SNOW ACCUMULATION AND MELT IN RELATION TO TERRAIN IN WET AND DRY YEARS

By

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Why are we interested in relating snow accumulation and melt to terrain? Certainly we hope to improve our methods of measuring standard snow courses so as to obtain more accurate estimates of the volume of water that is stored and can be delivered from mountain watersheds. Hopefully we may some day be able to select spots where only a few key measurements--taken by remote sensing and reporting devices--will enable us to calculate the total snow in the pack and its probable delivery dates. Through terrain-snow and other analyses, we may possibly learn how to best modify snow storage and melt.

This paper reports on an analysis of snow data from 163 snow courses in the central Sierra Nevada in California by factor analysis and principal component regression analysis. It includes recommendations on how the results can be interpreted in terms of their implication on how to locate representative snow courses.

Only a few terrain-snow studies have been made. In the western United States these include studies of Church (1912), Wilm (1948), Mixsell et al. (1951), Anderson and Pagenhart (1957), and Packer (1960). Representativeness of snow courses were analyzed by Wilson (1951) and Court (1964).

METHODS

To determine terrain-snow relations we must have wide differences in terrain and snow. We selected 163 snow courses, with consistent characteristics within the snow course and maximum terrain differences between the courses. We selected three years with wide differences in snow accumulation and melt,--1958, 1959, and 1960, and determined snow water equivalent on March 1, April 1, and May 1 in each of those years.

Terrain characteristics at snow courses were determined by using simple instruments, no more complex than an Adney level and the human eye, abetted by standard topographic maps and ordinary aerial photos. Snow water equivalent was measured with the Mt. Rose snow tube, averaged for 5 to 11 points in each course. We considered terrain effects on snow in two parts: first, the meso-terrain, representing the surroundings within a few hundred or thousands of feet around the course; and second, the local terrain at the snow course.

Meso-terrain variables included numbers of hours of topographic shade, density of the forest up to 1 mile to the windward of the snow course, and position of the course on the mountain slope, ridge versus valley, etc.

Local terrain variables included the topography and forest conditions at the snow course. Elevation, slope, and aspect were the measuring topographic variables. Their expression in quantitative terms and their interactions with meso-terrain and with the forest were the analysis variables. Forest contributions to local terrain effects on snow were expressed in simple variables of density of forest canopy, tree species, tree heights, sizes of openings, and position of the snow course within the forest or opening. Definitions, means, and standard deviations of the measured variables and analysis variables are given in Table 1.

Analytical Methods

Terrain-snow relations were determined by expressing the terrain differences as variables appraising their relation to snow by 3 multi-variate analysis techniques: (1) Factor analysis (Harman, 1960), including varimax rotation to diagnose which variables

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Table 1. Independent Variables

Symbol	Definitions, Means and Standard Deviations
W	Width of forest opening in tree heights, mean 1.7H, std. dev. 2.0H
D	Downhillness of position in forest openings or in forest near openings, indexed by downhill (D = 20), uphill (D = 10), neutral and within forests (D = 15), mean 15.0, s.d. 2.2.
C	Canopy cover density, mean 45.4 percent, s.d. 32.0.
SP	Species, 1 = red fir, 3 = red fir with lodgepole pine, 4 = lodgepole pine with red fir, 6 = ponderosa pine, white fir or pure lodgepole pine.
PS34	Position of course in opening is in southern one-half, PS34 = 1; otherwise zero.
PS12	Position of course in opening is in northern one-half, PS12-1; otherwise zero.
H	Tree heights in forest or of forest surrounding opening, mean 88.4 feet, s.d. 27.3.
SL	Slope of course, mean 22.3 percent, s.d. 11.4.
AZY	Azimuth of snow course from south, mean 83.6, s.d. 49.0.
F11	Forest canopy cover in south-southwest octant, zero to one-eighth mile from course, mean 32.4 percent, s.d. 21.7.
F12	Forest canopy cover in south-southwest octant, one-eighth to three-eights mile from course, mean 25.9 percent, s.d. 12.5.
F13	Forest canopy cover in south-southwest octant, three-eights to one mile from course, mean 24.7 percent, s.d. 12.4.
O	Course is with forest opening, O = 1, not in opening O = 0, mean 0.30, s.d. 0.46.
FO	Course is with forest near a forest opening, FO = 1; not near opening O = 0, mean 0.45, s.d. 0.50.
SLZO	Course is within openings; Slope-Azimuth-opening integrated variable, SL*D* (1. AZY/180.)*F)/10., mean 13.3, s.d. 25.0.
SLZFO	Slope-Azimuth-forest near opening variable SL*D*(1. AZY/180.)*FO/10., mean 21.8, s.d. 29.3.
SLZF	Slope-Azimuth-forest variable, SL*O*(1. AZY/180.)*F/10., mean 14.6, s.d. 29.3.
OD	Forest opening-downhill interaction O*D, mean 4.4, s.d. 6.9.
FOD	Forest near opening-downhill interaction variable, FO*D, mean 6.7, mean 6.7, s.d. 7.7.
CV1-5	Curvature positions on slope, 1 to 5 of Figure 1, 1.0 if at that position, zero otherwise.
CH	Canopy cover-tree height interaction, C*H, mean 41.2, s.d. 32.8.
E	Elevation of snow course, (E>3,500)/10., mean 370.4, s.d. 44.0.
EW	Elevation-width opening interaction, E*W/10., mean 61.7, s.d. 73.0.

