# SNOWPACK PATTERNS IN THE ALPINE TUNDRA, NIWOT RIDGE, FRONT RANGE COLORADO[1]

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Abstract.--Snowpack was monitored from April 1982 to August 1983 in a topographic saddle located at 3545 m asl as part of the University of Colorado Long-Term Ecological Research Program (CULTER). Data were reported on a map summary sheet which showed snow depth, change since last survey, mean grid depth, mean change, and year-to-date summary. Snowpack development, meltoff patterns, and relationship to vegetation are described. Results indicated that winds cause marked heterogeneity in depositional areas which might affect avalanche forecasting. Changes in snowpack can cause changes in plant species composition which may alter the anchoring capacity of avalanche chutes.

## INTRODUCTION

The dynamics of snowpack patterns in the mountains influence many abiotic and biotic phenomena ranging from avalanches to plant distributions. However, little is known about areal snowpack patterns in alpine tundra. Patterns of tundra snowpack accumulation and meltoff and their relationship to plant communities have not been described other than at large scales or by widely spaced Soil Conservation Service snow surveys.

The following study was initiated as part of the University of Colorado Long-Term Ecological Research Program (CULTER) to investigate meso-scale snowpack patterns. The goals of the study are

1) to document tundra snowpack and patterns,
2) to provide data for comparisons among years,
3) to explore the relationship of snowpack to the biological realm.

The study provides a record of snow depths and changes in snowpack on an alpine tundra grid for each snow season. From these data, accumulation and meltoff patterns, rates of change, and relationships to plant communities can be observed. Comparisons are possible between specific dates and seasons. This paper will report mainly on accumulations patterns with only brief mention of meltoff patterns and biological relationships.

## STUDY SITE

Niwot Ridge, an east-west-trending extension from the Continental Divide, is located about 40 km WNW from Boulder, Colorado. The ridge lies above timberline for about 10 km of its length. Studies were conducted on an area known as the Saddle Grid. The grid is 350 by 550 m with the 350-m side oriented due magnetic north in 1967. The grid consists of 88 grid points located at 50-m intervals (fig. 1). Grid points are marked

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 11 | 21 | 31 | 41 | 51 | 61 | 71 |
| 2 | 12 | 22 | 32 | 42 | 52 | 62 | 72 |
| 3 | 13 | 23 | 33 | 43 | 53 | 63 | 73 |
| 4 | 14 | 24 | 34 | 44 | 54 | 64 | 74 |
| 5 | 15 | 25 | 35 | 45 | 55 | 65 | 75 |
| 6 | 16 | 26 | 36 | 46 | 56 | 66 | 76 |
| 7 | 17 | 27 | 37 | 47 | 57 | 67 | 77 |
| 8 | 18 | 28 | 38 | 48 | 58 | 68 | 78 |
| 9 | 19 | 29 | 39 | 49 | 59 | 69 | 79 |
| 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
| 10a | 20a | 30a | 40a | 50a | 60a | 70a | 80a |

Figure 1. Location of the 88 grid points on the Saddle grid. Points are spaced 50 m apart, north is to the right of the page, and the prevailing wind is from the west (top of page).

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[1] Paper presented at the International Snow Science Workshop, Aspen, Colorado, October 24-27,1984.

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the the poles or probing if markings were not visible. When poles were missing, depths were probed by measuring from known pole locations and attempts were made to dig out poles covered by snow. Measurements were taken level with the general contour of the snow surface and were recorded to the nearest centimeter. Individual measurements were subjectively judged to be accurate within two centimeters of the snow contour. Changes in snowpack were estimated from depth measurements between survey dates.

Data were summarized on report forms including maps showing depth at each grid point and change since the last survey. Topographic maps of snow depth can be developed by adding contour lines. Mean depth and mean change were calculated for each map. A year-to-date summary of snow data was shown on the right of each report page (fig. 2).

## RESULTS AND DISCUSSION

A detailed listing of results through August 1983 is available as a data report from the CULTER program for $5.00. The reference is Halfpenny, J.C. and O.D. Pollak. 1983. Snow survey data from the Saddle, Niwot Ridge, Colorado, 1982-1983. CULTER/DR-83/9. 53 pp. Orders should be sent to the Institute of Arctic and Alpine Research, University of Colorado, Campus Box 450, Boulder, CO 80309. Future data will also be available in report form. Key aspects of the snowpack study will be reported here.

