ARIZONA'S ELEVATION SNOW DENSITY STUDY ON THE SAN FRANCISCO PEAKS

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ABSTRACT: Variability in storm snow density along an elevation gradient has been frequently observed, however, systematic attempts to correlate these variables have not. In this study, storm snow depths and densities were sampled from five study sites ranging in elevation from 2174m to 3536m on the western aspects and base of San Francisco Peaks, Coconino County, Arizona. Over four winters (2020-21 through 2023-24) near-synchronized sampling was conducted when precipitation parameters met specific protocols. Each site was paired with an automated weather station to enable further analysis of factors contributing to densification. Findings are potentially useful for snow water resource assessment and prediction, as well as, to assess the immediate impact of storm snow loading on pre-existing weak layers, and the potential for destabilization of the seasonal snowpack.

KEYWORDS: snow density, snow water equivalent, San Francisco Peaks

1. INTRODUCTION

The San Francisco Peaks of Northern Arizona are a unique prominence not typically found on the Colorado Plateau. Due to their isolation and relatively high elevation, they have been the foci of a myriad of research projects since the life zones research by C. Hart Merriam in the late 1880s. The Peaks, as they are locally known, rise approximately 1829m above the surrounding Colorado Plateau, culminating at 3851m on Humphreys Peak. This study establishes five study plots, at five different elevations on the western aspect of the mountain complex.

The primary objective of this study was to assess the influence of elevation on storm snow densification. A secondary objective was to assess changes in storm snow density from each sampling site over the four-winter study period. Using the same sampling methodology, equipment and multiple samplers, data were collected in a near-synchronized timeframe from the five sites following qualifying snowstorms, in accordance with predetermined criteria for a sampling event.

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The study took place starting with the first significant snowstorm of the 2020-2021 season and continued throughout the last significant snowstorm of the 2023-2024 season. This allowed the opportunity to capture both ENSO (El Niño-Southern Oscillation) positive and negative anomalies and thereby determining any patterns relevant to these climatic fluctuations.

2. METHODS

There were five sampling sites for the study. Their locations were as follows:

National Weather Service, Flagstaff Office (FGZ) Bellemont, AZ at 2174 m

White Horse Park, AZ (WHP) at 2499 m

Top of Sunset Chairlift at Snowbowl (SCL) at 3045m

Top of Grand Canyon Express Chairlift at Snowbowl (GCL) at 3292m

Top of Agassiz Chairlift at Snowbowl (AGL) at 3536m

Due to the challenges of sampling across a large elevation gradient of 1362 vertical meters, specific criteria were established to activate a sampling event. Since storm character can vary dramatically throughout the winter in the intermountain/radiation snow climate of the San Francisco Peaks, sampling events were determined based on meeting minimum snow accumulation thresholds at the lowest elevation site, the National Weather Service Office.

Thresholds were as follows:

- At least 2 inches of snow accumulation in a 12-hour period.
- Sampling was conducted between the hours of 0800 and 1700 MST depending on the availability of technicians, and ski lift access at the highest three sites.
- Snow events with a rain component at the lowest site were not included in the study.

Uniform datasheets were used to record data. Field forms were time-stamped via cell tower timekeeping to establish the degree of synchronicity in sampling times, and submitted electronically with a photo to prevent data loss. These included surface snow on a crystal card to identify forms, sizes and estimate degree of riming.

A communication tree was established with all technicians. A sampling occurrence was determined in conjunction with National Weather Service staff according to the forecast. Notices were then sent to the technical team that an event was eminent. Notifications happened approximately 12 to 24 hours prior. The wildcard was lift operation delays at Arizona Snowbowl Ski Resort. For this reason, the initiation of sampling was often determined by the Snowbowl team once lift operation status could be determined. On some occasions, lift closures or wind holds prevented near synchronized sampling, or resulted in an incomplete dataset for a specific event. This was particularly true for the AGL site, where rime ice accretion sometimes delayed lift operation by many hours or even a full day.

A training video on use of snow sampling equipment was developed to ensure uniform techniques. Snow Water Equivalent (SWE) tube and scale kits produced by Snow-Metrics were used in tandem with calibrated 24-hour storm boards. These were compliant with standards set forth by Snow, Weather, and Avalanche Guidelines for North America (SWAG). Each snow sampling site was paired with an automated weather station within 140 meters.

