THESIS

SNOW DEPTH VARIABILITY IN SAGEBRUSH DRIFTS IN HIGH ALTITUDE RANGELANDS, NORTH PARK, COLORADO

Submitted by

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ABSTRACT

SNOW DEPTH VARIABILITY IN SAGEBRUSH DRIFTS IN HIGH ALTITUDE RANGELANDS, NORTH PARK, COLORADO

In high altitude rangelands, such as those in Colorado, sagebrush and other shrubs can affect transport and deposition of wind-blown snow, thus enabling the formation of snowdrifts. Sagebrush management techniques could have significant effects on snow accumulation patterns. Snow that potentially could have been trapped by the plants may return to the atmosphere through sublimation. Soil moisture and subsequent plant growth may be affected by this sublimation. Measurement of snow depth and the spatial variability of these measurements might be important information for understanding snowdrift formation processes. Determination of the most effective measurement scale for understanding important ecologic and hydrologic processes in this environment is therefore essential. Directional variogram analyses and Moran's I statistics are two efficient methods for representing the spatial variability of snow depth at different measurement scales in shallow rangeland snow packs.

The three following hypotheses are tested to determine the nature of snow depth spatial variability in the high altitude plateau rangeland of North Park, Colorado, using directional variogram analyses and Moran's I statistical methods: (1) Sagebrush plant

dimensions (microtopography) are less spatially autocorrelated than the variations in snow depth measurements in resultant snowdrifts around an individual plant; *(2)* As winter progresses and the voids within sagebrush plants are filled with wind-distributed snow, the resultant surface evolves into a progressively less spatially variable microtopography; *(3)* When measuring a shallow rangeland snow pack, smaller scale measurements produce a progressively more spatially variable dataset of snow depths and a therefore less spatially autocorrelated snow surface texture.

Results of both the variogram and Moran's I analyses indicate that the first hypothesis may be supported. Variogram gamma values and fractal dimensions for the sagebrush canopy microtopography tend to be larger than for the corresponding snow depth measurements. This specifies more spatial variability in the sagebrush surface than in snow depths. The Moran's I values also indicate that there is less spatial autocorrelation within sagebrush plant geometry than there is among snow depth measurements in resultant snowdrifts.

The second hypothesis is also supported by the results of both variogram analyses and Moran's I statistics. Variogram analyses indicate that snow depth becomes less spatially variable (with lower sill values) as the winter progresses. There is also evidence of a "leveling-off" of the spatial variability occurring later in the season. Variogram coefficients of variation and fractal dimensions are also very close in value. The Moran's I values also indicate more positive spatial autocorrelation among snow depths throughout the winter season.

Results of the variogram analyses for the multiple scale snow depth datasets do not support the third hypothesis. The results actually indicate that smaller scale snow depth measurements produce a more spatially autocorrelated dataset in shallow rangeland snow packs. As scale in snow depth measurements increases, both lag distances and gamma values increase slightly, as well. The Moran's I values are more supportive of the third hypothesis, indicating that mid-range small-scale snow depth measurements may be the least spatially variable.

ACKNOWLEDGMENTS

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CHAPTER 1 – INTRODUCTION

The practice of reducing sagebrush cover on rangelands in Colorado has been a common management technique for years (Hutchinson 1965; Hyder and Sneva 1956; Robertson 1947; Sturges 1975; Sturges 1989). A rangeland may be defined as an ecosystem whose vegetation type is dominated by grasses, forbs, and shrubs. By this definition, between forty and fifty percent of the earth's land surface is covered by rangelands and these are typically managed as native systems (Meiman, Paul. Personal interview. 3 March 2010). Rangeland managers often use chemical or mechanical means to treat mountain big sagebrush (*Artemisia tridentata* Nutt.) in order to reduce competition for space, nutrients, and water on rangelands in Colorado and throughout the western US. This reduction in competition results in the proliferation of grasses, forbs, and sprouting shrubs; regardless of whether or not the areas are reseeded. The reduction of sagebrush cover is done primarily to create a more suitable habitat for wildlife such as sage grouse or elk, reduce brush fire hazards (Hill and Rice 1963), or to encourage grazing by domestic livestock (Hyder and Sneva 1956). However, the reduction of sagebrush on western grazing lands may also affect water yields from these lands (Hutchinson 1965). Both chemical and mechanical methods for sagebrush reduction have been shown to affect the hydrologic variables of windblown snow, growing season water demand, and ablation of snow during spring melt (Hutchinson 1965).

The effects of such rangeland management techniques on soil moisture due to snow melt and subsequent plant growth are not yet fully known, but one key step in understanding such processes is the measurement of snow accumulation patterns that result from wind movement of snow and their interaction with sagebrush. Snow depth measurements can be performed at various scales and hydrologists are still determining which scales may be appropriate for different ecosystems and vegetative land cover types. Past investigations have shown that scale is central to any assessment of the spatial distribution of snow (Bloschl 1999; Deems *et al.* 2006; Trujillo *et al.* 2007). The amount of variability at each scale is controlled by the process interactions governing snow accumulation, metamorphism, and ablation; as the process interactions change with scale, so too does the variability in the snow cover (Deems *et al.* 2006).

In high altitude rangelands, such as those in Colorado, sagebrush and other shrubs can cause near-ground turbulence of wind-blown snow, thus enabling the formation of snowdrifts. These snowdrifts may be a critical source of stored moisture in these semi-arid climates (Hutchinson 1965; Pomeroy *et al.* 2006; Sturges 1975; Walker *et al.* 2001), which is released during spring melt. Sagebrush reduction could have dramatic effects on this stored moisture, allowing snow that potentially would have been trapped by the plants to return to the atmosphere through sublimation (Benson 1982; Bowling *et al.* 2004; Essery and Pomeroy 2004; Pomeroy and Li 2000). Measurement of snow depth variability around sagebrush could be important in understanding wind, snow, and plant interactions. Determination of the most effective measurement scale for understanding important ecologic and hydrologic processes is therefore essential. The scaling properties of wind-terrain-vegetation interactions are a critical focus for understanding patterns of snow accumulation over different scales (Deems 2007).

1.1 Background

a. Sagebrush characteristics

Big sagebrush is a rangeland shrub that grows up to 1 meter tall and typically occupies semi-arid lands (elev. 1200 m – 2800 m) in western Colorado (Sturges 1975). This shrub is particularly adapted to areas with a warm and dry growing season, where vegetation relies primarily on moisture stored in the soil at the time of snowmelt (Sturges 1975). Root dimorphism of sagebrush allows for effective use of soil moisture through both shallow and deep root systems. The deep roots permit sagebrush to tap moisture reserves deep in the soil and to remain physiologically active through the summer drought period (Sturges 1975). Sagebrush can also facilitate growth of forbs and graminoids through hydraulic lift of deeply stored moisture to surface soil via the deep root system of the plant (Sturges 1975). The intermountain regions of Colorado usually receive a large percentage of their annual precipitation as snow. Big sagebrush lands, particularly those vegetated by mountain big sagebrush, include some areas of heavy snow accumulation that support perennial stream flow (Sturges 1975).

Big sagebrush is associated with deep, well-aerated soils. Lunt *et al.* (1973) speculated that the species may be intolerant to wet soil conditions and to flooding. The general absence of big sagebrush from fine textured and poorly drained soils in the desert is a reflection of their relatively high oxygen requirements for root growth (Lunt *et al.* 1973).

b. Accumulation and wind effects

Several major factors in the sagebrush-water yield relationship become apparent after the reduction of this shrub on rangelands. Wind is an extremely important part of the physical environment on mountain big sagebrush lands because of its role in snow accumulation. Blowing snow is a distinctive hydrologic feature of mountain big sagebrush communities (Sturges 1975). Sagebrush cover can cause near ground turbulence that can trap more snow than in areas with only herbaceous cover. Observations in rangeland environments show that snow depth varies at both small and medium scales with vegetation height if there is sufficient wind-blown snow to fill in the vegetation completely and if strong winds do not scour snow from the vegetation (Pomeroy and Gray 1995). It has also been surmised that sagebrush leaves and twigs reduce wind velocity, so that drifting snow is deposited and held in place (Hyder and Sneva 1956). ***Figure 1-1*** shows the effect of plant size on snow accumulation due to wind influence and its similarity to snow accumulation induced by man-made wind barriers.

Removal of such vegetation can reduce snow accumulation throughout the winter season because snow has a tendency to saltate and sublimate across the extremely wind exposed intermountain rangelands of Colorado. Mass balance studies conducted in tundra regions, similar to Colorado high altitude grazing lands, suggest that sublimation could be responsible for significant losses of snow mass. Benson (1982) conducted measurements on the flux of wind-blown snow on Alaska's Arctic slope using surface snow and snowfall measurements to estimate snow redistribution and reported that 58% of annual snowfall remained on the tundra, 11% was transported to drifts in a river valley, and 32% was unaccounted for and presumed to have sublimated in transit.

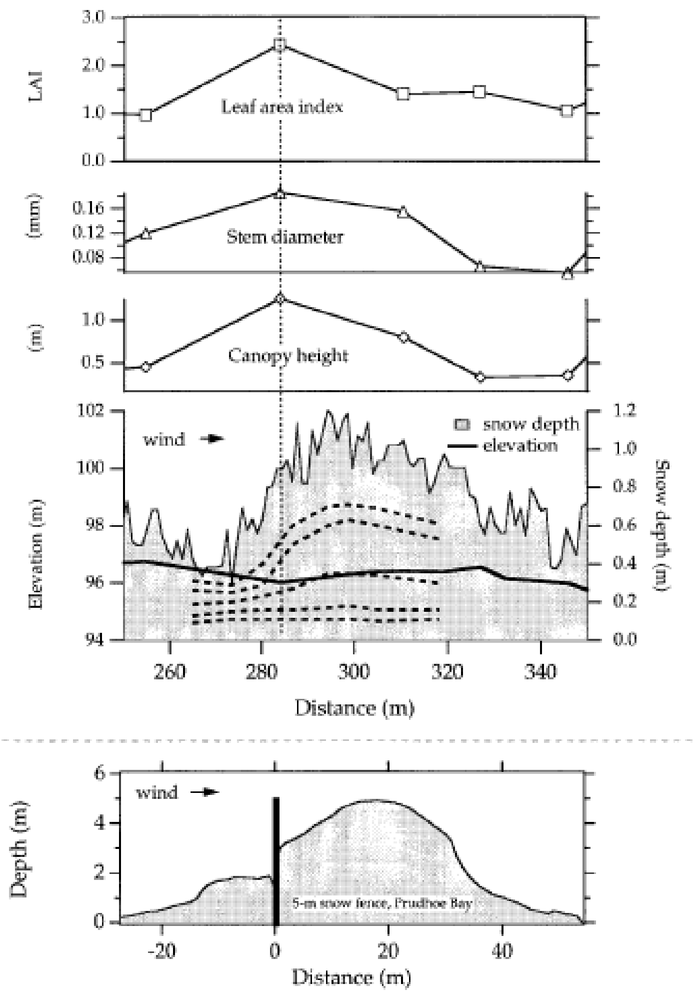


Figure 1-1: Downwind variation in snow depth, as a function of shrub characteristics (taken from Sturm et al. 2000)

Some methods of control of mountain big sagebrush, such as brush beating, might alter the hydrologic landscape of Colorado's intermountain regions, as could fire, a natural component of the rangeland system. If, as Essery *et al.* (2004) suggested, shrub accumulation is greater than, and open area accumulation is less than, the estimated snowfall because snow is blown off open areas and trapped by shrubs, soil moisture levels could become much more unbalanced, with greater variation between adjacent, small, localized areas.

The effect that sagebrush has on retaining wind-blown snow appears to reach a plateau when the plant becomes completely buried in, or covered by snow. An apparent smooth surface is created by the "filling-in" of sagebrush canopy with wind-blown snow. Once the plant is buried, the surface seems to become as aerodynamic as open areas without shrub cover, provided they are on a similar slope and aspect. The accumulation of snow in sagebrush areas is also limited by the moisture available as precipitation. The average shrub snow water equivalent (SWE) initially increases with increasing shrub height as the potential of the shrubs to trap wind-blown snow increases, but this is eventually limited by the supply of moisture in the form of snow (Essery *et al.* 2004). ***Figures 1-2a*** and ***1-2b*** are photographic depictions of typical snowdrifts produced by sagebrush and wind interactions in the high altitude rangeland of North Park, Colorado.

Blowing-snow processes have been somewhat neglected in large-scale climate models in years past, but may play an important role in the water, atmospheric moisture, and energy budgets of snow-covered regions (Bowling *et al.* 2004). Redistribution of wind-transported snow between catchments can strongly affect the water balance at small scales (Pomeroy and Li 2000). Much of the blowing snow that could be trapped by sagebrush might be lost to sublimation in the atmosphere surrounding Colorado rangelands where *Artemisia tridentata* shrubs have been removed. This reduction in snow accumulation could result in a loss of water availability for soil recharge during spring melt. The combination of redistribution and sublimation loss has an important control on spring runoff generation (Marsh and Pomeroy 1996).

(a)

(b)

Figure 1-2: Wind blown snow accumulates in drift patterns around and behind sagebrush near Walden, North Park, Colorado in December 2007

c. Effect of topography on wind blown snow

It is also theorized that vegetation has more of an effect on snow retention than topography at small scales. A simulation performed by Essery *et al.* (2004) showed that snow redistribution over existing topography without any shrub cover results in a much greater accumulation of snow on slopes in the lee of the prevailing wind than on windward slopes; in contrast, shrubs are able to trap snow on both lee and windward slopes. Although the snow distribution is strongly controlled by vegetation, the influence of topography is apparent in the accumulation of snow on lee slopes (Essery *et al.* 2004). ***Figure 1-3*** illustrates the effect of vegetation versus topography on SWE distribution in their simulation.

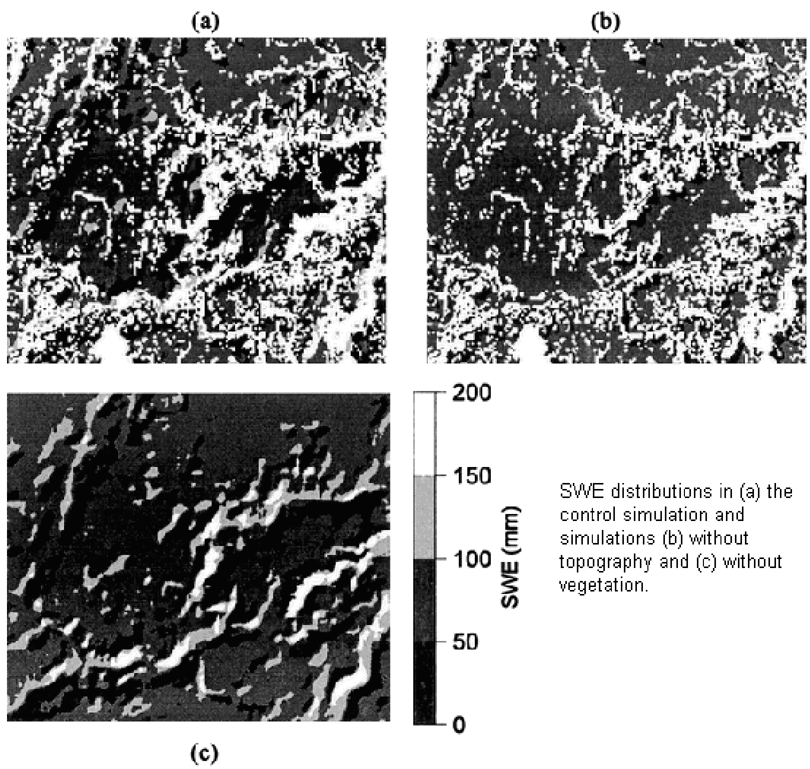


Figure 1-3: SWE distribution as affected by topography and vegetation (taken from Essery and Pomeroy 2004)

If vegetation is the controlling factor in wind blown snow distribution, reduction of sagebrush cover may alter the hydrologic processes of shrub lands dramatically. This assumes the shrub treatment would be performed in an area that is not topographically efficient for trapping snow, regardless of vegetative cover types. Further investigations utilizing wind blown snow models need to be performed.

The connection between sagebrush distribution and topography is strong at middle and large scales of measurement. At these resolutions, there may not be a discernible way to separate their effects from one another when assessing snow-catching abilities; however, it is fairly apparent that vegetation is the controlling factor in snow accumulation at small scales (Deems *et al.* 2006). Many of the factors determining vegetation distribution, including slope, aspect, wind exposure, soil moisture, active layer depth in permafrost, soil depth and structure, fire history, nutrient availability, and the location of late-lying snow drifts, are influenced by topography and winter wind direction. Topography and wind influence the growth of brush (Walker *et al.* 2001).

d. Albedo

Observations have been made regarding melt rates of the snowpack in sagebrush-covered areas. While the snow seems to persist longer in the sagebrush- covered areas, snowmelt also appears to begin sooner and progress at higher rates in these areas in comparison to the areas without sagebrush cover. This difference is most likely due to varying albedos between sagebrush and herbaceous ground cover. Albedo is an object's reflectivity and is defined as the ratio of total-reflected to incident short-wave radiation.

The typical range of snow albedo variation tends to be between 0.8 and 0.95. Hutchinson (1965) observed that metamorphism and subsequent melt of snow began earlier and proceeded at greater rates in and adjacent to sagebrush plants. Solar (short-wave) radiation penetrates into a snowpack, but a limited amount is absorbed because of snow's high albedo. Some of the incident radiation penetrates the snowpack, however, and intercepts sagebrush plant parts (Hutchinson 1965). The lower albedo of these materials allows absorption of the radiation, which results in a warming of the plant parts.

e. Emissivity

Heat from solar radiation (short-wave) is lost to the snow by conductance or through long-wave radiation emitted from the plants. Robertson (1947) suggested that sagebrush hastens melting and sublimation of snow by acting as "black-body" radiators and by increasing the surface area of the snow. Snow has great powers of absorption for long-wave radiant energy (Hutchinson 1965). Pomeroy *et al.* (2006) restated this finding:

> *The changes associated with increased shrub (and decreased snow) exposure include substantially lower albedo, greatly reduced transmittance of short-wave radiation to the snow surface, more positive net long-wave radiation at the snow surface, and accelerated snowmelt rates.*

Figure 1-4 shows the relation between albedo and short-wave radiation in reference to various types of shrub-snow cover interactions.

f. Soil moisture and sagebrush water demands

Another factor in the sagebrush/snow hydrologic relationship is the plant's water demand. A study in southern California showed that converting from a scrub oak brush (*Quercus dumosa* Nutt.) to grass actually increased water yield. A substantial soil moisture saving and potential groundwater yield was obtained under grass, but when deep rooted summer-growing forbs (such as lupine) invaded the grass, soil moisture and percolation gains were lost (Hill and Rice 1963). Because the grasses became dormant early in summer, they did not reduce soil moisture to the same extent and depth as did the deeper-rooted brush (such as scrub oak), which used water all summer (Hill and Rice 1963).