Maximum snowpack accumulation for the whole grid usually occurs in late May. Maximum mean depth in 1982 was 112.6 cm which occurred on May 22, 1982. Maximum mean depth for 1983 was estimated at 176.6 cm and occurred on or after May 31, 1983. Maximum depths at individual grid points, however, do not occur on the same dates. Maximum accumulations tend to occur earlier (March) on the eastern side of the grid and later (May) on the western or deposition side of the grid. Maximum depths for individual grid points are graphed in figures 3 and 4.

Total snowfall for the winters of 1981-1982 and 1982-1983 was similar (fig. 5). However, the snowpack patterns for these two years were dramatically different (fig. 6). The timing of the occurence of heavy snowfall during the winter is very important to the development of the snowpack because of redistribution of snow by wind. Figure 7 compares the timing of snowfall for the two winters on a monthly basis. On the windy Niwot Ridge, heavy snows during March, April, and May contribute more to snow accumulation than equivalent snows earlier in the winter.

The pattern of snow accumulation during the winter is not a simple one of continuous addition of snow to the snowpack, especially within the deposition zone. The pattern is very complex and consists both of deflation and deposition. Figure 2 shows a typical post-snowstorm pattern of accumulation when winds are not part of the storm

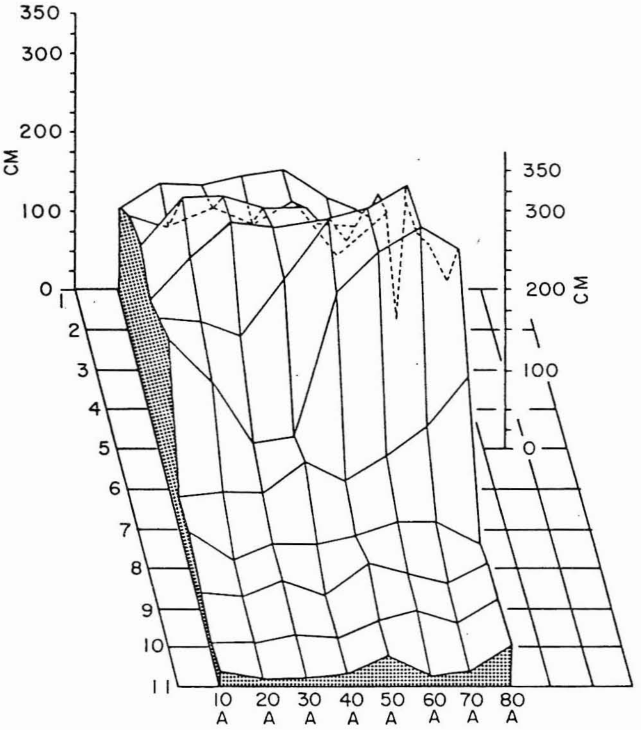


Figure 3. Maximum accumulation of snow at each grid point for 1982. The maximums do not all occur on the same date.

