Seasonal and storm snow distributions in the Bridger Range, Montana
by Michael Jon Pipp

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Computer modeling of seasonal snowpack distribution and storm snowfall is a common tool for hydrologist and avalanche forecasters. Spatial scales for models range from global to local with temporal scales ranging from hours to months. The measurement stations available to constrain the models are widely spaced so that meso-scale resolution is difficult. Local-scale seasonal and storm snow distributions were measured to assess the variability and factors that control snow distributions between stations. A network of eleven measurement sites was established in the Ross Pass area in the central Bridger Range, MT. Sites were measured for elevation, aspect, slope, radial distance from Ross Pass, distance from the range crest, and distance north-south of the Pass. Atmospheric data was collected from National Weather Service Rawinsondes at Great Falls, MT. Surface meteorological data was collected locally. The Natural Resources Conservation Service (NRCS) - Snow Survey measures snowpack at four locations in the Bridger Range, two north and south of the Ross Pass Study Area (RPSA). Seasonal snowpack was measured on April 1,1995 at all fifteen sites using Federal snow samplers. Storm snowfall was measured from storm boards at the RPSA sites with modified bulk samplers and spring scales. Results show that the NRCS estimated April 1, 1995 snowpack to have a snow-elevation gradient of 937 mm km-1. Snow accumulation was average when compared with the previous four years. The RPSA April 1,1995 snowpack was significantly different than that predicted from simple elevation based gradient estimates from NRCS data. RPSA had drier high elevation sites and wetter low elevation sites and an overall smaller snow-elevation gradient of 468 mm km-1. Nominal clustering of storm snow distributions identified four classes and two sub-classes prevalent during the season. Correlation analysis showed that distance east of the ridge was significant in 81% of storms, while elevation was significant in only 50%. Due to strong covariance between variables, partitioning the signals is not possible and either variable is considered reasonable as a linear predictor of storm snow distribution. Snow distributions in the RPSA strongly resemble observed spatial patterns using small-scale snow fence and shrub barrier models.

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MONTANA STATE UNIVERSITY
Bozeman, Montana

August 1997

APPROVAL

of a thesis submitted by

Michael Jon Pipp

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGMENTS

This project was partially funded by grants from the Jim Edie Foundation and the John Montagne Family Fund. Their financial support is gratefully acknowledged. The Natural Resources Conservation Service - Snow Survey, Bozeman office, supplied logistical and technical assistance during the length of the project. Hardcopy Rawinsonde data was received from the National Weather Service - Great Falls, MT from November through March. I would like to thank my advisor, Dr. William Locke, for his patience and direction over the duration of this project. Also, appreciation and thanks are extended to the people who assisted me in the field; Phillip Farnes and Dr. William Locke with site selection during the summer of 1994; Dr. Steve Custer and his Snow Dynamics class with April 1 snow cores; and most importantly Brian Guldberg, my most reliable and dependant field assistant (and pub tender) who's contribution to data collection was invaluable. Finally, many thanks go to my family, Ralph and Faith Pipp for their encouragement and support and especially to Andrea, wife and field assistant, for her understanding, support, and many sacrifices.

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ABSTRACT

Computer modeling of seasonal snowpack distribution and storm snowfall is a common tool for hydrologist and avalanche forecasters. Spatial scales for models range from global to local with temporal scales ranging from hours to months. The measurement stations available to constrain the models are widely spaced so that meso-scale resolution is difficult. Local-scale seasonal and storm snow distributions were measured to assess the variability and factors that control snow distributions between stations. A network of eleven measurement sites was established in the Ross Pass area in the central Bridger Range, MT. Sites were measured for elevation, aspect, slope, radial distance from Ross Pass, distance from the range crest, and distance north-south of the Pass. Atmospheric data was collected from National Weather Service Rawinsondes at Great Falls, MT. Surface meteorological data was collected locally. The Natural Resources Conservation Service (NRCS) - Snow Survey measures snowpack at four locations in the Bridger Range, two north and south of the Ross Pass Study Area (RPSA). Seasonal snowpack was measured on April 1,1995 at all fifteen sites using Federal snow samplers. Storm snowfall was measured from storm boards at the RPSA sites with modified bulk samplers and spring scales. Results show that the NRCS estimated April 1, 1995 snowpack to have a snow-elevation gradient of 937 mm km^{-1}. Snow accumulation was average when compared with the previous four years. The RPSA April 1, 1995 snowpack was significantly different than that predicted from simple elevation based gradient estimates from NRCS data. RPSA had drier high elevation sites and wetter low elevation sites and an overall smaller snow-elevation gradient of 468 mm km^{-1}. Nominal clustering of storm snow distributions identified four classes and two sub-classes prevalent during the season. Correlation analysis showed that distance east of the ridge was significant in 81% of storms, while elevation was significant in only 50%. Due to strong covariance between variables, partitioning the signals is not possible and either variable is considered reasonable as a linear predictor of storm snow distribution. Snow distributions in the RPSA strongly resemble observed spatial patterns using small-scale snow fence and shrub barrier models.