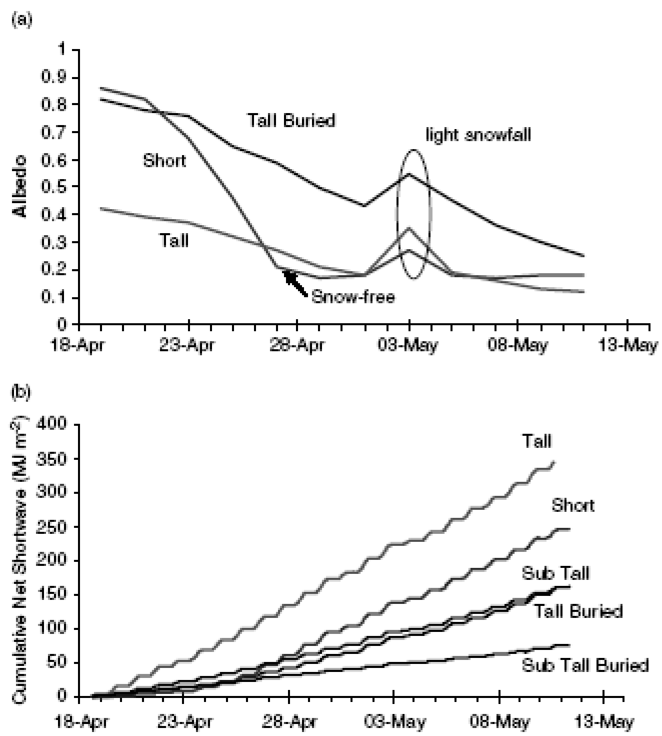


Figure 1-4: Change in shortwave radiation during snowmelt and shrub exposure (taken from Pomeroy et al. 2006)

On the contrary, a Colorado study showed that in the first year following grubbing and herbicide treatments, soil moisture levels started slightly higher and growing season precipitation was more effective on treated plots (Hyder and Sneva 1956). Soil moisture was depleted more slowly on untreated plots than on treated plots and by the third year after treatment, the earlier depletion of soil moisture on treated plots was striking (Hyder and Sneva 1956).

If sagebrush reduction does create a snow mass imbalance due to wind blown effects, and more snow is trapped in the untreated areas, it could create subnivian thermal isolation pockets around the sagebrush, promoting growth, as stated earlier. Some researchers theorize that too much moisture around mountain big sagebrush could result in mortality of the plant, although only in reference to snowdrifts induced by topography or snow fences (Ganskopp 1986). Big sagebrush does not tolerate high moisture levels, because saturated soils result in inefficiency of the plant roots' ability to receive oxygen. A study of Wyoming Big Sagebrush showed that the shrub was severely affected by surface flooding or elevated water tables (Ganskopp 1986). Declines in vigor were immediate, and surface flooding resulted in nearly complete mortality of sagebrush within 21 to 28 days of inundation (Ganskopp 1986). Ganskopp (1986) also speculated that excessive soil moisture is detrimental to big sagebrush and anaerobic conditions in some soils prevent successful establishment of the shrub.

In another experiment, snow fences were utilized to create large snowdrifts over naturally occurring big sagebrush. Snow depth was measured at a site downwind of the snow fence, both before, and after installation of the fence. This site was located downwind at a distance of 3.2 times the height of the fence. Snow depth measurements tripled after fencing, so that both the duration of snow cover and of water logged soils was substantially increased (Sturges 1989). The prolonged soil saturation was primarily responsible for the substantial loss of mountain big sagebrush downwind of the snow fence (Sturges 1989). An increase in SWE due to wind displacement of snow in natural shrub cover adjacent to grasslands converted from sagebrush was observed. However, over saturation during spring melt in the shrub areas was not shown to cause shrub mortality. Only in the case of snow fences has over saturation been proven to cause mortality.

g. Plant nutrients, available water, and growing conditions

A study performed in the low Arctic showed that snow redistributed to shrubs can contain high chemical loads of essential plant nutrients, such as inorganic nitrogen (Pomeroy *et al.* 1995). As mentioned above, mass balance studies have suggested that removal of shrubs in certain local areas might cause excess blowing snow to redistribute to the areas with untreated, natural shrub cover, causing these areas to contain higher than normal amounts of snow. Sturm *et al.* (2001) found that the deeper snow associated with taller, denser shrubs was a better insulator per unit thickness than the snow outside of shrub patches since it contained a higher percentage of depth hoar. Depth hoar are large-grained, faceted crystals that tend to form near the ground, due to large temperature gradients within the snowpack. More depth hoar around the base of sagebrush plants, compared to rounded grains, aids in thermal insulation, resulting in higher subnivian temperatures. Hutchinson (1965) also observed that a layer of depth hoar around the base of sagebrush plants was present and that the thickness of this layer decreased steadily throughout the winter, while the individual crystals grew larger with age. This condition can protect shrubs from winter desiccation and wind abrasion, promote greater winter decomposition and nutrient mineralization, and thereby provide a positive feedback loop that could enhance shrub growth (Sturm *et al.* 2001).

h. Spatial variability of a shallow snow pack

Several different techniques for measuring snow depth in high altitude rangeland environments exist, including satellite imagery, orthophotography from aircrafts, lidar altimetry (a type of microwave remote sensing), and in-situ field measurements. A data collection campaign that included sites in high altitude rangelands in Northern Colorado occurred in 2002 and 2003; to better understand microwave remote sensing for measurement of snow and frozen soil properties, NASA funded the Cold Land Processes Field Experiment (CLPX) (Cline *et al.* 2003). Snow packs in these areas tend to be shallow and are typical of the distinct cold-region physiographic regime of prairie and arctic / alpine tundra snow covers (Tedesco *et al.* 2005).

Snow cover in rangeland areas tends to be relatively shallow and therefore more vulnerable to the influences of wind and sun. This often results in highly variable depth measurements during a winter season. Manual field measurement practices in these areas may require modification of standard procedures. A “shallow” snowpack often accumulates and ablates a number of times during a snow season, resulting in rapid fluctuations in depth and density (Dickinson and Whiteley 1972). The weather conditions experienced in the study region, the metamorphism of the snowpack, and in particular the formation of ice lenses in the snow due to melt and refreezing, undoubtedly have a major influence on the density of snow and its variability (Dickinson and Whiteley 1972). Because of the unpredictability of shrub tundra/prairie regions, researchers have considered utilizing a large number of snow depth stakes in conjunction with a few random density samples for the estimation of mean water equivalent over an area (Dickinson and Whiteley 1972). Likewise, McKay (1968) has also suggested the use of limited density observations, focusing more on mapping the spatial variability of depth.

i. Statistical analysis methods for snow variability

There are various statistical methods for representing the spatial autocorrelation of snow depth variability at different scales in shallow rangeland snow packs, and a number of spatial interpolation methods exist. Selecting the most suitable method of interpolation can be greatly dependant on the level of accuracy required and the computational efficiency of the method (Erxleben *et al.* 2002). Variogram analysis and Moran's I calculations are two effective ways of representing snow depth spatial variability. Spatial variability can be defined as a quantity that is measured at different spatial locations, with values that differ across those locations.

Sampled variability may be either smoother or rougher than what exists on the ground. To assess this scaling effect induced by the data collection, we must know the process scale (Deems *et al.* 2006). An effective method of estimation of the process scale is calculating the correlation length from a variogram. The correlation length is the lag distance (length) beyond which there is no correlation between adjacent points (Deems *et al.* 2006). The correlation length (or "sill") is the scale where the semivariance reaches 95% of the spatial variance and only exists for stationary (constant mean) or locally stationary processes (Webster and Oliver 2001). Another test for spatial correlation is based on Moran's I test statistic. This test statistic is formulated as a (properly normalized) quadratic form in terms of the variables that are being tested for spatial correlation. Moran's original specification standardizes the variables by subtracting the sample mean, and then deflating by an appropriate factor (Kelejian and Prucha 2001).

1.2 Research Objectives

The objectives of this study include testing several hypotheses regarding the spatial autocorrelation / spatial variability of snow depth measurements in wind-induced snow drifts behind sagebrush plants in a high altitude rangeland at several differing small scales from three distinct datasets. The first hypothesis asserts that sagebrush plant dimensions (microtopography) are less spatially autocorrelated than the variations in snow depth measurements in resultant snowdrifts around an individual plant. The second hypothesis states that once snow completely covers the sagebrush microtopography, the snow depths become less spatially variable with less surface roughness, as a result of wind interactions. Finally, it is hypothesized that when measuring a shallow rangeland snow pack, progressively smaller scale measurements produce a progressively more variable dataset of snow depths and therefore, a less spatially autocorrelated dataset of snow depth measurements. These hypotheses are tested through several methods of statistical analyses.

Measuring snow depths at differing resolutions could also be an effective research tool when drawing conclusions about the reduction of shrub cover and resultant snow accumulation and melt pattern changes. The influence of snowdrift melt around sagebrush plants is therefore tested. In areas where sagebrush plants have been reduced in cold rangeland environments, snow drifting does not appear to be a common phenomena. As shrub cover is removed, wind-borne snow particles tend to be lost back into the atmosphere through sublimation and thus, less snow is stored for subsequent available moisture. This could lead to substantially wetter soil surrounding sagebrush plants during early spring melt. A surface soil moisture test is performed in this study to investigate such a scenario.

1.3 Study Areas

One area representative of Colorado’s high altitude, intermountain rangelands is the North Park area, which is located between the Medicine Bow, Park, and Rawah mountain ranges. This region provides an excellent field research area due to abundant mountain big sagebrush habitat. A field campaign of medium scale (25 cm resolution) data collection performed by several research scientists associated with the Cooperative Institute for Research in the Atmosphere (CIRA) occurred in this region in 2008. NASA funded the CLPX project, which included sites in North Park. The 25 km x 25 km North

Park Meso-cell Study Area (MSA) was one of the foci of the experiment (Cline *et al.* 2003). Snow packs in this area tend to be shallow and are typical of the distinct cold-region physiographic regime of rangeland and arctic / alpine tundra snow covers (Tedesco *et al.* 2005). Within the North Park MSA, there were three intensive 1 km x 1 km study areas (ISAs), with a sampling of at least five manual measurements in each 100 m x 100 m resolution grid cell. Snow depth measurements were taken in February and March of 2002 and 2003.

The CIRA study (25 cm scale) included one 50 m x 50 m plot and two 1 km transects located within the CLPX Michigan River ISA. For this study, a third dataset was co-located within the CIRA/CLPX region of North Park, Colorado to facilitate a multi-scale, multi-data source study. These latter data (WSD) were collected by the Watershed Science program at Colorado State University and include four 2m x 2m study plots and one 5m x 4m plot. Both sagebrush plant surface microtopography and snow depth measurements were taken at a fine scale of 5 to 10 cm between 2007 and 2008.

Figures 1-5 and ***1-6*** show the location of the North Park MSA within the state of Colorado and the locations of the CLPX ISA's within the North Park MSA. ***Figure 1-7a*** is an orthophoto of the region of North Park surrounding the Michigan River ISA. ***Figure 1-7b*** is a topographic map of the same area, showing the locations of the ISA and the Arapahoe National Wildlife Refuge (ANWR). This area is located outside of Walden, Colorado, just to the South of the Arapahoe National Wildlife Refuge.

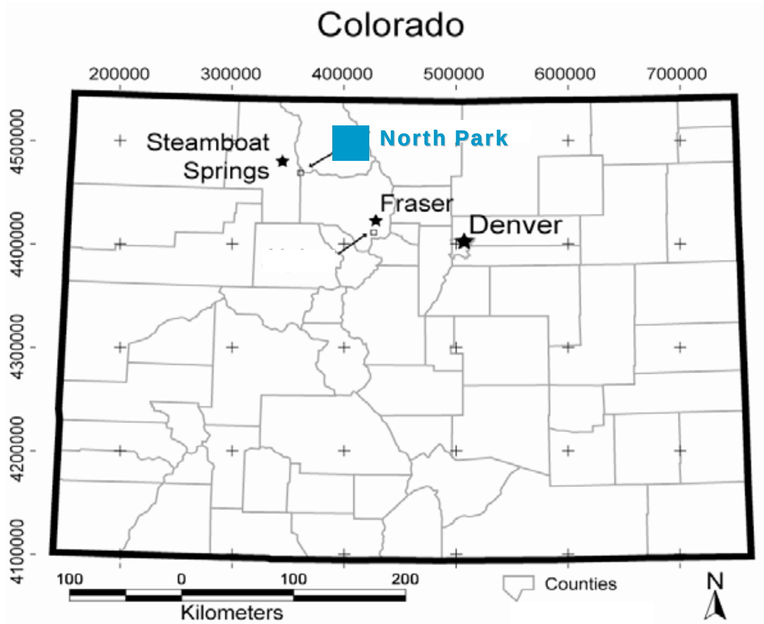


Figure 1-5: Location of CLPX North Park MSA within the state of Colorado
(Source: Cold Land Processes Field Experiment Plan, December 2001)

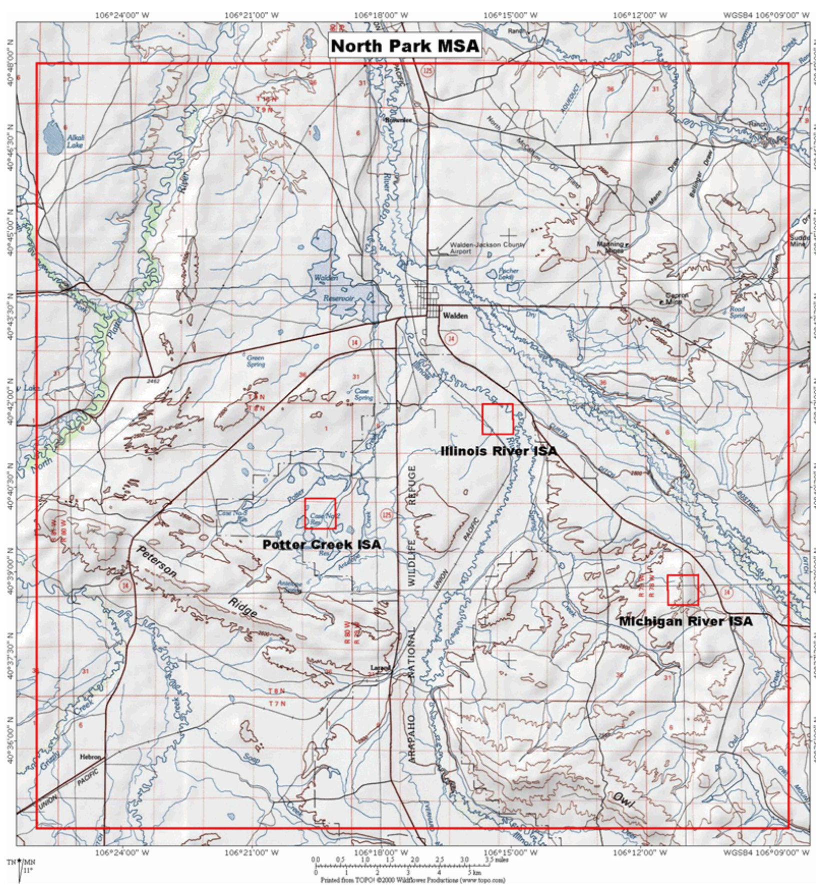
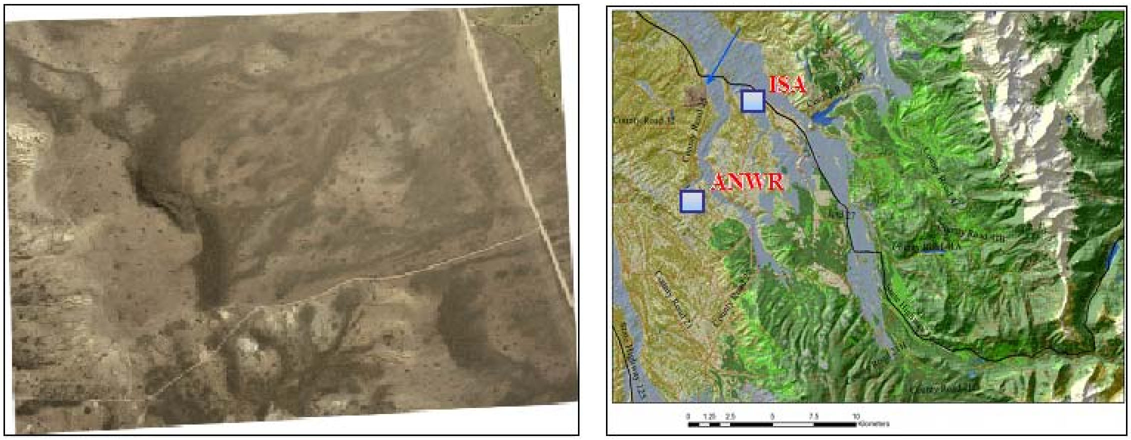


Figure 1-6: Detail of CLPX North Park MSA with ISA locations
(Source: Cold Land Processes Field Experiment Plan, December 2001)



(a) *(b)*

***Figure 1-7: (a) Orthophoto and (b) topographic map of Michigan River ISA and surrounding areas near Walden, CO** (courtesy of CIRA)*

While quantitative field measurements were collected during the 2007-2008 winter for both the CIRA and WSD datasets, a more qualitative, pilot study was also performed within the North Park MSA during the 2006-2007 winter. The pilot study was performed by the Watershed Science program at CSU and was an investigation of snowdrift geometry and melt patterns. Data were collected during that winter in an area adjacent to Owl Ridge, which is located on the Arapahoe National Wildlife Refuge (ANWR).