3. RESULTS

The results show high season to season variability in snowfall densification (Figure 1) and also define a consistent pattern from site to site. Lowest mean densities were sampled at the WHP, and second lowest densities sampled at AGL. Consistently highest density snow was sampled at the lowest elevation site, FGZ. The second and third densest snow was sampled at the two mid-elevation sites at Snowbowl: SCL, and GCL. These two sites illustrated the greatest range of density values and vied for the highest density placeholder during 2020-21 and 2023-24, due to some exceptionally high-density events that may have skewed the averages.

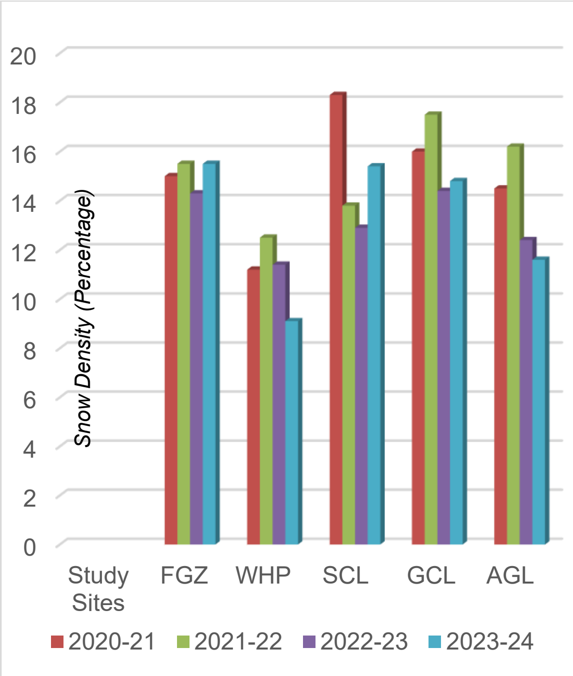

Figure 1: Illustrates season to season variability, and a consistent pattern.

Weather station data was collected with the intent to explain anomalies and to clarify the extent to which elevation serves as an independent variable on snowfall densification. The specifics of this analysis are ongoing, but the parameters to be correlated are wind velocity and run, temperature, and relative humidity for a specific timeframe prior to sampling at each site. In the interim, we conducted spot reviews of weather station data for 20 sampling events over the four winters, see below.

Table 1: Spot reviews of sampling events.

Event Avg. (20)	*SCL site 3045m*	*GCL site 3292m*	*AGL site 3520m*
Max. temp.	-2.8°C	-5.3°C	-5.8°C
Min. temp.	-10°C	-12.4°C	-13.2°C
Max. RH	96%	92%	93.2%
Min. RH	74.3%	75.7%	78.4%
Max. wind	11.9m/s	7.2m/s	7.2m/s
Max. gust	24m/s	13.7m/s	13.4m/s

Comparing both sampling methods, the snow stake vs tube values of height of snow, indicate similarity when averaged over the entire period of the study (Figure 2). A consistent pattern of highest densities at the lowest and mid-elevation sites FGZ, SCL and GCL, and lowest densities at WHP and AGL sites is evident. Inconsistencies along the elevation gradient appear to result from the competing influences of wind, a positive one, and cold temperature, a negative one. At higher elevations riming is a secondary factor possibly resulting from the turbulence and rapid ascension of super saturated air as this encounters the mountain barrier. At the highest elevation site, cold temperatures appear to dominate over wind as an influence.