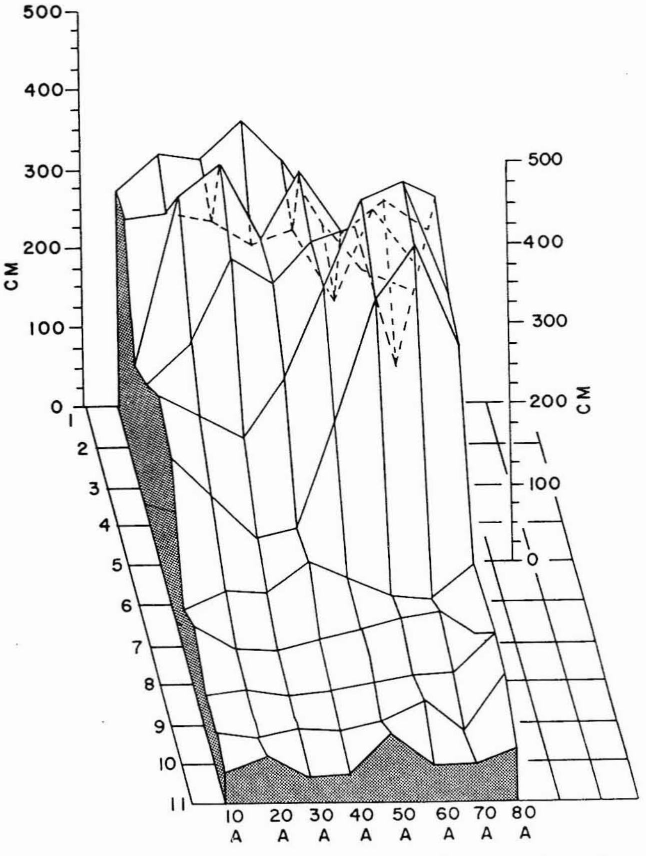
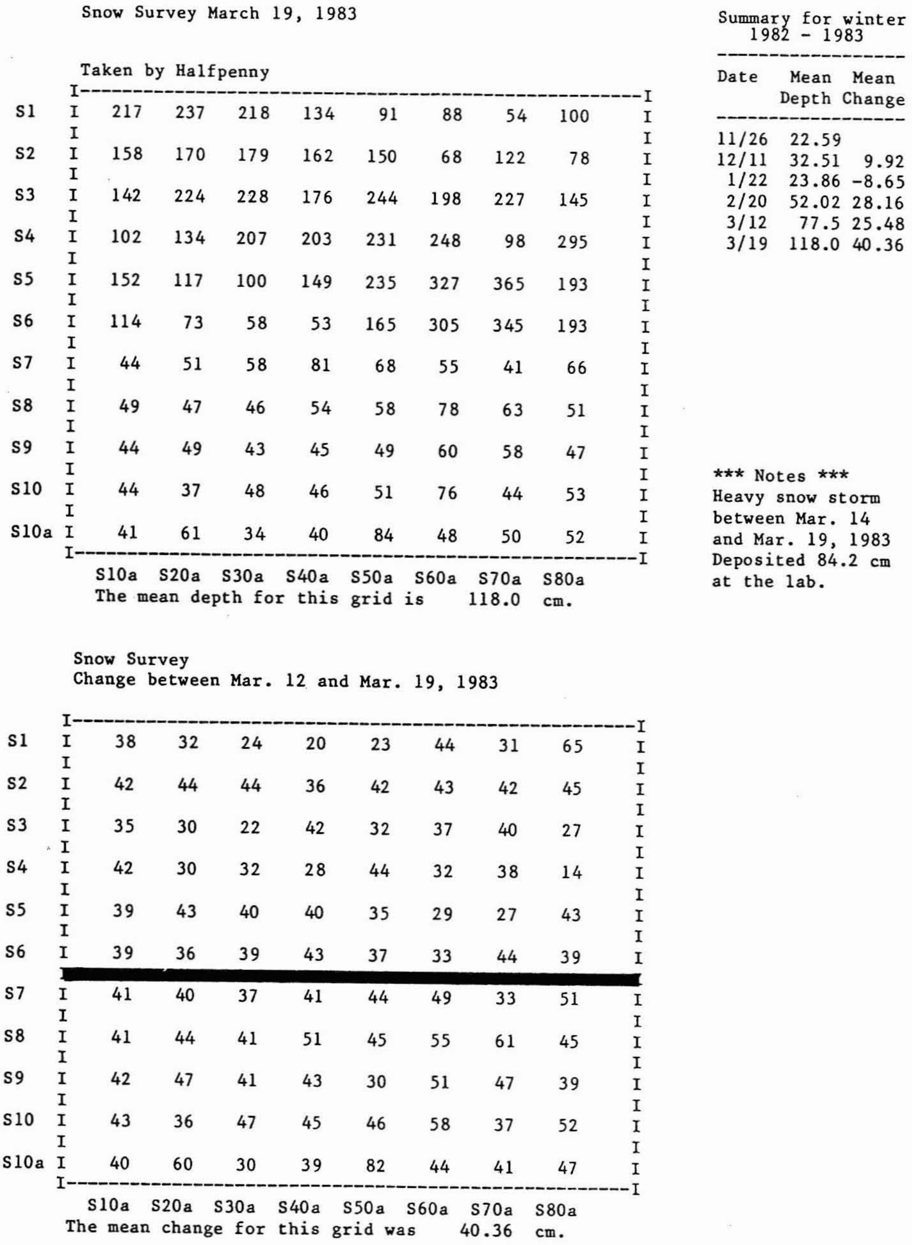