were independent within the data, hence possibly able to help explain snow variation. (2) Principal components analysis to determine the quantitative relation of the terrain variables to snow. (3) Contributions of individual factors in explaining differences in snow. Although the first two techniques have been known for many years, only recently have computer programs made them usable in hydrology (Fiering, 1964; Burket, 1964; Wallis, 1964).2/

RESULTS

The results of a factor analysis of the measured variables at the snow courses--slope, azimuth, tree height, etc.--indicated that our sampling had satisfactory distribution (Table 2). There were two exceptions: the azimuth variable (AZY), which was already expressed in the slope-azimuth variables; and the distant forest variable (FI3), which apparently was poorly sampled, hence could not be evaluated with these data.

The analysis variables express the variables in the forms that would be expected to be directly related to snow accumulation and melt. For example, slope and azimuth were combined; curvature and position were expressed as class variables--present or absent; squares of variables were included to test for curvilinearity of effects; joint variables were included to test for interaction effects. In all, 45 variables of terrain were developed--variables that were tested for their importance in affecting snow in particular seasons and in different years.

Snow water equivalents on March 1, April 1, and May 1 of 1958, 1959, and 1960 were the dependent variables.3/ Snow on these nine dates was related to terrain variables by principal components analysis (Cooley and Lohne, 1962).

Principal components analyses were made to answer two questions: (1) What relation of snow to simple terrain variables would prove useful in selecting snow course sites that would be "representative" in widely different years? (2) What factors contribute most to explaining differences in snow between courses?

The analyses yielded 405 coefficients.4/ These have been interpreted to answer specific questions of differences in terrain-snow relations that may be helpful in establishing and comparing snow courses.

Before outlining the quantitative effects of the different terrain variables on snow, let us see which were important in explaining variation in snow between courses. The variables associated with each factor (dimension) are given in Table 3. The factor contributions to explained snow differences are in Table 4. Five factors, each with some consistency, explained at least 10 percent of the variation in snow between courses; factor 4 was associated with the slope-azimuth variables; factor 1 was associated with forest cover conditions at the course; factor 3 was associated with advective heating by the "distant" forest to the south-southwest of the course; factor 6 was associated with

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2/ Mathematical formulation of factor contribution from rotated factor weights is due to Prof. W. M. Meredith (University of California, Berkeley); John Bauer developed the programing. Factor analyses employed the University of California BCTRY computer package of Prof. R. C. Tryon. Extensions of programs to "hydrologic dimensions" were by J. R. Wallis.

3/ Snow water equivalent on each date was determined by adjusting measurements on nearby dates, using degree-day factors for each individual course and year. Means and standard deviations for the nine dates were 35.0 ± 9.3, 60.1 ± 13.0, 60.3 ± 12.1, 25.2 ± 6.9, 23.5 ± 7.7, 14.2 ± 9.1, 24.7 ± 8.1, 30.4 ± 10.8, and 20.1 ± 10.0 inches.

