ASSOCIATION BETWEEN WEATHER CONDITIONS, SNOW-LIE AND SNOWBED VEGETATION.

1998

Phd

CATHARINE HILARY MORDAUNT,
DEPARTMENT OF ENVIRONMENTAL SCIENCE,
UNIVERSITY OF STIRLING.

ACKNOWLEDGEMENTS

My thanks go to all those who have assisted in this project: my external examiner, Des Thompson, my supervisors John Harrison, Ian Simpson, Hilary Kirkpatrick and Andrew Batchell; the Department of Environmental Science at Stirling University, and particularly Donald Davidson; a number of friends who have helped with parts of the fieldwork or commented on aspects of the study, including Sandy Winterbottom, Rachel Marsden, Mandy Towrie and Wendy Smith; my parents John and Gill, for motivation and support throughout; Beinn, my dog, for keeping me company during fieldwork and the sheep at bay; and my husband David, for acting when required as field assistant, for giving me the means to continue the project and for consistent advice, help and support. I owe a particular debt of gratitude to John Harrison, for all the time and effort he has put into supervising the project and believing in me.

I would like to thank the University of Stirling for the provision of a studentship (1991-1994) to fund this research, and the Nature Conservancy Council for Scotland (that was) for the assistance offered in the early part of this study.

ABSTRACT

Snowbed vegetation contains both vascular plants and bryophytes. The latest snowbeds cover areas that are of predominantly, if not exclusively, bryophyte flora while the vascular plants are generally confined to the periphery of such late snowbeds. It is hypothesised that the exclusion of vascular flora from the snowbed core is the result of the shortened growing season generated by late-lying snow, which the bryophyte flora is better able to tolerate. The snowbed bryophytes cannot, however, tolerate the competition offered by the vascular flora in the peripheral areas from which they are absent.

Data indicate that some of the bryophyte snowbed species are inhabiting optimal conditions in the snowbed core, rather than tolerating sub-optimal conditions. Adaptation and acclimation responses observed in peripheral vascular species indicate that these are inhabiting sub-optimal conditions in the snowbed periphery.

The relationship between snow-lie and climate is examined, with to the construction and examination of a second hypothesis that snowbed loyalty in the Scottish Highlands is high, while duration of snow cover is variable. Snow-lie loyalty is the product of prevailing wind conditions, which are persistent and consistent in Scotland leading to consistency in late snowbed location, while the occurrence of mid-winter thaws at all altitudes makes duration of snow cover through accumulated snow depth much more variable.

Increased zonal flow in winter has affected snow-lie in the Scottish Highlands, with a slight decrease in snow-lie duration in recent years. It is not clear whether this pattern

applies to all altitudes and accumulations at higher levels, especially in the western Highlands, may be increasing as a result of steeper winter-time lapse rates. With late snowbed location varying very little, it is possible that the consequences of global warming may not necessarily mean an extinction of the late snowbed bryophytes in Scotland, which constitute an important part of Britain's montane flora.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

Lowland snow cover varies on a global scale from no snow cover at sea level in tropical latitudes, to permanent snow and ice cover at the Poles. Higher temperatures and minimal seasonal variation in incoming short-wave solar radiation in the Tropics contrasts with low temperatures and a highly seasonal regime at the Poles where in the winter season there is little or no solar radiation and summer has very high total levels of incoming short-wave radiation. Between these two extremes there is an increasingly seasonal climate with increasing latitude and greater spatial and temporal variability in annual radiation patterns. Altitudinal climatic gradients, with air temperature decreasing and precipitation totals increasing as elevation increases, complicate this simplistic picture with snow cover generally increasing with altitude, as may be seen on the high tropical peaks of Kilimanjaro and Mount Kenya in Africa, or in the Andes of Central and South America. Regional-scale patterns of differences in the duration of snow cover may therefore be observed in all the major mountain ranges of the world, save some of the polar nunataks. Seasonal snow cover is therefore typical of many regions of the middle and high latitudes, and is particularly characteristic of the mountain ranges in these regions, where the steeper climatic gradients are superimposed upon the relatively larger-scale gradients of latitude (Gjaerevoll, 1956; Knight, Rogers and Kyte, 1977; Flock, 1978; Miller, 1982).

Topographic complexity imposes further, smaller-scale variations in snow cover duration, primarily through the development of a snow cover of variable depth. Variation in the depth of accumulated snow gives rise to variation in the timing of release from an overlying snow cover, since an increasing quantity of radiation will be required to melt a thicker snow cover. In areas where snow accumulation is spatially variable and therefore release from the overlying snow cover temporally variable, difference in the underlying vegetation may be observed related to the timing of release.

The loyalty of late snowbeds to specific locations is determined by the interaction of topography and wind during the winter half-year (Gjaerevoll, 1956; Gray and Male, 198; Wijk, 1986; Watson, Davison and French, 1994). In mountain areas where there is a dominant, prevailing wind, such as maritime mountain ranges, and the pattern of snow accumulation is therefore consistent, late snowbeds are likely to be loyal to specific locations. High snowbed loyalty will generate persistent reduction in the potential growing season year on year and thus allow the development of a specific vegetation type in the area of the snowbed.

The effects of an increase in the duration of snow cover relative to surrounding areas of earlier exposure are four-fold. With light and heat two of the dominant factors affecting the growth of plants, the onset of the growing season for the vegetation lying beneath is delayed by the opacity of the snow, allowing little radiation to penetrate beneath the top few centimetres (Gray and Male, 1981; Oke, 1987), and by the isothermal regime at the vegetation/soil-snow interface, which remains close to 0°C until the overlying snow has thinned to between 5 and 15 centimetres (Oke, 1987), a situation which will also protect the underlying plants from early-season frosts. As the snow bank melts it provides a source of irrigation both beneath the snow and downslope from the bank. Finally, the weight of the overlying snow may cause mechanical damage to plants with rigid stems, such as woody shrubs (Bell and Bliss, 1979; Wijk, 1986).

The delay in exposure of plants beneath late-lying snow banks reduces the period of time during which they may grow and reproduce, particularly if these plants are sensitive to freezing temperatures which usually accompany the termination of the summer season in mountain regions. Plants inhabiting areas which become snow-free earlier experience a longer growing season, but are also exposed to frosts typical of the early part of the season. Vegetation in and around the late snowbed is also less likely to experience drought typical of the most exposed locations.

The interaction of these environmental factors of snow-lie depth and duration, and irrigation downslope generates a vegetation types which may be divided into two principal categories, termed chionophilous (snow-loving) and chionophobous (snow-fearing). Chionophilous species are found only in areas of late snow-lie, and chionophobous in areas of minimal snow-lie, with the duration of snow-lie the most important environmental variable determining their distribution. In between these two extremes lie many species and vegetation types which may be mildly chionophilous or chionophobous, or indifferent, and for whom other environmental variables are more important in determining their distribution and success.

The interaction of climatic factors governing the location and duration of late snowbeds, that is wind, temperature and precipitation, is highly complex in the Scottish Highlands where steep altitudinal gradients characteristic of maritime mountain ranges (Barry, 1992) are accompanied by steep latitudinal climatic gradients (Brown, Horsfield and Thompson, 1993; Brown, Birks and Thompson, 1993) and steep gradients of continentality, longitudinally across the country, generated by proximity to the North Atlantic Ocean (Birse, 1971; Kirkpatrick and Rushton, 1990). Snow-lie varies from an average of only a very few days each year at sea level to approximately 220 days per year at 1200m (Manley, 1971) with the theoretical altitude of net snow accumulation only 1620m (Barry and Chorley, 1987). Therefore, in spite of their relatively low elevation (maximum altitude 1344m) and latitude (59°N), the Scottish Highlands do contain late and even semi-permanent snowbeds, and their accompanying chionophilous plant communities, such as those in an Garbh Choire, Braeriach.

In the Scottish Highlands, a range of chionophilous plant communities may be found, forming one of the five functional groups of montane vegetation demonstrated by Thompson and Brown (1992). Chionophilous communities are set alongside species-rich communities, mires, anthropogenic and chionophobous communities. The species characteristic of chionophilous and chionophobous communities form an integral part of the definition of biogeographical zones in Scotland, being characteristic of the highest mountain zone (Brown, Horsfield and Thompson, 1993; Carey *et. al.*, 1995) and of considerable conservation importance as a result of their rarity, restricted location and high diversity (Thompson and Brown, 1992).

Fluctuations in climate are at present affected by anthropogenic forcing, through the introduction of gases and particulates into the atmosphere by industrial and agricultural activity (Houghton *et. al.*, 1990). The location of the Scottish Highlands at the interface between the Atlantic Ocean and the north-west European land mass, and lying in the zone of the Polar Front where cold polar air meets warm tropical air, makes it an area of high sensitivity to changes in climate. One of the variables which is likely to be very responsive to changes in climate is the duration of snow-lie in the

Scottish Highlands, as can be seen in the historical record (Manley, 1968; Pearson, 1973a, 1973b, 1975a, 1975b, 1976; Kemp, 1976).

If chionophilous plant species are located only in areas of late snow-lie and depend on its persistence for their continued existence, then they may be forced into extinction in the British Isles as a result of climate affecting the duration of snow-lie. Such a loss has important implications for conservation, since these species represent a part of the glacial flora which inhabited Britain during the last glaciation. While it may not be possible to conserve their habitat in the long-term, since it is climatically determined, a reduction in the extent and distribution of some of the key montane species makes their short- and medium-term protection an high-priority objective for Scottish conservation. Additionally, it is relevant to identify the likelihood of their survival in the longer-term, since such an assessment, were it to be positive, would add weight to their need for protection in the more immediate future.

The questions raised by the position of late snowbed vegetation in the Scottish Highlands focus on the relationships between plants and snow, and between snow and climate. The severity of the Scottish upland climate appears to be comparable to that found at much higher altitudes in all but the most oceanic mountain ranges, but few, if any studies exist between here and other, comparable sites, such as the coastal ranges of North America, or the Southern Alps of New Zealand. Those aspects of the Scottish upland climate which generate such relatively late-lying snow are only poorly understood, with very little climatic data available from the mountains north of the Highland Line. It is an important priority for future research to investigate what those factors are, and to determine how unique the altitudinal gradients are within a global context.

While the wider issues are beyond the scope of this work, the information on climate and snow-lie which is available for the Scottish Highlands will be reviewed and brought together, to demonstrate what is known and the extent of the lack of knowledge. Two aspects of snow-lie require examination: the loyalty of late snowbeds to location and the consistency in their duration into the summer months.

With regard to the relationship between snow-lie and plants, it is necessary to address the issue of how complex the relationship is, at both a community and species level, and how robust it may be to changes in overlying snow cover. Establishing the relative fragility of these communities allows policy decisions concerning their protection to be made with greater certainty.

The hypotheses which stem from these questions and which will be tested in this thesis are:

1. That late snowbeds throughout the Scottish Highlands have high loyalty to location, generating a consistent pattern of snow-lie year on year, while the duration of snowbeds is more variable, making the vegetation subject to different timing of release from overlying snow.

2. That thresholds exist of average snow-lie duration which determine the presence or absence of certain species from different parts of the snowbed, that the peripheral vascular plants are excluded by the shortened growing season but are able to outcompete the stress-tolerant snowbed core bryophytes in more peripheral areas, and that the snowbed bryophytes are consequently confined to sub-optimal conditions in the snowbed core.

Summary points:

1. A seasonal snow cover can be readily observed in mid-latitude mountain ranges where steep altitudinal climatic gradients are superimposed over latitudinal climatic gradients.

2. The pattern of snow accumulation, determined by the interaction of topography and wind, leads to differences in the timing of snow cover removal.

3. Specific, chionophilous, vegetation types are generated by a longer-lying snow cover, where snow-lie duration is the dominant, determining factor, through the reduction in heat and light by the overlying snow, irrigation from the melting snowbed and mechanical damage from the weight of overlying snow. The snowbed offers protection from early- and late-season frosts and drought.

4. The steep snow-lie gradients of the Scottish Highlands offer snow cover of sufficient duration to allow late snowbed vegetation to exist, albeit as a rarity, in spite of the relatively low elevations.

5. The location of Scotland makes this area likely to be sensitive to climate change, which may have a significant impact on snowbed vegetation.

CHAPTER 2

CLIMATE AND SNOW

2.1 Climate - General.

The Scottish Highlands lie on the western seaboard of north-west Europe, unprotected, as England is, by Ireland to the west, and experience a strong maritime climatic influence. The mountain ranges of the Highlands are small in area and low in elevation, mostly between 300 and 900m, but nonetheless exhibit steep climatic gradients (Barry, 1992).

A latitudinal climatic gradient may be identified as temperature declines northwards (Chandler and Gregory, 1976). The decrease can be seen in the comparison of monthly mean daily maximum and minimum temperatures at R.B.G. Edinburgh and Wick, shown in Figure 2.1. The difference between the two stations is less during winter than summer, and less between minimum temperature than maximum temperature. In the context of this research, where snow-lie duration is the most important variable affected by climate, a little more snow is likely to fall in the north than in the south (as would be expected) and, more importantly, lower summer temperature in the north will generate slower melting of late snowbeds.

Although the Scottish Highlands lie at approximately 58° north, at the same latitude as Labrador on the other side of the Atlantic Ocean, the climate at sea level is less severe in winter and milder in summer with a flatter annual temperature curve. This is a result of the ameliorating effects of the Gulf Stream, a warm ocean current originating in the Caribbean which passes northwards along the British coast as the North Atlantic Drift.

FIGURE 2.1

Monthly averages of maximum and minimum temperature at Edinburgh RBG and Wick.

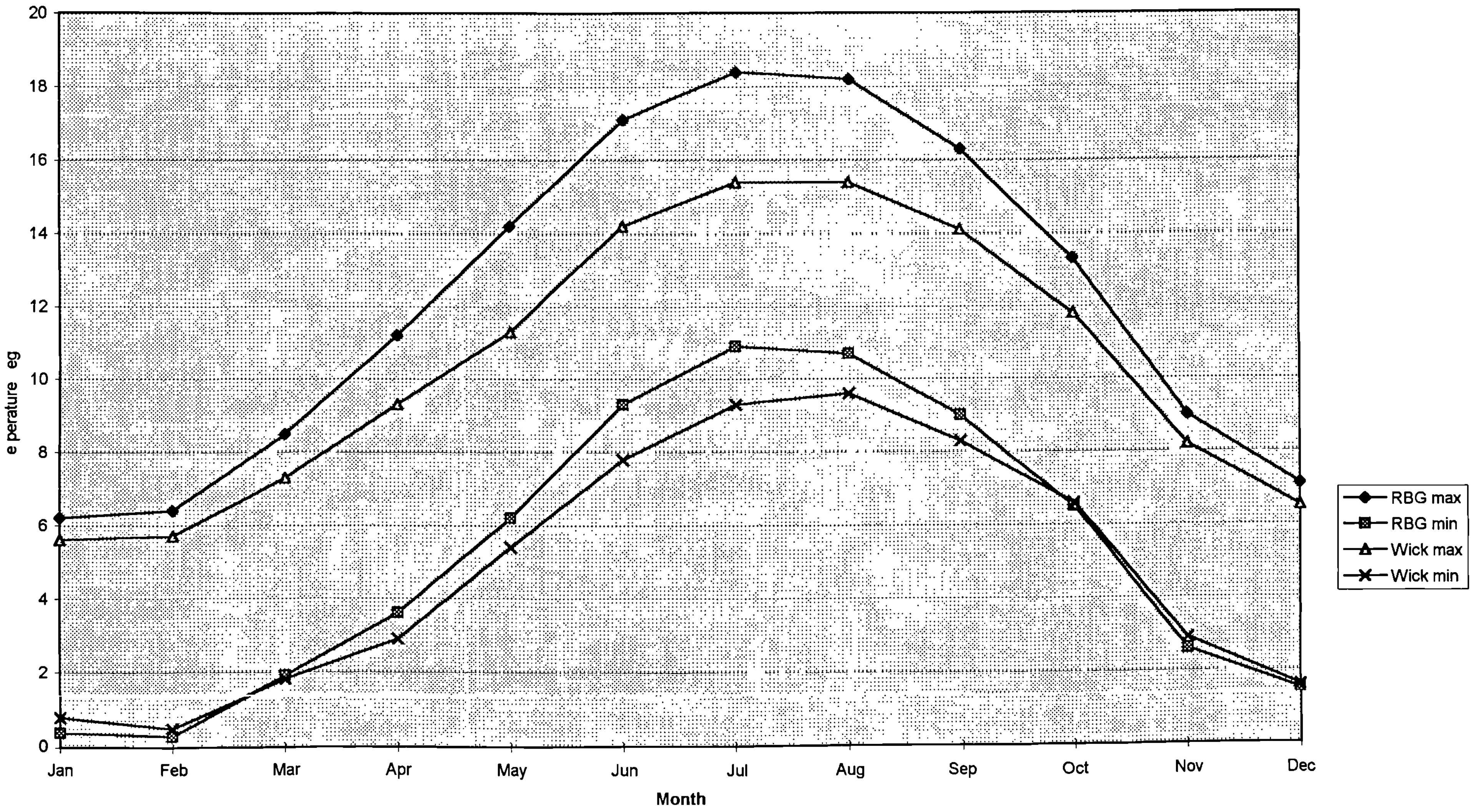
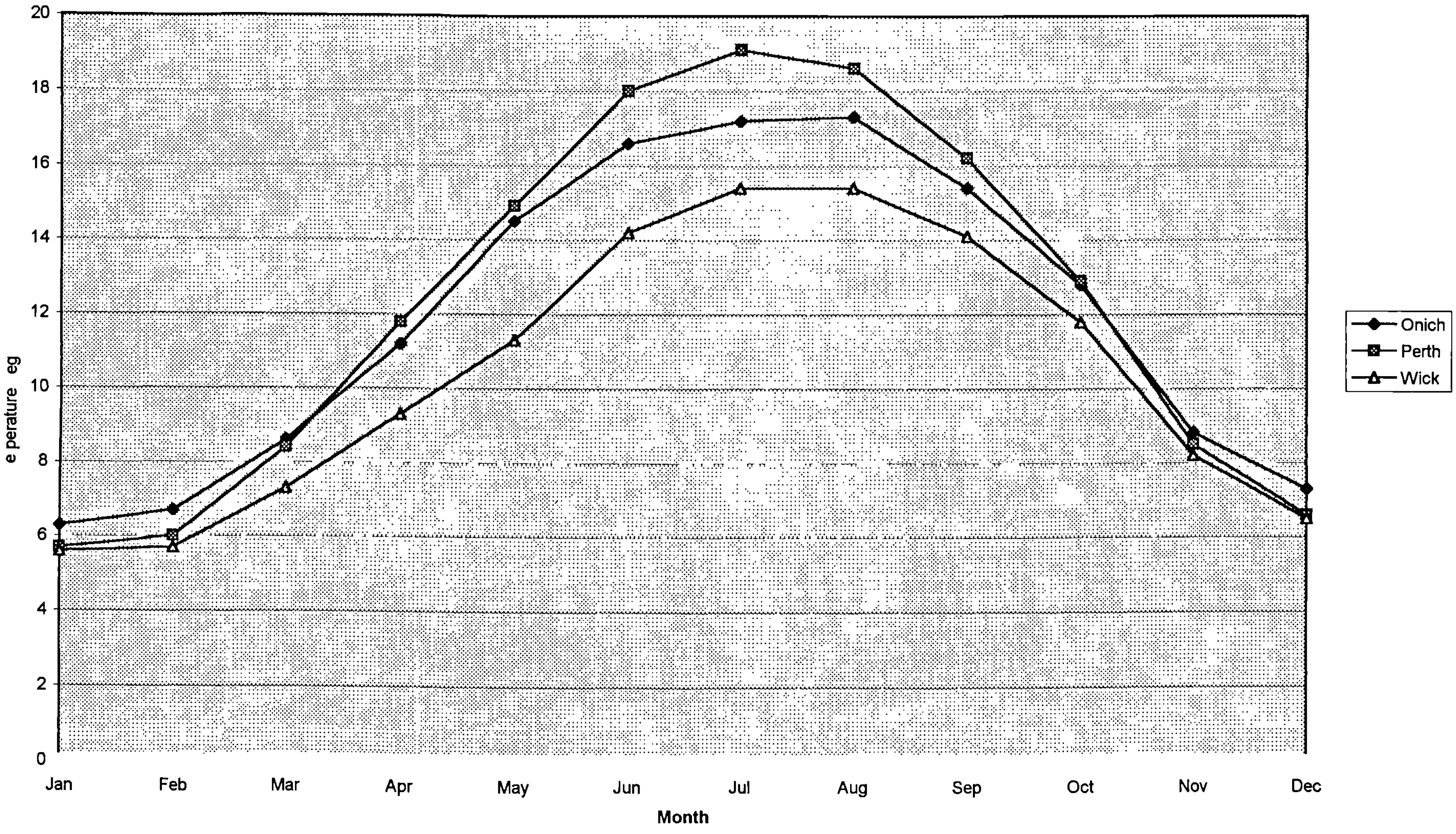


FIGURE 2.2

Monthly averages of daily maximum temperature for Onich, Perth and Wick.



Because the North Atlantic Drift fails to fully penetrate the North Sea, its effects are largely confined to the western seaboard of Ireland and Scotland, with a pronounced gradient eastwards in mean annual. The gradient identified is a part of the gradient of continentality, giving rise to warmer summers and colder winters with longer snow-lie in the east than the west. This is illustrated by the average daily maximum temperature curves shown in Figure 2.2, for three Scottish stations, Onich, Perth and Wick, whose location is given in Figure 2.3.

The atmospheric circulation in the northern Hemisphere mid-latitudes is westerly, generally strong in all seasons but more pronounced in the winter half-year, with a surface weather pattern of quasi-stationary highs and mobile highs and lows (Chandler and Gregory, 1976; Mayes, 1996). Much of the weather received by Scotland is dominated by eastwards-moving low pressure systems originating in the eastern sector of the North Atlantic (Ratcliffe and Murray, 1970), giving a flow of air masses of predominantly maritime origin, as shown in Figure 2.4. These maritime air masses are generally saturated following their progression across the North Atlantic, and in winter are also warmed by the underlying ocean, thereby enhancing their capacity to hold moisture. As they travel across Scotland, and are forced to rise by high ground, condensation is enhanced and there is a marked increase in precipitation intensity and duration. Those areas of western Scotland where substantial land barriers are first encountered by maritime air masses therefore experience very high annual precipitation, possibly in excess of 5000mm yr^{-1} on windward slopes (Harrison, 1997), most of which falls during the winter half-year when the circumpolar mid-latitude zonal flow is most intense. This is demonstrated in Figure 2.5.

FIGURE 2.3
MAP SHOWING SELECTED
SCOTTISH METEOROLOGICAL STATIONS.
SOURCE: THE METOROLOGICAL OFFICE,(1989).

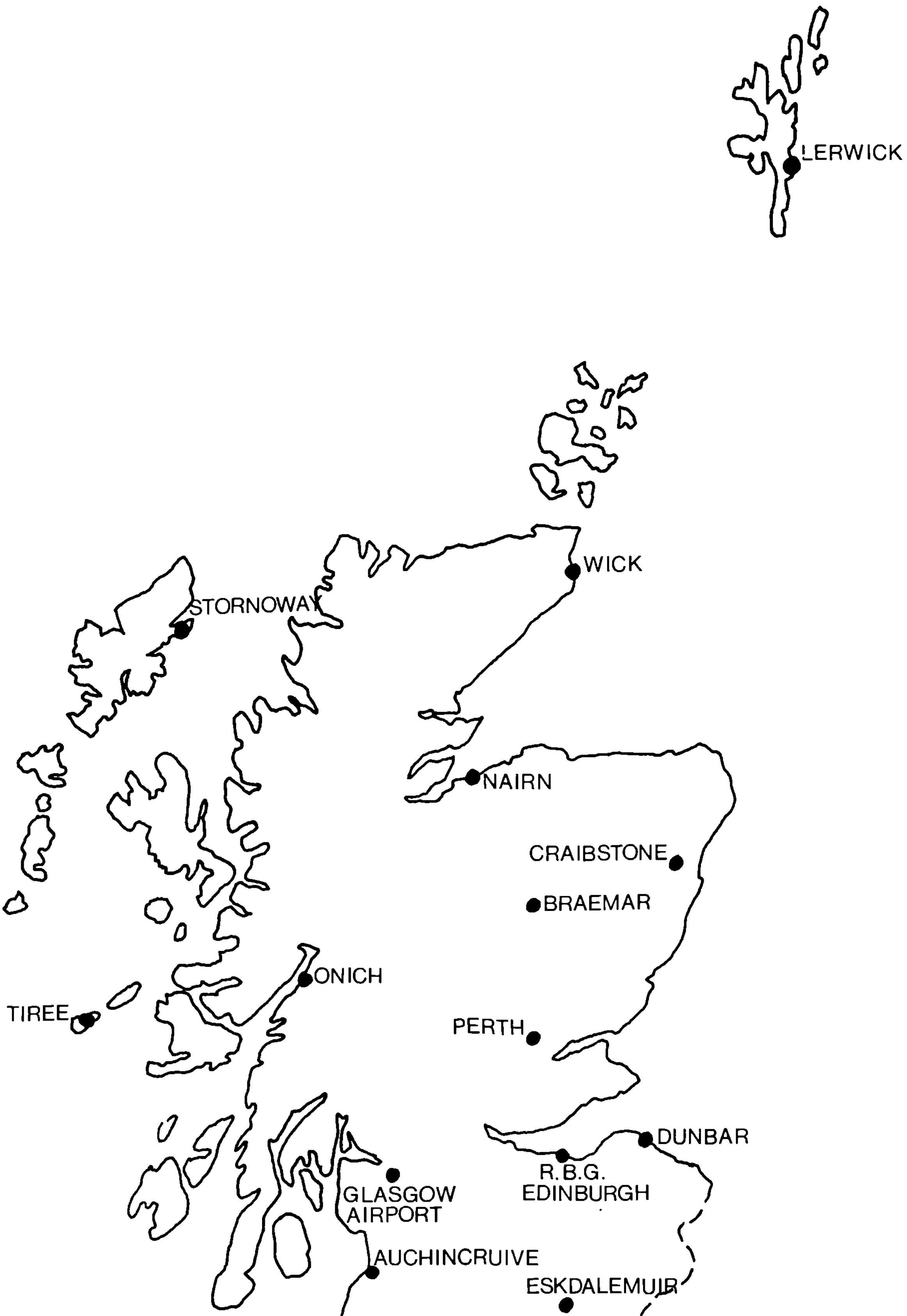
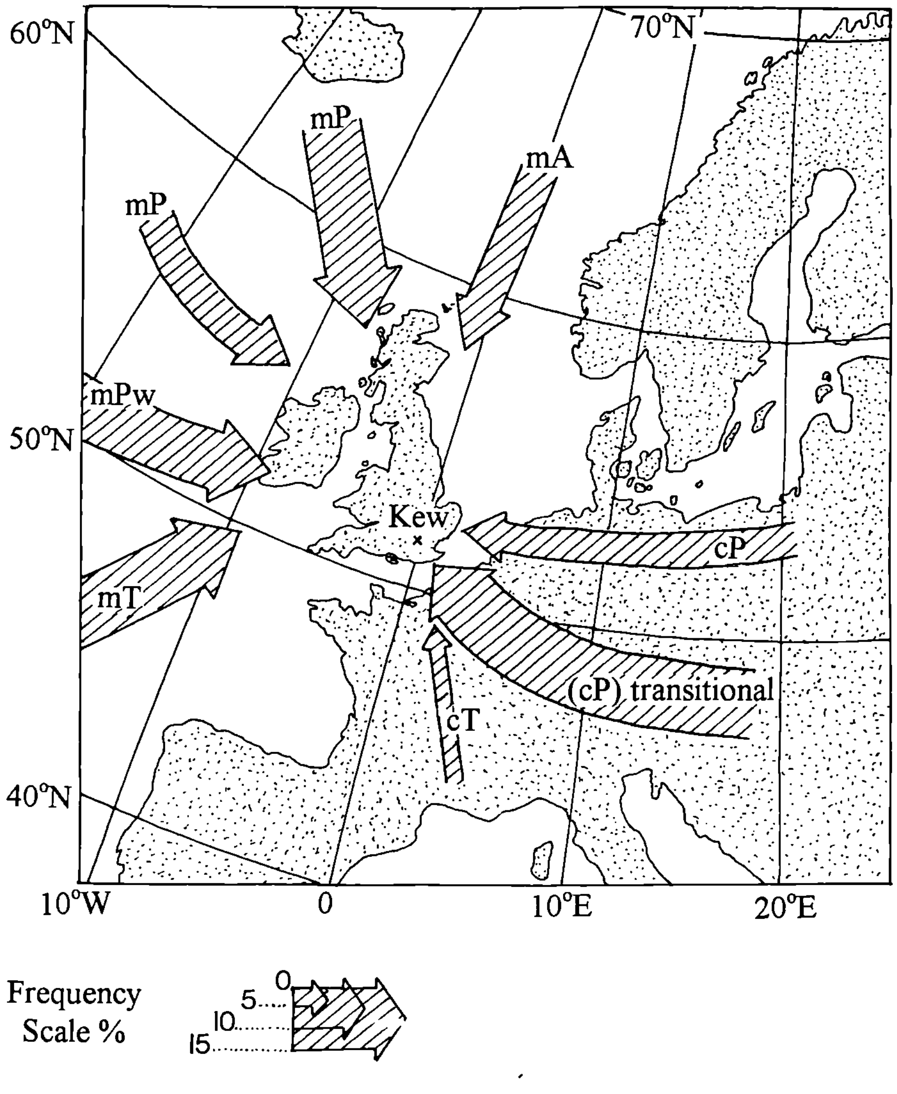


FIGURE 2.4



Notations:

mP	polar maritime air
mPw	returning polar maritime air
mT	tropical maritime air
cT	tropical continental air
cP	polar continental air
mA	arctic maritime air

AVERAGE AIR MASS FREQUENCIES FOR KEW (LONDON) IN JANUARY.
ANTICYCLONIC TYPES ARE INCLUDED ACCORDING TO THEIR DIRECTION OF ORIGIN.

SOURCE: BARRY AND CHORLEY (1987) AFTER BELASCO (1952).

FIGURE 2.5

MAP SHOWING AVERAGE ANNUAL
PRECIPITATION IN THE BRITISH ISLES, 1941-70.
SOURCE: THE METEOROLOGICAL OFFICE, HMSO (1989).

The importance of the westerly component of precipitation to total amounts is shown in Figure 2.6 from Weston and Roy (1994). Precipitation is greatest over the parts of the mainland first encountered by air masses from different directions, with flow from westerly sectors ((a) and (d)) accounting for 69% of the total number of rain days measured and with total rainfall at least an order of magnitude greater than that from any other direction. The dominance of westerly flow is confirmed by Davison (1985), using geostrophic wind data and therefore eliminating the effects of topography affecting all meteorological stations, who gives values for the four main quadrants as follows: north - east, 13.6%, east - south, 25.9%, south - west, 36.7% and west - north, 23.7%.

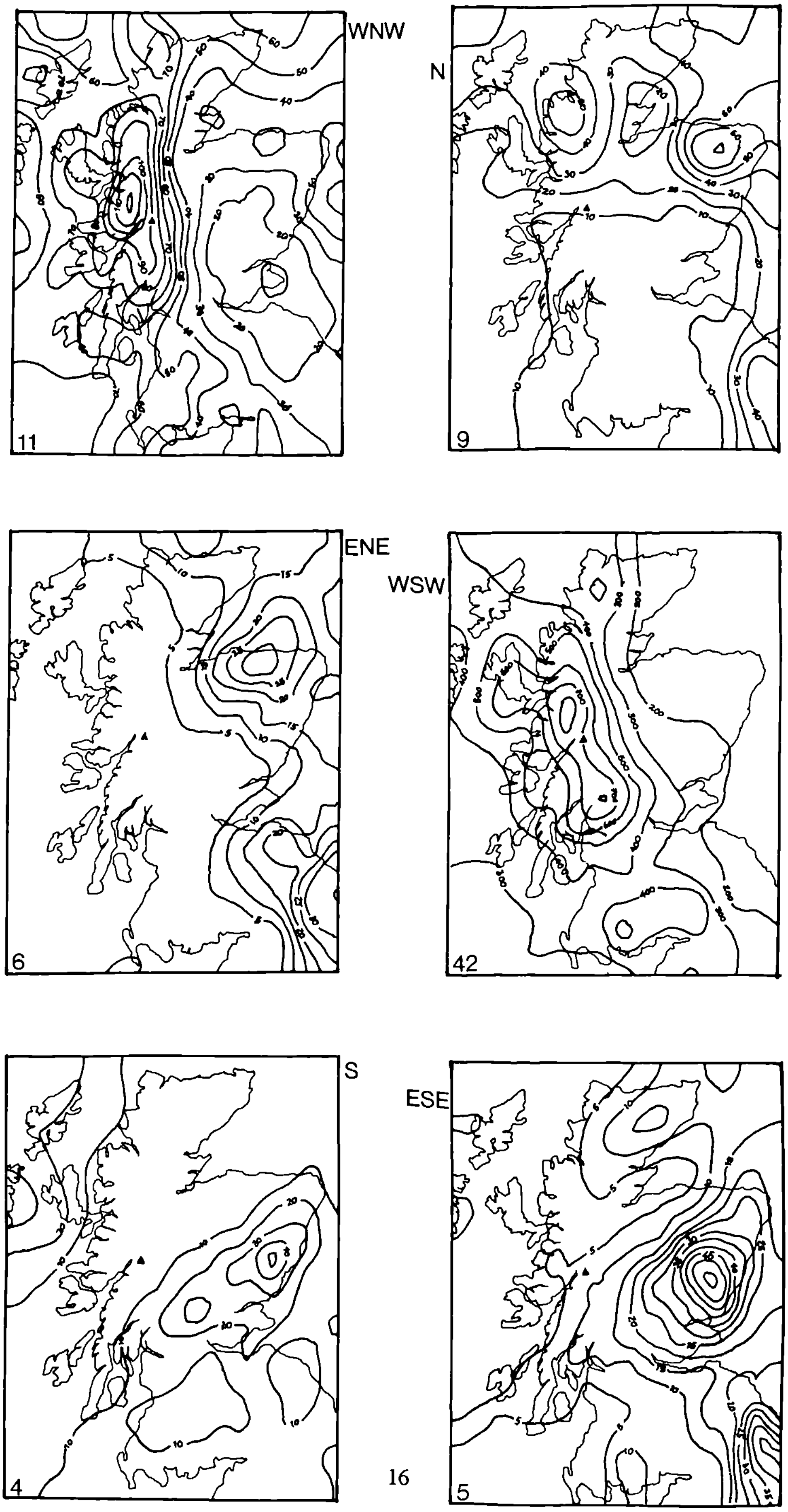
Therefore a strong west-to-east precipitation gradient exists, complimenting the gradient of annual temperature range to give an overall gradient of oceanicity/continentality similar to that shown by Kirkpatrick and Rushton (1990) in northern Ireland. In summary, this gradient is typified by the mild (in winter), cool (in summer), cloudy, windy and wet conditions of the west coast, contrasting with the clearer, sunnier, colder (in winter) or warmer (in summer) conditions of the central and eastern Grampians. Wind speeds remain high in the east, particularly in the mountains, owing to the decrease in surface roughness as topography changes from the deeply-bisected glens of the west to the smoother summit plateaux of the east.

In addition to gradients of decreasing temperature northwards and oceanicity eastwards, and superimposed over these two gradients, is that of altitude. Study of the climate of the Scottish Highlands at altitude is severely hampered by the lack of data (Manley, 1936, 1942, 1943; Harrison, 1974; Taylor, 1976). Only two meteorological stations operate in the montane zone, both of which are Automatic Weather Stations

FIGURE 2.6 TOTAL RAINFALL (mm) FOR OCCASIONS OF FLOW DIRECTION.

Each sector of equal size: (a) west-north-westerly; (b) northerly; (c) east-north-easterly; (d) west-south-westerly; (e) southerly; (f) east-south-easterly. The number of raindays for each sector shown in the bottom lefthand corner. From Weston and Roy, 1994.

Author's note: sectors centred on compass points named above cannot be of equal size. It is assumed that the six sectors cover the following bearings; (a) 270 - 330°; (b) 330 - 30°; (c) 30 - 90°; (d) 210 - 270°; (e) 150 - 210°; (f) 90 - 150°.



(AWS) and therefore less reliable and comprehensive than manned stations, lacking observations such as snow cover and snow depth. Cairn Gorm AWS, situated at the summit of Cairn Gorm (1245m) in the eastern Highlands, has been in operation since March 1977, though not continuously (Barton, 1984, 1987), while Aonach Mor AWS (1000m), located on the flanks of Aonach Mor, close to Ben Nevis in the western Highlands, only became operational in early 1992. Restricted to ski facilities by their need for mains electricity and telephone lines, and subject to severe riming, wind damage and local topographic effects (Curran *et. al.*, 1977; Barton, 1984; 1987), the data generated are neither complete nor necessarily directly comparable, but represent the only consistent information available about montane climate in Scotland.

The most detailed observations come from the Ben Nevis observatory (McConnell, 1988), which operated between 1883 and 1904, at which point it was closed due to lack of funds (Barry, 1992). Partial analysis of the data generated by this fully-manned station was made by Buchan (1890) and Buchan and Omond (1902, 1905, 1910), but was halted by Buchan's death in 1907. However, the data should be viewed with caution, in spite of the thoroughness of recording methods, since they were collected over a century ago, during which time climate may have changed and methods of recording climatic phenomena have developed extensively. For example, wind speed was measured in 'Ben Nevis units', rather than knots, miles per hour or metres per second.

Given the dangers of making generalisations about climate from data runs of less than 30 years (Oliver, 1964), the next best alternatives are Braemar, at 339m, Glenmore Lodge, at 341m and Eskdalemuir, in the Borders, at 242m. All three of these stations show, to a greater or lesser extent, the altitudinal climatic gradients of temperature, precipitation, wind speed and snow-lie. Confirmation of the shape and values of these gradients, which may vary spatially and temporally, is patchy, but what evidence does exist is presented here.

2.2 Variation in Temperature with Altitude.

Temperature in the free atmosphere generally decreases with increasing altitude. The rate at which this takes place is termed the lapse rate. The upper limit of lapse rates in a stable atmosphere is that of the dry adiabatic lapse rate, 9.8°C km^{-1}, but super-adiabatic lapse rates occur in unstable air. The saturated lapse rate varies with temperature according to the amount of moisture available for latent heat release, with values ranging from roughly half the dry adiabatic rate at low levels and latitudes to almost as high as the dry rate at the tropopause. A typical value used is 6°C km^{-1} (Tabony, 1985a) but with steeper rates found in relatively warm, moist, unstable air masses, this value is not representative of rates typically found in the western Highlands (Manley, 1945; Taylor, 1960, 1976; Barry, 1992), while it may approximate those of the eastern Highlands. The inherent instability of the westerly flow reaching the western coasts of Britain, combined with the thermal gradients between the land surface and the adjacent ocean create conditions where lapse rates may be maximised (Tabony, 1985a). As the seasons change, so the degree and duration of radiation changes, giving rise to different thermal gradients between land and sea, and between lowland and upland. The intensity of the mid-latitude westerly circulation is also affected by seasonal changes in radiation, which change the characteristics of air masses. Thus lapse rates also change with the seasons, as was first recognised in Britain by Manley (1942).

The steepest lapse rates have been reported in cold polar maritime air masses in spring

(Oliver, 1964; Harding, 1978; Green and Harding, 1980). At this time the strengthened winter circulation of the mid-latitude westerlies combines with differential heating of land and sea, with land surfaces responding immediately to increases in radiation while the ocean and atmosphere lag behind by approximately one month (Tabony, 1985a). Increases in radiation receipts cause melting of the thinner snow cover at lower altitudes while the deeper cover higher up remains, maximising the altitudinal gradient of snow depth and giving rise to maximum thermal contrasts between upland and lowland (Barry, 1992). The steepest altitudinal gradients at this time will be found across areas of melting snow (Barry, 1992) and the combination of factors gives rise to the steepest lapse rates. This spring maximum is also found in Norway up to a level of 2000m (Green and Harding, 1980).

Other research, such as Smith (1975), shows maxima in summer and autumn on different slopes and in different locations in the Pennines and Wales, though the majority of studies in Britain on general lapse rates indicate the spring maximum. Summer rates may be higher in areas of high cloudiness, where a greater proportion of radiation is dedicated to evaporation, rather than surface heating (Tabony, 1985a).

The environmental lapse rate over mountain slopes, or the topographic lapse rate, varies according to a number of different factors, as mountain slopes are affected by radiative and turbulent heat exchanges which modify the temperature structure in the atmosphere (Barry, 1992). Topography and aspect determine the radiation receipts at the surface and local drainage of air, giving rise to local changes in both the mean temperature gradient, as well as that of mean minimum temperature (Smith, 1975; Harding, 1978; Tabony, 1985a, 1985b). Finally, the time of day will affect lapse rates as radiation levels change, as will the amount of bright sunshine. Harding (1978) found a linear relationship in summer between daily sunshine totals and mean maximum temperature, as would be expected. Examples of

TABLE 2.1

EXAMPLES OF LAPSE RATES FOR BRITAIN.
SOURCES AS SHOWN.

Source	**Location**	**Lapse rate** ($^{\circ}C\ km^{-1}$)
Oliver (1964) (mean annual temperature)	South Wales	7.5
Harding (1978) (mean annual temperature)	Devon	9.1
	West Midlands	9.3
	Staffordshire	10.2
	Central Wales	8.4
	North Wales	8.6
	West Pennines	9.0 and 9.1
	Trans Pennine	8.6
	East Pennines	8.1
	Strathclyde	8.1 and 8.2
	Ben Nevis	7.3
	Cairngorm	8.3 and 7.8
	Moray	4.7
Harding (1979) (mean maximum temperature)	Pennines	9.5
Jones, Tinsley and Court (1979) (mean annual temperature)	Upper Don	6.4
Johnson (1985)	Balquhidder	8.9 (mean annual temp.) 10.2 (mean max. temp.) 7.3 (mean min. temp.)
Omond (1910)	Ben Nevis	0.2% of observations between August 1890 and July 1903 with av. temp. gdt. > 10.5

measured lapse rates in Britain are given in Table 2.1.

Owing to the lack of climatic data from Scotland's mountain environment, lapse rates are usually determined using only two stations, an upper and a lower one, which allows no investigation of the shape of lapse rate curves (Harrison 1974). Although some research indicates that the relationship between temperature and altitude is linear (e.g. Harding, 1978), without a greater number of stations it is not possible to verify this. The relatively low altitude, in comparison with elevation of the highest peaks, at which many of the studies have been carried out, combined with a lack of more than two recording points and the contrast between a vegetated and snow-covered surface, necessitates a cautious approach to any assumptions concerning environmental lapse rates in the montane zone. The combination of steep maritime lapse rates in spring, and the likelihood of substantial snow cover above 900m in the western Highlands generates a powerful argument for lower melt rates, or even further accumulation for the sheltered north- and east-facing late snowbeds in that area than might otherwise be expected.

The range of temperature has a more complex relationship with altitude; minimum temperatures are far more affected by local topography, such as the presence of frost hollows, katabatic drainage and temperature inversions at night, especially in winter, or by cloudiness and wind speed, than maximum temperature(Oliver, 1964; Harding, 1978; Laughlin, 1981). Mean maximum temperatures therefore largely drive environmental lapse rates, but may not adequately represent the microclimate of snowbeds and associated vegetation, where minimum temperature is likely to be lower than surrounding areas due to their location in sheltered hollows. Thus melt-freeze cycles in late snowbeds are more likely to take place throughout the summer than is indicated by exposed meteorological stations such as Cairn Gorm and Aonach Mor.

The range of temperature, both diurnal and annual, appears to decrease with increasing altitude due to increased cloudiness and wind (Oliver 1964; Tabony, 1985b) at least between 750 and 3400m, (Linacre, 1982). Buchan (1890) reported only small departures from the daily mean; +/- 1.0°C in summer and 0.2°C in winter. The range is smaller in winter as the shorter day length and higher cloudiness reduces the amount of radiation received at the surface (Barry, 1992). However, it is also apparent that the diurnal range of temperature may show very considerable variation within short time periods (less than one hour), particularly in unstable maritime air and this effect is more pronounced at higher altitudes (Oliver, 1964).

Temperature changes with altitude are therefore complex, particularly on the west coast of the Scottish Highlands where topography is complex and relief is high. The spring maximum in lapse rates is highly significant with respect to snow-lie at higher altitudes, with the presence of snow generating a positive feedback through its high albedo, and enhancing the delay in melt. As a result, strong contrasts exist between moderately late snowbeds at intermediate altitudes and the very late snowbeds found above 1000m, and between the temperature-controlled melt of the eastern versus the western Highlands. Thus work carried out in the Cairn Gorm mountains is not necessarily representative of the situation in the western Highlands.

It is important to note, from studies of soil temperature lapse rates (Gloyne, 1971; Green and Harding, 1979), that screen temperature measurements at altitude may severely overestimate temperatures at the surface (Harrison, in Taylor, 1976), indicating that temperatures taken at this height above the surface are not representative of the thermal environment experienced by plants at the surface, as indicated above for minimum temperatures. Equally, since minimum temperature can show much greater variation than maximum temperature and is less closely related to the environmental lapse rate, it is particularly difficult to establish the thermal limits of the growing season for montane higher plants.

