SNOW LOSS ON THE SAN FRANCISCO PEAKS: EFFECTS OF AN ELEVATION GRADIENT ON EVAPO-SUBLIMATION

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1. Contents

1. Introduction

1.1. Overview

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 in Flagstaff, Arizona. Organizations on both sides of the issue have cited rates of evapo-sublimation (the combined effects of evaporation and sublimation, hereafter referenced as E-S) to characterize the effects that snow, created from effluent, will have on ground water and the environment. However, there have been no local scientific studies regarding E-S at elevation in the San Francisco Peaks to quantify these numbers. The mountains receive roughly 6.6 m of snowfall annually, and has been hypothesized that at least 20%, and potentially a much greater percentage of accumulated snowpack is lost to E-S (Avery, Dexter and Wier, et al. 1993).

Evapo-sublimation is one of the more complex energy fluxes to measure when examining a natural environment. Recent advances in instrumentation allow precise measurement of turbulent water vapor fluxes from snowpack in the boundary layer using ultrasonic anemometers and hygrometers. This measurement method is referred to as eddy covariance (Gustafson, et al. 2010). An advantage of eddy covariance is that it does not require modeling or derivation to arrive at E-S rates, and can capture high frequency accurate measurements of E-S. However, the instruments required for eddy covariance measurements are complex, fragile, and necessitate large, clear, low-angle areas to properly deploy. These methods are not well suited to alpine environments where frequent strong winds may damage instruments, and where canopy distribution and rugged terrain may not provide adequate area for equipment deployment. For these reasons, methods used in this research were simpler and less equipment-intensive, and thus more readily implemented in the mountainous terrain of the San Francisco Peaks of northern Arizona.

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, Bryazgin and Alexandrov 1997, Fujita and Abe 2006, Froyland, et al. 2010). A 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 sample is level with the surrounding snowpack. The snow sample is then exposed to the atmosphere for a regular duration, and when the time period has elapsed the sample is weighed a final time. The change in mass is converted into an E-S rate based on surface area of the container exposed to the atmosphere. Depending on atmospheric conditions, this may indicate E-S if mass is lost, or deposition if mass is gained. Deposition could be the result of condensation, precipitation, or snow being advected into the pan by wind. This method has drawbacks in its exposure to environmental conditions and thus the possibility for data inaccuracies, but is a simple, mobile, and robust method of measurement given adequate experimental design.

An alternative method of measuring E-S that has received significant investigation in recent decades is the isotopic enrichment of a snowpack due to E-S (Taylor, et al. 2001, Neumann, et al. 2008, Sokratov and Golubev 2009, Gustafson, et al. 2010). This method is based on the principle that the process of E-S preferentially removes the lighter isotope of both oxygen and hydrogen, and thus enriches the snowpack with the heavier isotope of each element. Changes in isotopic content have been shown to correlate well with E-S rates, and this process could be an extremely versatile method of measuring E-S using minimal field equipment.

The primary motivation for developing any method of measuring E-S from snow is to quantify the amount of snow lost to the atmosphere. Significant research has been done on the various types of ablation that may affect a snowpack, including snow lost to E-S, wind, and melt. Most snow lost to melt will eventually reach a local aquifer or stream system, and thus can contribute to water resources used in the region. Snow lost to E-S however, returns to the atmosphere and is likely transported a significant distance out of the watershed. E-S can occur throughout seasonal snowpack accumulation, and can be responsible for a significant quantity of snowpack loss (Dexter, et al. 1999). Precise values for the amount of snowpack loss are of particular interest to those responsible for water resources in the arid southwest, due to population growth and the potential impacts of climate change.

1.1.1. Process of Evapo-Sublimation

The manner in which water content is removed from a snowpack (ablation) is of great importance to those relying on snowpack as a water source. The quantification of these processes and how they change in response to environmental variables has been studied extensively, particularly for the processes of evaporation, sublimation, and melt. Water can exit the snowpack in two primary directions, downward into the surface underlying the snowpack, or upward into the atmosphere. Downward transport is accomplished via meltwater percolation through the snowpack to the soil underlying the snowpack. Upward transport may be accomplished either as vapor from evaporation (meltwater →

vapor), vapor from sublimation (snow crystals → vapor), or physical removal of snow grains from strong winds. This research focuses on the micro-scale processes through which snow is converted to vapor and removed from the snowpack.

The phase of a group of water molecules is dependent upon both temperature and pressure. Water can exist in either the solid, liquid, or gas phase, or can be at equilibrium with respect to multiple phases simultaneously, depending on environmental conditions. The precise temperature and pressure at which water is in thermodynamic equilibrium with all three phases is termed the triple point. At this triple point, miniscule changes in either temperature or pressure cause the water molecules to preferentially enter the corresponding phase.

The triple point is relevant to this research as it is at temperatures and pressures lower than those of the triple point that the solid and vapor phases of water are at equilibrium, and thus the point at which sublimation will occur. The triple point of water exists at a temperature of 0.01° C and a pressure of 6.12 mb. This pressure constraint does not reference the general atmospheric pressure, but rather the partial pressure exerted by water molecules contained in the snowpack. Two specific changes in environmental conditions can cause sublimation to occur: an increase in temperature (energy) of the water molecules contained in the snow surface due to insolation, or an increase in the vapor pressure gradient due to changing atmospheric conditions or scouring of moisture from the near-surface boundary layer. When one or both of these environmental changes occur, water molecules cease to exist in equilibrium between solid and vapor states, and preferentially enter the vapor state (i.e. sublimate).

Evaporation from snow is driven by similar changes in conditions with two exceptions. The snowpack temperature is greater than 0.01° C, and the water molecules in the snowpack exist in the liquid phase as near-surface meltwater that hasn't yet percolated through the snowpack to ground below. The determinant of which process occurs is the environmental temperature, and therefore the temperature of the snowpack. If this temperature is much greater than 0° C and has been for some time, meltwater will have formed and provide the vapor source from within the snow crystal matrix, rather than the matrix of snow crystals itself. This is because the process of evaporation requires less energy than sublimation. Both processes are endothermic, in that they require energy to occur. The energy required for evaporation to occur is the enthalpy of vaporization (water → vapor), and is 2.26 kJ/g. The energy required for sublimation to occur is the enthalpy of fusion (snow → water) plus the enthalpy of vaporization, and is 2.83 kJ/g.

1.2. Literature Review

This literature review discusses two primary means of measuring E-S: gravimetric methods and isotopic fractionation. Gravimetric methods involve measuring changes in mass, and in this study include both pan and lysimeter measurements. Isotopic fractionation (hereafter referred to as I-F) is the preferential enrichment of the more massive isotope relative to the lighter isotope, as the result of some physical process (e.g. E-S). The following literature provides context under which these methods are valid, as well as previous studies using these methods that produced peer reviewed results. The evolution of isotope enrichment studies is also discussed, as there has been some disagreement concerning the validity of using isotopic fractionation as a proxy for E-S.

There is also a review of the current state of snow research on the San Francisco Peaks, providing background for this study.

1.2.1. Pan and Lysimeter Measurements

Pan and Lysimeter measurements have frequently been used in locations where instrument-intensive data collection is not feasible such as the North Pole (Radionov, Bryazgin and Alexandrov 1997, Froyland, et al. 2010), the Antarctic (Fujii and Kusunoki 1982, Fujita and Abe 2006), and in extreme alpine environments where high wind speeds prohibit the use of more delicate instrumentation (Tarboton 1994, Suzuki, et al. 1999, Jackson and Prowse 2009).

Radionov, et al. (1997) took lysimeter measurements near the North Pole using a two tiered plexiglass tray, an upper tray to contain the snow sample, and a lower tray used as a catchment for water that melted and percolated through the snow sample. Measurements were recorded every 2-6 hours. This separated meltwater from the snow sample, and limited the amount of mass loss due to evaporation from water. Evaporation still occurred from meltwater suspended in the snow sample, however.

An expedition on a floating sea ice station in the Arctic Ocean during from 1957-1958 took E-S measurements using plexiglass pans (Froyland, et al. 2010). These samples were taken using a pan with a surface area of approximately 700 cm^2 and 5 cm in depth. The bases of the pans were not perforated, and thus meltwater remained in the pan. Exposure periods were 12 hours, taken from June through September.

Similar experiments to those reported in Froyland *et al.* (2010) were done to measure sublimation from Antarctic snowpack using pans roughly four times smaller in surface area (Fujii and Kusunoki, 1982) or 2.5 times larger in surface area (Fujita and Abe 2006). The duration of exposure and surface area of the pan was used to convert the change in mass into an energy flux.

Zhang, et al. (2004) examined E-S rates at both clear and canopy sites in eastern Siberia. Transparent plastic pans 22 cm in diameter (380 cm^2) and 20 cm deep were filled with a representative snow sample and buried so that the top of the pan was 1 cm above the snow surface. Measurement of mass before and after a three hour interval relayed how much mass was lost to sublimation during that time period. Using the surface area of the pan, change in mass was converted into a sublimation rate in mm/day. The authors determined that E-S rates were higher in their open site by 33-39%. They attribute this to greater wind speeds and the effects of decreased boundary layer stability at the open site, allowing for near-surface vapor to be mixed upwards, out of the layer.

Lysimeters have also been used in alpine environments where the implementation of more complex instrumentation isn't possible. Suzuki, et al. (1999) measured E-S on Mt Iwate, Japan, using transparent plastic cylinders 16.8 cm in diameter and 10 cm in depth (exposed surface area of 221.7 cm^2). These containers were used to measure evaporation from the snow surface every hour or two, except during nocturnal periods. These measurements were collected as part of an analysis of the spatial variability of snowpack energy balance examined on a forest density gradient. The authors determined that evaporation rates were highest at dense canopy sites and lowest at open sites. They attribute this difference to decreasing nocturnal cooling energy as forest density increases.

Tarboton (1994) attempted to measure sublimation at an elevation of 1350 m using large lysimeters (1 m^3), that contained soil, grass, and snow. The lysimeter prevented meltwater from percolating through the base of the device, and thus any change in mass was due to surficial processes acting on the snowpack. Possible changes in mass as stated by the author were due to precipitation, condensation, sublimation, or wind drifting. Changes in mass were recorded via datalogger every 30 minutes for three- or four-day measurement periods. Every three or four days the instruments were checked and the snow within the lysimeter was separated from the rest of the snowpack.

The intent of Tarboton's research was to correlate E-S measurements using lysimeters with an energy balance snowmelt model. However, data from the lysimeter measurements was found to be invalid for several reasons. When precipitation occurred, the snow over the lysimeter would be fused with the external snowpack. It was therefore difficult to assert that changes in mass were occurring only over the lysimeter, because the matrix of snow crystals may easily have extended from the snow sample in the lysimeter to the snowpack outside the lysimeter. The author also experienced problems with the datalogger, as the electronics of the device were affected by diurnal temperature cycles. This manifested itself as a large diurnal oscillation of measurements. Because this electronic oscillation was much greater in magnitude than daily E-S rates, the effects of E-S were masked and the data was not usable.

Most recently, Jackson and Prowse (2009) used lysimeters to capture spatial variation of snowmelt and sublimation along both elevation and canopy gradients in a high elevation basin in western Canada. The lysimeters were clear plastic "pails" 20 cm in diameter (314 cm^2) with holes drilled in the base to allow water to percolate into a catch pan below. The pails were filled with surrounding snow and buried so that the top edge of the lysimeter was flush with the snow surface. The lysimeters were distributed as an array along both elevation and canopy gradients. E-S was found to increase with elevation, but there was no significant difference found between clear and canopy sites at the same elevation.

