EFFECTS OF AN ELEVATION GRADIENT ON EVAPO-SUBLIMATION IN THE SAN FRANCISCO PEAKS

Final Technical Report for the Watershed Research and Education Program

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January 2012

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INTRODUCTION

Snow pack dynamics on the San Francisco Peaks of northern Arizona are at the forefront of the debate regarding the sustainability of using reclaimed water to create snow at the Snowbowl ski area. Organizations on both sides of the issue have cited rates of evapo-sublimation to characterize the effects that snow, created from treated effluent, will have on ground water and the environment. The rates cited are not based on empirical data however, as there have been no scientific studies regarding evapo-sublimation at elevation in the San Francisco Peaks. The impacts of making snow with reclaimed water could be significant and have far reaching consequences for both the environment and for people living in the region. The mountains receive roughly 260 inches of snowfall annually, and it has been hypothesized that the majority of the snowpack is lost to evapo-sublimation. Evapo-sublimation is defined as the cumulative effect of evaporation and sublimation on snowpack that occurs when the surface temperature of a snowpack fluctuates above and below 0ºC. Estimates of the efficiency of evapo-sublimation range from between 20% to 100% of total snowpack being lost to the atmosphere. This level of uncertainty is too large to draw meaningful conclusions regarding the consequences of using reclaimed water to make snow. This uncertainty is exacerbated by the unknown evolution of the chemical content in water molecules used to make snow. The nature of the impact is unknown, and a scientific examination of the processes affecting the snow will diffuse some of the uncertainty surrounding the issue.

Evapo-sublimation is one of the more complex energy fluxes to measure when examining a natural environment. There is not a simple instrument that has the ability to give instantaneous readings in the field. A traditional method of measurement is to use the change in mass of a sample of snow as a measure of energy flux (Fujii and Kusunoki*,* 1982; Radionov *et al*., 1997; Fujita and Abe*,* 2006; and Froyland *et al.,* 2010). A transparent container designed to simulate the snowpack environment is filled with a snow sample and the mass is recorded. The container is then placed in the snow such that the top of the snow surface is level with the surrounding snow. The snow sample is exposed to the atmosphere for a predetermined duration, after which the sample is weighed a final time. The change in mass is converted into an energy flux in mm of snow water equivalent (SWE). Depending on atmospheric conditions, this may indicate either sublimation or deposition. Deposition could be in the form of condensation, precipitation, or snow blown into the pan by wind. This method has drawbacks in its sensitivity to environmental conditions and thus the possibility for contamination of data, but is a simple and mobile method of measurement.