2.3 Changes in Airflow with Altitude.

The strength and characteristics of the mid-latitude westerlies, driven by a strong circumpolar vortex which intensifies with height, lead to the expectation that in middle and high latitudes wind speed will increase with increasing altitude (e.g. Reiter, 1963 in Barry, 1992). Topography exerts two basic influences on wind speed; compression of the air mass as it rises over topographic barriers leads to an acceleration of airflow, while the surface exerts a frictional force, mostly as 'form drag' with obstacles 0.1-1.0 km in size setting up dynamic pressure perturbations (Barry, 1992). In theory, as slope angles increase, so the rate of drag increases exponentially (Taylor *et. al.* 1989), but in practice much depends upon the wind direction relative to the topographic barriers, i.e. whether they are parallel to, or perpendicular to, wind direction. In the Scottish Highlands the steep angles of the west coast mountains, plus their greater relief and surface roughness, suggest that wind speeds on western summits would be lower than over the more rounded summits of the east. Certainly the levels of wind speeds available for Ben Nevis - an annual mean of 6.5 ms^{-1}, January mean of 9.0 ms^{-1} and July mean of 4.5 ms^{-1} - are lower than might be expected (Barry, 1992) but do seem to be representative of free-air data (Thom, 1974). Davison (1985), using geostrophic wind, found wind speeds in the high Cairngorms more comparable with those of Niwot Ridge at 3750m in the Rocky Mountains (mean annual wind speed 11.0 ms^{-1}) than with other, lower mountain ranges; Barton (1987), analysing data from Cairn Gorm AWS gives an annual mean figure of 13.3 ms^{-1}, with 2.5 minute means of over 40 ms^{-1} and gusts of over 60 ms^{-1} while Moran (1988) gives the highest gust to that date on Cairn Gorm as 71.4 ms^{-1} (171 mph; 275 kph) at 0049 hours on 20.3.86, direction 168° and temperature -5.4°C. This confirms the much windier conditions experienced at Cairn Gorm which, even if the AWS readings are higher than those of the surrounding plateau, indicates higher wind speeds in general over the eastern than the western Highlands.

The rate of increase in wind speed with altitude does not appear to be linear; Pears (1967), investigating the wind environment on Creag an Leth-Choin (Cairngorms) between March 1961 and March 1963 using tatter flags found the *rate* of increase decreasing with increasing altitude, as would be expected, but nonetheless reported an eleven-fold increase in the rate of tatter between 381m and 880m. Gloyne (1967) also reports an increase in the speed and persistence of strong winds with increasing altitude, while Pearsall (1950) demonstrated that the 13 years of Ben Nevis data gave an annual average of 261 gales per year with wind speeds of more than 50mph, compared to the sea level figure of 40.

Although as a physical force wind plays an important role in terms of reducing the height to which plants can grow, it also exerts an important influence on the thermal environment of plants and animals when combined with temperature. Wind chill stress is very real to plants, as it is to human beings, with evaporation from tissue surfaces causing cooling through evaporation. Baldwin and Smithson (1979), using Steadman's index for wind chill, examined the level of wind chill in upland Britain. The results of their work are shown in Table 2.2 for data from Ben Nevis, 1344m (1895-1900), Cairn Gorm, 1090m (1967-68 and 1970-73) and Eskdalemuir 242m (30 years). As can be seen, wind chill at 1344m on Ben Nevis is, on average, very cold for December, January and February, cold for March, April, October and November and reaches a cool minimum in August. Although July is usually the warmest month at altitude (Tout, 1976), lower winds in August give generally lower

TABLE 2.2
WIND CHILL FOR THREE UPLAND STATIONS.
SOURCE: BALDWIN AND SMITHSON (1979).

Wind chill in cal.$m^{-2}s^{-1}$

Sensations for different wind chill:

Exposed flesh freezes	>400
Bitterly cold	325-400
Very cold	275-325
Cold	225-275
Very cool	160-225
Cool	80-160

Monthly mean

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Ben Nevis	312	304	265	233	240	220	156	149	193	239	265	306
Cairngorm	267	258	275	217	189	170	141	139	164	233	227	235
Eskdalemuir	150	153	126	121	108	89	80	74	97	107	134	154

Daily extremes

Ben Nevis	834	623	531	417	289	401	377	377	403	435	574	801
Cairngorm	412	464	428	376	331	296	264	270	326	364	390	354

Hourly extremes

Ben Nevis	938	841	735	651	-	-	-	-	-	-	788	865
Cairngorm	507	540	485	-	-	-	-	-	-	-	-	428

levels of wind chill. "The rates of change from winter to summer and *vice versa* are steep at all sites, the gradients tending to become greater with increasing severity of the climatic conditions." (Baldwin and Smithson, 1979, pp 298). They also identified a close positive linear relationship between elevation (x) and wind chill (y), according to the equation $y = 0.109x + 93.6$. The extreme values are very high, with the highest value (938) being recorded on Ben Nevis on 12.1.1895. The climatic conditions at the time were transitional between anticyclonic, which had in previous days allowed very cold air to stagnate, and cyclonic with strong south-easterly winds ahead of a depression approaching from Ireland. According to Baldwin and Smithson, this sequence of events is likely to give the highest levels of cooling in upland Britain, though it is often not recorded since at automatic stations such conditions often cause instrument failure (Terjung, 1966). One of the most significant features of wind chill outlined above must be the duration of very high extremes through to April; it is unfortunate that no values are given for extremes in the summer months, since this would enable useful information about the plant environment to be made available.

High wind speeds experienced at the higher altitudes in the Scottish Highlands, resulting primarily from the strong zonal flow of the mid-latitude westerly circulation, thus have important impacts on the plants of the montane zone, subjecting them to the physical stress of the force exerted by the wind, plus the physiological stresses of both desiccation and wind chill. Indirectly the wind plays another important role through the redistribution of snow to lee slopes, and the fragmentation of snow crystals during transport, generating a reworked snowpack of greater density than the original. At wind speeds of greater than approximately 60 mph, snow crystals become so fragmented during transport that they remain in the atmosphere and are not redeposited (S. Blagbrough, pers. comm.). Such speeds are not uncommon in the Highlands during the winter and spring months, making this an important mechanism in the accumulation and ablation of the snowpack.

2.4 Precipitation Changes with Altitude.

Different problems to those outlined above exist in attempting to assess how precipitation changes with altitude, since rain gauges are more easily installed, require no power source and need not be visited every day. A number of rain gauges exist in the Scottish Highlands, operated either by the River Purification Board, British Alcan, or other, individual users. However, the relatively comprehensive network still fails to address the issue with the majority of gauges located at lower levels, and there being no method of assessing the proportion of precipitation which falls as snow. Furthermore, snow is subject to redistribution by wind which, in the Scottish Highlands is a particularly prevalent phenomenon. Changes in precipitation with increasing altitude may also a vary with location, as recognised first by Salter (1921). However, the introduction of radar to detect precipitation in recent years has helped to provide a clearer picture of orographic enhancement of precipitation than is available for lapse rates.

As uplift takes place, by forced ascent when an air mass encounters topographic barriers, either the vertical motion inherent in a cyclonic system may be intensified, or conditional instability and associated showers may result, particularly in polar maritime air masses (Smithson, 1970; Barry, 1992). With higher wind speeds, the loss of water vapour content at higher altitudes is compensated for with the arrival of newly-uplifted, moist air, thus ensuring that precipitation levels may continue to increase up to high levels (3500m in the Alps; Havlik, 1968). Higher levels of instability in cyclonic maritime flow and higher associated wind speeds create more vigorous orographic enhancement than is found in anticyclonic or continental flow. With predominantly cyclonic, westerly flow in Britain and the principal source of moisture lying to the west, the highest levels of intensification are found over the western mountains (as shown in Figures 2.5 and 2.6).

Changes in synoptic patterns and flow directions therefore affect the exposure of a rain gauge and the level of rainfall it receives. This can be seen through the work of a number of authors in Britain, a summary of which is shown in Table 2.3. West slope gradients are generally higher than east slope gradients, as found by Ballantyne (1983), although the shape of the topography may change the situation, as found by Burt (1980). While west slope gradients are broadly linear (e.g. Ballantyne, 1983), east slope gradients tend to be curvilinear (Ballantyne, 1983; Burt, 1980), with high levels of precipitation immediately on the steep lee side of ridges (Burt, 1980). As distance from the ridge increases, so the level of precipitation tails off exponentially as a result of moisture depletion of the air mass from previous rainfall and warming of the air mass during descent. It therefore depends on how great the distance is between gauges on an east slope as to how steep the precipitation gradient is.

Smithson (1969) found significant variation in precipitation gradients west of Loch Lomond, depending on local topography and individual rainfall events, but found the highest levels of enhancement in spring and winter in undifferentiated fronts and polar maritime air streams. Harrison (1985) found the highest levels in autumn and winter, with lower levels from April to July, but there is general agreement in higher levels of orographic enhancement during the winter and early spring months (except February which can be more dominated by anticyclonic conditions) when cyclonic flow is at its

TABLE 2.3
PRECIPITATION GRADIENTS FOR DIFFERENT LOCATIONS IN BRITAIN.

SOURCE: BALLANTYNE, 1983; HARRISON, 1985.

Source	*Area*	*General gradient*	*West slope gradient*	*East slope gradient*
Unwin, 1969	Snowdonia	4.58	-	-
Harrison, 1973	Cardigan Bay - Plynlimon	-	2.28	-
Taylor, 1976	Upper Wye and Severn	1.71	-	-
Rodda, 1962	Ystwyth catchment	-	1.67	-
Hill *et. al.*, 1981	Glamorgan Hills	3.25	-	-
Pearsall, 1968	Central Pennines	-	1.88	0.98
Burt, 1980	Southern Pennines	1.81	1.32	2.02
Harrison, 1985	Gargunnock Hills	1.18	-	-
Harrison, 1985	Ochils	1.65	-	-
Gloyne, 1968	Scottish Highlands	-	2.81	0.88
Ballantyne, 1983	Fisherfield forest, W. Ross	-	4.65	2.67

most intense, and lower levels in the summer when cyclonicity is reduced.

Browning, Hill and Pardoe (1974, 1975), investigating the level of orographic enhancement in warm and cold sectors of depressions in wintertime found the greatest level of enhancement in warm sectors with a deep moist layer and strong south-westerly to westerly winds. They identified that the "rate of condensation during forced ascent over a mountain barrier is roughly proportional to the wind component normal to the barrier and it increases with wet bulb temperature" (Browning, Pardoe and Hill, 1975, pp334). This condition is generally found in the warm sector ahead of a cold front, confirming Douglas and Glasspoole (1947)'s and Holdgate (1973)'s findings of highest levels of rainfall between the warm and cold fronts. However, conditions for high orographic enhancement do not always exist in this zone; both seeder and feeder clouds are required, with the presence of high wind speeds, a low level jet and ascent upwind of Snowfall the hills allowing maximum replenishment the depleted feeder cloud (Browning, Pardoe and Hill, 1975, Browning and Hill, 1981; Harrison, 1985). Little orographic enhancement was identified in the surface cold front where heavy rainfall took place irrespective of altitude.

With strong cyclonic flow in winter and early spring, with intense orographic enhancement of precipitation and associated steep lapse rates, it follows that high levels of solid precipitation will be found on the western mountains above the freezing level and that there will be a high level of drifting in the accompanying strong winds (Ward, 1981). The high degree variability in temperature in a frontal system, with a sector of warm air surrounded by colder air and strong winds to enhance evaporation are likely, however, to make the elevation of snow-lie very changeable, giving the more ephemeral snow cover at lower and intermediate altitudes so typical of the western

Highlands. It is significant that the amount of precipitation during zonal flow is so high, since in the sheltered and shaded locations of many of the late snowbeds large accumulations of snowdrift result from the high winds associated with zonal flow at altitude in the Scottish Highlands.

2.5 Snowfall and Snow-Lie.

Snow cover affects local and regional climate by depressing the temperature in the air above it (Cohen, 1994). Lamb (1972) showed how snow cover can delay warming by several weeks in western Europe and a number of empirical studies show temperature anomalies of 5°C reduction, with effects lasting from several days to several months (Namias, 1960, 1962; Wagner, 1973; Dewey, 1977), while models of climate indicate anomalies of 1 to 10°C reduction in air temperature over areas of snow (Walsh and Ross, 1988; Cohen and Rind, 1991). Thus the presence of a snow cover has a positive feedback mechanism to enhance its survival in above-freezing temperatures, by steepening the lapse rate of temperature as described earlier. The presence of a snow cover also increases the chance of rain falling at low temperatures turning to snow, by depressing the temperature of the air immediately above the snow cover (Cohen, 1994), though whether this is purely a product of the snow cover or also involves loss of energy through precipitation is not clear.

Precipitation at surface temperatures close to freezing will fall at higher levels in the cloud as snow; as this snow melts as it approaches the surface, the loss of latent heat of fusion causes cooling in a layer 200-300m deep above the surface (Stewart, 1985). Lumb (1983) observed that when wet-bulb temperatures were 0°C at 300-400m altitude when snowfall commences, within one hour the level of snowfall will have dropped to 150-200m. Therefore the prolonged duration of precipitation associated with frontal systems so typical of the Scottish Highlands enhances the proportion which falls as snow rather than rain.

Snowfall in western Scotland often takes place at temperatures slightly above freezing and this is the kind of snow which is most beneficial for the skiing industry since its high moisture content leads to a reduced amount of drift (Nevis Range, 1992, pers. comm.), but which is therefore not likely to make a significant contribution to accumulation in the late snowbeds. However, prolonged precipitation associated with deep low pressure systems will gradually turn from sleet or wet snow at onset to drier and colder snow. This mechanism will, to some extent, offset any trend towards rain rather than snow in the hills during winter should zonal flow continue to be strengthened, as shown by Mayes (1996).

A number of different authors have estimated temperatures at which snowfall is more likely to take place than rainfall; Glazyrin (1970, in Barry, 1992), examining snowfall in central Asia shows that the temperature at which the probability of 50% of precipitation falls as snow rises from 1°C at 500m a.s.l. to 4°C at 3500-4000m. Davison (1985) states that snow may fall in the Eastern Highlands at temperatures of up to 7°C, but more commonly falls at temperatures below 4.5°C; he defines the surface air temperature at which precipitation will take place as snow to be 2°C. Manley (1969) states that the probability of precipitation falling as snow is highest at temperatures below 3°C, while Ward (1981) found that 90% of all precipitation in the Cairngorms falls as snow when the daily maximum temperature falls below 1°C, and that 90% of all precipitation falls as rain above 7°C. The temperature at which precipitation falls as snow or rain is important in the Highlands, particularly the western Highlands since air temperature is often close to freezing, but given the cooling which takes place during prolonged precipitation, it is the temperature at onset combined with the duration of precipitation which is crucial. A threshold temperature may, however, exist below which a sufficient proportion of the precipitation is falling as snow, generating a complete cover on the ground surface beneath and enabling cooling of the overlying air to take place; and above which insufficient snow cover is generated to allow cooling (and enhanced snowfall) to take place.

The estimated values for the proportion of precipitation falling as snow in the winter months for Ben Nevis and Cairn Gorm, at 800m, is shown below (from Thom, 1974; Davison, 1985):

	Cairn Gorm	Ben Nevis
December	72.9%	44.0%
January	84.9%	53.0%
February	83.1%	53.0%
March	70.4%	51.0%
April	43.6%	49.0%

The relatively higher figure for Ben Nevis in March and April Davison attributes to steeper lapse rates at this time of year, as would be expected, while the greater proportion of snowfall in the Cairngorms is related to the lower temperatures experienced there as a function of reduced oceanicity. With lapse rates of around 8°C km^{-1} for winter and early spring (see above), it follows that the proportion of snowfall in the western Highlands would rise to nearer 100% at 1300m throughout the winter and early spring months.

The origin of air masses which contribute most to snow cover in the eastern and western Highlands differ, as shown in Figures 2.4 and 2.6, with the western Highlands experiencing most snowfall from maritime air masses of polar or arctic origin, while the eastern Highlands receive their snow from arctic or polar continental air. Winters with strongly cyclonic (zonal) flow will give high accumulations of snow at higher elevations in the western Highlands and little in the east, while blocking conditions allowing the incursion of polar/arctic continental air will give deep accumulations at all levels (owing to the colder nature of the air) in the east with little in the west.

Although the quantities of precipitation associated with westerly air streams are greater and therefore the eastern Highlands lie largely in a rain-shadow location, it is, nonetheless, the Cairngorms which are the snowiest mountains in Britain (Watson, 1992; Watson, Davison and French, 1994). Greater gathering ground for snow on the eastern plateaux, lower winter and spring temperatures in the east than in the west, and a higher percentage of total precipitation falling as snow in the east (see above; Jackson, 1978) are all factors in determining this distinction. However, the differences between west and east become less with increasing altitude, although differences still remain, as may be experienced from year to year in the location of the best skiing.

It seems most likely that the threshold temperature for precipitation generating a snow cover is increasing in elevation as global warming takes place, but with seasonally variable lapse rates, its average elevation is unlikely to remain consistent through the season. In the western Highlands where environmental lapse rates may be super-adiabatic, an increase in temperature at sea level of 2°C would mean an increase in the elevation of the threshold temperature for snow accumulation of approximately 200 - 300m. With the latest snowbeds confined to elevations of more than 1000m, and snowfall usually taking place in winter and spring at present at 500 - 800m, it is unlikely that precipitation state will change over the late snowbeds in the future. In other words, if late snowbeds do diminish in depth and therefore duration, it will be because of mid-season thaws, rather than a change from snow to rain at elevations of over 1000m in winter and spring.

Changes in the atmospheric circulation in the mid-latitudes are discussed further in Chapter 9, but it is important to note that there is an identifiable shift towards a higher proportion of westerly and fewer easterly air streams (Mayes, 1991; Hulme and Jones, 1991), giving rise to decreasing duration of snow-lie and higher snow-lines in general (Harrison, 1992), with less persistent snow cover in the early part of winter (up to January), more gales and heavy precipitation and a higher incidence of late snowfall in late April (Green, 1975; Harrison, 1993). Green (1975), Spink (1980) and Watson, Davison and French (1994) identify the ephemeral nature of snow-lie in the early part of the winter - October through to late December - and point out that snow accumulation in Scotland is not consistent through the winter as it is in the Arctic, with ablation of snow at all levels possible. This must be in part because lapse rates are at their lowest in winter (November - February) and steepest in spring (March - May), with a high frequency of westerly air streams in the last three months of the year. The passage of a warm sector may, therefore, melt whatever snow cover exists by a net downward flux of sensible and latent heat, since air temperatures at altitude are not consistently below freezing.

The incidence of higher temperatures at station level in March and April will be offset by steeper lapse rates, prolonging winter at higher altitudes relative to station elevation. High temperatures for December with shallower lapse rates indicate less severe conditions in early winter at high altitude, declining into more severe conditions in January and February. In summary "Snow cover varies greatly from winter to winter, with complete snow cover possible at any time from October to May, whilst rapid thaws can denude most of the massif of snow at any time in the winter" (Purves, Barton and Wright, 1994, pp 199). The occurrence of thaws throughout the winter months may explain, at least in part, why the density of snow in Scotland is higher than expected, as found by Ferguson (1984).

Jackson (1978) has developed formulae to describe the duration of snow cover at any altitude, using the median value of snow cover at sea level; the mean value is too biased by a heavily skewed distribution to be of use. His work identified an exponential increase to 400m, above which altitude the relationship becomes linear. Comparisons with data from Vancouver, British Columbia, show that there are great similarities between the two locations, with maritime air masses causing substantial increases of snow cover with altitude. Thus a steep gradient exists of snow cover with respect to map distance (Harrison, 1993), particularly in the west where the mountains are generally steeper. However, it seems unlikely that the relationship remains linear with increasing altitude and it is expected that the curve will steepen as the summits are reached. High levels of exposure an summit ridges and plateaux reduce the potential for snow accumulation and therefore these areas become snow-free earlier than the accumulation zones downslope.

The relationship between snow depth and altitude is complex (Barry, 1992), particularly in the Scottish Highlands where snowdrift and wind-drift are such prevalent phenomena and there is evidence that the rate of drift is exponential to the level of wind speed, rather than linear (Fohn, 1980; Ward, 1981; Davison, 1985), thereby increasing its significance. Topography plays an important role in the distribution of snow cover since, in conjunction with the direction of the wind, it determines where drifts will develop and how deep they become.

The predominance of snow-drift and wind-drift from southerly and westerly directions shown by Davison (1985) indicates that slopes of northerly and easterly aspect will be particularly heavily loaded. Additionally, because wind directions have been predominantly westerly since the last glaciation, corries are generally found to have northerly and easterly aspects, where weathering and erosion have been most effective. Steep-sided corries, often ringed at the back and sides by cliffs, are efficient traps for snow and drifts reach great depths close to corrie headwalls. Avalanche debris is also common in this situation, with heavily-laden slopes above prone to avalanche under the weight of snow. The combination of strong prevailing winds in both speed and persistence of direction, with the incidence of appropriate traps on lee slopes generates much greater drift depths than might otherwise be expected in the Scottish Highlands.

Additionally, a rapid change of slope at the edge of a plateau or along the top of a ridge, generates snow build-up in the form of a wave lying on the lee side of the ridge. The pattern of wind which produces this wave-form, termed a cornice, is shown in Figure 2.7 while hollows or down slopes generate lee eddies which may produce a scouring effect in the lower part of the hollow, or down from the break in slope. Snow deposition on the lee side of a ridge in the Alps for two snowfall events is shown in Figure 2.8, which demonstrates a high level of deposition immediately after the break in slope, plus the effects of scouring below that point.

Cornices developed on very steep slopes, or above cliffs are usually released during

FIGURE 2.7

DIAGRAM TO DEMONSTRATE THE BUILD-UP OF SNOW INTO A CORNICE ON THE LEE SIDE OF A HILL.

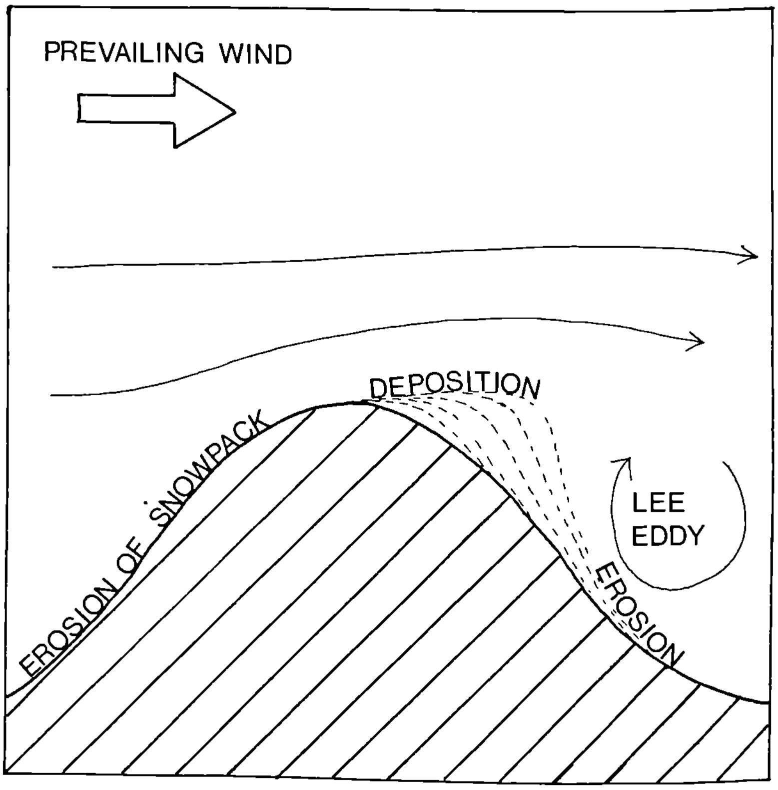
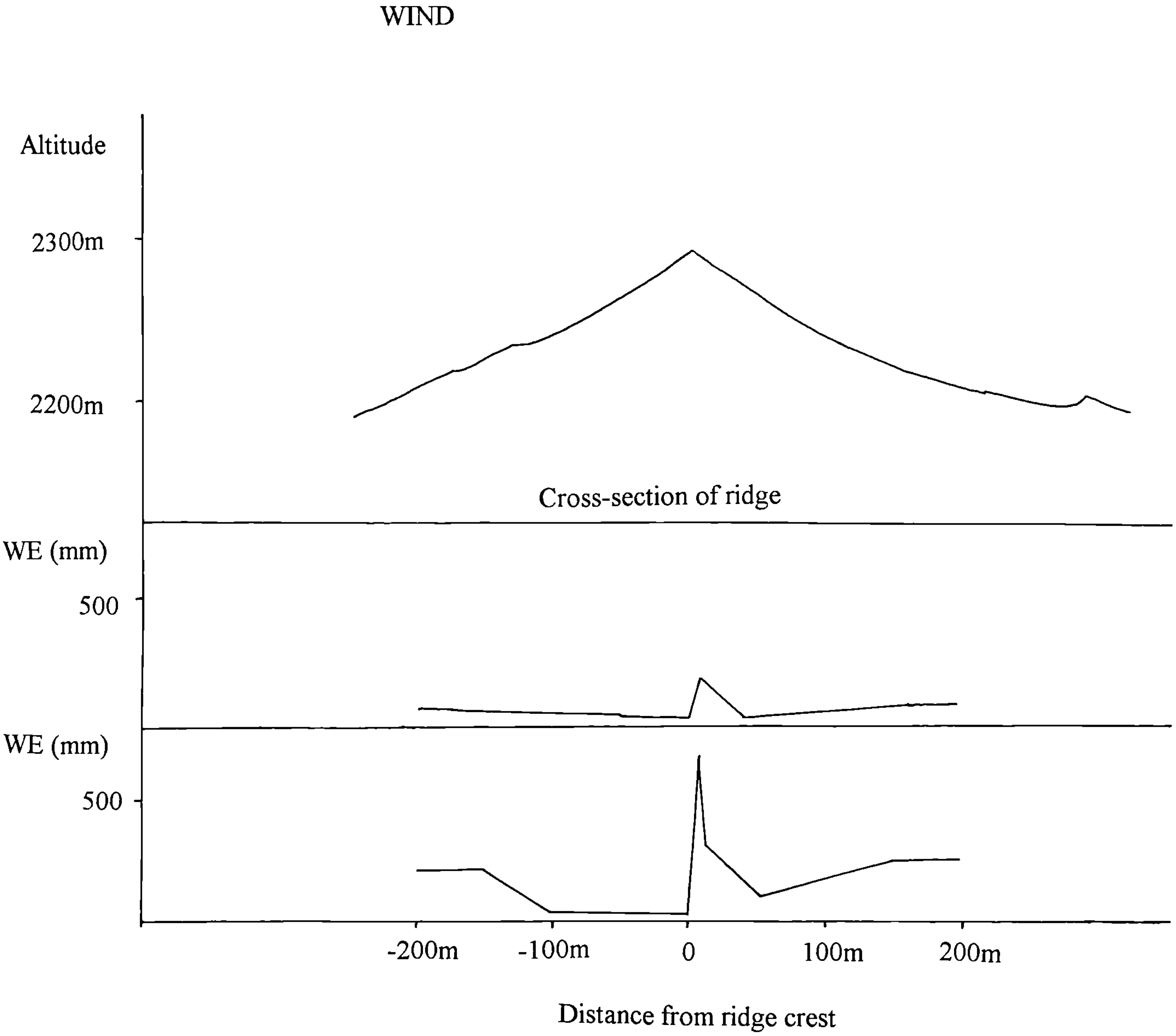


FIGURE 2.8

SNOW DEPOSITION OVER A RIDGE; MEAN AREAL MASS BALANCE IN WATER EQUIVALENT.

SURPLUS SNOW DEPOSITION ON LEE SIDE AND
IRREGULAR SNOW ACCUMULATION PATTERN CAN BE OBSERVED
FOR TWO DIFFERENT SNOWFALL EVENTS.

SOURCE: FÖHN, 1980.



thaws or periods of heavy deposition, but those developed on gentler slopes, of 50° or less, will not normally release unless overlying bare rock slabs. These cornices can generate ideal accumulation sites for late snowbeds.

Gullies formed within the cliffs of north-east-facing corries also provide a suitable situation for the formation of late-lying snowbeds: the most well-known semi-permanent snow patches in the Scottish Highlands are in Observatory Gully, Ben Nevis and an Garbh Choire, Braeriach, both steep-sided north-easterly facing corries with shaded and sheltered gullies where the snow lies longest. Snow build-up in the gullies from deposition is supplemented by substantial cornice development, while a sheltered microclimate and low insolation receipts in summer enhance the durability of these snowbeds (Watson, Davison and French, 1994). The lower rates of melting found in these gully locations also mean that thaws throughout the winter and early spring will have less impact on these snowbeds.

2.6 Snow Melt.

Heterogeneous snowpacks, developed in areas of seasonal snow cover, melt in a very complex way. Long-wave radiation and convective heat transfers take place at the snow-air interface, while short-wave radiative transfers, although strongest at the surface, may penetrate to some depth. There may also be small amounts of energy released from the ground beneath the snowpack, causing limited melting at the base (Gray and Male, 1981), while rocks buried within the snowpack or located at the ground surface absorb energy more efficiently than their surroundings. Melt water is released from the snowpack when it becomes isothermal at 0°C, though in deep packs melt may take place in the upper layers before the structure of the pack is completely isothermal. Melt water or rain falling onto the snow surface will drain slowly through the upper layers but channels quickly develop, allowing rapid movement of water to lower levels. Ice layers in the snow, or layers of high density neve, may be impermeable to percolating water so lateral, as well as perpendicular channels will develop. With rain falling on a snowpack, changes in temperature with depth can also be very rapid, depending in part on the rapidity with which water can percolate through the snowpack. The changes in thermal structure in a snowpack with rainfall onto it is shown in Figure 2.9. In mountain areas such as the Scottish Highlands, where snowpacks are highly stratified and spatially variable, the internal retention and movement of water is complex and analysing the transmission process very difficult.

The total radiation receipt at the snow surface, the condition of that surface, the density of the snowpack, its thermal stratification (or lack of it) and water content all affect the radiation balance of snow. Soiled old snow reflects much less short-wave radiation than new snow with reflection coefficients in visible and u/v wavebands falling from as high as 0.98 in fresh snow to 0.40 in ageing snowpacks. Radiation also penetrates the snow up to depths of 10m for short-wave radiation in ice, though only to 1m in fresh snow, with the radiant energy flux decaying exponentially from the surface according to Beer's Law. Internal water movements and phase changes further complicate matters, with the percolation of rainfall and melt waters and possible subsequent refreezing representing heat and mass transfers and heating of the snowpack through the release of latent heat, while the scattering effect of crystalline structures increases the effective path length of radiant energy.

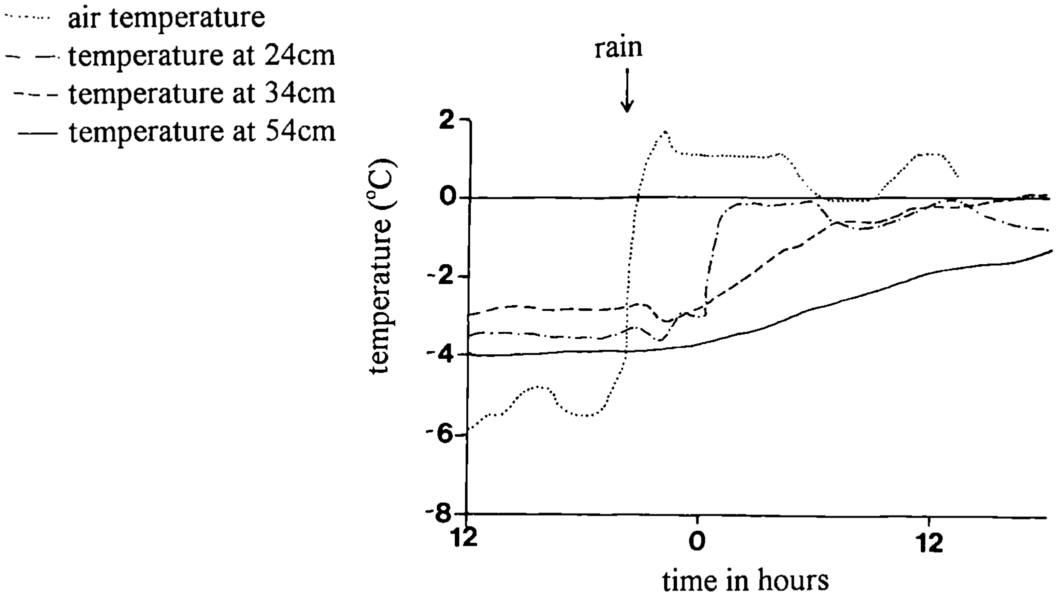
Because radiation penetrates through snow, melting from the warmed surface beneath the snow may become significant as the snow cover thins, from depths of 0.15m or less

FIGURE 2.9

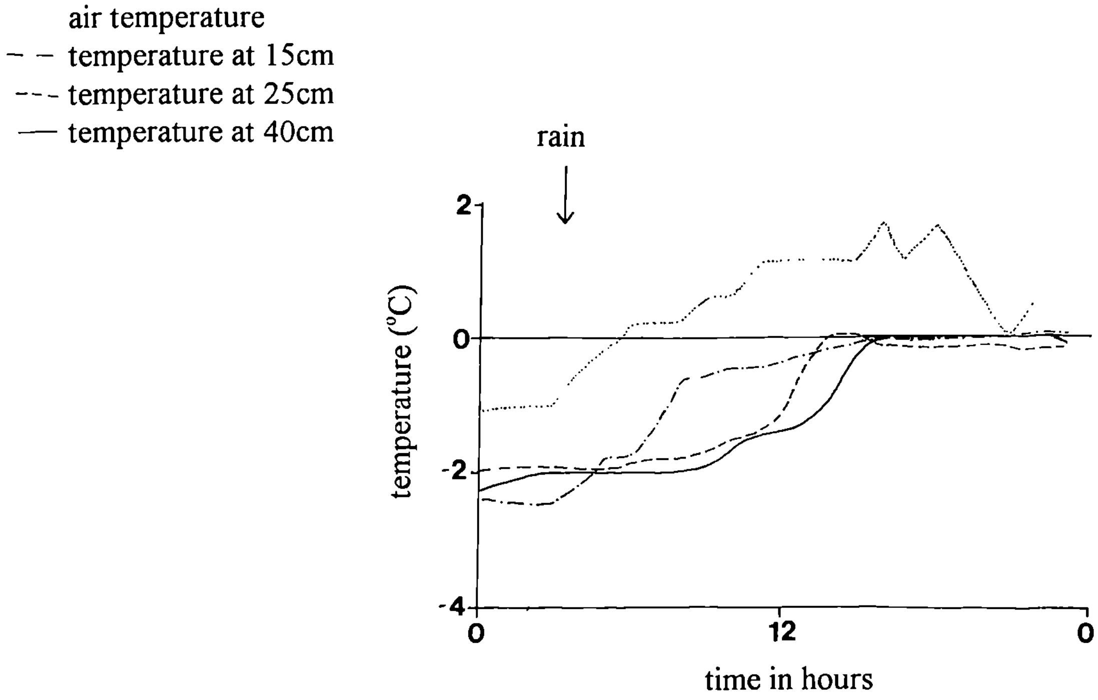
SNOW TEMPERATURE PROFILES AND IMPACT OF RAIN ON SNOW

SOURCE: CONWAY AND RAYMOND, 1993.

A. Rapid change in air temperature and delayed response of the snowpack.



B. Temperature change following rain producing an isothermal snowpack.



(Oke, 1987). At this point the rate of melt increases and, additionally, vegetation may experience the change from short-wave to long-wave radiation, signalling the thinning of the snowpack and possibly acting as a trigger for beneath-snow growth (Richardson and Salisbury, 1977; Oke, 1987). Fluctuations in temperature at the edge of the snow may be great, with freeze-thaw cycles common (Gardner, 1969).

Meltwater and rainfall percolating through the snowpack does so only slowly in new snow, but creates, and then preferentially follows, channels within the pack, allowing water to penetrate to great depths; this not only transfers energy to deep within the snowpack but also destabilises it and may cause avalanching or sloughing (Conway and Raymond, 1993) and the partial or complete destruction of one snowfield.

Ferguson (1984) showed that the high density of snow in the Scottish Highlands greatly affected its durability, with extensive metamorphosis of the snowpack through the action of wind and repeated *freeze-thaw creating conditions of greatest resistance* to melting through the inhibition of meltwater transmission. The absence of depth hoar in deep and older Scottish snowpacks increases their stability and further reduces the rate at which they melt. The evolution of Scottish snowpacks, which differs from many other countries with seasonal snow cover, in some measure explains why an area of such low elevation and mild lowland climate can generate snowbeds which survive into the summer season.

Predicting the rate of snow-melt from air temperature alone, as is normally possible at other locations, is fundamentally inadequate in the Scottish Highlands (Ferguson and Morris, 1987), but these authors proposed that the use of wind data in addition to temperature data might produce better predictions. The greatest levels of melt were achieved with warm airflow and higher wind speeds, with or without rainfall, conditions typical of cyclonic air flow, unlike the findings of McGregor and Gellatly (1996) for the Pyrenees where high levels of radiation typical of anticyclonic conditions generated the greatest levels of melt. Condensation of water vapour onto the surface of the snow from a moist air mass above it takes place under conditions such as are commonly found in the Scottish Highlands, since the surface vapour pressure of the snowpack is low, generating significant quantities of energy because the latent heat of vaporisation is 7.5 times greater than the latent heat of fusion required to melt the equivalent mass of snow (Oke, 1987). High wind speeds renewing the moist air supply above the snowpack enhance this process.

It is not clear whether the particular conditions found in Scotland differ significantly from those found by other authors (Grainger and Male, 1978, for the Canadian Prairies; Yarnal, 1984, for western Canada; Hay and Fitzharris, 1988, for New Zealand; Brazel *et. al.*, 1992, for Alaska; Aizen and Aizen, 1993, for Tien Chan) all of whom agree with McGregor and Gellatly (1996) that high insolation produces the greatest levels of melting rather than the high levels of melt induced by the mild, relatively moist but predominantly windy conditions typical of oceanic mountain ranges, although some of the authors above have worked in areas of high oceanicity, such as New Zealand. It seems likely therefore, that the hyperoceanic climate of the Highlands, and particularly that of the western Highlands where conditions for the highest levels of snow melt are very infrequent, will rarely, if ever, achieve the conditions for maximising snow melt, thus making these mountains snowier later than other, more continental areas with marginal seasonal snow cover.

Temperatures at which melt takes place are in theory any above freezing, but given the above, Davison (1985, pp 29) states that "in practice....days on which snow could have melted should have maximum air temperatures of above 2.5°C and not having snowdrift or wind-drift occurring." Examination of Davison's figures for thaw days during the winter/spring season (December to April) show that the mean number of days with high temperatures and rainfall less than 1.0mm are 4.7 in December, 2.7 in January, 3.8 in February, 8.1 in March and 14.8 in April. The mean number of thaw days with high temperatures and rainfall greater than 1.0mm are 4.5 in December, 2.8 in January, 2.4 in February, 4.9 in March and 6.9 in April. The effect of cooling during precipitation events in spring months can clearly be seen in these figures. A thaw day is defined by station (300m) maximum air temperature greater than 6°C. However, with spring lapse rates of 10°C km^{-1} this could still mean that air temperature at 900m and above could be below freezing, particularly with the cooling effect a snow cover has on overlying layers of air. Therefore the figures for thaw days given above should be treated with circumspection for snow cover at the higher levels in the Highlands. Equally, the definition of the temperature at which thawing takes place seems somewhat arbitrary, apparently taking no account of phenomena such as thawing in low air temperature and intense solar radiation (Kohl and Jordan, 1995). Although Davison's contribution to the understanding of the distribution of snow through drift should not be underestimated, flaws in parts of his argument must cast some doubt on the validity of the rest.

During the melt season, the acidity of meltwater may change substantially. Particulate pollutants from the atmosphere are often the objects around which snowflakes form, which in turn scavenge more pollutants from the atmosphere as they fall through it.

New snow is therefore by nature more acid than its rainfall counterpart and the enrichment of some ions, such as Cl^-, Na^+ and Mg^+, increases with altitude, causing an increase in snowpack acidity with increasing altitude (Helliwell, 1997). Most ions, such as H^+, NO_3^-, SO_4^{2-} and Cl^-, are not held in the ice crystals, but instead in the interstitial water at the grain boundaries (Hibberd, 1984). This water is flushed preferentially from the snowpack, with fractionation of ions also taking place, such that the onset of the main melt is observed as a flush of acidity in snow-melt and, further downstream, in stream water (Morris and Thomas, 1985; Schoendorf and Herrmann, 1987; Craig and Johnston, 1988; Tranter *et. al.*, 1988; Hewitt, Cragin and Colbeck, 1991; Hendershot, Mendes and Lalande, 1992; Davies *et. al.*, 1991; Davies *et. al.*, 1993; Jenkins, Ferrier and Waters, 1993). The degree of fractionation and preferential elution is determined by the metamorphic processes undergone by the snowpack (Hewitt, Cragin and Colbeck, 1991), while in the Cairngorms, the back trajectory of the air masses generating snowfall is also significant in determining the initial acidity of the snow (Tranter *et. al*, 1988; Davies *et. al.*, 1991; Jickells *et. al.*, 1992).

Concern has been expressed about the possible effects of acid deposition in general (Thompson and Baddeley, 1991) and acidic flush events in particular (Woolgrove and Woodin, 1996) on underlying vegetation. Experiments undertaken by Woolgrove and Woodin on the snowbed bryophyte *Kiaeria starkei* indicate that lasting damage may be sustained following irrigation with highly acid meltwater for plants which have both been exposed to daylight and been subjected to a "beneath snow" regime. However, problems exist with both the procedures used and the conclusions drawn. Irrigation treatments with simulated meltwater of pH 3.2 were the only treatments to generate damage in the plant, but reports of the "black" snowfalls of the Cairngorms on which this treatment is based, recorded only snowfalls of acidity that low, while meltwater acidity was less acid at approximately pH 4. Treatments with simulated meltwater of pH 4 did not show damage to the plants. The "beneath snow" regime used included a temperature of +2°C and 2% penetration of natural daylight. Unless snow cover has thinned to a depth of less than 0.15m, temperature at the snow-vegetation interface is largely isothermal at between 0 and +1°C, while the composition of penetrating radiation differs from that of natural daylight, being only short-wave radiation. In addition, the paths followed by meltwater in the main period of the melt are unlikely to result in the constant irrigation of large areas of the snowbed core vegetation.

Meltwater percolating through a snowpack rapidly becomes channelised, both vertically and horizontally. The highly stratified nature of Scottish snowpacks, the great depth of the snowbed patches until relatively late in the melt season and their location on the uppermost sections of hillslopes indicate that very little meltwater will reach the ground surface beneath the late snowbeds until well after the main period of melt has taken place. That which does percolate to such depths is likely to become either rapidly channelised on the ground surface, or percolate into the substrate, where base cation exchange will rapidly reduce its acidity (Craig and Johnston, 1988). The location of the late snowbeds on generally moderate to steep slopes with a gravel substrate and little soil stratification will enhance the propensity of meltwater to move to shallow groundwaters. As the late snowbed continues to melt later in the season, smaller-scale, local acid flushes are likely to take place, as indicated by Woolgrove and Woodin, but unless accompanied by a "black" snowfall, their acidity is likely to be much less.

The problems outlined by Thompson and Baddeley (1991) for *Racomitrium lanuginosum*, generally found on summit plateaux and a strongly chionophobous species, are not paralleled in the snowbed, since the location of *R. lanuginosum* makes it more prone to severe riming than the development of a persistent snow cover generating preferential elution. Rime in the Cairngorms was reported by Ferrier, Jenkins and Elston (1995) to contain sea salt at concentrations 2 - 5 times greater than the concentrations of snow deposited over the same period, while excess sulphate concentrations were double and nitrate concentrations 4 times higher.

Acid deposition takes place in the Scottish Highlands (Mason, 1992), and it is likely to have some effect on the vegetation of the montane zone. However, all studies reported here have been conducted in the Cairngorm mountains, in the east central Highlands. The back trajectories of the "black" snowfalls generating by far the greatest acid inputs indicate former Eastern Europe, particularly the Baltic states as the source (Davies *et. al.*, 1992), while the synoptic conditions under which they fall are associated with a decaying anticyclone over the British Isles with a depression and associated frontal system in the west, as was the case during the deposition of fall-out from Chernobyl (S.J. Harrison, 1997, pers. comm.). Under these conditions the majority of precipitation and therefore also acid deposition will take place in the eastern part of the country (Weston and Roy, 1994) with very low levels reaching the western part. Additionally, while some acid deposition does reach the west, it is heavily diluted with much "cleaner" maritime deposition. Therefore, while the threat may remain for damage to some montane vegetation in the east, much of the vegetation in the west, and particularly snowbed vegetation, seems unlikely to be adversely affected. Acidity readings from the Aonach Mor snowbed may confirm or deny the foundation of this proposal.

2.7 The Survival of Late Snowbeds.

According to Manley (1971) the survival of snow patches into the summer is likely to be dependent on two things; the accumulated temperature during the melting season (early May to late October) and the depth of snow accumulated in the previous winter, in particular during a cold April and May. Watson, Davison and French (1994) also identified the snow depth achieved prior to melt through the measure of snow-drift, especially during January, February, March and April, as one of the two factors most closely correlated with snow-patch survival, the other being winter and spring temperature. Their results, however, show no links between summer climatic conditions and snow-patch survival until October is reached, at which time only a few patches remain. More critical is the temperature during winter (November to March) and spring (April to June). Spring precipitation, snow-drift and temperature were more important than winter, since the frequency of thaws during the months up to February means that there is not a consistent increase in snow depth throughout the winter, as in Arctic locations. The importance of spring temperatures as opposed to snow-drift through the winter and spring increased at lower altitudes where snow-lie is more ephemeral. At higher levels snow depth remained the most important factor determining patch duration.