CHAPTER 1

INTRODUCTION

Background

Water is one of the most important resources in the western United States and the winter snowpack contributes an estimated 80 percent of the annual runoff and water supplies for the region (SCS 1972). Human uses of snow-generated water include agricultural, municipal, recreational, and industrial. Economic and recreation activities are strongly influenced by the distribution of snow and computer modeling of its distribution is now an important management tool for forecasters. However, the variability in seasonal and storm snow distribution is poorly understood at the local-scale of individual basins. Better understanding of meso-scale factors may help improve the models of snow distribution used for water supply and avalanche hazard forecasts at this scale.

Numerical models of snow distribution rely upon data collected from a network of automated and manual snow survey sites. This network is managed by the United States Department of Agriculture - Natural Resource Conservation Service (NRCS) Snow Survey, formally the Soil Conservation Service (SCS) Snow Survey. The network contains automated snow telemetry (SNOTEL) stations with a daily and sub-daily sampling interval and manual snow courses with monthly and bimonthly sampling intervals.

SNOTEL stations (Figure 1) are supplemented with 2,530 snow courses (SCS 1994). This measurement network is placed in the mountains at elevations above 1,525 m (5,000 ft) (Beard 1994) and is higher than those typical for National Weather Service (NWS) climate stations. The distribution of these stations allows synoptic-scale forecasting. Only a few snow survey sites are