Figure 4. Maximum accumulation of snow at each grid point for 1983. The maximums do not all occur on the same date.



```
         Snow Survey March 19, 1983


         Taken by Halfpenny
        I-------------------------------------------------------I
S1      I  217   237   218   134    91    88    54   100        I
        I                                                       I
S2      I  158   170   179   162   150    68   122    78        I
        I                                                       I
S3      I  142   224   228   176   244   198   227   145        I
        I                                                       I
S4      I  102   134   207   203   231   248    98   295        I
        I                                                       I
S5      I  152   117   100   149   235   327   365   193        I
        I                                                       I
S6      I  114    73    58    53   165   305   345   193        I
        I                                                       I
S7      I   44    51    58    81    68    55    41    66        I
        I                                                       I
S8      I   49    47    46    54    58    78    63    51        I
        I                                                       I
S9      I   44    49    43    45    49    60    58    47        I
        I                                                       I
S10     I   44    37    48    46    51    76    44    53        I
        I                                                       I
S10a    I   41    61    34    40    84    48    50    52        I
        I-------------------------------------------------------I
          S10a  S20a  S30a  S40a  S50a  S60a  S70a  S80a
          The mean depth for this grid is    118.0   cm.
```

```
Summary for winter
   1982 - 1983
------------------
Date    Mean  Mean
       Depth Change
------------------
11/26   22.59
12/11   32.51   9.92
 1/22   23.86  -8.65
 2/20   52.02  28.16
 3/12    77.5  25.48
 3/19   118.0  40.36
```

```
*** Notes ***
Heavy snow storm
between Mar. 14
and Mar. 19, 1983
Deposited 84.2 cm
at the lab.
```

```
         Snow Survey
         Change between Mar. 12 and Mar. 19, 1983

        I-------------------------------------------------------I
S1      I   38    32    24    20    23    44    31    65        I
        I                                                       I
S2      I   42    44    44    36    42    43    42    45        I
        I                                                       I
S3      I   35    30    22    42    32    37    40    27        I
        I                                                       I
S4      I   42    30    32    28    44    32    38    14        I
        I                                                       I
S5      I   39    43    40    40    35    29    27    43        I
        I                                                       I
S6      I   39    36    39    43    37    33    44    39        I

S7      I   41    40    37    41    44    49    33    51        I
        I                                                       I
S8      I   41    44    41    51    45    55    61    45        I
        I                                                       I
S9      I   42    47    41    43    30    51    47    39        I
        I                                                       I
S10     I   43    36    47    45    46    58    37    52        I
        I                                                       I
S10a    I   40    60    30    39    82    44    41    47        I
        I-------------------------------------------------------I
          S10a  S20a  S30a  S40a  S50a  S60a  S70a  S80a
          The mean change for this grid was    40.36   cm.
```

Figure 2. Sample report page. The heavy line separates the depositional area from ablation area.

with extendable, 2x2-in. metal poles. Vertical height on the poles is marked in centimeters. The western end of the grid is at 3607 m, the bottom at 3545 m, and the eastern end at 3579 m. Prevailing winds are from the west, so east-facing slopes receive deposition, while west-facing slopes are scoured by the wind. A detailed vegetation map indicates that six plant communities occur on the grid.

## CLIMATE

A 32-yr record of climatic data is available from the Front Range Climatological Station known as D-1. D-1, at an elevation of 3743 m, is located three kilometers west of and 198 m higher than the Saddle Grid. Weather conditions at the D-1 station may be considered representative of those at the Saddle Grid. Mean annual temperature at D-1 is -3.8 C with a January mean of -13.2 C. The record low is -37 C. Mean annual wind speeds average 10.3 m/sec with the January mean being 13.9 m/sec. Mean total yearly precipitation is 102.08 cm with about 80% falling as snow. January has the heaviest snowfall with 13.77 cm of water equivalent. Mean monthly radiation is 355.3 cal/cm -2/d with January receiving only 180.0 cal.cm-2/d.

## METHODS

When weather permitted, snow depth was measured at visible poles by reading markings on activity. Mean snow accumulation for the preceding week totaled 40.36 cm. In figure 2, note the deposition zone above the heavy line and the removal zone below the line. Storms accompanied by medium to low winds show a pattern of accumulation on the western portion of the grid and removal on the eastern portion (fig. 8). Accumulation may also occur at some points within the removal area.