4/ The complete set of coefficients is available upon request from the Director, Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California 94701.

TABLE 2 - SELECTED FACTOR WEIGHTS FOR EACH VARIABLE FROM ALL DIMENSIONS IN DESCENDING ORDER FOR WEIGHTS GREATER THAN 0.3 ABSOLUTE VALUE.

VARIABLE NAME	FACTOR WEIGHTS 1	2	3	4	5	6	7
W	0.945						
D	0.987						
WSQ 1/	0.941						
DSQ	0.984						
SLZFO	0.732	0.418					
SLZFOS	0.693						
SLZF	-0.772	0.408	0.371				
SLZFSQ	-0.683	0.519	0.304				
SLAZ	0.968						
SLZSQ	0.949						
PS5	0.924						
PS6	0.598	0.497	-0.348	-0.313			
PS7	0.781						
PS8	-0.826						
CSQ	0.862						
HSQ	0.967						
XE	0.764						
PS34	0.881	-0.365					
PS12	-0.799	-0.527					
SPXS	-0.830						
C	0.938						
H	0.962						
SL	0.922						
AZY	-0.433	-0.334	0.329	0.313			
FI1	0.900						
FI1SQ	0.933						
FI2	0.737	0.510					
FI2SQ	0.695	0.532					
FI3	0.589	0.411					
O	-0.938						
FO	0.787	0.530					
SLAZO	-0.903						
SLZSQ	-0.760	0.330					
OD	-0.932						
FOD	0.775	0.518					
CH	0.856	0.377					
CHSQ	0.693	0.509	0.307				
E	0.977						
ESQ	0.979						
EW	0.934						
EWSQ	0.674						
CV1	0.771	-0.344					
CV2	-0.805						
CV4	-0.796						
CV5	0.572	0.431	-0.340	0.321			

1/ SQ or S as the last letter of the variables indicates it is a square.

TABLE 3.—VARIABLE NAMES IN ORDER OF THEIR ROTATED FACTOR LOADINGS FOR EACH DIMENSION.[1]

DIMENSION NUMBER	ORDER NUMBER 1	2	3	4	5	6	7	8	9	10
1	C	O	OD	SLAZO	CSQ	CH	PS12	SLZSQ	CHSQ	FO
2	W	WSQ	EW	CV1	EWSQ					
3	FI1SQ	FI1	FI2SQ	FI2	AZY	CHSQ				
4	SLAZ	SLZSQ	SL	SLZFSQ	SLZF	CV5	SLZSQ	AZY		
5	FO	FOD	SLZF	SLZFO	SLZFSQ	PS6				
6	ESQ	E	SPXS	CV1						
7	HSQ	H	CHSQ	FI3	CH					
8	D	DSQ								
9	XE	FI2	FI2SQ	FI3	AZY	CV5				
10	CV4	CV5								
11	PS7	SLZFOS	PS6							
12	PS34	PS12								
13	PS8	PS6								
14	PS5	PS6								
15	CV2	AZY	CV5							

1/ Only loadings greater than 0.3 listed, maximum 10 names, maximum 16 dimensions.

TABLE 4 Contribution of Physical Factors to Snow on Snow Courses, Central Sierra, California, 1958-1960.

Date	Factor Contribution[1] 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Mar. 1, 1958	17	1	3	37	4	15	16	1	1	4	1	0	0	0	0	100
Apr. 1, 1958	17	1	9	36	5	16	11	0	1	2	0	1	0	0	1	100
May 1, 1958	17	1	12	34	6	17	10	0	2	1	0	0	0	0	0	100
Mar. 1, 1959	29	1	7	39	8	8	5	0	1	1	0	0	0	1	0	100
Apr. 1, 1959	21	1	11	44	7	9	5	0	1	1	0	0	0	0	0	100
May 1, 1959	7	0	10	37	20	12	2	0	5	0	2	0	1	1	3	100
Mar. 1, 1960	13	0	1	69	1	4	10	0	0	0	0	0	0	1	1	100
Apr. 1, 1960	19	0	13	37	11	7	5	0	1	2	0	1	1	2	1	100
May 1, 1960	5	0	7	44	16	16	6	0	3	1	0	0	0	1	1	100