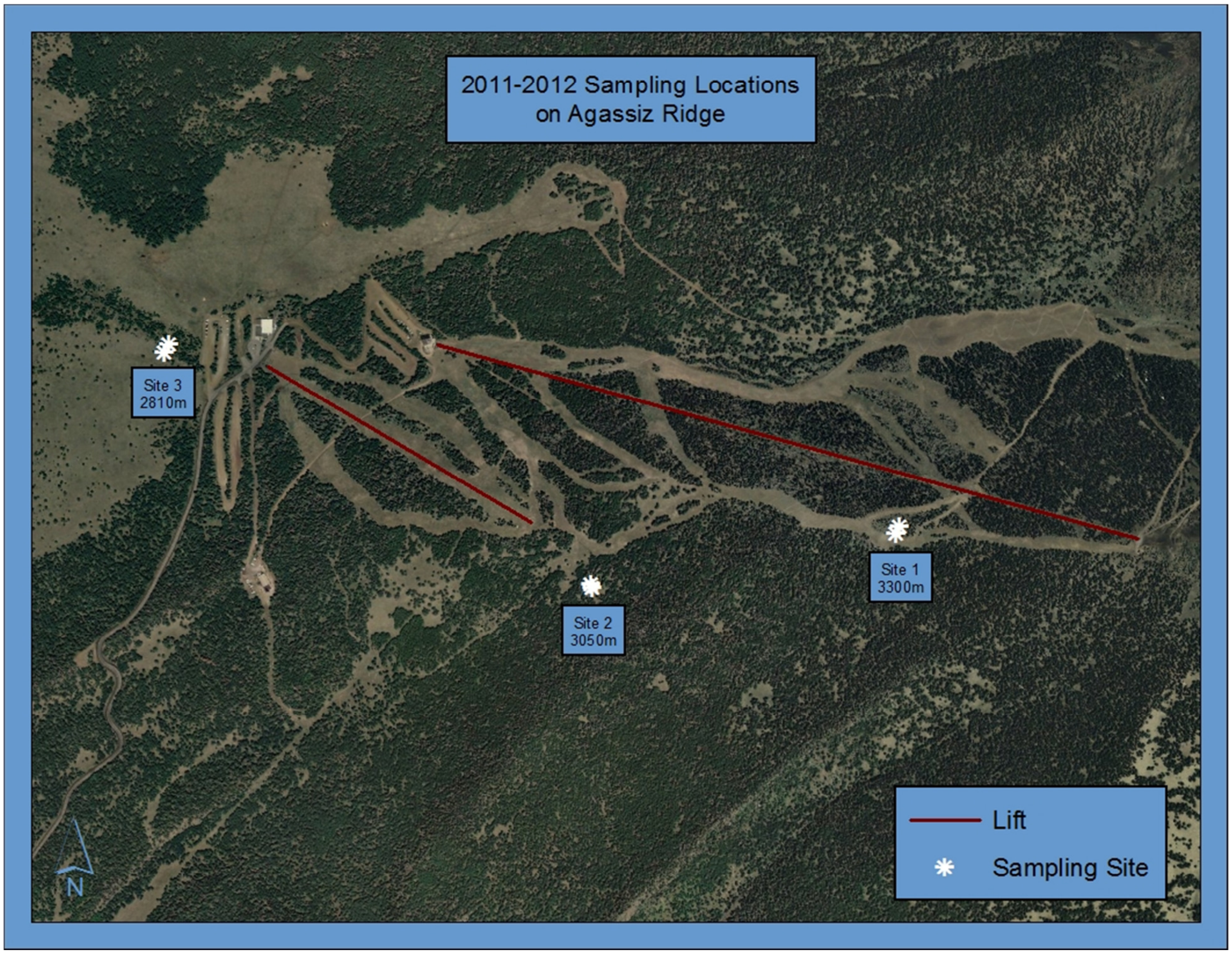
An alternative method used as a proxy for evapo-sublimation is isotope enrichment (Taylor *et al.* 2001; Neumann *et al.* 2008; Sokratov *et al.* 2009; Gustafson *et al.* 2010). Gustafson *et al.* (2010) used isotopic tracers to measure sublimation in the Jemez Mountains in New Mexico. This study incorporated the collection of snow samples to test several isotopes and chemical characteristics of the snowpack. Their results illustrating the isotopic enrichment of $\delta^{18}O$ signify a significant correlation between sublimation and the enrichment of the snowpack with ^{18}O. The enrichment of a sample with ^{18}O occurs both during evaporation and sublimation, but in this study the ambient temperature never rose above freezing, indicating the increase in $\delta^{18}O$ over time was due solely to sublimation.

RESEARCH STATEMENT AND PURPOSE

This study incorporates measurements of evapo-sublimation at numerous locations in close proximity to a SNOTEL weather station at as well as a MESO-West weather station. Two types of primary measurements were collected. The first is based on the measurement of change in snow mass after exposure to the atmosphere. For this, a transparent Plexiglas pan with an exposure area of 620 cm^2 was filled with snow and the mass was measured. The pan was buried such that the top of the pan was flush with the surface of the surrounding snow. After exposure for 24 hours, the mass was measured again and the change in mass was recorded.

The second method is the measurement of the isotopic content of snow samples. Isotopic fractionation of water isotopes occurs during snow evapo-sublimation as a result of an imbalance in vapor pressure. The change in isotopic content can be used as a proxy for the rate of evapo-sublimation (Neumann *et al.*, 2008, Gustafson *et al.*, 2010). Snow samples were collected after a storm cycle at 24 hour intervals to isolate the temporal trend in fractionation. The samples were analyzed with an isotope-ratio mass spectrometer by the Colorado Plateau Stable Isotope Laboratory to determine the change in $\delta^{18}O$. The rates of evapo-sublimation derived from these measurements were compared to pan measurements to determine how evapo-sublimation affects the snow pack over time. Measurements continued until there was no longer sufficient snow coverage at all three elevation sites. An analysis identifying spatial and temporal trends was performed when enough data had been collected.