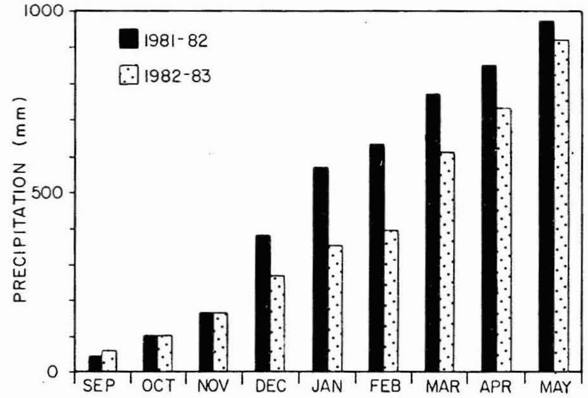


Figure 5. Cumulative snowfall for 1982 and 1983.

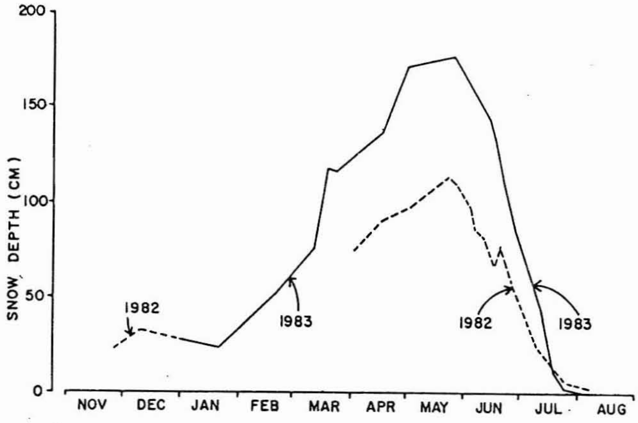


Figure 6. Mean snowpack for the entire grid for 1982 and 1983.

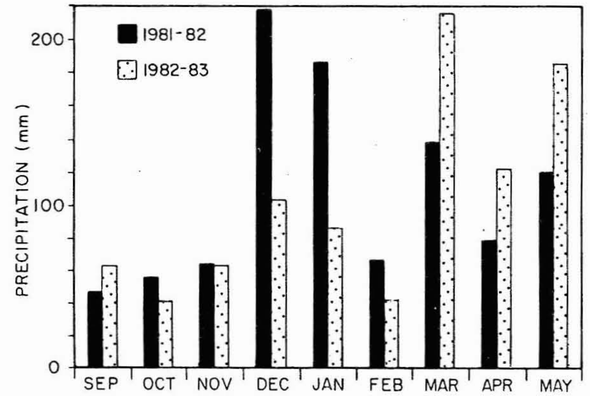


Figure 7. Monthly record of snowfall for 1982 and 1983.

```
      Snow Survey
      Change between Mar. 24 and April 2, 1983

     I-------------------------------------------------------I
S1   I   31    92    11    96    51   -29    50   -30        I
     I                                                       I
S2   I   54    56    34    36    67   -15    47    71        I
     I                                                       I
S3   I   25    40    42    45    17    12    53    79        I
     I                                                       I
S4   I   17    10    28    32    41    23    60     7        I
     I                                                       I
S5   I   21    27     0    36    26    31    52    77        I
     I                                                       I
S6   I    2     4    -5    -7    28    18    29    37        I
     I-------------------------------------------------------I
S7   I    9     2    -2   -17     8   -12    -2    -6        I
     I                                                       I
S8   I   -5   -11   -20   -17     3    -4    -7    -2        I
     I                                                       I
S9   I    4   -13   -17    -9    -6   -13     0   -24        I
     I                                                       I
S10  I    0     0    -1    -2    -5   -17     2    32        I
     I                                                       I
S10a I   -1    -2    -2    -1   -17    -2    10   -21        I
     I-------------------------------------------------------I
       S10a  S20a  S30a  S40a  S50a  S60a  S70a  S80a
      The mean change for this grid was    15.24  cm.
```

Figure 8. April 2, 1983 map showing change since March 24, 1982. Light winds have scoured the snow from the eastern area but deposition has been high on most of the western portion.