1.2.2. Isotope Fractionation

The measurement of sublimation using isotope fractionation (I-F) as a proxy is an experimental method derived from extensive use in glaciology, where it is used to infer past temperature from sediment or ice cores. Modern field measurements of sublimation are typically made via aerodynamic profile methods or using eddy covariance. These methods can be highly accurate and can capture E-S rates at high frequencies; however they require a large amount of fragile instrumentation (Gustafson, et al. 2010). When compared to these methods of measuring E-S, I-F is much less demanding of field equipment, and thus has appeal for remote high elevation fieldwork. Establishing I-F as a method of measuring E-S in remote locations and was the impetus for its inclusion in this research.

The precise relationship between E-S rates and change in isotopic content of the remaining snowpack has been under some debate recently. This is due in part to the large number of variables that affect E-S, as well as the difficultly in constraining these variables in the field. I-F methods were examined as early as the 1970s in an effort to establish a relationship between sublimation and I-F. Moser and Stichler (1975) conducted research into how I-F evolved with time and altitude in a natural snowpack.

They were able to demonstrate the existence of a significant relationship, and asserted that further examination was necessary to fully understand this area of study. These findings prompted subsequent investigation by themselves and other researchers.

Several subsequent research endeavors were unable to determine a relationship between E-S and I-F. The diverging results of field studies focused on assessing the validity of isotopic fractionation was the impetus for numerous cold-chamber laboratory studies (e.g. Sommerfield, et al. 1991, Neumann, et al., 2008, Sokratov, et al. 2009). These experiments were conducted under controlled conditions designed to eliminate environmental variability and isolate explanatory variables.

Sommerfield, et al. (1991) conducted cold-chamber research in which vapor, after having sublimated from snow, was collected and used to determine the fractionation coefficient between two phases. They defined this fractionation coefficient as the ratio of heavy to light isotopes in each phase. The fractionation coefficient the authors determined between solid and vapor at -5°C was 1.013. This indicates the ratio of O^{18}/O^{16} in snowpack that has undergone sublimation is 1.013 times greater than that of snowpack where sublimation has not occurred. This ratio is valid only for the snow type used in this study, for the environmental conditions under which the experiment was conducted, however. Results of the experiment led them to the conclusion that the isotopic exchange in snowpack was the result of water molecules being converted from water to vapor or ice to water to vapor, rather than straight from ice to vapor. This conclusion was the result of an indistinguishable fractionation coefficient between the ice-vapor and water-vapor systems at -5°C.

Neumann, et al. (2008) conducted a laboratory experiment to ascertain the significance of I-F occurring as a result of sublimation. A temperature range from -23° to -5°C and variable airflow rates were used to control environmental conditions. The isotopic content of water vapor introduced to the incident airflow was controlled, and used as a comparison for the resulting isotopic content of the snow sample. These experiments produced a significant correlation between isotopic enrichment and sublimation rate.

Cold chamber experiments were conducted by Earman, et al. (2006) to ascertain the cause of the natural evolution of isotopic content throughout an accumulation season. The authors attribute this isotopic change to several possible factors, including E-S, condensation, partial-melting and refreezing, and isotopic exchange with atmospheric water vapor. Temperatures were controlled to be below 0°C, thus removing the possibility of the snow sample experiencing melt or evaporation. The isotopic content of the snow sample was found to have been altered throughout the course of the experiment, and the authors assert that the only reasonable explanation is the exchange of vapor between the snow sample and proximate water vapor in the air within the chamber, therefore confirming a significant relationship between I-F and E-S.

Field measurements performed by Gustafson, et al. (2010) in the Jemez Mountains of New Mexico measured, among many other variables, the isotopic enrichment of natural snow samples. Their data indicated a negative correlation with snow water equivalent at sites in forest openings. They attributed a majority of the enrichment to sublimation and not the combined effects of E-S, as there were no signs of melting in the snowpack up to the date of data collection. The authors found these results to be statistically significant, but noted a degree of uncertainty given the ongoing debate. The authors cite the findings of Moser and Stichler (1975) and Earman, et al. (2006) as evidence of some uncertainty, as both sublimation and condensation will affect the isotopic signature. The two dimensional movement of water vapor over the course of the diurnal cycle has been demonstrated to negate the effects sublimation has on isotopic enrichment (Moser and Stichler 1975), as the enrichment is reversed during nocturnal condensation. In light of these studies negating the reliability of fractionation as a result of sublimation, the authors conducted further analysis. Based on the strength of surface vapor pressure gradients, the authors determined that I-F was indeed occurring and that the magnitude of the fractionation due to sublimation was greater than the reverse process during condensation.

1.2.3. San Francisco Peaks Hydrologic Research

The San Francisco Peaks and the region surrounding Flagstaff have been the subject of extensive hydrologic research, with particular focus on E-S. This is due in part to the magnitude of snowfall the area receives relative to the surrounding Southwestern region, as well as a deficiency in how much water is needed versus how much accumulates annually. Avery, et al. (1993) used climatic data to create a sublimation opportunity index (SOI) that was evaluated as a predictor for sublimation variability and significance in the snowpack of northern Arizona. Three-hour observations taken at the Flagstaff National Weather Service office were used to calculate the four components of the index, based on bulk transfer of latent energy. The index was corrected for periods without snow cover. The SOI was later compared to physical E-S measurements taken during the winters of 1990-91 and 1991-92. These measurements were taken near Northern Arizona University at an elevation of 2130 m using foam lysimeters and data logging systems incorporating both covered and open instrumentation to capture the range of solar radiation. They found that 20% of the snowpack was lost to E-S and the remaining 80% to meltwater.

Between 1991 and 1994, a study was done regarding the effects of high E-S rates on the augmentation of runoff (Dexter, et al. 1999). Data was gathered at locations in the surrounding Flagstaff region, generally located at elevations near 2130 m. The average E-S rate they determined was 1.56 mm/day, and roughly 46.8 mm/month. These rates were compared to precipitation accumulation rates from NWS data. Frequently, monthly average precipitation rates were equal to or slightly greater than E-S rates. The authors determined that the timing and variability of precipitation was a large factor in E-S rates.

In 2000 a study was designed to mitigate environmental variability in E-S experiments (Avery and Dexter 2000). This was accomplished through the construction of an E-S tunnel inside a temperature-controlled room. Instrumentation was designed to produce repeatable conditions of constant temperature, wind speed, radiation and humidity. For each of these variables, different intensity settings could be assigned and the experiment would be executed, producing a matrix of results. During the experiments, continuous mass measurements were taken of both the lysimeter and meltwater catchment container. “Daytime” and “nighttime” conditions replicated with the presence or absence of a radiant energy source. This incident energy was determined to be the dominant factor in the rate of E-S, more so than wind speed or humidity. During sample-runs both radiant energy and wind speed were increased to maximum levels, but there was no discernible change in E-S over previous maximums achieved. This indicated that radiant energy was the dominant factor in E-S rates.

Sublimation values and the energy balance of snowpack along a forest-edge transect were analyzed for diurnal patterns and the effects of canopy cover (Etter 2006). Lysimeters were used to evaluate sublimation rates at various sites in the general Flagstaff area. The elevation of all sites was roughly 2130 m. A statistically significant difference was identified between sites on the transect. The highest rate of sublimation was determined to be under the canopy site early in the season. The reverse was true late in the season. In late season, the higher rate of ablation occurred at the canopy site due to high levels of nocturnal infrared radiation. The clear site experienced high levels of deposition during the night period early in the season, which caused the overall rate of ablation to decrease below that of the canopy site. Late in the season the deposition rate was small enough that the clear site experienced higher overall ablation than the canopy site.

1.3. Project Purpose and Scope

This study incorporates three measurement methods of E-S at three elevations on Agassiz Peak in the San Francisco Peaks of northern Arizona (Figure 1.1). The three elevations span an elevation gradient of 490 m, and are within close proximity to the boundaries of Arizona Snowbowl Ski Area (hereafter referred to as AZSB). Data for this research were collected during the winters of 2011-2012 and 2012-2013, primarily from January to March.

Figure 1.1: Western ridge of Agassiz Peak, where samples were collected for this study. Sampling sites and lifts are shown, as is the summit of Agassiz Peak.

1.3.1. Study Area: San Francisco Peaks

The San Francisco Peaks are a group of mountains derived from an eroded stratovolcano, located roughly 15 km north of Flagstaff, Arizona. The base of the peaks is located near the center of the largest stand of Ponderosa Pine in the United States, on the Colorado plateau with an average elevation of roughly 2130 m. The mountain range consists of several notable peaks, including Humphreys Peak which is the tallest summit in Arizona (3851 m), Agassiz Peak (3766 m), and Fremont Peak (3648 m). The mountains are of significant prominence in the region, and accumulated snowpack on the mountains can provide a significant portion of the water for Flagstaff via a shallow perched aquifer in the caldera.

This research was conducted on Agassiz Peak, which is adjacent to Humphreys Peak (Figure 1.1) and is the second highest peak in Arizona. On the western ridge of Agassiz Peak lies Arizona Snowbowl, a ski area spanning about 3.14 km^2 of terrain. The lifts operated by this ski resort were the means of transport between sites on the elevational gradient. The sites were located adjacent to ski trails, in locations that minimized human interference.

1.3.2. Climatology

The San Francisco Peaks experience a unique climate due to their location on the Colorado plateau and relatively high elevation compared with the surrounding arid landscape of Arizona. Intense insolation and nocturnal radiational cooling contribute to large diurnal temperature swings, exacerbated by low humidity and minimal cloud cover. Precipitation is highly variable in timing, frequency, and quantity. The dominant winter precipitation regime is pacific storms transported by the jet stream, when atmospheric conditions favor a more southerly track. This southerly shift of the jet stream occurs periodically throughout an average winter, and occurs more frequently during the El Nino phase of El Nino Southern Oscillation.

Climatological values from 1998-2013 recorded the Snowslide Canyon SNOTEL site (elevation: 2960 m) illustrate temperature trends that are similar to those of the sites used in this research (Tables 1 and 2). Average monthly temperatures are below 0^{o}C from November through March, and increase rapidly into May, which has a monthly average temperature of 6.7 ^{o}C. The most extreme average minimum temperatures are seen from December through February, with corresponding low average maximum temperatures. The fieldwork for this research was conducted during the winters of 2011-2012 and 2012-2013, from January through March. For these months, temperatures were slightly warmer than normal for the 2011-2012 winter, and slightly cooler than normal for the 2012-2013 winter. Records of monthly accumulation of snow water equivalent (SWE) indicate that both winters during which data was collected exhibited monthly precipitation accumulations both higher and lower than normal average monthly values. The driest months were January of 2012, which was 14% of normal, and February of 2013, which was 63% of normal. February of 2012 and January of 2013 experienced greater precipitation levels than normal, with 119% and 150% of normal, respectively.