A comparison of the two measurement methods can be used to illustrate the differences in evapo-sublimation between elevations. The elevation gradient extends from 3,300 meters on Agassiz ridge to below the base of Snowbowl at 2,810 meters. Three elevations were chosen to illustrate this gradient, and at each of the three elevations two sites were constructed. One site was unobstructed from the atmosphere for the entire day (greater than 65% open), and one site was covered by forest canopy blocking the majority of incident insolation (less than 30% open). At each of the six sites evapo-sublimation was measured using both mass balance measurements and the collection of snow samples for $d^{18}O$ analysis. The sites are illustrated below on a map of Agassiz Ridge:

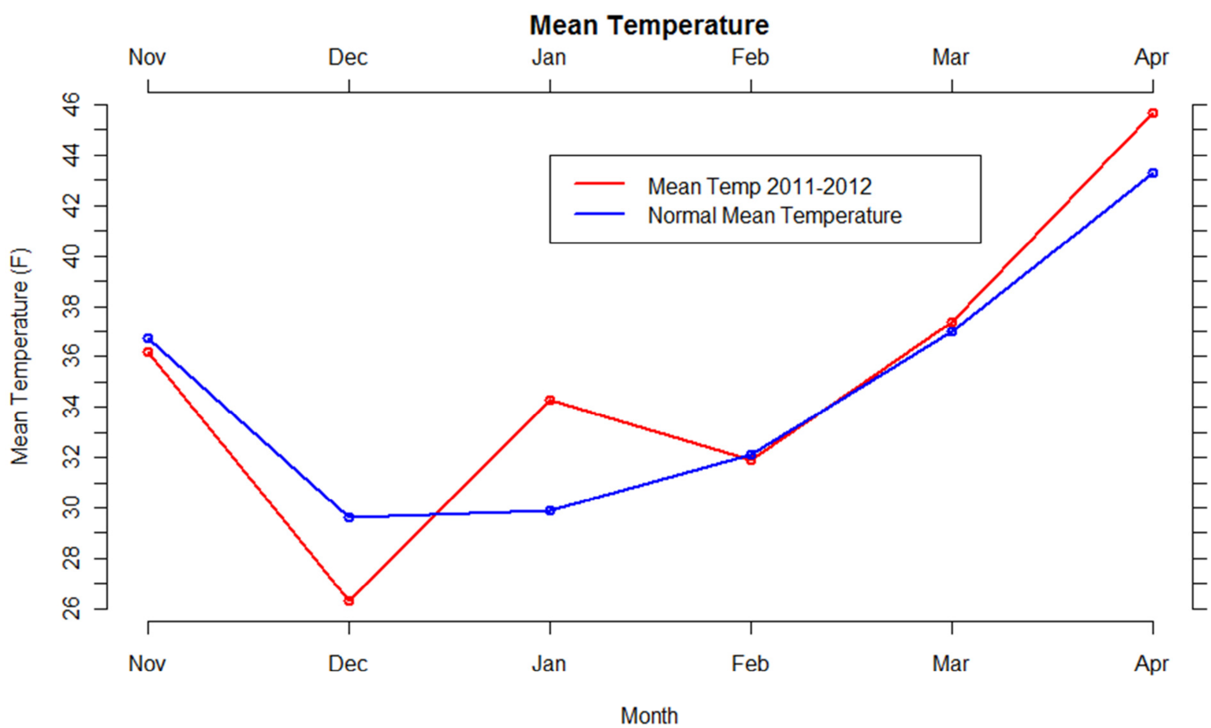


RESULTS AND DISSCUSSION

All sampling efforts ceased with the end of Snowbowl's winter operations on April 1st of 2012. This sampling process resulted in 102 mass balance samples and 102 isotope fractionation samples. These samples were collected over a total of 34 days, corresponding to 17 observation periods. Data was collected between late January and mid-March, with the bulk of the sampling periods occurring in February. Data contained within this analysis is derived from 66 mass balance samples and 66 isotope fractionation samples, as the remaining data have yet to be returned from the isotope laboratory.

