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Comparisons of Snow Deposition, Soil Temperature, Matric Potential and Quasi-Friction Velocity Between a Windward Site and a Lee Shelter in a Cold Desert

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COMPARISONS OF SNOW DEPOSITION, SOIL TEMPERATURE, MATRIC POTENTIAL AND QUASI-FRICTION VELOCITY BETWEEN A WINDWARD SITE AND A LEE SHELTER IN A COLD DESERT

by

Harvey L. Neuber

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

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ABSTRACT

Comparisons of Snow Deposition, Soil Temperature, Matric Potential and Quasi-friction Velocity Between a Windward Site and a Lee Shelter in a Cold Desert

by

Harvey L. Neuber

Utah State University, 1984

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Department: Biometeorology

Regimes of snow depth, soil temperature, soil matric potential and quasi-friction velocity in a windward site and a lee shelter were examined. The differences were analyzed from a biological perspective to characterize each location in terms of site favorability to plant growth. The chronology of wind and precipitation events was investigated.

Snow depth was measured with a system of stakes arranged around and in the interior of a rectangular plot encompassing both a windward site and a lee shelter. Soil temperature, soil matric potential and water potential were measured along a transect which originated in the windward site and terminated in the lee shelter. Soil temperature and water potential were measured by thermocouple psychrometer. Matric potentials was determined by the pressure-plate method. The regimes of quasi-friction velocity at both ends of the transect were determined by the logarithmic profile method, invoking similarity theory. Wind speed and temperature were measured at two

heights in each site. A computer program was used to search the wind and precipitation records and categorize and sum the precipitation events by wind direction.

The lee shelter exhibited tendencies toward theoretical optima of site favorability. The horizontal distribution of snow maxima was found to be a function of wind direction at the time of each precipitation event as well as the interaction of wind and the topographical features.

Snow was observed to accumulate to a greater depth in the lee shelter than in the windward site. Mean soil temperature over the study period was 8.5 ° C in the lee shelter while the windward site was 8.0 ° C. Soil temperature in the lee shelter was never observed to go below 0 ° C under a snowpack. The range of soil matric potential in the lee shelter was found to be about 14 atm at a depth of 20 cm and about 17 atm at a depth of 50 cm over the summer season. In the windward site the range of soil matric potential was approximately 30 atm at a depth of 20 cm and about 21 atm at a the 50 cm depth over the same period. The lee shelter exhibited lower (less negative) matric potentials than the windward site. These results were not corroborated by the measurment of water potential by thermocouple psychrometers. In the layer from 1.5 to 4.1 m, the mean quasi-friction velocity in the lee shelter was 39 cm s^{-1}, favoring snow deposition there over the windward site where the mean friction velocity was 21 cm s^{-1}. In the 0 m to 1.5 m layer, mean friction velocity in the windward site was found to be 55 cm s^{-1} while the lee shelter mean was

48 cm s^{-1}. These results indicate a distinct seperation of flow downwind of the windward site where the lee shelter resides in the turbulent wake of the windward site.

INTRODUCTION

The distribution of plant communities in the American West is discontinuous. In a given floristic zone, plants occupy preferred sites that exist at some point on a continuum from least to most favorable. Distribution discontinuities can be regarded as alternating zones whose characteristic regimes of environmental variables vary in hospitality to a certain species. This defines the interface between a plants' physiological requirements and its environment (Taylor, 1934). A distinction is made here between this approach and Liebigs' "law of the minimum" that implies only minimum values for individual processes and quantities. There may very well be maximum values, as in the case of solar radiation, that may serve as limiting factors (ibid). Since climate is the principal abiotic environmental driver, it could be said discontinuities in plant distribution may be due to microclimatic variation.

Many native North American plant species exhibit discontinuous distributions, in terms of both density and vigor of growth, tending toward maxima on north and east aspects. This topographic distribution is particularly striking on the Wyoming plateau where wind is a significant climatic parameter. Southwestern Wyoming is also typified by mean annual precipitation values on the order of 20 to 40 cm yr (source: NOAA, 1973). The interaction of wind and precipitation here results in maximum snow depositions on north and east aspects, corresponding dramatically with the vegetation pattern.

Since water may be the limiting factor to plant growth over much of this region, this observed correspondence appears to imply cause-and-effect. This study was undertaken to test the hypothesis that soil moisture is related to snow depth, on the assumption that greater snow results in higher soil water content. It also addresses the question of whether other physical processes may be interacting with topography, resulting in physical constraints to site favorability other than the availability of water.

The objectives of this study were:

(1) to determine how wind and topography interact to induce spatial variation in snow distribution, and

(2) to compare some of the differences in physical characteristics between a windward and a leeward site.

REVIEW OF LITERATURE

Wind has been shown to exert a great deal of influence upon plant growth. Krummholz and flag-form trees are both classic textbook examples of morphological and physiological responses of plant growth to the influence of wind. These representatives are generally regarded as evidence of individual plant responses, however, the effects of wind upon plants at the community or ecosystem level must not be overlooked. Several (Marshall, 1970; Odum, 1969; Oosting, 1956) have described the climatological effects of wind upon the plant's overall environment. Other than direct physical effects of wind upon plant growth, there are several indirect influences which are important to plant establishment and survival. Among these is the ablility of wind to act as a distribution mechanism , differentially allocating water, nutrients, propagules, etc. within an ecosystem (Oosting, 1956).

Vegetation can be regarded as an overall measure of environment. Billings (1969) said "...vegetation is a delicate integrator of environmental conditions and can be used as an indicator of such conditions." This statement implies Liebig's "law of the minimum" which asserts that an organism's establishment and survival cannot occur unless a complete set of minimum environmental conditions are satisfied. In the North American West, large regions exist where these criteria are not met or only very minimally satisfied. These areas are ones in which water is often the limiting factor to the phytosphere (Lundegardh, 1931). A characteristic common to many of these locations is that a large proportion of the annual precipitation occurs during the winter months in the form of snow. A characterization, therefore, of a particular site, in terms of plant establishment and survival must be one which considers snow cover and distribution as significant components of seasonal water availability. Oosting (1956) noted that the greatest variations in vegetation can usually be correlated with moisture. Thus, it is reasonable to examine the role of water as a useful predictor of "niche distribution" if it is a limiting factor.

In the presence of wind, the differential accumulation of snow is a function of fluctuations in surface roughness. Martinelli (1965) observed that natural barriers can significantly contribute to snow accumulation in an alpine life zone. Kuz'min (1960) and McKay (1971) both emphasized the importance of terrain in establishing snow cover patterns on the prairie. Contour trenching was shown to affect the areal distribution of snow (Curtis, 1971; Davidson, 1975; Doty, 1970). Studies have shown that vegetation itself serves as a roughness parameter that influences snow distribution (Hutchison, 1965; Rosenberg, 1966). In general, any element of variation in the surface roughness will result in some degree of deposition related to that element (Radok, 1977). In a region where snow and wind interact it is therefore appropriate to expect microclimatic variation as a result of imposing roughness features in the topography and to examine this microclimatic variability in terms of the wind-induced differential distribution of water.

The accumulation of snow in a lee shelter is thought to influence the local soil water. In this sense the snowdrift serves as a water reservoir, yielding itself to the soil upon melting, thereby enhancing the local water budget. This is subject to other physical factors such as surface permeability, hydraulic conductivity, etc. (Kramer, 1969). Several authors have described the beneficial effects on plant growth of local water availability near snow maxima in the lee of wind shelters (Bagdonas, et al, 1978; Guymon, 1978; Mckay, et al 1971; Rosenberg, 1966a). The local influence of meltwater adjacent to or under a snow drift, although relatively short-lived, may be of critical importance from the standpoint of plant survivability. Critchfield (1974) suggests that even a short period in the early spring may be critical to plant establishment and survival. His central theme is that any species of vegetation has some climatic optima under which its growth is most efficient. In cold desert environments plant growth is limited to a short period between winter cold and summer drought (Billings, 1969).

In direct relation to the water budget of a soil is the differential partitioning of radiant energy into sensible and latent heat. This is a function of the water available to the microsite (Lemon, 1963). Here, again, even though the presence of meltwater is temporary, this short period of time may be very important to germination, initial growth, etc. (Miller, 1981).

Many researchers have described the shelter's hospitality as a physical characteristic of the lee shelter itself. Oke (1978) found that the fluxes of latent and sensible heats are reduced by the damping of turbulence in a sheltered area. Rosenberg (1966b) established that evaporation rate is attenuated in a lee shelter thereby resulting in better conditions for seed germination. Even when differences in soil moisture between an open site and lee shelter were eliminated with irrigation, plants were observed to produce higher yields in the lee shelter (Brown, et al, 1972). The reduction of turbulence in the lee shelter is thought to result in overall improvement in water use efficiency (Rosenberg, 1974).

This information suggests that a lee shelter usually tends to optimize conditions suitable for plant establishment and survival when water is limiting. Specifically, the accumulation of snow tends to enhance the microenvironment, ultimately providing better conditions for plant growth. This, presumably, would be manifest as an increase in soil moisture. Other than light and temperature, soil moisture and rainfall have more influence on plant distribution than any other factor (Lundegardh, 1931).

Winter baroclinic storms, in the American West, are known to behave in a somewhat predictable manner. At the onset, wind direction is known, generally, to be from the south or southwest (Cole, 1975). During the progress of the storm surface wind direction generally changes, either gradually or abruptly, until it is usually out of the north or northwest (ibid). This pattern can become somewhat obscured in mountainous terrain (Oke, 1978). The direction of the wind then becomes a function of both topography and storm evolution. Climatologists have developed the wind rose (Critchfield, 1974) which graphically portrays climatic aspects of wind direction and speed. Here, an application would be one of importance to plant growth which relates wind direction and speed to precipitation events. The sequence of the precipitation event in relation to the wind direction is seen here to be critical to snow deposition. That is, the direction of the wind during and after the precipitation event will determine the areal distribution of snow drifts and, climatologically, establish those lee shelters favorable to plant growth.

The measurement of precipitation in mountainous areas has been a long- standing problem. Winter precipitation in mountainous terrain is almost always accompanied by strong winds (Fohn, 1976). This results in the drifting of snow and thus creates difficulty in the using of one stations' data as representative of an area (ibid). Even in flat lowlands the data from one station is not necessarily representative of an area. These spatial differences in precipitation are greatly influenced in mountainous areas by the topography itself (Miller, 1981)

MATERIALS AND METHODS

I. Site Description

Geography and Topography

A study site was chosen approximately 11 km southwest of Kemmerer, Lincoln County, Wyoming (110 30' W, 41 45' N). The site was located on the Elkol Strip Mine, owned and operated by the Kemmerer Coal Company. The mine lies directly adjacent to Utah Power and Light Companys' "Naughton" power plant. The site had been recently stripped and reclaimed. The reclamation process approximately restored the site to its original contour and aspect. The study site was located approximately 20 m in elevation below the crest of a prominent ridge. Approximate elevation of the site above mean sea level is 2250 m. The aspect of the study site is east northeast. The ridge on which the study site was located runs approximately North to South with the north end terminating in a high point (2350 m) and the south end falling away to an elevation of about 2200 m. To the west of the ridge the land slopes abruptly for approximately 100 m into a wide valley whose opposite side lies about 1 1/2 km to the west, the direction of the prevailing wind. This western ridge is the only prominent topographical feature upwind of the study site for several tens of kilometers. It serves as the divide between the Great Basin and the Pacific Ocean drainages. It is listed on most topographical maps as the "Bear River Divide" (figure 1).

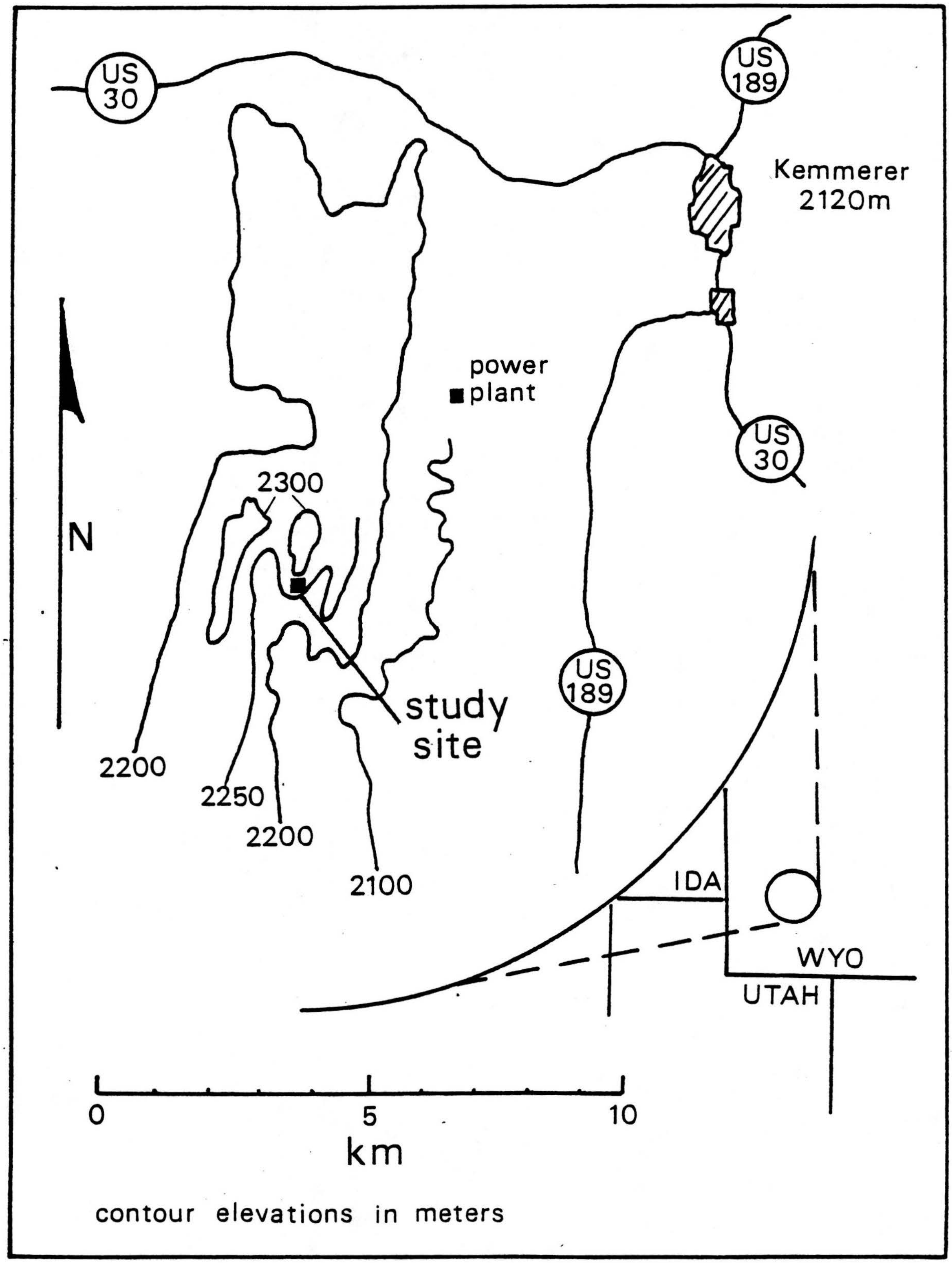

Figure 1. The study site.

Climatically, the study area falls into the Dsb climatic class, after Koeppen. The annual mean temperature is $4^{\circ}C$ with a July mean of $17.1^{\circ}C$ and a January mean of $-8.3^{\circ}C$. These, and any other figures cited here as "annual means" are for the town of Kemmerer (source: NOAA, 1973). The annual mean precipitation is 24.2 cm. Approximately 43% of the precipitation falls during the months of November through April; 28% falls during May and June. The prevailing wind is westerly. During the period of October, 1981 through August, 1983, approximately 90% of the winds measured at the study site were west of the North-South meridian (S. Smith, personal communication). Easterly winds are thought to be anomalous except as components of local or mesoscale atmospheric events.

Flora

Phytologically, the site lies within the Cold Desert Formation after the classification of Billings (1969). It is situated just outside of the Great Basin Ecosystem (MacMahon, 1979). The areas dominant native plant species is *Artemisia tridentata.* The vegetation distribution is strongly related to topoography, apparently limiting the larger species such as *Populus* spp and *Amelanchier* spp to aspects in the lee of the prevailing wind (personal observation). Windward sites are typified by much shorter vegetation species.

Soils

The soils on the site belong to the Aridisols order but are spatially highly variable. Topsoil composition also varies spatially with a preponderance of clay constituents. Dissolved salts have been shown to exhibit a high degree of variability on the site. Prior to the mining operation, the topsoil of the site was removed and stored in large piles for later use in the reclamation process. After the mining was completed the site was re-contoured and subsequently re-topsoiled with this stored topsoil. Topsoil thickness after reclamation was found to be highly variable in depth, ranging in thickness from a few centimeters to several decimeters.

II. Detailed Plot Description and Preparation

A study site was selected where marked differences in snow cover due to differential wind deposition were observed during the 1981-82 winter season. A rectangular plot of dimensions 30 m by 39 m was established using standard topographical surveying techniques. The plot was subdivided into thirty 3m by 3m squares. Elevations were measured at the four corners of each square, resulting in a rectangular grid system. The plot/grid was aligned with the long sides parallel to the North-South meridian and was located on the eastern side of the ridge with an approximate aspect of east northeast. The western edge of the plot is the higher side, falling away to the east at a slope of about 25%. In the south to north sense, the topography rises at an average slope of 6% with a prominent, elongated mound running diagonally from east southeast to west northwest near the midpoint. During the winter of 1981-82 the area to the south and west of the center mound was observed to be generally snow-free. This was likely a result of being continually swept clear by wind. This area of the plot will hereafter be referred to as the "windward site". Conversely, the remainder of the plot, to the north and east of the mound will be referred to as the "leeward site" or the "lee shelter" (figure 2). Snow depth on this site was observed to approach 1 m during 1981-82.