1.4 Overview of Document

Chapter 2 is the main document of this thesis. This document details the data collection and statistical analyses involved with the study of the spatial variability of sagebrush plant dimensions and snow depth measurements at varying small scales on the high altitude plateau of North Park, Colorado. The two methods of statistical analyses used in chapter 2, directional variograms and Moran's I, give numerical information regarding the nature of this spatial variability. Chapter 3 subsequently provides more background information and preliminary findings in regards to albedo, soil moisture, wind speed, and wind direction, as these factors may be significant contributors to the spatial variability as analyzed in chapter 2.

CHAPTER 2 – SNOW DEPTH AND SAGEBRUSH SPATIAL VARIABILITY ANALYSES

2.1 Hypotheses

The following three hypotheses are tested to determine the nature of spatial variability using several statistical methods: *(1)* Sagebrush plant dimensions (microtopography) are less spatially autocorrelated than the variations in snow depth measurements in resultant snowdrifts around an individual plant; *(2)* As a winter season progresses, the voids within sagebrush plants are filled with wind-distributed snow and snow depth measurements evolve into a progressively less spatially variable microtopography; *(3)* When measuring a shallow rangeland snow pack, smaller scale measurements produce a progressively more spatially variable dataset of snow depths and therefore, a less spatially autocorrelated snow surface texture.

2.2 Data Collection

The measurement scales for the three datasets (WSD, CIRA, and CLPX) consist of multiple small grid spacings (5 – 10 cm, 25 cm, and 100 cm, respectively) comparable by order of magnitude for both scale and extent (***Table 2-1***).

2.2.1. Watershed Science Program Dataset (WSD)

Over the 2007 to 2008 winter season, a field data collection campaign in the North Park rangeland included a series of fine scale (5-10 cm) three dimensional snowdrift geometry measurements collected around mountain big sagebrush. A grid (5 cm x 5 cm) was established for measurements from a snow depth probe. The probe measures snow depth with an approximate diameter of 1cm at a 1 cm resolution. The same scale and probe were used to measure the shrubs, prior to the beginning of snow accumulation. These measurements were conducted in four 2m x 2m plots with shrub cover of comparable size and spacing. Since the plots contained similar sized and spaced sagebrush, the measured variable in this study was assumed to be temporal, with snowpack evolution being assessed.

The plots were co-located near the CLPX and CIRA study areas using a hand-held global positioning system (GPS). A different plot was measured during each field visit in December 2007, in January, February, and March of 2008 to record temporal changes to the snow pack from wind and sun exposure. An additional 4m x 5m plot was also measured in January, February, and March of 2008 on a 5cm scale to document snow depth changes during a winter season over the same sagebrush microtopography, i.e., from both the sagebrush and terrain.

2.2.2. Center for Integrated Research in the Atmosphere (CIRA) Dataset

Over the winters from 2005 to 2008, CIRA conducted field data collection campaigns to model snow depth variation in several sagebrush rangeland areas in

Northern Colorado and Southern Wyoming. In February and March of 2008, three datasets were collected adjacent to the WSD plots, within the CLPX Michigan River ISA, in North Park, Colorado. These snow depth datasets were measured on a medium scale (25 cm) grid and included one 50 m x 50 m plot of gridded measurements and two 1 km snow depth transects. Snow depths were measured using an automated snow depth probe that records snow depth using a basket that slides up the probe and a built-in GPS system. This probe is different than the 1 cm diameter probe used in both the WSD and CLPX campaigns.

2.2.3. NASA's Cold Land Processes Experiment (CLPX) Dataset

The NASA Cold Land Processes Field Experiment (CLPX) was conducted in 2002 and 2003 in Colorado. The NASA CLPX was a multi-sensor, multi-scale experiment that focused on extending a local-scale understanding of water fluxes, storage, and transformations to regional and global scales (Cline *et al.* 2002; Elder *et al.* 2009; Hardy *et al.* 2008; Liston *et al.* 2008; Tedesco *et al.* 2005). Within a framework of nested study areas in the central Rocky Mountains of the western United States, ranging from 1-ha to 160,000 km^2, intensive ground, airborne, and space borne data were collected. Observations focused on mid-winter (late February), when conditions are generally frozen and dry, and early spring, a transitional period (late March) when both frozen and thawed, dry and wet conditions are widespread (Cline *et al.* 2002).

Within the North Park MSA, Michigan River ISA, manual snow depth measurements at different coarse resolutions (1, 5, 10, 15, 20, 25 m) were taken over four intensive observation periods (IOPs) for a 1 km x 1 km area (Table 2-4). Other variables were measured, including snow wetness, snow temperature, soil temperature, and canopy cover. Snow depth data for the CLPX IOPs in the Michigan River ISA are accessible through the National Snow and Ice Data Center (nsidc.org) in Boulder, CO.

2.3 Methods

2.3.1. Contour maps of sagebrush and snow microtopography

For the WSD dataset, snow depth measurements and sagebrush geometry measurements were used to generate 3-dimensional surface roughness maps and plan view contour maps. The 3-dimensional surface roughness maps provide a visual representation of snowdrift evolution over a winter season as a result of the interaction between the underlying sagebrush plant and the persistent winds that characterize the environment of North Park. These maps are generated using the statistical analysis program Surfer, Version 7.0 (Golden Software, Inc 1999) from the data as x, y, and z coordinates, with the x and y values being the Easting and Northing UTM coordinates for zone 13 and the z value being snow depth or sagebrush height. Spatial interpolation used universal kriging. Universal kriging is a geostatistical technique used by Surfer and other statistical analysis programs to interpolate the value of a random field at an unobserved location using actual observations of its value at nearby locations through a distance-weighted average. In this study, the kriging technique was used to estimate unobserved values of snow depths or sagebrush heights (the z coordinate) at x and y locations within the study plots, based on the adjacent physical data points measured in the field. These estimated values were then used to generate smooth 3D surface maps in Surfer.

The interpolated snowdrift maps were placed on top of the maps of the sagebrush for the 2m x 2m plots (A-D) to visually correlate snowdrift shapes to shrub shapes (***Figure 2-1***). These maps of sagebrush geometry and snow depth were also presented in plan view (***Figure 2-2***). The 4- x 5-m WSD Plot E was interpolated into a 3-D surface map for the three measurement months (January, February, and March of 2008) to show the evolution of the snowpack and changes in snowdrift geometry from wind scour over the winter season (***Figure 2-3***). Several cross sectional profiles of the WSD were produced to show the temporal evolution of the snowpack over the 2007-2008 winter season (***Figures 2-4 and 2-5***).

During the WSD field data collection campaign, an attempt was made to sample density by removing blocks of snow around shrubs. This method was not successful due to the extremely granulated texture of the snow, but this did create cross-sections in several snowdrifts, allowing observations of the inner structure of the snow pack. From these, it was confirmed that there were little or no void spaces within the snowdrifts, thus the solid 3-D snowdrift geometry models were an accurate representation.

2.3.2. Variogram analyses

The scaling of multi-resolution data can be assessed by the correlation length from a variogram (Deems *et al.*, 2006; Fassnacht *et al.* 2009). Semivariograms, $\gamma(r)$, are estimated using a number of lag distances:

$$\gamma(r_k) = \frac{1}{2(N_k)} \sum_{i=1}^{N_k} \{z_i - z_j\}^2$$

[Eq. 2-1],

where r is the lag distance of bin k, N is the total number of pairs of points in the kth bin, and z_i and z_j are the snow depth values at two different point locations i and j (Deems *et al.* 2006). Log-width lag distance bins are used to provide equal bin widths when the variograms are transformed to log-log space, and provide for a greater bin density at short lag distances than linear-width bins, aiding in resolving the variogram structure at short length scales (Deems *et al.* 2006).

For this study, each variogram had a maximum lag distance of 1,000 meters, presented in log-log space. Obvious extreme values (high or low) were removed, especially when too few data pairs existed (+/- 1 – 2 magnitudes of measurement different from surrounding lag distances). Power best-fit trend lines were calculated for the portion of lag distance that was linear in log-log space up to the correlation length. The correlation length was determined from the change (break) in linear segments in log-log space. A flat segment or one with no slope was indicative of data approaching near total spatial randomness.

The exponent, B, for each trend line is used to determine the fractal dimension, D, of each variogram (Isaaks and Srivastava 1989):

$$D = 3 - B/2$$

[Eq. 2-2]

The fractal dimensions of the three datasets (WSD, CIRA, CLPX) were assumed to be between two and three dimensions since snow depths and sagebrush geometry are measured on a plane (x and y coordinates) with vegetation height or snow depth (z value). The lag distance (measured in meters) and gamma values (in m^2) were recorded at the correlation length or scale break for each variogram (***Tables 2-2 & 2-3***).

2.3.3 Moran's I analysis

Spatial autocorrelation among each dataset was tested using the Moran's I method. This is a measure of spatial autocorrelation that accounts for the two-dimensional and bi-directional nature of spatial datasets (Kelejian and Prucha 2001), such as the snow depth measurements and sagebrush geometry. Moran's I is defined as:

$$I = \frac{N}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} \qquad \textbf{\textit{[Eq. 2-3]}},$$

where N is the number of spatial units indexed by i and j, X is the variable of interest, $\bar{X}$ is the mean of X, and w_{ij} is a matrix of spatial weights (Kelejian and Prucha 2001). A positive Moran's I value indicates a positive autocorrelation with a value of +1 indicating total correlation. A negative Moran's I value specifies a negative autocorrelation with a value of –1 indicating complete dispersion. A value of zero is a random spatial pattern.

Each dataset of x, y, and z coordinates for WSD, CIRA, and CLPX plots and transects are analyzed using the *Moran.I* function in the statistical analysis program "R" (version 2.6.1 (2007-11-26), Copyright (C) 2007, The R Foundation for Statistical Computing) and are presented in ***Table 2-4***.

2.3.4. Percent frequency histogram of snow depths

The snow depth datasets were used to generate a percent frequency histogram at each small scale for each sampling date. Each data range was divided into equal subintervals called bins or class intervals of 12 cm. This allowed for 10 equal bin divisions, since measurements of sagebrush height and snow depths were between 0 and 120 cm for all three datasets (WSD, CIRA, CLPX). A starting point for the first interval was chosen so that no measurement fell on a point of division between two intervals. This was done to eliminate confusion when placing values into the intervals (Ott and Longnecker 2001). A frequency table for each month from each scale of measurement was constructed by tallying the number of snow depth measurements falling into each bin. This number is known as the class frequency (Ott and Longnecker 2001). The percent frequency within each dataset was then calculated from the class frequency and the total number of observations for each month at each scale (***Figure 2-10***).

2.4 Results

2.4.1. Contour maps of sagebrush and snow cover surface microtopography

Sagebrush plant microtopography measurements for the WSD 2- x 2-m plots A and B were used to generate the 3-dimensional sagebrush surface contour maps seen in ***Figure 2-1*** as the black wire frame surfaces, as well as the plan view images on the left column of ***Figure 2-2***. The black 3-D sagebrush surfaces are underlain by the 3-D geometry of the resultant snowdrift contours generated from snow depth measurements shown as the gray wire frame surfaces (***Figure 2-1***). The plan view images of resultant snow depth measurement contours are adjacent to their corresponding sagebrush microtopography (***Figure 2-2***). A visual correlation between snowdrift geometry and sagebrush microtopography can be seen in ***Figures 2-1*** and ***2-2***.

The phenomenon of more spatially autocorrelated snow depth measurements evolving over the 2007-2008 winter season in the 4m x 5m WSD plot E is visually displayed in ***Figure 2-3*** as a series of 3-D surface maps (top row) and plan view topographic maps (bottom row) for the months of January, February, and March 2008. The snow surface/snow drift geometry becomes smoother as the 2007-2008 winter season progressed (***Figure 2-3***). Several cross sectional graphs (***Figures 2-4*** and 2-***5***) compare the snow depth measurements for WSD 2m x 2m plots A, B, C, and D on 8 December, 12 January, 18 February, and 12 March, respectively (***Figure 2-4***), as well as in WSD plot E over the 2007 – 2008 winter season (***Figure 2-5***). These plots visually confirm what is seen in ***Figure 2-3***; snow surfaces in the study area generally tend to become less spatially variable / more spatially autocorrelated during the winter.

2.4.2. Variogram analyses

The results from the multiple variogram analyses address the three hypotheses concerning spatial variability and spatial autocorrelation of snow depth measurements and sagebrush microtopography (***Tables 2-2*** and ***2-3***, ***Figures 2-6, 2-7,*** and ***2-8***). Variograms are grouped into comparative analyses; WSD sagebrush dimensions, WSD snow depth measurements, and snow depth evolution over the 2007-2008 winter season for WSD plot E are plotted into stacked directional variograms (***Figure 2-6***). Multiple scale, multiple dataset snow depth measurement directional variograms for the months of February and March are compared (***Figure 2-7***), as are the directional variograms for multiple characteristics of WSD Plot C; including the ground surface variation, snow depth measurements in February 2008, sagebrush microtopography, and snow surface roughness (***Figure 2-8***).

The fractal dimensions calculated from the variogram analyses of the sagebrush microtopography in WSD plots A, B, C, and D (***Figure 2-6a***) were 2.57, 2.63, 2.38, and 2.82, respectively (***Table 2-2***). The correlation lengths or scale break of the sagebrush microtopography for WSD plots A, B, C, and D were 0.32 m, 0.28 m, 0.36 m, and 0.42 m, respectively. The gamma values f, or the sill, are 0.0193 m^2, 0.0171 m^2, 0.0147 m^2, and 0.0133 m^2, respectively (***Table 2-2***). The sagebrush characteristics of density (number of plants per square meter) and percent of area covered by sagebrush are similar for each of the WSD plots, with densities ranging from 3 to 5 plants per m^2 and area covered by sagebrush ranging approximately from 47% to 62% (***Table 2-2***). Percent of area covered by sagebrush can be seen in the plan view contour maps of the plants in ***Figure 2-2***.

The fractal dimensions for the snow depth measurements in WSD plots A, B, C, and D (***Figure 2-6b***) were 2.06, 2.64, 2.38, and 2.55, respectively (***Table 2-3***). The correlation lengths were 0.24 m, 0.83 m, 0.63 m, and 1.26 m. The sills were 0.0042 m^2, 0.0004 m^2, 0.0015 m^2, and 0.0008 m^2 (***Table 2-3***). The average snow depths for the WSD plots A, B, C, and D were 17.4 cm, 32.1 cm, 32.5 cm, and 37.0 cm on 8 Dec, 2007, 12 Jan, 2008, 18 Feb, 2008, and 12 Mar, 2008, respectively (***Table 2-3***). The standard deviations and coefficients of variation for these plots were 6.24 cm, 1.88 cm, 2.93 cm, 2.50 cm, and 0.359, 0.058, 0.90, 0.068, respectively (***Table 2-3***). WSD plots B, C, and D tended to have similar average snow depths of 32 cm – 37 cm, measured later in the 2007 – 2008 winter season, and their respective statistics are comparable. The average snow depth for WSD plot A, measured earlier in the season in December 2007, was lower than the other plots, and conversely, it's standard deviation and coefficient of variation were higher by an order of magnitude (***Table 2-3***). The snowcover in plot A also has a lower fractal dimension and correlation length, and a higher sill value (***Table 2-3***).

The fractal dimensions calculated for the snow depth measurement evolution in WSD plot E over January, February, and March 2008 (***Figure 2-6c***) are 2.46, 2.47, and 2.47, respectively (***Table 2-3***). The correlation lengths for WSD plot E on 12 Jan, 18 Feb, and 12 Mar, 2008 were 0.55 m, 0.72 m, and 0.24 m, respectively. The sills were 0.0072 m^2, 0.0037 m^2, and 0.0020 m^2 (***Table 2-3***). The average snow depths progressed from 32.8 cm to 41.6 cm to 45.2 cm on 12 Jan, 18 Feb, and 12 Mar, 2008 (***Table 2-3***). The corresponding standard deviations and coefficients of variation were 8.02 cm, 5.80 cm, 4.46 cm, and 0.245, 0.139, 0.099, respectively (***Table 2-3***).

The CIRA 50 m square plot (measured on 11 March, 2008) appears to have two distinct slope lines (and no sill) when the results of its snow depth measurement directional variogram analysis are graphed in ***Figure 2-7*** (bottom). The corresponding fractal dimensions for these two slopes are 2.74 and 2.48 (***Table 2-3***). The fractal dimension of the February CIRA 1 km snow depth measurement transect calculated from the variogram analysis is 2.07. The March CIRA 1 km transect does not contain enough data to calculate a power best-fit trend line and thus a corresponding fractal dimension, nor a correlation length or a sill (***Figure 2-7***, bottom). This may have occurred because the CIRA snow depth transects were measured along a line, producing 2-dimensional data, while the other datasets in this study, which were measured in square or rectangular plots, produce three dimensional data. The correlation lengths for the variogram analyses of the snow depth measurements in the CIRA 50 m square plot and the February CIRA 1 km snow depth measurement transect are 2.51 m and 6.61 m, respectively. The sill for the 50 m square plot is 0.0070 m^2 (***Table 2-3***). The average snow depths for the CIRA 50 m square plot, February CIRA 1 km transect, and March CIRA 1 km transect are 49.7 cm, 37.2 cm, and 44.2 cm, respectively (***Table 2-3***). The corresponding standard deviations and coefficients of variation were 10.8 cm, 17.7 cm, 22.6 cm, and 0.217, 0.477, 0.511, respectively (***Table 2-3***).

The fractal dimensions for the snow depth measurements taken during CLPX IOP's 1 – 4 (***Figure 2-7***) measured on 21-22 Feb, 2002, 27 Mar, 2002, 21 Feb 2003, and 28 Mar, 2003 were 2.77, 2.28, 2.72, and 2.32, respectively (***Table 2-3***). The correlation lengths were 72.4 m, 145 m, 110 m, and 145 m, while the sills were 0.0105 m^2, 0.0218 m^2, 0.0057 m^2, and 0.0207 m^2 (***Table 2-3***). The average snow depths, standard deviations, and coefficients of variation were 18.0 cm, 18.0 cm, 9.00 cm, and 7.00 cm, and 10.0 cm, 14.0 cm, 7.00 cm, 8.00 cm, and 0.556, 0.778, 0.78, 1.143 (***Table 2-3***).