Increasing winds with or following the storm cause snow removal within the deposition area (fig. 9). Although the net effect of the storm event may be a mean addition to the grid, many to most grid points may actually have a loss. High winds, usually following a storm, may cause midwinter losses in snowpack (figure 10).

```
      Snow Survey
      Change between Nov. 26 and Dec. 11, 1982

     I-------------------------------------------------------I
S1   I    3     9     8     8    20    25    -1    10        I
     I                                                       I
S2   I  -11     7    36    12    12    11    -9    -5        I
     I                                                       I
S3   I  -11    35    39    32    32    41    79    36        I
     I                                                       I
S4   I   -4    11    28    19    27     3     9    49        I
     I                                                       I
S5   I  -17     9    -2     1    21    84   123    23        I
     I                                                       I
S6   I   15   -16    -7    -0     6    73    70    35        I
     I-------------------------------------------------------I
S7   I   -4    -1     3     7    -3    -1    -4    -2        I
     I                                                       I
S8   I   -3     3    -2   -13     9    -0     6   -11        I
     I                                                       I
S9   I  -11    -2     3    -4    -2   -15   -15    -4        I
     I                                                       I
S10  I   -1    -1    -3     0    -4    -1   -10    -4        I
     I                                                       I
S10a I   -2    -4    -3    -2     8    -3    -5  -7.4        I
     I-------------------------------------------------------I
       S10a  S20a  S30a  S40a  S50a  S60a  S70a  S80a
      The mean change for this grid was    9.920  cm.
```

Figure 9. December 11, 1982 map showing change since November 26, 1982. Stronger winds have increased the scour on the western or depositional portion of the grid. There has however been a net gain of snow on the grid.

```
        Snow Survey
        Change between Mar. 19 and March 24, 1983

     I-------------------------------------------------------I
S1   I   -11    -18    -10    -10     10     68      4     17    I
     I                                                       I
S2   I     8      9     15    -21    -14     41     30     21    I
     I                                                       I
S3   I     0     -6     -9     11      0     12     -7      9    I
     I                                                       I
S4   I    -3     11    -12     -9    -12     22    -52     18    I
     I                                                       I
S5   I   -13     -8     -3     -8     -6    -12    -11     -4    I
     I                                                       I
S6   I    -4      8     -9    -15    -16     -3    -10      0    I
     I-------------------------------------------------------I
S7   I   -28     -8    -11    -11    -31    -21    -18    -24    I
     I                                                       I
S8   I   -15    -20    -19    -34     -9    -19    -13    -40    I
     I                                                       I
S9   I   -23    -23    -23    -33      7    -22    -33     53    I
     I                                                       I
S10  I   -43    -36    -45    -43    -41    -16    -36     -5    I
     I                                                       I
S10a I   -40    -59    -29    -37    -54    -45    -47    -10    I
     I-------------------------------------------------------I
          S10a   S20a   S30a   S40a   S50a   S60a   S70a   S80a
        The mean change for this grid was      -11.4   cm.
```

Figure 10. March 24, 1983 map showing change since March 19, 1983. The heaviest winds have scoured most of the grid making for a net loss of snow since March 19, 1983.

Wind losses can be considerable, occasionally 150 cm of snow or more. The greatest wind loss for the grid averaged 11.4 cm per grid point within a six-day period. Individual grid points have lost as much as 59 cm with larger losses observed between grid points. Some loss may be associated with sublimation. However, as an observer standing in the path of these snow-laden winds will testify, most loss is a product of wind erosion.

Wind removal can greatly alter the snowpack stratigraphy within the accumulation zone. Anchoring or weak layers may be removed. Sastrugi formation may provide stronger or weaker anchors for new fallen snow depending on their orientation to the slope. Sastrugi formation makes the snowpack very heterogeneous. Therefore a snow test pit dug at one point may not reveal a weak zone nearby. The removal of snow may not be discernable to observers when reference points are not visible within the snowpack. This may be particullarily true when workers are looking over the edge into an avalanche starting zone. Wind-induced patterns within the starting zones of avalanches may have ramifications for avalanche forcasting. Further studies with reference points within avalanche starting zones are needed. Stakes would have to be placed before the snow season but the gained knowledge might outweigh the losses of stakes when an area slides.

Wind removal of snow from the Saddle Grid is substantial but not as great as the loss which occurs during the summer melt period. During summer meltoff the mean loss from all grid points has averaged as high as 54.3 cm/wk with individual points losing up to 90 cm/wk. Temperature is the primary controlling factor in summer meltoff (fig. 6). Even though the 1983 accumulation (176.6 cm) was 157% of that for 1982 (112.6 cm), meltoff was more rapid in 1983. The mean June, July, and August temperatures for 1982 was 5.90 C and for 1983 was 6.43. Thus by July 25, 1983 there was less snow left on the grid than at that time in 1982.