A linear transect was constructed within the perimeter of the plot, running from southwest to northeast. This orientation is roughly perpendicular to the mound and parallel to the horizontal gradient of snow deposition observed previously. The transect consisted of ten stations each fitted with thermocouple soil psychrometers (J. R. D.

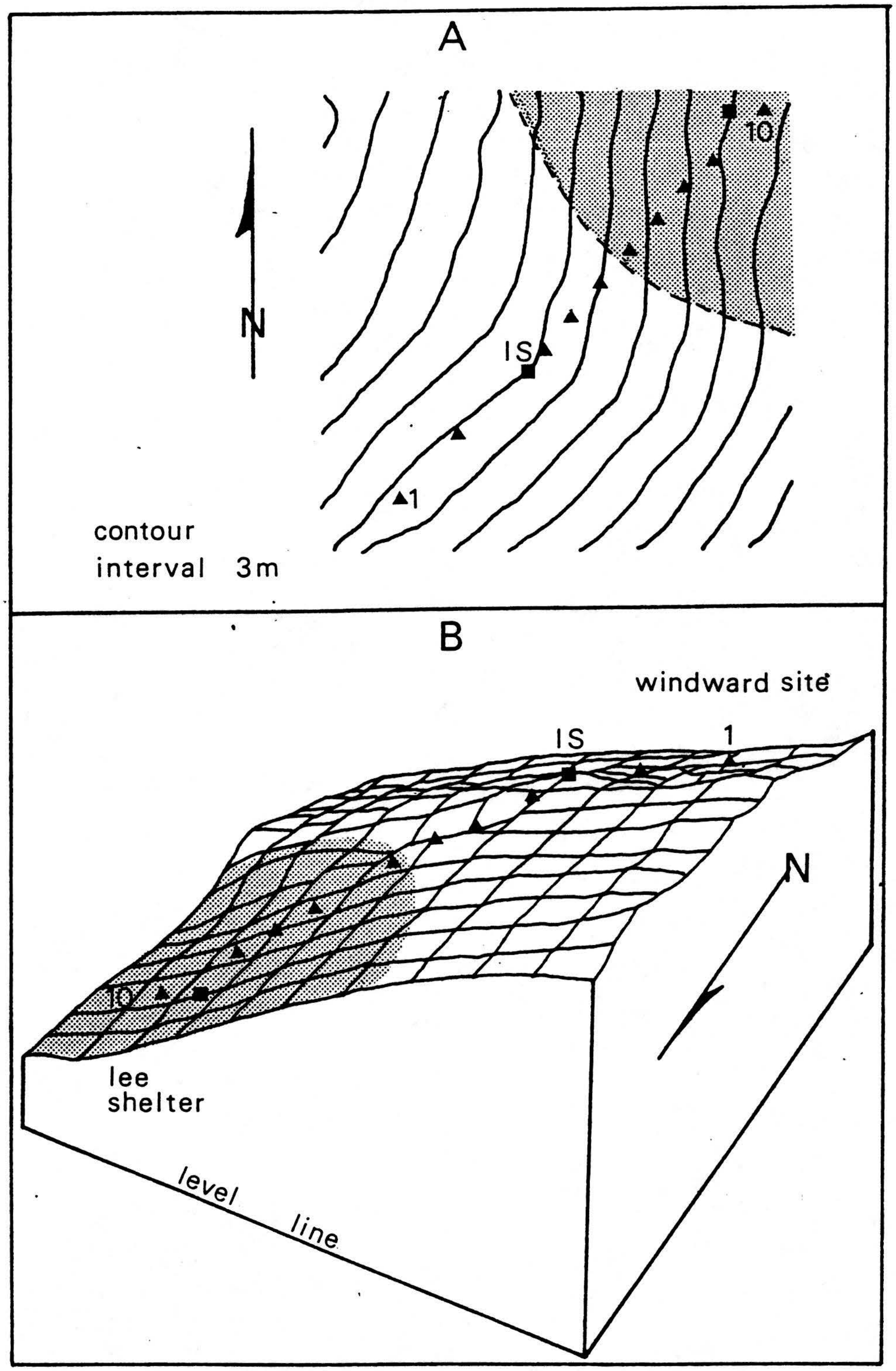

Figure 2. The study plot. The triangles denote the locations of snow depth stakes and psychrometers. The squares denote the locations where wind and temperature (atmospheric) were taken. The shaded area depicts the location where snow was deepest. (A) is a contour map; (B) is a three-dimensional cross section.

Merrill Equipment Co.). Stations 1 through 5 were placed in the windward site with station 1 being the most southerly. Stations 6 through 10 were placed in the leeward site. Station 5 was located at the apex of the mound, in the approximate center of the grid. Psychrometers were buried at each station at depths of 20 and 50 cm. Stations 1, 3, 5, 9 and 10 also included a "deep" psychrometer ranging in depth from 64 to 81 cm. This deep location was determined by the depth of excavable material overriding a much denser layer. Two additional stations were also located near this transect; one near station 4, in the windward site, and one near station 9, in the lee shelter. At both of these locations, psychrometers were also buried to depths of 5, 10, 15 and 20 cm. Soil samples were taken at each psychrometer depth for later determinations of moisture holding capacity. The readout device chosen for measuring soil water potential was a Wescor PR-55 psychrometer microvoltmeter. Soil water potentials were measured on Oct 7, 1982, Nov 23, 1982, Feb 24, 1983, then approximately every ten days from March 4, 1983 to Sept 29, 1983. Soil temperatures were measured on all the above dates with the addition of Nov 2, 1982, Nov 10, 1982 and Feb 4, 1983.

Soil samples were taken at each psychrometer station at depths of 20 and 50 cm on every sampling date from May 26, 1983 through the end of the study. These were taken to Logan, Utah for gravimetric determinations of water content. Since this process is destructive, the following scheme was used to standardize the sampling procedure: every sample was taken within a 1/2 meter radius of each psychrometer station with successive samples taken on the opposite side of the station (180 degrees) and displaced 20 degrees in a clockwise direction. The resulting hole was then backfilled with soil.

A 3 m meteorological observatory tower was located at the approximate center of the grid, near psychrometer station 4. The tower was fitted with two Weathertronics model 2030 3-cup anemometers and a Weathertronics model 2020 direction vane. The anemometers were placed at 1.5 and 4.1 m above the surface; the vane at 4.1 m. Temperatures on the tower were determined at heights of 0.3, 2.6 and 4.1 m with copper-constantan thermocouples. An underground instrument shelter was located adjacent to the tower containing a Campbell Scientific CR-5 data logger. The data logger was programmed for recording averaged data at 3-hr intervals throughout most of the study. Thirty minute averages were recorded for the period of August 4 to August 23, 1983. Also adjacent to the tower was a weighing type series universal recording precipitation guage by Belfort Instrument Co. Two non-recording rain and snow guages (Belfort) were located at the site; one in the windward site, near the recording precipitation guage and one in the lee shelter, near psychrometer station 10.

An Omnidata, Int'l "datapod" wind sensor was placed near psychrometer station 1 for the period of July 7 to July 31, 1983. An identical device was placed near station 10 for the same period. Both were programmed for the taking of 30 minute average values of wind speed and direction. Sampling height in each case was 1 m. Each system was composed of a WSD-321 wind speed and direction package coupled to a DP-214 datalogger, both by Omnidata, Int'l. During the period of August 4 to August 25, 1983 these two devices were arranged vertically on a mast erected near psychrometer station 10. One was located at 1.5 m and one at 4.1 m. Again, both were programmed for the taking of 30 minute averaged values of wind speed and direction. Great care was exercised in the sychronization of these devices with the CR-5 data logger in the instrument shelter thus avoiding temporal differences in wind speed measurement from the windward to the leeward sites. Temperatures were measured at the leeward site with copper-constantan thermocouples. In addition to the heights mentioned before, a thermocouple was placed for surface measurements in both the windward and leeward sites.

Snow depth was measured with a system of twenty snow depth stakes arranged around the perimeter and interior of the plot. A snow depth stake was also placed near each psychrometer station. Snow depth was checked approximately every ten days throughout the 1982-83 winter season. Snow density measurements were taken on each sampling date with the use of a laboratory built apparatus designed to determine the weight of a fixed volume of snow sample. This device was calibrated such that density could be read directly.

Moisture characteristic curves were determined for soil samples taken at the time of psychrometer installation for each psychrometer depth. These were determined in the laboratory by the method described in Hanks (1980). Tempe pressure cells were used for the -1/2 and -1 bar tensions, while the -5 and -15 bars tensions were found with the use of a Soil Moisture Equipment Co. high pressure chamber.

The mention, herein, of a particular manufacturer is not intended as an endorsement of any product over another.

RESULTS AND DISCUSSION

I. Precipitaion.

Total precipitation measured at the study site for the period of October, 1982 to September, 1983 was 622 mm. For the same period, the Kemmerer NWS station measured 597 mm, with a missing January value. At the Kemmerer NWS station this amounted to 220% of the thirty-year average annual value. The difference between the NWS station and the study site can be attributed to systematic differences due to orographic and horizontal variability. Undoubtedly, random differences are present also. By any means of comparison this period was unusually wet. The monthly values are given in table 1. A comparison between measured values at the study site and the thirty-year average values at Kemmerer is presented graphically (figure 3).

Aside from the precipitation totals, the temporal distribution of these data over the study period presents, perhaps, an even greater anomaly. During September, 1982, the study site recieved precipitation nearly an order of magnitude greater than the average value for Kemmerer. The significance here is that soil recharge occurred during an otherwise typically dry season. The September, 1982 precipitation was roughly equal to one-half of an average annual total. The use of the term "average" here is meant to refer only to a numerical process. This is in contrast to use of the term "normal" which has inappropriate climatological connotations since it is not known what "normal" means. In any case, the study period

Table 1. Measured precipitation values at the study site (12 UC), compared with Kemmerer NWS station and 30 year mean (Source: CD Bulletin)

1982	12 UC	Kemmerer NWS	Kemmerer 30 mean
Jun	8.0	12.7	36.1
Jul	64.5	51.6	13.0
Aug	9.5	31.5	20.8
Sep	128.0	116.3	18.5
Oct	15.0	17.8	18.8
Nov	23.5	20.3	18.0
Dec	20.0	19.8	18.0
1983			
Jan	15.0	----	16.9
Feb	26.0	22.6	15.5
Mar	42.0	41.4	17.0
Apr	65.5	58.7	18.3
May	52.0	64.0	31.2
Jun	30.5	13.2	36.1
Jul	15.0	18.0	13.0
Aug	115.0	103.1	20.8
Sep	74.5	----	18.5

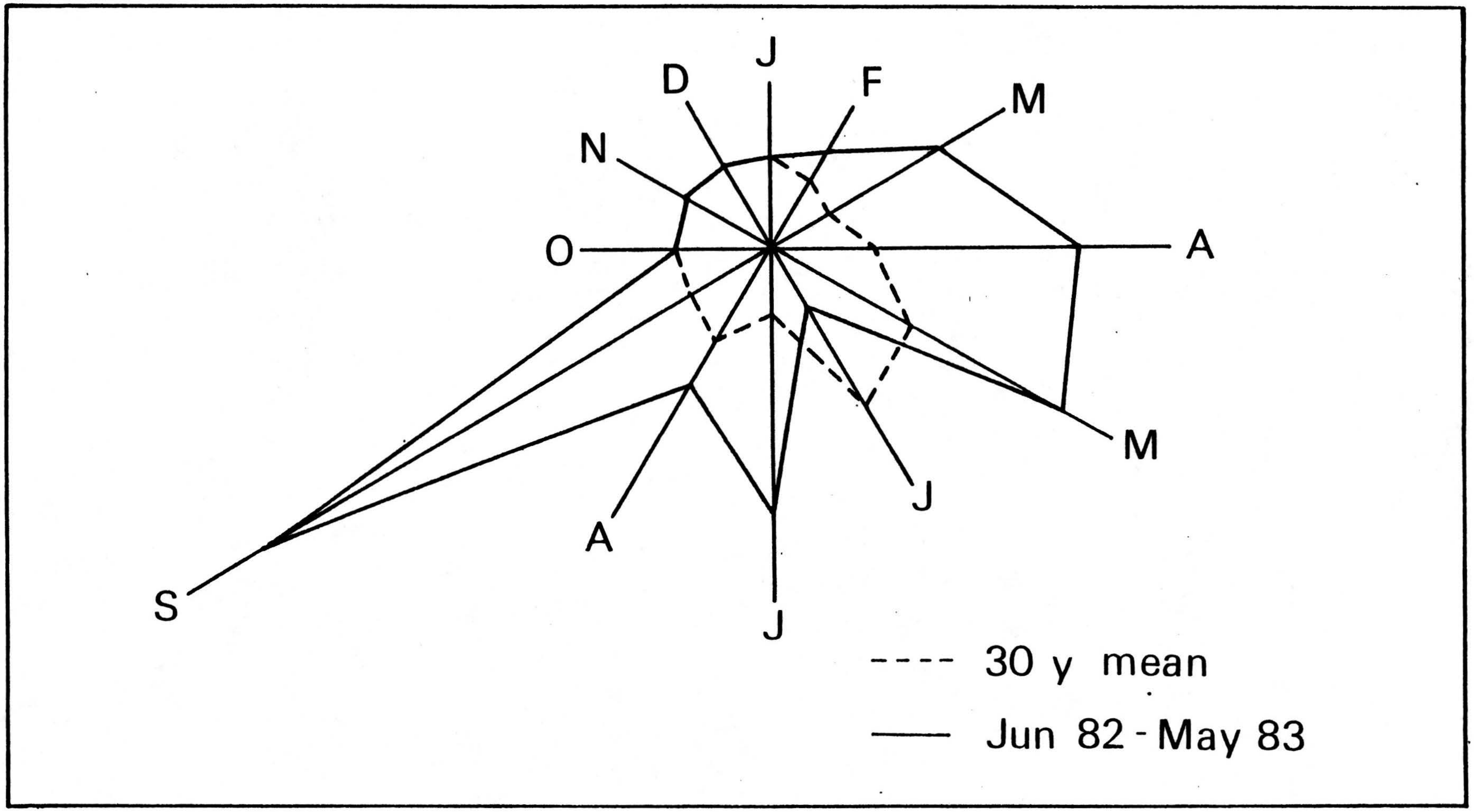

Figure 3. Precipitation, by month, plotted in a circular fashion. These are relative values, showing the differences between the climatological average (dashed line) and the values measured during the study period (solid line).

began with a completely (or nearly so) recharged soil profile, opposite to what generally occurs. This influx of water into the system during September gains additional significance in light of the absence of any significant removal mechanisms. Evapotranspiration rapidly declines as plants senesce or approach dormancy. Solar elevation also decreases rapidly during this time resulting in rapidly diminishing insolation and hence, decreased potential evapotranspiration.

The first observed snowfall occurred on November 19,1982. The last measureable snowfall occurred during the month of May. Snow was observed on the ground continuously from November 23, 1982 until March 4, 1983. On, or after, March 16 only new, transient snow existed at the study site. That is, snow was not observed to accumulate from one sampling date to the next. From March 16 through the end of the study snow depth was never observed to exceed 4 cm at any measuring location. Several precipitation events occurred during this latter period with the majority probably occurring as snow.

The measurement of snow densities proved to be a fruitless endeavor. Snow depth was often too shallow to extract a clean sample . Also, the presence, oftentimes, of aeolian soil in the snowpack was thought to render this measurement invalid.

Snowpack measurements during the study period show distinct differences between the windward and leeward sites (figure 4). These data are given in table 2. The majority of the precipitation events occurred when the wind was west of the North-South meridian.

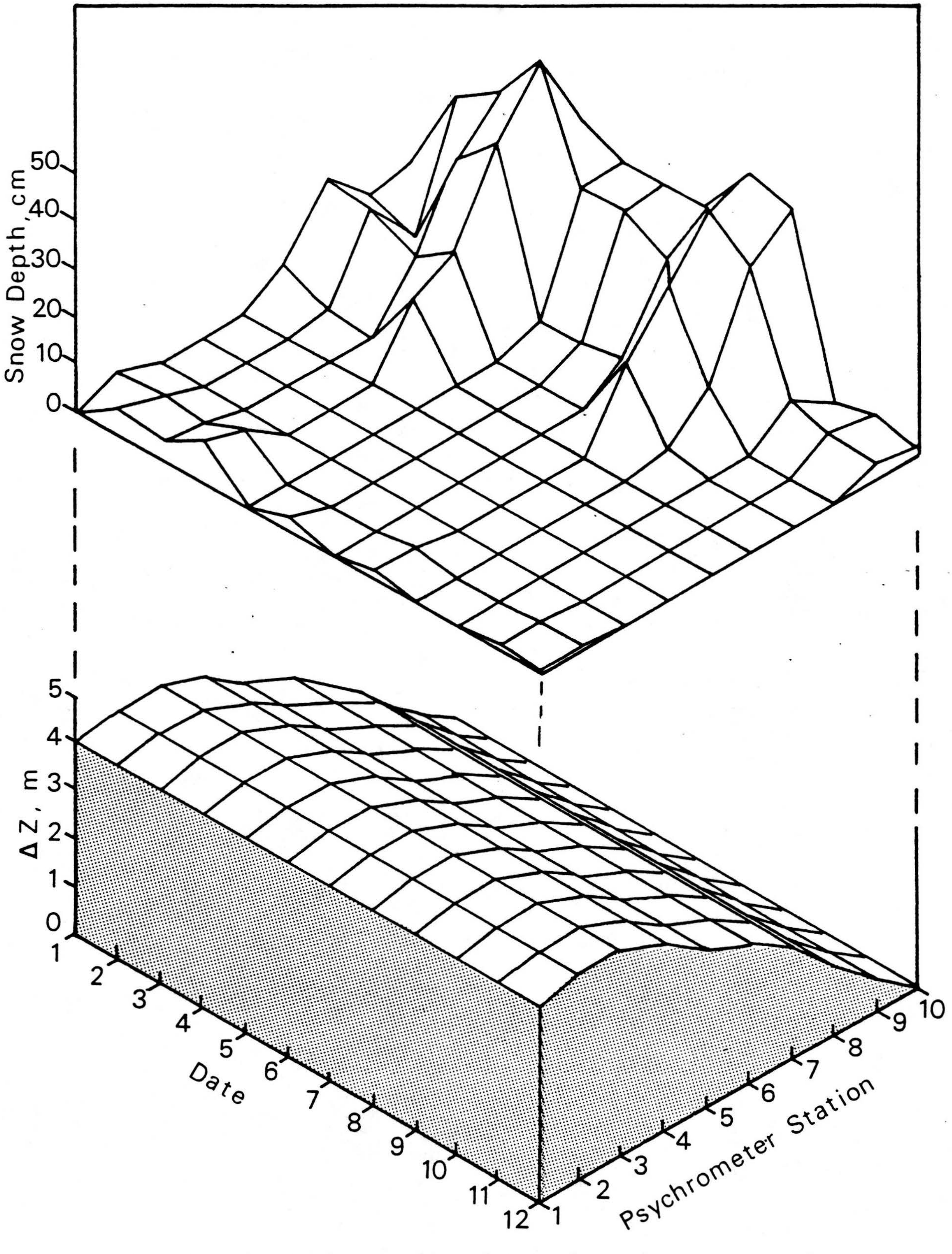

Figure 4. Snow depth, by sampling date and psychrometer station. Date 1 was Nov. 23, 1982; date 2 was March 24, 1983.