Monthly snow accumulation and snow depth values were recorded from 1988-2004 at Agassiz lodge, located on Agassiz Peak at 2880 m (Table 3). These records indicate the greatest average monthly precipitation occurs in the months of February and March. Average monthly snow depth increases throughout the season, from the start of the measurement period in November until the end of the measurement period in April. Although the processes of E-S and melt are undoubtedly taking place throughout the season, the cumulative effect is less than that of snow accumulation rates. This ratio likely reverses in May, when precipitation accumulation decreases drastically and snowpack meltout is common. During midwinter dry spells, it is not uncommon for non-forested southerly and southwesterly aspects to be snow free, while northerly aspects retain significantly more snowpack.

Month	Average Monthly Temperature (^{0}C)	Average Daily Minimum Temperature (^{0}C)	Average Daily Maximum Temperature (^{0}C)	Average Monthly SWE Accumulation (cm)
Nov	-0.3	-6.1	5.4	6.6
Dec	-4.1	-9.8	0.8	10.9
Jan	-3.9	-10.3	1.3	9.1
Feb	-3.9	-9.9	2.2	10.4
Mar	-0.8	-7.5	6.3	8.1
Apr	1.9	-4.4	8.5	6.6
May	6.7	-0.4	13.1	2.8

Table 1: Climatological data from Snowslide Canyon SNOTEL station: 1998-2013

Month	Avg Monthly Temp (^{0}C) (11/12)	Avg Monthly Temp (^{0}C) (12/13)	Avg Min Temp (^{0}C) (11/12)	Avg Min Temp (^{0}C) (12/13)	Avg Max Temp (^{0}C) (11/12)	Avg Max Temp (^{0}C) (12/13)	Total Monthly SWE (cm) (11/12)	Total Monthly SWE (cm) (12/13)
Nov	0	1	-5	-4	5	8	8.4	6.6
Dec	-5	-2	-11	-7	1	2	17.3	11.9
Jan	-1	-6	-7	-12	4	0	1.3	13.7
Feb	-3	-5	-9	-12	3	2	12.4	6.6
Mar	1	2	-5	-4	7	8	6.9	5.1
Apr	5	3	-1	-2	11	10	4.8	2.3
May	9	N/A	2	N/A	15	N/A	7.9	N/A

Table 2: Climatological data from Snowslide Canyon SNOTEL station during field measurements: 2011-2013

Month	Avg Snowfall (cm)	Avg Snow Depth (cm)
Nov	39.4	14.5
Dec	53.1	32.0
Jan	82.8	57.9
Feb	90.4	82.0
March	89.9	110.5
April	43.18	123.19

Table 3: Measurements taken at Agassiz Lodge (2880 m). Period of measurement: 1988 – 2004.

1.3.3. Research Statement and Hypotheses

This research seeks to ascertain the nature of the relation between E-S and elevation, and in doing so, determine if the relation can be characterized as positive or negative. The relation will be investigated using the following hypotheses:

H_O: There is no difference in evapo-sublimation rates between stations along the elevation gradient

H_A: There is a significant difference between stations along the elevation gradient

There will be three subsets of this investigation.

1. Incorporate a fourth elevation into the gradient and examine if the trends in E-S with respect to elevation found in the primary analysis remain valid.
2. Investigate the relation between E-S and canopy cover. If a relation is identified, a determination will be made as to whether open or canopy sites promote greater E-S rates.
3. Investigate the relation between E-S and isotopic fractionation, and determine how well the two methods correlate.

These relations will be examined using appropriate statistical techniques, and the results of the sub-investigations will be presented in the context under which they are valid.

2. Methodology

2.1. Introduction

Over the course of the 2011-2012 and 2012-2013 winters, I conducted fieldwork using three sampling methods to measure evapo-sublimation (E-S) on an elevational gradient:

1. Change in mass measured using acrylic pans
2. Change in mass measured using lysimeters
3. Isotope fractionation (I-F) of oxygen and hydrogen

During the 2011-2012 fieldwork effort I employed pan measurements and collected snow samples for I-F analysis. During the 2012-2013 fieldwork effort, I employed pan measurements and lysimeter measurements. For any given 24-hour sampling period, I used two methods at each of the six sites.

The ability to collect samples was dependent upon lift operations at Arizona Snowbowl (AZSB) as well as environmental conditions. As a ski area in the southwestern U.S., the accumulation of sufficient snowpack to begin lift operations rarely happens until late December or January. During the first season of fieldwork (2011-2012), I began taking measurements January 19th, and continued until March 6th, accounting for 16 of the 21 total measurement periods. The usable data I collected during the second fieldwork season consisted of 5 measurement periods, which occurred between March 1st and March 29th. The 2012-2013 winter was marked with an increase in wind closures and precipitation events. These events severely limited my data collection efforts despite greater snowfall and a longer operating season than the 2011-2012 winter. I took pan measurements of E-S for all 24-hour data collection periods. I used these measurements as a baseline to compare against I-F and lysimeter data. I took samples for I-F during the 2011-2012 winter, to provide an alternative measure of E-S and validate this as a viable field method. I began using Lysimeters to measure E-S during the 2012-2013 winter to establish a quantitative relationship with pan measurements to incorporate an additional elevation from the research of Etter (2006). This addition was done with the caveat that atmospheric and site conditions may have differed significantly between my research and the research of Etter (2006). In this manner I created a quasi-fourth elevation to further explore the effects of elevation on E-S.

2.2. Sampling Sites

2.2.1. Station Locations

I chose three stations based on elevational differences and accessibility from AZSB. In this text, station refers to the point on the elevational gradient. These three stations spanned an elevation range of 490 m, and formed the gradient on which I was examining the response of E-S to elevation. The gradient extended from 2810 m to 3300 m, from below the base of Snowbowl Ski Area to a midpoint on the western ridge of Agassiz Peak. The three stations on the elevational gradient were each separated by a vertical distance of approximately 250 m, station L being the lowest, station M being the middle, and station H being the highest. At each elevation station, there was a canopy site and an open site, yielding a total of six sites composing the elevation gradient. These sites are referred to by subscript (i.e. H_o is the open site of the high station, H_c is the canopy site of the high station). The canopy site was situated so that less than 30% of the sky was open, blocking a majority of insolation. The open site was situated so that at least 65% of the sky was open, and a majority of insolation would be intercepted by the snowpack. Uniformity of these physical characteristics was the paramount goal in station selection, to eliminate differences caused by variation in environmental and atmospheric factors and isolate the effects of elevation on E-S.

The three stations had to be accessible on foot through deep snow in a relatively short amount of time, and thus possible locations were constrained to either within AZSB boundaries or in close proximity to the boundary. A finite number of accessible locations existed that were located at regular elevation intervals. Due to this scarcity, station characteristics diverged in environmental factors to some degree, as detailed below.

Station L was the lowest point on the elevational gradient, located at 2810 m, and within 100 m of a parking lot. Station L was located on the northwestern edge of a 0.5 km^2 clearing which contained small isolated clusters of Ponderosa Pine trees, but was primarily free of vegetation (Figure 2.1). Terrain surrounding the station was of relatively gentle slope, ranging from 0-10 degrees (Figure 2.2), on a northwesterly aspect. The distance between open and canopy sites at this elevation was 21 m.

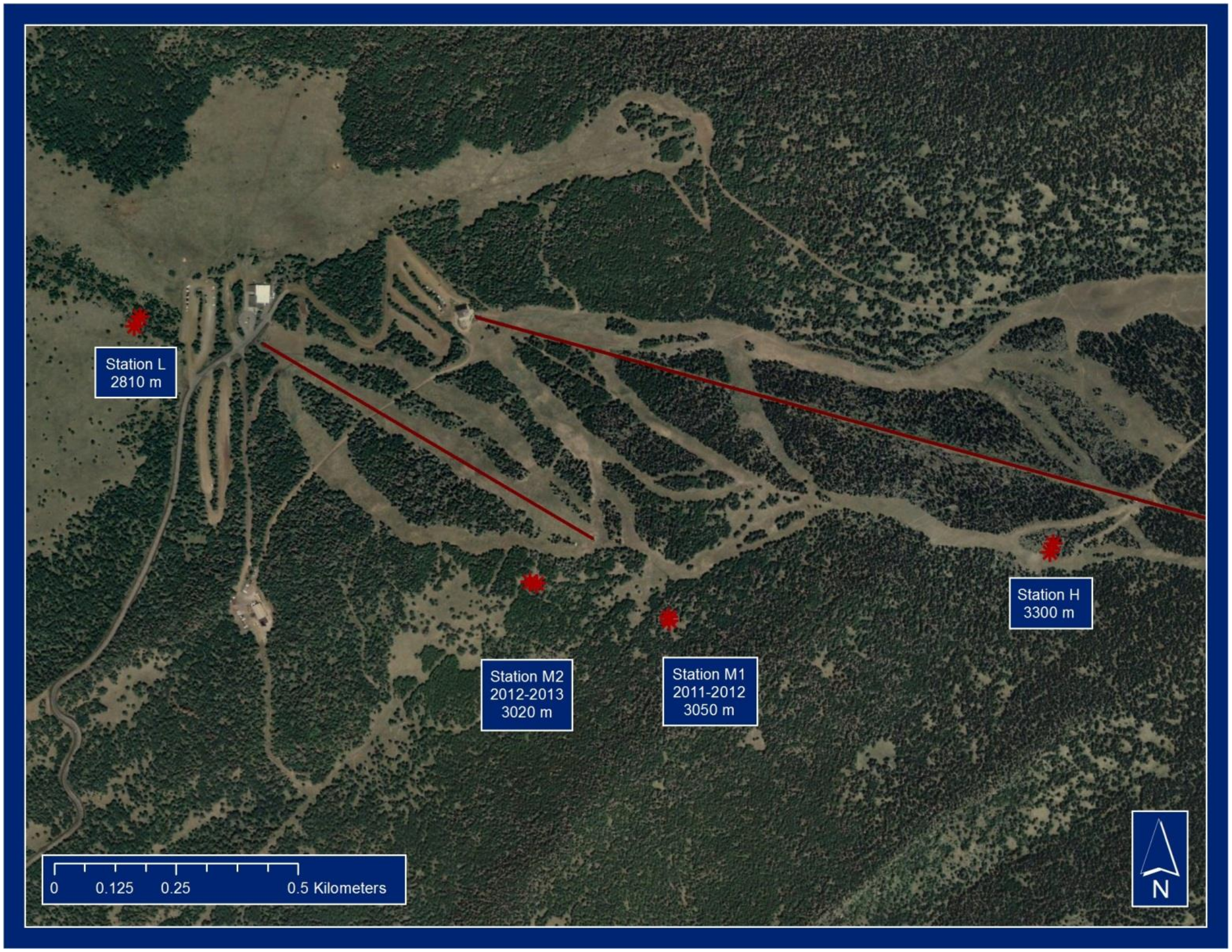

Figure 2.1: Station locations on Agassiz Peak. Shown are stations H, M1, M2, and L and surrounding vegetation density. Also shown are two primary lifts used for site access.

Figure 2.2: Slope variation in study area region: note relatively low slope angle (0^0 - 20^0) at stations L, M1, M2 and H. Station H borders a steep ridge, over which slope increases to between 20^0-30^0.

Station M was the midpoint on the elevational gradient, and was located at 3050 m, about 80 meters south of a ski trail. The slope ranged from 10°-20°, with a southwesterly aspect. The distance between open and canopy sites was 7 m. This station differed somewhat from stations H and L in that surrounding vegetation was denser than either the upper or lower elevations. At this elevation band there was no station within an accessible distance of AZSB that more closely resembled the vegetation characteristics of stations H and L.