A comparison of all variograms for multiple characteristics of WSD PLOT C is presented in ***Figure 2-8***, and includes the ground surface variation, snow depth measurements in February 2008, sagebrush microtopography, and snow surface roughness. Both the ground surface and snow surface datasets were interpolated using the WSD plot C ground elevation dataset obtained from the total station in April 2008. The plot C snow depth measurements and sagebrush microtopography variogram analyses results shown in ***Figure 2-8*** are the same as in ***Figure 2-7***, but in ***Figure 2-8***, they are compared to the plot C ground surface variation and snow surface roughness variogram analyses results. The fractal dimension, correlation length, and the sill of the ground surface were 2.51, 0.48 m, and 0.0013 (***Table 2-3***). The WSD plot C snow surface roughness variogram results did not provide enough data to calculate any associated statistics (***Figure 2-8***).

2.4.3. Moran's I analysis

The results of the Moran's I analyses for the multiple scale datasets involved in this study indicate that the spatial autocorrelation of snow depth measurements tended to be either positive or completely random (***Table 2-4***). The "Moran's I" statistical output for each dataset is plotted as a bar graph depicting the Moran's I values of sagebrush microtopography and subsequent snow depth measurements for WSD plots A, B, C, and D, as well as the Moran's I values for snow depth measurement evolution in WSD plot E over the 2007-2008 winter season and the Moran's I values for multiple scale snow depth measurements in the CIRA and CLPX datasets (***Figure 2-9***).

The Moran's I values of the snow depth measurements at the fine scale for WSD plots A, B, C, and D were 0.088, 0.107, 0.219, and 0.036 respectively, indicating spatial autocorrelations that were random, positive, positive, and random, respectively (***Table 2-***

4, Figure 2-9). The Moran's I of snow depth measurements in WSD plot E (also fine scale) in January and February of 2008 were 0.136 and 0.221, respectively, which both indicate positive spatial autocorrelation (***Table 2-4, Figure 2-9***). The Moran's I values for snow depth measurements in the CIRA 50 m square plot, February 2008 1 km transect, and March 1 km transect were 0.591, 0.363, and 0.437, respectively, which all indicate positive spatial autocorrelation at the medium scale (***Table 2-4, Figure 2-9***). Snow depth measurements made at the coarse scale in the CLPX IOP's 1, 2, and 4 produce Moran's I values of 0.034, 0.100, and 0.061, respectively, indicating random, positive, and random spatial autocorrelations, respectively (***Table 2-4, Figure 2-9***). The snow depth measurements made in both WSD plot E in March 2008 and in CLPX IOP 3 could not be processed by the statistical analysis program "R", version 2.6.1 software, and therefore did not yield any Moran's I values.

The results of the Moran's I analysis for the sagebrush microtopography in WSD plots A, B, C, and D were 0.000, 0.002, 0.000, and 0.034, respectively (***Table 2-4*** and ***Figure 2-9***). These results indicate that the spatial autocorrelation of sagebrush plant geometry measured at the fine scale may trend towards completely random spatial autocorrelation (***Table 2-4***).

2.4.4 Percent frequency histogram of snow depths

From the frequency histogram of snow depths generated in this study (***Figure 2-10***), the largest percentages of snow depth measurements for each month at each scale can be observed. Each set of data was divided into 10 equal bins with a width of 12 cm because measurements of sagebrush height and snow depths were between 0 and 120 cm for all three datasets (WSD, CIRA, CLPX).

In February of 2002 and 2003, the CLPX snow depth data at coarse resolution in the histogram shows approximately 52% of depth measurements falling between the 12 to 24 centimeter range, and 29% between 24 and 36 cm. For the coarse resolution measurements in March of 2002 and 2003, about 78% of snow depths were measured between 12 and 24 centimeters and 13% between 24 and 36 cm. In February of 2008, the CIRA snow depth data at medium resolution in the histogram shows approximately 30% of depth measurements falling between the 36 to 48 centimeter range, 22% between 48 and 60 cm, 20% between 24 and 36 cm, and 18% between 60 and 72 cm. For the medium resolution measurements in March of 2008, 39% of snow depths were measured between 48 and 60 centimeters, 28% between 60 and 72 cm, 11% between 72 and 84 cm, and 10% between 36 and 48 cm.

In December of 2007, the WSD snow depth data at the fine scale in the histogram shows approximately 84% of depth measurements falling within the 24 to 36 bin width, with an additional 12% within 36 and 48 cm. For the fine resolution measurements in January of 2008, about 62% of snow depths were measured between 36 and 48 centimeters, 22% between 48 and 60 cm, and 12% between 24 and 36 cm. In February 2008, 47% of the WSD measurements fall within the 48 to 60 centimeter range, with 45% between 36 and 48 cm, and 8% between 60 and 72 cm. In March 2008, 75% of snow depth measurements at the fine scale are between 48 and 60 centimeters, with an additional 19% falling within the 60 to 72 cm bin width.

2.5 Discussion

At the core of an effective analysis of spatial variability in snow cover characteristics is often the variogram (Blöschl 1999). Three hypotheses are tested to determine the nature of spatial variability of snow depth measurements and sagebrush plant surfaces using the statistical methods of variograms and Moran's I analyses. The first of these three hypotheses is that sagebrush surface microtopography is less spatially autocorrelated / more spatially variable than the microtopography of the snowdrift surface that results from wind – distributed snow accumulating around that same plant. The results of the directional variogram analyses show that the gamma values for the WSD plots' sagebrush microtopography tend to be slightly larger than for the corresponding snow depth measurements in the same WSD plots (***Tables 2-2*** and ***2-3, Figure 2-6***). This specifies more spatial variability in the sagebrush surface than in snow depths. For accurate atmospheric model simulations, the degree to which a snowpack can cover vegetation must be realistically represented (Strack *et al.* 2004). Both vegetation height and snow depth must be reasonably known to determine the amount of masking (Strack *et al.* 2004). It is purely coincidental that when the heights of sagebrush plants in each WSD plot were averaged, the values for plots A, B, C, and D decreased in each plot, respectively. It may be important to note, however, that as the WSD plots' plant height decreased, the sill decreased as well (***Table 2-2***). The fractal dimensions of sagebrush microtopography and snow depths in WSD plots B and C are almost equal, while those in plots A and D are both higher for the sagebrush (***Table 2-2***). Higher fractal dimensions might indicate more spatial variability in the sagebrush microtopography than in the corresponding snow depth measurements for WSD plots A and D. As the fractal dimensions of the sagebrush plant surfaces in these plots get closer to a value of 3, they approach complete spatial randomness. Deems *et al.* (2006) showed that snow depth and vegetation topography each show two distinct fractal distributions over different scale ranges (multi-fractal behavior) and the results indicated that different sampling resolutions (see Fassnacht and Deems, 2006) may yield different results and allow rescaling in specific scale ranges.

The Moran's I values for the sagebrush microtopography also indicated complete spatial randomness, as the values are all essentially zero (***Table 2-4*** and ***Figure 2-9***). The Moran's I values of snow depth measurements in the corresponding WSD plots show that there is more spatial autocorrelation between snow depth measurements than sagebrush plant geometry, except in WSD plot D, wherein the Moran's I values are essentially equal (***Table 2-4*** and ***Figure 2-9***). The sagebrush in plot D is small (***Table 2-2***), with a substantial amount of bare ground and the snow depths were measured in March after a full winter season of wind scour. ***Figure 2-8*** indicates that the sagebrush microtopography in WSD plot C is the most spatially variable characteristic. Snow surface roughness is less spatially autocorrelated than snow depths or ground surface elevation changes, which have equal spatial variability. ***Figures 2-1*** and ***2-2*** convey visually that not only do snowdrifts resultant from their corresponding plant surfaces appear to be less spatially variable than the plants themselves, but also that the snow surfaces appear more spatially autocorrelated (smoother) between December and January, despite the fact that snow depth measurements are not substantially greater.

The second hypothesis in this study is that as a winter season progresses and the voids within sagebrush plants are filled with wind-distributed snow, the resultant surface evolves into a progressively more spatially autocorrelated or less spatially variable microtopography. The results of the variogram analyses of snow depth measurements in WSD plots A, B, C, and D indicate that snow depths tend to became less spatially variable, with lower gamma values, as the 2007-2008 winter season progresses; except for WSD plot B (measured in January 2008), which had the lowest average gamma values (***Table 2-3*** and ***Figure 2-6***). The gamma values for snow depth measurements in WSD plot E show some evidence of a progressively smoother snowpack evolving throughout the winter season. The February and March datasets for plot E have very similar gamma values, somewhat lower than the January dataset, indicating a "leveling-off" of the spatial variability (***Table 2-3*** and ***Figure 2-6***). Average snow depth measurements for WSD plot E tend to be similar, as snow depths do not vary as much in the later part of the winter season, with these measurements ranging from 33 cm to 45 cm. Also, the coefficients of variation are similar and the fractal dimensions are almost equal.

The Moran's I values for snow depth measurements in WSD plots A, B, C, and E all indicate progressively more positive spatial autocorrelations among snow depth measurements as the 2007-2008 winter season progressed (***Table 2-4*** and ***Figure 2-8***).

Only in plot D does the Moran's I analysis indicate almost complete spatial randomness. This may be due to the sagebrush in plot D being smaller than in the other WSD plots (***Table 2-2***). There is a substantial amount of bare ground in plot D, so less snow may have been captured in this plot. A progressively less variable / more autocorrelated snow surface can be seen in WSD plot E (***Figures 2-3*** and ***5***), as well as in WSD plots A, B, C, and D (***Figure 2-4***). The wind blown snow may act as an equalizer for the sagebrush microtopography, filling in the shrub interspaces. Once shrubs are filled essentially to a flat surface, accumulation does not continue due to wind. In a simulation, Essery and Pomeroy (2004) found increasing shrub height to increase the potential amount of snow held by shrubs and when shrubs were filled up to a threshold height determined by the supply of snow, snow surfaces decreased in spatial variance. Snow depth measurements in this study became almost constant later in the season (***Figures 2-4*** and ***2-5***).

The third hypothesis is that when measuring a shallow rangeland snow pack, smaller scale (more dense) measurements produce a progressively more spatially variable snowpack and a less spatially autocorrelated snow surface. This hypothesis of decreased spatial variability with increased depth measurement scaling is based on the idea that statistical estimations of snow depths between actual measurement points become more uniform with increasing distance between point measurements. An analysis of scaling effects on snow characteristics showed that it may be difficult to infer the true snow cover variability from the variograms, particularly when they span many orders of magnitude (Blöschl 1999).

The results of the variogram analyses for the snow depth measurements in the WSD plots (fine scale), CIRA plot and transects (medium scale), and CLPX IOP's (coarse scale) show that as snow depth measurement dataset scales increase, so do their correlation lengths (***Table 2-3*** and ***Figure 2-7***). The CIRA snow depth datasets appear to have slightly larger variance than the WSD plots and the CLPX IOP's tend to have slightly larger variance than the CIRA data, although the differences are not substantial (***Figure 2-7***). These variogram results contradict the assumption made by the third hypothesis and indicate that smaller scale snow depth measurements produce a less spatially variable / more autocorrelated snow surface. As scale in snow depth measurements increases by orders of magnitude among WSD plots, CIRA data, and CLPX IOP's, their respective correlation lengths and variance tend towards increasing by orders of magnitude as well (***Table 2-3***). IOP 2 and IOP 4 were both measured in late March of their respective years and it may be important to note that their fractal dimensions, correlation lengths, and sills are essentially equal for both years (***Table 2-3***).

The Moran's I values for snow surface variability by measurement scale seem to indicate that the CIRA medium scale snow depth measurement resolution is more spatially autocorrelated than either the CLPX medium scale resolution or the WSD fine scale resolution. The WSD Moran's I values indicate more spatial autocorrelation than the CLPX data. These results are more supportive of the third hypothesis than the variogram results. The multi-scale snow depth measurement variogram analyses and multi-scale Moran's I analyses do not appear to give the same results in regards to the third hypothesis of smaller scale measurements and more spatially variable datasets of snow depths. This may be due to the nature of the Moran's I analyses, which are based on interpolated data. Erxleben *et al.* (2002) evaluated multiple spatial interpolation techniques for estimating snow distribution, including inverse distance weighting, ordinary kriging, modified residual kriging and cokriging, and a combination of binary regression trees and geostatistical methods. They found that none of the methods were adequate in modeling snow depth variability and suggest that there was not enough spatial structure in the data, at either small or large scales. A lack of spatial dependency of the interpolated data used in the Moran's I analyses in this study might account for results that conflict with those of the variogram analyses.

Histograms of snow depth measurements by scale and winter months (***Figure 2-10***) indicate that the most evenly distributed measurements are from the CIRA dataset. The CLPX and WSD datasets have similar distributions. The coarse scale snow depth measurements (CLPX) in February are more evenly distributed than those in March. Measurements in February at the medium scale (CIRA) are also more evenly distributed than those at the same scale in March, and both months at this scale are more distributed than the coarse scale CLPX data. At the fine scale (WSD), February still has the most evenly distributed percentages of snow depth measurements, followed by January, then March, and lastly, December. Overall, February is the most evenly distributed month in regards to snow depth measurement frequency at all three scales, followed by January at the fine scale, March at all resolutions, and lastly, December at the fine scale. The relatively even distribution of percent frequency of snow depths within the CIRA dataset could be important information to keep in mind for future research. Scaling is key to the creation of an accurate blowing snow model for shallow snow packs on exposed, high altitude rangelands with an extreme climate regime, such as is found in the research area of this study. The CIRA data set seems to be the most spatially autocorrelated (***Figure 2-10***). However, Bloschl (1999) suggests that in general, an optimum resolution size may not exist and that models' element scales may in practice be dictated by data availability and the required resolution of the predictions.

Table 2-3 indicates that WSD average snow depth measurements increased each month over the 2007-2008 winter season. There was a large increase between December and January of almost 100 percent average depth, with substantially smaller increases each month following January. WSD plot E average depth measurements in ***Table 2-3*** also increased slightly each month of the season, as did the CIRA data between February and March 2008. Average CLPX depth measurements are less conclusive, however, as February/March 2002 and February/March 2003 each had approximately the same average snow depth from one month to the next within their respective years. The CLPX snow depth measurements from 2002 – 2003 were noticeably smaller than the values from the 2007-2008 winter. This difference could be due either to scaling effects or, more likely, from changing weather patterns from different winter seasons. It is important to note that 2002 and 2003 were dry years (below average) until mid-March, when precipitation was above average in the mountains of Northern Colorado. A study by Cline *et al.* (1998) found that coarsening of spatial resolution did result in a loss of explicit information regarding the location of certain snow characteristics. It could be important to note for future studies that the WSD fine scale was the most effective resolution for monitoring detailed changes in snow depths (***Table 2-3***).

A progressively smoother snow surface evolved over the 2007 to 2008 winter season. This can be seen in the WSD cross sections shown in ***Figure 2-4***. As the winter continued, the snow pack decreased in spatial variability and increased in spatial autocorrelation, with a slight increase in depth. The snow surface became smoother, but there was little change in depth over the season because the wind distributed snow filled in the spaces between shrub plant parts until the entire plants were covered. This created a virtually smooth surface and additional snowfall tended to be lost to the atmosphere by sublimation in the dry climate of the North Park plateau. The variogram analyses shown in ***Figure 2-6b*** (WSD plots A, B, C, and D) correlate with the cross sectional surface roughness evolution shown in ***Figure 2-4***. December is the most spatially variable month in both figures, however, January is the least variable in ***Figure 2-6b***, while it is the second most variable in ***Figure 2-4***. February is more variable than March in both figures. The Moran's I analysis for the WSD plots A, B, C, and D indicate that the most variable / least autocorrelated month is March, while ***Figure 2-4*** shows it as the most autocorrelated. December, January, and February Moran's I analyses correlate to the cross sections much better, indicating increasing spatial autocorrelation and decreasing variability for each month, respectively.

A chronologically smoother snow surface can be seen in the WSD PLOT E cross sections (***Figure 2-5***). Throughout January, February, and March of 2008, the snow pack decreased in spatial variability, with a small increase in depth. The variogram analysis

(***Figure 2-6c***) correlates well with the smoothing of the snow surface, as indicated in the cross sections (***Figure 2-5***). In ***Figure 2-6c***, January is the most spatially variable month for WSD PLOT E. February is more variable than March at lag distances over 0.6 meters. However, at short distances, before the correlation length (lag distances between 0.1 and 0.5 meters), March appears more variable than February. In ***Figure 2-5***, February's snow depth measurements can be seen to have a greater range of values than in March, showing more spatial variability, as indicated by the sills (***Figure 2-6c***). The Moran's I analysis for WSD PLOT E indicates that the February is more spatially autocorrelated and less spatially variable than January, which correlates well with the cross sections (***Figure 2-5***).

Another approach to snow depth measurements in shallow snow packs on high altitude rangelands such as that of North Park, Colorado could be to utilize a scale between the medium and coarse resolutions. Blowing snow transport and sublimation fluxes can be scaled up to calculate open environment snow accumulation by accounting for their variability over open snowfields, and increase in transport and sublimation (Pomeroy and Li 2000). This may determine if measurements within this range could be more useful than the medium scale. For the study presented here, the medium measurement resolution seems to provide more detailed information in regards to spatial variability than the coarse scale, but not less than the fine scale. Therefore, the medium resolution may be more efficient than the fine scale. Scaling for spatial variability analyses may only be applicable in open, flat rangeland environments with relatively short vegetative cover.

A snow water equivalent (SWE) distribution model was developed by Liston *et al.* (2008) for the three CLPX MSA study areas, including North Park, Fraser, and Rabbit Ears. While North Park consists of an open, relatively flat rangeland dominated by sagebrush, the Fraser MSA is characterized by complex, mountainous topography with rugged peaks. The vegetation within the Fraser MSA consists of a coniferous, forested ecosystem, largely dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) and spruce-fir (*Picea engelmannii* and *Abies lasiocarpa*) (Liston *et al.* 2008). For both MSA's, the SWE distribution model showed much more spatial structure than in existing observations (Liston *et al.* 2008). The model also showed that SWE values are considerably lower in North Park than in Fraser, which is intuitive, considering the thinner snowpack in North Park. Due to the significant difference in snow pack regimes within these two MSA's, it is reasonable to assume that the findings in this study may only be applicable to shallow snow, but not deeper snow, such as in Fraser.