Table 2 . Snow depths by date and psychrometer station. Depths are rounded to nearest cm.

Date	11/23	12/9	12/22	1/4	1/14	1/25	2/4	2/15	2/24	3/4	3/16	3/24
Station												
1	0	5	4	8	0	3	0	2	0	0	2	1
2	3	3	3	5	0	0	0	2	0	0	2	1
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	5	1	3	0	0	0	0	0	0	0	0	0
7	15	15	12	15	0	0	0	13	13	0	0	0
8	8	5	23	30	3	3	5	20	8	0	0	0
9	10	26	30	41	30	23	18	30	26	5	4	4
10	8	8	15	26	18	18	18	33	30	0	3	1

However, several events occurred at the study site accompanied by east wind, i.e. when the wind was east of the North-South meridian. This was particularly true of those in the early part of the season. Of course, wind direction determines which site is favored for snow deposition. During these east wind precipitation events, the distinction of windward and leeward sites became obscured with deposition occuring in the normally windward site. The designations of windward and leeward, however, held quite well for most of the season with respect to snow deposition. The east wind precipitation events were considered to be a result of an anomalous general circulation pattern. This season was unusual in that the average position of the polar front jet stream was located much farther south than in most years. This displacement was often on the order of 10 degrees of latitude. When synoptic disturbances occurred, the study site was located quite far to the north with respect to the mean flow. A closed low pressure aloft often provided enough backing to the east to induce an easterly flow at the surface and aloft. The associated precipitation occurred as snow deposition in an easterly wind.

An analysis of the correspondence of precipitation with wind direction was done using three-hourly averaged data. A computer program was used to search the data records and categorize the precipitation events by wind direction. When the program located a precipitation event, the event was summed in one of eight direction categories (octants), each category comprising 45 degrees of azimuth. A detailed description of the categories is given in table 3.

Octant No.	Azimuth	Name
1	45 - 90 °	E-NE
2	00 - 45 °	NE-N
3	315 - 00 °	N-NW
4	270 -315 °	NW-W
5	225 -270 °	W-SW
6	180 -225 °	SW-S
7	135 -180 °	S-SE
8	90 -135 °	SE-E

Table 3. Description of the eight octants, each comprising 45 ° of azimuth.

This analysis was done for the following periods:

(1) October 28, 1981 to August 8, 1983

(2) October 28, 1981 to May 31, 1982

(3) October 1, 1982 to May 31, 1983

The results are given in table 4. For period 1, the most prominent feature of this analysis is the pattern of precipitation associated with a northwest to westerly flow (figure 5). This result lends credence to the procedure itself since any large data set encompassing a fairly wide temporal range should indicate the climatologically averaged mean flow. Although the majority of the events occured during a northwest to westerly flow (62%) these amounted to only 43% of the total precipitation for the period. This tends to indicate that the relative strength of these events, with their associated surface winds is lower than those of the other octants. This is an important consideration in the climatological definition

Table 4 . Precipitation by wind direction (see text)

Direction	# events	Amount, mm	Amt. event	% total
Period: Oct. 28, 1981 to August 03, 1983. # events = 333				
E-NE	23	39.5	1.72	7.4
NE-N	8	15.0	1.88	2.8
N-NW	27	54.5	2.02	10.2
NW-W	144	228.5	1.59	42.9
W-SW	93	134.5	1.45	25.3
SW-S	13	14.5	1.12	2.7
S-SE	12	18.0	1.50	3.4
SE-E	13	28.0	2.15	5.3
Period: Oct. 28, 1981-May 31, 1982. # events = 129				
E-NE	0	0	0	0
NE-N	2	1.0	0.50	0.5
N-NW	14	24.5	1.75	11.9
NW-W	83	154.5	1.86	74.8
W-SW	18	17.5	0.97	8.5
SW-S	3	3.0	1.00	1.5
S-SE	3	3.0	1.00	1.5
SE-E	6	3.0	0.50	1.5
Period: Oct. 10, 1982-May 31, 1983. # events = 145				
E-NE	19	20.0	1.05	9.9
NE-N	5	7.5	1.50	3.7
N-NW	2	3.0	1.50	1.5
NW-W	41	52.0	1.27	25.7
W-SW	63	98.0	1.55	48.5
SW-S	7	7.5	1.07	3.7
S-SE	5	4.0	0.80	2.0
SE-E	5	10.0	2.00	5.0

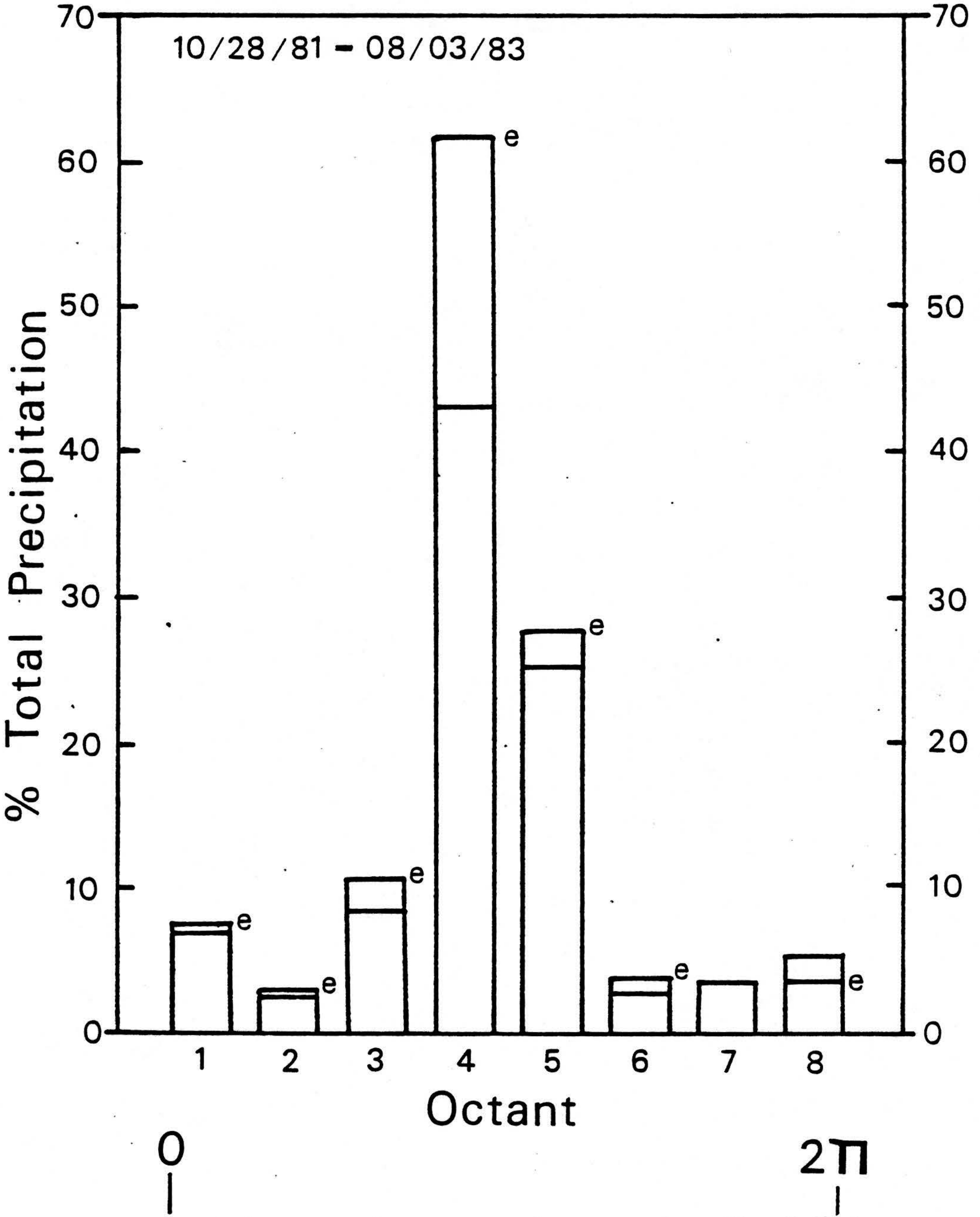

Figure 5. Precipitation, by octant (see text). The "e" denotes the value corresponding to the right vertical axis. The unlabeled value corresponds to the left vertical axis. For period 1.

of the lee shelter.

A striking contrast exists between the patterns for period 2 and period 3. The first winter period shows over 96% of the precipitation occurred during westerly events; less than 4% fell during easterly events (figure 6). During the second winter season, the proportions changed to 79% westerly versus 21% easterly, a reflection of the anomalous mean flow mentioned earlier (figure 7). Since no known surface wind record is available for the area, no direct reference can be made to the climatological average. However, since period 3 corresponds to the period during which an anomalous mean flow was observed, these results should be illustrative of the differences between the two winter seasons, with period 2 probably corresponding more closely to the climatological average.

The analysis was expanded to include certain other terms whose physical influences were thought to be important in the ultimate location of snow maxima. Terms for wind speed and precipitation amount were added resulting in a product analagous to an advective term. In this context, the term would describe the horizontal distribution of precipitation as a function of wind direction. The term was calculated for each octant by the following formula:

$$\Sigma \ (\mathrm{pr}_{\overline{V}} \ \overline{\mathrm{WVM}})_i \ \mathrm{x} \ (\text{precipitation amount})_i$$

here i is the individual precipitation event, $\overline{V}$ is the center of each octant (azimuth) and $\overline{\mathrm{WVM}}$ is the wind vector magnitude defined by $\overline{\mathrm{WVM}} = (x^2 + y^2)^{\frac{1}{2}}$, where

$$x = \Sigma \ S_i \ \mathrm{x} \sin \theta_i / n \ ; \qquad y = \Sigma \ S_i \ \mathrm{x} \cos \theta_i / n$$

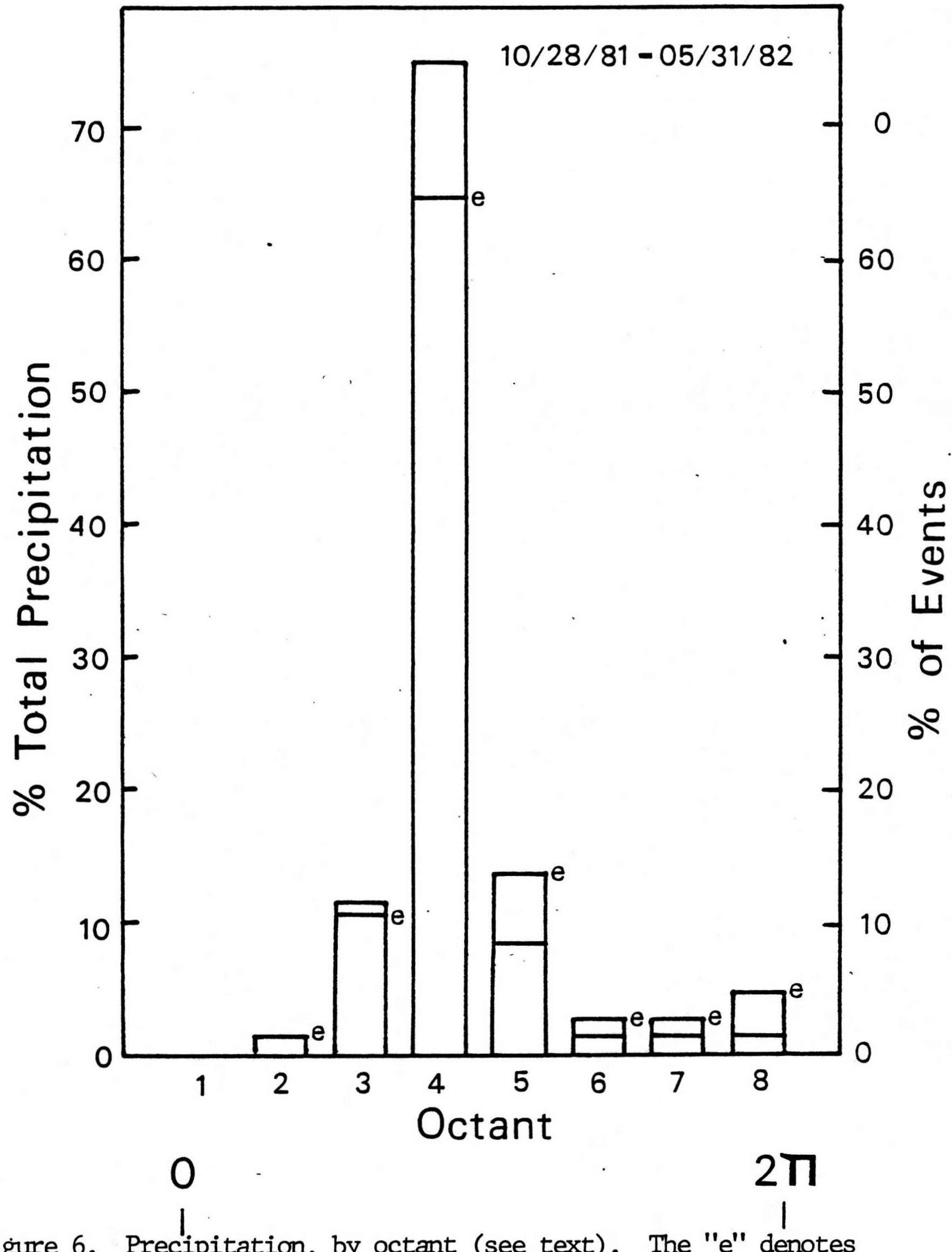

Figure 6. Precipitation, by octant (see text). The "e" denotes the value corresponding to the right vertical axis. The unlabeled value corresponds to the left vertical axis. For period 2.

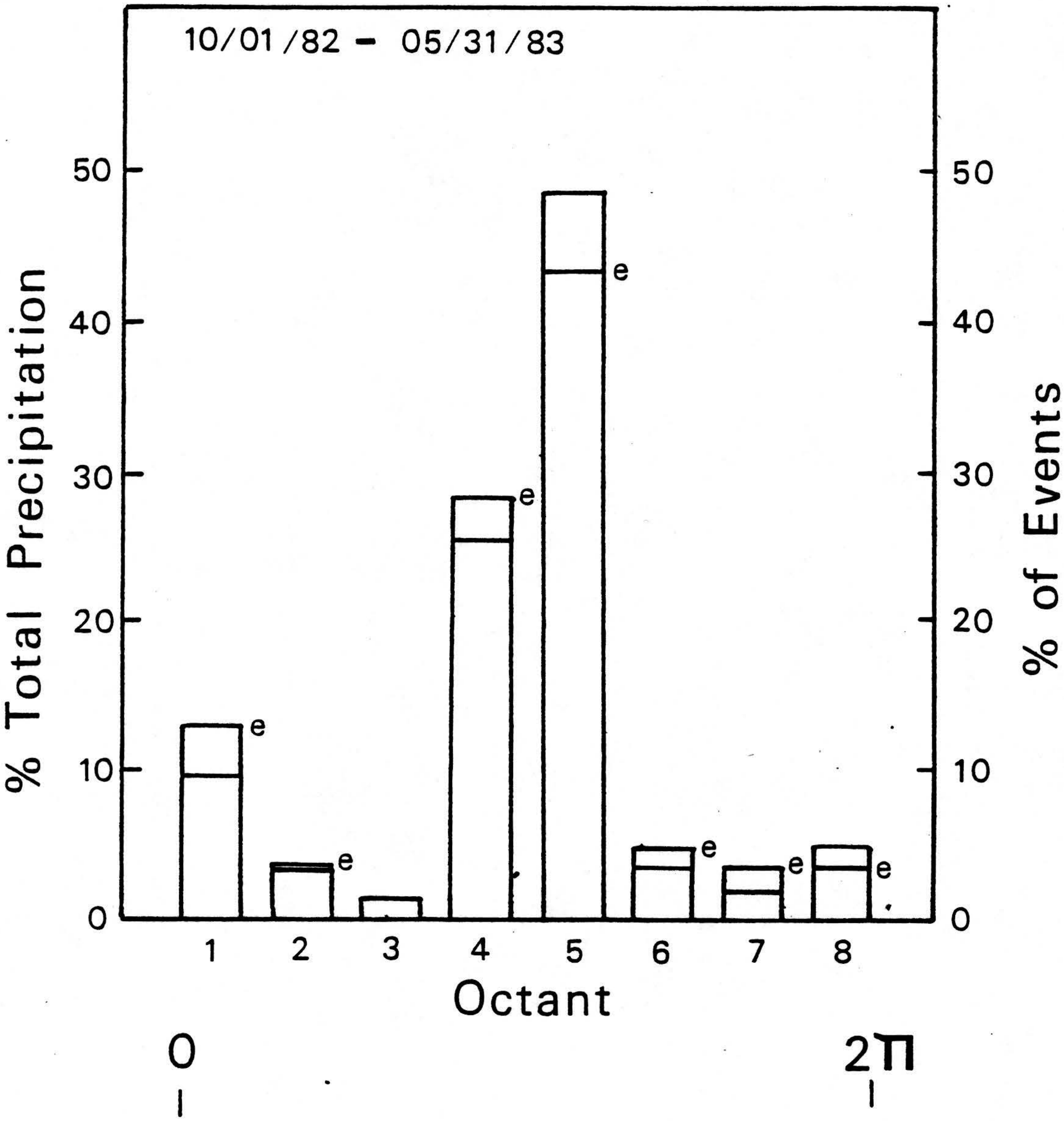

Figure 7. Precipitation, by octant (see text). The "e" denotes the value corresponding to the right vertical axis. The unlabeled value corresponds to the left vertical axis. For period 3.