These results complement the findings of Spink (1980) whose observations through the 1960's and 1970's provide a useful guide to the location of long-lasting snowbeds, confirm the persistence in the location of these beds and led him to conclude that January through to May were the vital period of snowfall, with particularly precipitation and temperature in March and April giving the essential criterion of summer snow survival.

Watson, Davison and French (1994) found an exponential decay curve for all snow-patches with a constant proportional loss of both snow-patch number and length. The number and length of snow-patches was not related to summer climate and the single most important regressor factor for snow-patch survival through to the following winter was the number or total length of snow-patches in July. Should a snow patch survive through to July, then because temperature starts to decline from that month onwards, its chances of complete survival improve.

Trends in summer snow survival identified by Watson, Davison and French (1994) show an increase in the variability of summer loss rates, plus a small negative trend in the duration of snow-lie in general. Their observations were confined to snow patches in and around the Cairngorms and these results conform with the observed increase in westerly air streams in winter months, reducing the supply of snow to the eastern Highlands and therefore the depth of accumulation.

No such observations are available for the western Highlands which may, at high altitudes, show an increase in summer survivals with an increased supply of snow and greater depth of accumulation, especially in spring. Such a difference between the western and eastern Highlands, given the differences between their climates at all times of the year. Colman and Moralee (1991), looking at snowfall and snow-lie data for Eskdalemuir identify an increase in snowfall concurrent with an increase in northerly and north-westerly showery air streams, which would agree with the proposal above, but also found an increase in the number of warm days and nights, and a decrease in the number of cold nights, though not days.

The interaction of climate and topography in the Scottish Highlands generates snowbeds of high loyalty and variable duration, at least in the Cairn Gorm massif, as found by Watson, Davison and French (1994). This statement forms the basis of one of the factors to be investigated, which is that high snowbed loyalty and variation in duration is also true of the western Highlands, depending on the depth of accumulation in the late winter and spring months at specific locations. Should this hypothesis be valid, then distinctive vegetation of the types identified by Rothero (1989) must be found. Since Rothero's (1989, 1990) sites included a number of locations in the western Highlands, including the eastern face of Aonach Mor, then to a certain extent this hypothesis is already validated through the literature. However, further verification is necessary to provide a firmer basis of understanding for the Scottish snowbeds.

Lack of information concerning the climate in the Scottish mountains is one of the most recurrent themes of the literature; any information available from the Aonach Mor Automatic Weather Station must therefore be given an high priority and should be examined in detail. There is also an apparent lack of co-ordination between the various different aspects of climate and snow-lie examined by different authors and organisations, with no attempt made by the Meteorological Office to integrate the climatic data from Cairn Gorm AWS and other Stations with information from the Snow Survey of Great Britain or observations made by other individuals, such as Green (1975), Spink (1980) and Pottie (1994). Other features, such as the surprisingly high density of Scottish snowpacks observed by the Avalanche Information Service and Ferguson (1984) need to be more closely related to prevailing weather patterns and the climate at altitude, while further work on lapse rates and their seasonal variation and sensitivity to climate change is another obvious target.

The hypothesis that snowbed loyalty is high but snow-lie duration variable has been, at least in part, verified through the literature. Further investigation is needed to check its applicability to the western Highlands. An investigation must now be made of the information available about the vegetation found in this environment and the specific attributes and strategies adopted which enable it to survive and procreate, to establish how the hypothesis that snowbed core vegetation is sub-optimally placed in the snowbed, and restricted by the competitive ability of surrounding vascular plants who themselves cannot tolerate the stress of late-lying snow, is addressed by the literature.

Summary points:

1. Three climatic gradients may be found across the Scottish Highlands, altitudinal, latitudinal and longitudinal, all of which are relatively steep.

2. The predominantly westerly circulation affecting the Scottish Highlands generates high wind speeds and levels of precipitation, with the steepest lapse rates in spring in cold, polar maritime air.

3. The environmental lapse rate is complicated by topography and the presence of an incomplete snow cover, but relatively little information exists for this location.

4. Wind speed increases with elevation, though not linearly, with the highest wind speeds in the eastern Highlands where friction exerted by topography is lower than in the west. Wind chill is high in the mountains and snow distribution strongly affected by the wind.

5. Strong cyclonic flow gives rise to vigorous orographic enhancement of precipitation, though the gradient of enhancement differs between season and slopes of different aspect.

6. Snowfall often takes place in air temperatures above freezing, with the long duration of precipitation events increasing the proportion that falls as snow as time progresses. In the western Highlands most snowfall comes from maritime polar or arctic air masses, while in the east it comes from continental polar or arctic air masses.

7. Topography and wind interact to redistribute snow, such that the greatest accumulations are on slopes of northern and eastern aspects.

8. The dense, heterogeneous snowpacks of the Scottish Highlands reduce the rate at which snow depth decreases during melting and increases the complexity of the meltwater flow.

9. High levels of acid deposition on air masses of eastern back-trajectory give rise to preferential elution of ions from the snowpack. Rapid base cation exchange takes place and thus this is unlikely to be adversely affecting snowbed vegetation at present.

10. The survival of late snowbeds in the Scottish Highlands is determined by winter temperature and accumulated depth at the end of winter, while loyalty to location in the Cairngorms is high due to persistence in the prevailing wind.

11. There is very little information concerning climate and snow-lie at altitude in the Scottish Highlands and it is not clear whether an in crease in temperature at sea

level predicted for climate in the future will be transferred to altitude, owing to variable lapse rates.

CHAPTER 3

VEGETATION AND THE MONTANE SNOWBED ENVIRONMENT

3.1 Montane Vegetation.

Montane vegetation is found above the level of the natural tree-line. The natural tree-line is seen in only a few isolated pockets, such as on Creag Fhialcach in north-east Scotland (Ratcliffe, 1981; McConnell, 1997, pers. comm.), in spite of the fact that montane communities are the least affected by anthropogenic influence in Great Britain (Ratcliffe, 1977). Estimations of the tree-line during the Holocene climatic maximum (9000 - 8000 BP) suggest an altitude of 793m a.s.l. in the Cairngorms, descending to approximately 520m a.s.l. in the north-west of the Scottish mainland and close to sea level in the Outer Isles (Poore and McVean, 1957; McVean and Ratcliffe, 1962; Birks, 1988; Brown, Horsfield and Thompson, 1993). The absence of birch scrub (*Betula pubescens, B. nana*) or extensive arctic-alpine willow scrub (*Salix* spp.) so common in Scandinavia makes present-day estimates of the limit of the montane zone and the level of the natural tree-line difficult to achieve, but work by Thompson and Brown (1992) using the presence of dwarf-shrub heaths and an increase in the proportion of small herbs, mosses and lichens to indicate montane communities suggests a maximum of 700-800m a.s.l. in the Cairngorms and central Highlands, descending north and north-west to 550m a.s.l. in the north-west Highlands, 350m a.s.l. in the far north-west of Sutherland and 200-300m in Orkney and Shetland. The rapid descent of the potential tree-line to the north and north-west is indicative of the very steep latitudinal climatic gradient experienced over Scotland and has particular relevance when coupled with the steep altitudinal gradients so typical of hyper-oceanic mountain ranges (Barry, 1992).

Although birch and willow scrub is relatively scarce, Scottish montane vegetation has many similarities with Norwegian montane vegetation of the low-alpine and middle-alpine zones (Poore and McVean, 1957) and is predominantly arctic-alpine in composition, in spite of the region's low latitude and elevation. Substantial surveys of arctic and arctic-alpine plant communities have been made in Norway (Nordhagen, 1940, 1943; Dahl, 1956; Gjaerevoll, 1956), Svalbard (Elvebakk, 1994), Iceland (Bjarnason, 1983), Greenland (Boecher *et. al.*, 1978; Daniels, 1994), North America (Britton, 1966; Hulten, 1968; Walker, 1985) and Asia (Anon, 1960-87; Aleksandrova, 1980, 1988; Razzhivin, 1994), which show that there are many similarities and common species throughout the arctic, the sub-arctic and their montane regions (Polunin, 1959; Walker, Daniels and van der Maarel, 1994). Some 60% of the vascular flora of the arctic regions is circumpolar, increasing with latitude to about 90% in the high-arctic (Polunin, 1959), with many circumpolar arctic species extending south to the mid-latitude alpine tundra (Bliss, 1962). However, individual species may show substantial genetic differences between their arctic and alpine populations giving two distinct biotypes (Crawford, 1989), such as *Ranunculus glacialis, Juncus trifidus* and *Arabis alpina* (Boecher, 1972). Such features indicate an ability to adapt to prevailing conditions through time, but may also be a product of the Pleistocene glaciations which effectively separated the circumpolar arctic flora, where glaciation was very limited, from the mid-latitude alpine flora (Crawford, 1989).

The large-scale climatic differentiation of arctic flora is mirrored in the mid-latitude alpine tundra, where the large-scale latitudinal gradients are replaced by steeper gradients of altitude (Gjaerevoll, 1956; Knight, Rogers and Kyte, 1977; Flock, 1978; Miller, 1982). Within this broad framework there are many smaller-scale variations depending upon the interaction of a whole range of topographic and climatic factors. Generally, the lower end of the gradient (whether latitudinally or altitudinally) shows a dominance of Gramineae and Cyperaceae (for example, *Carex* spp., *Poa alpina*) and shrubs (*Eriophorum* spp., *Cassiope* spp., *Vaccinium* spp.), with a gradual transition to vegetation containing more dwarf shrubs (*Betula nana, Salix herbacea, S. polaris, Loiseleuria procumbens*), small, cushion- or mat-forming plants (*Saxifraga* spp., *Silene acaulis, Dryas octopetala*) and cryptograms (Bliss, 1962; Crawford, 1989; O'Reiley and Page, 1990; Oksanen and Ranta, 1992).

The most important environmental factors affecting arctic-alpine plants are climatic variables (Bliss, 1971); the common theme is the severity of climate which produces the similarities observed in the vegetation of arctic and alpine regions. Generally temperature is low, with only a short season of sufficiently high temperatures to promote growth. The relatively low intensity of radiation typical of high latitudes is enhanced by long duration, giving a high total flux in unshaded locations; however, topographic gradients are steep as a result of the low elevation of the sun (Cox and Larson, 1993). At higher altitudes and on unshaded aspects radiation levels may be very intense and high temperatures at ground level are common, causing physiological drought. Desiccation, evaporation and chilling are enhanced by wind, especially on ridges and summits where wind speeds are greatest, making topographic shelter, or the shelter offered by other plants an important governing factor (Bell and Bliss, 1979; Carlsson and Callaghan, 1991). Wind also causes mechanical damage to plants with long, rigid stems and abrades leaves (Bell and Bliss, 1979) and may also remove leaf litter, thereby reducing nutrient cycling (Crawford, 1989) which may already be low by the restricted action of decomposers through low temperatures (Babb and Whitfield, 1977; McKendrick *et. al.*, 1978; Chapin *et. al.*, 1980; Chapin, 1983).

A series of adaptations and acclimation responses of arctic-alpine plants may be recognised which are important in an understanding of the ecology of Scottish montane communities, and particularly the snowbed communities. To combat the severity of climate the morphology of arctic-alpine species is generally low and compact and most species are perennials with considerable longevity. For example, the sedge *Kobresia bellardii* was observed by Bell and Bliss (1979) to commonly develop tussocks some 200-250 years old. Chaemetophytes become increasingly common as climate becomes more severe (Raunkier, 1934) and only one annual plant (*Koenigia islandica*) is recorded as surviving in the high arctic. The production of viable seed has been quoted as infrequent in many species and seedlings rarely observed (Billings and Mooney, 1968; Bliss, 1971; Billings, 1974; Bell and Bliss, 1979). However, there is increasing evidence for a substantial buried seed bank in several arctic locations (Leck, 1980; McGraw, 1980; Fox, 1983; Gartner, Chapin and Shaver, 1983; Roach, 1983) and some species have been observed to produce large quantities of seed under favourable conditions (Chester and Shaver, 1982). Seedlings do occur in natural tundra (Bell and Bliss, 1979; McGraw and Shaver, 1982), indicating that viable seed is produced and may be stored in the soil to germinate under favourable conditions (Gartner, Chapin and Shaver, 1986) while some species, such as *Luzula spicata*, may demonstrate specific germination adaptation to severe conditions (Amen, 1965; Sayers and Ward, 1966). Other species may take up to three years to complete flowering from floral initiation (Sorenson, 1941) and cyclical flowering events in populations of

Carex bigelowii have been identified by Carlsson and Callaghan (1990), which in turn affects the population size through the programmed death of flowering tillers.

In spite of the complex sexual reproductive strategies adopted by many arctic-alpine plants, most reproduction is vegetative, mainly through the extension of stolons and rhizomes but also in the production of polyploid individuals (Crawford, 1989). Polyploidy also increases as temperature decreases (Haskell, 1952; Johnson and Packer, 1965), while efficient dioecism is common among willows (Crawford and Balfour, 1983). The lower energy investment required in vegetative reproduction is compatible with the severity of the environment where the majority of energy assimilated by plants is placed in storage (Mooney and Billings, 1960; Troshin, 1967; Gartner, Chapin and Shaver, 1986), allowing rapid growth at the onset of the growing season to maximise the short period of higher temperatures, and also possibly related to the frost hardiness demonstrated by many species. Although initial growth rates are rapid in many species, overall productivity is low, primarily due to the short period when temperatures are sufficiently high to support good growth rates (Bliss, 1962; Bliss, 1966; Baier, Bazzaz, Bliss and Boggess, 1972; Tieszen, 1972; Chapin, Johnson and McKendrick, 1980). Lower energy investment in sexual reproduction and high investment in storage and initial growth of photosynthetic tissues are strategies compatible with the long-lived nature of arctic-alpines and are typical of stress-tolerant species of the Grime, Hodgson and Hunt (1988) model.

Acclimation responses are largely confined to tolerance of low temperatures during the vegetative cycle. It is particularly difficult to separate the acclimation and adaptation responses, but atypical responses in specific species will usually indicate acclimation rather than adaptation. Examples include apical development in montane species throughout the winter, except where encased in ice, observed by Kimball, Bennett and Salisbury (1973) while Bell and Bliss (1979) observed elongation in a winter-green sedge at temperatures of -4°C. Growth of shoots beneath an overlying snow cover has also been reported (Billings and Bliss, 1959; Mooney and Billings, 1960; Spomer and Salisbury, 1968) while Kimball *et. al.* (1973) found chlorophyll amounts in leaves to be inversely related to overlying snow depth. Frost hardiness has been related to high carbohydrate content of storage tissues (Troshin, 1967), which further emphasises the importance of a conservative strategy of growth in arctic-alpine species. Recent research in Japan also indicates the presence of a specific amylase active at severely low temperature in snowbed plants, allowing winter buds to develop in *Primula cuneifolia* spp. *hakusanensis* and *Fauria crista-galli*. (Shibata and Nishida, 1993).

Set within this international context of arctic-alpine vegetation, Scottish montane flora has a special place with many of the southern and oceanic outliers of the circumpolar arctic-alpine flora found here, such as *Armeria maritima, Carex bigelowii, Koenigia islandica*, and *Festuca vivipara*. Some communities, such as the chionophobous *Racomitrium lanuginosum* heath are particularly well-represented, while others are not found elsewhere (Ratcliffe and Thompson, 1988; Thompson and Sydes, 1992). All these communities are said to represent the relics of a glacial flora which was once much more common in Britain (Birks, 1973), and which remain today the most near-natural vegetation found here.

In the Scottish montane vegetation, Thompson and Brown's (1992) five-fold categorisation of the communities found is a useful tool since it indicates the underlying climatic gradients while adding the anthropogenic influences which confuse the natural picture. The five categories, chionophobous, chionophilous, species-rich, mires (including springs and flushes) and anthropogenic, can be used either singly or in combination to describe the predominant factors governing all the different montane communities. The three major sources of biodiversity identified are upland climate, regional variation in topography and synoptic climate, and regional and local modification (anthropogenic). The chionophilous and chionophobous communities are reported to contain the highest biodiversity and of the 37 communities covered (using Birks and Ratcliffe's (1981) community designations), 15 are defined as being purely chionophilous or chionophobous. Only 6 of the 37 communities are apparently not affected by the duration of snow-lie, 3 of which are mires, 1 species-rich, 1 species-rich and mire, and 1 anthropogenic (Thompson and Brown, 1992). The dominant variable affecting Scottish montane plant communities is concluded by Thompson and Brown (1992) to be the duration of snow-lie.

Using the National Vegetation Classification (NVC) community designations (Rodwell, 1991, 1992), the purely chionophobous communities are given in Thompson and Brown (1992) as H13, H14, H15, H17, H20, U9, U10b and U10c: chionophilous communities are H22a, U8, U11, U12, U13a, U18. A table of all relevant communities is shown in Table 3.1. While all of these communities are affected by duration of snow-lie, it is likely that only the most extremely chionophilous communities are dominated by the snow-lie variable. Extremely chionophobous communities are usually found in the most exposed locations where wind and desiccation are likely to be more influential on species' success, rather than the absence of a prolonged snow cover. Mildly chionophilous or chionophobous communities may equally be the product of a suite of environmental variables, such as altitude, aspect and irrigation, though still likely to be dominated by climate, in addition to the duration

TABLE 3.1

NVC COMMUNITIES ASSIGNED BY THOMPSON AND BROWN (1992) AS PURELY CHIONOPHOBOUS OR CHIONOPHILOUS.

CHIONOPHOBOUS COMMUNITIES

H13	*Calluna vulgaris - Cladonia arbuscula* heath
H14	*Calluna vulgaris - Racomitrium lanuginosum* heath
H15	*Calluna vulgaris - Juniperus communis* ssp. *nana* heath
H17	*Calluna vulgaris - Arctostaphylos alpinus* heath
H20	*Vaccinium myrtillus - Racomitrium lanuginosum* heath
U9	*Juncus trifidus - Racomitrium lanuginosum* rush-heath
U10b	*Carex bigelowii - Racomitrium lanuginosum* moss-heath, typical sub-community
U10c	*Carex bigelowii - Racomitrium lanuginosum* moss-heath, *Silene acaulis* sub-community

CHIONOPHILOUS COMMUNITIES

H22a	*Vaccinium myrtillus - Rubus chamaemorus* heath, *Polytrichum commune - Galium saxatile* sub-community
U8	*Carex bigelowii - Polytrichum alpinum* sedge-heath
U11	*Polytrichum sexangulare - Kiaeria starkei* snow-bed
U12	*Salix herbacea - Racomitrium heterostichum* snow-bed
U13a	*Deschampsia cespitosa - Galium saxatile* grassland, *Anthoxanthum odoratum - Alchemilla alpina* sub-community
U18	*Cryptogramma crispa - Athyrium distentifolium* snow-bed

of snow-lie. It is only when the duration of snow-lie reaches extreme levels that it becomes overwhelmingly dominant.

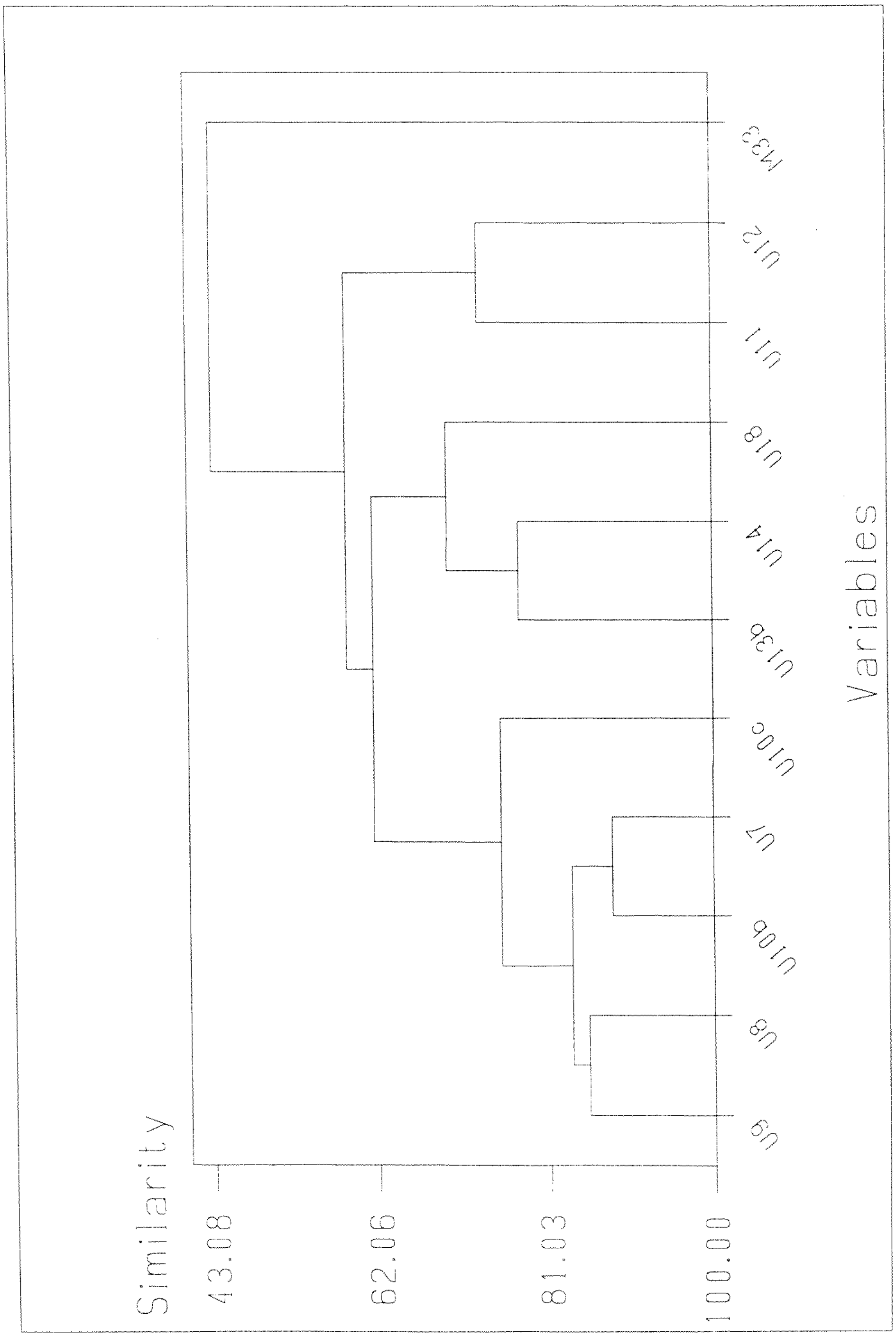
The separation of the highly chionophilous snowbed communities from other montane communities can be seen in the cluster analysis presented in Figure 3.1. Here the truly montane communities of the NVC, with an average sample altitude of 850m or more, have been compared for similarity using average distancing on correlation on a matrix of species constancy (I - V). Only species with constancy III or more in any one community have been included, to focus the analysis on the representative species, rather than rarities.

The separation of M33 from all other communities is the first striking feature of this analysis, followed immediately by the separation of the snowbed core communities, U11 and U12, from the remaining montane communities. More peripheral snowbed communities (U13b, U14 and U18) are then separated from the five communities more associated with chionophobous locations, U7, U8, U9, U10b and U10c. The presence of U8, described by Rodwell (1992) and by Thompson and Brown (1992) as chionophilous, amongst the chionophobous communities U7, U9 and the two sub-communities of U10, is interesting; again it is worth noting that these 11 communities and sub-communities are amongst the most poorly-studied in the NVC, having a total of only 278 samples between them, 97 of which are allocated to U10b and U10c. The matrix of correlation coefficients from the same analysis also indicates the similarities between U8 and the chionophobous communities. This simple investigation of similarity between the montane communities of the NVC has immediately highlighted discrepancies between the community description (Rodwell, 1991, 1992), the investigations of Thompson and Brown (1992) and their conclusions concerning snow-

FIGURE 3.1

CLUSTER ANALYSIS OF NVC MONTANE COMMUNITIES.

USING CONSTANCY VALUES FOR ALL SPECIES SHOWING CONSTANCY VALUES OF III OR MORE IN ANY ONE COMMUNITY.
CLUSTER ANALYSIS PERFORMED ON THE CORRELATION MATRIX OF THE COMMUNITIES ANALYSED USING AVERAGE DISTANCING.



lie, and the similarities in the species compositions of the communities. Much more work appears to be necessary in order to accurately assess the relationships between all the Scottish montane communities and the environmental variables governing their distribution, which may be started off by an improvement in the number of samples upon which these community designations are based.

The restricted growth window of opportunity available to arctic-alpine plants as a result of the severe climate is a fundamental feature of high latitudes and altitudes, leading to the hypothesis of Tieszen (1972) that any behaviour allowing plants to extend the available growing season by, for example, temperature acclimation, gives that species a competitive advantage (Bell and Bliss, 1979). Temperature adaptation and acclimation, outlined above, indicates a general ability in arctic-alpine species to utilise lower temperatures than many temperate species, thus extending the limited growing season in arctic and alpine locations. The growth threshold generally used by many plant ecologists is 6°C, but for arctic-alpine vegetation in general and Scottish montane vegetation in particular, a temperature of 0°C seems likely to be more appropriate. This is particularly true for the extremely chionophobous or chionophilous communities with a high proportion of bryophytes, since their optimal temperature range is lower than that of vascular plants (Furness and Grime, 1982a, 1982b).

3.2 Snowbed Vegetation.

The first researchers to show unequal snow cover as responsible for patterns in vegetation was Vestergren (1902), followed later by a number of others, particularly Nordhagen (1946) in Norway, and Billings and Bliss in North America (Bliss, 1956;

Billings and Bliss, 1959). The contrast between early and late snow-lie is more obvious in regions of variable topography since, for example, differences in the accumulation of snow and ablation generated by different aspects and slope angles are more acute. This has led to the definition of vegetation communities in more alpine regions as being predominantly snow-determined (Dahl, 1956; Thompson and Brown, 1992). However, there is, or rather should be, a marked contrast between these general vegetation classifications and those which focus solely on snowbed vegetation (Gjaerevoll, 1956; Rothero, 1989, 1990). Late snowbed vegetation is dominated by a bryophyte flora, with few, if any, vascular species. Therefore any classification which fails to take into account at least the dominant bryophyte species must be inadequate for snowbed vegetation. Many researchers, but not all, acknowledge the importance of bryophytes in snowbed vegetation but studies which actually include the species involved as part of the data are sparse in comparison with studies of the vascular flora. This may lead to taxonomic bias or selectivity in many plant ecology studies (Strong *et. al.*, 1985; Keddy, 1989; Cox and Larson, 1993), particularly in those areas where non-vascular plants make up a high percentage of the species involved (Young and Peacock, 1992). Therefore all snowbed vegetation classifications need to be approached with a degree of caution.

The syntaxonomy of snowbed vegetation of all arctic and alpine areas does, however, show several important similarities. Braun-Blanquet *et. al.* (1947) established the *Salicetea herbaceae* class of arctic and alpine snowbed vegetation of the northern hemisphere. This is widely accepted in the literature (Dahl, 1956; Gjaerevoll, 1956; Razzhivin, 1994; Daniels, 1994) and has a place in the classifications designed for the Scottish Highlands (Poore, 1955; McVean and Ratcliffe, 1962). More recent work has focused on the community aspects of snowbed vegetation, being more concerned with providing diagnostic tools for the description and designation of vegetation. Similarities at the community level are still apparent between the Scottish and Norwegian snowbeds (Gjaerevoll, 1956; McVean and Ratcliffe, 1962), with both sets of authors recognising the importance of bryophytes in the snowbed cores and the latest snow cover communities being almost exclusively assigned on the basis of the presence or absence of specific bryophyte species. However, it would appear that the Scottish snowbeds are less diverse in vascular species than their Scandinavian counterparts, with the complete absence of *Salix polaris, Thalictrum alpinum, Ranunculus glacialis, R. nivalis, R. pygmaeus, Cassiope* spp., *Saxifraga hyperborea* and *S. nivalis*, and only very rare occurrences of *Saxifraga tenuis, S. rivularis* and *Oxyria digyna*, thus rendering many of the Scandinavian and Greenlandic associations inapplicable in Britain. A possible reason could be the restriction of the snowbed flora in Britain during the Holocene climatic optimum, when average annual temperatures were approximately 2°C higher than today, and the consequent loss of some snowbed core species.

The snowbed communities identified by McVean and Ratcliffe (1962) and built into Rodwell's (1992) NVC, and, more recently by Rothero (1989) are shown in Table 3.2 and Figure 3.2. Rodwell identifies U11, U12, U18 and M33 as the communities associated with the most prolonged snow-lie, mirroring McVean and Ratcliffe (1962); these communities have some diagnostic vascular plants but a large number of the constant, dominant and commonly-occurring species are bryophytes. However, a serious failing in the NVC, as outlined above, must be the very small number of samples upon which high montane communities in general and these communities in

TABLE 3.2

THE NATIONAL VEGETATION CLASSIFICATION SNOWBED COMMUNITIES AND AFFINITIES WITH McVEAN AND RATCLIFFE 1962.

SOURCE: RODWELL 1991, 1992

NVC communities	McVean and Ratcliffe synonymy
U7 - *Nardus stricta-Carex bigelowii* grass-heath	*Nardetum medio-alpinum*
U8 - *Carex bigelowii-Polytrichum alpinum* sedge-heath	*Dicraneto-Caricetum bigelowii* *Polytricheto-Caricetum bigelowii*
U9 - *Juncus trifidus-Racomtrium lanuginosum* rush-heath	*Cladineto-Juncetum trifidi*
U11 - *Polytrichum sexangulare-Kiaeria starkei* snow-bed	*Polytricheto-Dicranetum starkei*
U12 - *Salix herbacea-Racomitrium heterostichum* snow-bed	*Rhacomitreto-Dicranetum starkei* *Gymnomitreto-Salicetum herbaceae*
U13 - *Deschampsia cespitosa-Galium saxatile* grassland	*Deschampsieto-Rhytidiadelphetum*
U18 - *Cryptogramma crispa-Athyrium distentifolium* snow-bed	*Cryptogrammeto-Athyrietum* chionophilum
M31 - *Anthelia julacea-Sphagnum auriculatum* spring	*Anthelia-Deschampsia caespitosa* nodum
M33 - *Pohlia wahlenbergii* var. *glacialis* spring	*Pohlietum glacialis*

TABLE 3.3

MONTANE NVC COMMUNITIES, SAMPLE NUMBERS AND AVERAGE ALTITUDE.

Community	No of samples	Average altitude and range
U7	96	756 (8-1220)
U8	27	1059 (823-1250)
U9	27	920 (915-1159)
U10b	52	909 (160-1166)
U11	31	1032 (915-1235)
U12	33	1046 (690-1250)
U13b	18	871 (692-1100)
U14	27	888 (640-1116)
U18	8	967 (823-1082)
M33	10	992 (868-1083)
H13	123	683 (105-950)
H19	199	784 (6-1159)
H20	53	718 (246-1174)

particular are based, as shown in Table 3.3, which offers three sub-montane heaths for comparison. Revision of these communities may well be necessary in the light of further work which may be undertaken. Rothero's more recent work (1989, 1990) looks in far greater detail at the snowbed core vegetation, predominantly bryophytes, and covers the main mountain massifs of Lochaber and the Cairngorms. Detailed analysis of his community descriptions and the results of the Two-Way Indicator Species Analysis (TWINSPAN) and Detrended Correspondence Analysis (DECORANA) presented in his work has allowed Figure 3.2 to be drawn in an attempt to show how the communities relate to one another and the environmental variables examined.

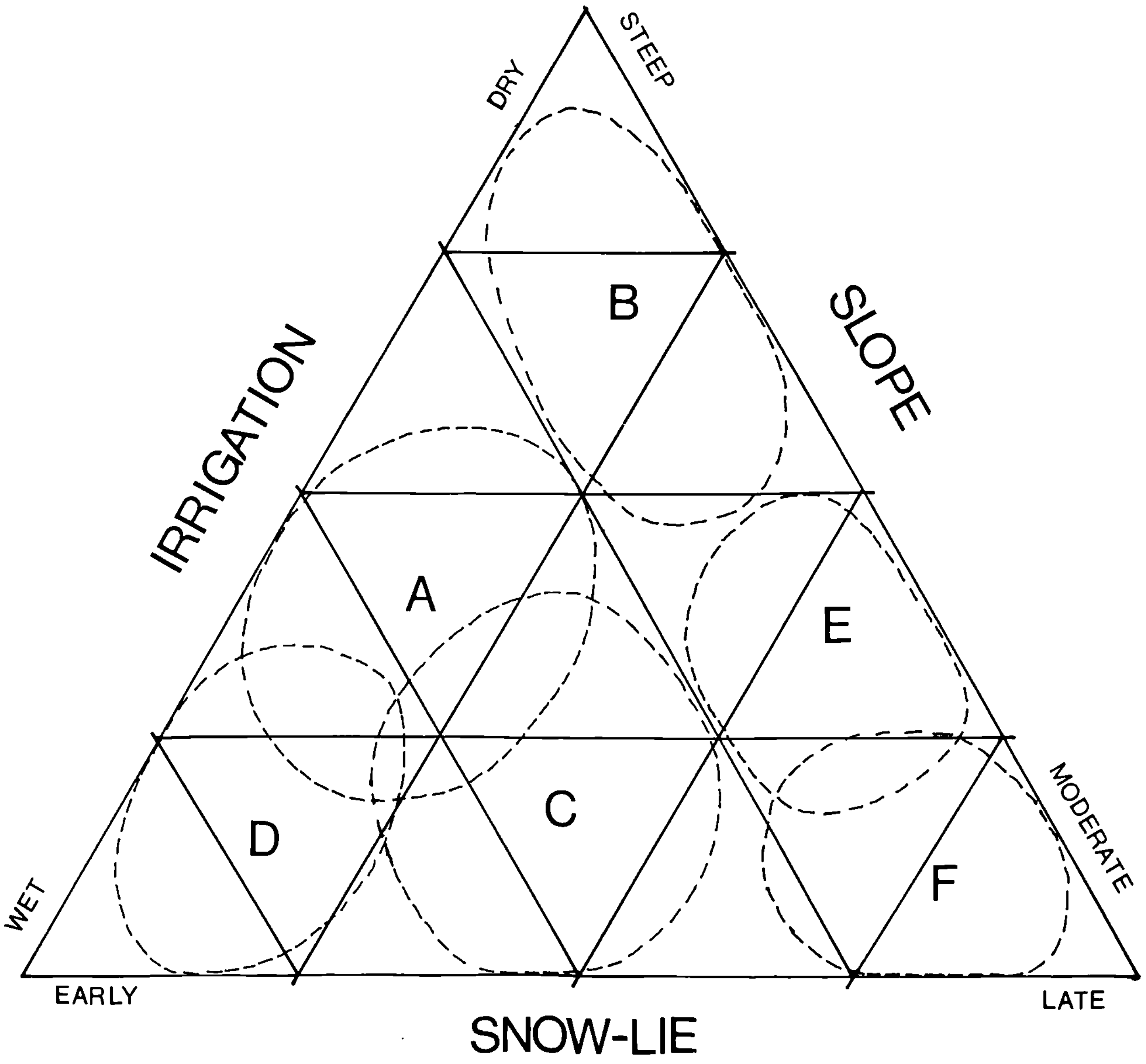
The most valuable aspect of Rothero's work is to identify the diversity of the snowbed bryophytes and to recognise that a number of identifiable associations exist within the snowbed core area where vascular plants are not found. The resolution of his study is finer than that of McVean and Ratcliffe (1962) or Rodwell (1991, 1992) and identifies the more subtle interaction of environmental variables at a smaller scale than that of the larger-scale duration of snow-lie. Therefore it may be recognised that while snow-lie duration is dominant in determining communities at the scale of the NVC (Thompson and Brown, 1992), at smaller scales other environmental variables do create identifiable variations in species composition, indicating a possible need to allocate sub-communities to any revision of the NVC snowbed communities.

A number of key Scottish snowbed species can be identified from the work of all the above authors, one of which is *Kiaeria starkei*, used by Woolgrove and Woodin (1994) in their investigation of the effect of acid meltwater. Other key bryophyte species include *Pohlia ludwigii, Polytrichum sexangulare, Anthelia julacea,*

FIGURE 3.2

DIAGRAM TO SHOW THE RELATIONSHIP OF ENVIRONMENTAL FACTORS AND THE SNOWBED VEGETATION TYPES IDENTIFIED BY ROTHERO (1989).

A:	*Pohlia ludwigii*
B:	*Marsupella brevissima - Anthelia juratzkana*
C:	*Marsupella brevissima - Lophozia sudetica*
D:	*Polytrichum sexangulare - Kiaeria starkei*
E:	*Racomitrium - Carex bigelowii*
F:	*Carex bigelowii - Dicranum fuscescens*



Marsupella brevissima and *Pohlia wahlenbergii* var. *glacialis*. Relatively few vascular plants fit the snowbed specialist list, but those that may do so include *Salix herbacea, Cerastium cerastoides* and *Gnaphalium supinum*.

Most species of arctic-alpines will fit into Grime, Hodgson and Hunt's (1988) stress-tolerant category, with little competitive ability. As the severity of climate increases, the niches offered will be filled by increasingly stress-tolerant species with reduced competitive abilities. Any niche in the arctic-alpine environment is therefore likely to be filled by plant species which tolerate the particular conditions found there better than other species, but for whom the conditions are unlikely to be optimal in the absence of competition. Less severe conditions will create niches in which more competitive species can successfully exclude the stress-tolerators, species which are lost as conditions become more severe.

Application of this model to the snowbed environment, using a continuum approach from the sheltered, well-irrigated, peripheral areas to the snowbed core is a particularly useful exercise, by reducing the variation of other climatic variables and isolating snow-lie duration as the dominant source of plant stress. It is hypothesised that for a snowbed environment located on a sheltered aspect with little topographic variation, more competitive species occupying the peripheral areas will gradually give way to stress-tolerators. The stress-tolerators will not be found in the peripheral areas, being unable to compete successfully, while the competitors will demonstrate declining cover values and performance as snow-lie duration increases. Performance of the stress-tolerators is expected to be maximised in the area where competitors reach low cover values, rather than in the snowbed core area, indicating that the snowbed core area is sub-optimal for these species.

The presence of late snowbed bryophytes in the western Highlands, as found by Rothero (1989) on Aonach Mor, indicates that late snowbed loyalty is high in these areas, as well as in the Cairngorms, though this does not inform further about the variability of snow-lie duration. The hypothesis that snow-lie loyalty to location is high throughout the Highlands is therefore reinforced by the botanical evidence presented in the literature, while the position concerning the variability of snow-lie duration remains unchanged.

Summary points:

1. The severity of climate is the dominant factor affecting arctic-alpine vegetation, leading to a variety of acclimation and adaptation responses.

2. A gradient of vegetation type can be observed as latitude or altitude increase, with grasses, sedges and shrubs giving way to dwarf shrubs, which in turn give way to cushion and mat-forming plants and cryptograms.

3. Montane vegetation which in the Scottish Highlands is found above the natural tree-line, is the most near-natural vegetation in Britain, similar to montane vegetation found in Scandinavia and for which the dominant factor is the duration of snow-lie. Classifications in Britain and Norway for montane vegetation reflect this single-factor dominance, though the British NVC classification is not finely-tuned..

4. Late snowbed vegetation is dominated by bryophytes, while peripherally vascular plants increase in cover. The investigations of some authors into snowbed vegetation omit the bryophyte flora and are therefore fundamentally flawed.

5. Two classifications of snowbed vegetation exist for the Scottish flora; the broader-

based NVC and a much finer-resolution study by Rothero (1989) of the snowbed bryophytes.

CHAPTER 4

METHODS

4.1 Study Area Description.

4.1.1 Site Selection.

Having outlined the background of the hypothesis to be investigated, a study site needed to be found where the necessary observations on snowbed vegetation could be carried out. Given the offer of assistance made by the North-West region of the Nature Conservancy Council for Scotland (now Scottish Natural Heritage), the focus in the search for a suitable site was the area around Ben Nevis, where the altitude of the mountain and its neighbours generate substantial snow accumulation and prolonged snowlie in north- and east-facing corries. A number of possible sites both here and elsewhere in the Highlands were examined and their suitability assessed. The criteria for site selection and the options considered are shown in Table 4.1. Most potential sites were ruled out by difficulties of access and high avalanche danger in winter; the best snowbeds are found in the back of steep, high corries with substantial wind-blown drift and build-up of potentially dangerous windslab. They also tend to lie beneath cliffs of variable height over which more or less substantial cornices develop in winter, making winter measurements of snow depth extremely hazardous.

A site was chosen on the Aonach Mor massif at the western end of the Grey Corries. This mountain lies close to Ben Nevis and has a sizeable summit plateau, by west coast standards, generating substantial snow build-up along its eastern face. The northern face is used by the Nevis Range Company for skiing and year-round access is available

TABLE 4.1
TABLE SHOWING THE SITE SELECTION CRITERIA AND THE VARIOUS SITES CONSIDERED FOR STUDY.

	Ben Nevis north face	Ben Wyvis	Creag Meagaidh	Ben Alder	Aonach Mor, Coire and Lochain	Aonach Mor, back corrie	Aonach Beag, NE face
Within SNH/NCC NW region.	yes	no	yes	no	yes	yes	yes
Permission of landowner; no conflict with sporting activities.	yes	no	yes	yes	yes	yes	yes
Easy access to site with no more than 2 hours travel each way.	no	no	no	no	yes	yes	no
Safe. Assessable avalanche danger. Possible to work without assistance.	no	yes	no	yes	no	yes	no
Snow patch formed on relatively open slope; not confined by a deep gully and with special microclimate.	no	yes	no	yes	yes	yes	yes
Not an important site for rare flora; some damage inevitable in carrying out research.	possibly	no	yes	no	no	yes	no
Away from human interference and regular trampling.	no	yes	yes	yes	yes	yes	yes
Area downwind of as substantial an area of plateau as possible; parallel site-type to Cairngorms.	yes	no	yes	yes	yes	yes	no
If possible, nearby location of some form of weather station, preferrably a high altitude automatic station.	yes - but only coastal	yes-but only coastal	yes-but not high altitude	no	yes	yes	yes
Assessment (number of positive marks out of 9).	**4**	**3 +**	**5 +**	**5**	**7**	**9**	**5**

via a gondola to 650m a.s.l.. Further ski development is now taking place in the eastern corries of the mountain but had not started at the time of fieldwork, although this area was used for a period of time in the early 1990's for off-piste skiing, until the death of a skier in the winter of 1992-3. The entire massif of the Grey Corries is owned by British Alcan, providing run-off for their aluminium smelter in Fort William, and no conflict with sporting use arose. The mountain itself is designated an SSSI, largely on the grounds of its botanical value, as it is a site of the rare Highland Saxifrage *Saxifraga rivularis* (site report, SNH, Fort William).

As part of the ski development, utilising the mains electricity available, but operated separately by the Meteorological Office, an Automatic Weather Station is situated near the top of the ski development, just below the summit plateau at 1000m. This station is providing invaluable data on the climate at this altitude and location on Scotland's west coast. It was a research station until the beginning of 1992, when it became fully operational. The presence of the station makes it possible to establish links between snowfall, snowlie and climate at altitude, and between climate and plant performance during the summer months, more accurately than is possible using lower level stations. This enables a more accurate picture of the parameters affecting snowbed vegetation to be drawn up. However, the short time period over which this station has been operating makes it unsuitable for examination of general climate at this altitude and location, and totally unsuitable for examination of trends in climate.

The parameters available for analysis from the Aonach Mor AWS are also limited; readings of wind speed and direction (mean and gust for different time periods), dry-bulb thermometer and humidity, from which dew point temperature is calculated, are taken every hour. There are no routine daily observations for precipitation of either rain or snow, nor of any of the other variables which may be taken at other manned stations. While this situation is restricting in terms of describing the climate experienced on the summit of Aonach Mor, the basic variables of wind, temperature and humidity that are recorded are a good base upon which to build. The lack of precipitation data is difficult to overcome but a ring of rain gauges around the massif, operated by British Alcan, give an approximation of rainfall. Snowfall is notoriously difficult to record, particularly with automatic equipment and no such measurements exist for other automatic summit stations in this country. Riming on the Aonach Mor AWS continues to be a problem affecting, in particular, the humidity sensor (C. Bridgewater, Research Division, Meteorological Office, 1994, pers. obs.); unlike the Cairn Gorm AWS (Barton, 1987) it is not retracted into a heated housing, as developments in the last few years have improved the operation of externally-sited instruments (C. Bridgewater, 1994, pers. obs.).

4.1.2 Topography of the Study Area.

A map at the 1:10,000 scale was drawn and is shown in Figure 4.1, (back cover). The area lies at the corners of 3 different maps, in both imperial and metric scales. It was therefore necessary to trace each map, having first enlarged the imperial maps by photocopying. A small amount of error can be seen in the join down the centre of the map resulting from the scale restrictions and distortion on the photocopier.