The Fraser MSA is located either within, or adjacent to, a larger study area, the Fraser Experimental Forest (FEF). The influence of harvest practices on snow accumulation and stream flow has been studied at the FEF for more than 60 years and reviewed in detail by Meiman (1987) and Troendle and Kaufmann (1987). Findings within the FEF demonstrate that as forest density is decreased by tree removal, there is a consistent increase in both snowpack accumulation and stream flow (Troendle and Reuss 1997). This is in contrast to rangeland environments, often dominated by strong winds and small shrub cover, wherein a reduction of shrubs can result in a decrease in snowpack accumulation as snow is lost to sublimation from wind effects. The differences in these environments are illustrated here to show that the findings of this study in regards to scaling and variability should be applied in the context of a rangeland ecosystem exclusively.

The data presented and analyzed in this study could be complemented by adding information about spatial variability in snow characteristics derived from LiDAR data. LiDAR (Light Detection And Ranging) is an optical remote sensing technology that measures properties of scattered light to find information of a distant target, in this case to find information about snow pack characteristics in high altitude rangelands. Laser pulses are used to determine distance to an object by measuring the time delay between transmission of a pulse and detection of the reflected signal. LiDAR was used in the CLPX experiment to collect data from several of the study sites, including North Park. A study done by Fassnacht and Deems in 2005 used LiDAR measurements from three montane NASA Cold Lands Processes Experiment study sites to examine the spatial scaling properties of snow depth over an 1100 by 1100 m area. Their results indicated that the choice of resolution must be consistent with the scale of spatial structure required. A resolution that is too fine will be inefficient, but a too-coarse resolution will not preserve the spatial structure (shown in the variograms) that adequately describes the patterns observed on the ground. This methodology of analyzing LiDAR data could be used to complement the in-situ measurements done in this study for comparisons of spatial variability.

According to the statistical analyses of spatial variability in this particular study, the optimal measurement resolution of snow depths and sagebrush microtopography appears to be the CIRA medium scale. This could be important information to consider when generating blowing snow models and conceptualizing the processes involved with wind redistribution of snow, such as snow melt. Optimal future management of snowmelt-derived water resources will require explicit physical models driven networks (Bales *et al.* 2006 and Painter *et al.* 2009). There are several ecological factors that may have a significant impact on the wind redistribution of snow that operate at such small scales as to necessitate further research in spatial variability at these resolutions. One of these factors is vegetative cover, especially in rangelands where the dominant plant types include shrubs, grasses, and forbs whose spatial variability increases with smaller scale measurements. Essery and Pomeroy (2004) indicated that snow accumulation in shrubs is sensitive to both regional shrub areal coverage and height. Blowing snow transport and sublimation was hindered by increasing aerodynamic roughness from exposed shrubs in tundra environments. Other factors include snow surface roughness and ground variation (Fassnacht *et al.* 2009), which appeared to have the most spatial variability at the 25 cm resolution. Measurements on a smaller scale than this may not pick up on any additional variations.

2.6 Conclusions

Sagebrush surface microtopography is less spatially autocorrelated, or more spatially variable, than the surfaces of subsequent snowdrifts that accumulate around that same plant. As the 2007-2008 winter season progressed, snow depth measurements seemed to evolve progressively to be more spatially autocorrelated, or less spatially variable. Snow surface roughness over this winter progressively lessened, which may be due to wind scour and accumulation in sagebrush plant void spaces.

From the variogram analyses, larger scale (smaller resolution) snow depth measurements in the shallow rangeland snow pack of North Park, Colorado produce a progressively more spatially variable dataset of snow depths and therefore, a less spatially autocorrelated snow surface texture. In other words, the variograms indicate that as resolution decreases, spatial variability increases. Conversely, results of Moran's I analyses show that smaller scale (higher resolution) snow depth measurements in this environment tend towards the more spatially variable / less autocorrelated snow surface. In contradiction to the variogram results, the Moran's I results indicate that as resolution decreases, spatial variability decreases, as well.

2.7 Future Work

The scope of this study was limited in temporal variability. Field datasets with more robust snow depth measurements in terms of numbers of years and frequencies per month could greatly enhance the viability of the statistical analyses presented in this study, if performed at varying resolutions in a consistent field site location. More research needs to be done in order to effectively make decisions about which snow depth measurement scale will be the most efficient for future snow depth measurement campaigns.

CHAPTER 2 – TABLES AND FIGURES

Table 2-1: Multiple small scale datasets utilized

Dataset	Scale	Grid Spacing (cm)	Extent (m)
CLPX	Coarse	10^2, $5x10^2$, $25x10^2$	1000
CIRA	Medium	25	500
WSD	Fine	5 – 10	2

Table 2-4: Moran's I analyses results

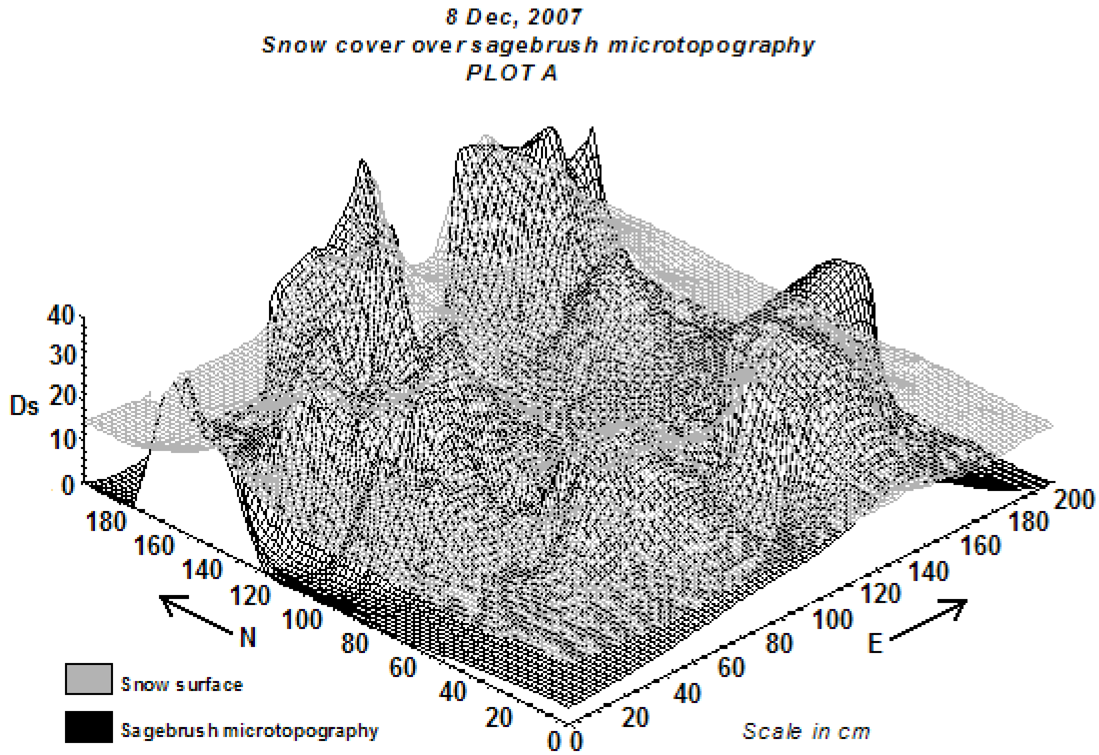
Dataset	Date	Scale (cm)	Moran's I	Spat Autocrltn
WSD PLOT A Sagebrush	4 Nov, 2007	5	0.000	random
WSD PLOT B Sagebrush	4 Nov, 2007	5	0.002	random
WSD PLOT C Sagebrush	4 Nov, 2007	5	0.000	random
WSD PLOT D Sagebrush	4 Nov, 2007	5	0.034	random
Snow covered plots				
WSD PLOT A Snow cover	8 Dec, 2007	5	0.088	positive
WSD PLOT B Snow cover	12 Jan, 2008	5	0.107	positive
WSD PLOT C Snow cover	18 Feb, 2008	5	0.219	positive
WSD PLOT D Snow cover	12 Mar, 2008	5	0.036	random
WSD PLOT E Jan	12 Jan, 2008	5	0.136	positive
WSD PLOT E Feb	18 Feb, 2008	5	0.221	positive
WSD PLOT E Mar	12 Mar, 2008	5	N/A	N/A
CIRA 50 m square plot	11 Mar, 2008	25	0.591	positive
CIRA 1 km transect Feb	6 Feb, 2008	25	0.363	positive
CIRA 1 km transect Mar	11 Mar, 2008	25	0.437	positive
CLPX IOP 1	21-22 Feb, 2002	100	0.034	random
CLPX IOP 2	27 Mar, 2002	100	0.100	positive
CLPX IOP 3	21 Feb, 2003	100	N/A	N/A
CLPX IOP 4	28 Mar, 2003	100	0.061	random

Table 2-2: WSD Sagebrush directional variogram analyses results

Dataset	Date	Fractal Dimension, D (m)	Correlation Length, Lag (m)	Sill, Gamma (m)	Sagebrush Characteristics by Plot: Density, # of Plants (per m^2)	Area Covered by Sagebrush (% of plot)	Average Ht of Sagebrush (m)
WSD PLOT A Sagebrush	4 Nov, 2007	2.57	0.32	0.0193	5	55.5 %	0.251
WSD PLOT B Sagebrush	4 Nov, 2007	2.63	0.28	0.0171	3	46.7 %	0.216
WSD PLOT C Sagebrush	4 Nov, 2007	2.38	0.36	0.0147	5	49.3 %	0.192
WSD PLOT D Sagebrush	4 Nov, 2007	2.82	0.42	0.0133	4	62.5 %	0.189

Table 2-3: Multiple scale snow depth measurement directional variogram analyses results

Dataset	Date	Fractal Dimension, D (m)	Correlation Length, Lag (m)	Sill, Gamma (m)	Snow Depth Measurement Statistics: Average Snow Depth (m)	Standard Deviation (m)	Coefficient of Variation
WSD PLOT A Snow depths	8 Dec, 2007	2.06	0.24	0.0042	0.17	0.62	0.359
WSD PLOT B Snow depths	12 Jan, 2008	2.64	0.83	0.0004	0.32	0.02	0.058
WSD PLOT C Snow depths	18 Feb, 2008	2.38	0.63	0.0015	0.33	0.03	0.090
WSD PLOT D Snow depths	12 Mar, 2008	2.55	1.26	0.0008	0.37	0.03	0.068
WSD PLOT E Jan	12 Jan, 2008	2.46	0.55	0.0072	0.33	0.08	0.245
WSD PLOT E Feb	18 Feb, 2008	2.47	0.72	0.0037	0.42	0.06	0.139
WSD PLOT E Mar	12 Mar, 2008	2.47	0.24	0.0020	0.45	0.05	0.099
CIRA 50 m square plot	11 Mar, 2008	2.74 & 2.48	2.51	N/A	0.50	0.11	0.217
CIRA 1 km transect Feb	6 Feb, 2008	2.07	6.61	0.0070	0.37	0.18	0.477
CIRA 1 km transect Mar	11 Mar, 2008	N/A	N/A	N/A	0.44	0.23	0.511
CLPX IOP 1	21-22 Feb, 2002	2.77	72.4	0.0105	0.18	0.10	0.556
CLPX IOP 2	27 Mar, 2002	2.28	145	0.0218	0.18	0.14	0.778
CLPX IOP 3	21 Feb, 2003	2.72	110	0.0057	0.90	0.07	0.778
CLPX IOP 4	28 Mar, 2003	2.32	145	0.0207	0.70	0.08	1.143
WSD PLOT C Grnd surface	14 Apr, 2008	2.51	0.48	0.0013			
WSD PLOT C Snow surface	18 Feb, 2008	N/A	N/A	N/A			



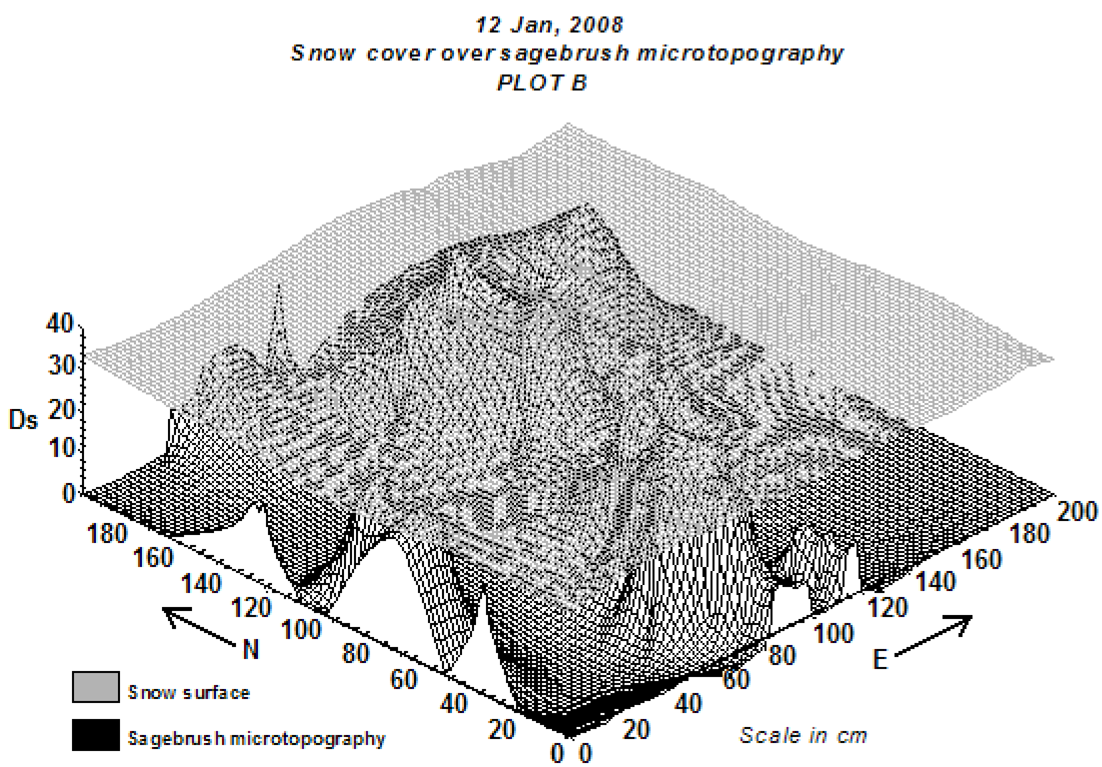


Figure 2-1: 3-D sagebrush plant and snowdrift microtopographic contour maps

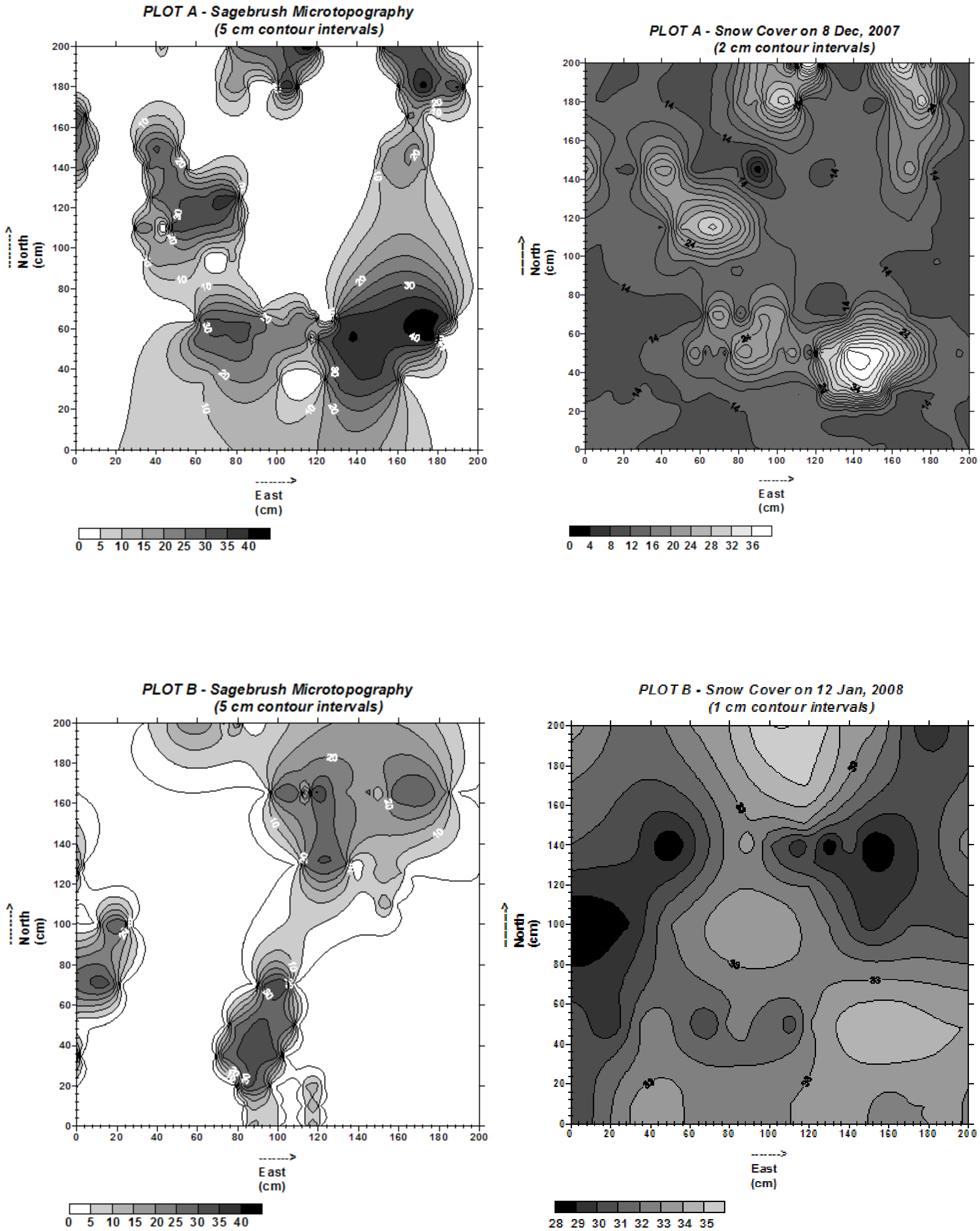


Figure 2-2: Plan view of microtopography of sagebrush cover and resultant snowdrift geometry in December 2007 and January 2008

