

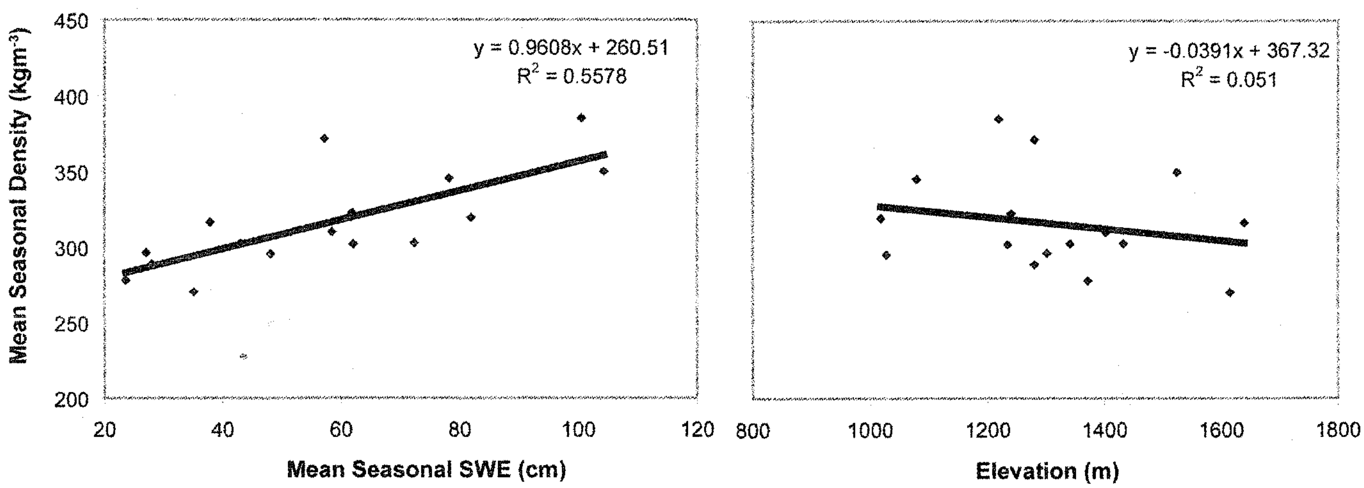

Figure 8. Regression of seasonal mean density with seasonal mean SWE and elevation

SUMMARY AND FUTURE WORK

Summary of primary results:

- Observed snow densities in the Washington Cascades ranged from 57-500 kgm^{-3}.
- Bulk snow density increased through the snow season due to metamorphism, melting, and compaction.
- Vertical gradients in density and large variability in the density at the snow surface were common in early to mid snow season, but snow density was vertically uniform by the end of the snow season.
- PCA revealed SWE and snow density evolution was largely coherent over the Washington Cascades. The first EOF/PC pattern explains ~85% of the total variance in SWE and ~84% of the total variance in density.
- PCA of SNOTEL density revealed interesting, but largely unexplained spatial patterns. Mean station snow density was correlated with SWE, but not elevation. Additional factors are required to explain observed snow density variability.

In the future, I plan to improve this analysis by:

- Extending the length of the snow density record to evaluate the robustness of snow density spatial patterns.
- Investigating the role of temperature variability as a control on snow density variability.
- Investigating how temperature and precipitation correlate with SWE anomaly PCA time series.

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