1/ Percent of explained variance attributable to each factor. For specific variables associated with each factor see Table 5. Explained variances were for each date, 62, 64, 71, 68, 67, 59, 72, 66, and 71 percent of total variation of snow between courses.

elevation variables; and factor 7 was associated with tree height. In late season of dry years the contrast between forest and forest near openings was important, explaining as much as 20 percent of the explained variance. Total explained variance for the different seasons and years ranged from 62 to 72 percent (footnote, Table 4). With these clues to which variables are important, let us interpret the quantitative effects of terrain variables on snow.

Elevation and Elevation Interactions

Snow differences with elevation become greater as the season progresses from March 1 to May 1, especially in dry years (Figure 1). One implication is that we cannot place snow sensors, such as snow pillows or radioactive snow gages, at a single elevation and expect them to index snow at all elevations in different years. Snow increases with elevation have been thought to fall off at elevations greater than 7,000 feet (Hannaford et al., 1958). These analyses show no decline in any year; in going from an elevation of 7,000 to 8,000 feet the increase in snow was 1 to 2 inches greater than the increase in going from 6,000 to 7,000 feet elevation. Snow measurements at a single snow course of the Cooperative Snow Investigations (Mixsell et al., 1951) at 8,600 feet is consistent with this finding.

Curvature and Curvature Interactions

Contrasts of ridge, slope, and bottom sites on snow accumulation were compared in two ways: by the index numbers 1 to 5, bottom to ridge, and by their class variables--present or absent.

	Bottom	Concave	Mid-slope	Convex	Ridge
Position No.	1	2	3	4	5
Excess or deficit of snow	-2.1	-0.4	1.6	-0.1	1.1

The reason why the "index variable" is poor becomes clear from the results. There was no uniform difference in snow between index 1 to 2, 2 to 3, etc. Although the ridge (class 5) and the bottom (class 1) were at opposite extremes, the intermediate classes were out of order.

Forest and Opening Effects

Forest openings, forests near openings, and forests away from openings, and the characteristics of each, affect snow accumulation and early spring melt. The effects depended also on the slope and azimuth at the site, the density of the forest, the species, the size of opening, and the position of the snow course with respect to the opening.

Dense forest (85 percent canopy) averaged 7.6 inches less snow than openings, with the differences ranging from 4.7 to 10.7 inches:

	1958	1959	1960
		- - -(inches) - - -	
March 1	7.6	7.7	5.6
April 1	10.7	7.0	9.5
May 1	10.3	4.7	5.3

In contrast to dense forests, forests near openings had about 1 inch less snow water equivalent, with very little variation between years and dates.

Effect of Size of Opening

For snow courses in openings, the width of the openings had more effect in the year of heavy snowfall than in the dry years. Snow in 1958 was 3 to 3-1/2 inches greater in an opening 4 tree heights across than in an opening only 1 tree height across; however, in 1959 and 1960 the differences averaged less than one inch. Larger openings were more effective in trapping snow at the higher elevations than small openings.

Snow varied with the part of the opening as well as the width, particularly on April 1 and May 1 in the dry years; then the south half of openings had from 1 to 3 inches more snow than the north half.

Tree size was important in that snow-water equivalent under small trees (40 feet height) was always at least equal to that under tall trees (140 feet height). But snow-water equivalent was distinctly more in April of dry years, when the small trees delivered 2 to 3 inches more water than the tall trees.

Species of trees exhibited difference in snow accumulation. Red fir stands had 3 to 6 inches more water than stands with lodgepole pine or ponderosa pine (so-called mixed conifer type). The differences were greatest on May 1, particularly in the dry years.

Cold air drainage obviously plays a role in delaying snowmelt in openings (West 1961), as well as in the forest adjacent to openings. The increase in snow in the downhill half of openings as contrasted to the uphill ranged from 3 to 5.5 inches; in the adjacent forest the downhill portions had 2 to 3.5 inches more, with the differences increasing with season (Mar. 1 to May 1). Position within the forests adjacent to openings did not have any influence on snow other than that associated with the slope position variable (D).