Between the two winters that I conducted fieldwork, AZSB built a retaining pond to hold water for snow making purposes. The clearing created to contain this pond extended into the 2011-2012 location for station M1, forcing me to find a new location. I chose a new location 275 m west, and 30 m lower in elevation (3020 m), referenced as station M2. At station M2, the distance between open and canopy sites was 14 m, a 7 m increase. Slope remained between 10-20 degrees, and aspect remained southwesterly. The new station 2 was 60 m from the nearest ski trail, though I never observed evidence of human interference. Surrounding forest density was similar in the immediate area. Stations M1 and M2 were both adjacent to clearings, but the clearing near the station M2 was roughly twice the size of that near the station M1 (Figure 2.1).

Station H was the highest point on the elevational gradient, located at 3300 m. Station H was located in close proximity to a dominant north-facing ridge. Slope in the immediate area was between 10°-20°, on a southwesterly aspect. The distance between open and canopy sites was 20 m. During the 2012-2013 fieldwork season there was adequate snowfall coverage to allow skiers to enter this site, but there was never any observed human interaction with the instruments.

2.2.2. Sampling Frequency

A single sampling period was 24 hours. When possible, I took samples on consecutive days so as to maximize productivity and number of samples. Frequently, however, environmental conditions prohibited this from occurring, and most measurements were not consecutive. Typically, I was able to capture one E-S measurement in a weekly period. From this pattern, while sample size was limited, overall seasonal variability of E-S was well represented.

The most frequent impediments to field data collection were precipitation, blowing snow from high winds, and periods of high skier traffic (e.g. weekends). Any quantity of measureable precipitation nullified the results of that measurement period. Measureable precipitation was determined by monitoring the Snowslide Canyon SNOTEL station data in addition to a visual inspection of the site. Trace precipitation amounts were not frequent, thus I was typically able to discern the occurrence of precipitation visually. Blowing snow was a frequent occurrence in the periods following precipitation. There was no definitive threshold above which snow was transported by wind, rather it was dependent on wind speed, temperature, and the length of time elapsed since the most recent precipitation. If temperatures increased rapidly following a storm, I was able to take measurements sooner than if temperatures were low and the snow remained unconsolidated. Evidence of blowing snow was examined as part of the daily site inspection upon arrival, and results were nullified if the occurrence of blowing snow was detected.

Due to the relatively small magnitude of mass change of the physical E-S process, precipitation or blowing snow could easily occur in larger magnitudes and nullify the E-S process. Preventing this influence with a physical barrier was not feasible, as this would block wind that would scour water vapor, affecting a primary component of the E-S process. Likewise, it was not possible to create a structure insulating the pan from precipitation, as energy from insolation is also a primary factor of E-S. Due to the climatology of the San Francisco peaks, and the strong winds that precede and follow low pressure systems, in the period immediately following a storm I was typically unable to take accurate measurements. Snow density was too low and winds were too strong. Therefore, the majority of E-S measurements for this study were taken in higher density snowpack (up to 0.44 g cm^{-3}). E-S rates in lower density snowpack may diverge from those in this research.

2.3. E-S Measurement Techniques

2.3.1. Pan and Lysimeter Construction

The pans were constructed out of a 6 mm thick clear acrylic plastic. The completed pans measured 20 x 30 x 5 cm, yielding a volume of 3000 cm^3 and exposed surface area of 600 cm^2 (Figure 2.3). I selected this size of pan to keep the maximum mass of snow under the 2000 g capacity of the Ohaus scale given the wide range of snow densities possible in this climate. Due to high temperature variance at the study location, snow densities ranged from 0.13 – 0.44 g cm^{-3} over the course of the sampling season. I fortified the seals at the seams of the pans using glue and adjustable clamps, and monitored the integrity of this process throughout the fieldwork season to prevent the loss of meltwater through bottom of the pan.

Figure 2.3: Pan at site H_C prior to 24-hour exposure.

In constructing the lysimeters I attempted to replicate the instruments used in the research of Etter (2006). The walls of the lysimeters were Thermax rigid sheathing material, which is 5 cm thick hydrophobic foam covered on both sides with reflective aluminum foil. Each lysimeter measured 20 x 20 x 7 cm, yielding an internal volume of 2800 cm^2 and an exposed surface area of 400 cm^2. These dimensions were precisely 2/3 the scale of the lysimeters used in Etter's research, to accommodate the mass range capability of the scale used to weigh the instruments. The foam box was bolted to a Teflon-coated baking pan using 6 mm bolts and wing nuts for ease of removal. To prevent vapor from escaping the meltwater pan, I glued a rubber seal at the interface between the meltwater pan and the foam base. I drilled a regular grid of 25 holes in the bottom, and inserted plastic drinking straws to facilitate the transport of meltwater into the Teflon pan (Figure 2.4).

Figure 2.4: Lysimeter after 24-hour exposure at site M_C.

2.3.2. Pan and Lysimeter Measurement Procedures

I measured the mass of the pan and lysimeter snow samples before and after exposure using an Ohaus Scout Pro portable scale with a 2000 g capacity and a 0.1 g resolution. The power source was 4 AA batteries. When first starting this fieldwork in the winter of 2011-2012, I used a linear calibration procedure at each site with two 1000 g masses to ensure accuracy before recording measurements of snow samples. This eventually proved to be unnecessary and beginning midway through the 2011-2012 fieldwork season I performed this calibration just once at the beginning of each day. Even after scaling back the frequency of calibration, there was negligible drift in accuracy of the scale.

I used an aluminum snow shovel blade to collect and transfer the snow sample to the pan and lysimeter measurements. The following procedure was implemented to ensure uniformity and accuracy. When filling the pans and lysimeters, replicating snowpack density was the primary goal, due to the relationship between snow density and E-S rates (West 1959). I took great care to not compress the snow while handling the sample. The top 5 cm of snow pack was collected using the shovel blade for pan measurements, and the top 7 cm of snow was collected for lysimeter measurements. I placed the snow in the respective container and leveled the top off to replicate the environmental snowpack surface. Earman, et al. (2006) determined that the surface of the snow can play a significant role in the rate of sublimation, as different surface shapes intercept wind in different manners. This can differentially scour water vapor from the surface, affecting E-S rates. I recorded the mass of the instrument, and then deposited the instrument in the snow so that the top was level with the slope and flush with the height of the adjacent snowpack surface. After the elapsed time period of 24 hours, I wiped excess snow and water from the exterior of the instrument, and recorded the mass (Figure 2.5).

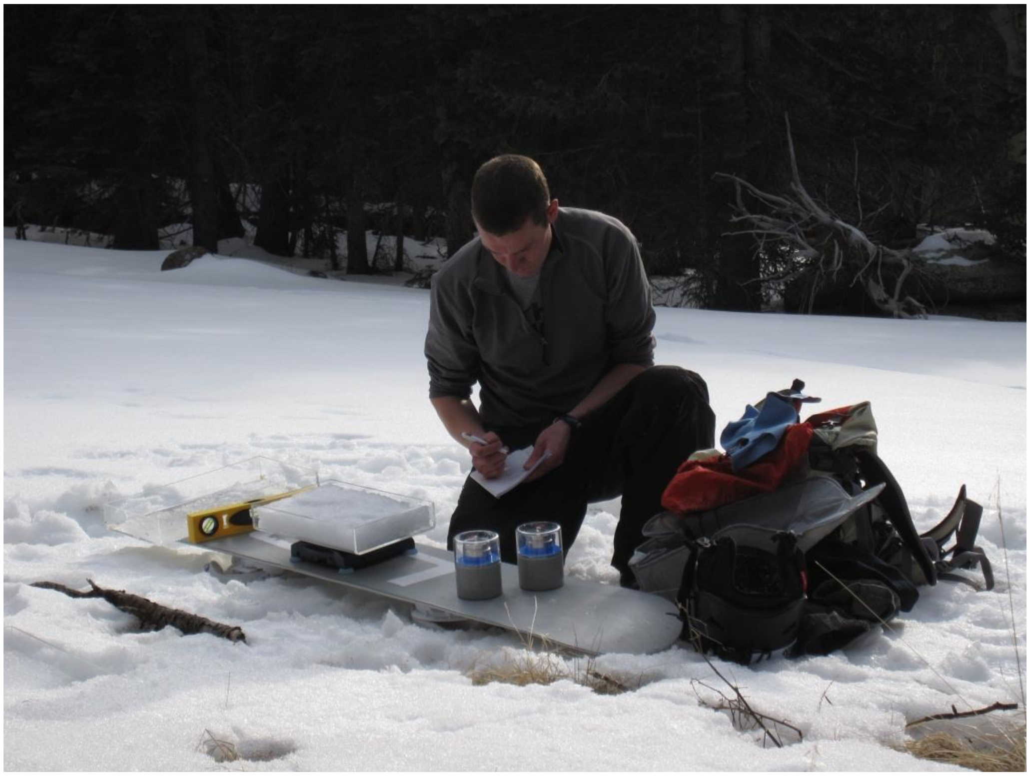

Figure 2.5: Recording mass post-exposure at site M_O.

2.3.3. Isotope Fractionation Measurements

I collected snow for isotopic fractionation measurements at the same precise location used for pan measurements. I collected the top 5 cm of snowpack, to minimize spatial variability between the snow samples for pan and isotopic fractionation measurements. Snow for isotopic fractionation measurements was collected using a polystyrene scoop, which was wiped down and stored in a sealed container while travelling between sites. I deposited the snow sample into a Whirl-Pak bag which I sealed after expelling as much air volume as possible. After the measurement period of 24 hours, I took another sample in similar fashion. I filtered the melted snow samples using a 45 micron filter, and the

Stable Isotope Laboratory at Northern Arizona University conducted the analysis using an isotope ratio mass spectrometer.

2.4. Statistical Analysis

2.4.1. Data Quality

The first step in this analysis was to perform a quality control check of the data. To do this I compiled the six data sets produced over the two fieldwork seasons (H_O, H_C, M_O, M_C, L_O, L_C). The total number of 24-hour sampling periods was 21, and thus there was a maximum of 21 possible values in each data (Appendix). However, various environmental disturbances caused some measurements to be erroneous, and these were removed from the data set. The occurrence of environmental disturbance was determined either from field notes in the case of blowing snow or tipping/leaking of the pans or lysimeters, or from the Snowslide Canyon SNOTEL site if the environmental disturbance was precipitation. If precipitation or blowing snow occurred during a sampling period, measurements from all six sites were removed from the dataset. If the disturbance was something that may have only influenced one pan, such as snow melting out around the pan causing spillage, then only data from that site was removed.

2.4.2. Elevation and Canopy Effect Analysis

The first relationship I examined was the dependence of E-S on elevation. I performed a series of statistical tests using R (v. 3.0.0) to conduct this analysis. To determine if the sample populations were derived from a normal distribution, I used a combination of tests. I conducted a visual inspection of Q-Q plots, and examined each data set using the Shapiro-Wilk test. Q-Q plots allow the user to examine how much their data diverge from a line of theoretical quantities derived from a normal distribution. The Shapiro-Wilk test examines the distribution using a null hypothesis that the data are sampled from a normal distribution. Therefore, a small p-value is evidence that the data are not sampled from a normal distribution.