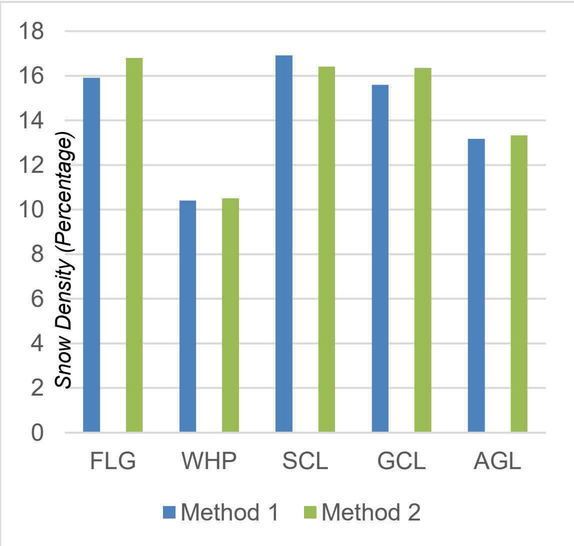

Figure 2: Cumulative new snow densities over the length of the study

Crystal card photos from sampling failed to identify patterns of correlation between degree of riming and elevation. In general, riming and graupel prevalence on crystal card photos from a single storm appeared fairly uniform at all three higher elevation sites. Even when a dominance of rimed forms was found at a particular site, this varied from storm to storm, with no pattern relevant to elevation emerging. Overall, the vast majority of crystal card photos from these three sites revealed a mix of rimed stellar habit fragments (.5 -1 mm), and graupel clusters (2-4 mm). Only on rare occasions were pure crystal habits evident and these were generally small (.5 mm).

Preliminary weather station data revealed a marked difference in wind and temperature characteristics between SCL and the two other higher sites, GCL and AGL. Based on spot checks on selected sampling events, SCL is warmer and windier than would be expected based on geography and environmental lapse rate (Table 1). These findings may help explain higher density values at this site, and highlight the role played by microclimates.

The role of microclimates across the study sites also appear to play a more crucial role than anticipated. FGZ is located approximately in the center of a large, open park setting (approximately 12 km^2) and is a local cold air sink. Similarly, the WHP site is located on the sheltered edge of trees of a much smaller open park (approximately 0.3 km^2). The WHP site commonly experiences the lowest minimum temperatures in Arizona due to its altitude (2499 m) and its proximity to cold air drainage from the San Francisco Peaks. Moreover, the forest edge to the east-west aspects of the WHP site allowed for minimal turbulence from windy conditions and effects of insolation.

4. DISCUSSION

Surface wind is a dominant factor affecting new snow densification, as falling crystals approach the land. The formation of wind slab with common densities ranging from 200 to 400 Kg/m^3 are testimony to the influence of high velocity winds.

The elevation of a particular locality can result in snow that has undergone a variety of changes, a few of which result in low density, fluffy powder; but many other factors promote densification. Early in the study, it became clear that a simplistic view based on environmental lapse, that the higher the elevation the lighter the snow, was erroneous. Temperature is obviously a primary factor of snow density; however, this study clearly shows that on the Peaks, wind velocity and riming are stronger drivers of densification.

Although photos of snow on crystal cards showing representative snow habits were included in the data collected, determining how to classify these is currently unresolved and challenging. The quantitative measure of heavily rimed forms such as graupel, and its specific influence on increasing sample densification is unestablished but certainly plays a role. In the case of our upper elevation sampling sites wind rime and graupel storms are commonly observed, potentially overriding the influence of colder temperatures.

Table 2: Mean snowfall densities by site, showing blue for La Niña and red for El Niño.

Site	*2020-21 Kg/m³*	*2021-22 Kg/m³*	*2022-23 Kg/m³*	*2023-24 Kg/m³*
FGZ	159.5	161.0	204.6	160.0
WHP	104.2	125.9	103.7	98.8
SCL	167.2	149.0	128.3	235.0
GCL	149.6	178.4	159.2	188.0
AZG	148.2	163.7	119.6	156.9
Avg.	145.7	155.6	143.1	159.7

Our choices of sampling sites may have adversely influenced results. The role of microclimates and variability are evident from the dramatic range of snow densities and depths recorded. Storm wind direction and velocity seem to be most variable and are therefore most accountable for the high range of value spread.

Our results failed to identify any significant relationship between densification and ENSO anomalies (Table 2). Many warmer storms failed to meet the sampling criteria at our lowest elevation site, instead producing rain. Of the storms that qualified, snow densities were consistent with other winters.

5. CONCLUSION

Elevation alone is a poor predictor of storm snow densification. Attributes contributing to new snow density are inconstant, subject to microclimatic influences and complex interactions. As a result, correlation with elevation is weak.

Thorough and detailed investigation of conditions which influence new snow densification at a specific site can potentially enable fairly accurate predictions, however, generalizing to a broader landscape scale is problematic.

6. ACKNOWLEDGEMENTS

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