Slope and Azimuth Effects

Variables expressing the combination of slope and azimuth (Table 1) allow comparison of results for 20 percent north versus south slope; these showed marked variation of slope effects between forests, openings, and forest near openings (Figure 2). Under conditions when average snow (at al sites) was greater than 20 inches, the largest contrasts between north and south slopes occurred in the forest; openings were next; and forests near openings least. Under heavy snowfall conditions, forests showed persistence of the north-south slope differences, but openings and the forests near openings showed very little contrast between slopes. Under all three forest conditions, maximum differences occurred at about 35 inches of snow storage.

Large-scale Forest Influences

If we make large-scale changes in the density and patterns of forests, the effects on snow accumulation and melt may differ from the effects measured in small-scale experimental tests. For one thing, we would expect large-scale changes in radiation balance (Miller, 1953). We might also expect changes in turbulence and effects on atmospheric snow formation (more snowfall associated with greater turbulence), on moisture transfer from trees and air to snow, on interception of snow by trees--hence on amount, distribution, and even the character of snow on the ground. We should not conclude that the forest merely redistributes snowfall. Meso-heat and turbulence effects may explain the unexpectedly large effects of cutting when large areas are cut, as at Yuba Pass in California (Anderson, 1964) and at Fraser, Colorado (Martinelli, 1965).

Principal components analysis indicated the possible magnitude of such meso-effects of forests for distances one-half mile to the windward (SSW) of snow courses. Take a snow course with a dense forest (66 percent canopy) to windward, and a comparable course with the forest canopy thinned to 33 percent. The analysis indicated the following increases in snow-water equivalent associated with thinning the canopy for distances up to 1/2 mile:

		Distance from course		
		0 - 1/8 mi.	1/8 - 1/2 mi.	Total
		- - - -(inches)- - - -		
Date:				
	March 1	1.4	2.1	3.5
	April 1	2.2	5.7	7.9
	May 1	0.7	5.1	5.8

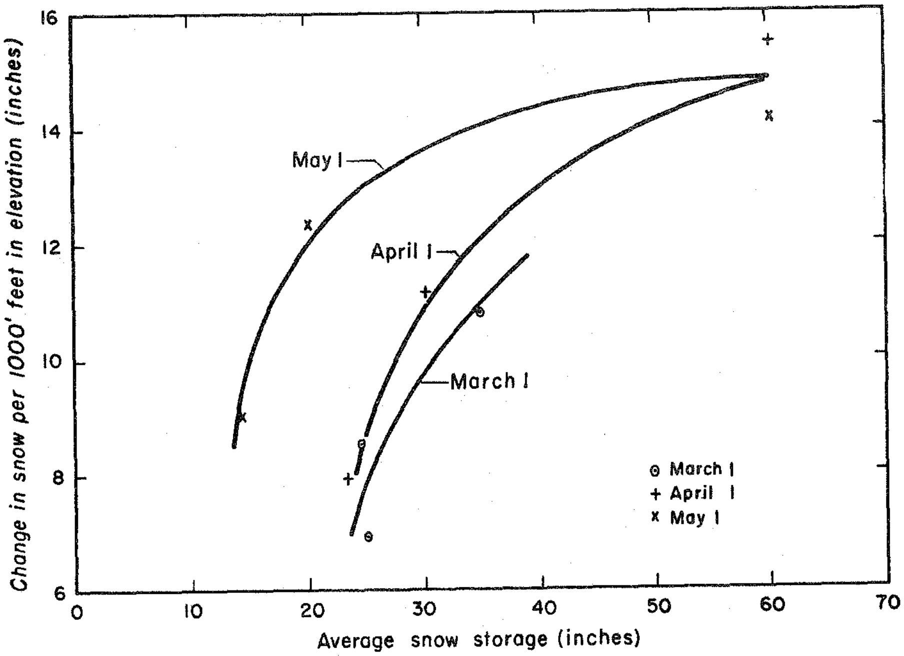

Figure 1.