The second step in the analysis was to conduct a visual inspection of equal variance using box plots and a quantitative evaluation using Bartlett's test. Box plots provide a simple visual means of comparing median values, the range from the 1^{st} and 3^{rd} quartiles (inter-quartile range), and the relative length of "whiskers", which are 1.5 times the length of the inter-quartile range. Once a cursory visual inspection was done, I used Levene's Test with the median as the point of centrality to determine if the variances between the stations were equal. Levene's Test is used to determine equality of variances between samples when the samples are not assumed to originate from normal distribution. The null hypothesis for this test is that variances are equal, and thus if the test calculates a small p-value, the null hypothesis is rejected, and one concludes that the variance is unequal between samples.

The third step in the analysis was to determine if the differences between the stations were statistically significant. This was accomplished using the Kruskal-Wallis non-parametric method. The Kruskal-Wallis test is similar to a one-way ANOVA, but does not make the assumption that the samples being tested come from a normal distribution like ANOVA does. The null hypothesis for this test is that there is no difference in the means of each group. In this test, the data were grouped into stations, and separated into open and canopy sites. To test if elevation was a significant factor, the

Kruskal-Wallis test was run with data grouped by station. To test if open sites and canopy sites exhibited different average values of E-S, the test was run on data from each station.

If the results from the Kruskal-Wallis test indicate significant differences between groups, then the next step in analysis is to determine which of the groups are different. The Mann-Whitney-Wilcoxon test was used can be used to accomplish this task. This test examines whether populations distributions are normal without assuming they follow a normal distribution, as the data being examined does not. The null hypothesis is that the populations are identical. Therefore, if the resultant p-value is small, a significant difference between the populations is detected.

Once a significant difference was identified between groups, it was then necessary to determine between which groups there was a difference. To do this, the Mann-Whitney test was used. This test compares two groups of data, and calculates a test statistic based on the rank of each individual component of the group. The null hypothesis is that the means of the two samples are equal, therefore a small p-value is evidence of significant difference between sample means.

2.4.3. Incorporation of Fourth Elevation

The goal of collecting lysimeter data during the second season of fieldwork was to establish a relationship between values measured by both pan and lysimeter methods, and use that relationship to add a fourth elevation of pan measurements. Pan measurements were the object of this analysis because the lysimeter data was not as robust, having been collected for part of one winter and resulting in six sampling periods of valid measurements.

To determine the relationship between measurement techniques, a linear correlation was calculated between the complete sets of data and evaluated to see if it was a valid relationship. I calculated the ratio of change mass change between pan and lysimeter measurements, then calculated the mean. The mean was then compared to a histogram of all ratios, to determine general accuracy.

Once the ratio of pan measurement to lysimeter measurement was determined, I applied that ratio to lysimeter measurements taken on the Colorado Plateau by Etter (2006). The resultant value was a hypothetical average of pan measurements taken at the same time lysimeter measurements were taken. This value was then used as a quasi "fourth" elevation (referenced as station P) in the elevational gradient. Given the strong potential for differences in environmental conditions between this research and that of Etter (2006), this analysis was not statistical in nature. Rather, the analysis was a hypothetical exercise to ascertain if the trend exhibited by data from this research was supported by data from the research of Etter (2006).

2.4.4. Isotopic Fractionation Data

To determine how well E-S correlated with I-F, I performed an analysis on the change in ratios of O^{18}/O^{16} and H^2/H as a function of pan measurements (change in mass). The change in the ratios of O^{18}/O^{16} and H^2/H over the exposure period was calculated as the difference between the snow sample taken prior to 24-hour exposure and the snow sample taken after the exposure. If the processes were well correlated, the sign and magnitude of E-S would be similar to the sign and magnitude of enrichment of the heavier isotope (O^{18} or H^2). The resultant correlation and absence of further inquiry into this relation is discussed in the results portion of this work.

2.4.5. Multivariate Analysis

The final subset of this analysis was to determine how well meteorological variables correlate with E-S rates. Meteorological records were obtained from minimum and maximum thermometers at each elevation station, as well as from the MesoWest station near the summit of Agassiz Peak and a SNOTEL station located in the caldera of the San Francisco Peaks. Due to the distance and location differences between the elevation stations and the meteorological stations, some variables had a low probability of being well-correlated causative factors (e.g. wind direction and wind speed at SNOTEL station, due to lack of proximity). However, some variables such as insolation and pressure recorded at the SNOTEL station, and wind speed and wind direction recorded at the MesoWest station would experience similar conditions as the elevational sites.

I fit linear models to E-S as a function of each variable (local maximum and minimum temperature, solar radiation and pressure at SNOTEL station, relative humidity, wind speed and wind direction at MesoWest station). The quality of fit was assessed using Akaike information criterion (AIC), which is a means of estimating information loss when representing data with a model. While this criterion is a relative value, it works well to compare models of the same type, particularly when adding additional dependent variables. When comparing a similar set of models, the model with the smallest AIC value represents the data with the least amount of information loss, and thus the best fit. The findings from this analysis are discussed in the results section.

3. Results and Discussion

An analysis of data quality was performed on all data collected. The first step in this process was to perform a quality control check on the six data sets (H_O, H_C, M_O, M_C, L_O, L_C). Precipitation was the most frequent obstruction of data integrity. 24-hour sampling periods during which precipitation was recorded at the Snowslide Canyon SNOTEL site were eliminated from the dataset. These eliminated sampling periods were 1/17/12, 1/18/12, 2/17/12, and 2/8/13. Blowing snow was also a frequent occurrence, and was recorded in field notes based on observations taken during the daily visual site inspection. Sampling periods eliminated as a result of blowing snow included 1/26/12 and 2/15/13. Further sampling periods were removed due to blowing snow, but the amount of snow transported was of such magnitude that I did not take end-of-period measurements, and thus did not count those days in the dataset. Examples of singular data points eliminated are sites L_C for 2/1/13 due to debris falling into the pan, and L_O for 2/10/12 due to meltout around the pan leading to spillage. There were 18 samples removed from analysis due to environmental interference (14% of all samples collected). Once data integrity was verified, I performed analyses of the pertinent relation using R statistical software.

3.1. Elevation Effect

To examine the relation between evapo-sublimation (E-S) and elevation, data from all six sites was grouped into two datasets: a dataset consisting of the open sites: H_O, M_O, and L_O, and a dataset consisting of canopy sites: H_C, M_C, L_C.

The first statistical test performed was the Shapiro-Wilk test for normality. This test evaluates if the assumption that the data originated from a normal distribution is valid. The six datasets were tested individually, and only the data for site H_O resulted in a significant p-value, indicating normality. The remaining five datasets failed this test (Appendix**)** and were therefore assumed to have originated from a non-normal distribution. I conducted the remainder of the statistical analysis using non-parametric methods, which make no assumptions about the distribution the sample originated from.

After normality (or lack thereof) was determined, I examined the similarity of variance between datasets. This was done using Levene's test, with open and canopy sites grouped by station (elevation). Both datasets resulted in large p-values (Appendix) and thus failed to reject the null hypothesis of equal variance. Equality of variance was therefore determined to exist between stations when grouped by open or canopy sites, allowing for further examination of the data for differences between stations i.e. differences between elevations.

The Kruskal-Wallis one-way analysis of variance was used to detect significant differences between stations of respective site type. Using a significance level of 0.10, a significant difference between stations was not detected within the open dataset (Appendix). In other words, variance of measurements at each station was too great to resolve the relatively small differences between stations for open sites. The canopy dataset, however, did exhibit significant differences between stations. This result then required further inquiry using the Mann-Whitney test to determine which combinations of stations differed significantly. A significant difference was detected M_C and L_C (Figure

3.1). This analysis indicates that the difference in elevation was determined to be significant only between the canopy sites of stations M and L. The differences between the remaining canopy sites were insignificant, as were all differences between open sites.

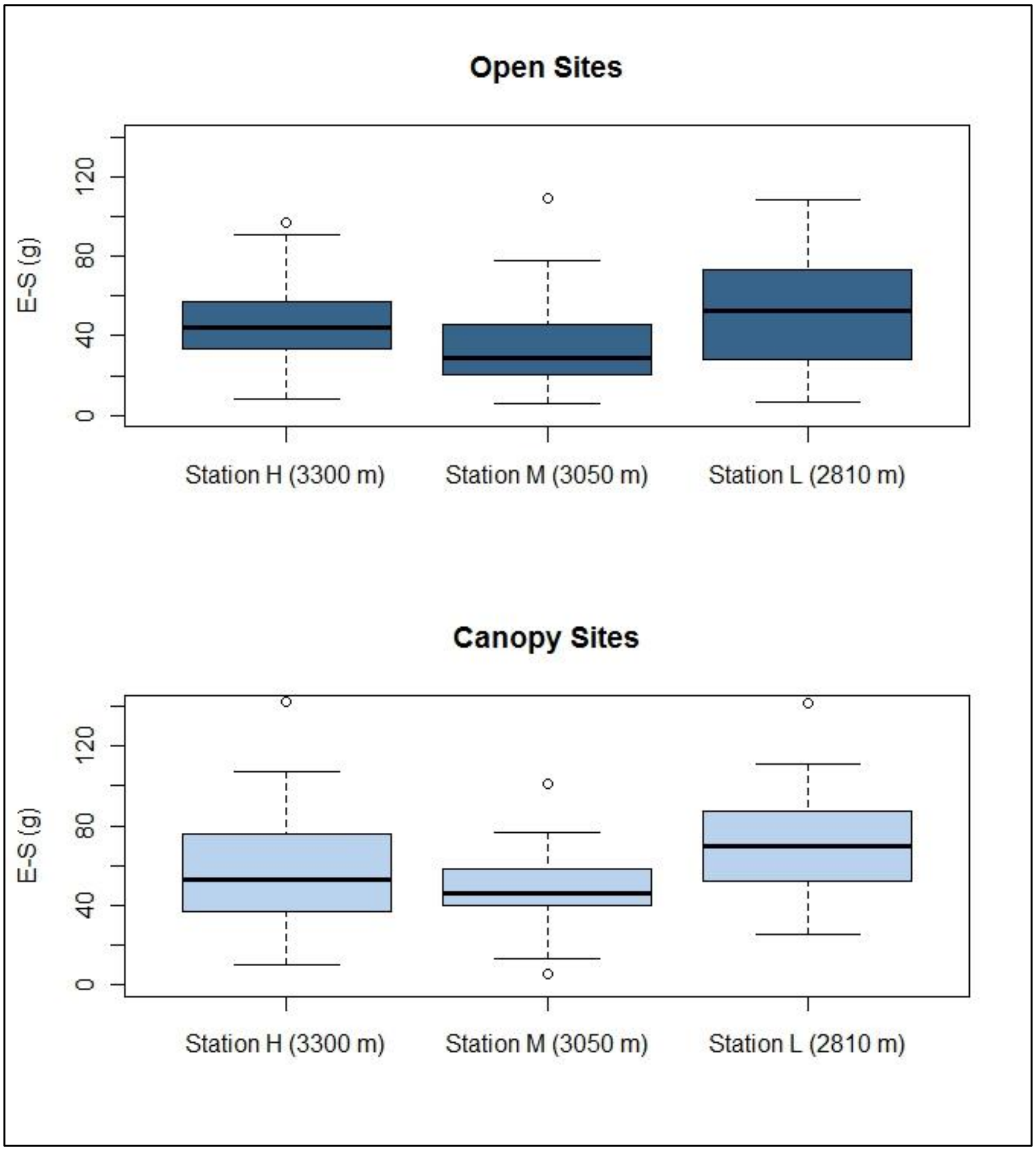

Figure 3.1: Boxplots of all data grouped by station and canopy cover. High variance prohibited the detection of statistical significance between all sites but M_C and L_C.