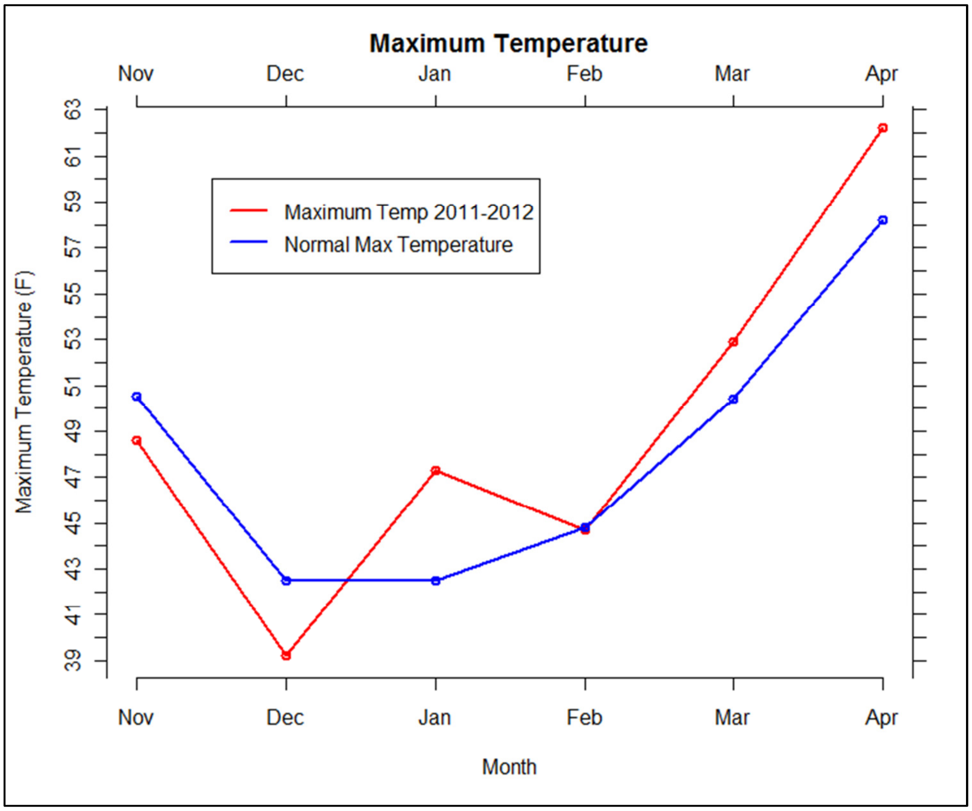
2011-2012 Winter Characteristics

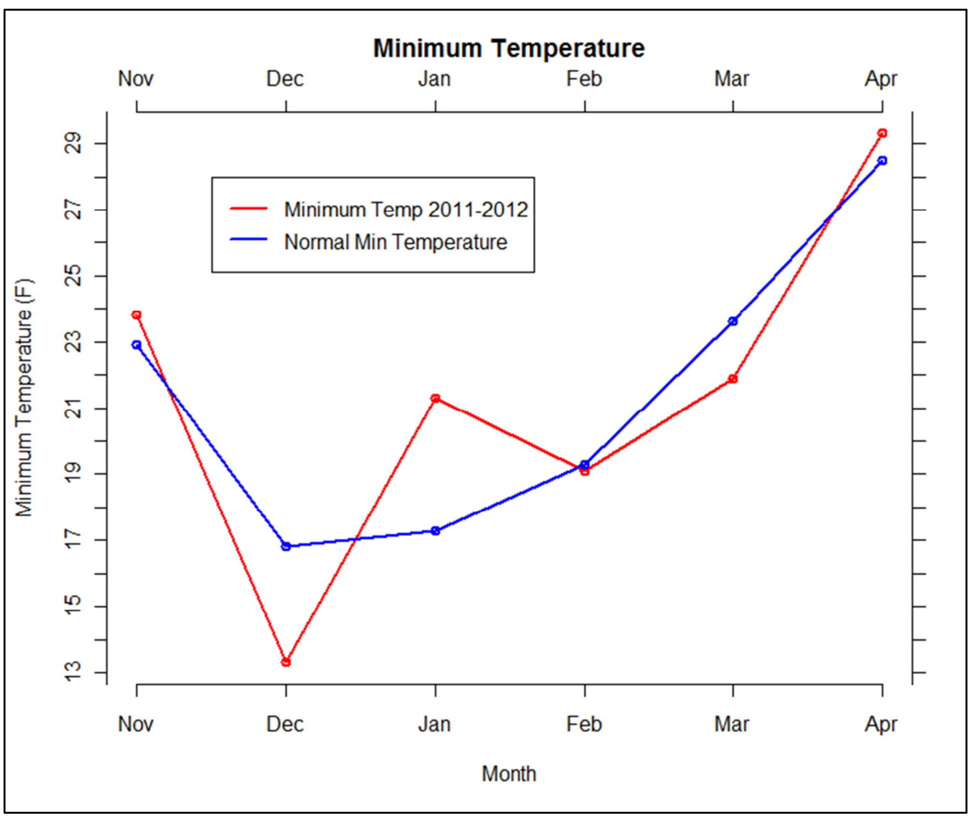
The winter of 2011-2012 in Flagstaff exhibited several characteristics that may have influenced evapo-sublimation results. Monthly climatological reports produced by the National Weather Service were used to illustrate relevant characteristics of the winter. Mean temperature fluctuated below and above normal in December and January, respectively. This is illustrated in the following plot:



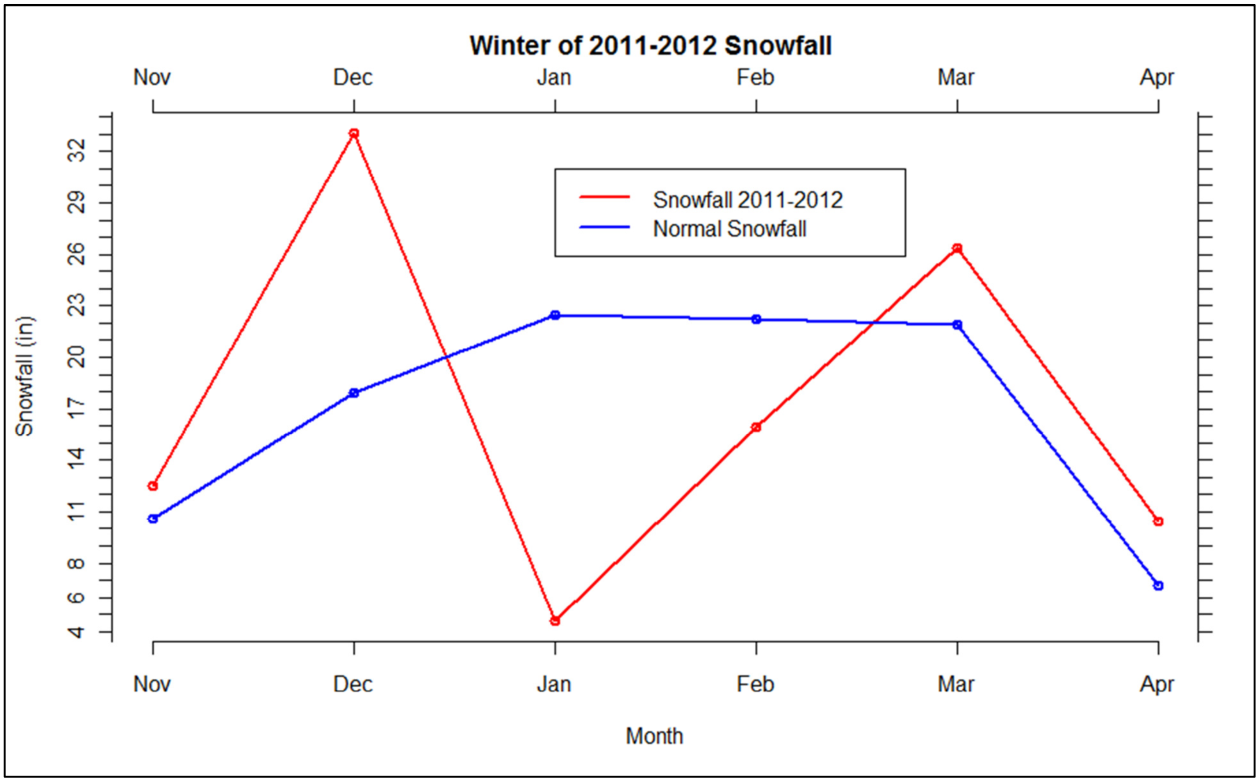
Samples collected during January may be affected by these above normal conditions, but for the bulk of samples which were taken in February and March, mean daily temperature was essentially normal.