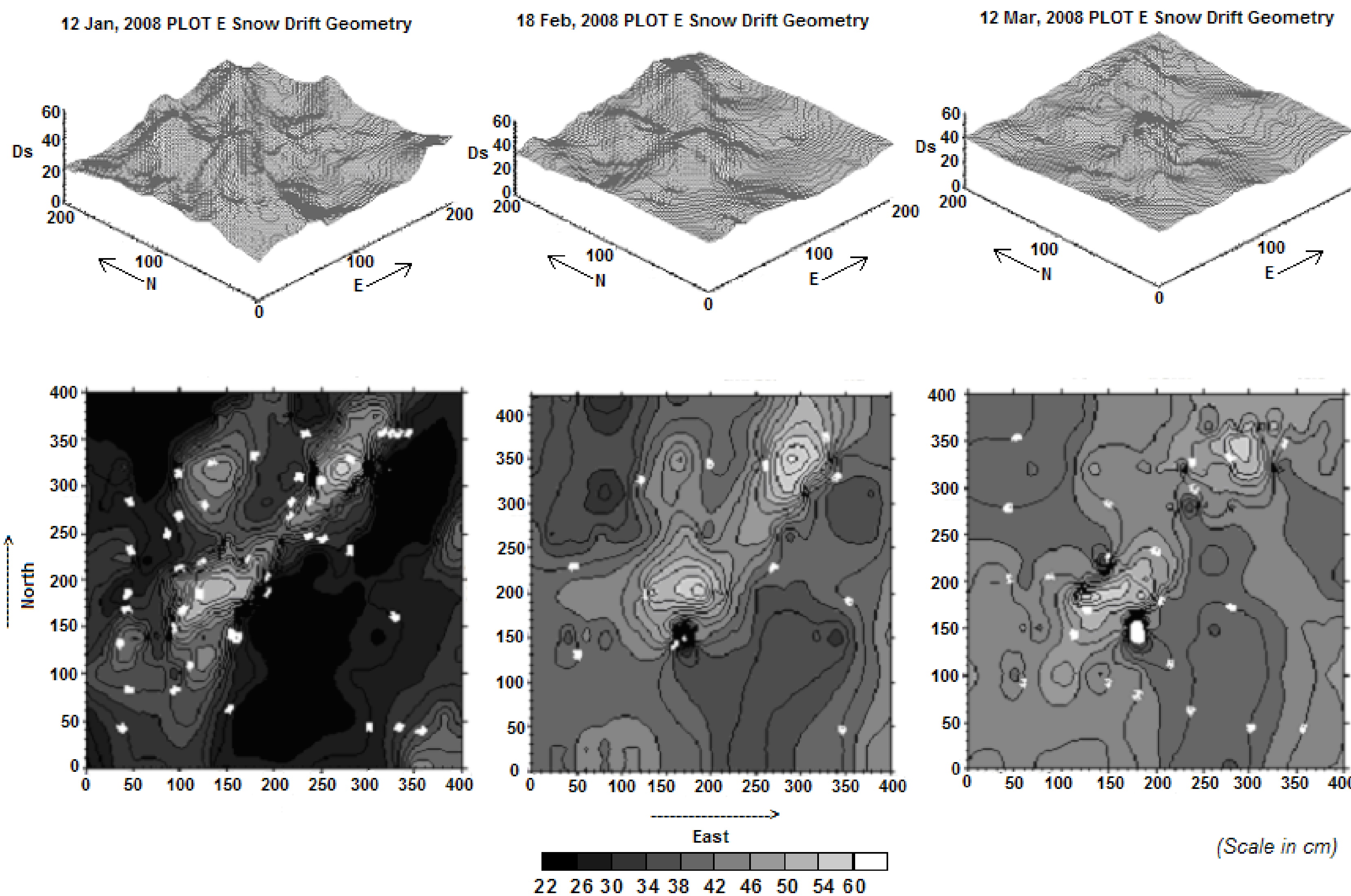


Figure 2-3: Evolution of snow accumulation/drifting over 2007-2008 winter due to wind scour

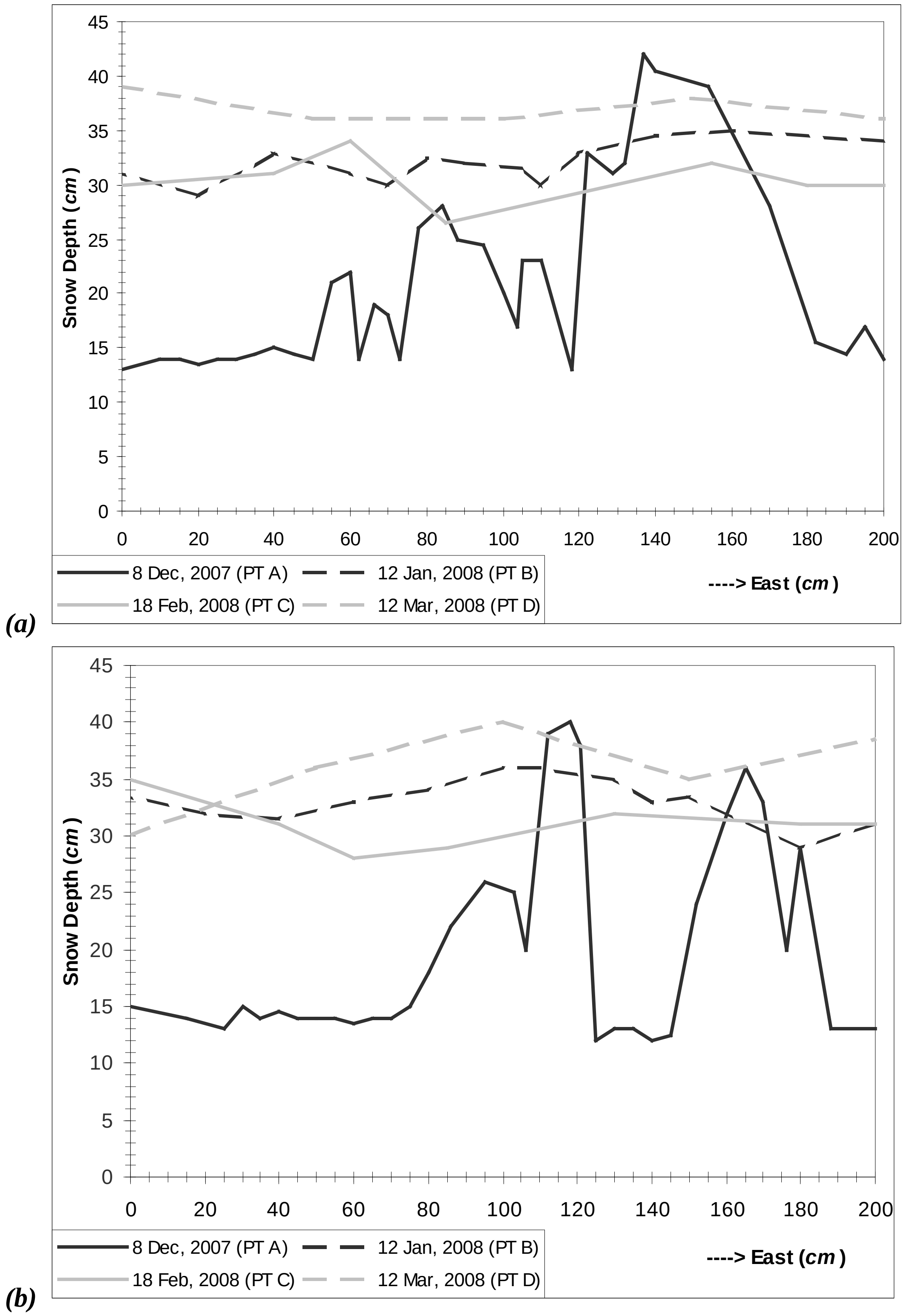


Figure 2-4: 2m x 2m WSD plots cross-sections show a progressively smoother snowpack evolution over the 2007-2008 winter season at (a) 50 cm north of origin and (b) 200 cm north of origin

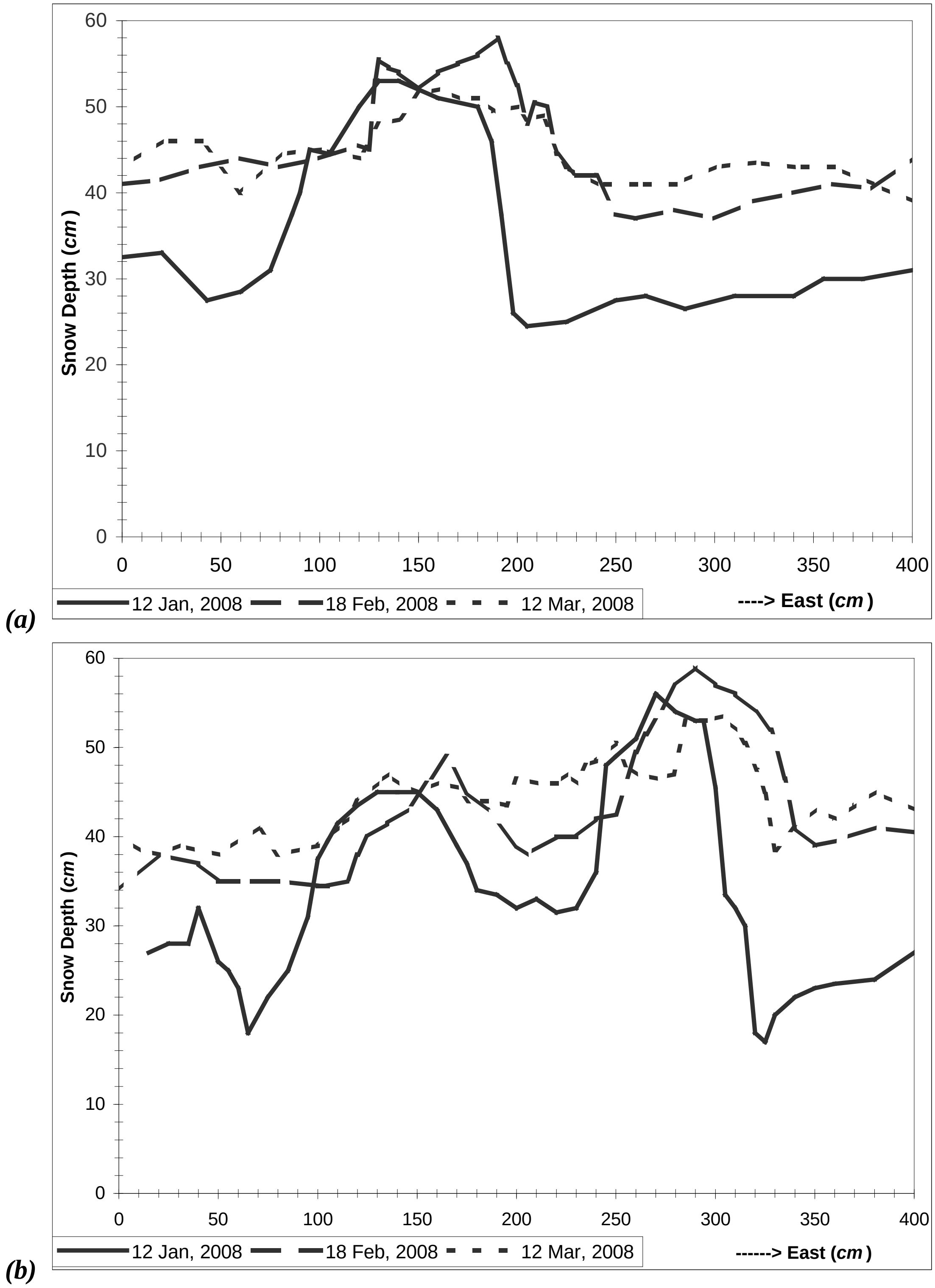


Figure 2-5: 4m x 5m WSD plot E cross-sections show a progressively smoother snowpack evolution over the 2008 winter season at (a) 200 cm north of origin and (b) 320 cm north of origin

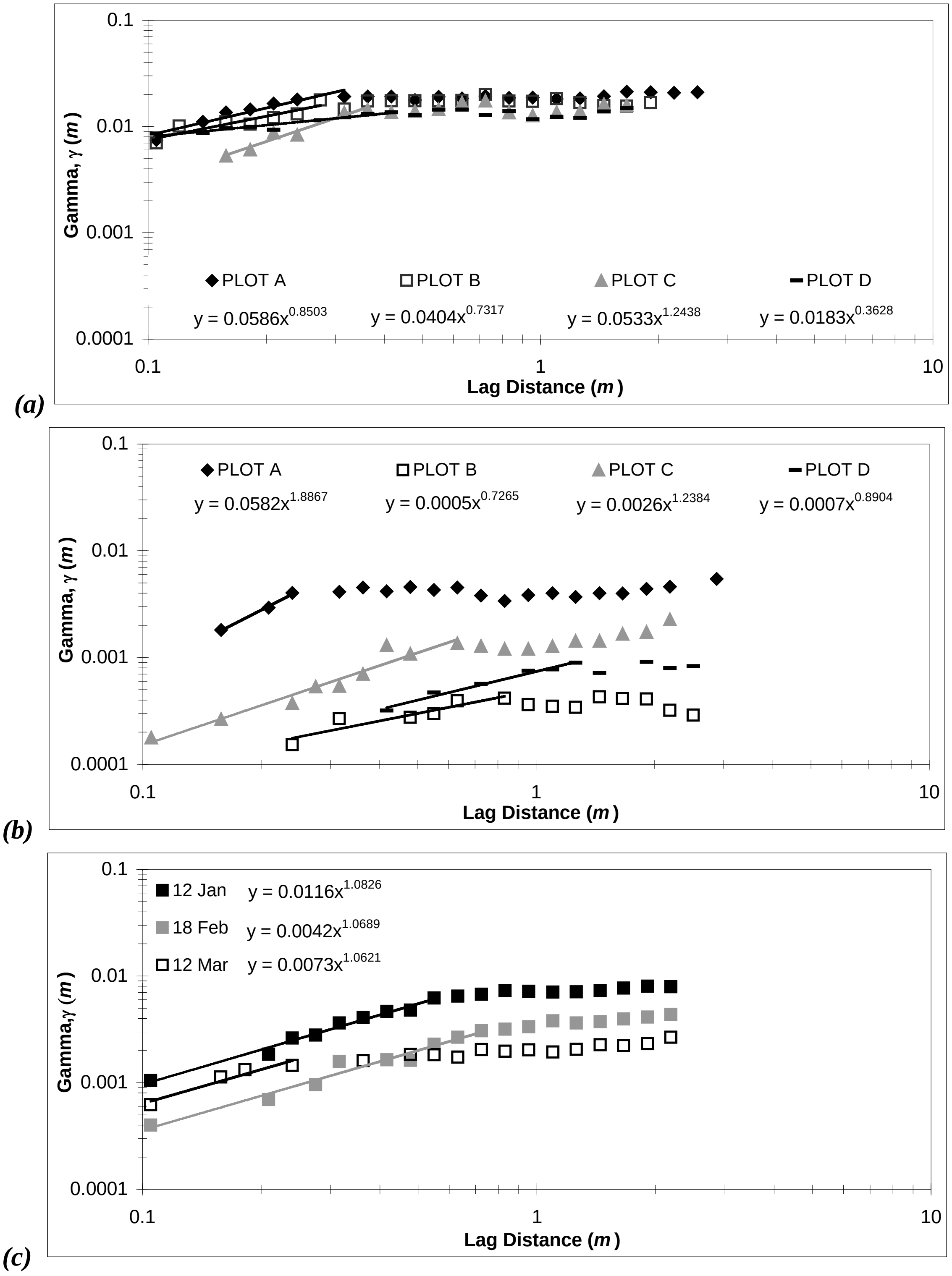


Figure 2-6: Results of the directional variogram analyses for spatial autocorrelation of (a) sagebrush microtopography in WSD plots A, B, C, & D (b) snow depth measurements of resultant drifts in WSD plots A, B, C, & D and (c) snow surface roughness evolution in WSD Plot E over the 2007-2008 winter

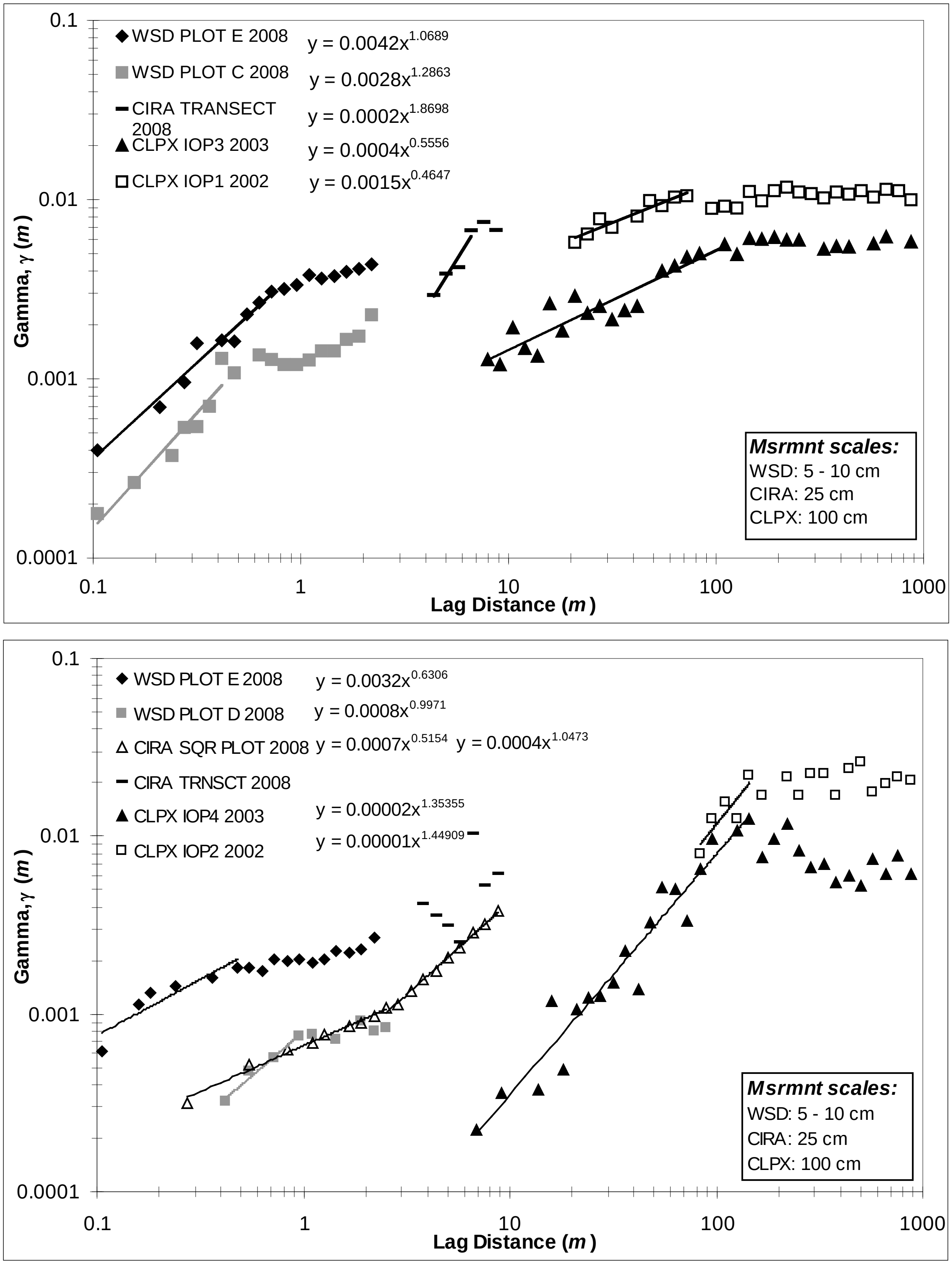


Figure 2-7: Results of the directional variogram analyses for spatial autocorrelation of snow depth measurements at varying small scales for WSD and CIRA over the 2007-2008 winter season and CLPX in 2002 and 2003; February snow depth measurements (top) and March snow depths (bottom)