3.1.1. Discussion

From a statistically-driven standpoint, the results of this analysis indicate that elevation has little to no effect on E-S, with the only significant difference existing between the canopy sites M_C and L_C. There are several possible reasons for the lack of a statistically significant relationship between elevation and E-S. The first, easiest conclusion to deduce is that there is not, in fact, any significant relationship between elevation and E-S. However, this may be too simplistic of a conclusion, as previous studies have found the opposite to be true (Montesi, et al. 2004, Jackson and Prowse 2009). While there is insufficient statistical evidence to pronounce the elevational stations in this research different, it may be that the effects of terrain sheltering, wind speed, and temperature have a stronger influence on E-S than elevation, and thus the effects of site characteristics overwhelmed the effects of elevation.

I performed a calculation of the sample size required to produce statistically significant differences between sites, given the same sampling distribution as in this research. While this type of analysis requires numerous assumptions, it is a useful exercise to gauge the order of magnitude of the required sample size. Sample size calculation is dependent on the number of groups being examined, effect size, significance level, and power of an experiment. Power is the probability of finding an effect that exists. Significance level is the probability of finding an effect that does not exist. Effect size is a less concrete value. Effect size references the significance of the variable being measured, and thus is difficult to quantify. Three values are commonly used in sample size calculations for one-way analysis of variance that correspond to small, medium, and large effect size (Cohen 1992). I performed the calculation with all three suggested values and determined that an effect size of relatively small, medium, and large resulted in a sample size of 322, 52, and 21 per group (per site) respectively. Given that the sample size per group in this study is 21, and there is not a statistically significant relationship between groups, one can conclude that elevation does not exhibit a large effect size on E-S. Therefore, the necessary sample size per group is larger than 21 and less than 322. While this information is conceptually useful, one must remember that the data collected may not exhibit the same distribution as what has already been collected, and thus may have different values of centrality and variance.

As a hypothetical exercise, we will assume that large enough group sample sizes were collected ($21 < n < 322$) and that the data still exhibit the same distribution. For the purpose of this analysis, we will examine the data based on the mean values of each site (Figure 3.2). While there is no linear trend (i.e. station L > station M > station H), the same pattern with respect to elevation is evident in both the open and canopy data: station L > station H > station M. Previous work has found E-S to both increase with elevation (Jackson and Prowse 2009) as well as decrease with elevation (Montesi, et al. 2004). While there is no monotonic trend in the data from this research, these results appear to lend more support to the view that E-S rates decrease as elevation increases. Due to the absence of a monotonic trend exhibited by this data, it is difficult to explicitly state the relationship of E-S and elevation. We can however, posit the reasons for station M's uniformly small E-S rates.

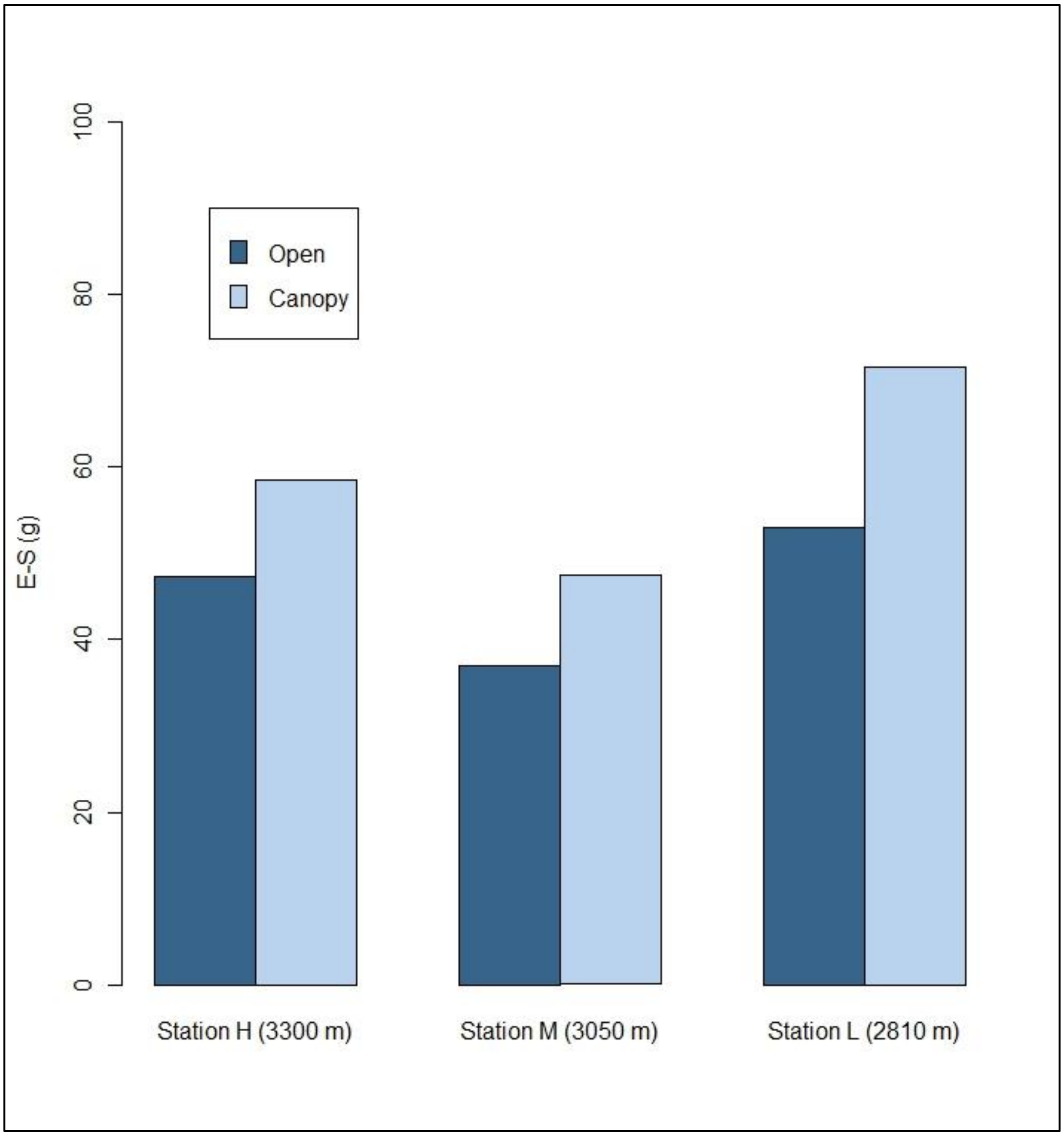

Figure 3.2: Mean values of E-S for all valid data.

The environmental factors that are influenced by elevation (pressure, solar radiation, humidity, vapor pressure, and wind speed) are, with the exception of wind speed, unlikely to have been altered from their normal state by site characteristics. The lowest mean E-S rates occurred at station M, and may be attributable to greater surrounding forest density and lowered wind fetch than at stations H and L. This increased forest density may have resulted in decreased wind speeds, which would then scour less surface water vapor and decrease the vapor pressure gradient, resulting in lower E-S rates. Aside from forest density, site characteristics are unlikely to have caused divergence between stations in environmental factors related to E-S.

3.2. Incorporation of Fourth Elevation

The fourth elevation added to the elevation gradient of this study contains the mean values for open and canopy sites from all data collected by Merrianne Etter on the Colorado Plateau at 2300 m (station P). These values were not used as input into the statistical or quantitative portions of this analysis, as there is too much variance between the two studies in terms of environmental factors. An additional confounding factor is that the difference in elevation does not match the elevation steps of the gradient established in this research. Despite the limitations of this fourth elevation, it is still a worthwhile comparison to see if the trend exhibited by this research is supported with the addition of a much lower site elevation.

The average values reported for Etter (2006) research were 30-minute means of E-S taken over 48-hour periods. The 30-minute means were 1.6047 g and 1.6897 g for open and shade sites, respectively (Appendix). I extrapolated these out to daily means, yielding a 24-hour mean loss of 77.0256 g and 81.1056 g for the open and canopy sites, respectively. These values were converted into equivalent pan measurements using the ratio of pan/lysimeter values of 1.448, which was calculated from the ratio of pan/lysimeter values from my measurements. These “converted” values were 111.5547 g and 117.4637 g, for open and canopy sites, respectively (Figure 3.3). There is a marked differential in the mean rate of E-S between this fourth elevation (2300 m) and the nearest station, station L (2810 m).

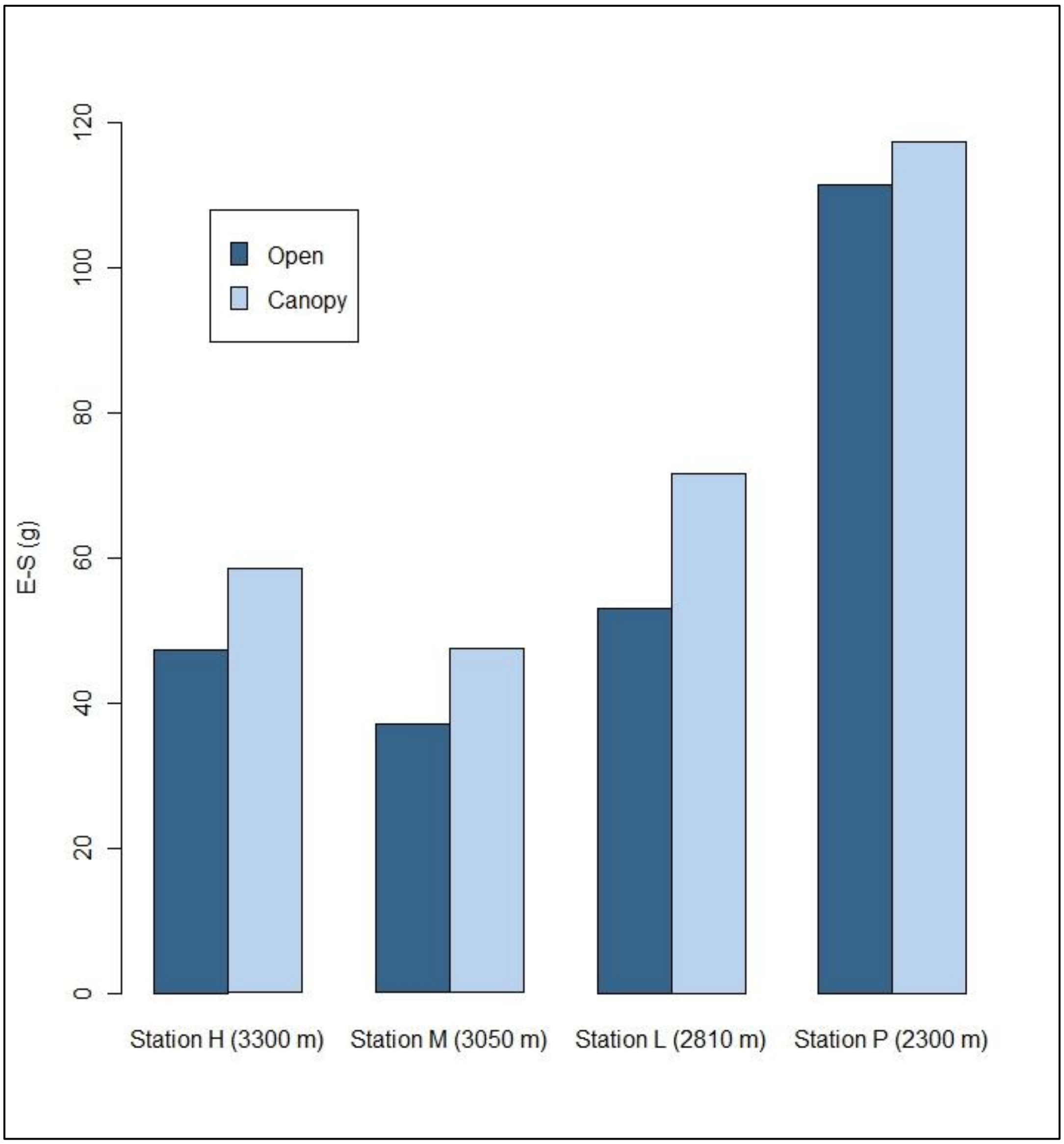

Figure 3.3: Open and canopy mean E-S rates from this research (stations H, M, and L) compared to those of Merrianne Etter’s research (station P).