..here S_i is wind speed and θ is wind direction, in radians. By projecting each wind vector onto the octant vector the mathematical result is that component of each wind event that exerts its influence parallel to the octant center. Following this line of reasoning, $\overline{\text{WVM}}$ was constrained to be > 0 relative to each of the eight octant vectors. Otherwise, negative products would have resulted. The physical interpretation of the results is aided by a careful interpretation of the vector arithmetic used in obtaining the product. The use of precipitation amount as a scalar multiplier increases the magnitude of each vector quantity without influencing its direction. The resultant scalar multiple then contains components of wind speed, direction and precipitation all three of which interact in the climatological determination of lee shelter distribution.

The results are given in table 5. Figure 8 shows a dramatic shift in the importance of wind direction with respect to precipitation amount when compared with the results presented above for period 1. Using a different graphic format, this comparison becomes even more striking (figure 9). The figures are drawn in a format similar to a wind rose. The difference here, though, is that each vector is drawn exactly 180 degrees out of phase and with the arrow pointing opposite to the direction in which the wind originates. This treatment yields insight into the effect each vector has on its opposite side of the compass. In this way, the size of each vector presented graphically indicates its degree of "leewardness". The "leewardness" of the northeast sector increases dramatically when the advective scalar multiple is plotted. The effect is probably

Table 5. Advective scalar multiples (see text).

Direction	Coefficient	% of total
SE-E	1.00	3.7
E-NE	1.33	5.0
NE-N	1.24	4.6
N-NW	3.47	13.0
NW-W	6.88	25.7
W-SW	6.89	25.8
SW-S	4.54	17.0
S-SE	1.38	5.2

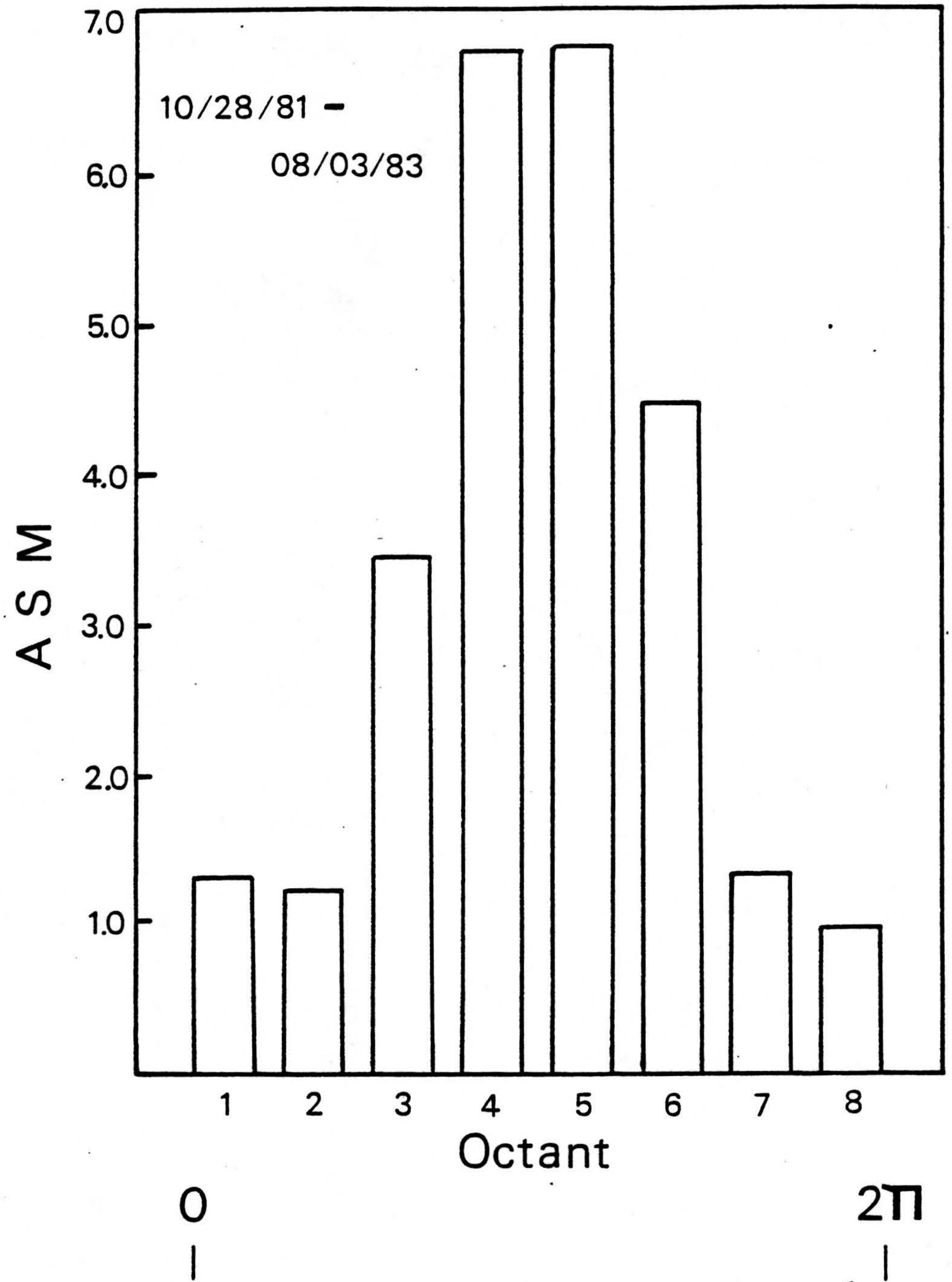

Figure 8. Advective scalar multiples, by octant. These values are relative, having been normalized on the multiple calculated for octant no. 8.

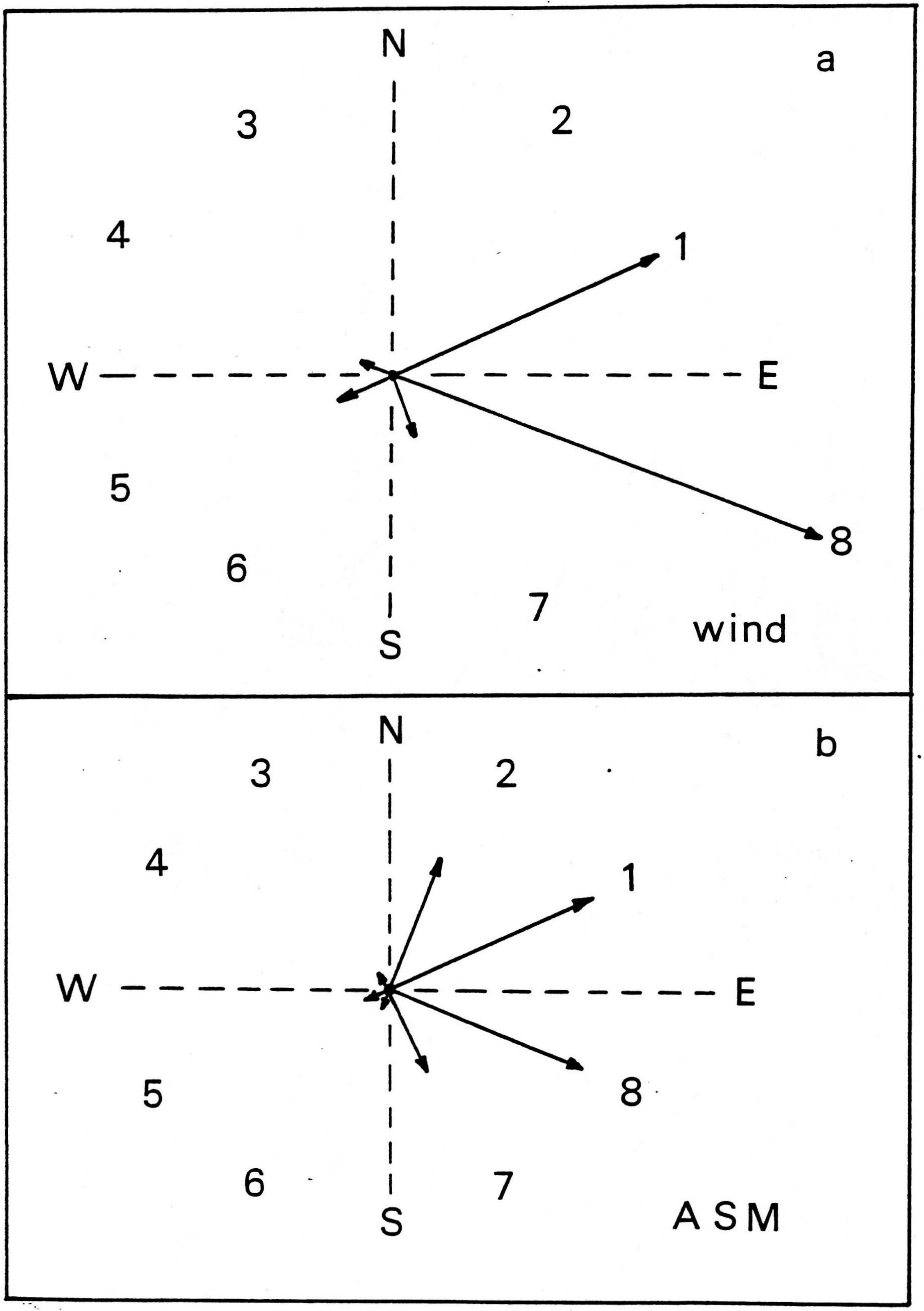

Figure 9. (a). Wind vectors plotted as a conventional wind rose; (b). Advective scalar multipes plotted in the same fashion.

only significant in the differential distribution of snow. Since snow is on the order of 1/10 as dense as rain, it is more likely to be influenced by wind. Indeed, no significant differences in catchment were observed from the windward to the leeward site when the precipitation was liquid (table 6). This analysis strongly supports the notion that moisture and hence, plant distribution is determined by the interaction of wind and topography.

Table 6. Precipitation (mm) measured at both windward and leeward sites.

	Windward	Leeward
1982		
10/7	75.7	81.3
10/12	2.0	3.3
10/21	0	0
11/3	9.1 (ice)	10.2 (ice)
11/16	5.8 (ice)	9.4 (ice)
11/24	2.0	1.0
1983		
5/26	71.0	142.0
6/6	30.0	30.0
6/15	3.6	3.8
6/27	0.5	2.0
7/7	12.2	12.7
7/13	1.5	1.8
7/18	2.5	2.8
7/27	5.3	5.3
8/4	1.3	1.3
8/9	1.3	1.5
8/15	0.5	0.4
8/22	104.1	111.5
8/31	4.6	4.8
9/8	61.2	64.8
9/15	T	T
9/23	0.8	0.8
9/28	9.1	10.2

II. Soil Temperature

Soil temperatures were measured at each psychrometer station throughout the study except during the period of December 9, 1982 through January 25, 1983. This was done either in conjunction with psychrometric measurements or, specifically, as in winter, for soil temperature data alone.

The ten psychrometer stations were evenly divided into two groups. Stations 1 through 5 were considered as representative of the windward site and stations 6 through 10 were considered as representative of the lee shelter. In every comparison but the regression analyses, all values for a given date and depth were pooled into the two groups described above. The mean values were derived from those data populations. A mean comparison test for all dates and depth was done to statistically verify the distinction, with regard to soil temperature, between "windward" and "leeward" sites. These were found to be significantly different (α=0.05). The following assumptions were made during the analytical procedures:

(1) Soil temperature was steady-state, in that each temperature was assumed to be truly representative with no regard to cooling, heating or hysteresis.

(2) Measurement of snow depth was without error, as an independent variable.

The results are given in table 7 and figures 10 and 11. Significant differences were observed on several sampling dates. A

Table 7. Soil temperatures.

(a). Mean differences between the windward and leeward sites. Negative values indicate warmer temperatures in the leeward site; positive values indicate warmer temperatures in the windward site, by date. * denotes significance >0.10.

20 cm

10/7	11/2	11/10	11/23	02/04	02/24	03/04	03/16
-.22*	.20	-1.12	-2.66*	-.94*	.08	.32*	-.50*

03/24	04/21	05/26	06/06	06/15	07/07	07/27	08/11
-.68*	-1.10*	-.16	.02	-1.04	.12	.30	1.46*

50 cm

10/7	11/2	11/10	11/23	02/04	02/24	03/04	03/16
-.86	.03	-.32	-3.1*	-.42*	-1.56*	.22	-.90*

03/24	04/21	05/26	06/06	06/15	07/07	07/27	08/11
-.38	-1.38*	.72	.28	-2.32*	-.56	-.46	1.74*

(b). Soil temperatures, all dates, by depth.

	leeward	windward	significance level
20 cm	8.42	8.06	0.10
50 cm	8.52	7.94	0.01

(c). Correlation coefficients (r) derived from regression tests between soil temperature and snow depth, by date.

	leeward	windward
11/23	.93	.84
02/04	.97	.67
02/24	.50	.32
03/04	.63	.51

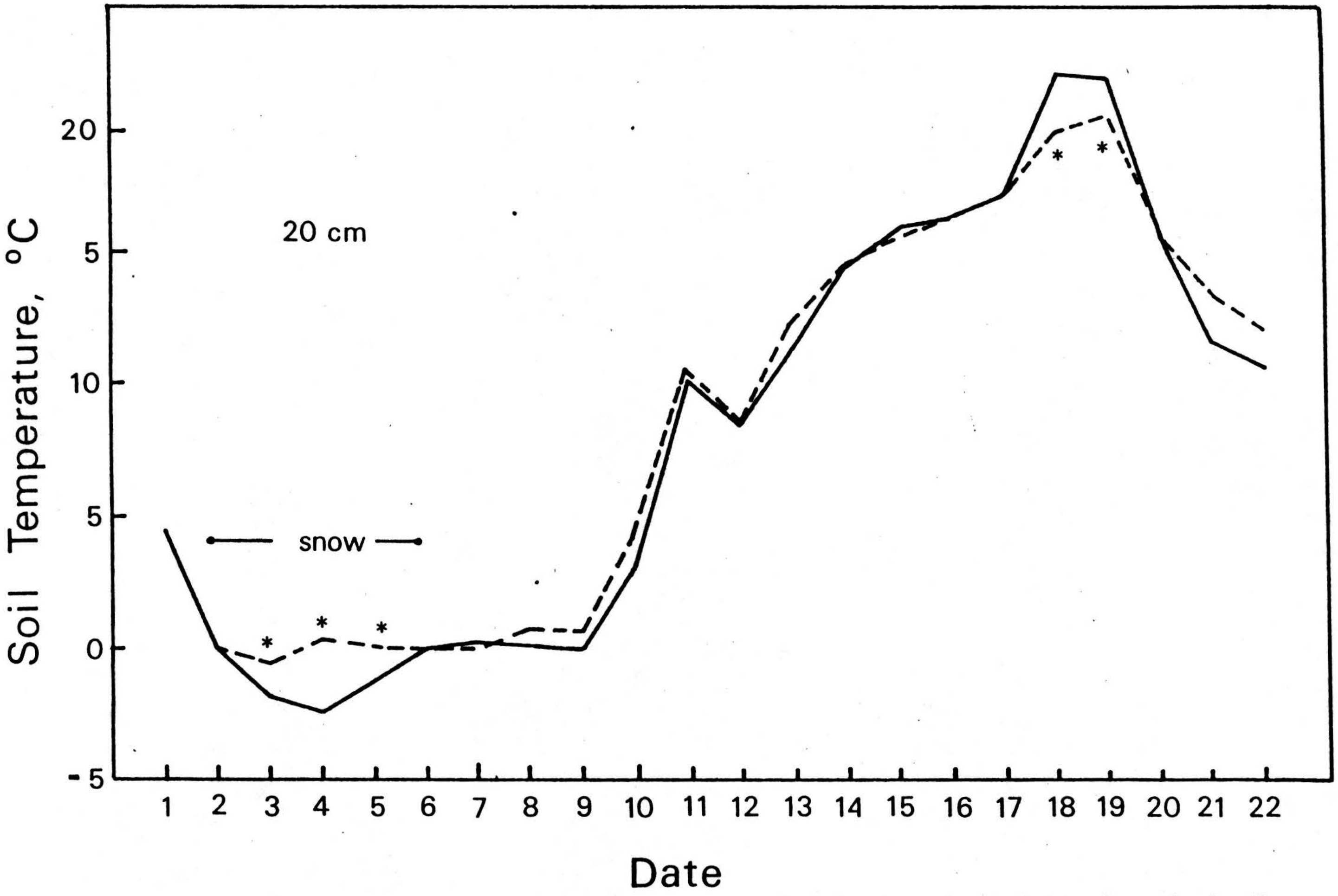

Figure 10. Soil temperature, by date, for both the windward site (solid line) and the lee ward site (dashed line). Date 1 corresponds to Oct. 7, 1982; date 22 corresponds to Sept. 29, 1983. These data were collected at approximately 10 day intervals. The * indicates significant differences at the 0.05 level or better. The presence of snow is indicated for the leeward site. For 20 cm depth.