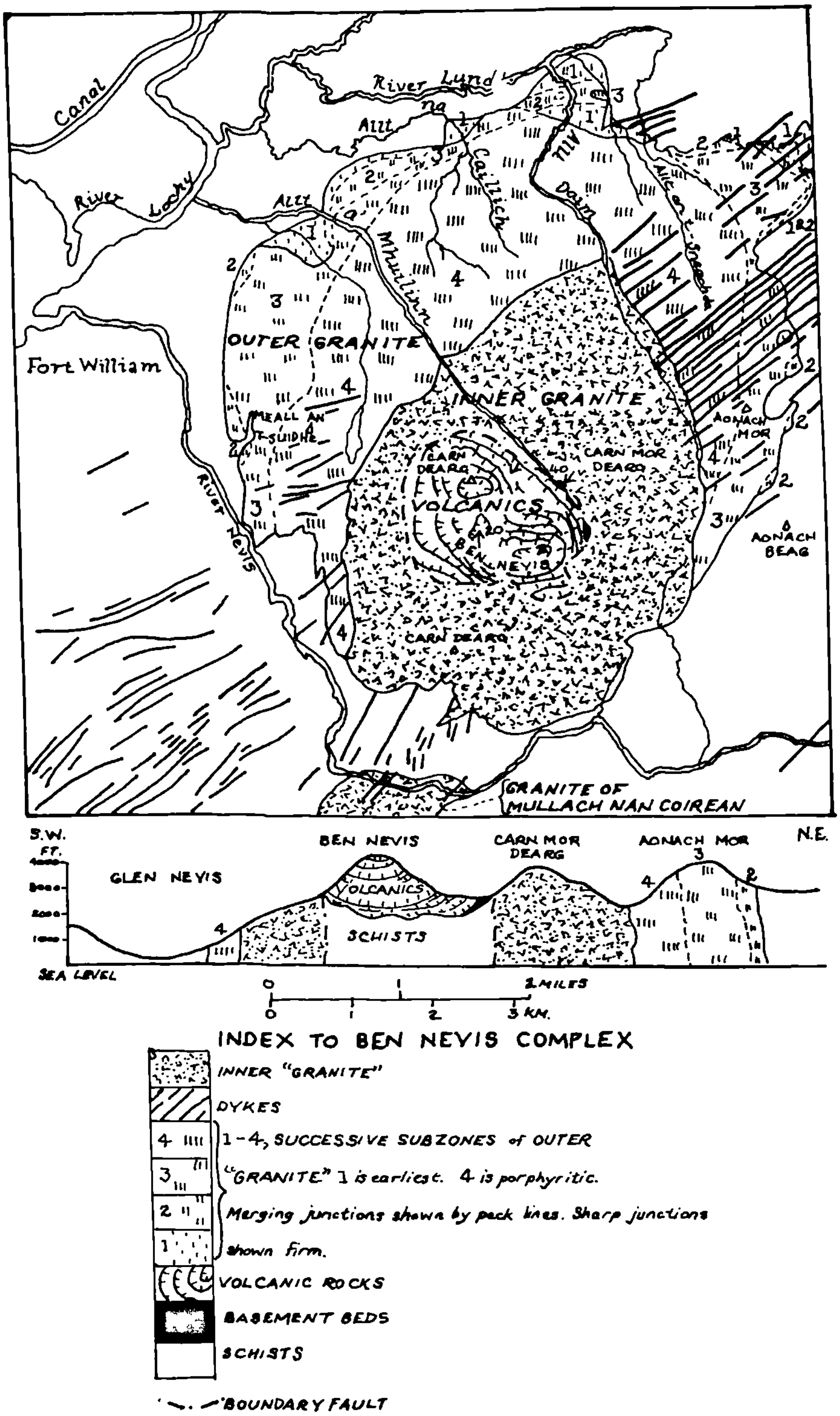
Topographically Aonach Mor combines a long north-south orientated plateau, some 2.5km long and 200m wide at its widest point. The area of the plateau is approximately 100ha. lying at an altitude of 1150m and above. The summit lies near the centre of the long axis, on the western side of the plateau and reaches an altitude of 1221m. To the north, there is a well-defined change of slope towards the Leac an t-Sneachda (the Slab of Snows), a broad sweeping hillside of approximately 17° slope throughout, with scree and boulder-fields at the top and montane grassland and wet heath lower down. It is on these slopes that the current ski development lies, with the burn running down the hillside (the Allt an t-Sneachda - Burn of the Snows) trapping the longest-lying snow. The eastern and western flanks of Aonach Mor are steep, rocky and relatively inaccessible. The western slopes are more broken with an average angle of 24° and are frequently bisected by small burns flowing west to the Allt Daim between Aonach Mor and Carn Mor Dearg. To the east, the flank of the mountain consists of five distinct upper corries, the largest and steepest of these being the second from the north, Coire an Lochain, where the backwall steepens to 80° and the slopes below have an average angle of 23°. The cliffs of this corrie's backwall trap a large amount of snow which is blown off the summit plateau in winter; a substantial cornice also builds up on the edge of the plateau which may contribute to the semi-permanent snowbeds found at the base of the cliffs.

Between the third and fourth corries a ridge (marked R on the accompanying map in Figure 4.2) descends from close to the summit of Aonach Mor to the subsidiary summits of Stob an Cul Choire and Stob Coire an Fhir Dhuibh. These northern three corries drain into the Allt Choille-rais, while the southern two corries drain into the Allt Coire an Eoin from the lower An Cul Choire beneath Aonach Beag. Beyond Coire an Lochain lies an unnamed corrie which is referred to as the back corrie for the purposes of this project. It is at the top of this corrie that the research site lies, where the east-facing backwall reaches the summit plateau. Here the angle of slope is 40°, occasionally rising to 50°, and the change of slope from the plateau to the corrie relatively smooth though rapid. Lower down in the corrie the slopes are in the order of 16°. Towards the south lies a col beyond which the slopes become very broken and treacherous, leading to the two relatively indistinct southern

FIGURE 4.2

GEOLOGICAL MAP OF THE BEN NEVIS COMPLEX

SOURCE: BAILEY AND MAUFE, 1960.



corries which themselves lead down to An Cul Coire. The back corrie is thus bounded on three sides by Aonach Mor and the subsidiary ridge R leading to Stob an Cul Choire and Stob Coire an Fhir Dhuibh. Access to the summit from the back corrie is possible either via the subsidiary ridge R or by ascending across the research site, marked as a box.

The gully found on the southern side of the back corrie is deep and rocky, containing a burn in summer and being well-irrigated by late snow. The rocks are treacherous and surveying of this area has therefore been somewhat cursory. The lower gully is the most well-defined and narrow part while above a rock step, about half-way up to the plateau, it divides into two hollows, both covered with boulder-fields. The heads of these two hollows, named Upper Gully Left and Upper Gully Right, rise steeply to the plateau at angles of 45 -50°, but are in the main mossy and grassy. The gully, especially in its lower part, accumulates a great deal of snow in winter, becoming 'banked out' in normally snowy years, and retains a significant area of snow on its north-facing wall until June or July. To the right (north) of the gully area lies an area of more uniform slopes, although in the lower section there is one rocky buttress and a concave area of drainage beneath the more uniform slopes. Above the more uniform slopes, the ground becomes slightly concave as it rises to the plateau edge, where it becomes sharply convex and flattens out onto the summit area. It is in the area of most uniform slopes and fewest rocky outcrops that the site lies, giving the gradation of communities desired. See map in Figure 4.1.

4.1.3 Geology of the Study Area.

Aonach Mor lies on the border between the Ben Nevis igneous complex and the surrounding Leven schists (Bailey, 1960; Anderson, 1935). The Ben Nevis Complex shown in Figure 4.2 comprises a central core of acidic igneous hornblende-andesite lavas with agglomerates, confined to the area of the Northern Corries of Ben Nevis, surrounded by an intermediate fine-grained pink 'Inner Granite' and a slightly more acid porphyritic 'Outer Granite' (Bailey, 1960). Swarms of porphyrite dykes lie in a south-west to north-east direction on either side of the pluton. The Leven Schists are greenish-grey mica-schists with steeply-inclined foliations dipping to the south-east.

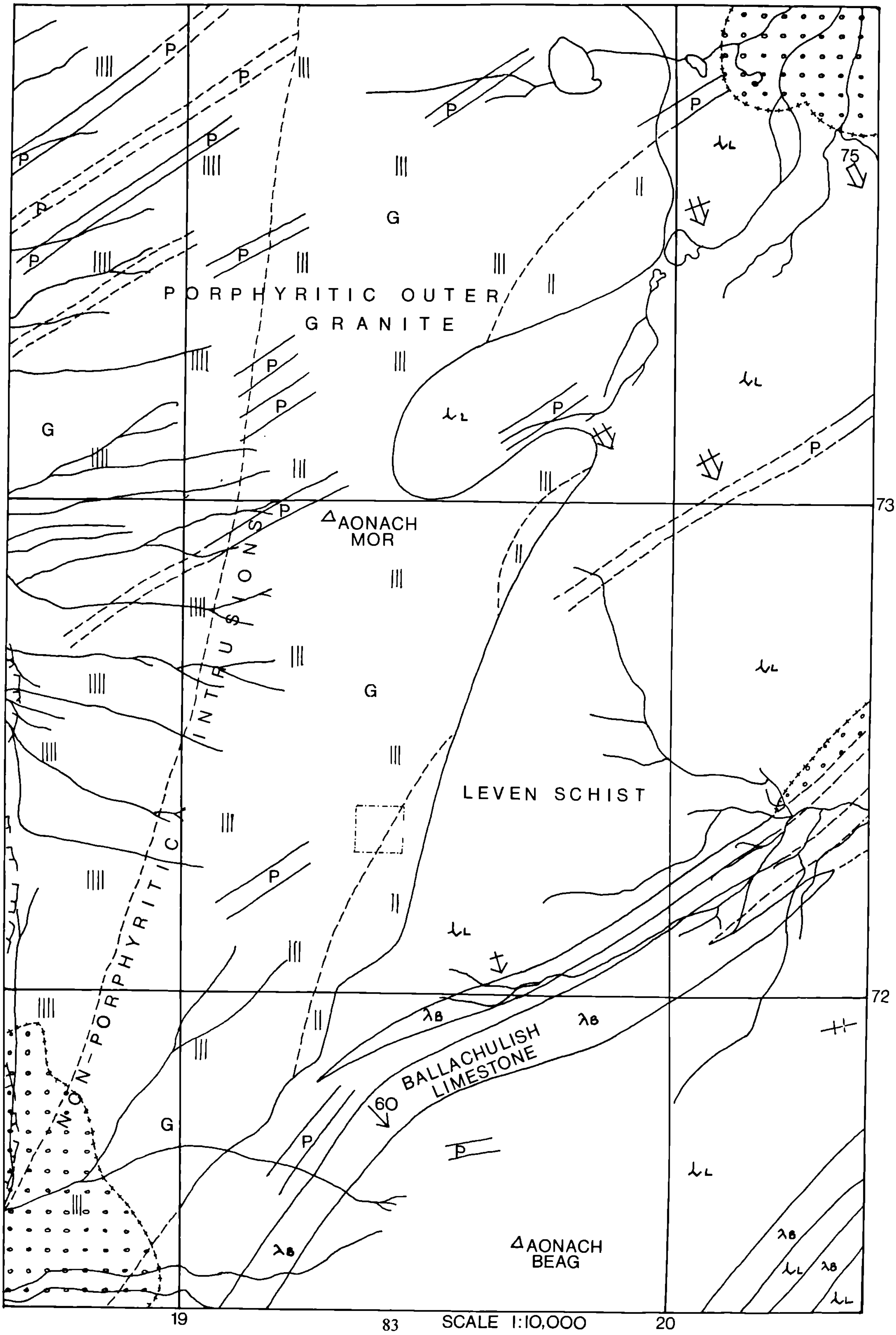
The site itself lies comfortably within the area of the 'Outer Granite' (see Figure 4.3) which contains some Quartz-Diorite but is otherwise pure, but the southern section of the back corrie lies in the mica-schists while the gully mentioned above follows the line of one of the porphyrite dykes. The chemical composition of the type of granite on which the site lies has been analysed by J. G. C. Anderson (1935) whose figures indicate an intermediate status of bedrock, neither acidic nor alkaline, with a good representation of basic minerals (CaO, MgO) and also the ferrous and aluminium minerals. The base status of the overlying soil is thus intermediate to slightly acid. It is not likely that availability of essential minerals is a limiting environmental factor for plant growth (SNH, 1992, pers. obs.), although the wetness of the site indicates that some leaching of nutrients will take place. The nutrient status of the site therefore differs markedly from other snowbed sites more extensively researched in the Cairngorms where the underlying granite is far more acidic and soils nutrient-poor (McVean and Ratcliffe, 1962; Rothero, 1989, 1990).

The topography of the area is, to a large extent, structurally determined with the high plateau found on Aonach Mor attributable to the resistant and massive nature of the granite intrusion. The line of the back corrie follows the contact between the Leven Schists and the Outer Granite, where the contact zone exhibits alteration, while the gully in the southern portion of that corrie describes the line of one of the porphyrite dykes.

FIGURE 4.5

GEOLOGICAL MAP OF AONACH MOR AREA.

SOURCE: ORDNANCE SURVEY, 1974.



For legend see over.

LEGEND TO ACCOMPANY GEOLOGICAL MAP OF AONACH MOR AREA.

ROCKS AND SEDIMENTS

P	Porphyrite dykes (trending NNE).
G	Outer, porphyritic Granite and quartz-diorite of Ben Nevis complex (plutonic intrusion). Stages I - IIII are successive sub-zones of the Outer Granite, of which I is the earliset and only II, III and IIII are shown.
⅄L	Greenish-grey mica-schists of the Leven series.
λB	Ballachulish Limestone (Moine series).
⁘	Morainic drift.

STRATA

↘	Inclined, amount in degrees.
⤨	Highly inclined.

FOLIATION

↘	Inclined, amount in degrees.
⤨	Highly inclined.
┼┼	Vertical.

BOUNDARIES

Uncertain boundaries shown in pecked lines, certain boundaries solid

++++	Boundary of Morainic drift.
⌐⌐	Margin of one plutonic rock cutting another.
⬚	Study site boundary

The western Highlands were more heavily eroded by Quaternary glaciation than the eastern massifs, with precipitation on the west higher than the east owing to greater proximity to the principal moisture source (North Atlantic Ocean), and therefore the volume of glacier ice would have been greater in the western mountains (Price, 1983). Equally, the northern and eastern faces of all the Highland mountains are more heavily glaciated with larger, steeper corries, which is the result of greater deposition of snow on these lee slopes while the western slopes would have been blown free of snow and have much less significant corrie formation. Thus the eastern corries of Aonach Mor are not merely structurally determined, marking the contact between the Leven schists and the 'Outer Granite', but are also more strongly developed owing to their easterly aspect and the consequent action of glacial erosion.

4.1.4 Climate and Aspect of the Study Area.

The back corrie of Aonach Mor faces broadly east and thus lies in the lee of the prevailing wind, which comes from the west. During the summer months although total radiation receipts are potentially high given the corrie's aspect (except in the gully which is shaded in the afternoon and evening), the presence of persistent cloud in the corrie tends to diminish actual radiation receipts. Even when the summit plateau was in sunshine, cloud was often observed to linger in the upper part of the corrie, particularly in westerly air streams, and the occurrence of cloudy weather and precipitation in the area is high. The corrie is relatively sheltered from westerly winds, and forms an area of deposition of snow borne on westerly air streams, as described by Figures 2.5 and 2.6 in Chapter 2. In winter, a substantial cornice and associated snow pillow builds up at the top of the corrie's headwall and it is this cornice which provides the depth of snow for the snowpatch on which the research site is centred. Sufficient snow exists in most years for some to lie as late as July.

Plates 1, 2 and 3 show snow build-up on the eastern side of the Aonach Mor plateau and the effects of wind erosion on an exposed snowpack, with snow layers of different density identifiable in Plate 1, and cornice development above the site (Plate 2) and over the Coire an Lochain cliffs (Plate 3).

The climate of Aonach Mor was examined using data from the Meteorological Office's Automatic Weather Station situated at 1000m on the Leac an t-Sneachda. While still a research station data were made available through the Meteorological Office's Research Division in Bracknell; unfortunately the quality of these data supplied on disk were not good and a gap of some 28 days existed. Before coming on-line a number of problems also existed with the instruments, which affected the data return in quantity as well as quality. Cross-checking with on-line data demonstrated a substantial difference between the two sources, particularly in the wind data (temperature data were largely missing) for the overlap period of 11 days. On this basis, it was thought prudent not to use the data supplied by the Bracknell Research Division.

Since the station became an official weather station in early 1992, data became available through the local Meteorological Office in Aviemore, though this was at the discretion of the local officer. Data sheets filled in by the staff were photocopied and then transcribed onto disk later. This process was necessary to avoid Meteorological Office charges and meant that only a short run of data, little more than 12 months, was collected and processed. However, these data demonstrate the severe and arctic/alpine nature of the climate at higher altitudes in this area, contributing towards a clearer picture of the climate experienced by the vegetation on and near the summit of Aonach Mor. The data are summarised in Table 5.3, in the following chapter.

PLATE 1

EROSION OF A RECENTLY DEPOSITED SNOWPACK ON THE CLIFFS ABOVE COIRE AN LOCHAIN, AONACH MOR.

PLATES 2 AND 3

CORNICE DEVELOPMENT OVER THE RESEARCH SITE AND THE COIRE AN LOCHAIN CLIFFS.

4.1.5 Study Area Vegetation.

The vegetation of the back corrie around and beneath the site was surveyed in 1993 using the National Vegetation Classification (Rodwell, 1991, 1992). The survey was not conducted under the prescribed methods for assigning vegetation to NVC communities. The following procedure was used, which more closely resembled vegetation survey work carried out by the author on Beinn Eighe and at Rassal, Kishorn, for the NCC, and in commercial forests for the Forestry Commission. Using photography, both lateral and aerial, a number of different vegetation zones were identified by differences in their colour and texture before going into the field. These zones were marked on plastic overlays and then located on the ground using recognisable landmarks, such as rocks, scree slopes, flushes and burns. Generally there was no difficulty in finding the limit of these zones since they coincided with significant changes in community composition on the ground. Occasionally additional detail was found on the ground which was not shown on the photographs; this was then added to the plastic overlay. This method differs little from that used by Brown, Horsfield and Thompson (1993).

Having determined the obvious boundaries, 10 quadrats of $1m^2$ were recorded within each vegetation zone. All vascular and some bryophyte species present were identified and measured for their cover values using the Domin scale of abundance. This was carried out over two consecutive days in August 1994 by the author and Amanda Towrie, whose training in NVC survey work was used to make an independent check of the accuracy of the survey. On return to the office, the similarities and differences between the quadrats were assessed. No discrepancies were found which indicated that the vegetation boundaries found on the ground using the photography were insufficiently detailed, although one boundary was discarded since the quadrat data from the two zones it defined were too similar to be separated. The zones were then assigned to different NVC communities. The data was checked using the MATCH software (part of the VESPAN package available through the University of Lancaster, Malloch, 1988) and, within the limitations of the software package, no discrepancies were found to indicate that the survey was inaccurate. The vegetation maps of this area belonging to Scottish Natural Heritage were unfortunately not available for comparison. The map composed from the data collected is shown in Figure 4.4 and is drawn to be superimposed on the oblique photograph of the back corrie shown in Plate 4. All mapping of vegetation and snow-lie corresponds with this photograph, given its excellent view of the corrie and recognisable features essential for accurate mapping. The aerial photography available proved to be too small-scale (1:25,000) to be able to pick out the small features necessary for this research. No attempt was made to transform the vegetation or snowlie maps onto a vertical scale and remove oblique distortion, since much of the detail of vegetation on the steeper slopes would have been lost.

The vegetation found in the back corrie of Aonach Mor is varied, reflecting the range of topography and geology. The summit plateau vegetation cover is composed almost entirely of *Racomitrium lanuginosum* heath with *Carex bigelowii, Silene acaulis, Armeria maritima* and *Luzula spicata* scattered amongst the large expanses of moss. The dryness and exposure of this area is thus reflected in the vegetation type (NVC community U10, *Carex bigelowii - Racomitrium lanuginosum* moss-heath) which is typical of the moister but nonetheless exposed summits of the western Highlands. Individuals of other species, including *Festuca vivipara, Juncus trifidus* and *Salix herbacea* are found throughout this community. Other bryophytes may also be found, notably *Racomitrium fasciculare*, and the lichen *Cladonia uncialis* is common. *Vaccinium* spp. and *Deschampsia* spp. are

FIGURE 4.4

MAP SHOWING THE VEGETATION OF BACK CORRIE, AONACH MOR.

VIEW CORRESPONDS TO THE OBLIQUE PHOTOGRAPH IN PLATE 4

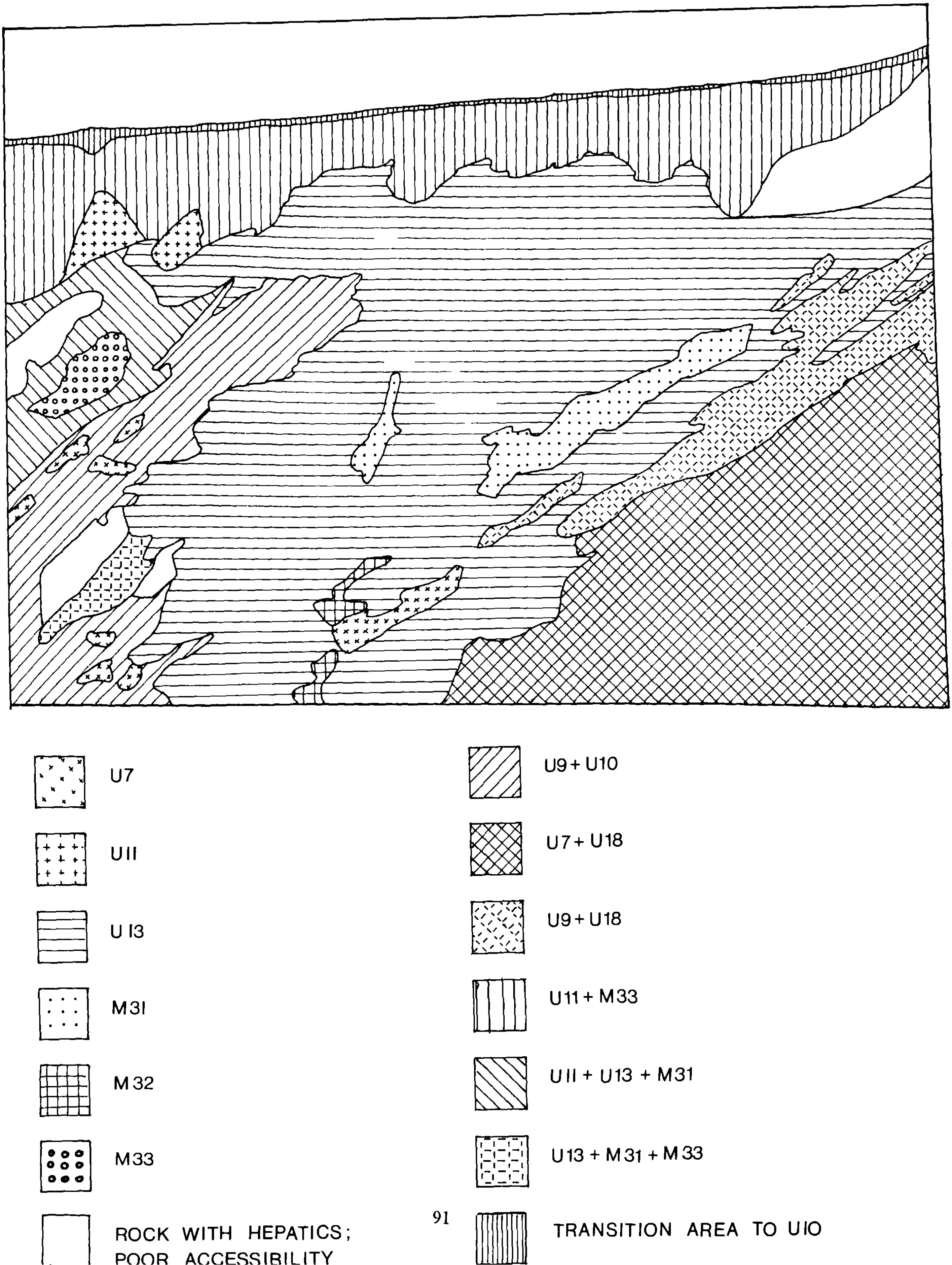
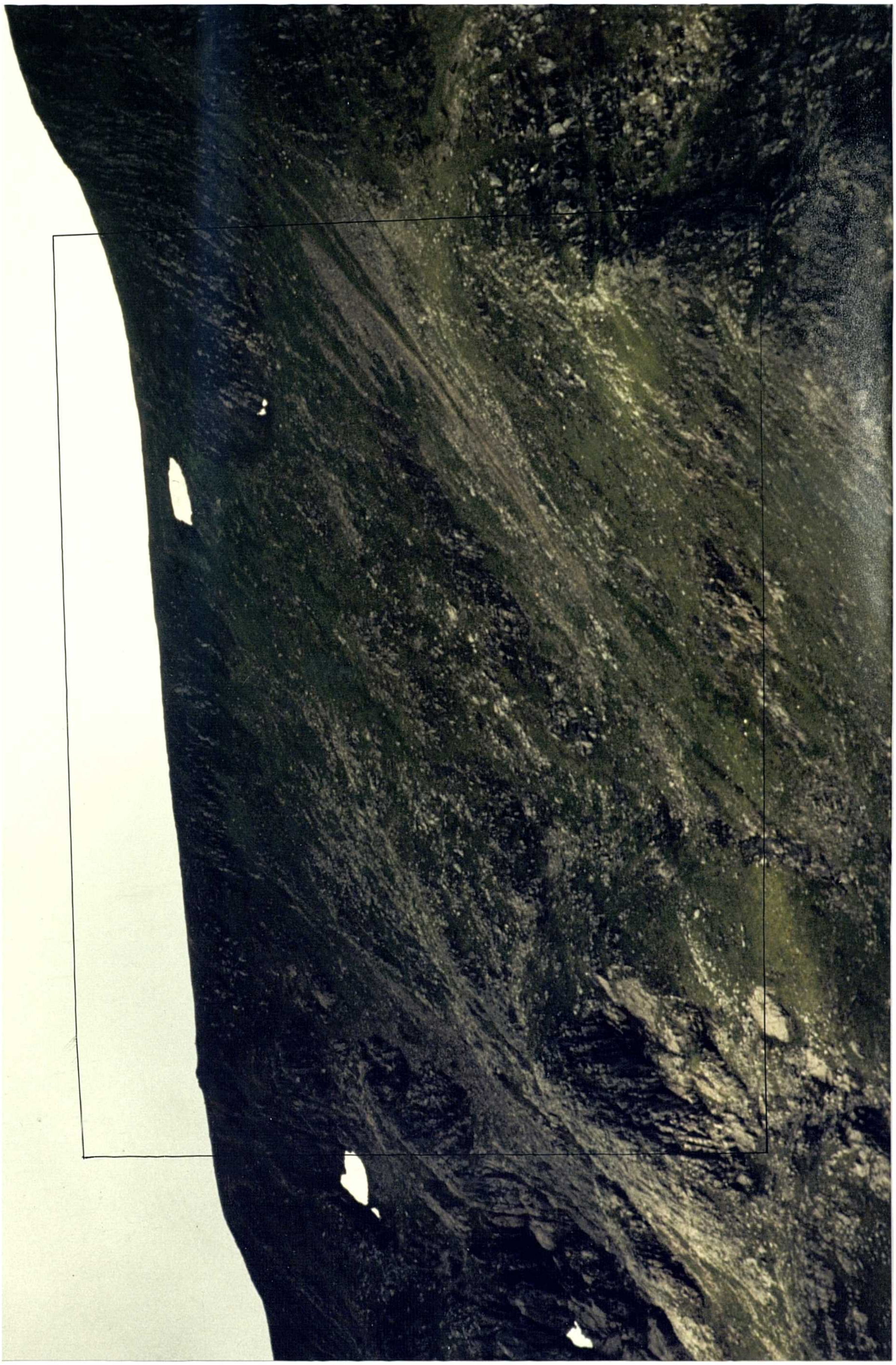


PLATE 4

OBLIQUE PHOTOGRAPH OF THE SITE FROM WHICH VEGETATION AND SNOWLIE MAPS WERE DRAWN.



absent.

During the winter this community on the summit plateau proper is covered by a thin veneer of verglas, or ice, with snow lying in the hollows; the redistribution of snowfall by wind is inevitable in this exposed and windy location, irrespective of the wetness of the snow. Towards the plateau edge snow accumulation becomes a little greater and the vegetation is subtly different, with gradually less *Racomitrium lanuginosum* and more *Racomitrium fasciculare*. Erosion of the moss carpet by wind is extensive with bare ground abundant. The gravel granite soil, with virtually no humic material, is readily eroded once the overlying vegetation has been removed. The eroded region is extended as the wind undermines and lifts further areas of moss from its bed. Pockets of erosion can be found throughout this community and are often exploited by the sheep in summer, providing some shelter from the wind, as shown in Plates 5 and 6. Recolonisation of the erosion hollow floor by *Racomitrium lanuginosum* should be noted in Plate 6, indicating that this is probably a natural and sustainable process.

In summer this community may be subject to severe desiccation when precipitation is infrequent and wind and radiation receipts high. Although humidity is often high, with cloud cover a frequent feature of the summit of Aonach Mor, evaporative losses must be great in such an exposed and windy situation. High wind speeds, which are typical of upland areas in Britain (for example, Pearsall, 1950; Gloyne, 1967), increase the stresses of desiccation and impose severe constraints on plant development (Gloyne, 1957; Roberts, 1972).

Descending from the flat part of the plateau across the lip of the back corrie, transitional communities are encountered. These form only a narrow strip along the plateau edge

PLATES 5 AND 6

COMMUNITY U10 ON THE SUMMIT PLATEAU AND EROSION POCKETS IN THE MOSS CARPET.

where the slope angle increases from the near-flat summit plateau to the 40° slopes of the back corrie. The bulk of the communities is composed of bryophytes such as *Racomitrium fasciculare, R. heterostichum, R. lanuginosum, Polytrichum alpinum, Oligotrichum hercynicum* and *Dicranum fuscescens* with a scattering of plants such as *Festuca vivipara, Luzula spicata, Huperzia selago, Cerastium cerastoides, Carex bigelowii, Deschampsia cespitosa, Saxifraga stellaris* and *Gnaphalium supinum*. Elements of the summit community, U10, as well as the surrounding communities, U11 and M33, may all be found in this zone of transition. This complex may best be described by NVC community U8 (*Carex bigelowii - Polytrichum alpinum* sedge-heath), although the data collected from the study quadrats located in this zone of transition (quadrats number 15, 16, 18, 20 and 25) returned a number of different community matches when analysed using the MATCH programme for NVC samples (Malloch, 1988), including U8, U11 and U12. These data are described and discussed further in Chapter 6, where an alternative community designation is proposed, since the communities do not fit comfortably into an existing description, being similar to both U10 and U11, and sufficiently distinct from surrounding vegetation to be separable. U12 might best describe the communities found in the vicinity of study quadrats 15, 17 and 19, but 16, 18, 20 and 25 do not really fit into this community description. They are much more like the *Racomitrium* heath found over the rest of the plateau, but are not sufficiently distinctive when compared with quadrat 15, 17 and 19. Given the observations of a gradual transition from U10 to U11 over this steadily-increasing slope from summit plateau to snow-bed, it may be most appropriate to describe them in the same way that Rothero (1989) describes his *Carex-Racomitrium* snow-bed, as a transitional type between his *Polytrichum sexangulare-Kiaeria starkei* snow-bed and U8.

Rothero's *Carex-Racomitrium* snow bed occurs in more mesic sites with a number of vascular plants, such as *Carex bigelowii, Salix herbacea, Huperzia selago, Gnaphalium supinum* and *Deschampsia cespitosa,* and a strong element of *Racomitrium* species, notable *R. heterostichum* and *R. fasciculare*. This corresponds closely to the situation found in quadrats 15, 17 and 19. Further discussion of this transitional area will be made in Chapter 6 using the quadrat data and making more direct comparison between them, Rothero's communities and the NVC. For the present it should be noted that the MATCH programme has not produced sufficiently fine-resolution results for use in this study and that the quadrats found around the plateau edge and on some parts of the plateau itself do not readily ascribe themselves to one or other of the NVC communities.

Below this complex lie the snowbed communities, described by the NVC classification as U11 - *Polytrichum sexangulare-Kiaeria starkei* snowbed and M33 - *Pohlia wahlenbergii* var. *glacialis* spring. The other main NVC snowbed communities, U12 (*Salix herbacea-Racomitrium heterostichum*) and U18 (*Cryptogramma crispa - Athyrium distentifolium*), are not represented in the site area though they may be found elsewhere on the mountain. The central part of the snowbed where snowlie is longest, and the area immediately below where irrigation is permanent, are occupied by the *Pohlia glacialis* spring where extensive, near-pure stands of the bryophyte *Pohlia ludwigii* are found. Surrounding this and separating the corrie lip communities and the downslope *Deschampsia* grassland from the central snowbed is the community U11 where a wider range of species is found, typically *Kiaeria starkei, Polytrichum sexangulare, P. alpinum, Pohlia ludwigii, Saxifraga stellaris* and occasionally individuals of *Deschampsia cespitosa*. Although in the centre of the snowbed *Pohlia wahlenbergii* var. *glacialis* is replaced entirely by *P. ludwigii*, this remains partly within the scope set out for that community by the NVC. The complete absence of *Pohlia wahlenbergii* var. *glacialis*, a constant in the NVC, is the main feature of this community which does not conform with the NVC. It is, perhaps, not sufficiently emphasised in the literature, but there was a lack of data in the composition of these snow-bed communities when the NVC was written (Rodwell, 1991, 1992). Rothero's (1989) communities include one which perfectly describes these pure *Pohlia ludwigii* snow-beds; his work has covered a very wide range and it may be that in time the NVC is amended accordingly, to change the *Pohlietum* from a *glacialis*-dominated spring to one in which either *glacialis* or *ludwigii* can dominate. Further discussion of the classification problems are found in Chapter 6.

Descending below the snowbed area the vegetation changes to a grassland of *Deschampsia cespitosa* within which the tiny *Galium saxatile* is abundant and bryophytes such as *Rhytidiadelphus squarrosus* may be found. The community is described as U13 (*Deschampsia cespitosa-Galium saxatile*) grassland in the NVC but some of the constant and normally abundant species described for this community are scarce or absent; for example, *Agrostis capillaris, Festuca ovina/vivipara, Nardus stricta, Deschampsia flexuosa, Hylocomium splendens* and *Rhytidiadelphus loreus* (Rodwell, 1992). *Deschampsia* is totally dominant and few other species, apart from the bryophyte *Rhytidiadelphus squarrosus* and vascular *Galium saxatile* exist in any abundance beneath its dense mat. The species-poor sub-community found here, possibly identifiable as a montane variant of the species-poor sub-community U13b, is thought to be less chionophilous than the more varied species-rich *Rhytidiadelphus loreus* sub-community, with *Deschampsia cespitosa* less dominant under more prolonged snowlie and other species able to grow in the less competitive environment (Rodwell, 1992). In no part of the corrie was the partially viviparous subspecies *Deschampsia cespitosa* ssp. *alpina* found.

This area is well-irrigated from the snowpatches above and experiences apparently very little desiccation in the course of a normal year. Within the grassland small areas of *Sphagnum* spp., most commonly *S. auriculatum* may be found marking springs and boggy ground in which species such as *Saxifraga stellaris* and *Pinguicula vulgaris* may also be found. The area is heavily grazed by sheep in the summer months, with most shoots showing evidence of grazing, pellet groups common and regular sightings of sheep in this area, concentrating on the grass *Deschampsia cespitosa.* Although not normally preferred by herbivores, there are data indicating that montane populations of *Deschampsia cespitosa* contain less silica in their leaves and are more palatable than the lowland variety, (Grime, Hodgson and Hunt, 1988).

The extent to which this community is natural is hard to determine. Grazing is certainly heavy but from July 1991 to October 1993 there was no indication that this was causing any lasting damage. Photosynthetic tissue is lost during grazing, which may enhance the exclusion of *D. cespitosa* from the snow-bed centre, where the stress of shortened growing season is hypothesised to become critical for this species, but it is predominantly the plants found in the near-pure swards of *Deschampsia* grassland located below the snow-bed proper which incur the greatest levels of grazing, being more easily accessible and less energy-intensive to browse. Occasional patches of completely dead *Deschampsia* were found, up to 0.5m in diameter, which suggest the presence of fungi. No investigation of this phenomenon was made, their occurrence being infrequent and of small extent. Examples are shown in Plates 7 and 8.

Towards the gully area, on the more rocky ground in the corrie, the vegetation type becomes less rich and well-irrigated and here the community is largely a mix of the NVC's U9 (*Juncus trifidus - Racomitrium lanuginosum* rush-heath) and U10 (*Carex bigelowii -*

PLATES 7 AND 8

TWO EXAMPLES OF DEAD *Deschampsia cespitosa* LEAVES WITHIN THE STUDY AREA.

Racomitrium lanuginosum moss heath), though it is a diverse version of the community U9, more normally found in more exposed and chionophobous positions. In pockets within these communities, where springs and burns are found or in boulder fields or other sheltered places, examples of a number of other communities may be found where the species are richer. These include U14 - *Alchemilla alpina - Sibbaldia procumbens*, U17 - *Luzula sylvatica - Geum rivale* tall-herb community (found on ledges in the gully), U18 - *Cryptogramma crispa - Athyrium distentifolium* snow-bed (found amongst the boulder fields), M31 *Anthelia julacea - Sphagnum auriculatum* and M32 *Philonotis fontana - Saxifraga stellaris* springs found in and around flowing water. The area in and around the gully contains a mosaic of different communities, including the snowbed communities U11, M31 and M33; this mosaic can be seen largely to reflect the topography and degree of sheltering found in this topographically complex area.

Directly below the research site the *Deschampsia* grassland descends almost to the corrie floor, contained within an area around a stream whose origins are found below the area of latest snow-lie. The left-hand side of this area of drainage is bounded by a rock buttress where the species *Juncus trifidus, Scirpus cespitosa, Carex bigelowii, Racomitrium lanuginosum* and a number of lichens from the family *Cladonia* can be found on the upper, drier parts. At the base of the buttress spring vegetation, including *Philonotis fontana, Pohlia ludwigii, Saxifraga stellaris* and *Anthelia* spp., is found. The right-hand side of the drainage basin is formed by the shoulder separating the back corrie from Coire an Lochain. Here the slopes are uniform in angle with only small rocky outcrops, largely covered with spring vegetation (M31), with extensive tracts of scree, holding communities U9 and U18 and grassland, covered by the communities U7 and U18. A summary of all the communities found in the back corrie is given in Table 4.2.

TABLE 4.2

GUIDE TO THE NVC COMMUNITIES FOUND IN BACK CORRIE, AONACH MOR.

U7	*Nardus stricta - Carex bigelowii* grass-heath
U8	*Carex bigelowii - Polytrichum alpinum* sedge-heath
U9	*Juncus trifidus - Racomitrium lanuginosum* rush-heath
U10	*Carex bigelowii - Racomitrium lanuginosum* moss-heath
U11	*Polytrichum sexangulare - Kiaeria starkei* snow-bed
U12	*Salix herbacea - Racomitrium heterostichum* snow-bed
U13	*Deschampsia cespitosa - Galium saxatile* grassland
U14	*Alchemilla alpina - Sibbaldia procumbens* dwarf-herb community
U17	*Luzula sylvatica - Geum rivale* tall-herb community
U18	*Cryptogramma crispa - Athyrium distentifolium* snow-bed
M31	*Anthelia julacea - Sphagnum auriculatum* spring
M32	*Philonotis fontana - Saxifraga stellaris* spring
M33	*Pohlia wahlenbergii* var. *glacialis* spring

4.1.6 Grazing and Disturbance.

The damage done to the vegetation by human feet is apparently rapidly increasing with much higher numbers having access to the plateau following the construction and year-round operation of the Nevis Range gondola; this follows casual observations made before and during the course of the research and no data were obtained to substantiate this claim. A number of sheep, between 10 and 50 and increasing each year over the period of study, also spend the summer grazing on the plateau which is causing noticeable damage, particularly the use of the small natural erosion hollows as shelter and their consequent enlargement, and the traffic of animals through fragile areas such as the research site. Therefore damage caused by grazing is exacerbated by trampling damage. These two factors are accelerating the rate of erosion processes. Records of the numbers of sheep were kept which showed a steady increase in the population, more than quadrupling from 1991, when only approximately 20 were found, to over 90 by the end of 1993. These data are now in the hands of the Scottish Natural Heritage office in Fort William.

Generally human intervention was insignificant in terms of the research whereas the effect of the sheep on the project was significant. The impact made by sheep increased during the period of study as the numbers encountered during fieldwork visits also increased. Sheep gain access to the summit plateau by means of a path which runs right across the middle of the site; they have also been observed moving about and grazing on all parts of the site, causing damage to the vegetation and the soft and mobile substrate. Apart from trampling damage, sheep will graze on the grass *Deschampsia cespitosa* wherever it is found - which is in most of the quadrats - and thus not only cause trampling damage by getting to it but also destroy the evidence to be measured in the research. Most significantly, the pegs and tags locating the study quadrats were regularly dislodged by the sheep.

4.2 Characteristics of a Snowbed Environment - Monitoring Methods.

Species' locations are the function of a suite of environmental variables plus the interaction and competition generated between each other. In this study the hypothesis is presented that the species occupying the area of late snowbeds are ineffectual competitors relative to species in surrounding communities, so the element of competition assumes a less dominant role, and that it is the stress of the late duration of snowlie which is the single most important environmental variable. However, in order that other evidence which might indicate that the hypothesis was incorrect could come to light, as many other environmental variables as possible were examined in the field. These measurements were constrained by the requirement of SNH that no destructive methods were used and by the remote site location. An additional hindrance, which dogged all the field measurements, was inclement weather, particularly during July and August 1993. Poor visibility, high winds and wind chill factor, low temperatures and rainfall were all conditions under which it was not possible to operate. The very exposed nature of the site made poor conditions worse and sometimes while the lower quadrats could be surveyed with only minor discomfort, the top quadrats were impossible without risk of hypothermia. Only a fraction of the number of days anticipated could be spent collecting useful data, though this shortfall was ameliorated to a certain extent by steady improvements in identification of plants, survey methods and the speed of approach and retreat.

The environmental variables and vegetation parameters which were measured or observed during the study are given below:

4.2.1 Topography

Slope profiles of the site were constructed to give an accurate topographic representation for this small area. A clinometer, measuring tape and ranging pole were used for this purpose and profiles made of the left-hand, right-hand and central transects of the site area.

The profiles were resurveyed in reverse and the same recordings made on each leg. Additionally, the distances measured for each leg, in this case 5m, amounted in total to the 100m of the transect to within 50cm. The accuracy of this method was acceptable, and the survey was not repeated.

4.2.2 Exposure and Wind Conditions

Different parts of the site experience different levels of exposure in winds from the same direction and this relationship changes with winds from different sectors. As an air mass approaches the summit of a mountain, it is compressed vertically. Thus winds experienced around the summits are higher than elsewhere, except in cols where wind is compressed horizontally as well as vertically and wind speeds are generally even higher than those at the summit. The summits of mountains are also, by being the highest ground in the vicinity, much more exposed than areas lower down which must experience some degree of shelter from surrounding topography; therefore wind speeds will be higher on summits, irrespective of the amount of vertical compression of the air. Air forms a wave shape as it passes over summits and is able, on the lee side, to expand again which allows deposition of the snow it carries and often sets up lee eddies. The prevailing winds in this area are from westerly and south-westerly directions, meaning that the field site lies on the lee side of the mountain. Therefore it is expected that the upper parts of the site would generally experience the high summit winds while further downslope wind velocities would be much lower. At some point downhill from the edge of the summit plateau the eddy effect would also be generally expected to be experienced with upslope winds being generated. Winds originating from eastern points of the compass would however, be experienced at all points of the site at high velocities as with these wind directions the site would lie on the windward side of the hill. Winds from the north and south would affect upper parts of the site but the concave nature of the site itself and the corrie within which it is found would afford some protection from these winds (i.e. those running parallel to the long axis of Aonach Mor).

The degree of exposure of the site affects the plant types which may occupy different parts of it as high wind speeds are very destructive of erect and non-robust plant tissues. It also affects the snow cover on the site, and thus the species distribution, by ensuring in most, if not all, years, a substantial cornice and downslope snow field builds up on the edge of the plateau on the site side; cornices on the other side of the plateau are rare and of short duration owing to the dominance of the westerly winds. Further effects of exposure include the energy budget at the surface with strong and turbulent winds having a considerable effect on sensible and latent heat losses (Harrison and Kelly, 1996). These losses can cause a strong chilling effect on the vegetation (Baldwin and Smithson, 1979) as well as affecting the levels of moisture at and near the surface.

A measure of the exposure of the site was ascertained using the topographic index devised by Harrison (1988). This is a relatively uncomplicated index which is suited to this form of coarse and simple approach where the precision of detailed microclimatic studies is not required.

Readings of the angle of declination or inclination of the surrounding horizon were taken from three locations; from the summit cairn on Aonach Mor, from the middle of the top site boundary and at the middle of the lower site boundary. The measurements taken were then used to produce the sheltergrams, using a centre value of -5.0°, as suggested by Harrison and Kelly (1996. The horizon was taken to be the ground-sky interface.

The area of the sheltergrams was then determined to give an index of topographic exposure (SL) using the following equation:

$$SL^2 = \sum_{n=1}^{m} \frac{\theta_n.\theta_{n+1}}{2} \, . \sin\left(\frac{2\pi}{m}\right) \qquad (1)$$

where θ_n is the angle of inclination or declination plus the central reference of -5°, the value of m is the number of compass points used, so that n=1 for a northerly bearing with values increasing clockwise around the compass (Harrison and Kelly, 1996).