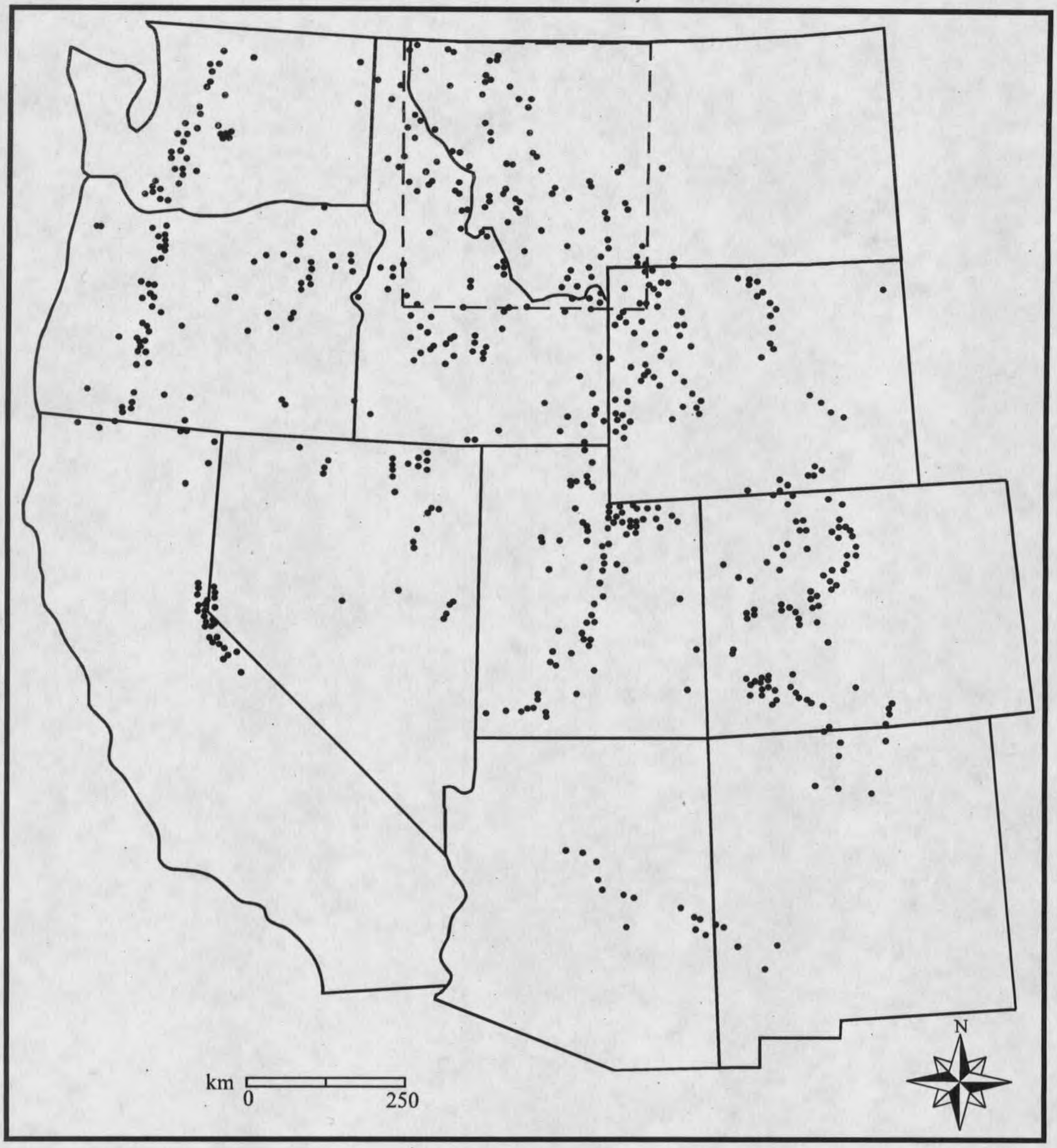

Figure 1. NRCS SNOTEL network as of 1988 representing the synoptic-scale. The dashed square represents the regional-scale depicted in Figure 2.

placed in individual ranges and these are stratified by elevation. Snow-elevation gradients are determined by the difference in snowpack accumulation between high-low elevation pairs. This gradient is then generally applied across the entire range to calculate snowpack accumulation and distribution (Custer et al. 1996).

Two types of sites are measured by the NRCS. SNOTEL sites (Whaley 1983) collect data by measuring the weight of the overlying **snowpack** (seasonal accumulation of snow measured as a depth in inches or centimeters) on a snow pillow (Goodison et al. 1981). Snow courses are transects of five to ten points where the snowpack is measured manually for depth and density (Goodison et al. 1981). Both SNOTEL and snow course data are reported as **snow water equivalent** (SWE), which is a measure of water content stored in the snowpack and is reported in inches or millimeters of water.

Avalanche hazard forecasts rely on the SNOTEL network for snow accumulation data in the subalpine region. New snow accumulation is used to determine the amount and rate of stress recently added to the existing snowpack. Accumulation rates at SNOTEL sites reported during storm events are extrapolated to alpine starting zones for hazard evaluation, thus making local- and meso-scale snowfall estimates important for recreationists.

The National Weather Service (NWS) also collects snow accumulation data with its surface-monitoring system (Dingman 1994). Hourly measurements are taken at 84 primary climate stations in eleven Western states and daily measurements are collected from a secondary network of cooperative weather stations. NWS snow accumulation data are reported as **snowfall**: snow accumulation during a specified period, measured as a depth of snow in inches or centimeters. The NWS network, however, is biased toward lower elevations, valley bottoms, and populated areas (Farnes 1971; Dingman 1994). This network arrangement is not well suited for determining precipitation in complex terrain (Vuglinski 1972; Custer et al. 1996).

Problem Statement

Water supply managers and avalanche forecasters use computer models as a tool to facilitate their assessment of snowpack and snowfall distribution. Computer models link measurements with atmospheric and boundary-layer processes operating over a hierarchy of spatial scales (Table 1). Water supply models usually operate at meso- to regional spatial scales and monthly to seasonal temporal scales. Models for avalanche hazard estimation operate at meso- to local spatial scales and daily or sub-daily temporal scales. An understanding of the variability in snow distribution at the meso-scale is important for the calibration and validation of physically-based models to improve resolution of water supply forecasting and avalanche hazard estimation models.

Table 1. Hierarchy and definition of spatial scales.