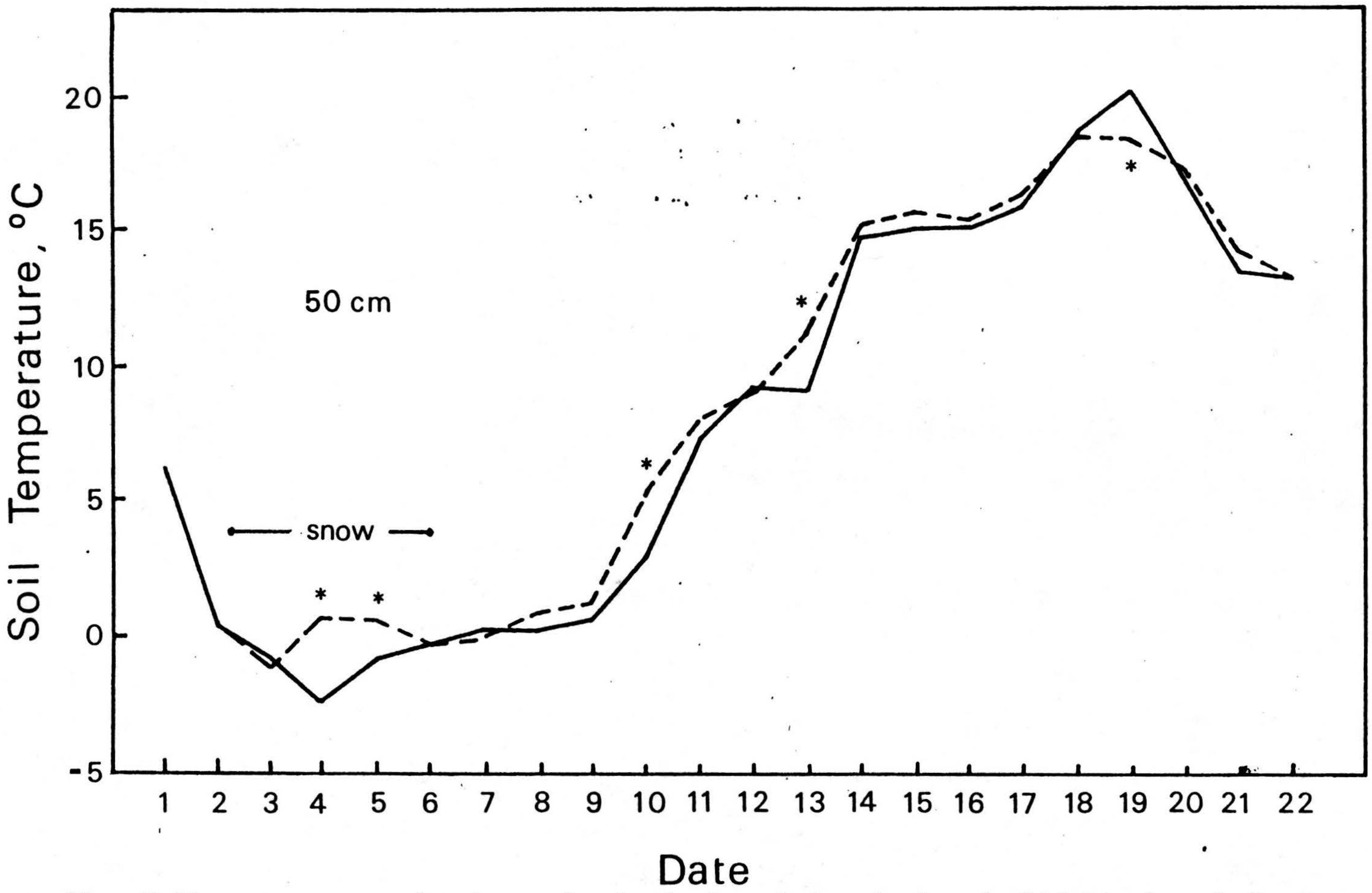

Figure 11. Soil temperature, by date, for both the windward site (solid line) and the leeward site (dashed line). Date 1 corresponds to Oct. 7, 1982; date 22 corresponds to Sept. 29, 1983. These data were collected at approximately 10 day intervals. The * indicates significant differences at the 0.05 level or better. The presence of snow is indicated for the leeward site. For 50 cm depth.

positive correlation existed between snow cover and the presence of higher soil temperatures. As can be seen, soil temperatures in the lee shelter were generally warmer in winter than those in the windward site. In summer, the reverse tended to be true. The presence of snow in the lee shelter is evidently the causal factor in the higher soil temperatures found there. Of additional interest is the direction of heat flux observed. In both sites the average heat flux into and out of the soil corresponded well with expected results. No differences in heat flux were observed from site to site, with respect to direction. However, with the presence of snow, the vertical gradient of temperature in the lee shelter was observed to be less steep than in the windward site and the mean annual temperature higher.

These results agree with theoretical expectations. The insulative property of snow is high due to its very low thermal conductivity. Even though the snow surface itself will radiate to a very low temperature, it protects the underlying surface from the same radiative heat loss. Conversely, soil temperatures were observed to fall much lower in the windward site, which was devoid of snow most of the winter.

In both the windward and leeward sites temperatures increased with depth during the winter. The direction of heat flux was from the subsoil to the surface. No significant surface heating occurs in the winter season due to the short day length and low solar angle. Although some diurnal heating may have taken place this was of no consequence since the flux was not observed at 20 or 50 cm.

The observation of dry soil on the windward site indicates that some heating did occur although the dryness may have been due, partly, to convective dessication.

The differences in soil temperatures between the two sites are probably more significant not in a numerical sense but in the fact that freezing temperatures were never observed beneath a snowpack. This fact may have beneficial implication to plant growth even though plants are normally dormant during this season. The warmer wintertime soil temperatures of the lee shelter are thought to be beneficial for the following reasons:

(1) Above-freezing temperatures minimize mechanical damage to plant parts such as roots. The absence of frost prevents the breakage and dessication associated with heaving.

(2) In the lee shelter the potential for active water uptake exists at the onset of the growing season with warmer temperatures. The sudden onset of clear weather in the Spring, with its associated warm temperatures and radiation heating, often places physical demands on a plant that simply cannot be met by one whose roots are in frozen soil. Where the subsoil is above freezing an existing plant has the ability to respond immediately to favorable growing conditions (Kramer, 1969).

(3) Warmer (above freezing) soil can accept meltwater from the snowpack as it occurs. Frozen soil could not accept meltwater, at least at the same rate, as easily as thawed soil. This would result in a potentially greater loss of soil moisture to the site due to

runoff.

(4) Microbial activity is demonstrably temperature dependent (Odum, 1969). A warmer soil, therefore, can support more activity than a cold soil. This would be especially important in the case of symbiotic, nitrogen fixing activity.

Although the foregoing discussion is speculative, at least this much can be said with certainty: there is a differential partitioning of energy from the windward site to the lee shelter between latent and sensible heat.

III. Soil Water

Soil water tensions were measured on each site visit beginning February 24, 1983, except for the following dates: April 5, 12, and 21, and May 5 and 19, 1983. For the period from February 25 to May 26 these data were collected by psychrometric means only. Beginning on May 26, soil samples were also collected for gravimetric determination of water content. A psychrometer mortality rate of approximately 25% was experienced over the season. In the following discussion, the direct measurement of soil water potential will be referred to as Ψ_w. Matric potentials determined by gravimetric means will be referred to as Ψ_m.

A. Gravimetric determination of θ_m, Ψ_m.

Differences in the predicted matric potentials from the moisture release curve determinations were observed between the leeward site and the windward site. Although general seasonal patterns emerged, there exists variability and trends that are difficult to explain. The coefficient of variation of these data approaches 50%. Several possible sources of variation can be given:

(1). Sampling scheme as related to soil variability.

Since gravimetric sampling is necessarily destructive, the same soil sample cannot be re-evaluated over time, nor the same region re-sampled. On the basis of bulk density values gathered on June 6 (table 8) and other data (to be presented later) there appears to be a great deal of variability in this soil even over a horizontal distance of only 2 m. Given these two conditions spatial variability in water content data from this soil is not surprising.

Table 8. Bulk densities, by station and depth.*

Depth, cm	1	2	3	4	5	6	7	8	9	10
20	1.34	1.31	1.29	1.19	1.27	1.19	1.23	1.34	1.30	1.36
50	1.38	1.26	1.22	1.33	1.33	1.26	1.41	1.33	1.33	1.30

* determined by the method described in Hanks, 1980.

The heterogeneity of the soil is related to differences in soil morphology, constituency and topsoil thickness. There are probably differences in the substrate characteristics as well. During spring and summer of 1982 these differences could be seen visually as differences in plant patterns. In terms of both vigor and species composition these differences were observed to occur at quite regular intervals which appeared to correspond with the reclamation technique in terms of machinery width, driving patterns, etc. In view of these considerations, the apparent randomness in the data achieves some degree of systematics. Even so, these errors are not addressed directly due to the lack of data necessary to evaluate these parameters.

(2). Sample handling.

In the typically arid environment of the study site, moisture loss from soil samples was certainly a source of error. This error, however, is felt to be minimal. Also, since every soil sample was handled in the same manner and by the same person, the variability of this error should be small. The actual time the soil was exposed to the environment was on the order of 1 minute. This type of error should have been more evident in the handling of wet samples where extraction of the sample from the soil auger is more tedious and it is therefore exposed to the environment for a longer time period. The bulk of the variability due to this type of error was observed during the latter part of the season when the soil horizon was quite dry. It is noted here that a small difference in water content will result in a correspondingly much larger difference in moisture tension due to the non-linearity of the tension-release curve. This is particularly true as one approaches the dry end of the curve.

(3). Data handling.

The process of predicting moisture tension from moisture characteristic relationships involves the juxtapostion of two data sets, each with its own inherent error. The laboratory procedure for obtaining soil water potential is subject to similar hazards as described above for obtaining gravimetric water content. An additional error is introduced when these two data sets are subjected to various curve fitting analyses. Although most of the curve fittings performed well, with very good results for r^2 and MSE (see table 9)

Table 9. Regression parameters by station and depth, by least squares method. All curves were quadratic.

Station	Depth cm	R^2	a	b	c	s	MSE
1	20	93.7	-74.1	5.49	-0.100	2.92	4.03
	50	87.2	-115.0	11.00	-0.241	4.16	7.77
2	20	99.9	-87.5	6.24	-0.112	0.26	0.04
	50	99.4	-77.5	5.37	-0.094	0.93	0.23
3	20	97.5	-61.4	4.19	-0.071	1.86	1.74
	50	86.0	-94.2	6.63	-0.115	4.36	9.39
4	20	79.4	-196.0	17.30	-0.377	5.29	15.79
	50	97.4	-133.0	10.40	-0.204	1.88	4.54
5	20	98.1	-105.0	7.85	-0.146	1.62	1.37
	50	99.3	-124.0	9.39	-0.179	0.98	1.17
6	20	83.2	-98.3	7.75	-0.148	4.77	11.40
	50	96.0	-77.8	5.67	-0.103	2.32	2.82
7	20	67.2	77.0	6.21	-0.124	6.67	23.21
	50	98.4	-87.4	6.31	-0.114	1.49	0.71
8	20	98.8	-59.0	4.41	0.082	1.28	0.71
	50	99.9	-75.8	5.27	-0.092	0.33	0.07
9	20	95.4	-61.6	4.82	-0.094	2.51	3.16
	50	78.3	-69.5	5.94	-0.125	5.42	15.00
10	20	84.5	-105.0	9.61	-0.203	4.59	10.61
	50	87.6	-140.0	11.50	-0.228	4.10	7.01

the predictive capacities of such generated equations are known to be limited. Extrapolation beyond the original data set is tenuous at best. Since the driest (most negative) moisture tension duplicated in the laboratory was -15 bars, values extrapolated to drier tensions should be regarded with care. To illustrate the nature of this extrapolation the reader is referred to table 10 which contains confidence intervals by date and station of the eight best curve fits obtained. The confidence interval for new (extrapolated) values is given by:

$$\hat{Y}_h - t(1-\alpha/2;\ n-2)\ s\ (\hat{Y}_h) = E\ (Y_h) = \hat{Y}_h - t(1-\alpha/2;\ n-2) s(\hat{Y}_h)$$

$$\text{where}\quad s^2\ (\hat{Y}_h) = \text{MSE}\ (1/n + \frac{(X_h - \bar{X})^2}{\Sigma\ (X_i - \bar{X})^2}$$

Differences in soil characteristics from site to site are manifest in the moisture characteristic curves. Figures 12 and 13 illustrate these differences as well as the variability within both the windward and leeward sites. Topsoil thickness generally increased from station 1 in the windward site to station 10 in the leeward site. Presumably, the windward site (stations 1 to 5) contained more subsoil per sample while the leeward site (stations 6 to 10) contaned more topsoil. The respective curve fits were found to be significantly different ($\alpha = .0005$).

The differences between the windward and leeward sites are shown graphically in figure 14. As was mentioned earlier, there appear to be seasonal trends in the data in both the leeward and windward sites. At 20 cm, matric tensions were significantly lower ($\alpha =$

Table 10. Confidence interval (in -bars), for stations and depth where MSE ≤ 2.0, by date

Station	Depth cm	Date 1	2	3	4	5	6	7	8	9	10	11	12
2	20	0.66	0.66	0.66	0.91	0.99	0.89	0.87	1.04	1.03	0.96	0.74	0.73
2	50	1.57	1.61	1.61	2.03	1.68	2.06	1.71	1.82	1.78	1.88	1.73	1.65
3	20	4.35	4.37	4.40	4.58	4.73	4.65	4.94	5.56	5.41	5.36	4.47	4.43
5	20	3.84	4.10	4.23	4.90	4.58	4.67	4.51	4.41	5.78	5.74	4.02	4.06
5	50	3.55	3.54	3.89	6.05	5.99	5.54	5.09	4.64	7.01	5.28	3.03	3.71
7	50	2.76	2.75	2.90	3.06	4.08	3.55	3.35	3.68	4.32	3.88	2.88	2.80
8	20	2.76	2.76	2.77	2.91	3.60	3.19	2.99	3.34	3.01	3.16	2.87	2.80
8	50	0.91	0.86	0.90	0.99	1.08	1.20	1.16	0.97	1.05	1.08	0.90	0.91

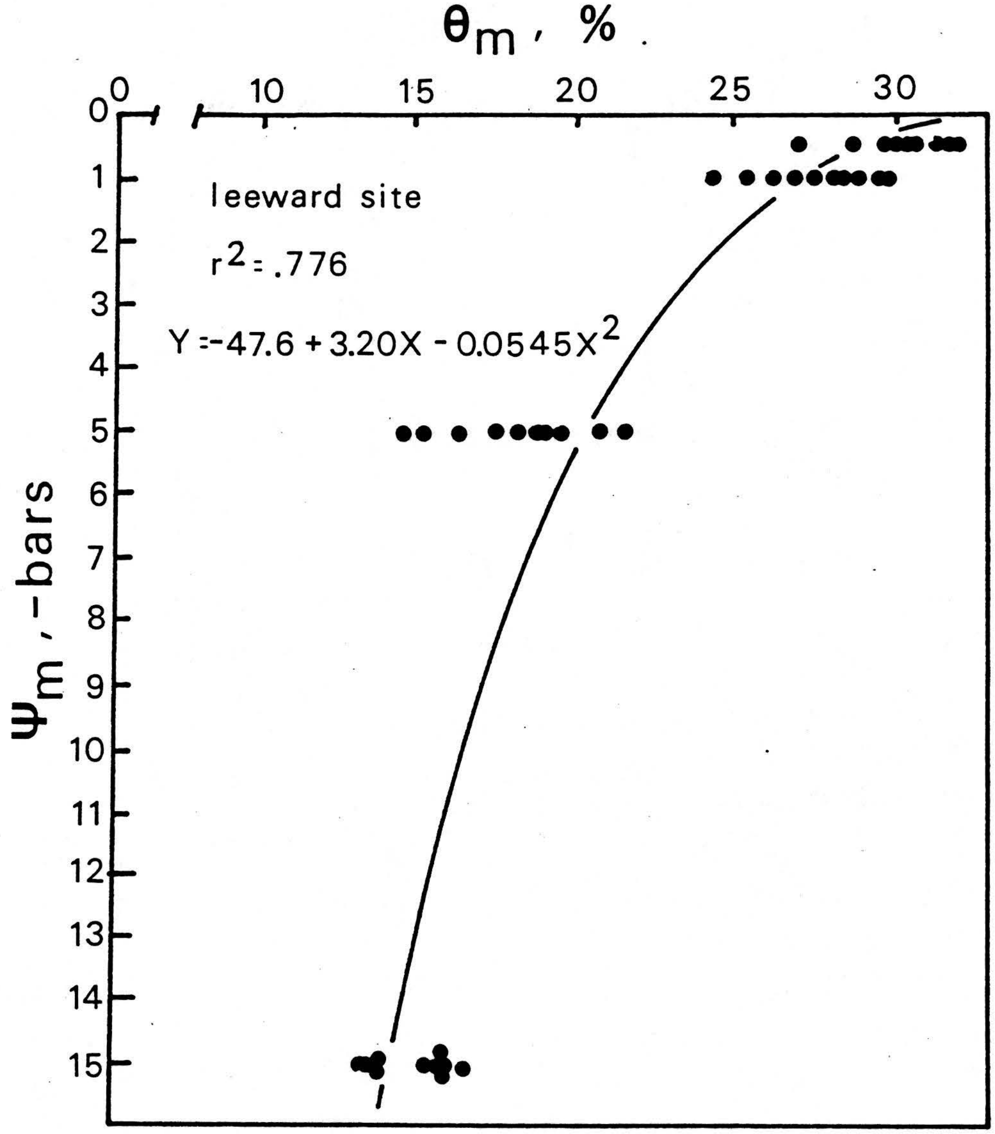

Figure 12. Generated moisture release curve for all sampling locations, at both 20 and 50 cm depths, for the leeward site.