Snowpack depth and duration are important controls influencing plant communities. For the two years of study, strong correlations existed between the location of the six plant communities on the Saddle Grid and the mean date on which they become snow free. Strong correlations also exist between community boundaries and the mean maximum depth of snow during the winter. This can be illustrated with the snowbed plant community (fig. 11). Those areas which do not become snow free until after July 19 and have a maximum of snow greater than 250 cm tend to develop plants communities with species characteristic of late-lying snow areas. These communities are termed snowbed communities.

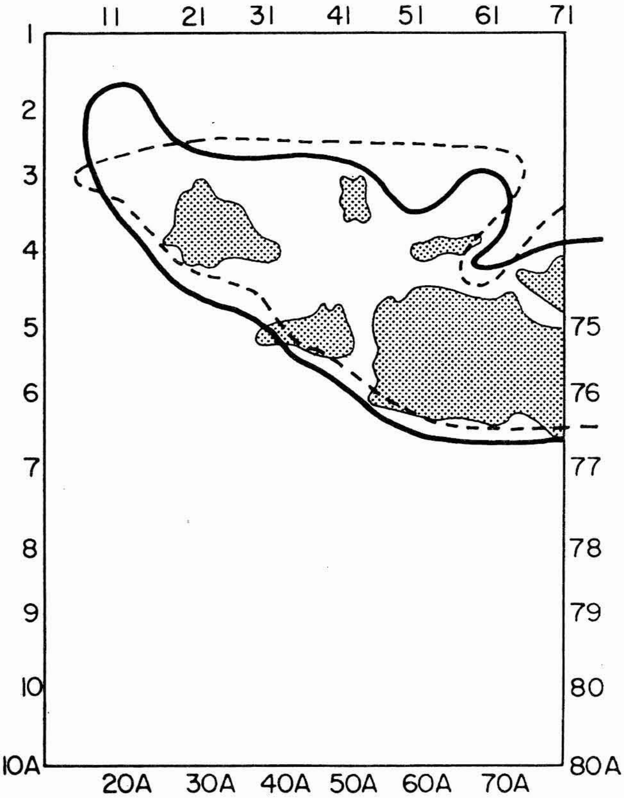


Figure 11. Map showing the relationship of the snowbed plant community to snowpack depth and duration. The shaded area is the portion of the grid where the snowbed plant community is located. The area en closed by the solid line averaged greater than 250 cm of maximum snowpack. The area enclosed by the dashed line did not become snowfree until after July 19th in 1982 and 1983.

Studies of vegetation on Niwot Ridge have shown that augmentation of snow cover by the addition of snow fences can dramatically change the plant community structure. Species may be lost and new species added. Although not shown, changes in species composition can probably be caused by decreasing snowpack. This decrease could be the result of redistribution of snow due to the erection of snow fences. Consideration of the close correlation between plant communities and the snowpack is important when evaluating possible changes in snow distribution patterns within avalanche zones. Changes in species compostion may change the anchoring characteristics of a particular slide zone.

## SUMMARY

Detailed studies of snowpack and patterns of accumulation, deflation, meltoff, and duration at Niwot Ridge reveal several factors which may be important in avalanche control. Winds, under the proper conditions, may cause changes within snow deposition zones which may hide or change snow stability patterns. Introduced heterogenity may make it possible for snow test pits to miss zones of weakness or strength. Anchoring properties due to sastrugi formation may be greatly altered. In high wind areas, the snowpack of accumulation areas may be a dynamic entity showing marked changes even in short periods of time. These changes may not be apparent because of the lack of visible markers.

Snowpack and duration affect plant community existence and species composition. Changes in snowpack resulting from control efforts, such as erecting snow fences, may alter the species composition. The altered plant composition may have different anchoring abilities for the snowpack.

Further work and experimentation is needed to assess the effects of wind in avalanche starting zones and changes in plant species composition within avalanche paths. Grids of snow stakes, which could be read from a distance, should be set up in the starting zones of avalanches for future studies.

## ACKNOWLEDGMENTS

This work was funded by NSF grant no. DEB 8012095 to the University of Colorado Long-Term Ecological Research program in the alpine tundra. The authors wish to thank the numerous volunteers who have helped with field work. We also thank Kathy Ingraham for her editorial suggestions.