The bearing of greatest shelter (ψ) was derived from the equation:

$$\psi = \tan^{-1}(S/C) \qquad (2)$$

where:

$$S = \sum_{n=1}^{m} \theta_n.\sin\left\{(n-1).\frac{2\pi}{m}\right\} \qquad (3)$$

and

$$C = \sum_{n=1}^{m} \theta_n.\cos\left\{(n-1).\frac{2\pi}{m}\right\} \qquad (4)$$

Accordingly the aspect of the site is given by $\psi + 180°$.

The modification of this measure of exposure is necessary as winds experienced here are not derived uniformly from the eight compass points. The dominance of westerly and south-westerly flow means that low horizon values in a westerly or south-westerly orientation have much greater significance than low values for easterly orientations. The weighting given follows the method outlined by Harrison and Kelly (1996) and gives the modified topographic index (SL_w) according to the equation:

$$SL_w^2 = \sum_{n=1}^{m} \frac{X_n . X_{n+1}}{2} . \sin\left(\frac{2\pi}{m}\right) \qquad (5)$$

where $X_n = \theta_n . f_n$ in which f_n is the wind frequency term derived from the percentage frequency (F_n) for the eight principal points of the compass:

$$f_n = F_n{*}\ 8/100 \qquad (F_9 = F_1)$$

The percentage frequencies of wind for this location were derived from fifty-year records acquired for Cape Wrath, Tiree and Eskdalemuir meteorological stations, used elsewhere in the thesis, which were averaged for each compass point for the entirety of the record and between the three stations, giving a good general picture of wind receipts through the west of Scotland. The frequencies derived are shown in Table 4.3.

Using a hand-held anemometer the wind strength actually experienced at the site, rather than theoretically, was determined. Comparison between these data and the data from Aonach Mor AWS was not possible, since the wind on neither occasion that it was measured was consistent in either strength or direction as recorded at the AWS. The dates on which the observations were made were the 1/7/92 and 2/7/92. Wind direction at the time was, according to the AWS on Aonach Mor, from 100 to 200° with gusts from 030° at the time of observations on 1/7/92 and from 150 to 190° with gusts from 140 to 150° on 2/7/92. The wind speeds were 09 to 11 knots on the 1/7/92 with maximum gust of 23 knots and 13 to 15 knots on the 2/7/92 with maximum gust of 29 knots. This high variability of both wind direction and speed is shown in the data from Aonach Mor where there are only occasionally periods of consistent winds; whether this is the result of instrumentation problems, topographic effects, or a natural variability in wind strength and

TABLE 4.3

WIND DIRECTION FREQUENCIES DERIVED FROM 49-YEAR RECORD FOR CAPE WRATH, TIREE AND ESKDALEMUIR METEOROLOGICAL STATIONS.

DIRECTION	**FREQUENCY, %**
NORTH	10.9
NORTH-EAST	7.3
EAST	8.8
SOUTH-EAST	9.6
SOUTH	16.1
SOUTH-WEST	22.1
WEST	16.0
NORTH-WEST	9.2

direction at altitude, is not clear.

The anemometer readings were taken from a height of 2m above the ground to obtain readings for the average wind speed for one minute and the maximum 5-second gust. The readings were taken twice on 2/7/92 but only once on 1/7/92. On 1/7/92 the transect along which readings were taken ascended the right-hand (northern) boundary of the site while those for 2/7/92 were taken on a diagonal transect across the site. The intervals between positions at which readings were made were 10m for the former and 3.9m for the latter transects.

4.2.3 Snow Depth

Initially it was expected that snow depth over the site would be sampled on a regular basis throughout the winter. From these measurements it was anticipated that a model might be generated to show how snow accumulated and diminished over the site. Such a model could have demonstrated the effect of wind-blown snow deposition and the build-up of the cornice, showing where maximum depth was achieved and how this related to the survival of snowpatches into the summer. For this purpose a steel avalanche probe was purchased, this being the most appropriate tool for penetrating the snow to considerable depths. However, the development of ice layers in the snowpack prevented the effective penetration of the avalanche probe and the systematic measurement of snow depth had to be abandoned. In itself, this is an interesting result since the occurrence of ice layers sufficiently dense to prevent the avalanche probe, which is of robust construction, from penetrating, is exceedingly rare in the experience of those people who operate in the Scottish hills in winter (Glenmore Lodge, 1996, pers. comm.). This may be true for the Cairngorms but the presence of such ice layers in two winters on Aonach Mor may indicate that the increased frequency of freeze-thaw cycles in the western Highlands commonly allow very dense neve to evolve. The implications for snowbed survival through the summer have been outlined earlier, with denser snowpacks melting less rapidly.

4.2.4 Snow Cover

The extent of snow cover was recorded to give a measure of the development and decay of the surface snow cover, and the loyalty of the late snowbeds to location. Snow cover of the site was measured using photography and ground observations. Photography of the site from a fixed point on the ridge north of Stob Choire an Fhir Dhuibh (marked P on the map in Figure 4.1) was undertaken whenever there was sufficient visibility. Photographs, either transparencies or prints, were taken at 28mm, 50mm and 105mm, giving a range of views from wide-angle to telephoto. The dates on which photography was possible, and which provided data for the snow-lie maps, were 18.5.92, 28.5.92, 8.6.92, 1.7.92, 27.4.93, 10.5.93, 26.5.93, 9.6.93 and 24.6.93.

From the photography it was possible to map the extent of the snowbed on each visit when photography could be obtained. On occasions when visibility was too poor, observations were made of the approximate extent of snow when actually working on the site. The extent of the snowbeds captured in photographs was verified and quantified with ground data, using a 50m tape measure to give the horizontal and vertical dimensions of the existing snowpatches. One end of the tape measure was secured to the edge of the snowpatch using an ice axe and the appropriate measurement made to the opposite edge. Measurements were made at the widest points of the snowpatches on lines running directly up/down and across the slope. These additional measurements lead to the belief that the maps showing snow cover variation over the course of the study are reasonably accurate -

at least to within 2m. The loyalty of the snowbed to location could then be assessed for the two field seasons over which measurements were taken, and an indication of the difference in melt date of different parts of the site could be obtained.

From these photographs, using the oblique enlarged photograph of the back corrie shown in Plate 4, three maps were composed to show snow-lie through 1992, 1993 and a generalised combination of the two. The maps generated have the same amount of oblique distortion as the photograph, having been superimposed upon it; no attempt has been made to produce a vertical map, primarily due to the lack of appropriate aerial photography. For the purposes of this investigation, constructing a true vertical image is not essential. Identifiable features such as boulders and rock outcrops have been used to transfer the snowbed photographic information onto the oblique photograph used as the basis of the three maps. With the limited resolution of the photographs available, it is estimated that the maps are accurate to approximately 10m.

4.2.5 Snow Profiles.

Some snow pits were dug and examined at similar locations near the site, along the cornice line. The development of snow layers in the snowpack was observed and simple measures made of each layer's hardness, using a scale of 1-5 as prescribed by the Scottish Avalanche Information Service. With practice it was possible to identify a highly stratified snowpack of many layers with definable boundaries over a relatively short distance.

Temperature profiles down through the snow were recorded by installing a Grant temperature logger with up to 21 probes (thermistors) set at 10cm or 15cm intervals vertically down a snow pit which was then back-filled. The Grant logger was successively installed in four such pits close to, but not actually on, the site. They were buried near the top of the cornice line where snow depth is at a maximum but unfortunately the data logger and its probes were usually re-exposed within 48 hours, before a return visit was made, and on one occasion the logger was transported about 400m downslope and all data effectively lost. On two occasions the installation was successful and temperature profiles of the snowpack were obtained.

Two different assays were made to establish the penetration of light through the snowpack using an environmental comparator with optical probe attached. The temperature was also measured on one of these occasions using a hand-held thermistor. A narrow snow pit was dug to a depth of 1m and the back face used to insert the probes. The light-sensitive probe, attached to the environmental comparator, was inserted horizontally into the back wall to its maximum depth, a distance of approximately 25cm, and the snow pit face obscured as much as possible using clothing, to prevent light contamination from the snow pit. The reading on the environmental comparator was then noted. Following the insertion of the relatively robust optical probe, a thermistor was inserted into the hole vacated by the optical probe and the temperature of the snow measured.

Most of the studies outlined above were carried out during the winter period. It proved impossible to conduct more studies of this nature, though initial efforts were made to visit the site more frequently in winter. However, with the very exposed conditions experienced at the cornice area of the back corrie it became obvious that these observations were particularly weather-dependent and that only in the most calm conditions could visits be made within an acceptable margin of safety. Equally, there were occasions when access to the hill was unsafe on the grounds of potential avalanche hazard.

4.2.6. Snow and Water pH.

A portable pH meter was used to determine the pH of water at various points in and around the site. With preferential flushing of pollutants and aerosol contaminants from the snowpack at the initiation of melt, a measure of the level of acidity experienced by plants beginning to grow downslope of the snowbed was required. Such a flush, should it take place after downslope plants have started to grow, could have adverse effects on growth.

The meter was calibrated using two bottles of fluid of known pH which could be transported into the field so that calibration could take place in the same environmental conditions as the actual readings. On each occasion this calibration took place before readings were taken and the calibration fluids were replaced at the end of 1992 since contamination will take place over time as the probe is transferred from the water being tested back to the calibration fluid. Under laboratory conditions the probe should be washed with distilled water but in the field this was an impractical procedure.

The spring below the snowpatch in the *Deschampsia cespitosa* grassland, near quadrat number 7 and approximately 150m below the snowbed, was sampled on 28/5/92, 17/6/92, 31/7/92, 5/9/92, 26/5/93 and 20/7/93. On 28/5/92, 17/6/92, 26/5/93 and 20/7/93 snow was removed from the snowpatch from the surface and from 5cm below the surface, stored in a sealed plastic container and removed from the site. When this had melted, usually 6-8 hours later, the pH of the remaining water was measured and recorded. When measuring pH, 5 separate readings were taken to reduce errors and the mean and range calculated. Measurements were taken from all three sites (upper and lower snowbed and spring) on 28.5.92, 17.6.92, 26.5.93 and 20.7.93. Additional measurements from the spring were taken on 31.7.92 and 5.9.92. These measures must contain a margin of error introduced as a result of contamination of the calibration fluids and absorption of ions during melting of the snow from air remaining inside the container. Therefore the results, given in the next chapter, must be viewed as indicative only, though a statistically significant change was measured.

4.3 The Pattern of Vegetation Associations - Monitoring Methods.

In order to address the hypothesis that snowbed vegetation is composed of species whose presence is determined rather by the absence of more competitive species through the shortened growing season, than by a positive competitive advantage, a programme of field research was established.

4.3.1 Establishing the Study Site.

Firstly, suitable examination of the snowbed vegetation and the communities surrounding it should take place. In order that statistical analyses such as regression and correlation could be performed on the data, randomly-spaced quadrats were required. A transect was considered, such as that used by Wijk (1986), but advice offered suggested that it was important to test the relationships between vegetation and environment and between different species using methods which necessitated the use of randomly-generated data. Therefore it was necessary to outline an area within which randomly-selected quadrats could be placed and to decide what number and size of quadrats would be appropriate.

It was necessary to attempt to eliminate any taxonomic bias which might arise from variance in growth form, life-cycle (Cox and Larson, 1993) and response to time dependent environmental variables such as moisture availability and temperature. Since a large number of the species involved were bryophytes, it was necessary to include as many of these species as possible, and to continue to sample specific quadrats throughout the snow-free season, from May through to September, because the timing of emergence of vascular and bryophyte species, and the length of their growing season varied. In this way taxonomic bias could be minimised (Young and Peacock, 1992).

The number of quadrats chosen reflected the assessment of how frequently it would be possible to carry out a complete survey of the quadrats, given how long each individual quadrat should take and how many days per week it was estimated could be spent on the hill. With one hour estimated for each quadrat, four quadrats possible in one day's work, three out of seven days with adequate weather for recording and a repeat of survey desired every fortnight, a total of 25 quadrats was chosen. Access to the site was facilitated using the Nevis Range gondola, without which fewer quadrats could have been examined.

Following Wijk's work (1986) a $1m^2$ quadrat was used. The standard NVC quadrat size of $2m^2$ (Rodwell, 1991, 1992) was considered too large for this type of flora, being designed to work best with much larger plant individuals, while Rothero (1989) used a smaller quadrat for the bryophyte-dominated snowbeds which he examined. However, he was not investigating areas of predominantly vascular flora and was also operating at a higher resolution than the present study, being an expert on bryophytes. Given the extent of vascular plants, their size and the low resolution employed for the bryophytes, a $1m^2$ quadrat was considered the most appropriate. This would also enable the data generated to be used to extend the NVC database for snowbed vegetation, as requested by Dr. Rodwell.

These 25 metre-square quadrats needed to be scattered randomly through and around the snowbed area. A trial was undertaken to determine the most appropriate size of site within which to place the quadrats and eventually a square of 100m x 100m was chosen, positioned such that the area occupied by the core snowbed vegetation lay across the middle of the square with a substantial amount of vegetation both above and below the snowbed. Roughly 40% of the total area was occupied by the snowbed vegetation, 30% by the *Deschampsia cespitosa* grassland below, and 30% by the transitional vegetation merging into the plateau. The plateau edge is sufficiently gently-sloping and away from the core of the plateau that none of the 'true' *Racomitrium lanuginosum* summit plateau community appeared, although the quadrats at the top (16, 18 and 25) superficially seemed to be the same as the vegetation right on the top of the plateau. The orientation of the study square needed to be such that the band of snowbed vegetation ran parallel to one of the axes; thus one axis should run along the line of contours and the other perpendicular to it. This ensured a fair representation of the different vegetation types available. Fortunately this transpired to be along the four principal compass bearings, with the plateau running north-south.

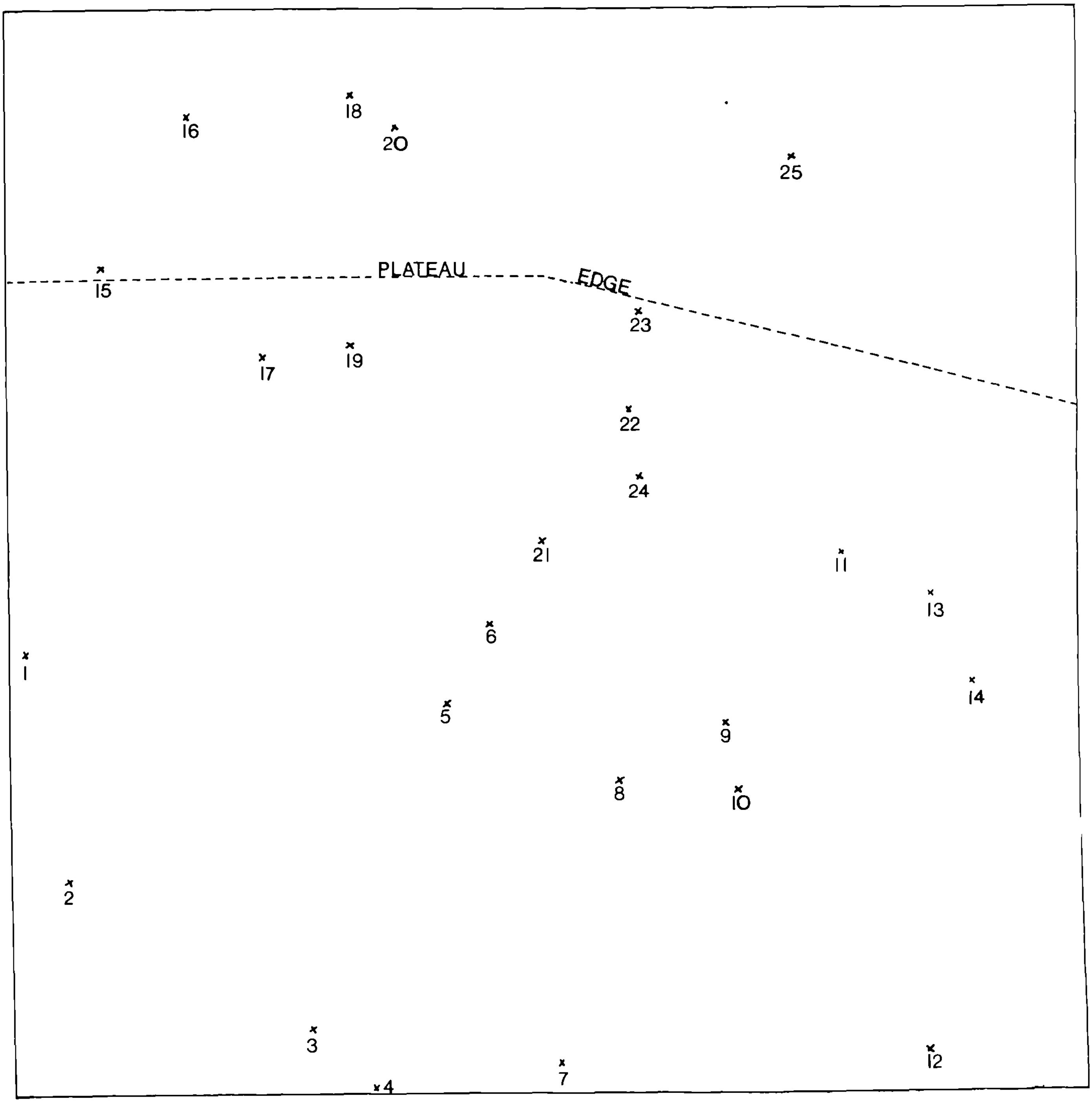
Having decided on the number of quadrats and marked out the 100m^2 using surveying rods, a sighting compass, a tape measure, small cairns and some assistance, it was then necessary to allocate co-ordinates for each quadrat. This was done randomly by drawing four golf balls out of a bag containing 10 balls numbered 0 to 9, with every ball drawn being replaced before the next ball was drawn. The first two numbers drawn for each quadrat represented the number of metres along the horizontal (north-south) axis of the study site, while the last two numbers referred to the number of metres along the vertical (east-west) axis. The position of the quadrats was then determined, again using the prismatic sighting compass, surveying rods and the tape measure. Having found the correct spot, a peg was placed in the ground with a strip of orange tape attached, on which was inscribed the quadat's number in indelible marker. This was then used to locate the bottom left hand corner of the portable wooden quadrat frame used to record the floristics of each quadrat on every site visit. The frame would be laid in the same orientation as the study site i.e. with its four sides along the four principal compass bearings. Conveniently, but purely by chance, the distribution of quadrats found the same number in both the above- and below-snowpatch vegetation, being 5, with the remaining 12 located in the snowbed area. The distribution of the quadrats within the study site is shown in Figure 4.5.

Marking the location of each quadrat using pegs proved extremely unsatisfactory since regularly the pegs from the uppermost quadrats disappeared, most likely removed by the sheep, and the system of relocation required a second person to assist with the surveying poles. Although attempted, it proved to be impossible to relocate quadrats with only one person, and a second person to assist this process was only infrequently available. Unfortunately no solution to this problem presented itself and SNH insisted that no permanent markers be used, nor any substance or procedure which might damage the vegetation. Therefore it was not possible to use, for example, an unpalatable dip for the orange tape to discourage the attention of the sheep to the markers.

One of the problems which resulted from the loss of pegs was that relocation entailed a certain degree of inaccuracy and two of the relocations were not to exactly the same position occupied by the original quadrat. This could be observed through the vegetation details recorded at the original and new sites, but could also be recognised through familiarity with the quadrats. A careful survey of the vegetation around the new proposed position was always made to attempt to make the relocation perfect. Wherever possible, solid and permanent features, such as stones, were noted with respect to their proximity to the quadrat; in the more mobile and featureless quadrats this procedure did not work.

In order to monitor the extent of snow lying on the site it was necessary to establish a fixed location from which to take photographs on every visit. Once the site was located it became feasible to look around for the most suitable location which was relatively easy to

FIGURE 4.5
DIAGRAM SHOWING THE LOCATION OF 25 QUADRATS WITHIN THE 100m² STUDY AREA.



reach and locate and from which the best possible view of the site could be obtained. A point along the ridge running parallel to the main plateau was chosen, on Stob Coire an Fhir Dhuibh, with an unobstructed view almost perpendicular to the back wall of the corrie and at a high enough altitude to see most of the site. This point was marked with a cairn. Its position is marked with a P on the map in Figure 4.1.

Within the duration of the studentship, which started in February 1991, three field seasons were available. The first field season was devoted to learning to identify the relevant species and acquiring the skills necessary to carry out the survey. It was also necessary to learn more about the different communities involved, their variations and the different combinations of species which defined one from the other. The first field season was also largely devoted to looking at a variety of site options and making a final choice for the study site. The large proportion of time spent acquiring the necessary expertise in the identification of the more common and visible bryophyte species was deemed necessary; lichens and bryophytes are less widely included in surveys "because of a false perception that they have little ecological or economic value (Seaward, 1977; Smith, 1982), and because they are taxonomically challenging. When they are included, multiple taxa are usually combined under the designation 'lichen' or 'moss', and in turn this combining process promotes the commonly held view that non-vascular plants behave - as a group -in a fashion that is different from vascular plants (Grime, 1979)." (Cox and Larson, 1993). The loss of all data from the first field season due to theft, although inconvenient, did not pose a serious problem to the project as a result of the orientation strategy adopted.

4.3.2 Summer Site Visits.

Visits to the site increased in frequency in both 1992 and 1993 as soon as some of the quadrats became free of overlying snow or ice and the vegetation started to grow. Visits involved an ascent in the Nevis Range gondola to the middle station, after which a one-hour walk contouring around the north-eastern end of Aonach Mor and ascending beside the Allt Choille-rais allowed the back corrie to be gained. Often an ascent of Stob Coire an Fhir Dhuibh was also made *en route* to allow photographs to be taken. The back corrie was then ascended just to the right of the gully, to gain the base of the field site. Total time from the car park was about 2 hours 30 minutes under normal summer conditions. Return was usually made along the top of the plateau and then down the path constructed by the Nevis Range company to the west of the chairlift, though in high winds retracing the outgoing route was preferred.

The uppermost quadrats on the summit plateau (nos. 16, 18, 20, 25) shown in Figure 4.6 were always the first to become free and show signs of growth, usually during May, since they were never covered by more than a thin layer of snow, some 10-20cm deep. The quadrats just below or on the edge of the plateau (nos. 15, 17, 19) would generally be snow-free by the middle of June as the cornice snow melted and the main mass slipped downslope, and showed a much more rapid development of shoots than the plateau quadrats. The *Deschampsia* - dominated quadrats at the bottom of the site (nos. 3, 4, 7, 12) were also usually snow-free in June and showed good, rapid development. The snow-bed quadrats, however, were covered until July or even August and then usually experienced the first transient winter accumulation of snow again in September. These quadrats showed further growth in bryophytes through to November but the more exposed quadrats and those where vascular plants dominated would show almost no living tissue by the beginning of September. Thus the period of botanical study and measurement commenced in May and reached a peak in August. During this time visits were made as

PLATE 9

ACCESS TO THE SUMMIT PLATEAU WAS FACILITATED BY THE GONDOLA OPERATED BY THE NEVIS RANGE COMPANY.

often as practicable, ideally with every quadrat visited once every week but in practice only once every two to three weeks.

Further problems were encountered moving around the site as it proved impossible not to damage the underlying vegetation. The high angle of slope, combined with the type of vegetation, which proved extremely soft and slippery when wet made it difficult to traverse, ascend or descend without uprooting the vegetation. Obviously extreme care was taken not to trample the quadrats themselves, but the extent of more general damage sustained when merely moving from one to another, particularly when the ground surface was wet, was considerable and proved a disincentive to visit the site too frequently. No obvious solution presented itself with any physical protection, such as the use of boards, impossible given the time and effort involved in putting them in place and moving around the site. The high angle of slope also mitigated against such practical solutions; the best method was avoidance, particularly after extensive rainfall, but in order to acquire the minimum necessary data occasional visits in inappropriate conditions were essential. The only other concession that proved possible to make to the fragility of the site was to wear light studded shoes rather than boots, which was done on every possible occasion. Damage did take place and although no absolute measurements were taken, it appears through qualitative observations that the level of erosion at the site has increased in the period of study.

The fragility of the site, as demonstrated by the need to take active measures to minimise damage, was largely attributed to two things: firstly, the lack of rooted vegetation in the bryophyte-dominated areas meant that the whole mat could slump under pressure. Secondly, the presence of water, usually in large quantities from the snowbed melt, lubricated the bryophyte mat and the gravel substrate and increased their mobility. Beneath the snowpatch during the spring and summer, it is therefore expected that the observed creep of both pack and vegetation is an important factor in plant survival. Additionally, the presence of sheep in large numbers, regularly using this site to ascend and descend the hill, will have a significant impact, more so than in more firmly-rooted vegetation.

4.3.3 Quadrat Measurements.

The same suite of observations on the vegetation were made on every visit and for every quadrat. Firstly the presence or absence of snow on the quadrat was noted. Quadrats fully covered with snow received no further study on that visit. If partially covered, the percentage covered by snow was estimated using the wooden quadrat frame. All areas within quadrats not covered by snow were observed in detail and a number of measurements taken as follows:-

1. The percentage of bare ground and the type of substrate exposed was noted, such as gravel, bare rock, or soil, using the 4% divisions made by twine strung across the wooden quadrat frame as a guideline.

2. Any erosion of substrate or vegetation mat was noted as well as any incoming debris from higher up the slope. Thus records were kept of quadrats both losing and receiving material, which proved to be a significant process at the site, particularly on the steeper ground.

3. The wetness of the quadrat, estimated on a scale of 1 (dry) to 5 (running water) was noted.

4. The percentage cover of each species of plant visible in the quadrat was estimated. This did not include dead tissues, nor could it take into account species which, although

present, displayed little or no live material at the time. Thus in each quadrat, as different species took different lengths of time to grow and fruit, the percentage cover of each species tended to change through the growing season.

5. The extent to which species were mixed intimately or separated. The Domin scale was used to give definitive values for each quadrat, the data for which were collected over a period of time to ensure that each species had been accurately recorded given the fact that each reached optimum growth at different times. The values given in Table 6.2 thus represent an overall picture of the quadrats' composition, independent of time during the growing season.

6. The occurrence of each species of vascular plant in the quadrat was observed and measurements of shoots and inflorescences made with a pair of Vernier callipers. Up to ten such measurements were taken for each species, depending on the number of shoots available. When shoots had been grazed, this was also noted. The greatest diameter of rosette plants (only *Saxifraga stellaris* falls into this category) was measured. The state of inflorescences (in bud, in flower, setting seed, seed dispersed) was noted and any die-back in shoots recorded.

7. Shoot lengths of bryophytes proved impossible to measure in the time scale involved, partly because of their small size and partly because of the need for more refined equipment, such as a microscope, necessary to perform this task accurately. In the field such detailed work was impossible. However, a suite of observations of the bryophytes was made on each visit which included:

(i) the state of each species in all parts of the quadrat, whether green and vigorous, partially or wholly desiccated and

(ii) the presence or absence of any capsules, their approximate numbers and condition (whether green and young, brown and ripe or over-ripe and open)

The vegetation observations were combined to give an overall picture of each quadrat with a Domin value for each species which represented the species abundance in general in the quadrat, rather than species abundance at any given time.

8. Additionally, temperature measurements were taken on a number of different visits (not every one) of the air temperature 5cm above the vegetation, the air temperature within the vegetation and the soil temperature at a depth of 3-5cm within the substrate. A hand-held thermistor was used for this purpose; the air temperature above the vegetation was taken at 5cm above the uppermost layer by propping the thermistor up at the appropriate height (a purpose-made stick was used for this), then immersed in the densest part of the vascular plant canopy and following that the bryophyte canopy. Finally the probe was gently pressed into the substrate for between 3 and 5cm after a similarly sized hole had been made using a pencil, to give a reading for soil temperature. At each stage the dial was allowed to settle, which sometimes took several minutes, before the probe was removed and replaced for the next reading; it was only when the dial had ceased to move that the temperature was recorded and the probe moved to the next measurement.

Although every effort was made to record all species present in every quadrat, a number of lichens and liverworts are likely to have been overlooked. This is due to the fact that many are very minute plants and occur in an intimate mixture with much bulkier species, often never giving more than a pin-head sized sample to observe (Rothero, 1989). The species which were observed are listed in Table 4.4. Any species which do occur in the quadrats and have not been recorded in the list is entirely the fault of the researcher. Given the

TABLE 4.4

TABLE OF SPECIES RECORDED IN QUADRAT OBSERVATIONS.

Deschampsia cespitosa

Carex bigelowii

Salix herbacea

Galium saxatile

Huperzia selago

Pohlia ludwigii

Polytrichum sexangulare

Dicranum fuscescens

Racomitrium fasciculare

Racomitrium lanuginosum

Scapania spp.

Anthelia spp.

Festuca vivpara

Luzula spicata

Saxifraga stellaris

Gnaphalium supinum

Sphagnum spp.

Polytrichum alpinum

Kiaeria starkei

Andraea nivalis

Racomitrium heterostichum

Rhytidiadelphus squarrosus

Marsupella spp.

Moerkia blyttii

period of study and the restrictions of time available for study, it was not possible to acquire the skill necessary to observe such a diverse range of species as may be found amongst the mosses, liverworts and lichens, which are all somewhat awkward to observe and identify. Some species whose family is relatively easy to identify, but whose individual species are not, have been recorded as *xxxx* spp., for example *Sphagnum* spp. and the aggregate *Racomitrium heterostichum.*

4.3.4 *Deschampsia* Pot Experiment.

The main hypothesis used to describe the distribution of the different species in and around the snow patch suggests that the absence of the dense sward of *Deschampsia cespitosa* is fundamental to the survival of the snowbed core vegetation by reducing the level of competition, and that *Deschampsia* is absent because it cannot tolerate the stress of longer periods of snow-lie. Thus a reduction in the extent of snow-lie through climatic change could prompt *Deschampsia* to over-run the snowbed vegetation and thereby cause its removal from this site.

In order to ascertain how the grass *Deschampsia cespitosa* coped with greater snow-lie than that found in the *Deschampsia* grassland below the snow-bed site, pots of *Deschampsia* were transplanted in a line right across the snowbed, ascending from near quadrat 9 to near quadrat 23, at the end of the 1992 field season. Their contents were then observed through the 1993 season, using the same measurements for vascular plants outlined above, until the pots were either lost (presumably to sheep) or removed at the end of 1993. The performance of *Deschampsia cespitosa* could then be compared between the pots and individuals in the snowbed area and in the grassland below. Differences in performance could then be attributed to the change in snow-lie regime. Although some changes in performance could be the result of the transplantation process, the pots most peripheral to the snowbed acted as control pots, being within the area normally inhabited by at least scattered individuals of *Deschampsia cespitosa.*

The pots also proved a useful illustration of the mobility of the site with many of them becoming completely crushed by general down-slope soil movement within the 12 months of their residence. Although this was in direct contradiction to the guidelines for study laid down by SNH where no disturbance of the site could be tolerated, the difficulties in obtaining adequate data to make any meaningful observations about the proposed hypothesis and a lapse in SNH's involvement in the project through the appointment of Andrew Batchell to a different area, meant that such a course of action was deemed appropriate.

4.4 The Climate - Snow Cover Link.

Observations of the vegetation and snow cover outlined above enabled an assessment to be made of the nature of the relationship between these two variables. This allowed part of the hypothesis to be addressed: that snowbed species inhabit the snowbed area because of reduced competition, and that species in surrounding areas with greater competitive ability are excluded by the increased levels of stress inflicted by the prolonged period of snow-lie and reduced growing season. Additional information about the loyalty of late snowbeds to location was sought to verify the findings of Watson, Davison and French (1994), indicating that late snowbeds have high location loyalty and that a change in positioning of the deep drifts which generate the late snowbeds is highly unlikely. It was also necessary to investigate the relationship between variation in climate and snow-lie in the western Highlands, to assess the sensitivity of late snowbeds to changes in climate and the amount of variation in snow-lie duration normally experienced. Once the current sensitivity of the snowbeds had been assessed, it could then be set in the context of predicted climatic change for the future. By establishing these links, the likelihood of survival of the snowbed species could then be indicated. All data included in this part of the analysis were obtained through published documents, though much of the presentation and analysis is new and not available elsewhere.

4.4.1 Data from Scottish Meteorological Stations.

Weather statistics for Meteorological Stations are available through the Monthly Weather Report. This report, published by the Met. Office, gives the total number of days in the month of a variety of data, recorded daily, such as barometric pressure, incidence of ground- and air-frost, snowfall and snow-lie, and twice-daily or four-times-daily data including wind speed and direction. Temperature data were not collected because no meteorological station is located close enough to the study site to give a realistic picture of the thermal regime experienced there; the data from Aonach Mor proved more useful, although of only short duration. However, wind speed, wind direction and pressure data gave information about the types of air mass affecting the country while frost and snow data gave a useful guide to how cold any given month had been. Wind speed data were recorded as the number of days at the time of collection with wind speeds within certain bands of the Beaufort Scale (calm, 1-3, 4-5, 6-7 and 8+); wind direction was recorded in eight quadrants centred on the eight principal compass points.

Given that the study site lay on the western side of the Highlands, where little work on the late snowbeds has been carried out, stations located on the western side of Scotland were chosen to give a realistic picture of the oceanic climate experienced there. The amount of work required to transcribe the Monthly Weather Report longhand from the library and then onto computer meant that data from only three stations were feasible to collect. For the purposes of examining any trends that might exist in the data, a long data set was required; 50 years was considered the minimum length necessary. Few stations have been in operation over that length of time, fewer still are located in the western half of Scotland. Given the constraints imposed above of length and consistency of record and location, the selection of possible stations was small. Ideally, montane stations would have been used, but only two stations are located in the montane zone, one at Aonach Mor, the other at Cairn Gorm. Data from Aonach Mor were used in this study, but only one year's data was available, while the Cairn Gorm data did not meet many of the criteria mentioned above, in terms of length of record and location in western Scotland. Eskdalemuir was preferred to Braemar with its more westerly location and is the only upland station available in the western half of the country. From the shortlist the stations chosen were Cape Wrath, Tiree and Eskdalemuir. Their location is shown in Figure 2.3.

Cape Wrath and Eskdalemuir gave a good geographical separation over which to measure the pressure gradient across the country, with Eskdalemuir, although in the Borders, the only long data set for an upland station in the west. The data set from Tiree is more complete than almost any other and also gives a more accurate picture of weather largely unaffected by topography. The closest stations to the study site, Onich on Loch Linnhe and Fersit near Spean Bridge, were not chosen because of problems with their location (Onich) and length of data set (Fersit). Forestry in vicinity of Onich station has subjected it to increasing amounts of shelter over recent years giving rise to a skewing of the data for both wind and precipitation (D. N. McVean, 1992, pers. comm.). Although a similar situation arises at Eskdalemuir according to Young (1985), information from the current

Superintendent for Eskdalemuir Observatory, Mike Porter, in a personal communication, stated that no changes would be apparent for wind direction given the size of the sectors, at 45° and the aggregate monthly values used. He also stated that the trend of decreasing wind speed identified at Eskdalemuir which triggered concerns about the sheltering effects of nearby plantation forestry were apparent generally throughout the area, although reservations remain about the decrease in wind speed (Harrison, 1997, pers. comm.).

More problematic is the change in instruments from the Dines pressure tube anemograph (PTA) situated on the top of Eskdalemuir Observatory, to a remotely-located electronic recording system (DALE) installed in 1965 (Young, 1985; Porter, pers. comm.). The PTA was also more sensitive to winds developing from calm, since the newer electronic equipment requires a wind speed of 5-7 knots before it starts to move, though once moving will record lower wind speeds (Porter, 1997, pers. comm.). It is therefore necessary to be wary of any apparent changes in wind speed or direction taking place in 1965. Similar problems exist at most other stations (Porter, 1997, pers. comm.), though the choice of Cape Wrath and Tiree should minimise any differences by removing the possibility of changes in local shelter and topography.

Data on wind speed, wind direction, air and ground frost and the occurrence of snowfall and snow-lie were therefore collected for the three stations, Cape Wrath, Tiree and Eskdalemuir and placed in database form. They were kept in monthly and quarterly form, so that seasons could be compared as well as individual months. Each entry contained a record of the number of days in the given month when the given climatic variable was observed. Data collected more than once-daily (wind speed and direction), were recorded for 0300 and 1500 hours for each day. These times were chosen since 0300 approximates to the time when wind speeds are least (c.0600) and 1500 when greatest (1400) (Smith, 1983). It was also important to make observations as consistent as possible, both within the data set as a whole and within any one year. In winter, 0900 and 1800 hours will both be during hours of darkness, with net radiation losses, while in summer these times will be during daylight hours with strong net radiation gains. By using 0300 and 1500, times closest to the radiation minima and maxima for both summer and winter were chosen, with 0300 always dark (except for Cape Wrath when this time will be dawn at midsummer) and 1500 always light. From January 1943 to September 1944 inclusive data were available for 0100 and 1300, rather than 0300 and 1500, while October, November and December 1944 records were taken at 0000 and 1200 hours. Since the start of 1945, 0300 and 1500 were used.

Errors of a variety of different types occur in the Monthly Weather Report data. Often these are corrected in later editions, but some errors were identified in the number of days recorded for wind variables within one month which were uncorrected. It was only when all the records for either wind speed or wind direction for any given month at a given time were added together, plus the number of calm days, that these errors became apparent. In order to ensure that all such errors were identified, additional columns were introduced to the database which summed the appropriate columns and checked the total against the number of days (28, 29, 30 or 31) in that particular month. Once the error was identified and further checking revealed no correction in the MWR, then that month's data were deleted. The reason for deleting the data was that there were no indications as to which of the wind directions or speeds was in error and therefore where an adjustment could be made. Months with only one day's error in the total were left in the data set since the error term involved was small.

Missing values in the data set made some statistical analyses impossible to perform. In these cases, where figures for the same month in other years were zero, 1, 2 or 3, a zero was inserted. Where a zero value was not appropriate, when other years contained values of 4 or above, an average value comprised of the five years on either side of the missing figure was inserted.

4.4.2 The Snow Survey of Great Britain and Monthly Weather Report Snow Data.

Snow-lie records are available through the Snow Survey of Great Britain, collected by the Meteorological Office, and provide most of the data relating to snow conditions in the Highlands since its first publication in 1946. Initially published in the Journal of Glaciology, it is now a separate Met. Office publication, though in 1994 was behind in publication and nothing more recent than the Survey of 1990-91 was available (Met. Office, 1995, pers. comm.).

The snow-lie on a number of different hills is recorded in the Snow Survey, giving the observed level of the snow line for every day with visibility. The hills used have changed during the period 1946 to 1991; the most appropriate hill with snow observations in the early part of that period is Ben Nevis, but data cease in 1961 and the nearest alternative station which starts collecting data at that time, presumably to compensate for the loss of the Ben Nevis observations, is Creag Meagaidh. With no overlap of recording, it is not possible to assess from the data how these two locations differ, though it is probable that snow-lie at Creag Meagaidh is less ephemeral and generally lower because of its location further inland. Ben Nevis is also likely to have a deeper covering of snow, being close to the sea and the first land mass over 900m encountered by westerly or south-westerly air flows and 1000m in north-westerly air flows, thereby achieving greater orographic enhancement of precipitation in wetter air streams than achieved by Creag Meagaidh.

The data are displayed in the Snow Survey as a graph of the snow line level for each day, and are also given as a graph of the total number of days during the season with snow lying at a given level. In the former case, the format of the graphs changed during the 44 years of publication, with metrification in 1966-7 and an absolute change in the altitude of distinctive features against which the snow-line is assessed. In order to examine these data other than visually, and to standardise them, each graph was transposed into numerical values; the original data from which the graphs are produced is currently not available outside the Meteorological Office (Met. Office, 1994, pers. comm.). From the numerical data comparable graphs were generated, similar to those given in the Snow Survey but in a more standard format. Gaps in the data set make any statistical analysis extremely difficult, particularly since in more recent years the incidence of gaps has increased giving a bias in snowiness towards earlier years. For gaps where the snow level on either side of the gap was the same, that figure was used to fill in the gap. For gaps of only one or two days which preceded an observed drop in the snow level, it was assumed that the cloud obscuring the snow-line was responsible for the precipitation giving the new, lower level. In this case, the lower snow-line was inserted for the one or two days of no visibility. The year-average level of snow-lie was determined by dividing the total snow-lie by the number of days of observations.

Data of snowfall and snow-lie at Braemar are also available through the Snow Survey, alongside that from Eskdalemuir and a compilation of data from Fort Augustus and Corpach, west of Fort William. Examination of these data, which give monthly total figures for the number of days of snowfall and snow-lie covering 50% or more of the ground at 0900 hours, identify the degree of relationship between snowfall and snow-lie at the same sites and between sites, using correlation coefficients generated by Pearson's Product Moment. This method was most appropriate for this quantitative data, being a parametric test, having first determined that the data were of approximately normal distribution. Data which demonstrated a heavily skewed distribution, such as snowfall or snow-lie for low level stations and examining data for a whole year, thus containing a large number of zero values, was transformed using a logarithmic function. Trends in the monthly totals of snowfall and snow-lie were also examined using linear and quadratic trend models and a 5-year moving average model. Least squares linear regression was also conducted between the data and year number, giving a value of the statistical significance of any trend.

Further snow-lie records were available for the three Meteorological Stations used to examine other weather statistics. Records of the number of days of snow or sleet falling and snow lying on 50% or more of the surrounding area at 0900 hours per month were collected from the Monthly Weather Report published by the Meteorological Office for Cape Wrath, Tiree and Eskdalemuir. These data give a measure of the snowiness of each month but does not indicate when during the month the snow fell, how quickly it melted, nor from which direction it came.

4.4.3 Literature Relating to Snow-Lie in the Highlands.

Observations of snow-lie and late snowbeds in the Highlands have been made over a number of years by Green (1975), Spink (1980), Davison (1985), Harrison (1993), Pottie (1994), and Watson, Davison and French (1994). More general literature relating to the snowiness of British winters may be found in Jackson (1977), to snow cover in Britain in Jackson (1978) and to snowfall in Britain in Manley (1969). One of the most noticeable features of all these articles is the high degree of variability in snow-lie, at least at lower levels, and that the variability is skewed with the highest totals deviating much more from the mean than the minimum (Manley, 1969). Also apparent from Manley (1969), Green (1975), Harrison (1993) and Watson, Davison and French (1994) is the decreasing duration of snow-lie with the increase in recent years of westerly air streams at the expense of easterly ones and the importance of spring temperatures, rather than winter. The survival of late snowbeds is less variable with the difference between snowy and unsnowy winters more apparent at intermediate altitudes (Manley, 1969; Watson, Davison and French, 1994), primarily because the latest snowbeds are topographically determined and located at high altitudes where snow accumulation is less affected by high winter and spring temperatures.

Minor negative trends in late snowbed survival have been identified (Watson, Davison and French, 1994), significant at the 90% confidence level. There are also indications that the variability of late snow-lie has increased since 1981 (Watson, Davison and French, 1994). Other data will be presented in Chapter 8 to compliment these observations and to allow discussion of the likely impact of climate change on the late snowbeds.

One crucial feature of late snowbeds identified by all the authors, and by others cited in Chapter 3, is the persistence in their location, which is of overriding importance with respect to snowbed vegetation which cannot readily migrate. Thus, although snow-lie duration may vary, and possibly increasingly so, the location of late snowbeds is not considered to be variable. This will be further tested in the Aonach Mor snow cover records of this study.

Summary points:

1. A study site was selected on Aonach Mor, Lochaber, using a variety of criteria.

2. The site was located in the area of a cornice, at the head of a corrie and below the relatively extensive summit plateau of Aonach Mor. The geology is a relatively base-rich granite, aspect easterly with an Automatic Weather Station (AWS) located at the nearby ski facility providing meteorological data. The vegetation of the corrie and plateau show a range of upland communities indicating the influence of snow-lie, irrigation and base-status. Grazing and disturbance are present on the site

3. A programme of measurements of snow was implemented, including snow cover, snow depth, snowpack profiles and snow and meltwater pH.

4. The pattern of vegetation associations was investigated through monitoring of random, fixed quadrats and through the implementation of an experiment involving transplanting pots of *Deschampsia cespitosa*.

5. Data from three Meteorological Stations, the Snow Survey of Great Britain and a variety of literature sources was collected to examine the links between climate and snow-lie at altitude.