Scale	Domain	Horizontal Extent	Variables
Global	Planetary	10,000 km	ocean currents, pressure cells/winds, insolation
Synoptic	Continental	1,000 km	physiography, pressure cells, jet streams
Regional	Regional	100 km	regional topography, frontal systems, jet streams
Meso	Neighborhood	10 km	wind fields, air mass characteristics, large-scale topography
Local	Basin	1 km	wind fields, air mass characteristics, local-scale topography
Micro	Site	0.1 km	ground cover, forest structure, .aspect, slope

(adapted from Linacre 1992)

The existing NRCS snow survey network provides adequate coverage for synoptic scale (Figure 1), regional scale (Figure 2), and in some cases meso-scale (Figure 3) topographies. However, at sub-network scales, i.e., local- and even meso-scale, snow distribution variability is not easily predicted from the snow survey network. An understanding of the error produced at meso and smaller scales is important for "hierarchal nested" model tests. In regions of complex terrain, hierarchal nesting of meso- and local-scale models embedded within synoptic and regional scale models may provide a better representation of meso- and local-scale precipitation distribution

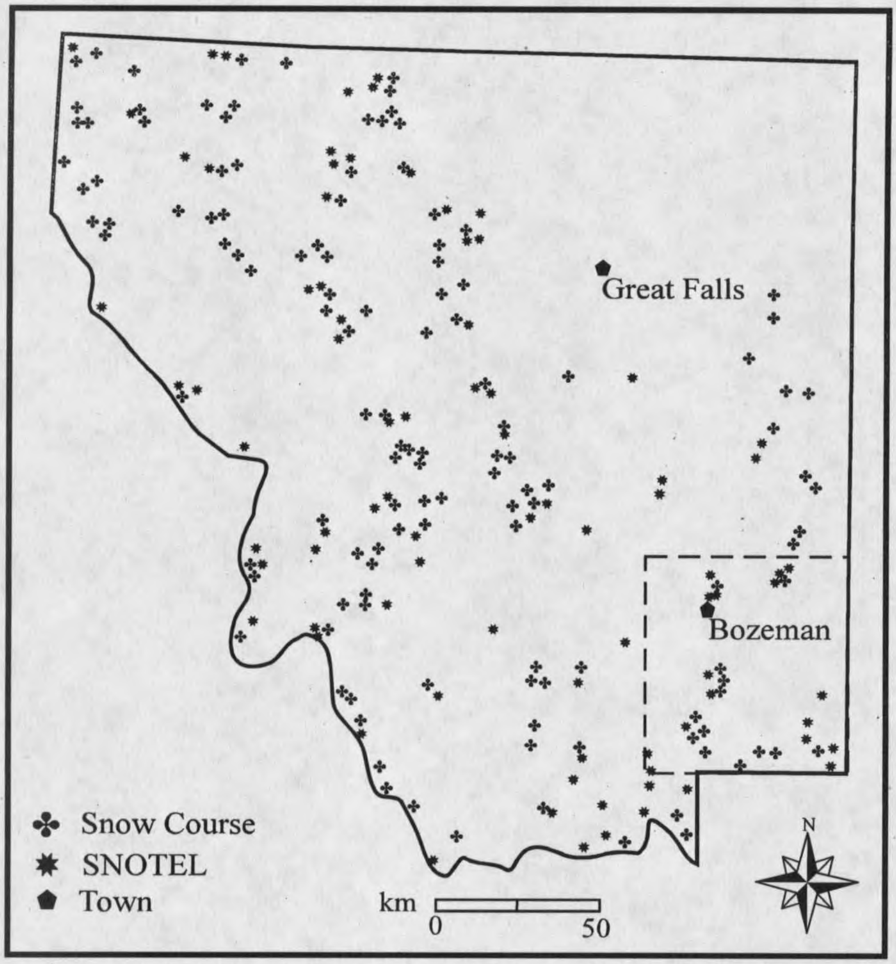

Figure 2. NRCS snow survey network in western Montana as of 1993 representing the regional scale. The dashed square represents the meso-scale depicted in Figure 3.

(Alford 1985; Barry 1992b).

An important component of precipitation models is validation. Since snow accumulation trends are consistent within meso-scale ranges but highly variable at regional scales (Locke 1989), use of the existing measurement network is adequate for validation of meso-scale models in regions of adequate data (Custer et al. 1996). However, the latest generation of high-resolution models operates at a sub-network local-scale and the existing measurement network is inadequate