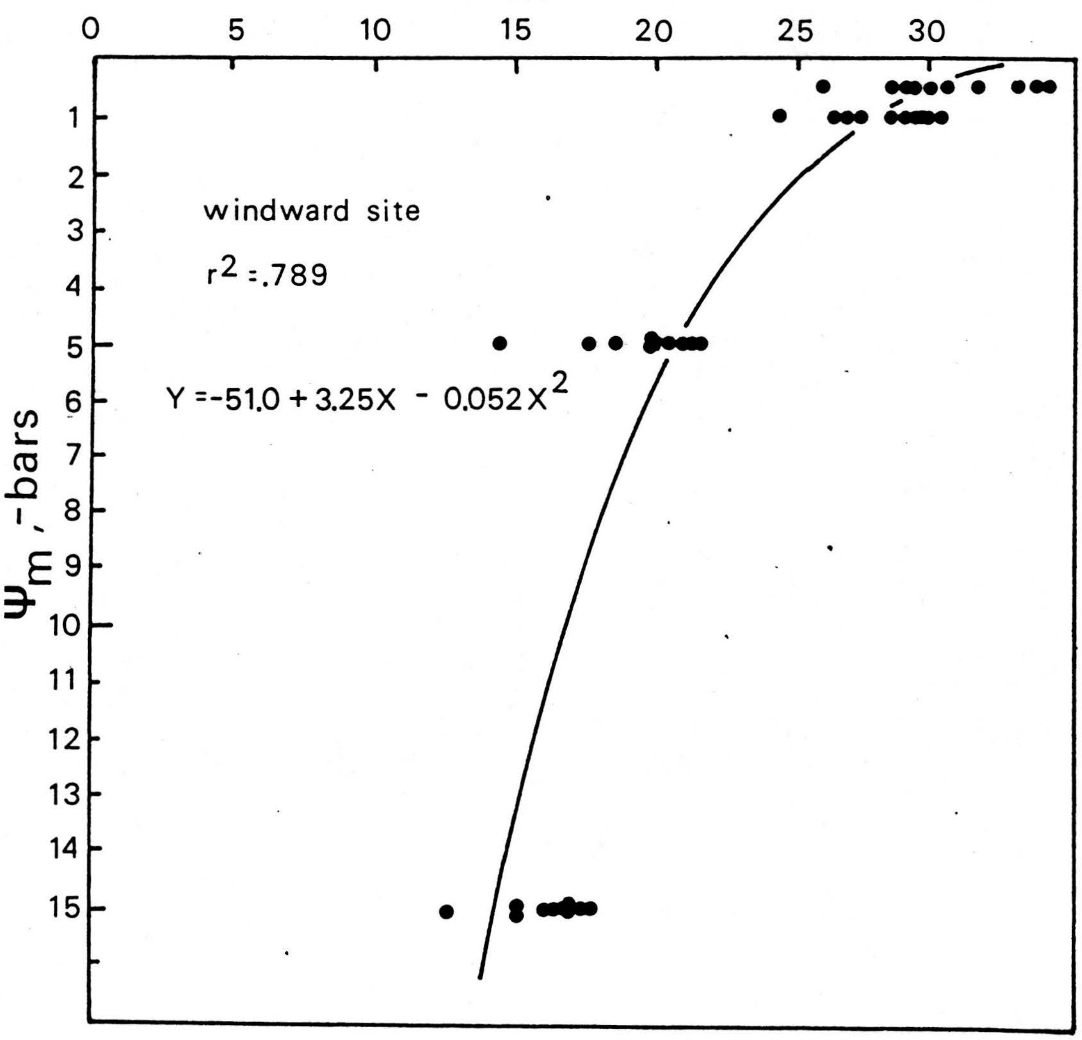

Figure 13. Genrated moisture release curves for all sampling locations, for both 20 and 50 cm depths, for the windward site.

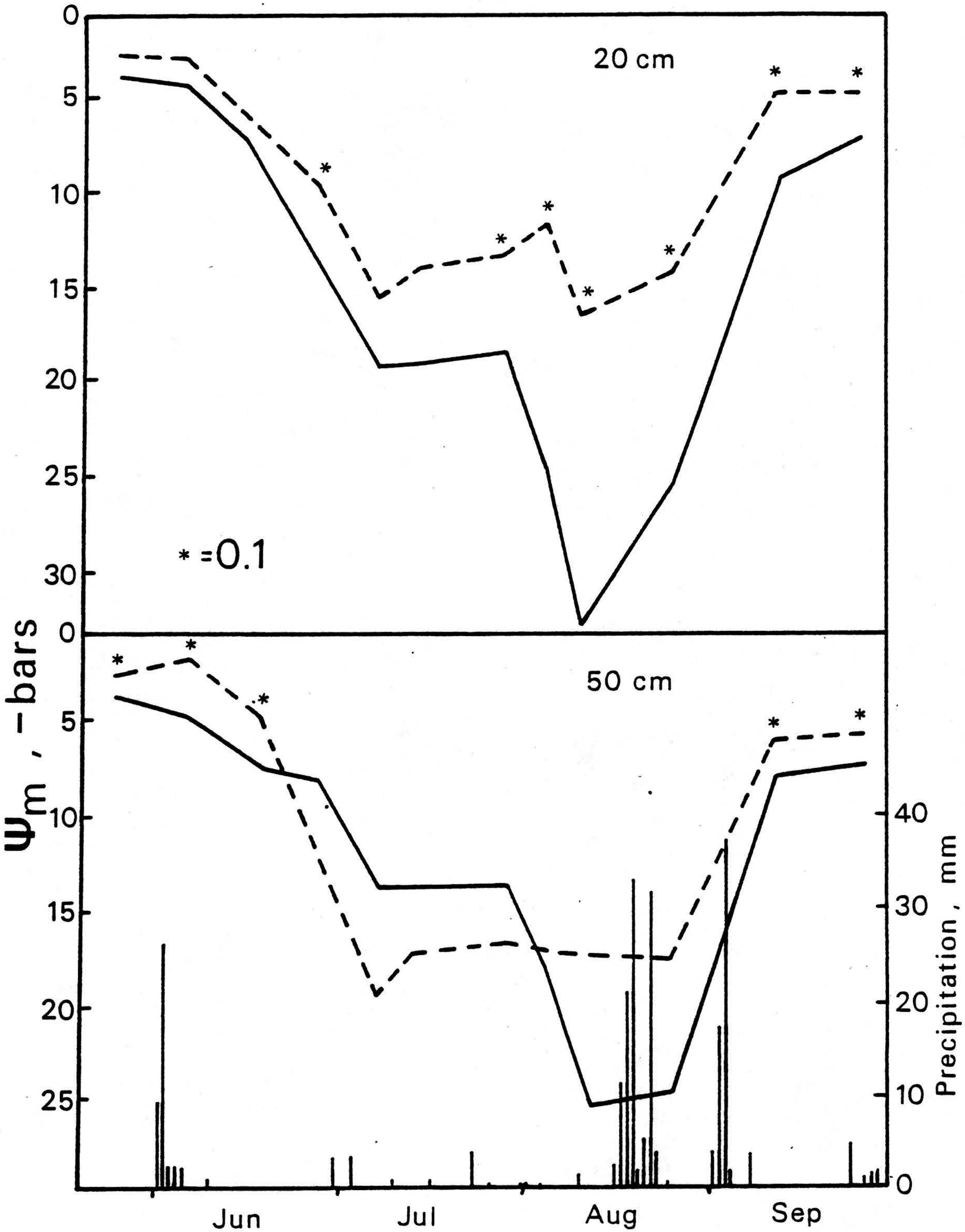

Figure 14. Seasonal march of soil matric potential determined by the moisture release curve method. The leeward site values are denoted by the dashed line; the windward site values are denoted by the solid line. The precipitation measured at the two sites over the same period is superimposed.

0.1 or better) for seven out of the twelve sampling dates. No explanation is offered for the upward trend at 20 cm for the period from July 7 to August 14. Natural vegetation was allowed to flourish on the transect until July 13 at which time it was removed. Since more vegetation existed in the leeward site than in the windward, the curves illustrate some rather surprising results. Aside from evaporation and drainage, the only other major mechanism for water removal from the soil (plant growth) should have caused greater water depletion in the leeward site than in the windward site. This was observed to occur at 50 cm and not at 20 cm. Invading pioneer species may be well adapted to rapid root penetration into the subsoil where soil water is more tenacious, and less subject to evaporation and dessication by surface phenomena. There is, however, no evidence in the literature to corroborate this. Table 11 shows the plant species observed on the transect within a 1 m radius of each psychrometer station.

In terms of initial plant establishment, germination, etc., the most striking differences are those observed at the very early part of the growing season. If differences due to site do exist, this period of time is thought to be of critical importance in an ecosystem where plant growth is constrained in an environment typically either too dry or too cold.

B. Psychrometric determinations of Ψw

The results presented in part A are not well corroborated by similar measurements made by thermocouple psychrometers. Early sea-

Table 11. Plant species observed on July 13, 1983, within a 1 m radius of each psychrometer station along the transect.

Station #	Species	Number of Individuals	Height
1	Lactuca spp.	10	25-30 cm
	Agropyron spp.	1	60
	Bromus tectorum	1	15
2	Lactuca spp.	9	30-40
	Liarifolium spp.	2	40
	Bromus tectorum	5	15
3	Salsola kali	13	2-5
4	Agropyron spp.	1	50
	Hordeum jubatum	2	40
	Bromus tectorum	4	15
5	Liarifolium spp.	1	60
6	Liarifolium spp.	>25	50-100
	Agropyron spp.	>10	50-75
7	Liarifolium spp.	>25	50-100
	Agropyron spp.	>10	50-75
8	Liarifolium spp.	>25	50-100
	Agropyron spp.	>10	50-75
	Hordeum jubatum	1	60
9	Hordeum jubatum	8	40-60
	Thlaspia arvense	>25	25-40
10	Salsola kali	>25	5-10

son readings showed a drier horizon in the windward site than in the leeward site. Assuming the data is representative of actual moisture tensions, this seems plausible. However, since soil temperatures in both sites were very near freezing the reliability of the measurements is suspect, having been made at the very fringe of instrument design limits. Obviously, lower water tensions would be expected in a frozen soil than in a thawed soil.

The tremendous variability of these data make analysis difficult. With gravimetric determinations as a basis for comparison the psychrometer data follow no similar pattern. At 20 cm, the data show the windward site to be wetter except on three sampling dates. In fact, the windward site was found to be wetter on every date where differences were significant at the 10% level or better (figure 15). The question then arises as to which data set is to be taken as more representative of actual soil conditions. The following discussion will address this point. In the same format as was applied to the variability of the gravimetric data, the possible sources of data variability in the psychrometric data are given.

The sources of variability in these data are:

(1). Faulty instrumentation or calibration.

The direct measurement of water potential involves the measurement of two variables that are known to be both spatially and temporally transient. The quantity, Ψ_w, is given by:

$$\Psi_w = R\,T / V_m \ln (e/e_s)$$

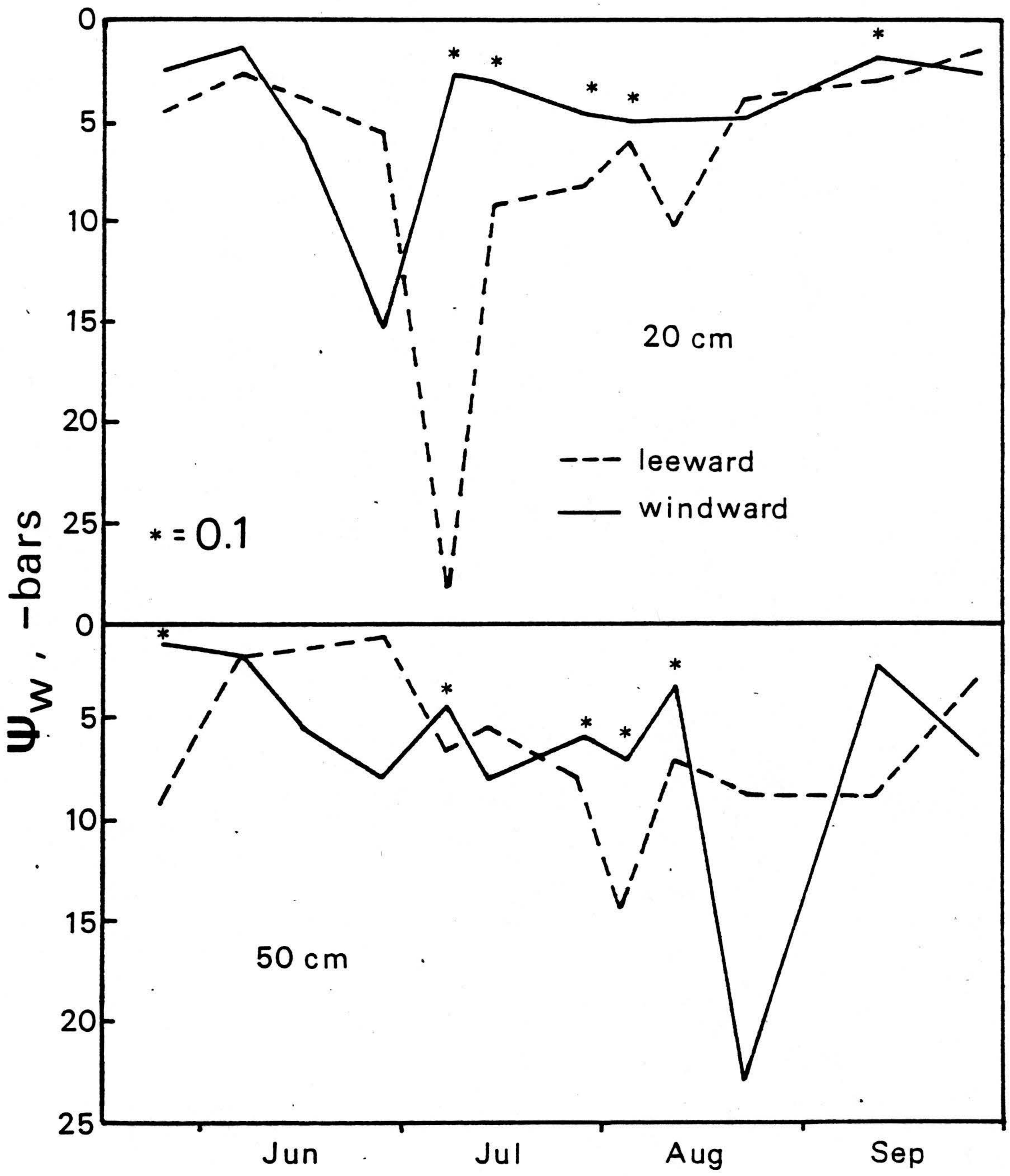

Figure 15. Seasonal march of total water potential as measured by thermocouple psychrometer. The * denotes statistically significant differences at the 0.10 level or better. For both 20 and 50 cm depths in both the windward and the leeward sites.

where: Vm is molar volume of water, R the universal gas constant, T temperature (K), e and e_s, vapor pressure of the ambient air (in this case, soil air) and saturated vapor pressure, respectively, both at temperature T. For e/e_s nearly 1, $\ln(e/e_s) \cong (e/e_s - 1)$. So, for $e/e_s \cong 1.0$:

$$\Psi_w \cong R\,T / V_m\ (e/e_s - 1)$$

The role of the thermocouple psychrometer is to evaluate (e/e) electrically and produce an output for conversion to Ψ_w. In application, certain problems have, historically, been encountered. These are due to the fact that (1) over the wet range of -15 bars $< \Psi_w < -0$ bars the actual vapor pressure difference between ambient air and saturated vapor pressure is very small. These minute differences must be measured with a precision that is often difficult to achieve in the field. Related to this, vapor pressure is known to be a strong function of temperature. This leads to (2) the fact that temperature must be controlled or, at least, very precisely monitored. To help offset or avoid additional error, precise calibration under controlled temperature conditions has become standard practice. The calibration process yields an "ideal response" under known conditions that provides a basis for comparison with field data. The psychrometers used in this study were all calibrated using a standardized technique. In addition, a calibration model (Brown and Bartos, 1982) recently developed for temperature correction considerations was applied in the data reduction. Instrumentation was purchased new in 1983. Although no operator calibration was done, the readout device was assumed to be operating at manufacturers specifications.

(2). Operator error.

Psychrometric measurements are traditionally taken just prior to sunrise when the soil is known or assumed to be in approximate thermal equilibrium. Any heat flux present can be measured directly as a temperature gradient within the psychrometer itself. These gradients are usually referred to as "zero offset". The psychrometer measurements taken in this study were done midmorning (approx 1000 hrs). As shown in table 12, zero offset was rarely found to be significant. This may be due to the fact that the daily heating "front" had simply not reached the measured depths by 1000 hrs on most days. This was enhanced by the good fortune of having overcast skies on several sampling dates. When zero offset was a high value, the reading was discarded and not used in the mean value calculations for the given sampling date. Most zero offset values appeared to be randomly distributed while a few (see 8-50, 9-50 and 9-D) seemed to have some regularity, perhaps due to faulty psychrometer construction or installation or because of poor meter operation. Either equipment malfunction is of equal probability.

(3). Soil variability.

As discussed earlier, the heterogeneity of the soil is apparently high. The bulk density and moisture characteristic curves bear this out. Another soil parameter has also been found to exhibit a high degree of variability. In soil samples taken from topso-

Table 12. Psychrometer zero-offset readings in microvolts. Missing values were due to either faulty connectors or psychrometer mortality. Some psychrometers appeared to be simply intermittent.