CHAPTER 5

CHARACTERISTICS OF A SNOWBED ENVIRONMENT

5.1 Topography.

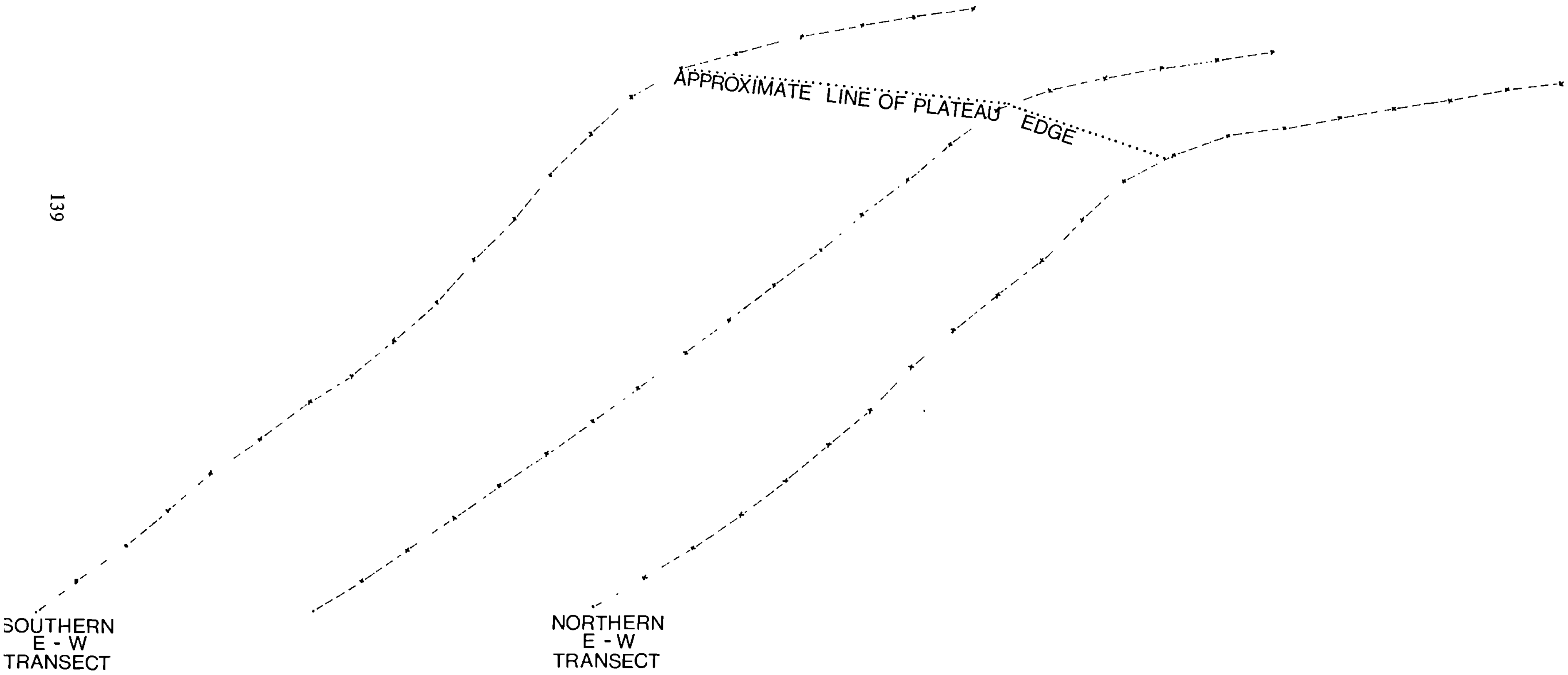
The results of the topographic survey are given in Figure 5.1, from which the concave nature of the site can be observed, showing a hollow in which a good depth of snow can accumulate. The edge of the plateau as the slope steepens convexly downhill marks the main area in which winter snow builds up as a cornice. Below the cornice area, in the hollow, a good depth of snow accumulates as the snow pillow, apparent from the even snow slope shown in Plate 2. The location of the hollow relative to the change of slope at the plateau edge is crucial. It is likely that the hollow is in part generated by the build-up of snow along the edge of the Aonach Mor plateau, in much the same way as a nivation hollow develops. Whatever the reason for its location, the distance that it lies from the plateau edge determines the depth of snow accumulation which develops there; too high, and it will be scoured by the lee eddy, too low and it does not benefit from the snow pillow which is deposited immediately below the lee eddy. The exact coincidence of hollow and the latest snow-lie indicates that its location is determined by factors relating to the accumulation of snow, reinforcing the durability of the late snowbed by increasing the depth of snow which may accumulate here.

The photographs in Plates 10 and 11 shows the slumping of snow at the top of the main snowpatch during the summer. Downslope movement of substrate was also observed during the *Deschampsia* pot experiment. This slumping and surface creep causes erosion of the surface layers of vegetation and substrate, particularly when lubricated by meltwater, and further enhances the concave nature of the site. Frost heave, an additional destabilising

FIGURE 5.1

SLOPE PROFILES FOR RESEARCH SITE, AONACH MOR.

SLOPE ANGLE MEASURED EVERY 5m ALONG VERTICAL TRANSECTS AT EITHER SIDE AND THROUGH THE CENTRE OF THE 100m^2 SITE.



PLATES 10 AND 11
DOWNSLOPE SLIPPAGE OF THE CORNICE-LINE SNOWBED
DURING SUMMER. DATED 24.6.93.

factor, was observed in substrate close to the edge of the snowbed, as shown in Plate 19. Lack of observed damage in the bryophyte mat suggests that movement takes place in a substantial depth of the substrate, rather than just the surface layer. The loose nature of the gravel substrate, unbound by roots, would make this more likely.

Slope angles are high in the late snowbed area (around 40°), but in spite of the near-ideal conditions for avalanching with optimum slope angle for this 38° and a smooth mat of vegetation on which to slide at full depth, no activity was observed at this location. The high density of the snow observed here is one explanatory factor for the absence of avalanching, in addition to the shape of the ground which generates compressive forces in the snowpack over the hollow and makes it more stable. Loading from above is also minimised by the shortness of the slope above. A lack of full depth avalanches during the melt season indicates that meltwater is not flowing along the base of the snowbed, but instead is percolating rapidly into the ground.

5.2 Exposure and Wind Conditions.

According to the equations above, the topographic index (SL), the bearing of greatest shelter (ψ) and the aspect (ψ+180°) are given for the three parts of the site in Table 5.1.

TABLE 5.1

VALUES OF DECLINATION TO THE HORIZON, θ, AND SHELTER INDEX FOR STUDY SITE AND SUMMIT ON AONACH MOR.

	SUMMIT OF AONACH MOR		**TOP OF STUDY SITE**		**BOTTOM OF STUDY SITE**	
BEARING	Angle of horizon, °	θ	Angle of horizon, °	θ	Angle of horizon, °	θ
North	0	5.0	+4.0	9.0	+11.0	16.0
North-east	-1.0	4.0	-1.0	4.0	-1.0	4.0
East	-0.5	4.5	-0.5	4.5	0	5.0
South-east	-0.5	4.5	-0.5	4.5	0	5.0
South	-1.0	4.0	+5.5	10.5	+8.5	13.5
South-west	-2.5	2.5	+4.5	9.5	+29.0	34.0
West	-1.5	3.5	+3.0	8.0	+38.0	43.0
North-west	-0.5	4.5	+2.0	7.0	+34.5	39.5

Shelter index		**6.46**		**12.13**		**39.57**

From the formula outlined in Chapter 4, a shelter index for each part of the site was calculated, giving the corrected index for prevailing wind directions. These are:

Summit	6.46	Top	14.27	Bottom	47.87

When compared with the uncorrected indices, it can be seen that the correction for prevailing wind affords the bottom of the site a higher index of shelter, while the top section is more exposed. This steep gradient in exposure levels can also be seen by looking at the sheltergrams in Figure 5.2. The shape of the site therefore offers substantial levels of shelter, particularly from prevailing winds, and also generates a steep gradient of shelter from the top of the site to the bottom. This change in exposure conditions would in itself generate a significant change in the pattern of vegetation.

One problem associated with this method is its restriction, in this instance, to the eight compass points. Aonach Mor is one of the highest mountains in the area, but only 3 kilometres away on a bearing of 232° magnetic, lies the massif of Ben Nevis, at an altitude of 1344m. Likewise, to the south lies Aonach Beag, at 1234m, on a bearing of 170°. Both of these mountains generate shelter with positive angles to the horizon in their direction, but neither lie on one of the main compass points. With the predominant wind direction on Aonach Mor in the region 200 - 220°, the shelter effect of Ben Nevis is likely to be significant. A dotted line on the sheltergram for the summit readings indicates the direction and extent of sheltering offered by Ben Nevis to the summit area. The hill becomes invisible, dropping below the horizon which is very close by, at the top of the study site. It would be possible, but very time-consuming, to obtain a much more accurate picture using finer resolution with, perhaps, 32 or 64 different points. In this instance, it was not considered necessary, with Ben Nevis being the only mountain massif not well-represented

FIGURE 5.2

SHELTERGRAMS FOR AONACH MOR.
a) SUMMIT CAIRN, b) TOP OF SITE, c) BOTTOM OF SITE.

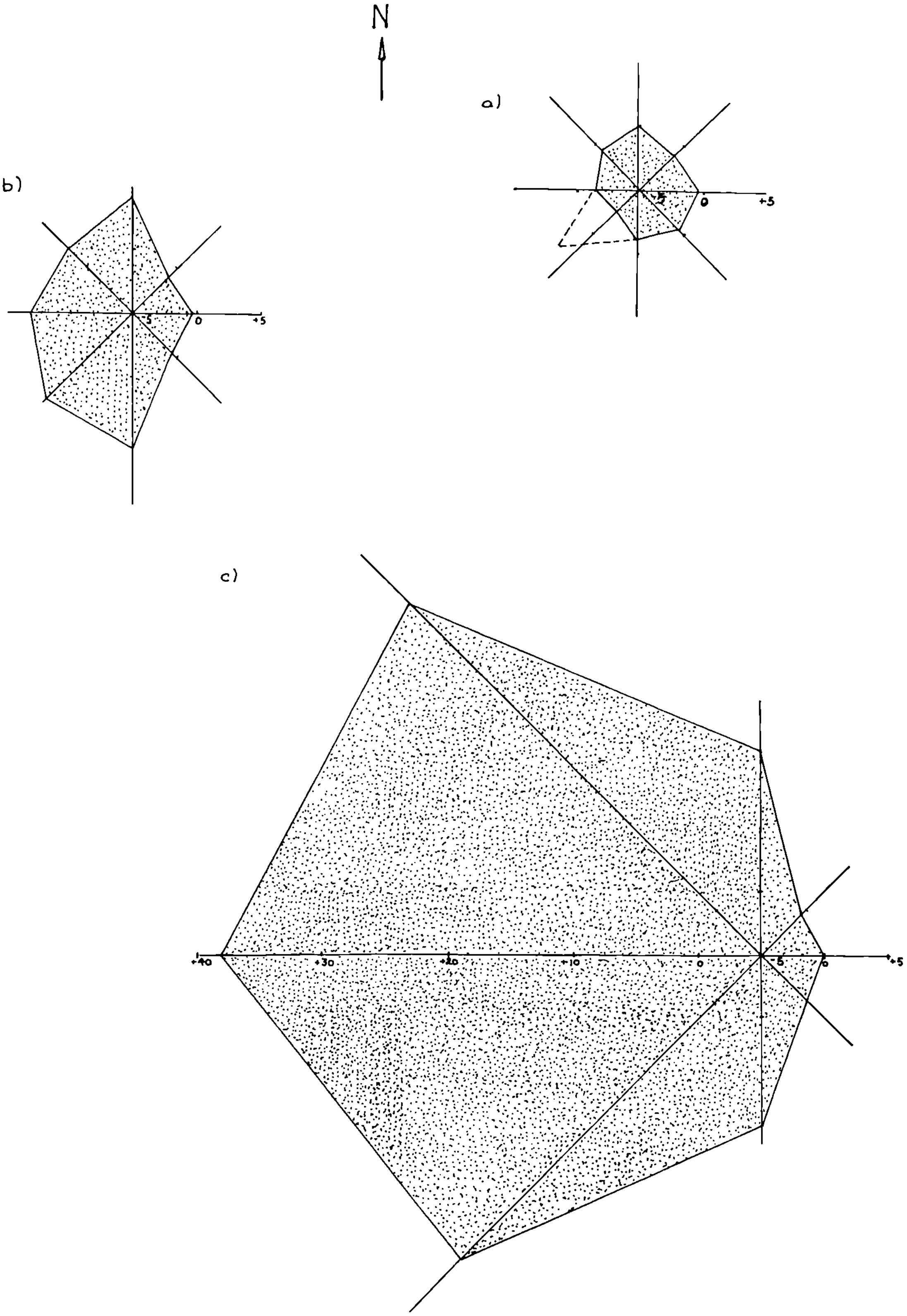
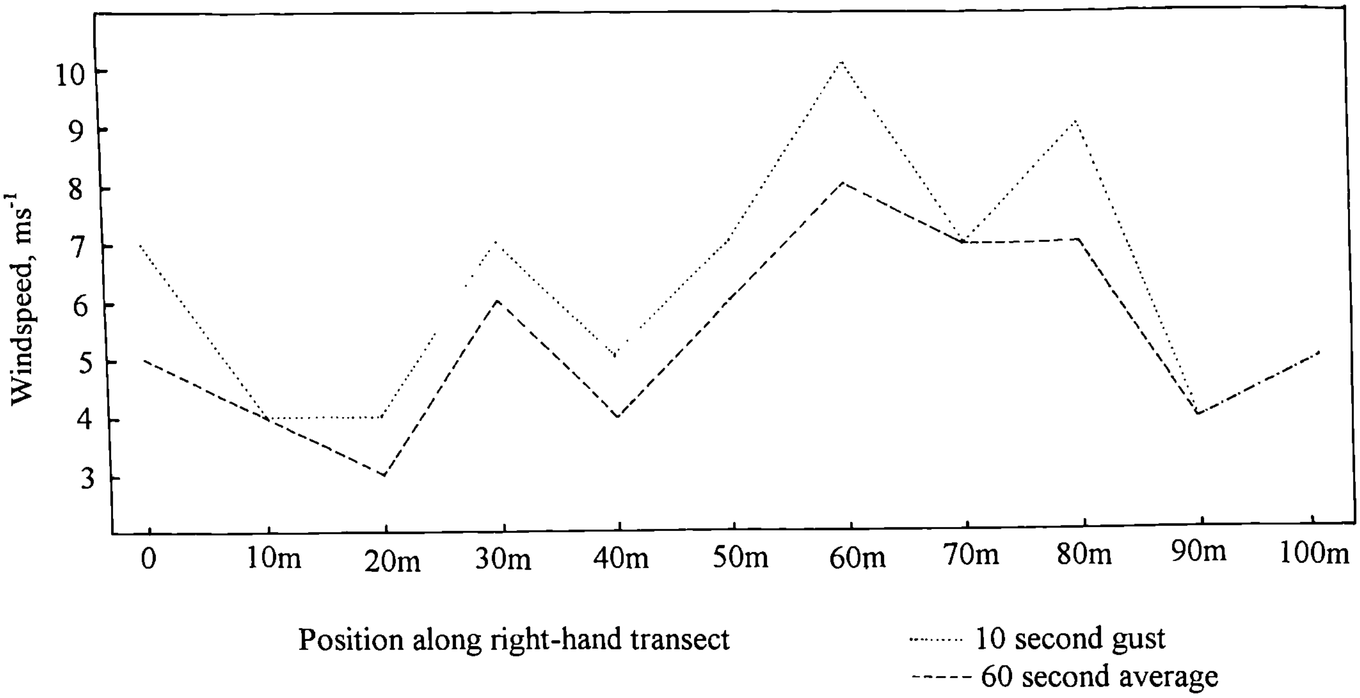
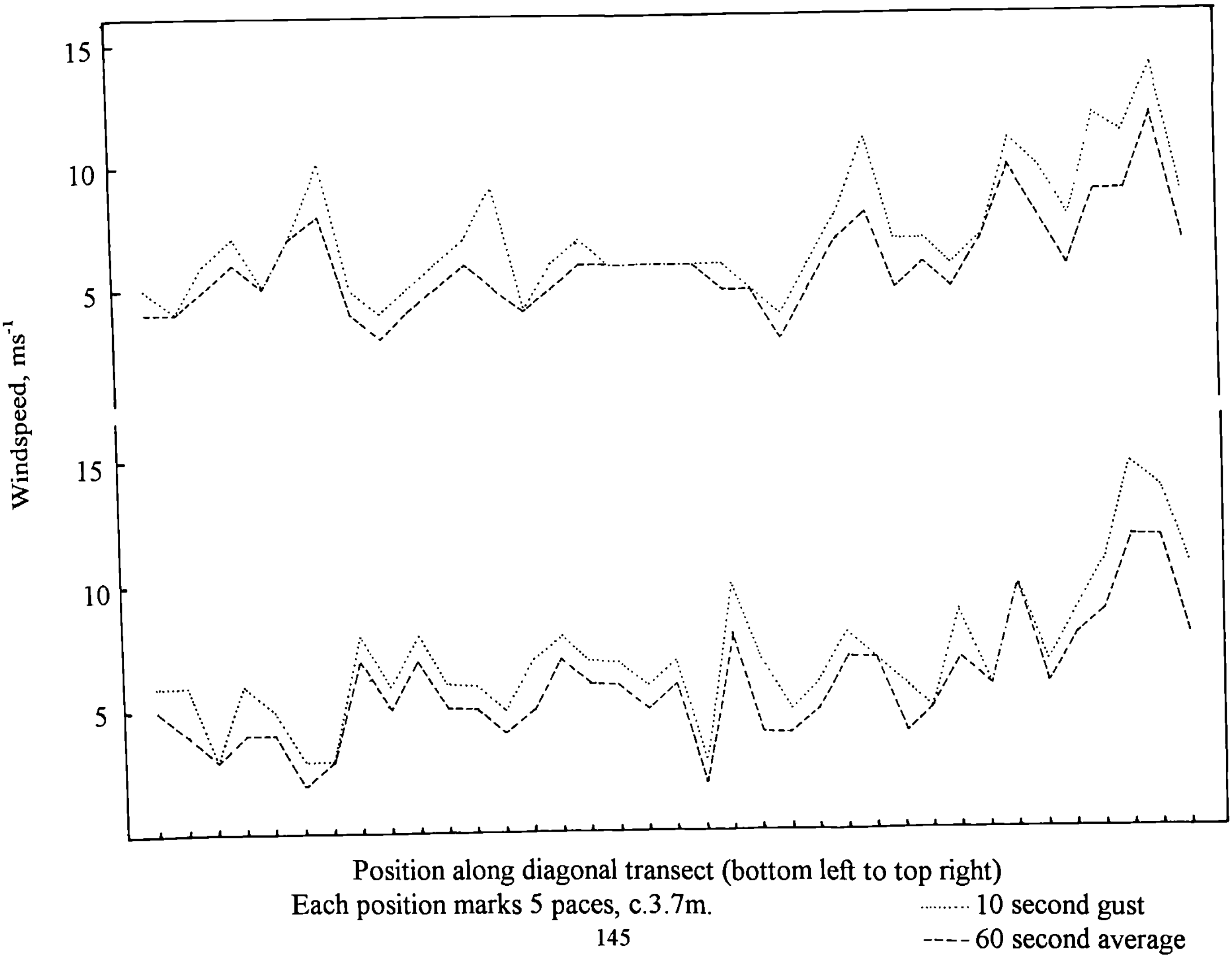


FIGURE 5.3
DIAGRAMS SHOWING WINDSPEED PROFILES AT AONACH MOR SITE, JULY 1992.

1. Profile taken along right-hand (northern E-W) transect on 1.7.92, starting below plateau edge near quadrat 12.



2. Profile taken from bottom left-hand corner of site (near quadrat 2) diagonally up to top right-hand corner (beyond quadrat 25) on 2.7.92. Two readings for each position.



in the original diagrams, and being readily added as shown in Figure 5.2(a).

The results of the anemometer readings taken across the site are displayed in Figure 5.3. As can be seen, there is a sudden increase in wind speed as soon as the edge of the plateau is reached. The peak at 30m in the upper profile is mirrored by peaks low down the transect in the lower profiles, indicating that this may be the location of a small eddy feature. Interestingly, the uppermost readings are all lower than those 10m further down the transect; this indicates that there is a small degree of topographic shelter operating on the area around the top of the site. This could in part explain why the vegetation here differs from that in the central part of the plateau, since only a small degree of sheltering can make a significant difference in the growth of different species (Carlsson and Callaghan, 1991). The lack of smoothness in the curves also indicates elements of topographic sheltering, even though the slope is fairly even and smooth. The extent of change in shelter over the site is apparent and is another indicator of the steep climatic gradients found over short distances in such alpine locations.

5.3 Snow Cover.

From the photographs, in conjunction with the slope profiles of the site shown in Figure 5.1, it is possible to confirm the concentration of the greatest depth of snow during early summer in the concave hollow several metres below the cornice line. Although some distance downslope of the area of maximum build-up of snow on the cornice line, slippage of the snowbed was observed, as shown in Plates 10 and 11, bringing cornice line snow down towards the hollow, while greater snow accumulation over the hollow, in the form of a snow pillow, is observed.

Maps compiled from the photographs and superimposed on the photograph in Plate 4 are shown in Figures 5.4, 5.5 and 5.6. The first map shows snow-lie in 1992, the second in 1993 and the third a generalised compilation of the two specific years. The generalised map shows the situation of the site boundary, the lower left corner corresponding to the corner labelled A and the bottom right to the corner labelled B. It is possible to see the core of the longest lying snow covering the area in which quadrat 11 was situated, confirmed by the data obtained through the quadrat observations. It seems likely that in exceptionally cold or snowy years this core does not melt until very late in the season. 1993 showed generally much longer snow-lie than 1992, with substantial snowfall through the winter and cold weather to delay snow melt throughout the summer. Conditions were particularly poor in July and August; there are no data for the quadrats from 14.8.93 to 27.10.93 but on both these dates quadrat 11 was covered with snow. However, the snow lying on 17.10.93 was not substantial in depth and was also fresh with no layer of dense old snow lying beneath it, so it is concluded that the old snowbed did completely melt at some stage between those two dates, with the duration of the snow-free period consequently less than 9 weeks. None of the snow in the back corrie of Aonach Mor could therefore be described as semi-permanent, although it does show considerable duration. Semi-permanent snow-beds can, however, be found beneath the cliffs of Coire an Lochain, and were observed to survive through both 1992 and 1993.

The pattern of snow-lie is, unlike the duration of snow-lie, very consistent between the two years. This feature observed in a number of different studies of snow-bed vegetation (Billings and Bliss, 1959; Burrows, 1977; Wijk, 1986; Stanton *et. al.*, 1994) and in studies of late-lying snowbeds in Scotland and elsewhere (Watson, Davison and

FIGURE 5.4

MAP TO SHOW THE DURATION OF SNOW-LIE IN AONACH MOR BACK CORRIE, 1992.

VIEW CORRESPONDS TO THAT OF THE OBLIQUE PHOTOGRAPH IN FIGURE

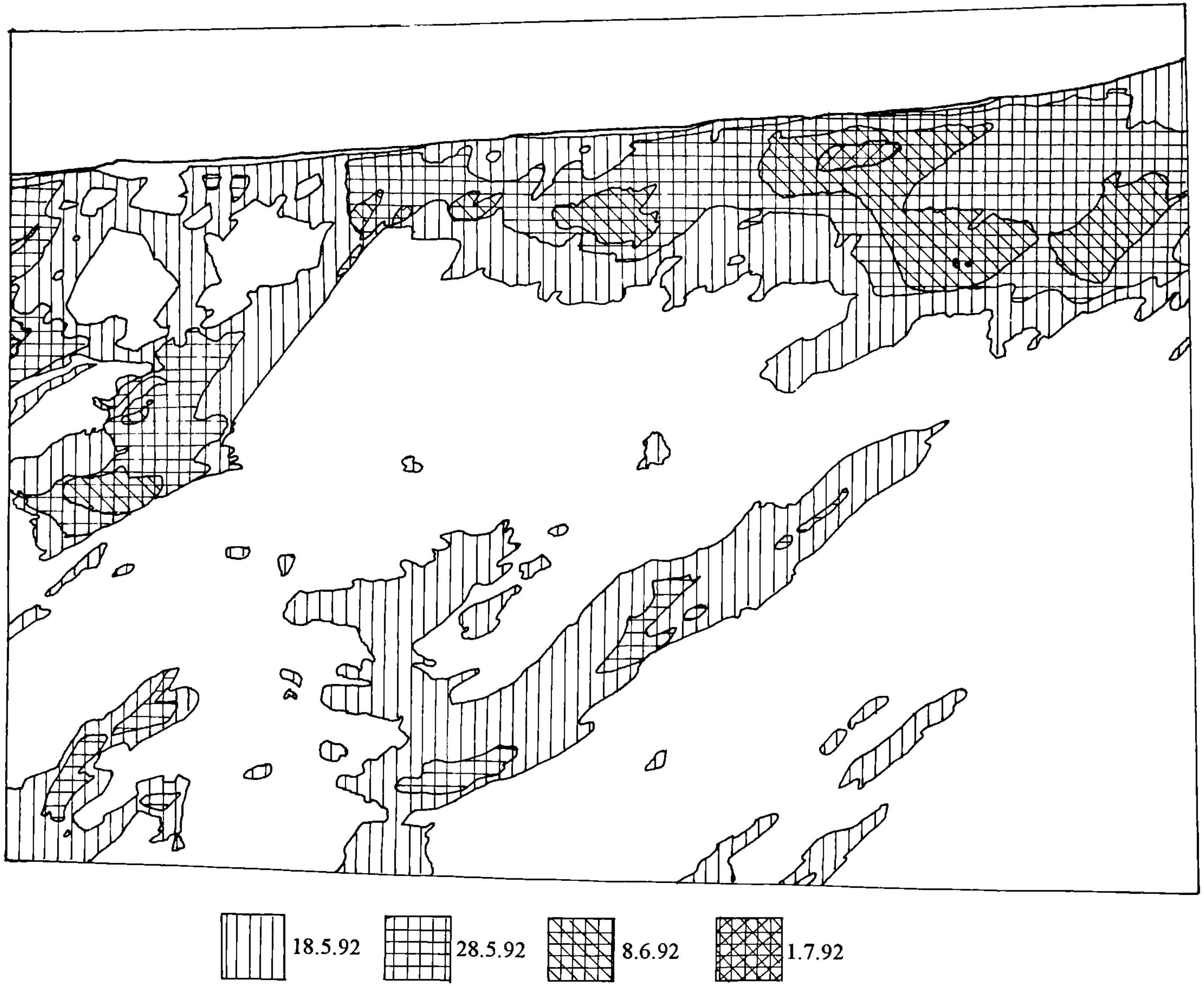


FIGURE 5.5

MAP TO SHOW THE DURATION OF SNOW-LIE IN AONACH MOR BACK CORRIE, 1993.

VIEW CORRESPONDS TO THAT OF THE OBLIQUE PHOTOGRAPH IN FIGURE

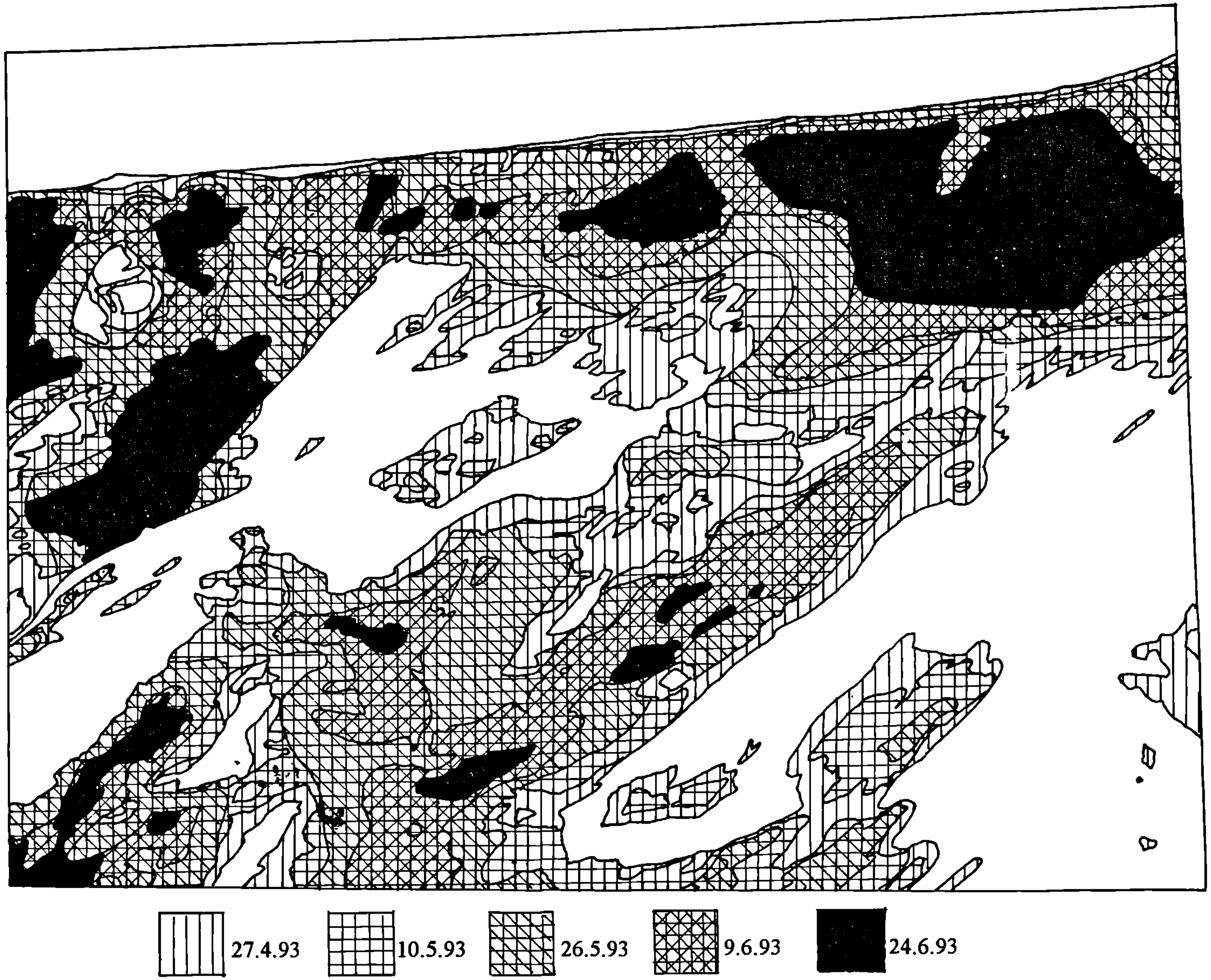
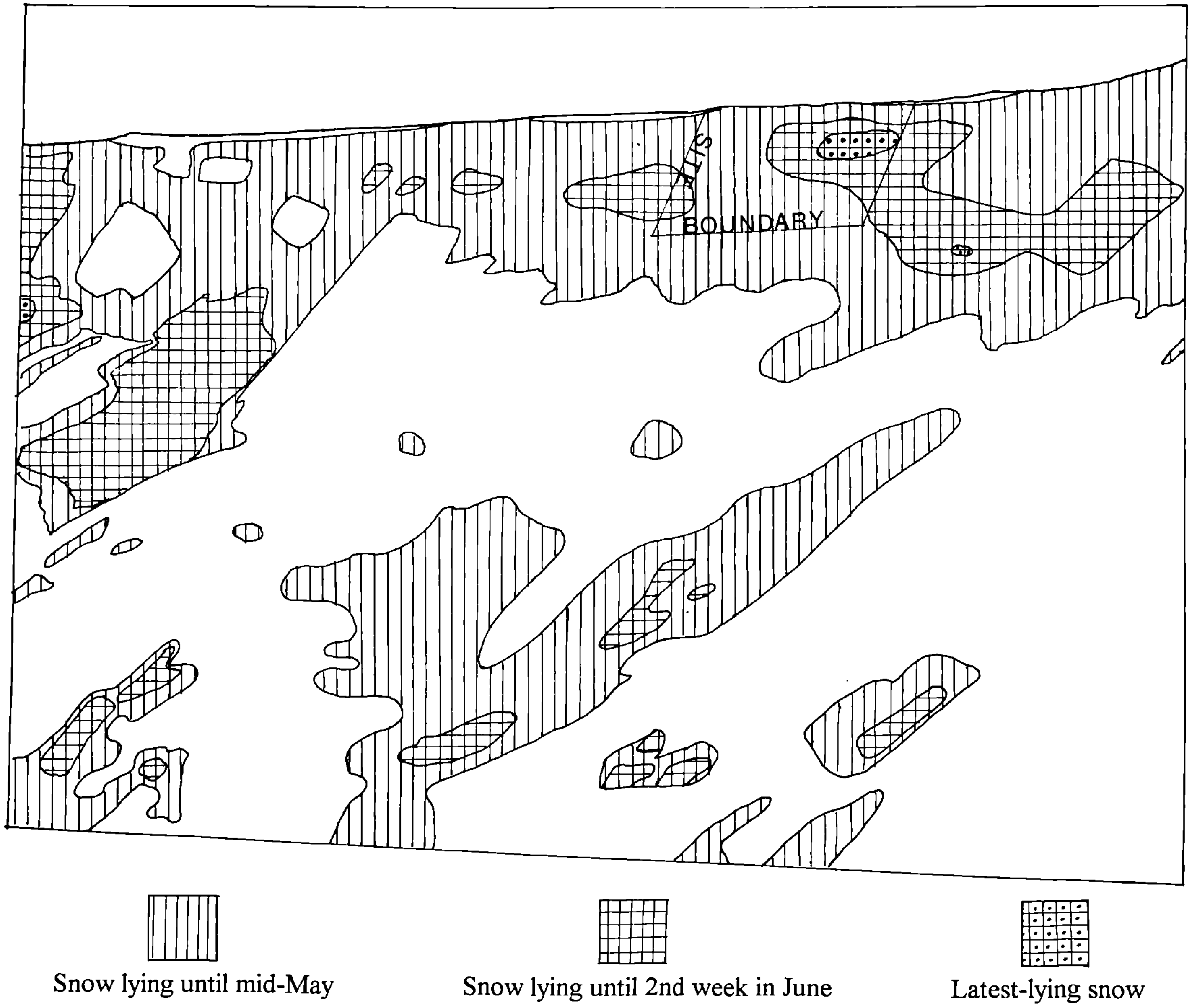


FIGURE 5.6

MAP TO SHOW LIKELY AVERAGE DURATION OF SNOW-LIE IN AONACH MOR BACK CORRIE.

VIEW CORRESPONDS TO THAT OF THE OBLIQUE PHOTOGRAPH IN FIGURE



French, 1994; Pottie, 1994), is therefore corroborated by the Aonach Mor data for 1992 and 1993. In the case of the western Highlands, it is due to the strong dominance of westerly and south-westerly winds interacting with topography and giving rise to consistent snowdrift onto eastern slopes. The strong loyalty of late snowbeds to location is therefore confirmed for the western Highlands as well as the eastern and central Highlands by both indirect inference from the climatic data and observations from the field.

While consistency to location is a common feature of late snowbeds beneath which late snowbed vegetation is found, there is also an observed variation in the duration of snow-lie both in the literature and at this site. The location of the vegetation in relation to the average duration can be investigated by examining the coincidence of community boundaries and date of snow release. A visual comparison of the snow-lie maps and the vegetation map (Figure 4.5) for the back corrie gives a very strong indication of the degree of relationship, but says nothing about the nature of that relationship, nor the influence of other factors. Further investigation can be made through the quadrat data, by relating the vegetation data collected throughout the snow-free season to a measure of the duration of snow-lie. The strength of the statistical relationship will indicate the presence or absence of other environmental factors, some of which may also be examined, such as moisture availability, and others which still require further study.

5.4 Snow Profiles and Conditions Beneath the Snow.

Examination of the snow layers in snow pits indicated a stable, strong and well-consolidated snowpack. No layers of hardness 1 (very soft) were encountered and no layer

PLATE 12

A VIEW OF COIRE AN LOCHAIN, TAKEN ON 27/4/93, SHOWING HEAVY SNOW BUILD-UP BELOW THE CLIFFS AND AVALANCHE DEBRIS, LARGELY GENERATED BY CORNICE COLLAPSE.

was more than one point different from adjoining layers, making the snowpack potentially very stable. No avalanche activity was ever observed at this location, though debris was observed in Coire an Lochain, as shown in Plate 12, taken on 27/4/93. The plethora of shallow layers indicates that build-up is largely the result of wind-drift, rather than individual precipitation events, which tend to produce fewer, thicker layers. This conforms with the information available from ridge-site studies outlined in Chapter 2 and with the high frequency of windy conditions on Aonach Mor. The consistent hardness of the layers with prevalent melt-freeze metamorphism observed, indicates that dry snow is a rare occurrence, which is commensurate with the maritime location of the hill, and that consolidation takes place between precipitation/drift events.

The temperature of the snowpack remained at a relatively constant level, below 20cm below the snow surface. This temperature varied from +0.8°C to -1.0°C. Above 20cm below the snow surface, temperature varied much more, becoming higher when above ground temperatures were high, and usually falling at night. These results indicate that the snowpack behaves as observed by other researchers, with temperatures becoming more stable around -1.0°C as depth increases beyond 15 - 20cm.

No plant growth of any kind that could be measured using the methods employed was observed beneath the snow and on release from snow cover all the quadrats monitored showed no sign of activity of any kind. The observations of authors such as Billings and Bliss (1959), who recorded pre-exposure growth of vascular plants in species including *Deschampsia cespitosa* was therefore not replicated at this location.

The results are of the measures taken of light penetration and temperature through the snowpack taken in a snow pit are shown in Figures 5.7 and 5.8. The measures of light

FIGURE 5.7

DIAGRAM TO SHOW LIGHT PENETRATION THROUGH SNOWPACK, AONOCH MOR, 18.5.92.

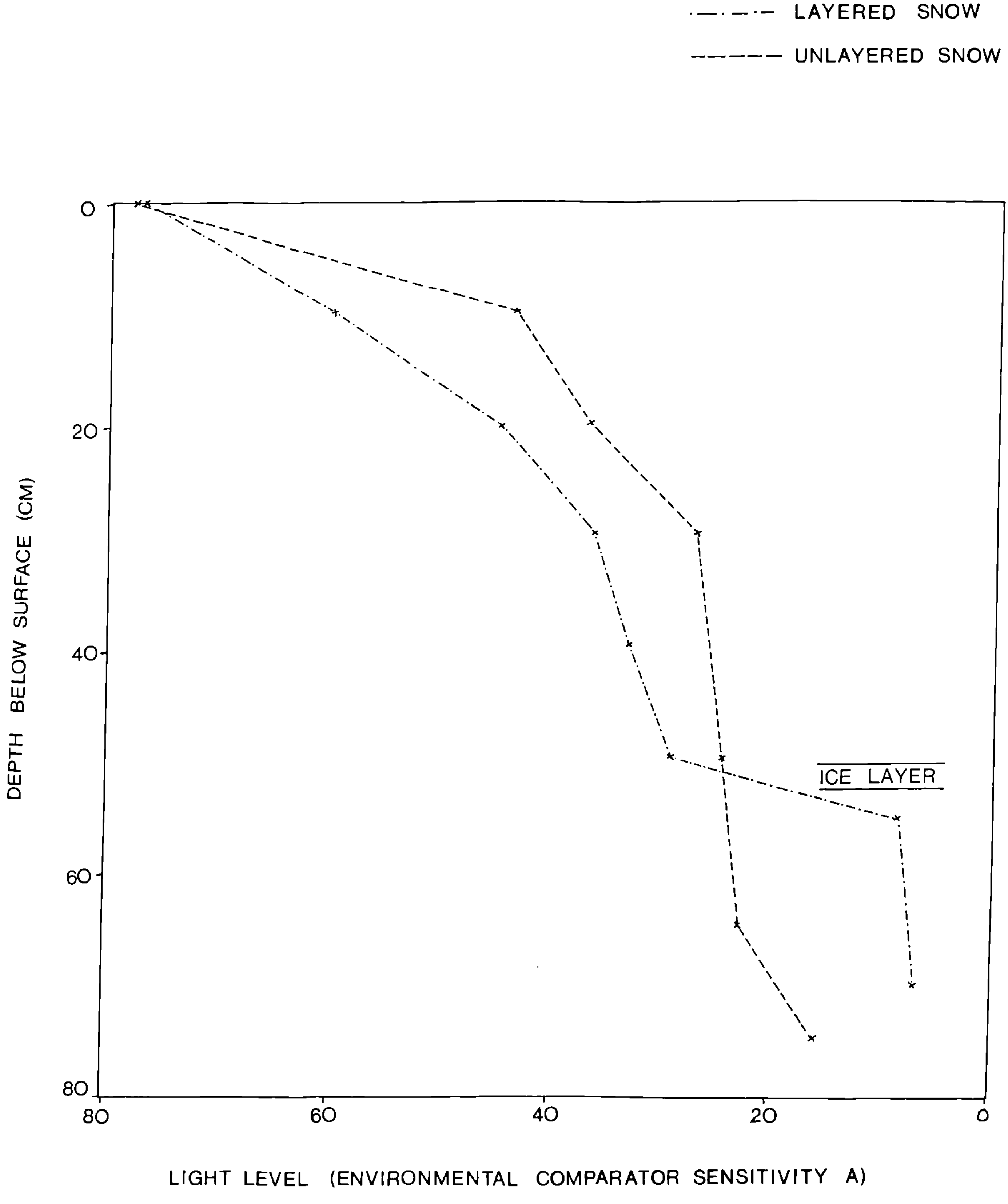
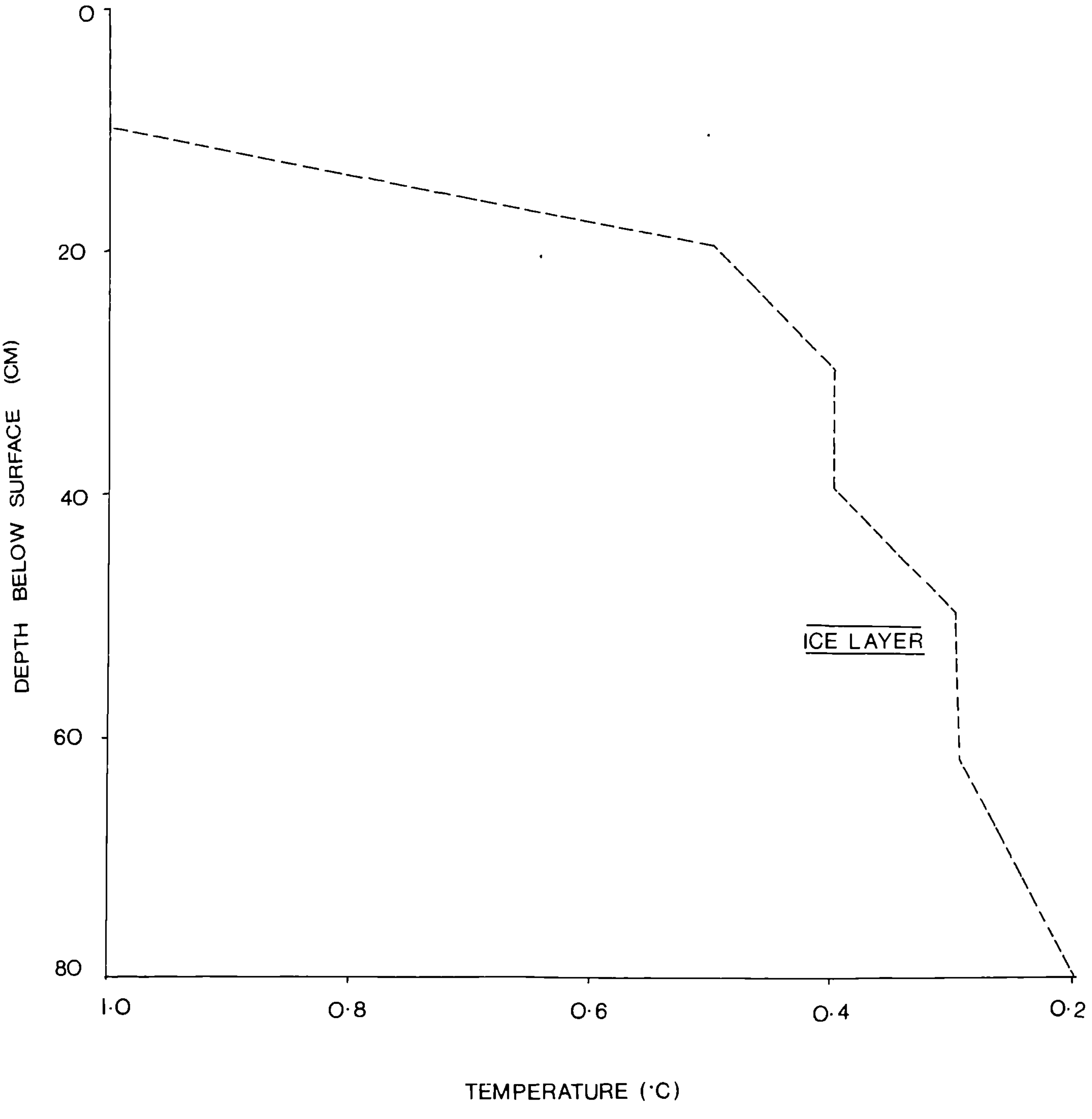


FIGURE 5.8

DIAGRAM TO SHOW TEMPERATURE PROFILE THROUGH LAYERED SNOWPACK, AONACH MOR, 18.5.92.



penetration will not be particularly accurate with some contamination from light in the snow pit. However, the shape of the curves in Figure 5.7 follow the flux decay for short-wave radiation described by Beer's Law, where the rate of absorption is highest at the surface and decreases with depth (Oke, 1987). An interesting feature is the blocking effect of a layer of hard neve or ice at 50cm depth in the layered snowpack. Oke (1987) states that the penetration of short-wave radiation, at least, is much greater through ice and old snow than through new snow, which has a much higher albedo. For some reason, perhaps due to the presence of particulate matter absorbing incoming radiation, or possibly an increase in the scattering of light with a more crystalline structure, this layer is more opaque and is not transmitting light in the expected manner. There were no indications in the field that this layer contained anything unusual, and it appeared to differ from surrounding layers only in its hardness. As indicated by Oke (1987), that short-wave radiation may penetrate to depths of 1-10m, light was measured to penetrate to nearly 80cm using this relatively crude method.