3.2.1. Discussion

The addition of the fourth station supports the trend exhibited by the original three stations: E-S rates decrease as elevation increases. The converted values from station P are considerably higher than station L – the nearest station in elevation. This supports the assertion that E-S decreases with increasing elevation. This assertion is given further support when examining the differential of E-S increase between the fourth elevation and station L. Stations H, M and L have elevation differences of between 240-250 m, whereas the difference in elevation between station L and station P is 510m – greater than twice the difference between stations of this study. The magnitude of E-S rates seems to correlate well with this increased elevation differential, as the largest difference in E-S rates between adjacent stations is between station L and station P.

3.3. Evapo-Sublimation as a Function of Canopy Cover

The relationship between evapo-sublimation and canopy cover was examined using data grouped by station, to compare open and canopy sites. This yielded three datasets, each containing an open and canopy site. From the previous analysis of effects of elevation on E-S, it was determined that the data were not sampled from a normal distribution. Addressing this non-normality required the use of non-parametric methods, as in the previous analysis.

As the normality assumption had already been addressed, the first step was to use Levene’s test to determine equality of variance. The results of Levene’s test on all three data groups indicated the assumption of equality of variance was valid (Appendix). Due to the simplicity of the relationship being examined (open vs. canopy) it was not necessary to use the Kruskal-Wallis test to detect a general difference between multiple groups. Instead, the Mann-Whitney test was used to detect differences between open-canopy pairs. In other words, the test was used to detect if there was a significant difference between open and canopy sites for a given station. A significant difference was detected between open and canopy sites at stations M and L, whereas station H did not exhibit a significant difference between open and canopy sites (Appendix). These results indicate that E-S rates at canopy sites were significantly higher than open sites at stations M and L, but not at station H (Figure 3.4).

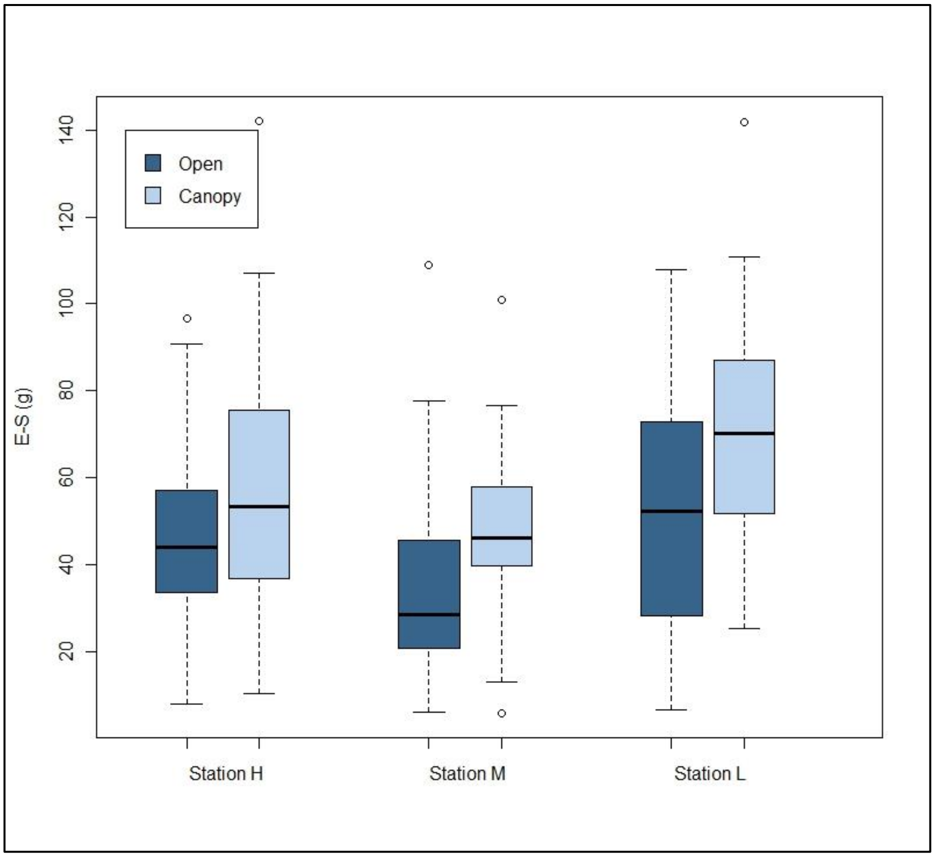

Figure 3.4: Boxplots of open and canopy data, grouped by station. Note the presence of outliers, which were determined to be valid measurements

3.3.1. Discussion

Stations M and L exhibit E-S rates that are statistically higher at canopy sites when compared to the open site of the same station. While station H exhibits the same relationship in that the canopy site has a greater E-S rate than the open site, the relationship is not statistically significant. As in the discussion of the relationship between elevation and E-S, this discussion will examine the hypothetical scenario that an adequate number of samples were taken to confirm the site differences as they currently exist.

Canopy sites had an average of 23% higher E-S rates than the open site of the same station. This confirms previous work contrasting E-S rates between open and canopy locations (Gustafson, et al. 2010). While E-S rates are higher under forest canopy, rates of melt are higher in locations exposed to greater amounts of insolation, and is therefore why snow remains for longer periods of time under forest canopy (Jackson and Prowse 2009). The trend of higher E-S rates at canopy sites versus open sites may not have been significant at station H due to greater wind speeds than stations M and L. These higher wind speeds may have advected energy away from snowpack under forest canopy, energy that otherwise would have driven both diurnal and nocturnal E-S, increasing rates over the open site.

3.4. Isotope Fractionation Analysis

An analysis was performed on the isotope fractionation (I-F) data from the 2011-2012 fieldwork season to determine if I-F was a valid method of measuring E-S. Ratios of O^{18}/O^{16} and H^2/H were measured by the Colorado Plateau Stable Isotope Laboratory from snow samples taken at the beginning and end of each 24-hour sampling period. An increase in the ratio of heavy to light isotope (O^{18}/O^{16} or H^2/H) would be indicative of E-S (Sokratov and Golubev 2009). Because there was net loss of mass during all sampling periods, snow samples should show enrichment of the heavy isotope for the period, and that enrichment should be proportional to the magnitude of E-S for that sampling period. Isotope enrichment was reported from the laboratory as per mil (‰), as the isotopes being enriched (O^{18} or H^2) are scarce when compared to their abundant counterpart (O^{16} or H).

To determine the validity of the relationship between pan-measured E-S and I-F of Oxygen or Hydrogen, a linear regression was calculated for each pair of data (i.e. both measurement types from site H_O).The resultant coefficients of determination (R^2) were poor. If the two processes were highly correlated, R^2 values would approach 1 (or -1 for a negative correlation). Values near zero indicate a lack of substantial relationship, and that one variable is a poor predictor of the other. The coefficient values for nearly all regressions were near zero (Appendix). The largest correlation coefficient was 0.12, which was not a statistically significant result.

There are several possible reasons this portion of the experiment was not successful in capturing the relationship between E-S and I-F. The first possibility is that these results accurately reflect the effects of E-S on I-F, and that the correlation of the two processes in actuality is not great. This is possible, but lacking somewhat in merit as previous studies have determined that E-S and I-F correlate well (Earman, et al. 2006, Sokratov and Golubev 2009). The relationship between I-F and E-S is found to be particularly robust in semi-arid environments (e.g. the southwestern US) where equilibrium fractionation is low (Earman, et al. 2006). It is therefore unlikely that the small correlation values calculated in this analysis accurately describe the effects of I-F. Gustafson, et al. (2010) concluded that there are high levels of horizontal spatial variability in the E-S process, driven by small differences in solar forcing. That conclusion in addition to the lack of correlation exhibited by the data in this study indicate that a greater number and greater spatial distribution of both E-S and I-F measurements are necessary to capture the true effects of I-F on E-S.

3.5. Multivariate Analysis of Meteorological Variables

I examined the relation between E-S measurements and meteorological variables to determine causative factors of E-S. The sources of meteorological data were threefold: local minimum and maximum temperature, meteorological data from a nearby SNOTEL station, and meteorological data from a nearby MesoWest station. Of all the variables examined, the best linear model fit was E-S as a function of local maximum temperature (Figure 3.5).