Station	Depth	Date 1	2	3	4	5	6	7	8	9	10	11	12
1	20	3.0	0.8	-4.6	-14.8	-4.7	-2.0	-8.1	-1.1	-6.8	0.7	-0.5	--
	50	0.7	--	1.2	4.6	1.6	3.6	-8.2	-1.1	1.2	--	--	--
	D	--	--	0.9	--	-0.9	0.7	-1.4	--	--	--	--	-1.2
2	20	4.8	6.6	-2.8	0	-7.8	2.0	3.0	4.2	2.4	4.4	-0.7	-10.1
	50	6.0	15.3	9.3	-7.1	1.2	-4.7	-1.9	-0.9	-4.6	-0.8	0.1	-1.5
3	20	0.9	0.3	17.0	--	4.8	-2.4	-0.2	2.8	--	-2.8	0.3	--
	50	2.1	3.5	2.9	-0.0	-5.9	-3.3	-7.7	-16.3	-4.6	-29.8	-0.8	--
	D	2.3	--	--	-1.2	0	-3.2	-3.4	1.2	1.2	-4.7	-0.7	-19.4
4	20	6.3	0.8	1.2	--	--	0.7	3.9	--	-21.8	1.2	--	--
	50	5.9	1.5	45.3	-1.9	0	22.2	1.7	1.5	--	-4.1	0.2	--
5	20	2.4	1.7	1.1	-1.2	-2.0	-0.3	-7.7	-16.9	--	-0.2	--	0.8
	50	3.6	0.3	-0.6	3.5	2.6	2.0	--	0.6	--	1.2	-0.8	-0.8
	D	1.6	1.8	1.5	-3.7	-8.2	0.3	-4.4	-3.5	-2.8	3.9	1.0	--
6	20	2.9	0	-0.4	0	-1.4	1.4	1.7	2.3	1.7	0.1	-0.9	-0.6
	50	1.8	1.6	-1.3	-1.0	-2.4	-2.0	1.0	-1.1	-4.1	-0.8	-1.0	--
7	20	0.1	0.9	0.8	-0.8	-0.7	-0.7	-1.2	0	0.5	0	0	0.8
	50	3.6	3.7	-0.9	-0.5	-2.1	-2.6	2.3	-3.2	-2.6	-2.3	1.1	-14.3
8	20	0.8	-0.6	1.0	1.0	-17.5	-0.7	-0.9	-2.9	-4.3	2.7	-0.3	1.3
	50	5.9	7.6	4.5	-6.5	-6.9	-10.7	-3.9	-33.0	--	1.0	1.1	-3.0
9	20	2.0	1.2	-1.1	-1.2	-2.3	-1.2	1.0	-1.8	-0.4	-8.5	-0.8	--
	50	1.3	1.0	-0.4	1.0	0.7	0.3	0	-0.3	-1.4	-1.4	-0.1	1.0
	D	6.1	5.7	5.9	-5.0	-8.6	-8.3	-3.1	-4.2	-3.4	--	2.1	-1.0
10	20	0.6	-0.2	2.1	-0.6	10.5	0.5	-1.1	1.2	0.5	--	-1.2	--
	50	3.8	2.6	1.1	-2.4	1.6	-6.5	-5.2	-14.6	-5.5	-4.2	0	--
	D	7.8	3.2	31.	0	3.5	-2.4	--	-2.4	0.8	--	1.7	--

ils adjacent to the study site, the sum of exchangeable cations was found to range from 6 to 118 meq/100 g soil. The importance of this is obvious since:

$$\Psi_w = \Psi_m + \Psi_s + \Psi_p$$

where: Ψ_m is matric potential, Ψ_s is solute potential and Ψ_p is pressure potential. Ψ_p is assumed to be 0 under conditions less than saturated. Ψ_s, on the other hand, cannot be neglected unless it is known to be insignificant. When the sum of exchangeable cations exceeds a value of 4 meq/100 g their effect on matric potential becomes important (Jurinak, 1983) since:

$$\Psi_s = EC\ (\ 0.36\ )$$

where: EC = sum of exchangeable cations / 10. The average EC value for these data was 3.9 with a coefficient of variation of 55%. It must also be recognized that the effect of solute potential is not constant over a range of moisture contents. As the soil dries, the relative concentration of dissolved salts goes up approximately linearly. Electrical conductivity also responds approximately linearly to the drying of the soil. The contribution of solute potential to total water potential becomes increasingly important upon drying. For example, at field capacity of a soil with a bulk density of 1.35 g cm^{-3} and a 0.2% salt content the contribution of solute potential to Ψ_w is -4.3 bars for a total Ψ_w of -4.6 bars. At a θ_m of 15.25%, Ψ_w goes to -14.3 bars with a solute component of -7 bars. Although the psychrometer responds to Ψ_w as does a plant, large discrepancies between water potential measurements and matric potential determinations arise since the laboratory determination of matric potential does not account for sample differences caused by dissolved salts. Keeping in mind that

$$\Psi_w = \Psi_m + \Psi_s + \Psi_p$$

total water potential and matric potential are not equivalent tensions unless solute and pressure potentials are zero. Since exchangeable cation determinations were not made on the soil samples taken directly from the study site no direct correction can be applied to the existing psychrometric data. The above observations, however, illustrate the importance of such data and are certainly worthy of consideration in assessing posssible sources of variability in the existing data set.

(4). Sampling scheme.

As effective sample size decreases, expected variability increases with most types of data. Assuming that the soil at the study site is both horizontally and vertically heterogeneous, a comparison between sampling schemes of both ψ_w and ψ_m is appropriate. By design, the thermocouple psychrometer samples a very small region of the soil profile. To minimize thermal effects, psychrometer designers have miniaturized the device to an extent that effectively renders it a "point source" instrument. In contrast, the determinations of were done on soil volumes that exceeded 200 g (dry weight). The relative disparity in these sample sizes may very well account for much of the discrepancy between and as well as the absolute variability of ψ_w.

(5). Insensitivity.

As was mentioned earlier, the effective range of sensitivity of the thermocouple psychrometer definitely tends, from an agricultural perspective, towards the dry end of the soil moisture spectrum. This fact, incidentally, is what particularly suits the psychrometer to arid land research. From the data shown in table 13, it can be seen that over half of the soil water measurements taken at the site by gravimetric means yielded Ψ_m values between 0 and -15 bars. This particular season's wet soil horizon may have aggravated the data variability problem since actual soil moisture was often in the range of maximum psychrometer insensitivity.

Summary

From the gravimetric determinations of soil water and the corresponding predicted values of soil matric potential, the leeward site appears to be the wetter. The results obtained by thermocouple psychrometer do not corroborate this. Based on the results and discussion presented above the conclusion was made that the gravimetric data are more representative of actual field conditions. This conclusion is supported by the comparison of statistical variability between the two data sets (table 13). There appear to be more possible sources of error in the psychrometric data and, hence, more variability. Table A1 (see appendix) contains the unprocessed psychrometric field data used in this study.

Based on the gravimetric determinations, there appears to be a cause and effect relationship between soil moisture and the previous presence of snow. Since a strict hydrology of the site was not done, however, it must be kept in mind that there could be other mechanisms that would bring about a similar pattern. Since the leeward site is lower in elevation than the windward site, drainage is a legitimate possibility.

Table 13 Means and standard deviations, by date, comparing direct psychrometric instruments and predicted water potentials from moisture characteristic curves. w = windward, l = leaward. All values are negative (-)

	Depth cm		5/26		6/6		6/15		6/27		7/7		7/15		7/27		8/4		8/11		8/24		9/11		9/24	
			w	l	w	l	w	l	w	l	w	l	w	l	w	l	w	l	w	l	w	l	w	l	w	l
$\overline{\psi}_w$	20	$\overline{\chi}$	2.4	4.7	1.6	2.8	6.0	3.9	15.4	5.7	2.6	28.1	3.0	9.3	4.6	8.1	5.0	5.8	26.0	10.0	4.7	3.9	1.7	2.8	2.4	1.4
		s	3.6	7.7	1.7	1.9	6.0	7.3	25.5	7.3	3.1	19.3	1.9	9.6	3.0	7.4	4.5	8.8	30.7	11.0	5.1	3.4	0.9	0.4	1.1	1.1
	50	$\overline{\chi}$	1.3	9.3	2.0	2.1	5.3	1.7	8.0	1.0	4.4	6.4	7.9	5.3	5.6	7.9	6.7	14.4	3.2	7.0	23.0	8.8	2.4	8.7	6.8	3.0
		s	1.1	13.5	1.8	2.1	7.8	1.8	7.6	0.6	6.5	7.2	13.0	8.0	3.0	6.4	7.0	10.9	0.6	10.9	31.5	10.1	1.8	2.7	6.0	3.1
$\overline{\hat{\psi}}_w$	20	$\overline{\chi}$	3.7	2.5	4.1	2.9	7.0	5.7	13.8	9.5	19.2	15.5	19.0	14.1	18.4	13.3	24.5	11.7	33.0	16.3	25.5	14.0	9.1	4.8	7.2	4.8
		s	2.0	1.7	2.7	2.2	2.5	2.2	9.6	8.6	8.1	6.9	8.6	3.4	5.6	4.4	7.4	5.0	13.3	9.8	7.1	4.5	4.2	1.6	2.4	1.6
		$\overline{\chi}$	3.5	2.4	4.8	1.8	7.3	5.0	8.0	11.9	13.8	19.5	13.8	17.2	13.8	16.8	18.2	17.1	25.5	17.7	25.0	17.7	7.7	6.0	7.2	5.8
		s	1.4	1.1	1.4	1.5	1.5	1.8	4.6	4.1	4.2	10.9	7.6	6.8	6.3	8.9	7.3	9.2	17.3	12.5	15.4	9.8	2.8	2.8	1.9	1.9

$\overline{CV}_{\overline{\psi}_{w20}} = 102\%$

$\overline{CV}_{\psi_{m\,20}} = 46\%$

$\overline{CV}_{\overline{\psi}_{w50}} = 98\%$

$\overline{CV}_{\psi_{m50}} = 47\%$

IV. Turbulence.

A. Theory.

A measure of turbulence can be expressed by the parameter of friction velocity. From micrometeorology, the neutral logarithmic wind profile is given:

$$\delta u / \delta z = u_* / k\, z \qquad (1)$$

where u is average wind speed at height z, k is von Karman's constant (= 0.4), and u* is friction velocity. Friction velocity is a function of u, k, and a "hidden" height parameter, z_o. Upon integration, the "log law" becomes

$$\bar{u}(z) = u_* / k \ln (z/z_o) \qquad (2)$$

where z_o is a constant of integration. z_o is related, but not equal, to the height and spatial density of the roughness elements (plants, etc). It can, however, be defined as the height at which the neutral logarithmic wind profile extrapolates to zero. Since the logarithmic profile theory was developed for use over horizontally homogeneous surfaces, the use of it here represents a major departure from rigorous convention. In fact, a major assumption upon which the logarithmic profile theory was developed has been violated. Even if one assumes the windward site in this study to be under the influence of a homogeneous horizontal flow the lee shelter cannot fall under the same assumption since it is located downwind of the windward site, in the wake of the higher topographical feature. In view of this fact, the calculation of friction velocities that follow very likely result in some relative measure of the turbulence structure, but should not be regarded strictly as friction velocities, per se. However, in order to apply the logarithmic wind profile theory to the comparison between these two sites, one must determine some physical meaning for z_o. Here, the implication is that z_o is related to both plant and topographic features as roughness elements.

From (2) one can solve for u_*. This parameter is also known, from fluid dynamics, to be directly proportional to τ, the surface shearing stress:

$$u_* = (\tau/\rho)^{\frac{1}{2}}$$

where ρ is density of air. Assuming the density of air varies little horizontally, and $u_* >> \rho$, u_* can be seen to be proportional to τ. Since u_*/u is constant for a given surface (Lettau, 1939), the evaluation of this ratio yields drag coefficients that are characteristic for a given surface roughness:

$$C_D = \tau/\tfrac{1}{2} \rho u_* = 2 (u_*/u)^2$$

where C_D is drag coefficient. From this discussion, it can be seen that friction velocity is a function of the influence of the surface roughness as it modifies the flow. With this physical meaning, the determination of friction velocity is a useful approach to assessing the influence of topographic perturbations on the mean flow.

From a slightly different perspective, the friction velocity is also known to be an important physical characteristic of turbulent, vertical exchange. Turbulence, as a disturbance on the mean flow, implies the presence of vertical motion in an otherwise horizontal airstream. It therefore follows that as turbulence increases, vertical exchange also increases. The characteristic speed of eddy rotation and, hence, vertical turbulent exchange, is the friction velocity. $u*$ appears explicitly in the equation for the vertical exchange coefficient, K_x (Oke, 1978):

$$K_x = k\, u_* \,(z_1 - z_2)$$

where K_x is representative of a variety of exchangeable entities such as heat, momentum, mass, etc.

B. Application.

As was implied at the beginning of this discussion, the logarithmic wind profile is only applicable to a neutral atmosphere. Neutrality, in this context, is extended beyond the thermodynamic sense, to include the effect of horizontal wind speed upon vertical motion. It is also conditional, depending on the extent of horizontal motion as well as vertical free convection. Deviations from the logarithmic profile are, consequently, functions of stability. The Richardson number is an expedient means of assessing atmospheric stability:

$$Ri = g/\overline{T} \cdot \frac{(\delta T/\delta z)}{(\delta u/\delta z)^2}$$

Where g is acceleration of gravity, T is average temperature (Kelvin) in the layer z and u is wind speed. Ri is dimensionless and represents the ratio of buoyancy forces (numerator) to the inertial forces (denominator) in turbulent flow. Thus, in strongly unstable conditions (free vertical convection) the numerator dominates and $Ri < 0$. Ri increases with an increase in $\delta T/\delta z$; it is reduced by an increase in the wind speed gradient, $\delta u/\delta z$. Ri is 0 under neutral conditions and $Ri > 0$ in stable atmospheres. In application, atmospheres are assumed to be neutral when $Ri < 0.01$.

Now, the logarithmic wind profile can be expressed in a form to include ϕ:

$$\delta u/\delta z = u_* \, kz \, (\phi_m)$$

where ϕ_m is a dimensionless stability function that accounts for curvature in the wind profile due to buoyancy effects. Under neutral conditions ϕ_m is 1.0. The evaluation of ϕ, and, hence, the relative stability of an atmosphere can be calculated on the basis of the Richardson number.

ϕ function methodology was developed on the basis of another stability parameter that embodies the physical determinants of stability. Its major component, called the Monin-Obukhov length, L, has units of length. This allows for a physical, descriptive interpretation of the nature of stability in turbulent regimes. It can be regarded as the depth of the mechanically mixed layer near the surface. By forming the ratio z/L, a dimensionless stability parameter arises that is very similar to the Richardson number since, in each case, the roles of buoyancy forces and inertial forces form the basic relationships. This realization allows for the application of the function based on the Richardson number. In fact, the following relation has been derived (as given in Hanna, 1982):

$$(z/L) = Ri \quad \text{(stable)}$$

$$(z/L) \cong Ri/1\text{-}5Ri \quad \text{(unstable)}$$

In lieu of values for (z/L), corrections to the logarithmic profile equation can be made based on the Richardson number (after Businger, et al, 1971):

unstable case: $kz / u_* \cdot \delta u/\delta z = \phi_m (z/L) = (1-15(Ri))^{-\frac{1}{4}}$

stable case: $kz / u_* \cdot \delta u/\delta z = \phi_m (z/L) = 1 + 5(Ri/1-5Ri)$

With this result, it is now possible to derive friction velocity under any stability regime, given values for u, z and Ri.

Determinations of a friction velocity-like parameter were made using the above theoretical basis in an effort to describe a physical characteristic that differentiates the windward site from the lee shelter. Because of the violated assumptions mentioned earlier, this parameter calculated in the same way as friction velocity will be referred to as "quasi-friction velocity". This parameter is probably strongly related to the actual friction velocity and, perhaps, proportional to it. A comparison of this quantity between the windward site and the lee shelter should lend insight into the respective turbulence structures. To distinguish this parameter from friction velocity the notation "${}_*u_*$" will be used.

C. Results.

Quasi-friction velocities were calculated for both the windward and leeward sites during the period of August 4 through August 25. These were calculated for two layers at each site: 0 to 1.5 m and 1.5 to 4.1 m. Mean values for the two sites, at each layer are given (table 14):

Height	Windward	Leeward	$\overline{D}$ Signif. level
0 - 1.5 m (layer 1)	55	48	.05
1.5 - 4.1 m (layer 2)	21	39	.00005

Table 14. Mean quasi-friction velocities, for both sites, by layer. Values given are in cm s^{-1}.

As indicated, the vertical distributions of ${}_*\mu_*$ for the two sites are similar, that is ${}_*u_* \propto 1/z$. A vertical "gradient" of friction velocity in the strict sense is inappropriate since friction velocity is a function of surface shearing stress. A vertical gradient of quasi-friction velocity then implies vertical differences in shearing stress. This could only be a result of the presence of a shear layer other than the surface itself. Vertical differences in quasi-friction velocity imply a separation of flow where shear occurs at the interface of the mean flow with adjacent airstreams or eddies. Since the decrease in quasi-friction velocity with height in the lee shelter is about 1/3 that of the windward site, this indicates that the lee shelter is located at a lower elevation than the windward site, with respect to the mean flow. Assuming that ${}_*u_* \rightarrow 0$ as the flow becomes more laminar (or less turbulent), the windward site appears to be closer, in the vertical sense, to that level (z) where the flow is, perhaps, more parallel to the surface. This is appealling since this entire discussion has been predicated on the basis of topographical differences whose influences are thought to be most strongly felt in the vertical sense. Following this reasoning, the lee shelter represents a local maximum, in the vertical extent of turbulent diffusion. Figure 16 presents this theoretical concept graphically.