It certainly seems likely that the plants found in this area may be able to exploit penetrating light and prepare themselves for exposure, in the same way that they may respond to increasing temperatures with thinning snow-cover. No evidence of this was observed during the entire period of investigation although the responses may well be internal and involve no production of green tissue. Recently exposed areas showed no signs of growth for at least two days after snow cover had been removed and the only plant apparently able to exploit removal of snow within the first five days by showing any signs of shoot growth was *Deschampsia cespitosa*. Bryophytes took much longer to show signs of rehydration and growth, from approximately five days for species such as *Pohlia ludwigii* to up to approximately twenty days for *Polytrichum sexangulare*. Although it is impossible to be absolutely precise about these data since the site was not visited on a daily basis, the observations were nonetheless rigorous and as accurate as they could be, given a return period of 7-14 days. Observations of this nature were made throughout the site area and were not confined to the quadrats, with plant activity in and around the edge of the snowpatch observed on each occasion in a qualitative manner. It must be stressed that although these observations were made in a systematic and rigorous manner, they are not quantitative and should not be taken as such.

Qualitative data suggest that the vascular plants are able to respond immediately on release from snow cover whereas the bryophytes cannot or need not, since a large discrepancy was observed between the time period taken for *Deschampsia* to put out new shoots and the time taken by any of the bryophytes; the bryophytes have less need to exploit the earlier part of the growing season since they are able to continue to grow and put out capsules well into the autumn when the vascular plants have little or no tissue above ground left alive.

These observations offer conflicting evidence to that shown by Woolgrove and Woodin (1996), who observed activity in *Kiaeria starkei* shoots when in a "beneath-snow" regime. The type of activity observed by these authors was not tested in this study and would be very difficult to assess outside the laboratory environment. However, the long lapse in the response of bryophytes to the removal of a snow cover observed in the field indicates that there may be difficulties in accurately replicating the beneath-snow environment in a laboratory. The long response time of *Polytrichum sexangulare* in particular, coupled with its habit of folding into a tightly-budded state when not photosynthetically active, cast doubt on the application of the findings for *Kiaeria starkei* by Woolgrove and Woodin (1996) to other species of snowbed bryophytes.

TABLE 5.2

TABLE OF pH FROM AONACH MOR SITE

SAMPLES TAKEN FROM THE TOP AND BOTTOM OF THE SNOWBED, AND FROM THE SPRING 150m BELOW THE SNOWBED SITE AND BETWEEN QUADRATS 4 AND 7.

DATE	UPPER SNOWBED pH	UPPER SNOWBED range	LOWER SNOWBED pH	LOWER SNOWBED range	SPRING pH	SPRING range
28.5.92	4.61	0.80	4.50	0.92	6.08	0.65
17.6.92	5.45	0.34	5.35	0.62	8.10	1.23
31.7.92	-	-	-	-	8.34	0.98
5.9.92	-	-	-	-	8.48	0.39
26.5.93	5.01	0.19	4.95	0.75	6.21	0.84
20.7.93	5.40	0.75	5.23	0.69	7.45	0.83

F-values for regression	**16.93 ****		**8.45 ****		**58.08 *****	
F-values for ANOVA	**13.99 *****		**7.27 ****		**46.49 *****	

*** denotes significance at the 99.9% confidence limit
** denotes significance at the 99% confidence limit

5.5 Snow and Water pH.

The results of the pH measurements of the snowbed and downslope spring are shown in Table 5.2. The significance of the changes observed from May through to September, with pH rising from 6 to over 8 in the spring was examined using one-way analysis of variance (ANOVA) and regression against date expressed as Julian days. The dates were transformed according to the month of observation, with May as month 1 and September as month 4. The change is significant at the 99.9% level for both tests. Changes in the lower and upper snowbed values over time are significant at the 99% level using ANOVA, and 99% for the lower snowbed and 99.9% for the upper snowbed using regression. Correlation between the three sets of readings was significant at the 99.9% level. Increasing pH observed here as season and melt progresses is as expected from the literature (Hibberd, 1984; Morris and Thomas, 1985; Schoendorf and Herrmann, 1987; Craig and Johnston, 1988; Tranter *et. al.*, 1988; Hewitt, Cragin and Colbeck, 1991; Hendershot, Mendes and Lalande, 1992; Davies *et. al.*, 1991; Davies *et. al.*, 1993; Jenkins, Ferrier and Waters, 1993). However, the pH levels are higher than elsewhere in Scotland, indicating that, as proposed, the pollution concentrations in snowbeds of the western Highlands are lower than the east. The difference between Aonach Mor and Cairn Gorm is even more apparent in the meltwater pH, with apparently much greater levels of cation exchange taking place at Aonach Mor relative to Cairn Gorm and consequently much higher meltwater pH.

Downslope increases in pH are potentially important since pH could be an additional limiting factor for *Deschampsia cespitosa* in this environment. Olsen (1923, in Crawley, 1986), shows that the pH preferences for *D. cespitosa* are much more alkaline than for many other meadow species in Denmark. His results, measured in the field and therefore integrating the role of calcium as a critical component of plants' reaction to pH, gave the greatest percentage of this species recorded in the 5.5 - 5.9 range of pH, with none present in sites more acid than 5.0. *D. flexuosa*, on the other hand, showed greatest concentration in the 3.5 - 3.9 range, indicating that this species is far more tolerant of acidity than *D. cespitosa*. High acidity of the melting snowbed, as indicated by the pH of the snow itself and meltwater just downstream, and shown by Stanton *et. al.* (1994) throughout the growing season, could therefore be an important factor in excluding the species *D. cespitosa* from the snowbed core. The need for immediate response of *D. cespitosa* to release from snow in the later-melting areas to maximise growing time may conflict with the relatively alkaline requirements indicated above. Investigation of the pH requirements of montane populations of *Deschampsia cespitosa* are also needed since a number of features, such as the die-back observed at the end of season, indicate differences between lowland populations and this population. However, data presented in the *Deschampsia* experiment, in Chapter 6, indicate that this is an acclimation response, rather than an adaptive response, and thus the picture is confused. If the montane tolerances for pH are the same as the lowland tolerances observed in Denmark, then pH is more likely to be a limiting factor than has been previously considered.

More detailed study is needed of the acidity of the snowbed microenvironment in relation to its vascular vegetation and changes experienced both temporally and spatially within and around the snowbed. It is also concluded that the concerns expressed by Woolgrove and Woodin (1996) for the bryophyte flora of the central snowbed core in respect to acid discharge during melt are not applicable at this location, since recorded pH at this site did not fall to the levels which were observed to inflict damage by Woolgrove and Woodin. In general, therefore, the snowbed vegetation of the western Highlands is less likely to be adversely affected by pollution in this way than the eastern Highlands.

5.6 Climate at Altitude on Aonach Mor.

The monthly summary of climate data from the Aonach Mor AWS is displayed in Table 5.3 for the period 22.2.92 to 31.3.93. Graphic analysis of wind, temperature and humidity data is shown in Figures 5.9 to 5.14. The average wind direction data (hourly means) show a very strong dominance of south-westerly winds, but surprisingly westerly winds are less common than southerlies, north-westerlies and north-easterlies, while easterlies are very uncommon for the period shown. The graph of maximum wind direction (10 minutes in any hour) in Figure 5.12 indicates that gustiness follows a similar pattern as that of average wind direction and that therefore it is no more affected by topography than the average wind data.

From the map shown in Figure 4.1 it can be seen that the Leac an t-Sneachda, where the AWS is sited, is relatively sheltered from the south-east and, to a lesser extent, from the east. South-westerly winds could also be affected by the mass of Ben Nevis and Carn Mor Dearg but the lower occurrence of westerly winds is not accounted for by topography. Therefore it would appear that the data from the AWS is broadly representative of geostrophic winds and the conditions likely to be encountered on the summit of Aonach Mor.

Average and maximum wind speeds, shown in Figures 5.11 and 5.12, show a normal distribution, although both are positively skewed with a low frequency of high winds

TABLE 5.3
MONTHLY DATA SUMMARY FOR OBSERVATIONS FROM AONACH MOR AWS.
SOURCE: METEOROLOGICAL OFFICE, AVIEMORE.

Month	Av. wind direction °	Av. wind speed kts	Max wind direction °	Max wind speed kts	Mean temp °C	Max temp °C	Min temp °C	Mean rel. humidity %	No. non-missing	Max. rel. humidity %	Min rel. humidity %	max wind gust (kts)
Feb 92	217	32.6	219	55.2	-1.8	4.3	-5.5	91.51	202	100	20	97
Mar 92	179	23.3	188	38.3	-2.0	5.0	-9.7	90.03	430	100	24	78
Apr 92	164	21.5	178	33.4	-1.5	5.5	-7.9	87.78	589	100	38	67
May 92	163	18.7	171	32.7	4.5	14.9	-5.0	77.63	454	100	30	86
Jun 92	191	15.6	193	25.6	6.5	17.2	0.1	81.34	717	100	9	73
Jul 92	203	21.4	199	32.8	5.3	13.6	-0.3	91.99	741	100	22	71
Aug 92	210	22.8	206	35.3	4.4	10.1	0.0	93.85	729	100	35	89
Sep 92	181	19.4	188	31.2	3.7	11.6	-0.9	95.83	705	100	40	80
Oct 92	123	15.4	139	23.2	-0.1	13.0	-5.8	91.90	744	100	9	72
Nov 92	224	25.2	222	42.1	-1.1	7.4	-6.8	91.33	374	100	23	87
Dec 92	177	23.1	187	37.2	-1.7	5.5	-7.7	82.32	69	100	57	93
Jan 93	212	33.1	214	56.3	-3.7	5.2	-16.4	92.67	3	97	89	132
Feb 93	205	23.0	218	36.3	-0.8	8.0	-9.3	94.93	465	99	14	90
Mar 93	193	23.4	197	39.3	-0.1	7.8	-6.2	91.03	739	100	18	84

FIGURE 5.9

WIND ROSE OF AVERAGE WIND DIRECTION,

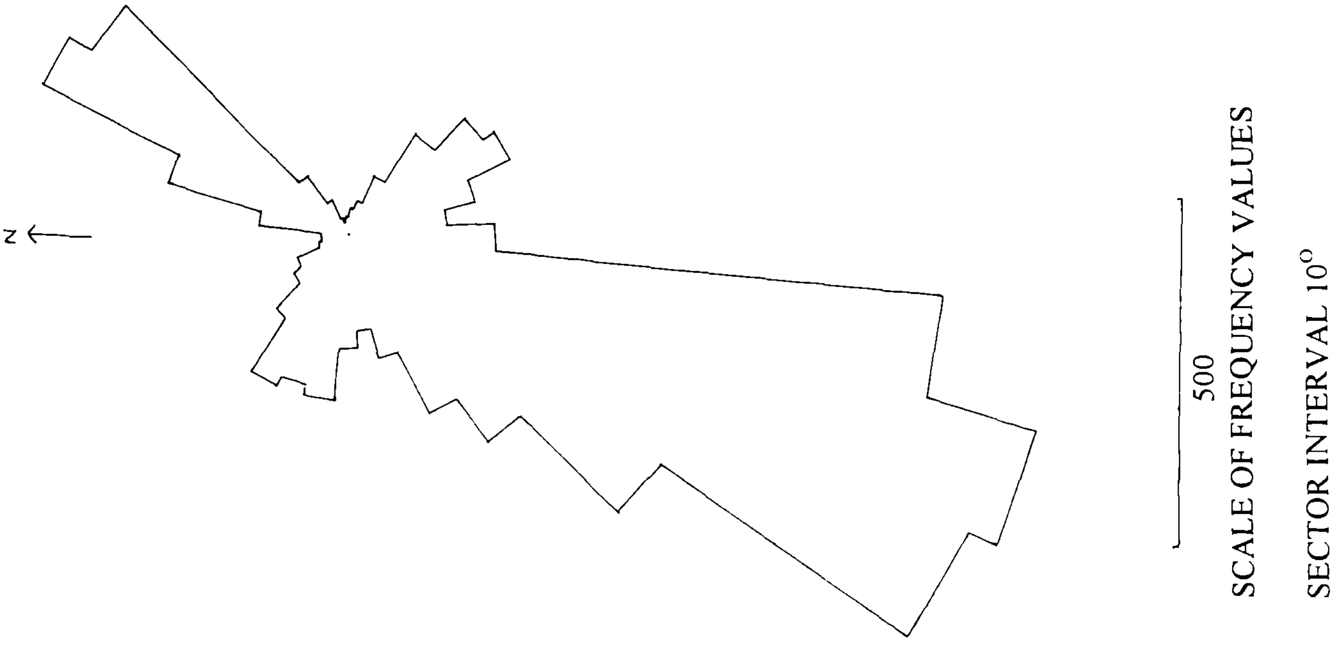


FIGURE 5.10

WIND ROSE OF MAXIMUM WIND DIRECTION, AONACH MOR.

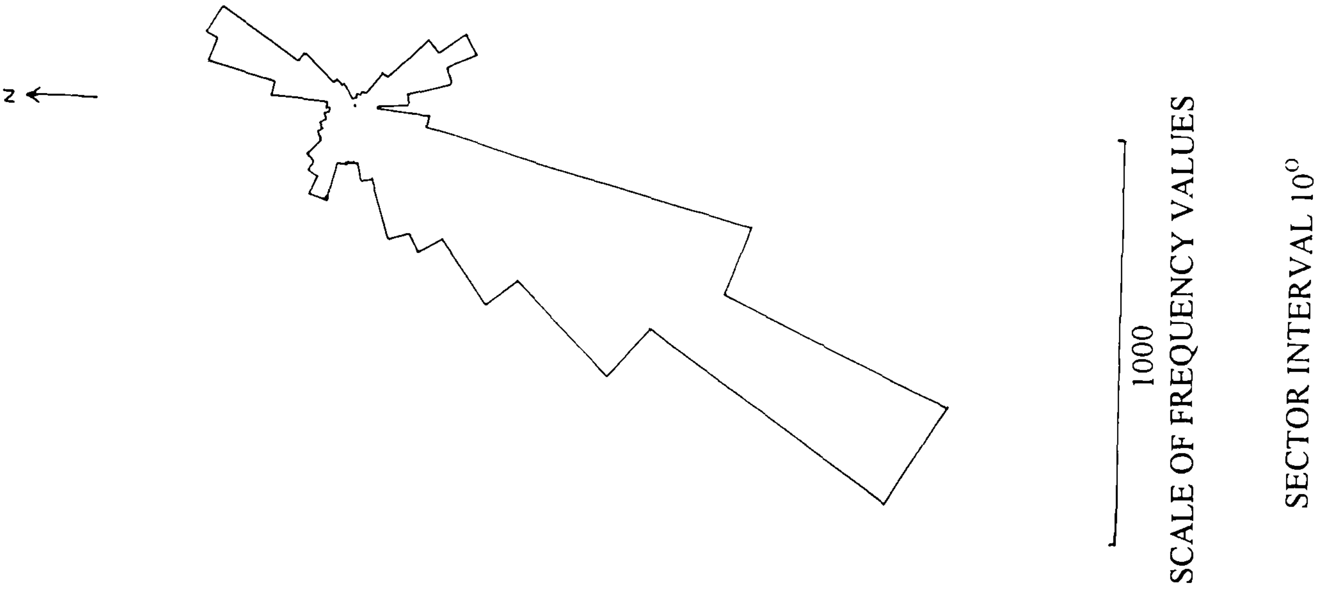


FIGURE 5.11

HISTOGRAM OF AVERAGE WIND SPEED, AONACH MOR

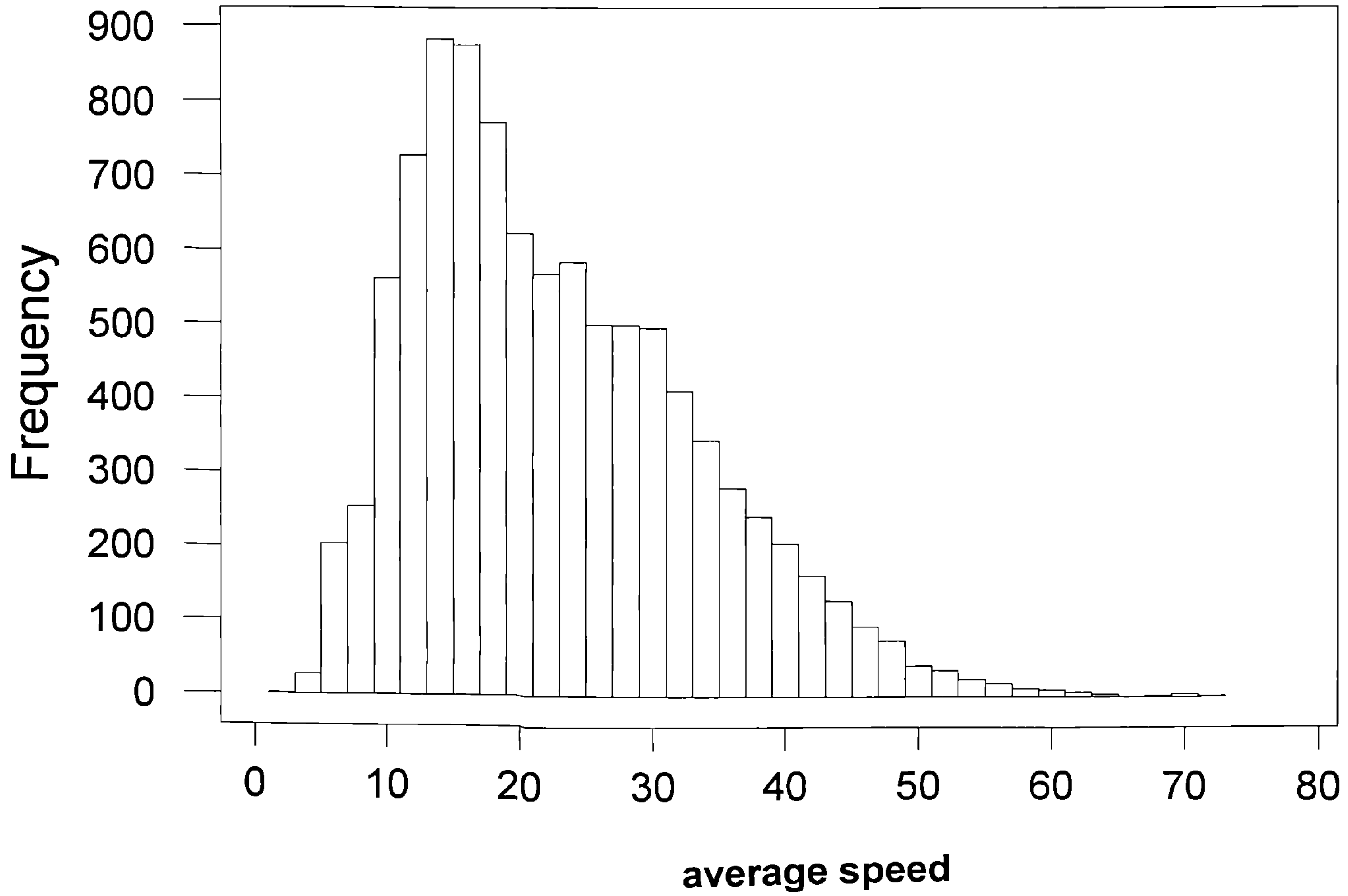


FIGURE 5.12

HISTOGRAM OF MAXIMUM WIND SPEED, AONACH MOR

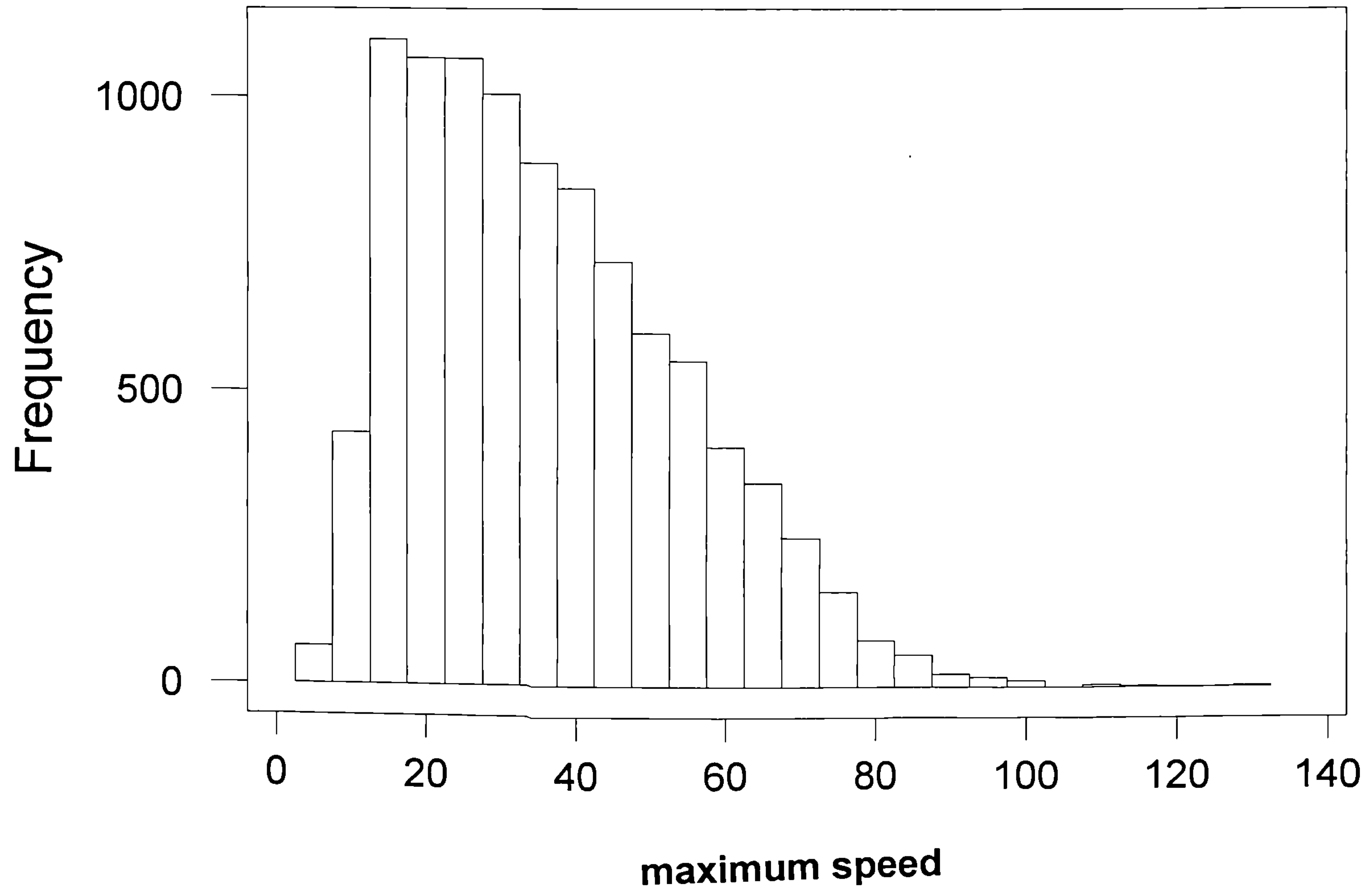


FIGURE 5.13

GRAPH OF TEMPERATURE DATA, AONACH MOR

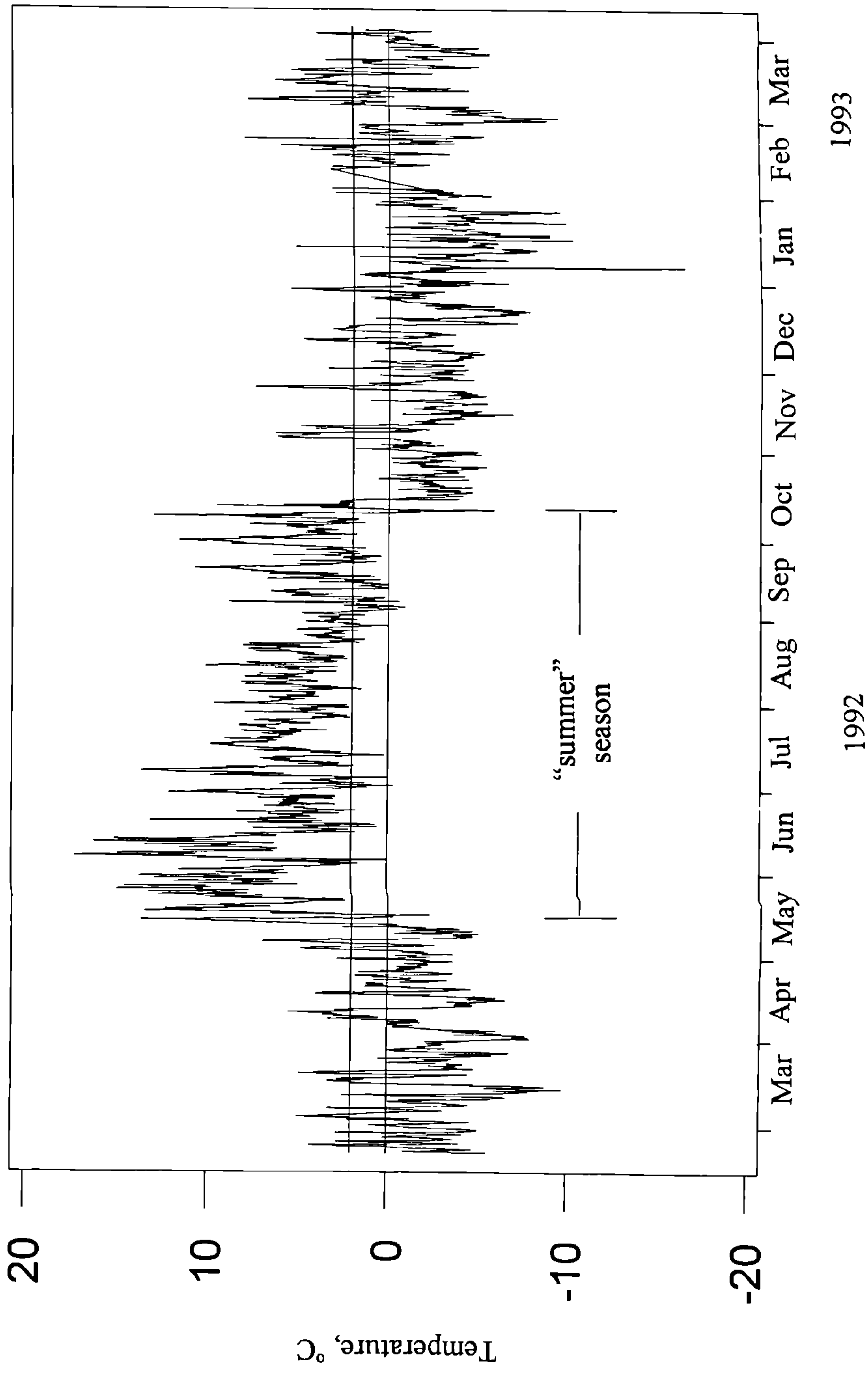
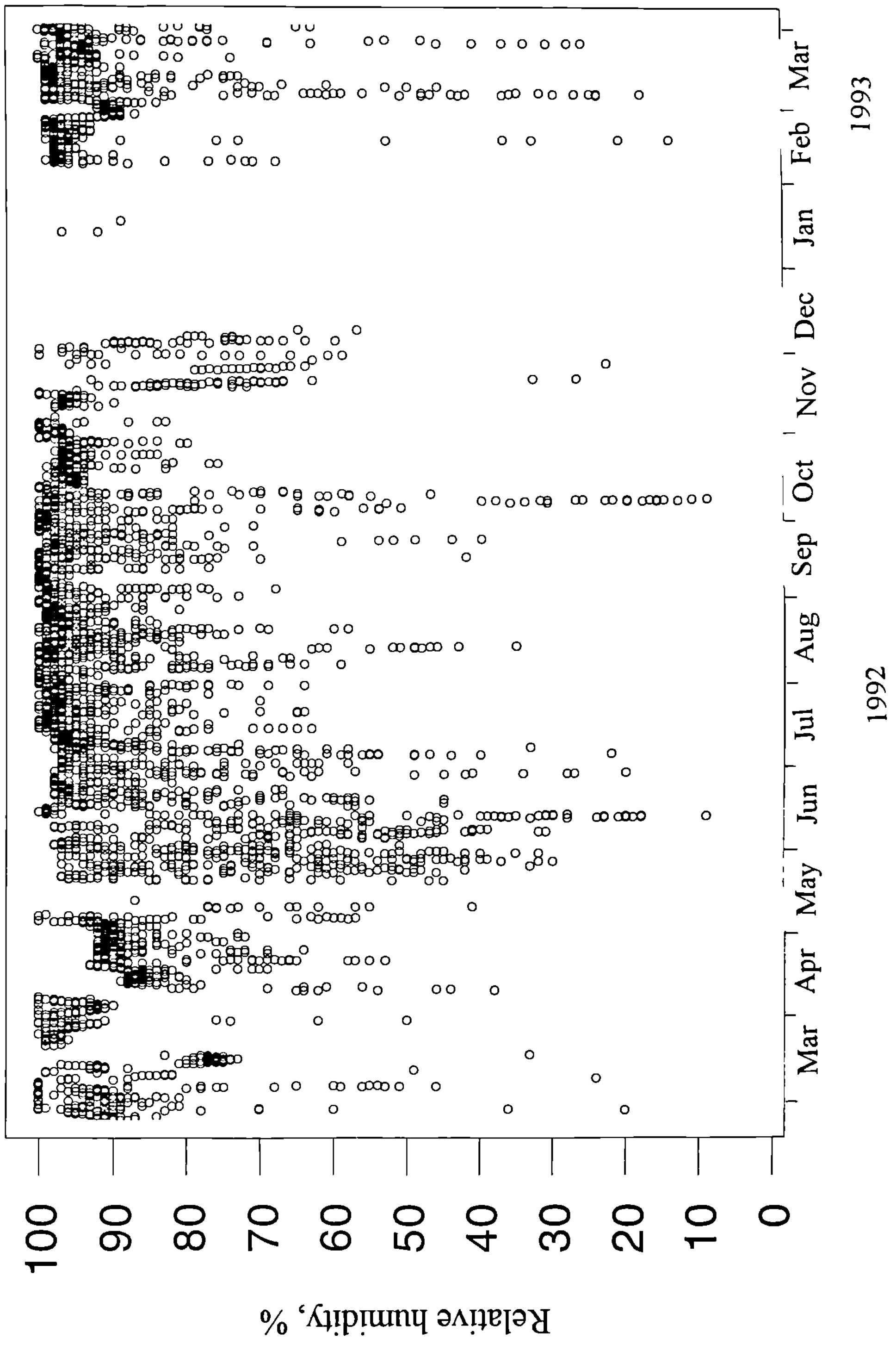


FIGURE 5.14
GRAPH OF HUMIDITY DATA, AONACH MOR



relative to the mean. The mean average wind speed of all data is 22.3 knots, with a median value of 20.0, while for maximum wind speed the average is 36.2 knots, median value 33.0. Measures of skewness for both these data columns give values of 0.749 and 0.693 respectively, confirming the relatively high level of skew. Kurtosis, a measure of the size of the peak of the distribution curve, has values of 0.226 and 0.056 respectively, showing that the maximum wind speed data most closely approximate the normal distribution while the average data are both flatter and more skewed. For these data for the period in question the following conclusions may be drawn:

a) Average wind speeds over each hour have a mean value of 22.3 knots, 25.5 mph or 9.2 ms^{-1}, which is much less than that on Cairn Gorm and equates better with data from other montane stations elsewhere in the world, such as Niwot Ridge (Davison, 1987). It is, however, a much higher figure than that given by the Ben Nevis data (5.4 ms^{-1}) which, although appears to compare well with free air data (Thom, 1974), would seem to be rather low (Barry, 1992).

b) Maximum wind speed, an average of the windiest 10 minute period during any one hour, has a mean value of 36.2 knots, 41.4 mph or 14.9 ms^{-1} which is closer to the average figure of 13.3 ms^{-1} for Cairn Gorm (Barton, 1987). Aonach Mor is therefore less windy in general than Cairn Gorm, which may experience accelerated wind speeds owing to its conical topography (Barton, 1987), but still experiences wind speeds more typical of much higher alpine locations elsewhere in the world.

c) The commonest wind direction is 210°, south of south-west, with a low occurrence of westerly winds (260° - 280°) and easterly winds (80° - 100°). High wind speeds are more common from southerly and south-westerly directions and less common from the north-east. This confirms the general pattern in Britain, with high winds strongly associated with cyclonic flow and low pressure features crossing the North Atlantic, and in particular the compression of isobars around a low pressure system and in advance of its associated fronts.

All the available temperature data are given in Figure 5.13. The pattern of temperature during the period in question shows a strong distinction between two seasons, a winter season with an average temperature of -1.5°C, and a summer season with an average temperature of 5.4°C, the latter starting on May 16th 1992, where a marked transition is made from temperatures fluctuating around zero to temperatures consistently above zero. This feature will mark the onset of the main melt. The end of the summer season and return to winter conditions takes place on October 8th. This distinction is also apparent from the wind direction data for "summer" and "winter" seasons, shown in Figures 5.15 and 5.16, indicating a very strong dominance of south-westerly winds in the summer, but a much stronger component of north-easterly and, to a lesser extent, north-westerly winds in winter. In due course, when a number of years of data are available, it will be possible to determine whether this pattern is a normal feature of climate at this altitude. If so, then a marked distinction between a two-season year can be made, with the summer season stretching for approximately 5 months from mid May to mid October, and a winter season of approximately 7 months. The 5-month summer should then be viewed as the potential growing season for montane vegetation, able to exploit the period when average temperature is above 0°C.

The number of freeze-thaw cycles was determined for the Aonach Mor data using 3 different thresholds of temperature defining the transition from a thaw to a freezing event. The overestimation of ground temperature made by temperature sensors sited

FIGURE 5.15
WIND ROSE OF AVERAGE WIND DIRECTION IN "SUMMER", AONACH MOR.

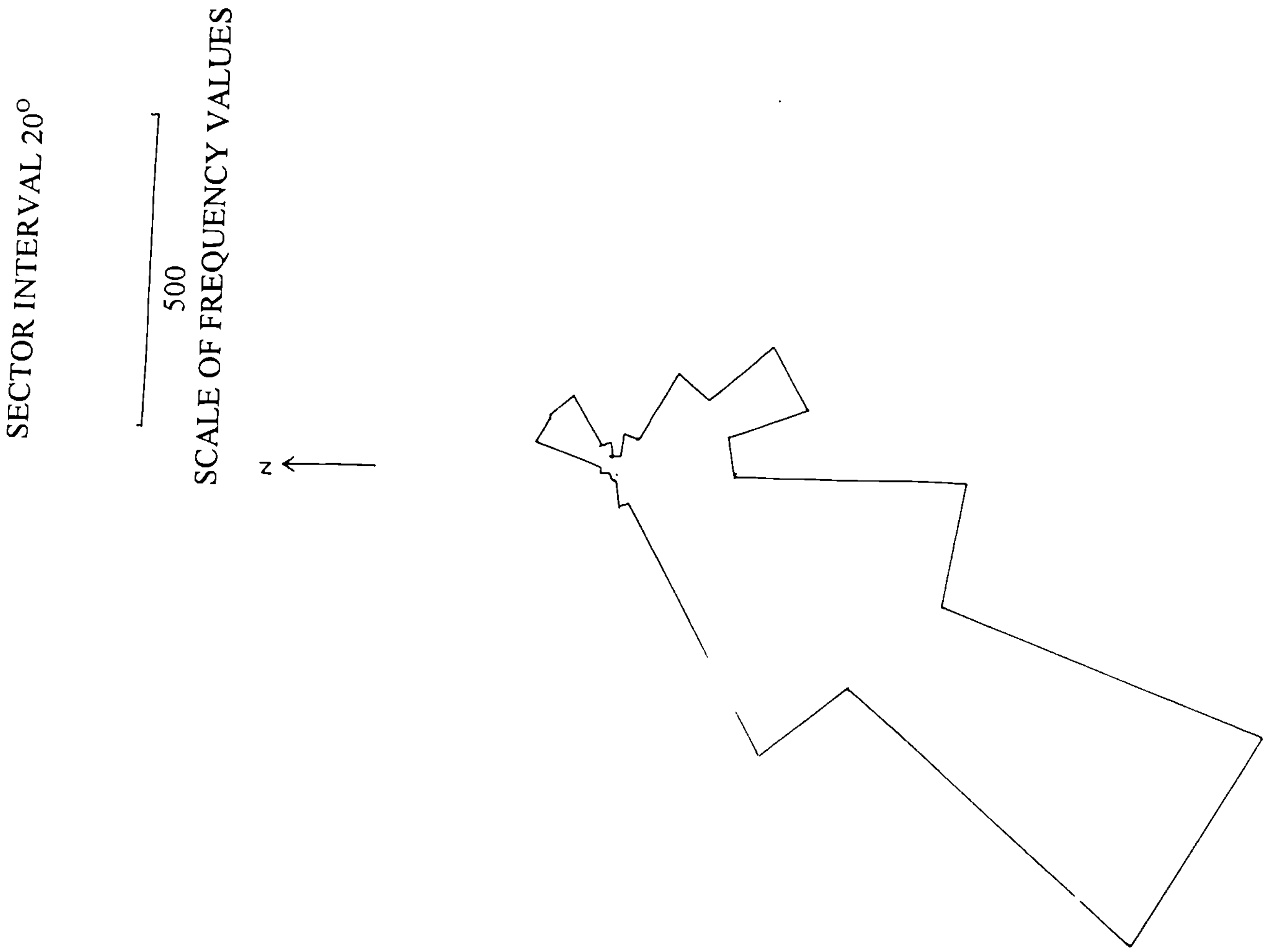
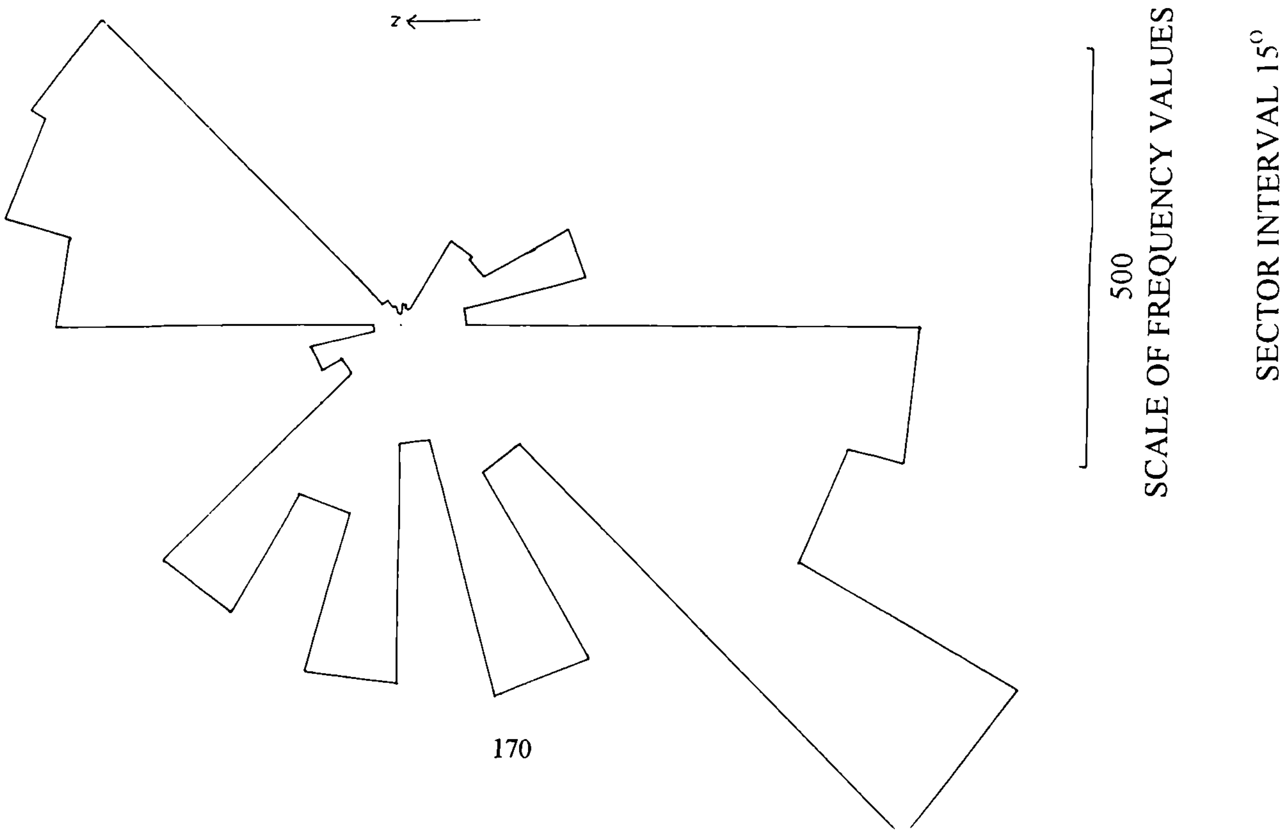


FIGURE 5.16
WIND ROSE OF AVERAGE WIND DIRECTION IN "WINTER", AONACH MOR.



in Stevenson screens (Harrison in Taylor, 1976), and therefore the likely overestimation of ground temperature made by a temperature sensor sited some distance from the ground at an AWS makes the use of the 0°C threshold alone inappropriate. Thresholds of 0°C and 2°C were used, with 2°C being the most likely to reflect a freeze-thaw event at ground level. One cycle was counted each time temperature rose above the threshold level and then fell to the threshold temperature or below it. Monthly totals of freeze-thaw cycles for the 2 thresholds are given in Table 5.4. The total number of cycles in the time period in question remained almost identical, irrespective of threshold, but the distribution of cycles varied, with fewer in spring, late autumn and winter (winter season) as the threshold temperature increased and thus a greater proportion of the time was below the threshold, while the number of cycles in the summer season increased as threshold temperature increased. Therefore, it seems likely that the vegetation growing above 1000m on Aonach Mor will experience a number of freeze-thaw events throughout the summer season which will restrict the occurrence of frost-sensitive species and ensures the arctic-alpine nature of the flora.

Use of the 0°C threshold temperature offers a picture of temperature fluctuations which may occur following further climate change, and indicates that although the seasonal split remains the same between winter and summer, (see Figure 5.13), the occurrence of frost in the summer season should fall. Equally the number of thaw incidents in the winter would increase leading to more ephemeral snow-lie, though the increased number of cycles could also lead to an even denser, and therefore more durable, snowpack, at least over the late snowbeds. The majority of winter temperatures would still lie below the threshold, with only approximately a 6%

TABLE 5.4

MONTHLY TOTALS OF FREEZE-THAW CYCLES OBSERVED FROM AONACH MOR DATA

MONTH	Number of cycles @ 0°C	Number of cycles @ 2°C
February (20th - 29th) 1992	6	3
March 1992	8	8
April 1992	10	6
May 1992	7	4
June 1992	0	7
July 1992	1	8
August 1992	1	7
September 1992	5	20
October 1992	3	9
November 1992	10	4
December 1992	14	4
January 1993	13	1
February 1993	13	9
March 1993	12	10
TOTAL	**103**	**100**

increase in temperature above the threshold relative to the 2°C winter season total on the basis of area below the temperature curve.

The die-back observed in *Deschampsia cespitosa* coincides with the substantial increase in freeze-thaw cycles at the end of August, using the 2°C threshold, indicating that this species is sensitive to freezing damage relative to the bryophytes which remained vigorous until covered by snow at the end of October. A change from the 2°C regime to the 0°C regime, would reduce the number of frosts in September to 5 and therefore greatly enhance the length of the actual growing season for this species and give it ample opportunity to expand into niches which are currently less favourable.

Relative humidity has been one of the most difficult parameters to measure (Met. Office, pers. comm.) and frequently the results have been unsatisfactory, or absent. Figure 5.14 gives the data which are apparently not too badly affected, with values of 8% or lower and 120% or higher discarded, and values of 101 to 119% reduced to 100%. The concentration of low values in the late spring and early summer - at the start of the summer half-year - is apparent and concurs with the data shown in Figure 5.17 for rainfall at Sgurr Finisgaig on the northern end of Aonach Mor, with April May, June and July the driest months of the year, although there is a substantial amount of variation between years. Precipitation data for Onich is compared with the Sgurr Finisgaig data in Figure 5.18 and confirms the enhancement of precipitation with altitude, even though Sgurr Finisgaig has a more continental location and is therefore likely to experience more of a rain-shadow effect than Onich on the west coast. Low figures at Sgurr Finisgaig in January, February and March are explained by the high proportion of precipitation falling as snow and therefore under-recorded.

FIGURE 5.17

5-YEAR MEAN MONTHLY PRECIPITATION RANGE, SGURR FINISGAIG 1979-1984.