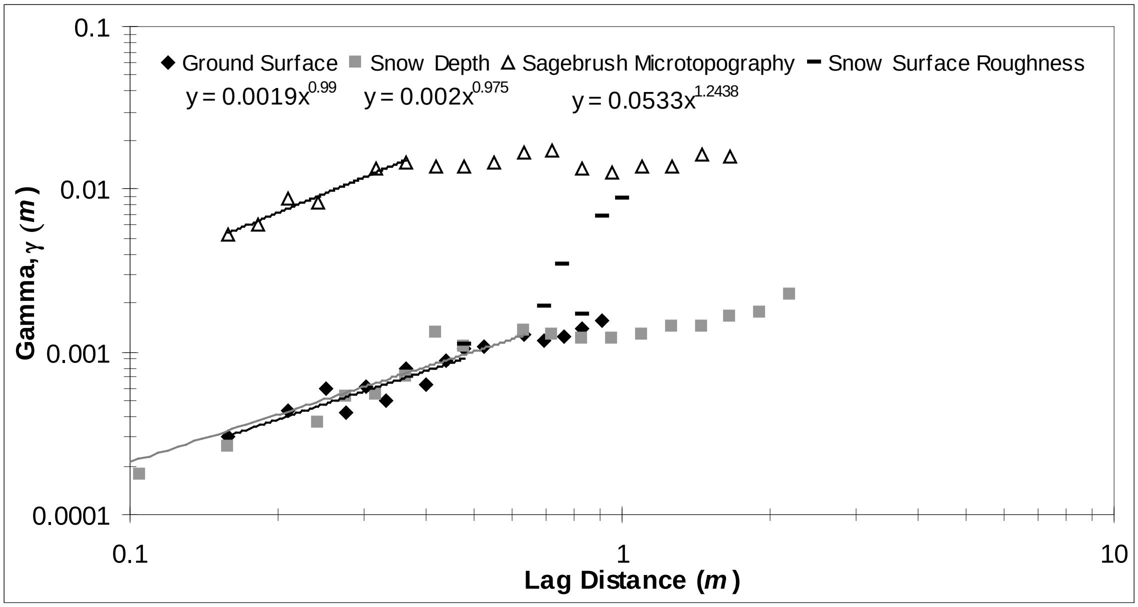


Figure 2-8: Results of the directional variogram analyses for spatial autocorrelation in WSD PLOT C of ground variation, snow depth measurements on 18 Feb, 2008, sagebrush microtopography, and snow surface roughness (from interpolated data)

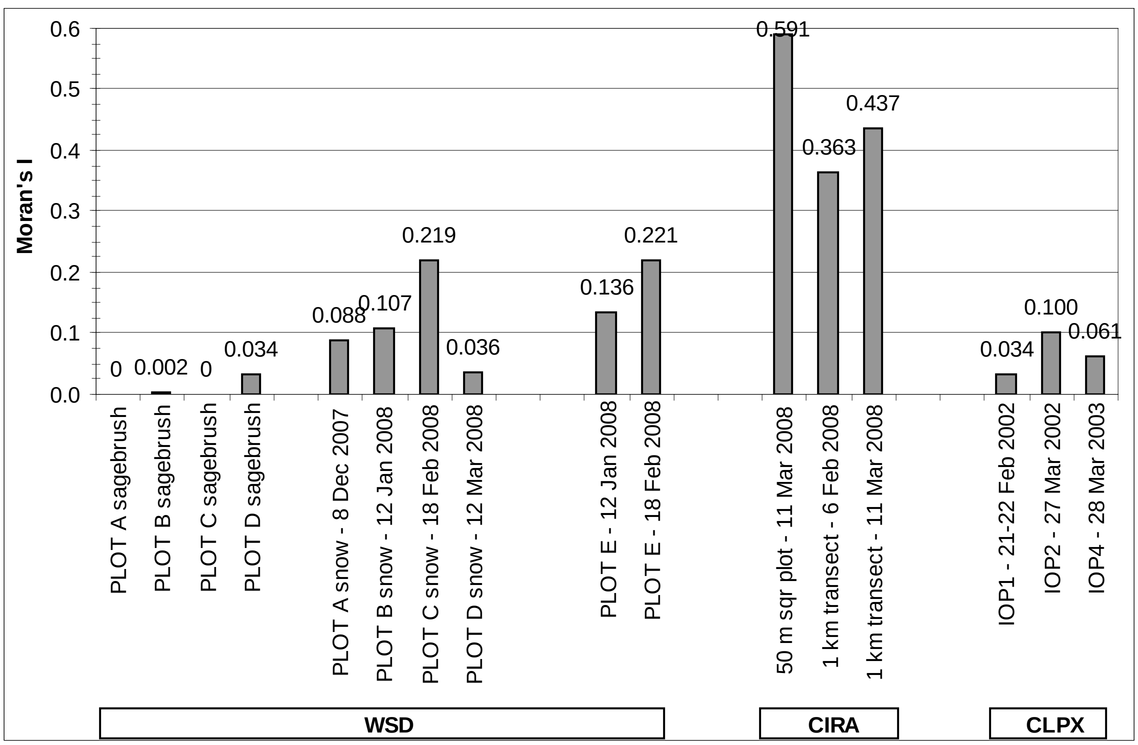


Figure 2-9: Results of the Moran's I analyses for spatial autocorrelation of sagebrush microtopography and subsequent snow depth measurements for WSD plots A, B, C, and D (fine scale); spatial autocorrelation of snow depth measurements for WSD Plot E (fine scale); CIRA 50 m square plot and 2, 1 km transects (medium scale); and CLPX IOP plots 1, 2, 4 (coarse scale), respectively (from interpolated data)

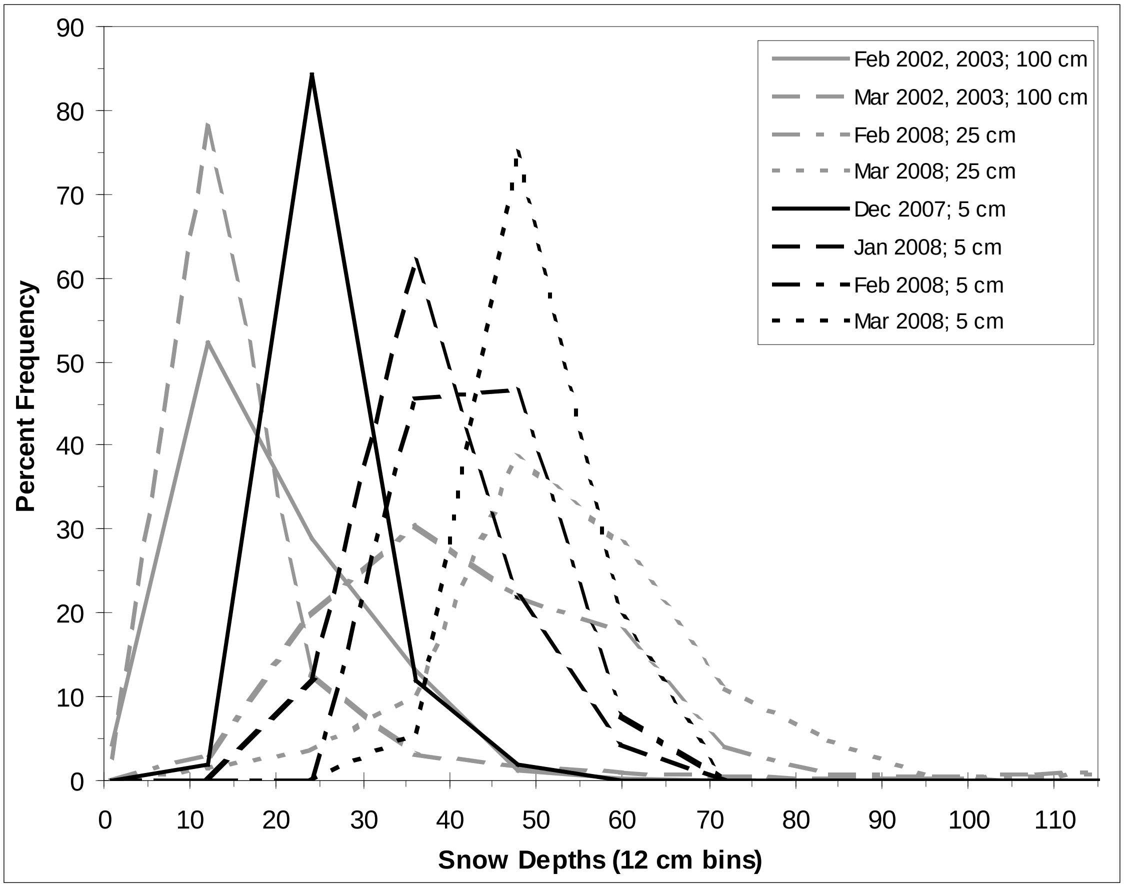


Figure 2-10: Frequency histogram of snow depths by month, year, and measurement scale

CHAPTER 3 – ADDITIONAL ANALYSES

3.1 Introduction

The spatial variability / autocorrelation of sagebrush microtopography and snow depth measurements around these plants in the high altitude rangeland of North Park, Colorado can be calculated through various specific statistical analyses. The two methods of statistical analyses used in this study, variograms and Moran's I, give numerical information regarding the nature of spatial variability of sagebrush microtopography, snow depth measurements, and the scale of snow depth measurements in a high altitude rangeland. The effect of spatial variability on the albedo of sagebrush and snow surfaces may also be significant. Albedo differences in ground surface types might affect the timing of spring snow melt and resultant soil moisture. The interaction of winds characteristic of this environment with shrubs results in snowdrift formation and in snow depth variability. Chapter 3 reviews some preliminary findings in regards to albedo, soil moisture, wind speed, and wind direction in North Park.

3.2 Methods

3.2.1. Albedo measurements

The albedo of an object is a measure of how strongly it reflects light from the sun, i.e., it is reflectivity. Albedo is defined as the ratio of total-reflected to incident solar

radiation. Possible values of albedo range from 0 (dark) to 1 (bright). In the case of a snow surface, the cleaner and whiter the snow, the higher the albedo, the less radiation from the sun the surface will absorb, and the more it will reflect, therefore snow melts more slowly. Conversely, darker snow, perhaps as a result of dust or exposed plant parts, results in a low albedo and more absorption of radiation, hastening snowmelt.

Two different sets of data were collected to investigate the albedo phenomenon in regards to the sagebrush – snow relation; quantitative and qualitative. The qualitative set of data includes photographs and observations of preferential snow melt patterns in relation to big sagebrush cover at the research area near Owl Ridge in North Park on March 26 2007.

The quantitative data were obtained using a pyranometer, an instrument for measuring solar irradiance. This instrument measures broadband solar irradiance on a planar surface and has a sensor designed to measure the solar radiation flux density. The pyranometer CM3 is manufactured by Kipp and Zonen B.V. and contains a sensor that measures the solar energy that is received from the whole hemisphere (180 degrees of field view). The output is expressed in Watts per meter squared (W/m^2). This apparatus is connected to a 12-volt power source and a laptop with software to collect the output data.

In this study, the pyranometer was placed on a plain piece of white paper, meant to simulate full snow cover conditions over the sagebrush. It was then placed on the paper with a sample sagebrush shrub and a sample cinquefoil shrub of comparable canopy area. For each of the three conditions, plain paper, paper with sagebrush, and paper with cinquefoil, the pyranometer was placed in both an upwards and downwards orientation at a height of approximately 30 cm in order to measure both incoming and outgoing radiation, respectively. Both incoming and outgoing radiation measurements are recorded as averages over ten second intervals for two minutes for each condition.

Figure 3-1 is a series of photographs, which illustrate the arrangement for this experiment. For each of the three radiative conditions, the albedo (**α**) is computed as a ratio of outgoing radiation ($\mathbf{Q_{Kout}}$) over incoming radiation ($\mathbf{Q_{Kin}}$):

$$\boldsymbol{\alpha} = \mathbf{Q_{Kout}} / \mathbf{Q_{Kin}}; \mathbf{Q_K} \text{ expressed in W/m}^2; \boldsymbol{\alpha} \text{ is unit less} \qquad \textbf{\textit{[Eq. 3-1]}}$$

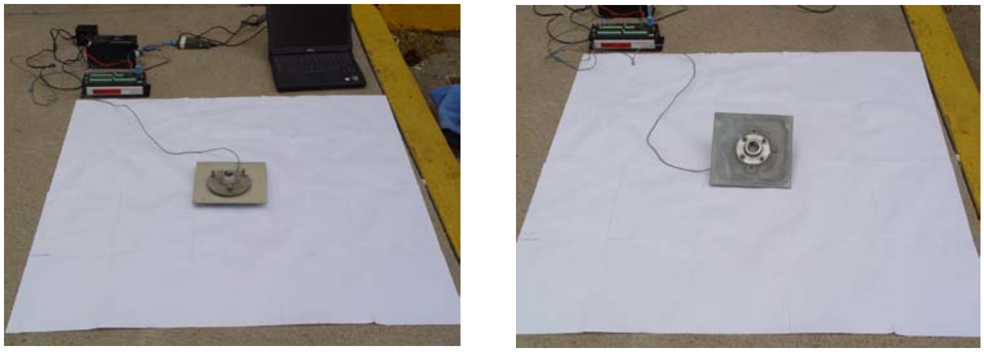


Figure 3-1a: Full snow cover condition with pyranometer measuring incoming and outgoing radiation

Figure 3-1b: Cinquefoil in snow condition with pyranometer measuring incoming and outgoing radiation

Figure 3-1c: Sagebrush in snow condition with pyranometer measuring incoming and outgoing radiation

3.2.2. Soil moisture measurements

During a visit to the Owl Ridge site on April 2 2007, surface soil samples were taken in order to quantify the early spring snowmelt behavior and its impact on soil moisture levels in both sagebrush cover and areas with no sagebrush. Three pairs of transects were utilized in retrieving soil samples. Each pair consisted of one transect in an untreated area with natural big sagebrush cover and one transect in an adjacent, treated area where sagebrush cover had been reduced. Each transect is 10 meters long. Four samples were extracted from the soil surface using a technique that involves a metal ring, placed plumb to the soil surface and hammered into the ground. The sample is then leveled off in the ring to obtain the same sample volume each time and scraped into a plastic, airtight bag. For each transect, a starting point was selected based on the location of the treated areas. A stratified random sampling technique is used to determine both the angle of the 10-meter line, as well as the spacing of the location along the line where each soil sample is taken. The random numbers come from a random number generator.

Each soil sample was weighed, dried in an oven at 104^{o}C for 24 hours, and then weighed again, according to the standard soil moisture sample test (Gardner 1986). The dry weight ($\mathbf{W_D}$) is subtracted from the wet weight ($\mathbf{W_W}$) to find the volume of water contained within the sample. The water volume is then divided by the volume of the sampling container ($\mathbf{V_c}$) to obtain percent volumetric moisture.

$$\%\text{ Moisture by Vol.} = (\mathbf{W_W} - \mathbf{W_D}) / \mathbf{V_C} * 100\% \qquad \textbf{\textit{[Eq. 3-2]}},$$

where W and V are expressed as cm^3.

3.2.3. Photographic observations of sagebrush snow drift geometry

On the first visit to the research area near Owl Ridge on March 2 2007, a preliminary qualitative set of data was collected. These data consisted of photographs and observations made of the preferential accumulation of wind-blown snow in areas of tall sagebrush cover. Due to an earlier than expected onset of springtime conditions in many areas of North Park, Colorado, full snow melt in many of the sagebrush covered rangeland areas occurred by the third week of March 2007, including the research site for this project. While this is considered unusual for the region, further quantitative observations could not be made in this location. Observations and supporting photographs to illustrate wind-blown snow accumulation patterns around example sagebrush plants are provided in the Results section.

3.2.4. CLPX wind data analysis

During the NASA CLPX campaign, meteorological observations were collected at 36 sites throughout the Small Regional Study Area (SRSA) in Colorado. Identical meteorological towers were located close to the four corners of nine 1 km x 1 km Intensive Study Areas (ISAs). At each site, measurements of air temperature, relative humidity, wind speed, and wind direction were made at 2 m or 4 m above ground level. Snow depth, soil moisture, and soil temperatures were also measured. Hourly meteorological observations were recorded between 20 September 2002 and 1 October 2003, although continuous data were not always collected over the entire time period at all towers (Houser and Kunera 2005).

Measurements of all parameters were made every 10 seconds. For all parameters except snow depth, soil moisture content and soil temperature, measurements were averaged over every 1-hour period. For snow depth, soil moisture content, and soil temperature, no average was taken and instead a single sample measurement was recorded at the mid-point of each 1-hour period (Houser and Kunera 2005). From the CLPX corner meteorological station data, the average hourly wind velocities and directions within the Michigan River ISA are of interest for this study. Corner meteorological station data in the Michigan River ISA was accessed through the National Snow and Ice Data Center (NSIDC), Boulder, CO.