Average daily minimum and maximum temperatures depict similar conditions with the exception of March, during which maximum temperatures were higher and minimum temperatures were lower. This indicates a greater than normal diurnal temperature range for the month of March, shown below:


Maximum Temperature
Maximum Temp 2011-2012
Normal Max Temperature
Maximum Temperature (F)
39
41
43
45
47
49
51
53
55
57
59
61
63
Nov
Dec
Jan
Feb
Mar
Apr
Month


Minimum Temperature
Minimum Temp 2011-2012
Normal Min Temperature
Minimum Temperature (F)
13
15
17
19
21
23
25
27
29
Nov
Dec
Jan
Feb
Mar
Apr
Month

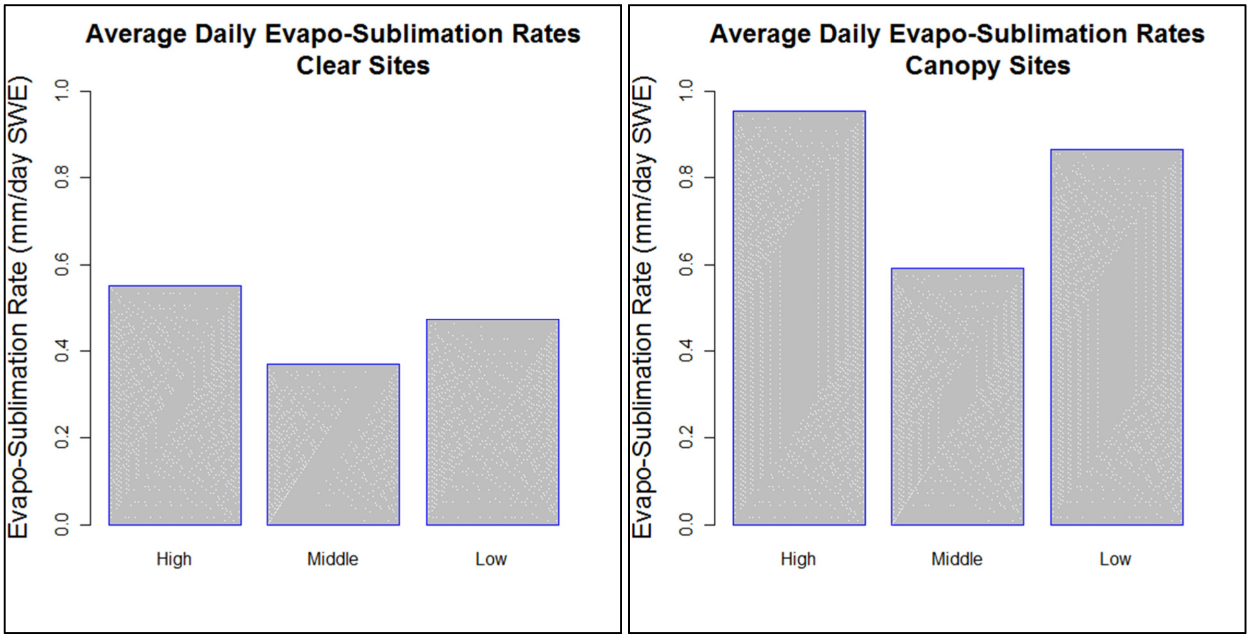
Total seasonal snowfall at Snowbowl was recorded at 208 in. for the 2011-2012 winter season. This is below the normal snowfall total of 260 in for this location. The monthly distribution of snowfall totals are displayed below:



Snowfall was significantly higher than normal for the month of December, by nearly 16 inches. January and February display periods of below normal snowfall, with January nearly 18 inches below normal and February nearly 6 inches below normal. March was slightly above normal. This indicates that for most of the data collection period, the snowpack being sampled was a more mature, dense snowpack than is typically found at this location. Observed snow densities were significantly higher than is found in new snow as a result of long periods of exposure between significant storm cycles. This could have implications for evapo-sublimation rates depending on the extent to which the increased density affected pore size and thus vapor pressure gradients.

Mass Balance Data

A total of 66 samples were used in the analysis of the mass balance data to conform to the sample size and timeframe of the isotope fractionation samples. The resulting data is presented below:



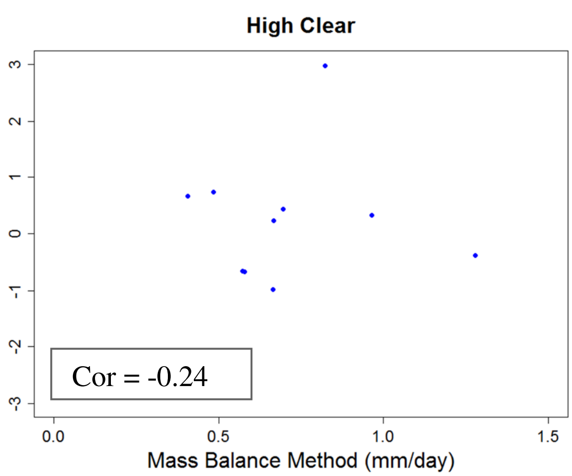
Data is distributed into high (3300 m), middle (3050 m), and low (2810 m) elevations, as well as into clear versus canopy sites. Evapo-sublimation rates are averages in mm/day of SWE. Canopy sites display higher evapo-sublimation rates than clear sites at every elevation. The high site has the highest rate in both clear and canopy sites, followed by the low site, and lastly the middle site has the lowest rates in both the clear and canopy sites. This is contrary to what was expected, but may be explained by siting differences between the three elevations. Advected energy plays is a significant factor in evapo-sublimation (Avery and Dexter, 2000), and thus the available wind-run at each site may be a reason for the relatively low rates at the middle elevation sites. The high site was located near Agassiz ridge, and thus was exposed to the updrafts that frequently occur at that site. The low site was near the lower extent of the forested area. Below that point was a meadow with significant open area. This could allow wind to propagate and advect energy from across the meadow to the lower sites. The middle elevation, however, was a clearing surrounded by dense forest. This would prohibit significant amounts of energy being transported to the site, which would decrease evapo-sublimation rates relative to the high and low sites.

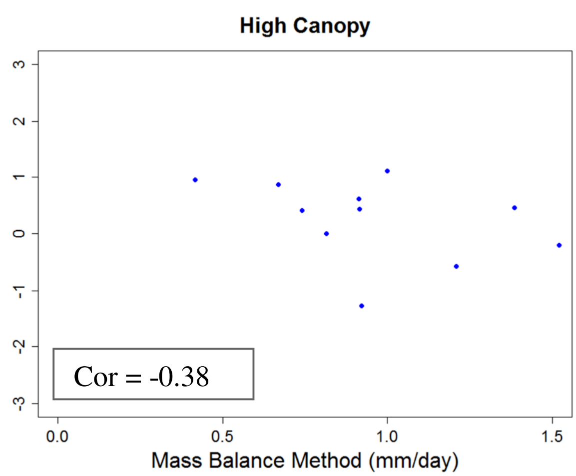
The differential between clear and canopy sites may be explained by the downward longwave radiation fluxes emitted by the canopy cover at night. At each elevation, the canopy site displays a higher evapo-sublimation rate than the corresponding clear site. This is counterintuitive, as from anecdotal experience snow in open areas disappears before snow under canopy cover. This may be attributed to a higher melt rate in open areas. When collecting samples, frequently the pans in clear sites would have standing water when those under canopy cover would not. Were the snow samples not contained in a Plexiglas pan, this water would have infiltrated lower portions of the snowpack and eventually reached ground. The difference between canopy and clear sites is robust, as the elevational characteristics in evapo-sublimation rate are displayed at all three elevations.