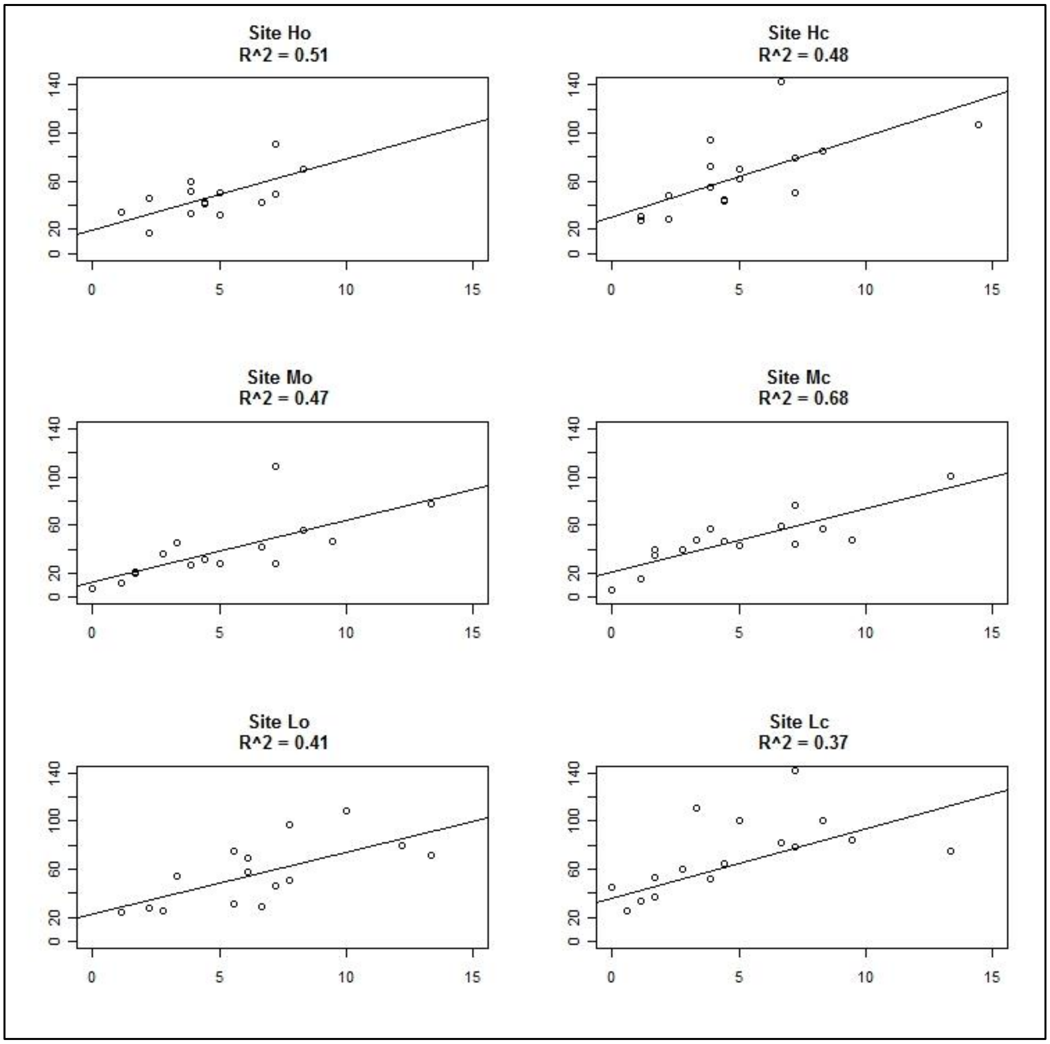

Figure 3.3: E-S as a function of local maximum temperature for each site. X-axis: daily maximum temperature (^{0}C). Y-axis: E-S (g).

Subsequent analysis was conducted to investigate if additional dependent variables improved the model. Variables examined were local minimum temperature, relative humidity, pressure, solar radiation, wind speed, and wind direction. Model quality was assessed using Akaike information criterion (AIC). The average AIC value for all six models of E-S as a function of local maximum temperature was 93.69. By itself, this value is not of great significance. It can, however, be used to compare with other model configurations of similar type (i.e. E-S as a function of pressure). When adding further dependent variables to a model, AIC should decrease, indicating that the model is a better fit for the data. No combination of variables uniformly decreased values of AIC, indicating that the simple linear model of E-S as a function of local maximum temperature was the best predictive model. Therefore, maximum temperature had the greatest influence on E-S rates. The results of this analysis are skewed, however, as many environmental factors have highly variable spatial distribution, and values measured at each elevation station may have produced a different outcome.

4. Conclusion

4.1. E-S on an Elevation Gradient

Evapo-sublimation (E-S) rates were examined on an elevation gradient using two primary means of measurement. E-S was generally found to decrease with increasing elevation, though the middle station exhibited uniformly lower rates than both the high and low elevation sites (Figure 3.1). I postulate that the relatively low rates observed at this middle elevation were due to a greater density of surrounding forest canopy than either the high or low elevations. The increased forest density decreased wind fetch, and thus lowered wind speeds at the middle elevation. These lower wind speeds were not as efficient at scouring vapor from the near-surface boundary layer, and thus the resultant vapor pressure gradient was weaker and did not drive E-S rates as strongly as at the high and low elevations. This decreased vapor pressure gradient acted to mask the effects of elevation on E-S, and prevent the middle elevation from supporting the trend exhibited by the remaining stations.

The results of a statistical analysis indicate that variance levels were too high to conclude statistically significant differences between E-S rates at elevational sites (Figure 3.1). Only one combination of sites (M_C and L_C) exhibited significant differences. The null hypothesis was therefore not rejected, and the statistical conclusion of this portion of the analysis indicates the absence of a significant relationship between elevational sites given the sample size and variance of data collected.

4.1.1. Incorporation of Fourth Elevation

A fourth elevation was derived from E-S rates on taken on the Colorado Plateau in the Flagstaff area and added to the elevational gradient (station P) for a subset of the primary analysis. This fourth elevation was not used in a statistical analysis due to the potential for confounding factors and divergent environmental variables, but was used to examine the validity of the relation between E-S and elevation identified in the primary analysis. Data from station P supported the results of the primary analysis that E-S decreases with elevation (Figure 3.4). E-S rates at station P were considerably higher than the nearest elevation on the gradient (station L), which corresponded with the considerable difference in elevation between station P and station L relative to differences in elevation within the gradient. While this additional data had many constraints with regards to quantitative input, it was valuable to compare the results as a fourth elevation in a cursory analysis and solidify the findings of the primary analysis.

4.2. E-S and canopy cover

At each elevation, data was collected from an open site and a canopy site to establish a relation between canopy cover and E-S. A statistical analysis determined that stations L and M exhibited higher E-S rates at canopy sites than open sites. Station H exhibited the same trend, but the relation was not significant. The lack of significance at station H may be attributable to frequent high wind speeds relative to stations M and L, advecting energy from under the canopy site, acting to lower the E-S rate relative to the open site.

4.3. Isotopic Fractionation

Samples of snow were collected at locations and intervals identical to pan measurements of E-S to ascertain the significance of the relation between E-S and isotopic fractionation (I-F). Change in the ratios of O^{18}/O^{16} and H^2/H were correlated with E-S rates as from pan measurements. The expected relation was that an increase in the magnitude of E-S would result in an enrichment of the ratio of heavy to light isotope. The analysis yielded low correlation values between data at all elevations and sites. This indicates a lack of significant relation between E-S and I-F. However, numerous studies have observed a significant relation between the two processes (e.g. Sommerfield, et al. 1991; Neumann, et al. 2008, Sokratov, et al. 2009). The lack of significant relation observed in this study may be due to the high spatial variability of E-S and I-F, and the low spatial variability of the distribution of snow samples collected.

4.4. Future Work

The results of this work serve to advance the current state of knowledge on snowpack ablation dynamics in alpine regions. This work contributes to the small number of studies conducted regarding E-S rates at elevation, and acts to reduce a deficiency in the scientific community's understanding of the process of E-S over large-scale elevation differences. The results presented may be used by those focused on water resource management, particularly in arid climates and other regions for which snowpack contributes a significant portion of annual water content.

Future work that may assist to solidify the findings of this study would act to isolate the effects of elevation on E-S to a greater degree, by locating sites along an elevation gradient that are even more identical in terms of surrounding forest and terrain characteristics. Additionally, to capture spatial variability of E-S, a study in which multiple samples are collected at each open and canopy site would eliminate the possibility of small-scale spatial variability in E-S influencing the results. Incorporating these modifications would result in a research endeavor that acted to reduce a majority of variability not associated with elevation, and produce E-S rates that were highly representative of the true effects of elevation on E-S.

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6. Appendix

6.1. E-S as a function of Elevation

Shapiro-Wilk Test for Normality

Dataset	Shapiro-Wilk Test Stat.	P-value	Passed Normality (Y/N) (α=0.10)
Station 1 clear	0.9475	0.3876	No
Station 2 clear	0.8911	0.03371	Yes
Station 3 clear	0.9647	0.748	No
Station 4 canopy	0.9538	0.428	No
Station 5 canopy	0.9545	0.4704	No
Station 6 canopy	0.9719	0.8327	No

Levene’s Test for Equal Variance (center = median)

Dataset	F-Statistic	P-value	Equal Variance (α=0.10)
Clear grouped by site	0.777	0.4653	Yes
Canopy grouped by site	1.1538	0.3231	Yes

Kruskal-Wallis Rank Sum Test

Dataset	Chi-squared	P-value	Existence of Difference Between Samples (α=0.10)
Clear grouped by site	4.2214	0.1212	No
Canopy grouped by site	6.3334	0.04214	Yes

Mann-Whitney Test

Station Comparison (canopy sites)	Test Statistic	P-value	Difference Detected (α=0.10)
1-2	228	0.292	No
1-3	131	0.1562	No
2-3	88	0.01217	Yes

6.2. E-S as a function of Canopy Cover

Levene’s Test for Equal Variance (center = median)

Dataset	F-Statistic	P-value	Equal Variance (α=0.10)

Station 1	1.5005	0.2286	Yes
Station 2	0.1039	0.7491	Yes
Station 3	0.0137	0.9076	Yes

Mann-Whitney Test For Sample Difference

Dataset	W-Value	P-value	Difference Detected (α=0.10)
Station 1	143.5	0.2926	No
Station 2	122	0.09038	Yes
Station 3	91	0.07005	Yes

6.3. Isotopic Fractionation

O^{18}/O^{16}

Dataset	R^2	P-value	Significant Relationship (α=0.10)
Station 1 clear	-0.09992	0.979	No
Station 2 clear	-0.09828	0.9029	No
Station 3 clear	-0.09857	0.7559	No
Station 1 canopy	0.1221	0.1306	No
Station 2 canopy	-0.09465	0.8294	No
Station 3 canopy	-0.07893	0.7333	No

H^2/H

Dataset	R^2	P-value	Significant Relationship (α=0.10)
Station 1 clear	-0.07714	0.6549	No
Station 2 clear	-0.09836	0.9052	No
Station 3 clear	-0.1111	0.9951	No
Station 1 canopy	0.0669	0.1998	No
Station 2 canopy	-0.04216	0.4734	No
Station 3 canopy	0.03267	0.2608	No

6.4. Fourth Elevation (Data from Merrianne Etter's Research)

Mean Mass Change in 30 Minutes (g)

	980126	980310	980409	990129	990410	Average (30 min)	Average (24 hours)
Clear	-1.1957	-2.1638	-1.3977	-0.1803	-3.0862	-1.6047	77.0256
Canopy	-1.4565	-1.4052	-1.6477	-1.0641	-2.875	-1.6897	81.1056

6.5. Multivariate Analysis

Station/site	Correlation with Max Temp (R^2)	P-value	AIC
1 clear	0.5148	0.001564	80.8723
1 canopy	0.4785	0.001257	109.7721
2 clear	0.4692	0.002896	90.3305
2 canopy	0.6824	< 0.001	78.1996
3 clear	0.4079	0.006178	92.565
3 canopy	0.3662	0.005954	110.6181
Average			93.6907

Station/site	Correlation with Min Temp	P-value	AIC
1 clear	0.1588	0.07862	89.2268
1 canopy	0.2229	0.03199	116.5548
2 clear	0.4464	0.003873	90.6324
2 canopy	0.7008	<0.001	77.3045
3 clear	-0.06358	0.6928	101.3017
3 canopy	-0.2168	0.4291	118.7356
Average			99.0098

Station/site	Max Temp + Mean Wind (MesoWest) (R^2)	P-value	AIC
1 clear	0.5178	0.004984	81.6789
1 canopy	0.4953	0.003275	110.0436
2 clear	0.4297	0.01365	92.2079
2 canopy	0.6844	0.0003918	78.9033
3 clear	0.3735	0.02397	94.1617
3 canopy	0.3808	0.01371	111.0504
Average			94.6743

Station/site	Max Temp + Solar Radiation (SNOTEL) (R^2)	P-value	AIC
1 clear	0.4744	0.008357	82.9412
1 canopy	0.4472	0.006193	111.5909
2 clear	0.4763	0.008177	90.9271
2 canopy	0.7388	0.000126	76.0679
3 clear	0.3661	0.02573	94.3381
3 canopy	0.4437	0.006471	109.2271
Average			95.84872