Hourly average wind speeds from each corner meteorological station in the Michigan River ISA from December 2002 through March 2003 were utilized to generate a frequency histogram of hourly average wind velocities. To construct the histogram, each monthly data range is divided into equal subintervals called bins or class intervals of bin width 4 m/s. A frequency table for each month was constructed in a Microsoft Excel spreadsheet by tallying the number of wind speed measurements falling into each bin. This number is known as the class frequency (Ott and Longnecker 2001).

Wind speed and direction for meteorological data in the Michigan River ISA for this time period were also analyzed in order to construct a wind rose for each corner. The CLPX corner meteorological data provides wind speed direction numerically within a 360-degree measurement system. These values were converted to one of 16 cardinal directions and each direction was divided by percentage of wind speeds falling within 5 m/s wide categories for that direction.

3.3 Results

3.3.1. Albedo

Figure 3-2 is a series of photographs illustrating the snow melt patterns associated with big sagebrush, which may be due to albedo, differential accumulation and preferential melt. Differential accumulation, or the uneven distribution of snow, in this environment, may occur because of variation in ground surface topography, sagebrush dimensions, and wind speed and direction. Preferential melt may be related to differential accumulation, as areas with smaller snow depths and/or exposed plant parts tend to melt out faster, as affected by albedo. Photographs were taken at the Owl Ridge research area in North Park on March 26 2007.

Figure 3-2: Albedo–induced snow melt patterns around Big Mountain Sagebrush in North Park

The results of the quantitative analysis of albedo readings from the pyranometer are shown in ***Figure 3-3***.

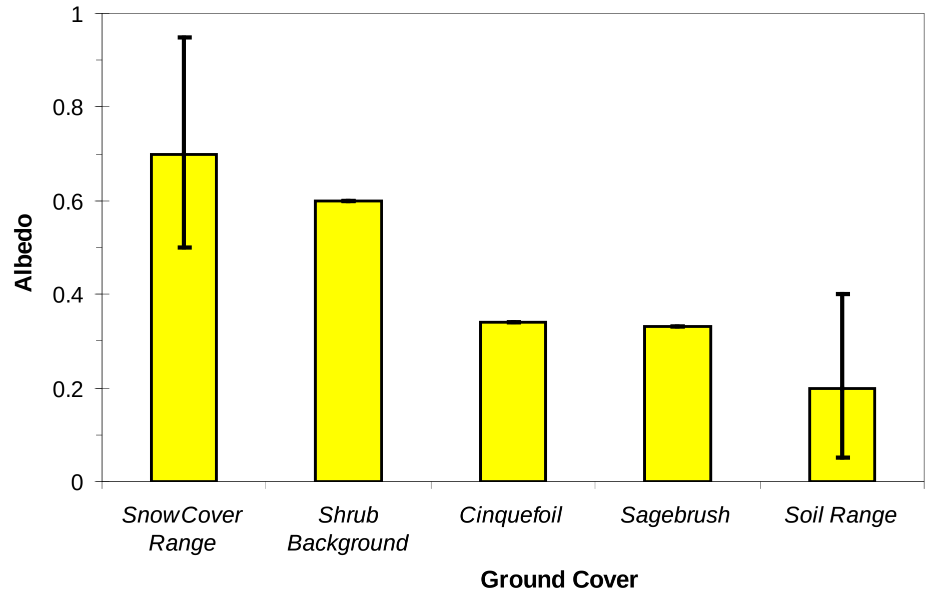


Figure 3-3: Comparison of albedo ratios for ground cover types of interest

3.3.2. Soil moisture measurements

Percent moisture by volume of the surface soil samples are shown in ***Figure 3-4***. The "treated" samples were taken from soil in areas where sagebrush may have been thinned or removed. The texture of the soil in the treated areas tended to be softer and contain more organic matter, while the soil in the untreated areas was harder and rockier. Consistently, soil samples from the "treated" areas, where sagebrush cover had been reduced, contains a higher percentage of volumetric soil moisture. For soil samples 1, 2, and 3, the difference in volumetric soil moisture is roughly 13%, 28%, and 4% higher, respectively. Initially, it was anticipated that the soil would be wetter in the "untreated" areas, due to the increased ability to retain blowing snow for spring melt within the sagebrush plants. However, the drier soil in the natural sagebrush cover might be due to a slower rate of spring melt; characteristic of a deeper snowpack in areas where vegetation holds onto wind distributed snow. It is important to note that these soil moisture samples were taken on only one day at the very beginning of the spring season in April when the snow on the ground had just disappeared by melting.

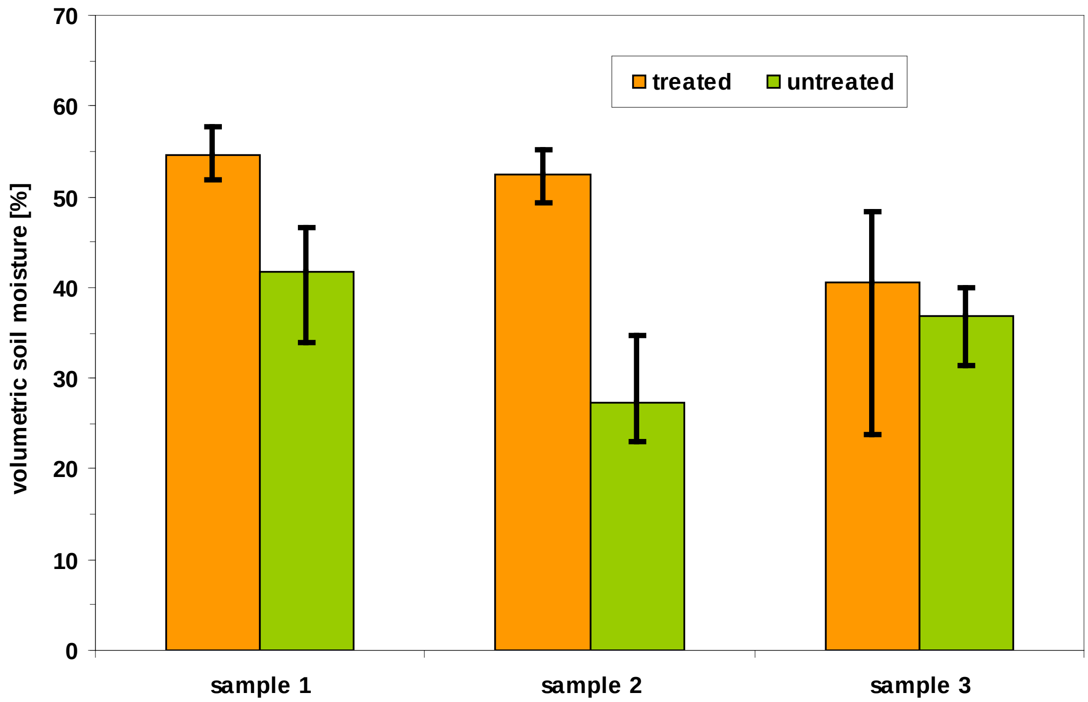


Figure 3-4: Soil moisture content of areas with sagebrush (untreated) and without sagebrush (treated) near Owl Ridge

3.3.3. Qualitative observations of sagebrush snow drifts

Figure 3-5 is a series of photographs illustrating wind and snow accumulation at high-altitude, exposed rangelands such as those near Owl Ridge, North Park, Colorado.

Figure 3-5: Wind blown snow accumulates in drift patterns around and behind sagebrush near Walden, North Park, Colorado

3.3.4. CLPX wind data analysis

Deems *et al.* (2006) indicated that wind speed and direction frequency distributions were related to directional differences in the fractal dimensions for vegetative cover and snow depths at multiple scales. ***Figure 3-6*** is a wind velocity frequency histogram for meteorological station data within the CLPX Michigan River ISA for December 2002 through March 2003, which may help characterize the nature of the wind regime in North Park.

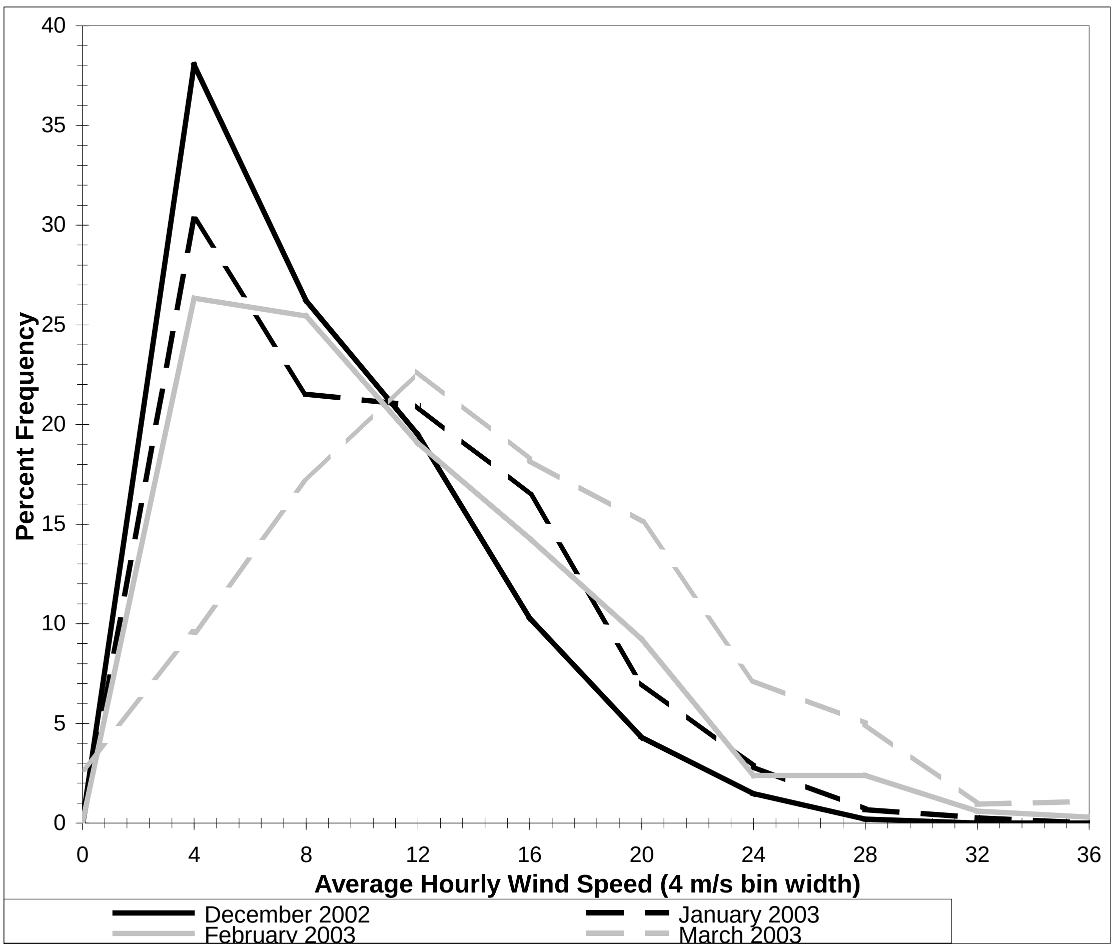


Figure 3-6: Histogram of average hourly wind velocities; North Park Michigan River CLPX Corner meteorological Data for December 2002 through March 2003

Figure 3-7 is a series of four wind roses summarizing both wind speed and direction by the 16 cardinal directions for average hourly wind data within the CLPX Michigan River ISA from September 2002 to 2003. Each of the four roses represents each corner meteorological station. For the northeast corner meteorological station (***Figure 3-7a***), approximately 20% of the wind blew in the due north direction, with 14% NNW, 15% NW, 13% SNW, 14% W, 8% NSW, 5% SW, and 2 – 3% each in the SSW, S, SSE, and SE directions. About 50% of wind speed observations at the NE corner fell between 0 and 5 m/s, with an additional 26.6% between 5 and 10 m/s, 15.5% between 10 and 15 m/s, 6.2% between 15 and 20 m/s, and 1.3% between 20 and 25 m/s. For the southeast corner meteorological station (***Figure 3-7b***), approximately 6% of the wind blew in the northwest direction, with 10% SNW, 15% W, 27% NSW, 20% SW, 7% SSW, and 2 – 3% each in the N, NNW, S, and SSE directions. About 45% of wind speed observations at the SE corner fell between 0 and 5 m/s, with an additional 30.7% between 5 and 10 m/s, 15.7% between 10 and 15 m/s, 7.3% between 15 and 20 m/s, and 1.3% between 20 and 25 m/s. For the northwest corner meteorological station (***Figure 3-7c***), approximately 5% of the wind blew in the due east direction, with 6% NNE, 9% N, 10% NNW, 11% NW, 14% SNW, 18% W, 9% NSW, 6% SW, 4% SSW, and 2 – 3% each in the S, SSE, and SE directions. About 33% of wind speed observations at the NW corner fell between 0 and 5 m/s, with an additional 31% between 5 and 10 m/s, 18.9% between 10 and 15 m/s, 10.4% between 15 and 20 m/s, 4.2% between 20 and 25 m/s, and 1.8% between 25 and 30 m/s. For the southwest corner meteorological station (***Figure 3-7d***), approximately 11% of the wind blew in the due north direction, with 10% NNE, 8%

NNW, 7% NW, 10% SNW, 16% W, 18% NSW, 7% SW, 4% SSW, and 2 – 3% each in the NE, S, SSE, and SE directions. About 45% of wind speed observations at the SW corner fell between 0 and 5 m/s, with an additional 19.6% between 5 and 10 m/s, 14.3% between 10 and 15 m/s, 12.5% between 15 and 20 m/s, and 7.1% between 20 and 25 m/s.

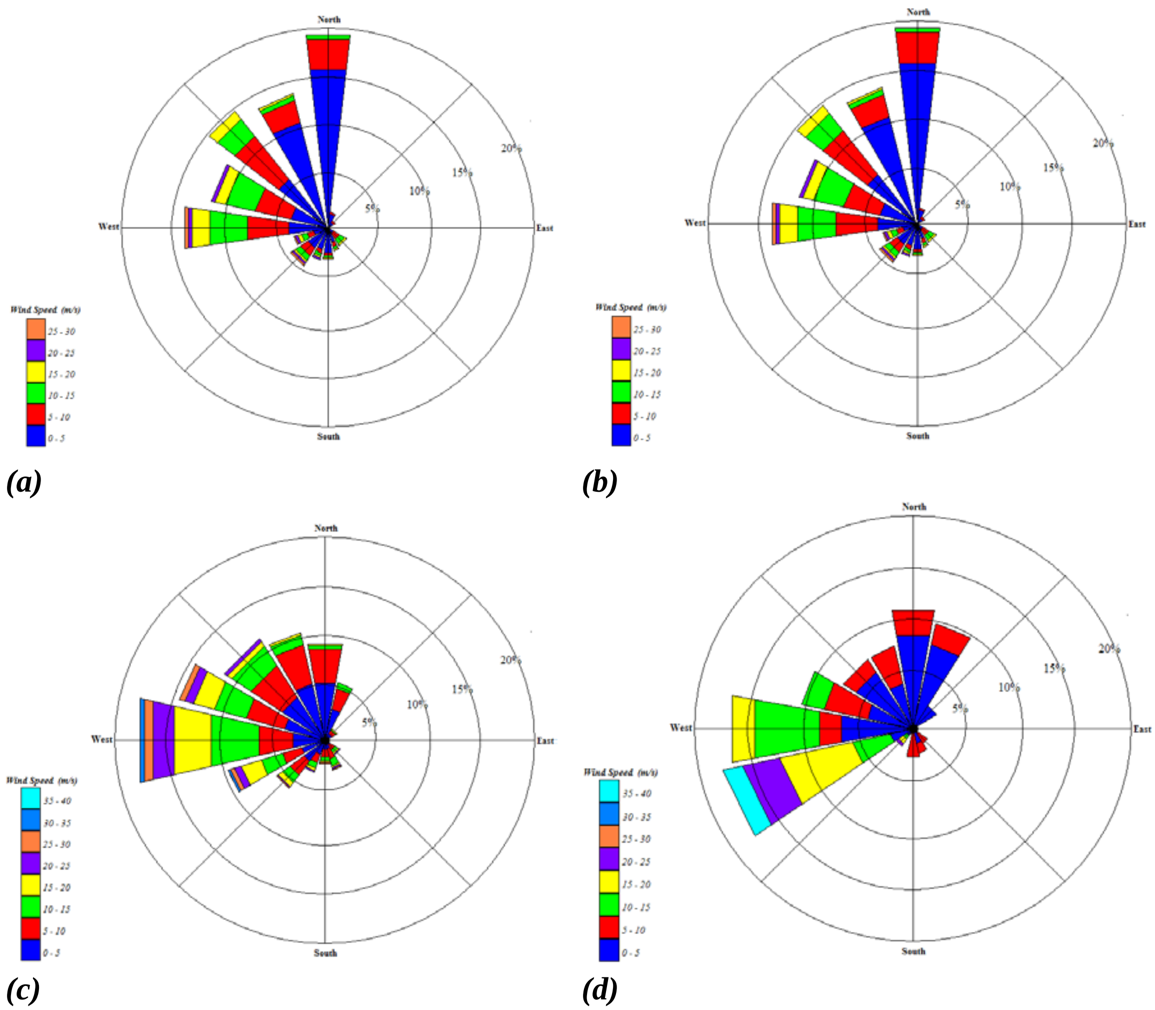


Figure 3-7: Wind roses for CLPX corner meteorological ***stations, Michigan River ISA; (a) NE corner, (b) SE corner, (c) NW corner, and (d) SW corner***

3.4 Summary

The spatial variability of sagebrush microtopography in the high altitude plateau rangeland of North Park, Colorado may affect snow depth due to the persistent winds typical of this environment. Albedo differences in ground surface types may influence the timing of spring snowmelt and the resultant soil moisture that sagebrush plants rely on. Wind and albedo therefore both play an important role in snowdrift formation and snow depth variability. Chapter 3 reviews some preliminary findings in regards to albedo and soil moisture measurements due to melt of snowdrifts. More research is necessary to effectively draw conclusions about the nature of the interactions between wind, sagebrush, snow, albedo, and how the alteration of one of these ecological factors may influence the others.

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