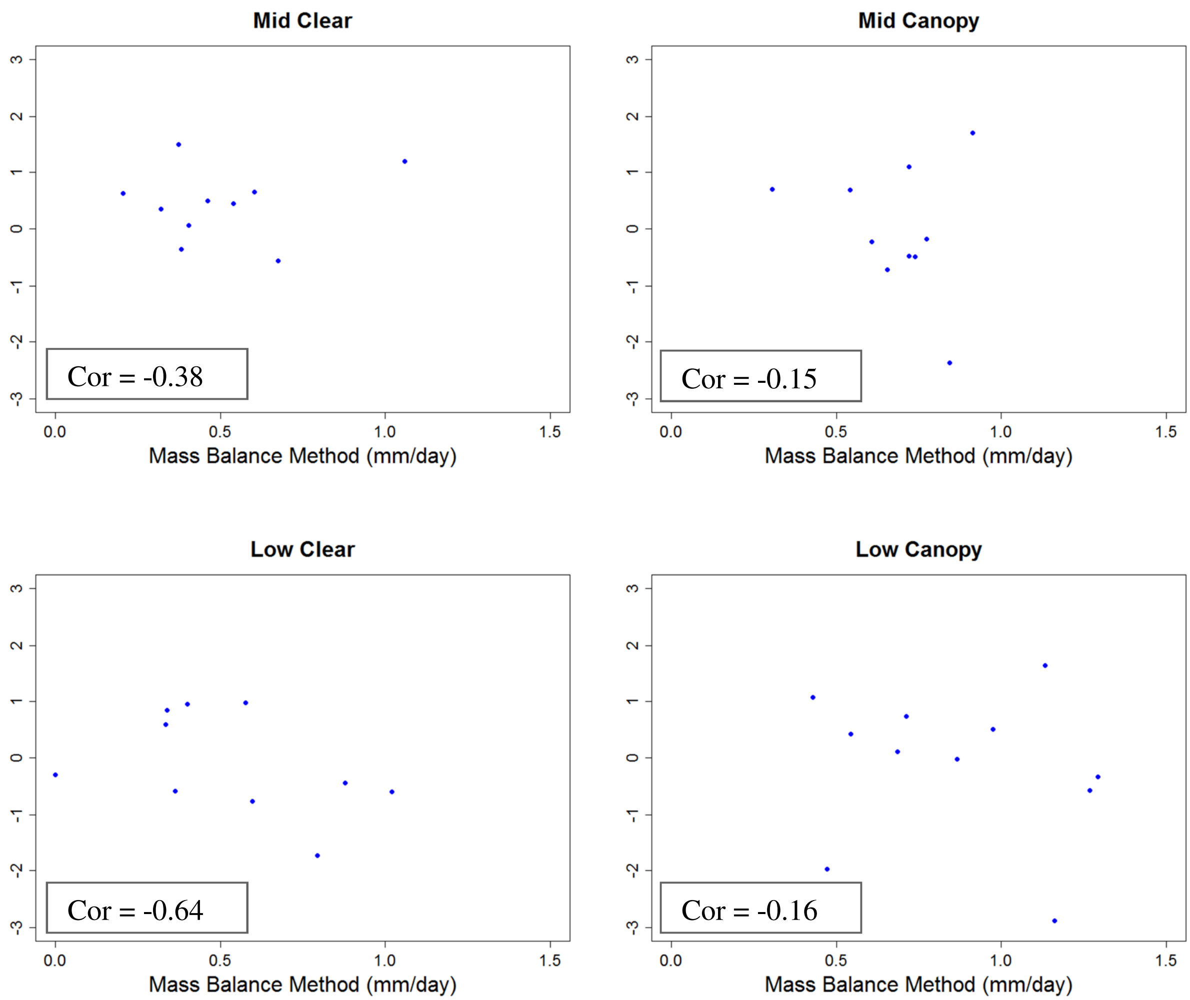
The minimum average daily evapo-sublimation rate measured was 0.37 mm/day SWE, observed at the middle clear site. The maximum rate of 0.95 mm/day SWE was observed at the high canopy site. These values correspond to seasonal snow losses attributable to evapo-sublimation of between 63 mm – 163 mm SWE. Based on a seasonal snowfall accumulation of 520.7 cm, these rates account for between 17% - 43% of total snow loss being the result of evapo-sublimation. The remainder of the snowpack is presumed to infiltrate the surface as meltwater.

Isotope Fractionation Data

There are 66 isotope fractionation samples available for analysis at this time. The remaining samples are in queue at the isotope laboratory. Of the data present, the change in $\delta^{18}O$ over a sampling period was plotted against the mass balance data of the corresponding site. The results are displayed below with correlation values between the two methods:







The correlation values between the two methods of measurement are low, indicating a lack of agreement between the two methods. The sign of the correlation values is correct, as evapo-sublimation would result in enrichment in ^{18}O and an increase in $\delta^{18}O$, and a decrease in snow sample mass. Reasons for the low correlation values are unknown. These correlation values may improve with the inclusion of the remaining data yet to be received. A screening process will be performed once the data set is complete, which will remove sample periods during which there were high winds following recent storms, as well as anomalous values. These processes may improve correlations between the methods.

CONCLUSIONS

Daily evapo-sublimation rates measured using mass balance methods indicate the percentage of seasonal snowpack lost to evapo-sublimation is between 17% - 43%. The effect of elevation on evapo-sublimation may be weak compared to the impact of advected energy. Available wind run and energy may play a more significant role than elevation in the rate of evapo sublimation. Further work aimed at incorporating measurements at locations with uniform characteristics in terms of factors affecting wind run may eliminate this signal from the data.

The correlation between mass balance and isotopic $\delta^{18}O$ measurements is universally weak. This may be improved with the incorporation of the remainder of the dataset, as well as the elimination of anomalous values. Future work will examine environmental factors that are responsible for low correlations, as well as temporal trends that may be affecting correlation between the two methods of measurement.

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