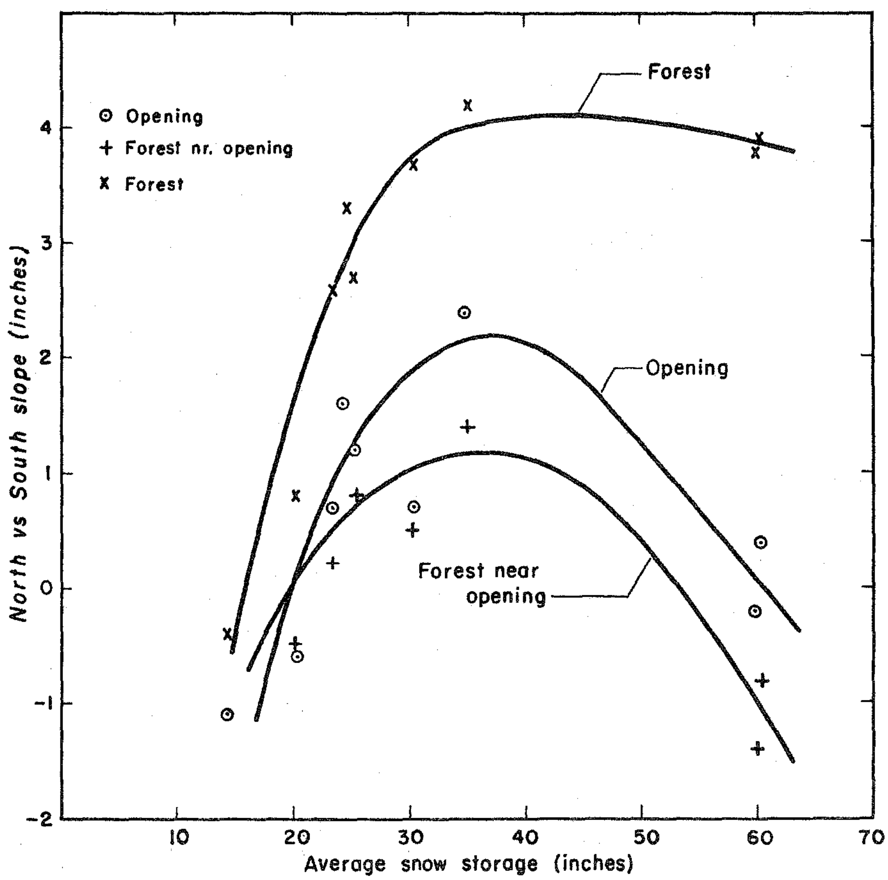

Figure 2.

No effects were apparent for differences in forests 1/2 to 1 mile to windward. Total effects of 3-1/2 to nearly 8 inches for the 0 to 1/2 mile distance certainly merits further study.

Topographic Shade

Hours of "topographic shade" consistently melted snow instead of preventing its melt. Perhaps at the low sun angles, topographic shade was less important than reflection of solar radiation and long-wave radiation from the adjacent slope on to the snow course; hence snow melt resulted. This effect is not trivial; for example, there were 2 inches less snow on May 1, 1959, for each hour of "topographic shade" than during the previous 2 months.

Solar Radiation

Solar radiation variables added nothing to explaining variation in snow not already included in slope and azimuth variables. The slope and azimuth variables are easier to obtain; so, for selection of snow courses they, rather than radiation have been reported here and are recommended.

East Slope vs. West Slope

East slopes were like west slopes as far as could be told by inclusion of our east slope variable (XE). Deviations associated with east slopes were small, ranging from -0.6 to 0.4 inch, for all seasons and years.

SELECTION OF REPRESENTATIVE SNOW COURSES

To represent snow on mountain basins, or at least to give year to year indexes of basin snow, snow courses should have these characteristics:

1. Wide variation in elevational distribution of courses.
2. Location below ridges rather than on the ridge, particularly if the ridge is unforested.
3. Location with average forest to the windward for at least 1/2 mile.
4. North and South exposures represented.
5. Both forest and open sites sampled, preferably with parts of courses in forest or number of courses proportional to forest in the basin. Courses should cross openings and extend into south and north margins, or run east and west with part of the course in forest margin.
6. Average or neutral cold air drainage in courses: locations exclusively at downhill margins of openings avoided.

Such a selection of course locations should make it possible to index snow accumulation and melt season to season and year to year with fewer snow courses.

LIST OF FIGURES

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