As described previously, the location where snow was observed to be deepest also exhibited the highest soil moisture levels (gravimetric data). This seemingly linear relationship may, however, contain factors that are not superficially observable as cause-and-effect. Since the overall status of a local water budget is affected by outflow as well as inflow, the outflow may be an important budget parameter. That is, a soil or plant community is subject to a certain "drying regime" as well as a "wetting regime". A site that is favored (as in the case of snow drifting) for wetting may or may not be favored in a drying regime. It is conceivable that soil exposed to enhanced wetting may also be subject to enhanced drying as well. On the other hand, a soil receiving little water input may maintain a surprisingly high water budget in the absence of excessive outflow demand. Ideally, where soil water is the limiting factor, a site which differentially accumulates and conserves soil moisture will ultimately result in a more favorable microclimate for plant growth. In this light, a layer-by-layer comparison of quasi-friction velocity, from site to site yields interesting results.

Figure 17 shows the traces of quasi-friction velocities in both sites for layer 2 on August 21. In almost every case, the lee shelter exhibited the higher value, indicating greater turbulence

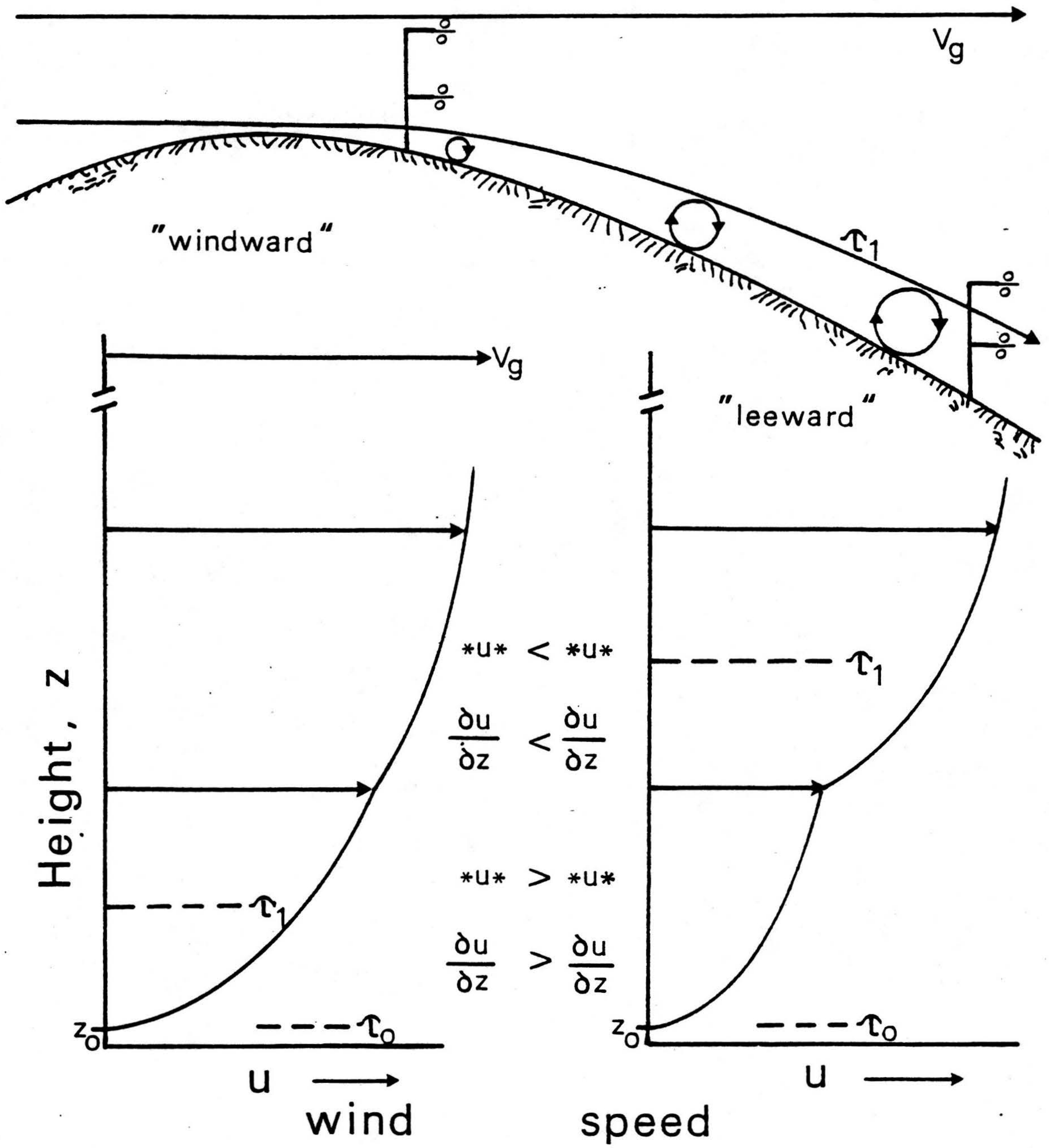

Figure 16. Proposed regimes of wind speed with height, by site, based upon observed differences at two elevations, z_1 and z_2. The differences in calculated "quasi-friction velocity" imply the presence of a shear layer that is higher in elevation in the leeward site than in the windward site, with repsect to the surface. The discontinuity of the logarithmic profile is more pronounced in the leeward site, indicating a shelter effect with repspect to wind speed. The proposed location of the shear layer is given, denoted by τ_1.

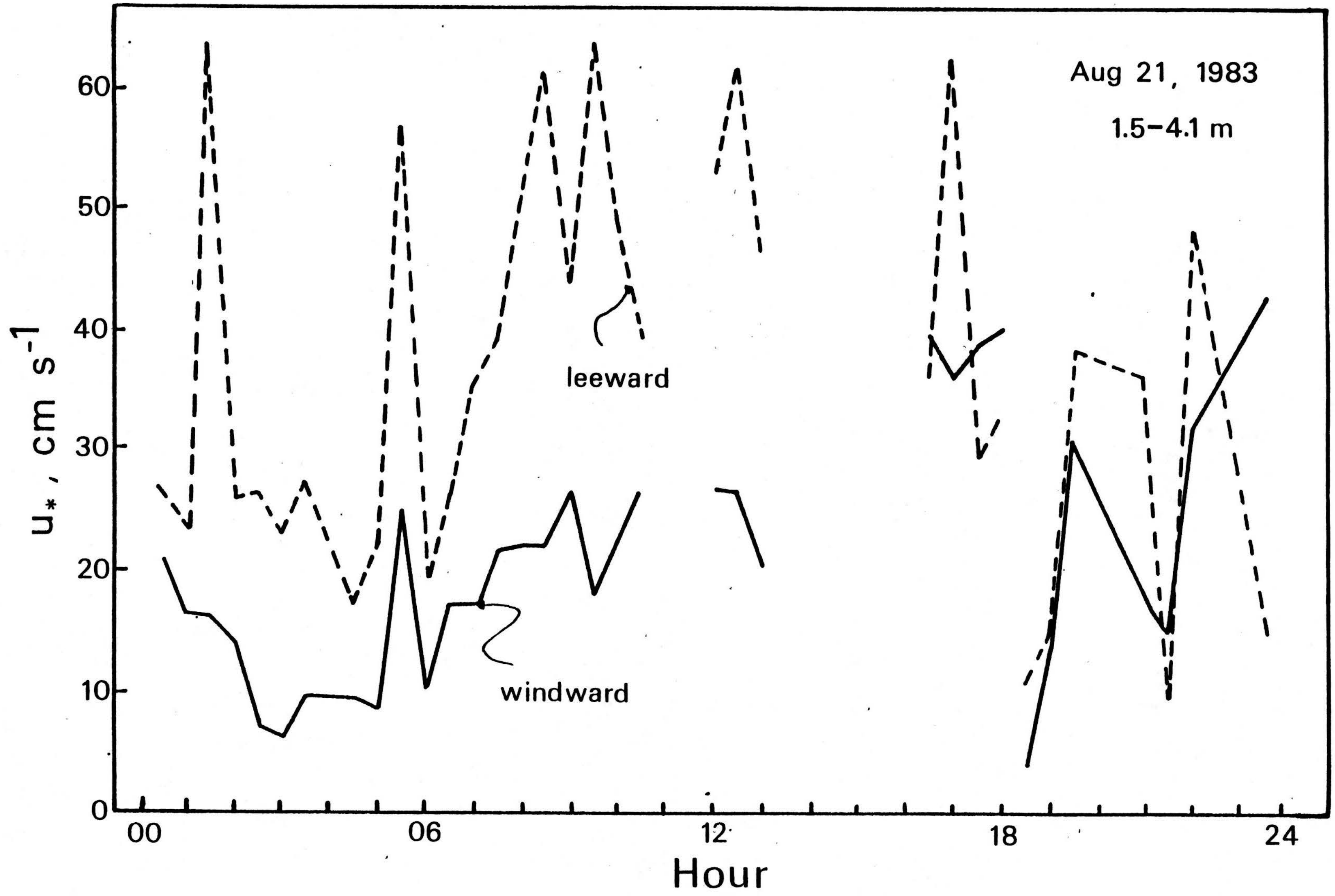

Figure 17. A comparison fo quasi-friction velocities between the windward and leeward site for August 21. 1983 for the 1.5 to 4.1 m layer.

and potential for vertical transport in this layer. Since the ratio u_*/u is constant for a given surface, the potential for vertical transport in the lee shelter is greater than that in the windward site. During and after a winter storm this potential could very likely be realized in the deposition of snow. In this way, the leeward site would be favored with respect to a wetting regime. Given, the above discussion, coupled with the observed snow deposition patterns, the evidence is strong that this is so.

A site-to-site comparison of $_*u_*$ values in the lower layer shows the windward site to have higher quasi-friction velocities (figure 18). Again, since u^*/u varies only as a function of surface shear, the potential for vertical exchange is greater in the windward site for this layer. With respect to drying, the windward site exhibits greater potential evapotranspiration than the lee shelter. If the windward site is closer to the mean flow (in the vertical sense) the higher quasi-friction velocity observed there would be a quantitative measure of the higher shearing stress exerted by the surface of the windward site. The surface in the lee shelter would not exert the same amount of stress on the mean flow since it is located lower in elevation, with respect to the mean flow. The occurrence of natural vegetation in the lee shelters as oppposed to ridgetops in the Intermountain region is strong empirical evidence to support this. Besides mechanical stress imposed on ridgetop plant life, a chief vegetation distribution mechanism may be a response to evaporative demand which would potentially be higher in windward sites than in lee shelters. Higher quasi-friction velocities in the

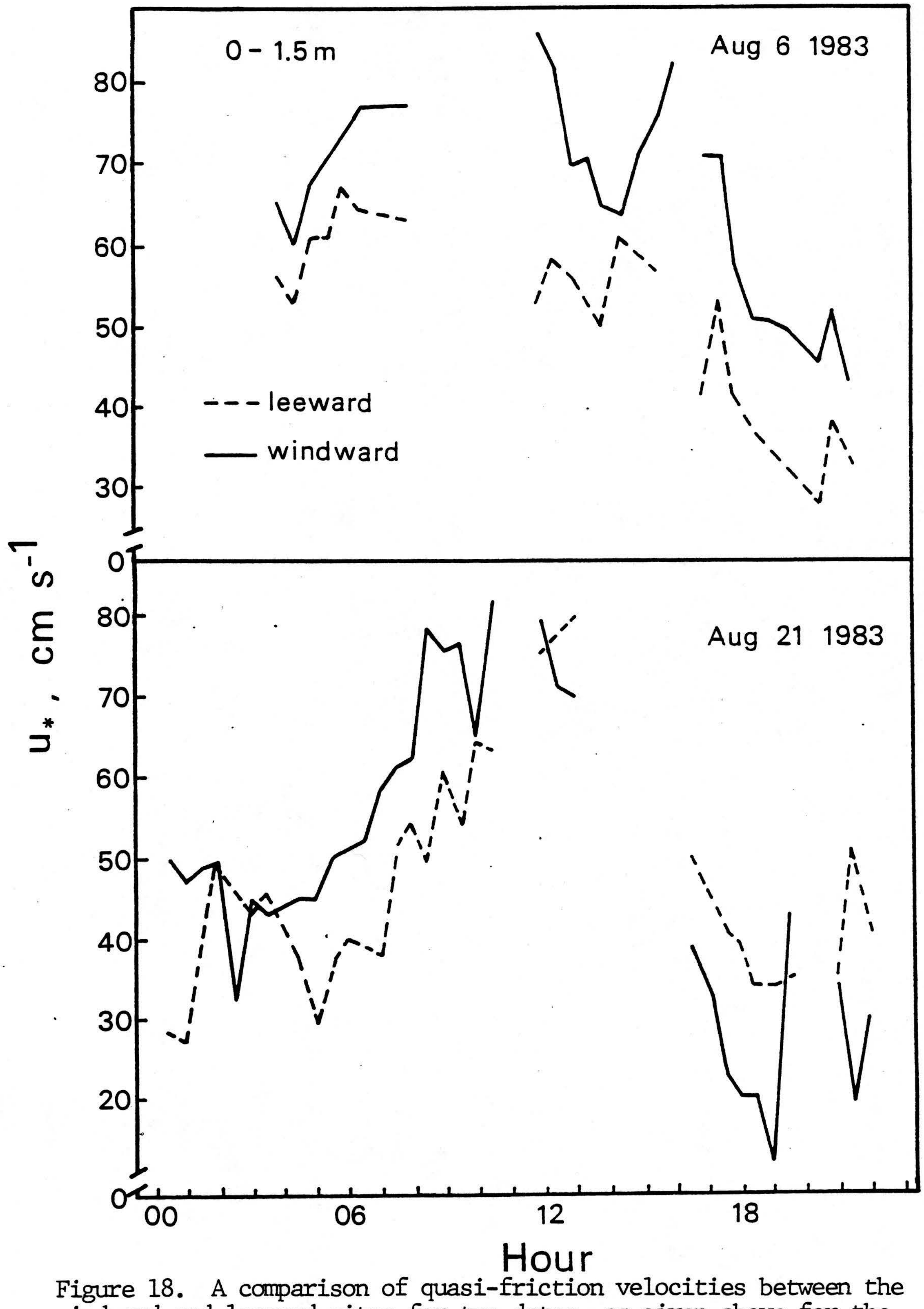

Figure 18. A comparison of quasi-friction velocities between the windward and leeward sites for two dates, as given above for the 0 to 1.5 m layer.

windward site would also be an indication of the erosion potential of the wind. Since snow probably accumulates, on occasion, in windward sites, its transient nature may in part be related to the quasi-friction velocity. Insolation differences from site to site also influence the overall evapotranspiration mechanism. In this study no attempt was made to determine differences from the windward site to the lee shelter. It is felt, however, that large differences in net radiation between the two sites did not exist as their respective aspects are approximately the same.

It could be argued that these data were selectively discussed and analyzed toward some preconceived notion. A simple rebuttal rests comfortably on the assumption that wetting and drying processes are both layer dependent. For example, higher quasi-friction velocities in layer 2 of the lee shelter could not possibly enhance surface drying since the surface does not occur in that layer. On the other hand, even though quasi-friction velocities in the windward site might favor snow deposition there over the lee shelter, this could only occur in a very shallow vertical extent. In fact, the snow depth "potential" in either site is probably a strong function of the distribution of quasi-friction velocity with height as discussed earlier. Since snow particles are very large compared to water vapor or carbon dioxide molecules, a threshhold quasi-friction velocity capable of supporting vertical snow transport may exist. Since quasi-friction velocity decreases 3 times faster in the windward site, this supposed threshhold would simply exist at a much lower elevation there, relative to the surface. Physically, this "threshhold" of quasi-friction velocity is very likely a result of a distinct separation of flow that is induced by the higher windward site. In this sense, the lee shelter is then located in the turbulent wake induced by and downwind of the windward site.

SUMMARY

The observed differences between the windward site and the lee shelter were:

1. Snow accumulated to a greater depth in the lee shelter than in the windward site.

2. Averaged soil temperatures at two depths were found to be higher in the lee shelter than in the windward site.

3. Matric potential was found to be lower (less negative) in the lee shelter than in the windward site.

4. A regime of quasi-friction velocities was found in the lee shelter that differentially favors it over the windward site in terms of greater snow deposition potential and lower evapotranspiration potential.

An analysis of the chronology of wind and precipitation events indicated that north to east aspects were preferred in terms of the spatial distribution of snow.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that there are physical differences between a windward site and a lee shelter. There is evidence for a cause-and-effect relationship between differential snow deposition and soil moisture. From the ecological perspective, these findings are important considerations in the characterization of vegetation distribution. The importance of wind is evident: the spatial variability of plant growth is strongly related to the interaction of precipitation, wind and topography in these regions.

Recommendations for Further Research

1. Hydrology. The results of this study indicate only trends. Little differentiation between sites other than "wet" and "dry" can be made. Since the disposition of precipitation is subject to complex factors, a strict hydrological study could yield insights into the overall soil water budget mechanism. Factors such as sublimation, drainage through the soil and overland flow are all known to be significant watershed parameters. These factors, in turn, are important in the dynamic interchange and partitioning of energy in an ecosystem.

2. Micrometeorology. In the same vein, the present study yields only patterns and typical values. Since the dynamics of ecosystem energetics are intimately tied to energy input, a detailed study of energy balances here would be useful in the determinations of energy flow within the ecosystem. In this study insolation was ignored even in the knowledge that surface energy balance can be

strongly related to aspect. Also, even though the application of modern micrometeorological theory was strictly adhered to in the wind measurements, the use of rather crude instrumentation and the violation of a major assumption together detract from the elegance of the results.

3. Biology. A primary objective of the study was to physically describe a lee shelter's favorability to plant growth. Although these considerations are strongly supported in the literature, the conclusions here exist only in the realm of speculation. Actual field trials of plant success are needed to test the biotic responses to differing climatic regimes of wind, precipitation, temperature and solar radiation.

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