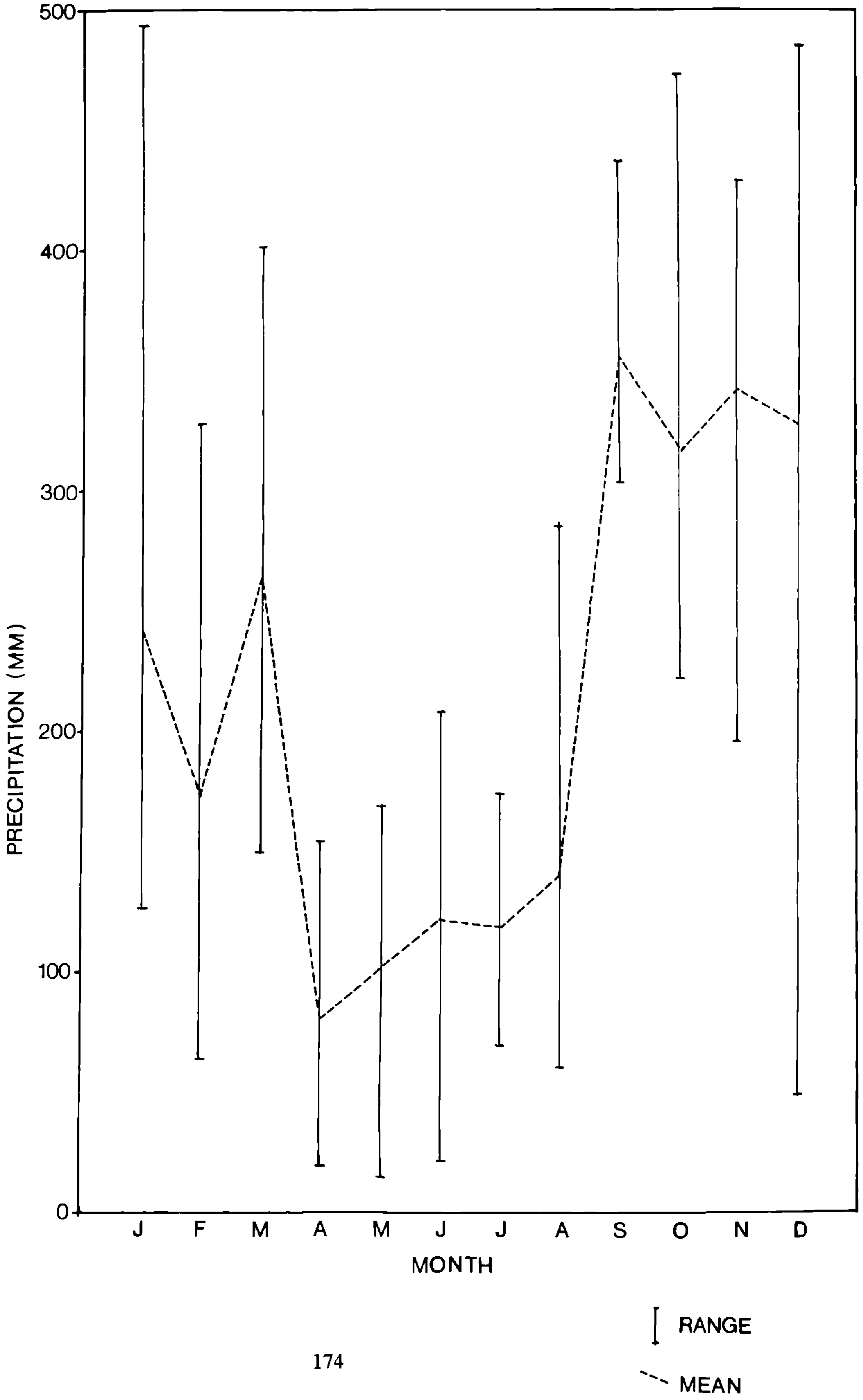
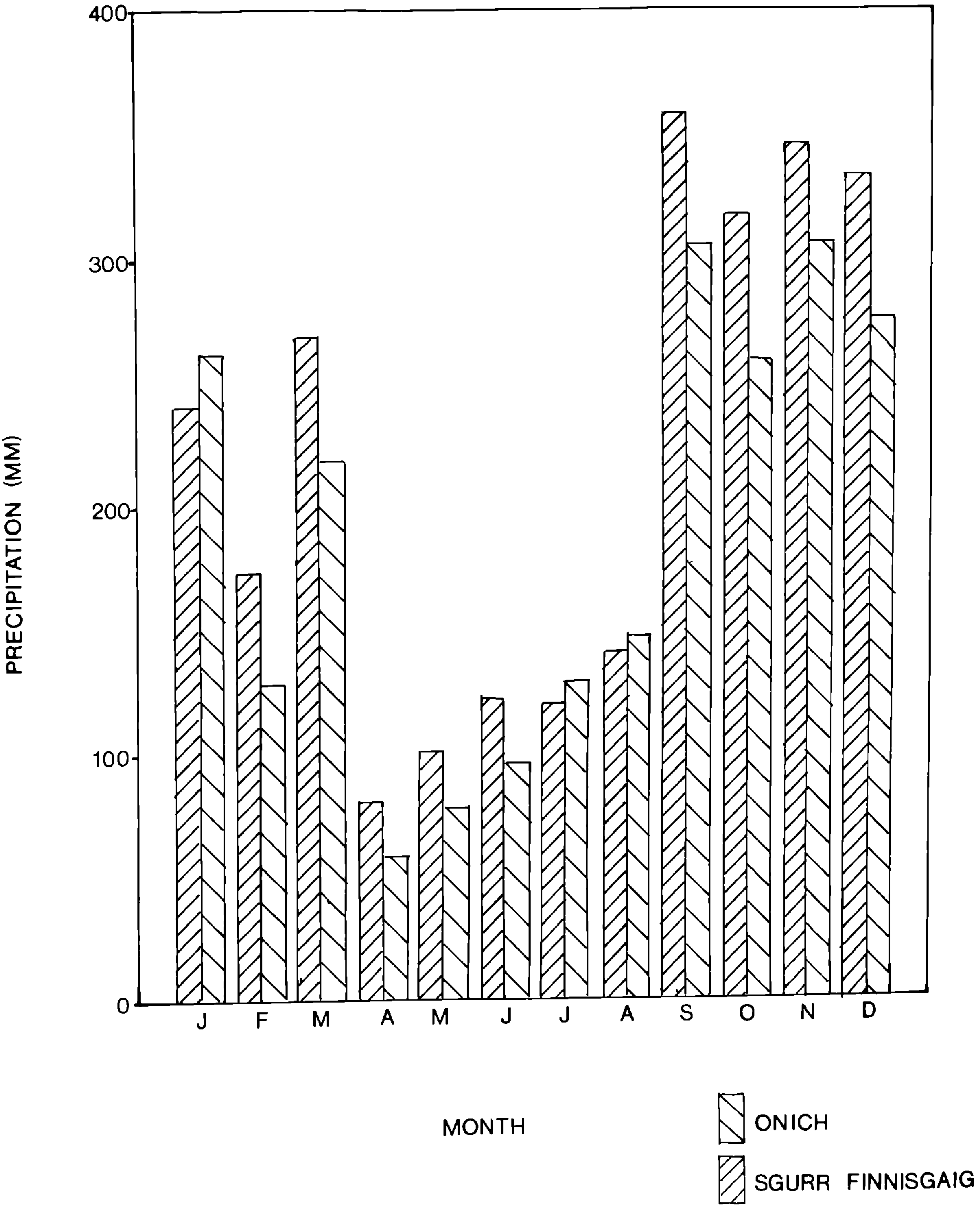


FIGURE 5.18

5-YEAR MEAN MONTHLY PRECIPITATION, SGURR FINISGAIG AND ONICH, 1979-1984.



Correlations between the variables recorded at Aonach Mor are all significant at the 99.9% level for all except average wind direction and temperature, and maximum wind direction and temperature. Strong positive correlations exist between temperature and dew point temperature, wind speeds and wind directions. Negative correlations are found between temperature and relative humidity, and between temperature and wind speed. Therefore higher temperatures are accompanied by low relative humidity and wind speeds. Optimum conditions for snow melt would entail high temperature, high wind speeds and low humidity, so conditions here are less than optimal for the melting of the snowpack.

The results of the Aonach Mor data confirm the arctic-alpine nature of the site and indicate an environment where temperature is often below freezing, snow may fall at any time of the year, and conditions for plant growth must be considered to be marginal. High winds are common, especially in winter, leading to a high component of wind and snow drift and the consequent increase in volume of the late snowbeds at the expense of surrounding windward and summit slopes.

Summary points:

1. The topography of the site, combined with aspect and wind, allow a substantial depth of snow to accumulate in the form of a cornice, which becomes a late-lying snowbed and beneath which snowbed vegetation is found.

2. Snow-lie duration is highly variable for this site, while the location of the late snowbed is not variable.

3. The density of the snowpack is indicated to be high, with a high level of stratification.

4. Snow was relatively acid, but meltwater became rapidly neutralised.

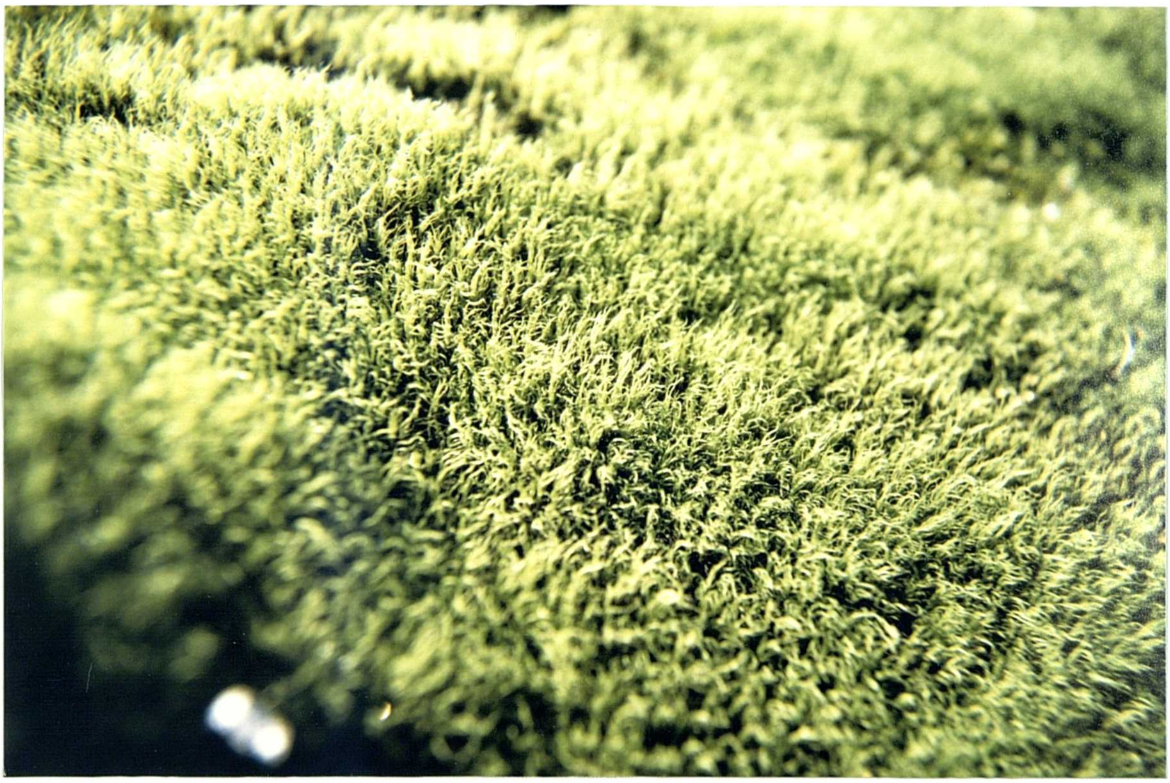
5. The climate as indicated by the AWS, is severe, with a two-season year and a high incidence of freeze-thaw cycles, variably distributed but present in all parts of the year. Wind direction is predominantly south-westerly and average speed is high.

PLATES 13 AND 14

BARE GROUND SHOWING THE COARSE NATURE OF THE SUBSTRATE AND AN EXAMPLE OF *Festuca vivipara*.

PLATES 15 AND 16

EXAMPLES OF *Kiaeria starkei* AND *Polytrichum sexangulare*.



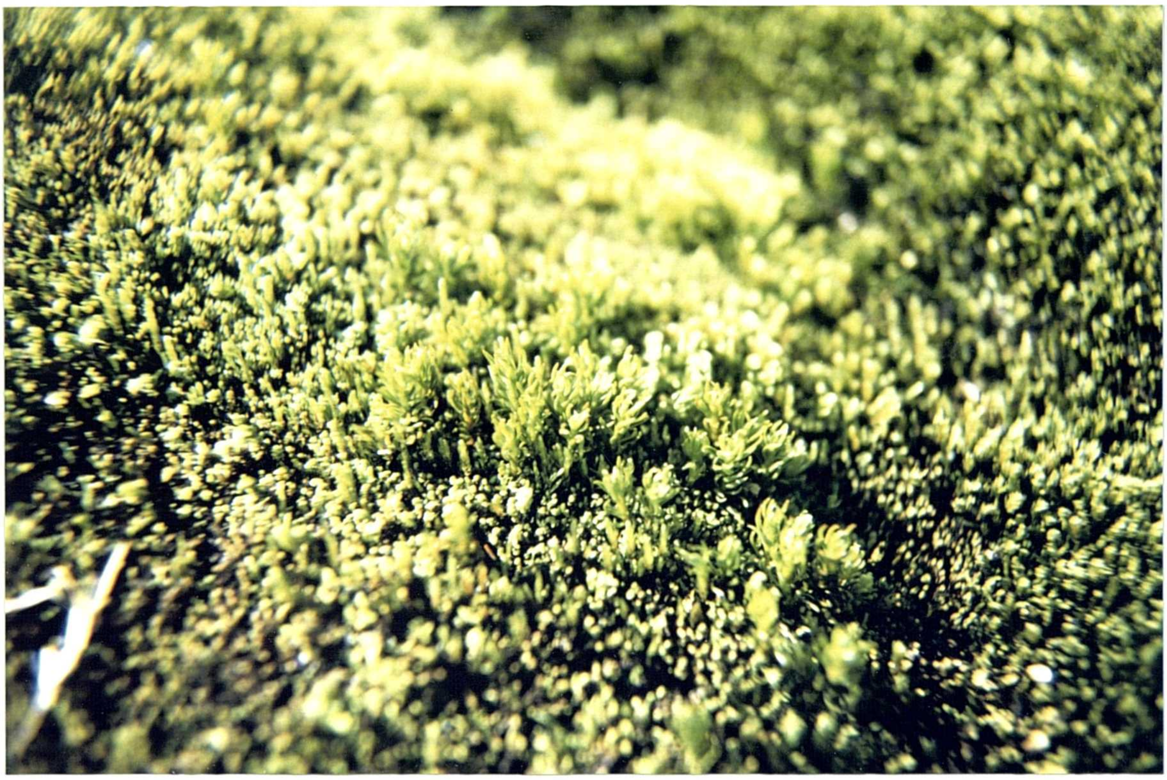


PLATE 17 AND 18

EXAMPLES OF *Pohlia ludwigii* AND *Saxifraga stellaris*.

PLATE 19

BARE GROUND SHOWING OVERTURNING BY FROST-HEAVE

CHAPTER 6

THE PATTERN OF VEGETATION ASSOCIATIONS

6.1 Quadrat Measurements.

The results of the series of measurements undertaken in the quadrats are given below. Contour plots were constructed for many of the vegetation and environmental variables measured to give a visual impression of the distribution of different features within the 100m^2 site. Further analyses were also undertaken using a variety of statistical techniques.

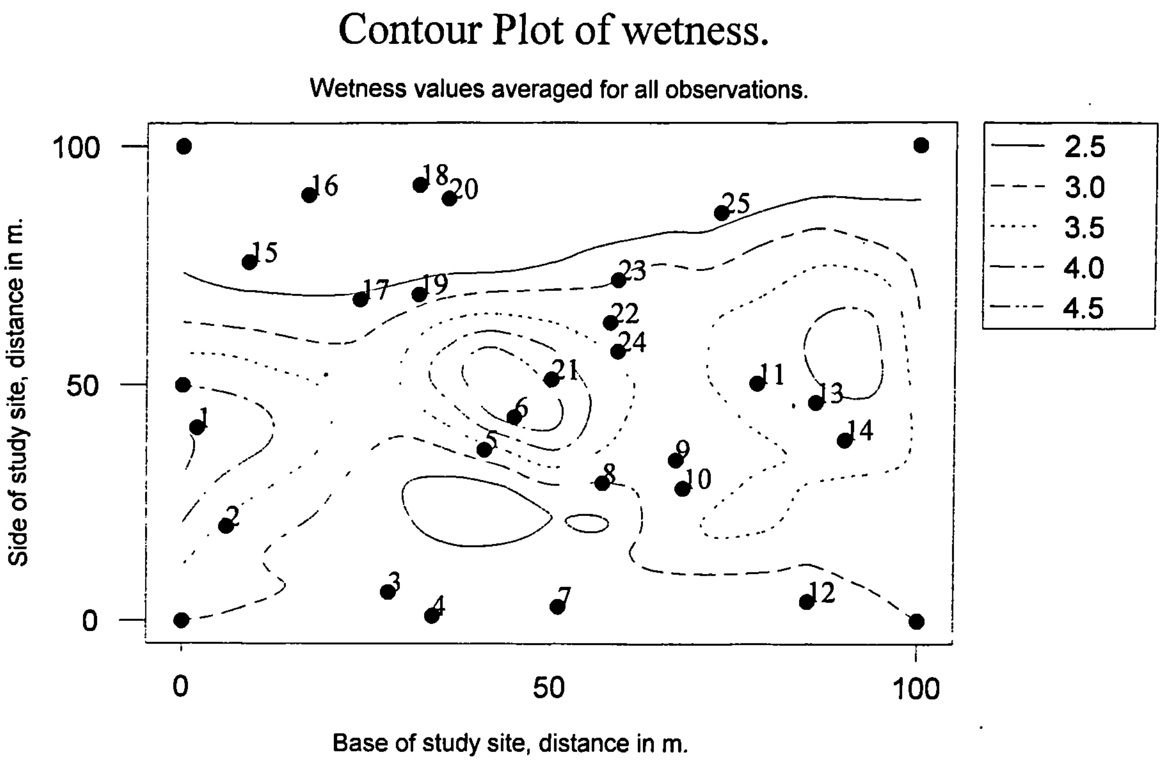
6.1.1 Wetness.

Wetness was described for each quadrat using the scale of 1 (dry) to 5 (wet with surface water) on each vegetation visit. The mean wetness for each quadrat was then calculated by averaging all the figures given. These are displayed in Table 6.1 and a contour plot constructed from the data in Figure 6.1. The lack of more than 25 data points in a 100x100 point square makes this plot coarse with no information for the boundary areas, so, as with all contour plots, it was refined by adding values to each of the four corners comparable with the values found in the nearest quadrats. These are detailed in Table 6.1, along with values for the average duration of snow-lie in each quadrat, with value 1 the least duration of snow-lie and 9 the greatest. The pattern of concentration of the wettest areas in the centre of the site, where concavity is greatest and where the bulk of the snowbed is to be found, is apparent with a significant change to much drier conditions away from the snowbed and on the plateau. This should be viewed in conjunction with Figure 6.2, a contour plot on the same matrix giving ranked values for the duration of snowlie on each quadrat. The coincidence of the two plots is

TABLE 6.1
TABLE SHOWING THE AVERAGE WETNESS AND SNOWLIE VALUES FOR 25 QUADRATS PLUS FOUR CONTOUR PLOT CORNER VALUES.

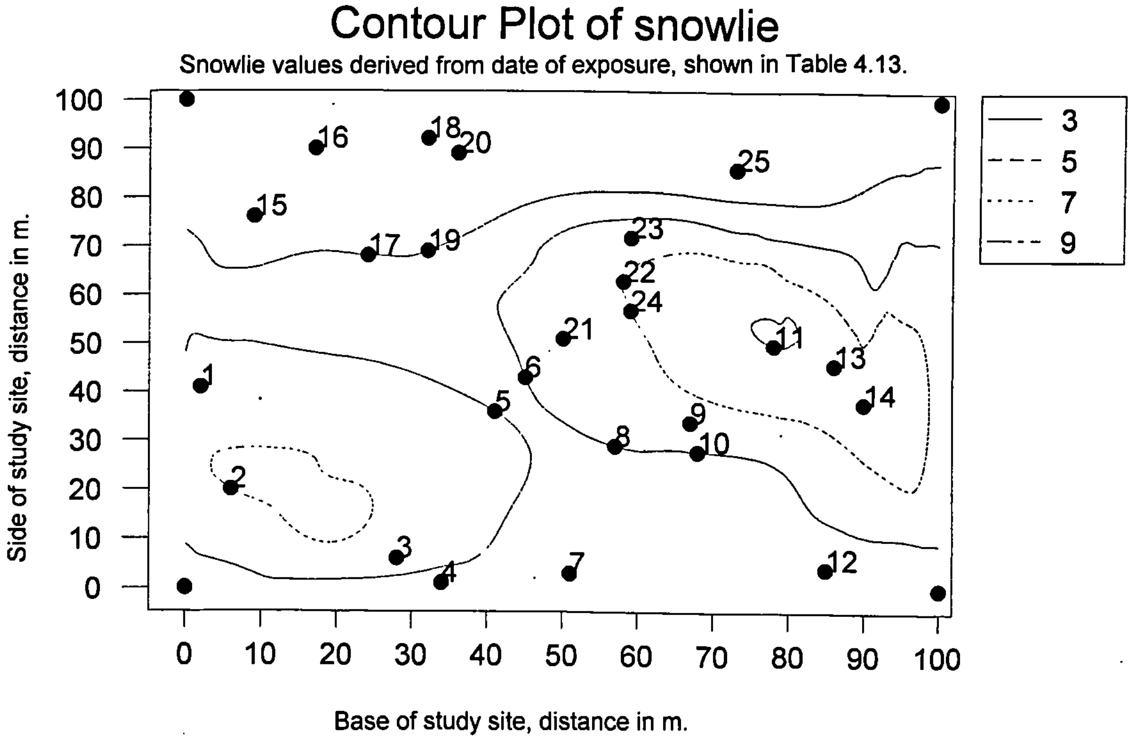
Quadrat number	wetness	snowlie
1	4.5	6
2	3.4	7
3	2.9	6
4	3.0	4
5	3.3	5
6	4.7	5
7	2.8	4
8	3.0	5
9	3.1	6
10	3.2	5
11	3.7	9
12	2.8	4
13	3.9	8
14	3.7	8
15	2.3	2
16	2.2	1
17	2.6	3
18	2.1	1
19	2.8	3
20	1.6	1
21	4.4	6
22	3.2	7
23	3.0	6
24	3.4	7
25	2.3	1
bottom LH corner	3.0	4
bottom RH corner	3.0	4
top LH corner	2.2	1
top RH corner	2.3	1

FIGURE 6.1



1 = dry
5 = wet

FIGURE 6.2



apparent. Irrigation of the site is therefore very closely related to the location of the late snowbed, as is expected. Consistent irrigation as demonstrated here should be considered in the light of the acidity of the melt waters, given the acid nature of the snowbed itself. The wettest areas immediately surrounding the snowbed may experience acid flow for much, if not all, the potential growing season, even if pollutants have been flushed preferentially at the initiation of melt, since the snow pH measurements indicate a relatively high level of acidity remaining throughout the growing season. While this is unlikely to affect the snowbed bryophyte species, as shown earlier, there may be adverse effects for the vascular plants, and in particular *Deschampsia cespitosa*. It should also be noted that the snow-lie contour plot, generated from the quadrat data, coincides well with the snow-lie maps drawn up from the photography, giving confidence in the accuracy of both these methods.

6.1.2. Temperature.

Measurements of temperature in the quadrats took place on four separate occasions: 10.8.92, 5.9.92, 9.6.93 and 20.7.93. Data from the AWS are available for the two dates in 1992 and the following represent the conditions recorded on those days:

10.8.92	temp. 7.5 - 7.9°C	rel. humidity 80%	wind 11 - 14 knots from 200°.
5.9.92	temp. 1.9 - 2.5°C	rel. humidity 80%	wind 11 - 13 knots from 210°.

Information recorded at the time gave rather different conditions for the two dates in 1993, with 9.6.93 very still, warm (temperature at sea level 14°C) and humid, whereas 20.7.93 was cloudy and windy, with the same sea level temperature but feeling much colder.

The temperature measurements from those quadrats from which records were taken are shown in Figures 6.3 to 6.6 (a). The 1992 records, although taken on days of very similar wind conditions, show variation in the relationships between the temperature at different levels. In August 1992 air temperature and substrate temperature have a similar range, although the amplitude of the air temperature range is slightly larger. The difference between the vegetation temperature measurements and the air, shown in Figures 6.3 to 6.6 (b), and substrate measurements is also smaller. In September air temperature is generally lower than all the other measures, much more so in the upper quadrats than the lower ones, and the difference between vegetation and substrate temperature is less. This demonstrates, as the year wanes, the lag between the reduction of air temperature and that of the substrate, which acts as a store of energy absorbed during the summer months. The data for 9.6.93 shows this lag acting in a similar fashion in the early summer, where air responds more quickly to radiation inputs and the volume of the substrate takes much longer to warm up.

The effect of higher wind speeds on air temperature and the temperature in the higher and more open vascular canopy can be clearly seen in Figure 6.6, a day which felt windy and cold. Those quadrats on or close to the summit plateau (15, 16, 18, 20, 22

FIGURE 6.3a

QUADRAT TEMPERATURE MEASUREMENTS I : 10.8.92

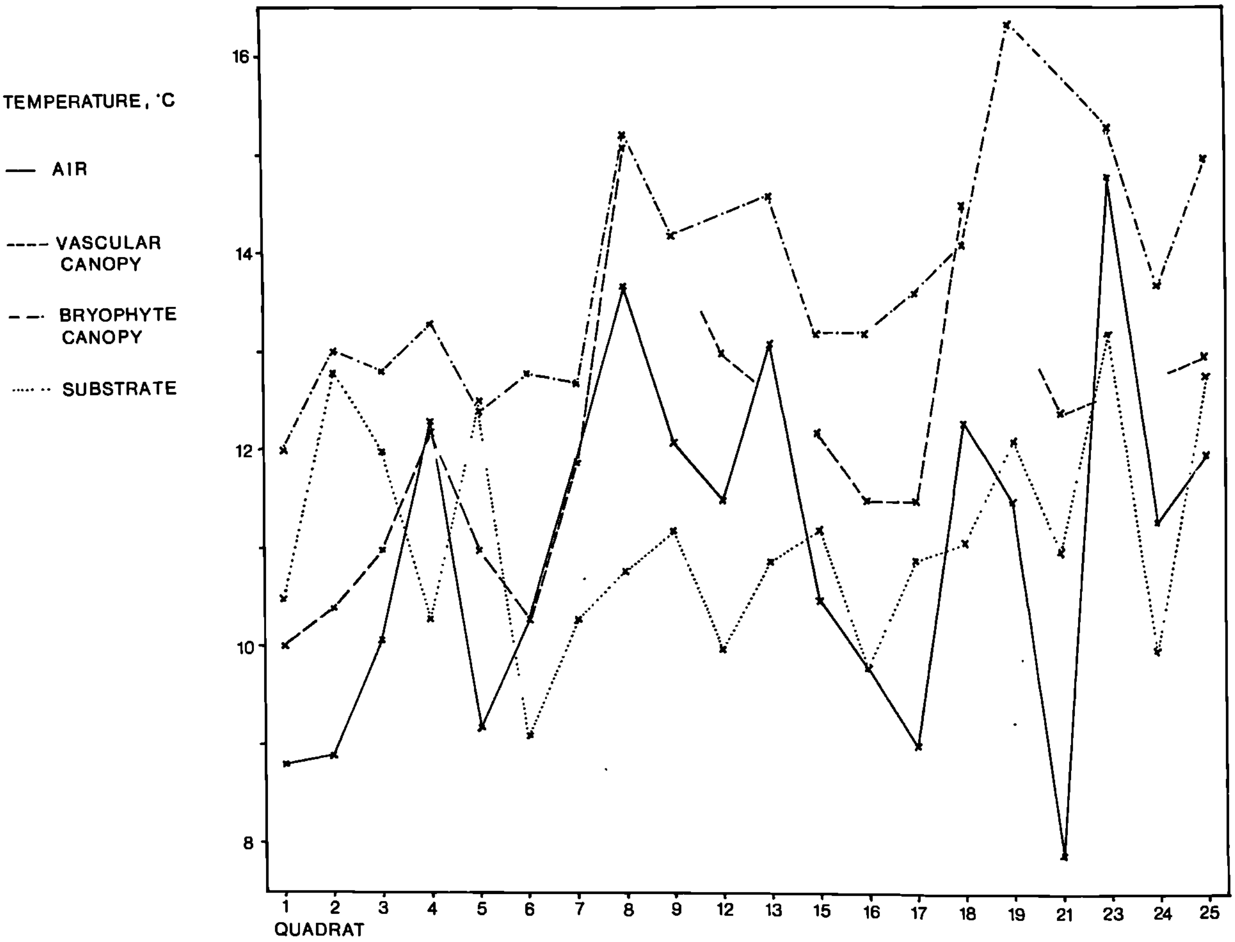


FIGURE 6.3b

DIFFERENCE BETWEEN AIR TEMPERATURE AND CANOPY TEMPERATURE.

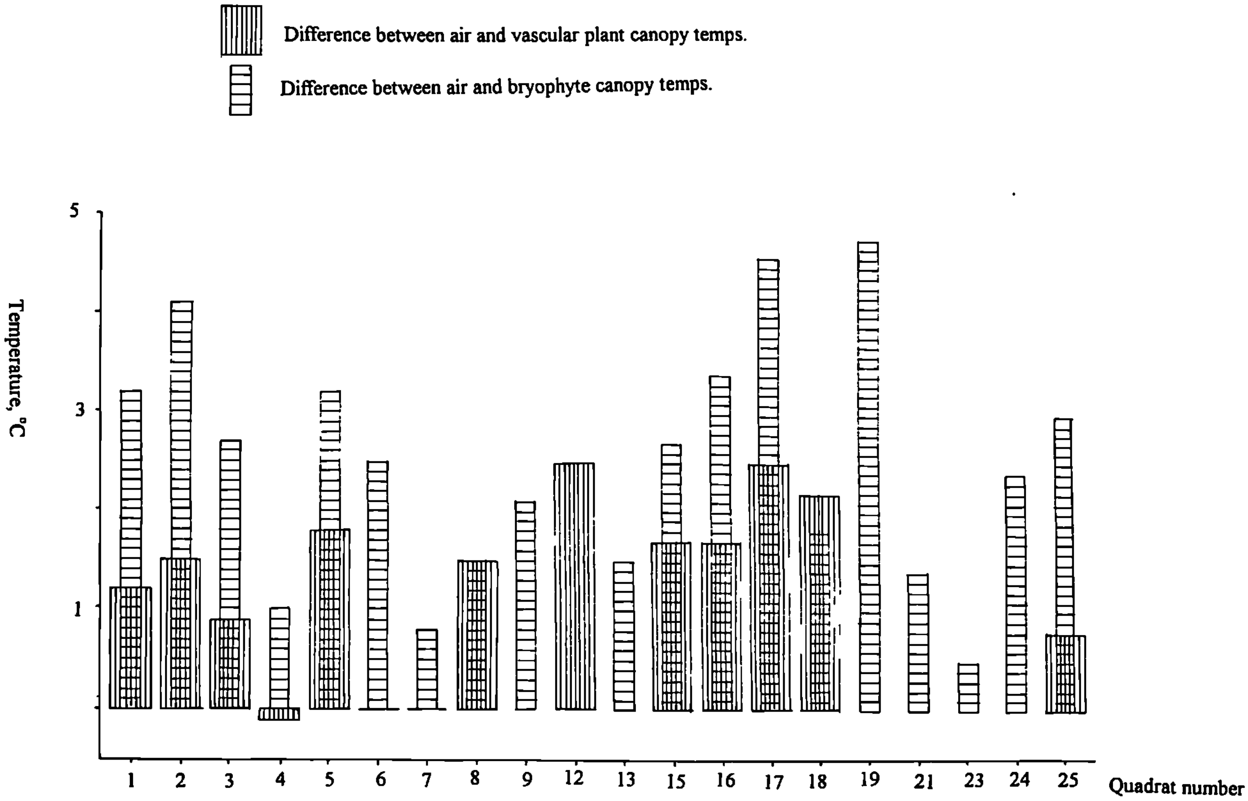


FIGURE 6.4a

QUADRAT TEMPERATURE MEASUREMENTS II : 5.9.92

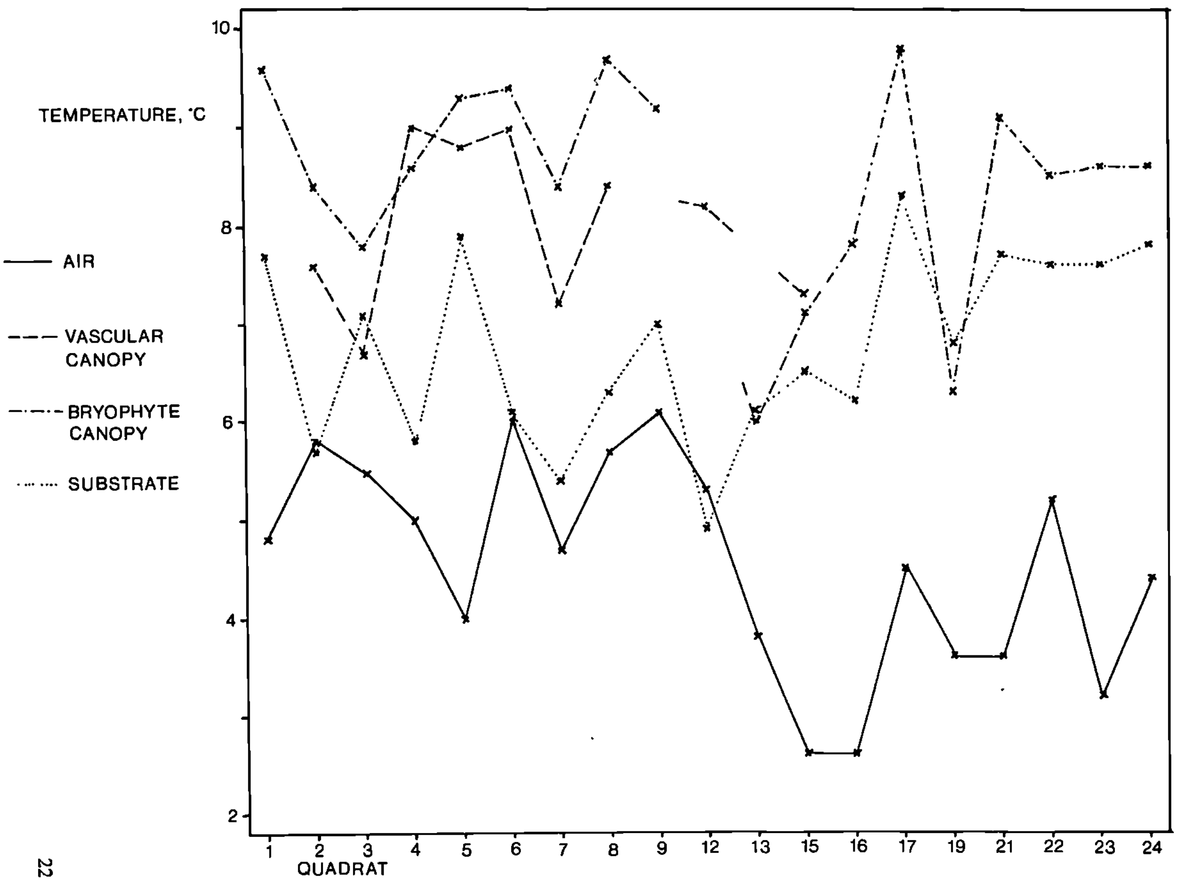


FIGURE 6.4b

DIFFERENCE BETWEEN AIR TEMPERATURE AND CANOPY TEMPERATURE.

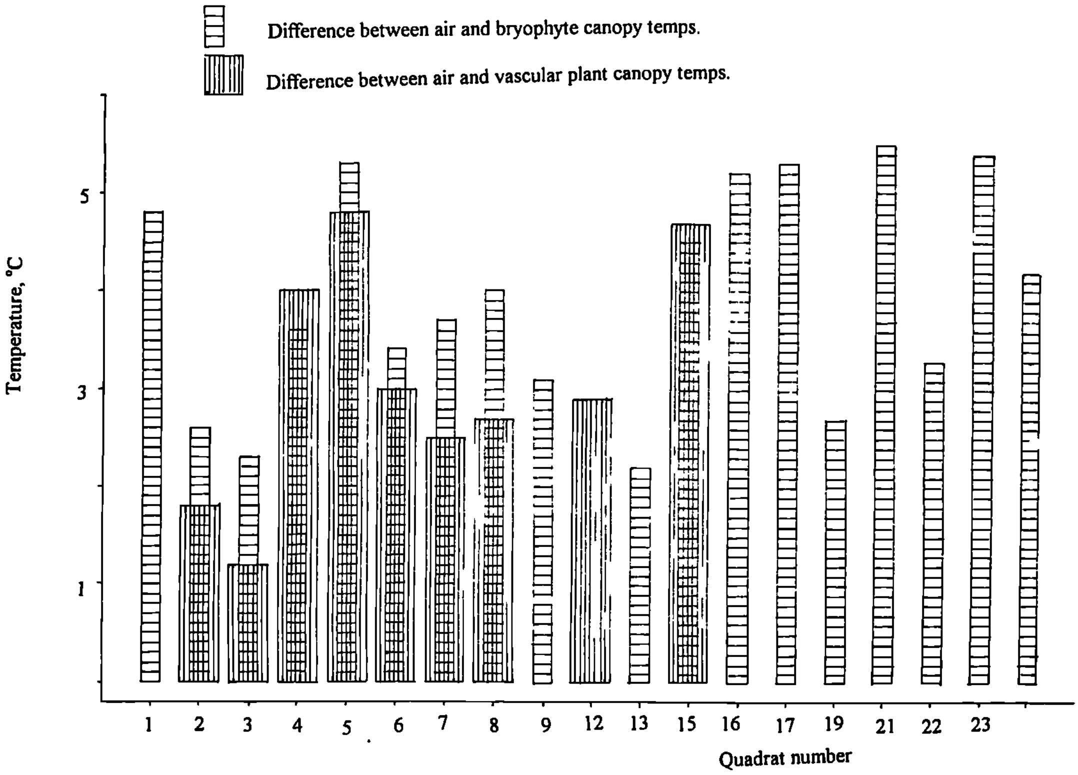


FIGURE 6.5a

QUADRAT TEMPERATURE MEASUREMENTS III : 9.6.93

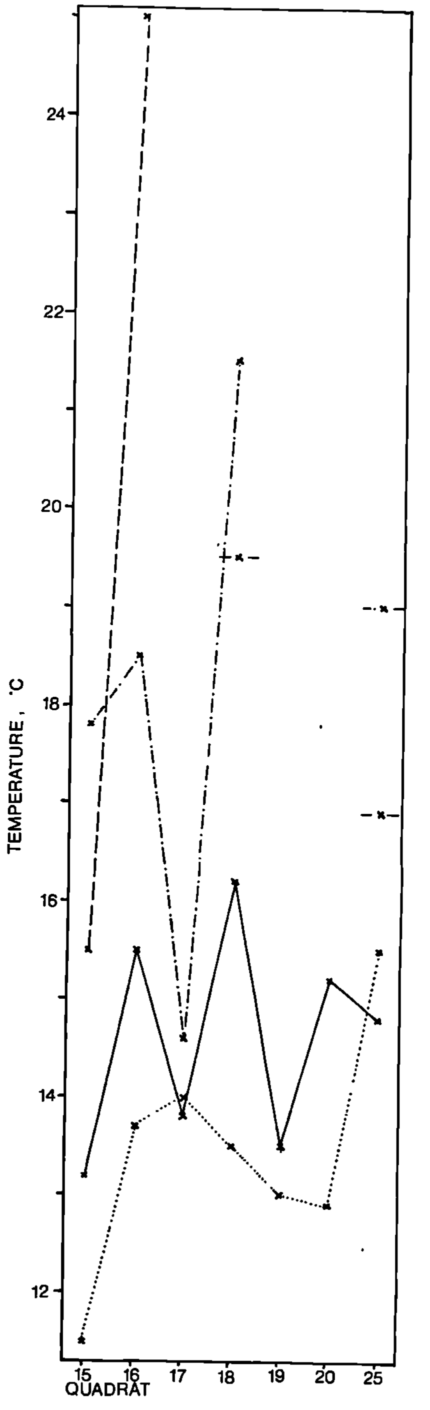


FIGURE 6.5b

DIFFERENCE BETWEEN AIR TEMPERATURE AND CANOPY TEMPERATURE.

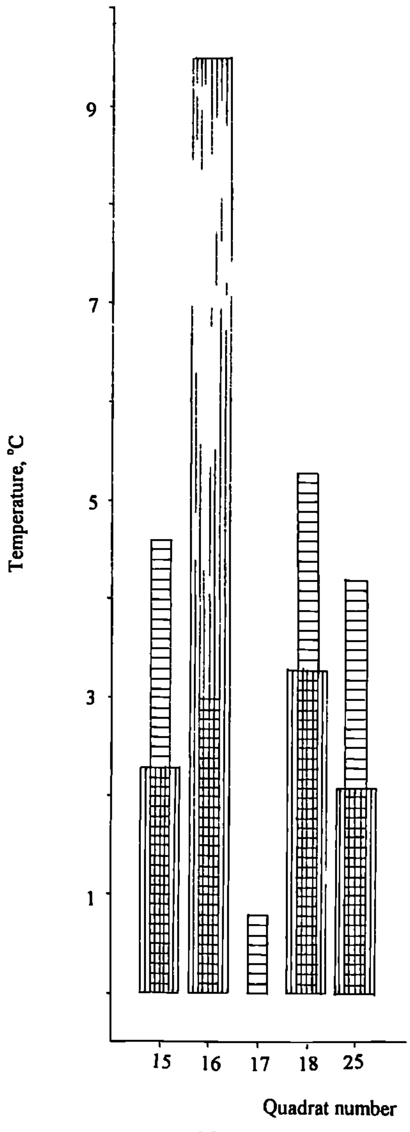


FIGURE 6.6a

QUADRAT TEMPERATURE MEASUREMENTS IV : 20.7.93

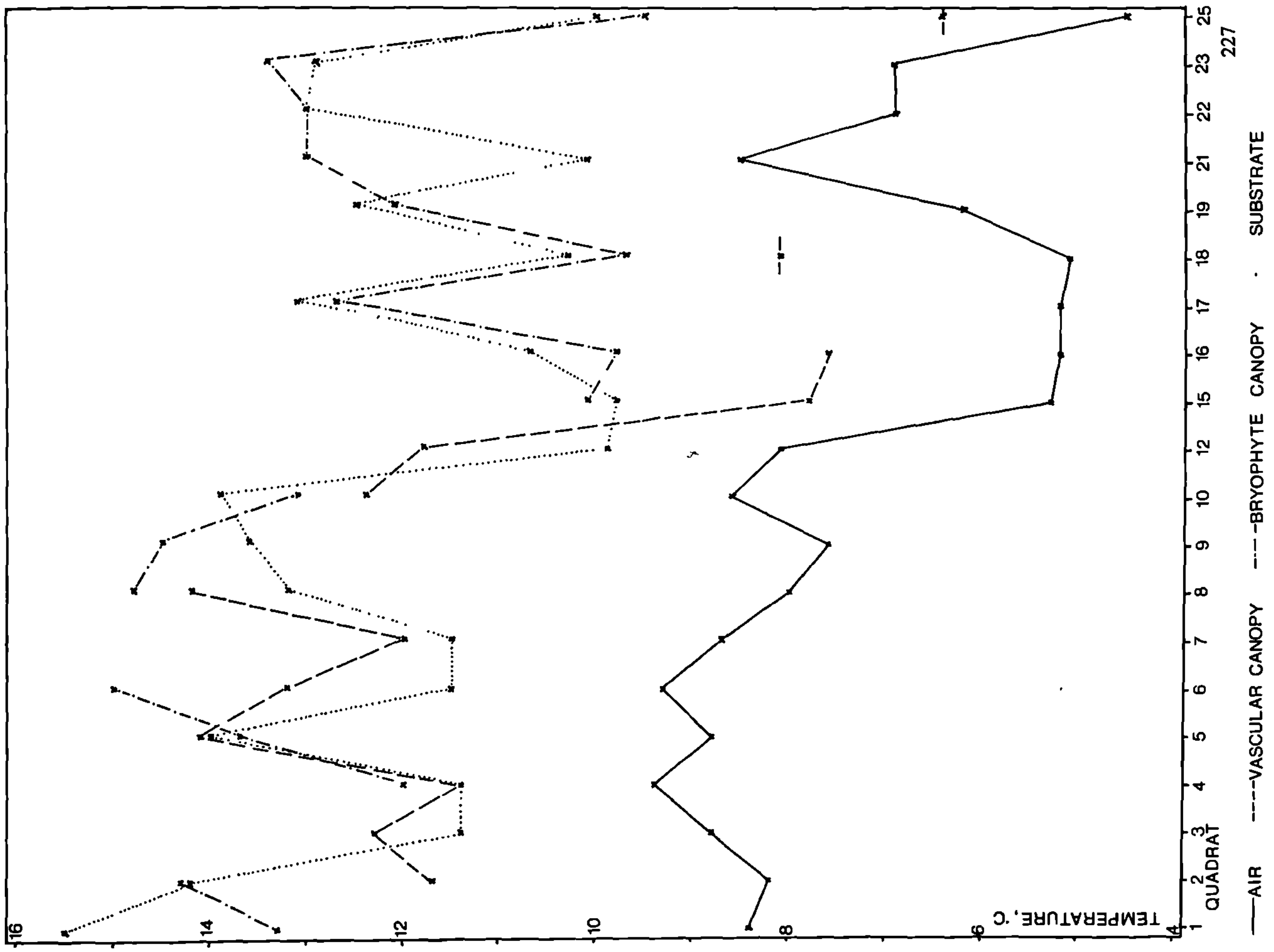
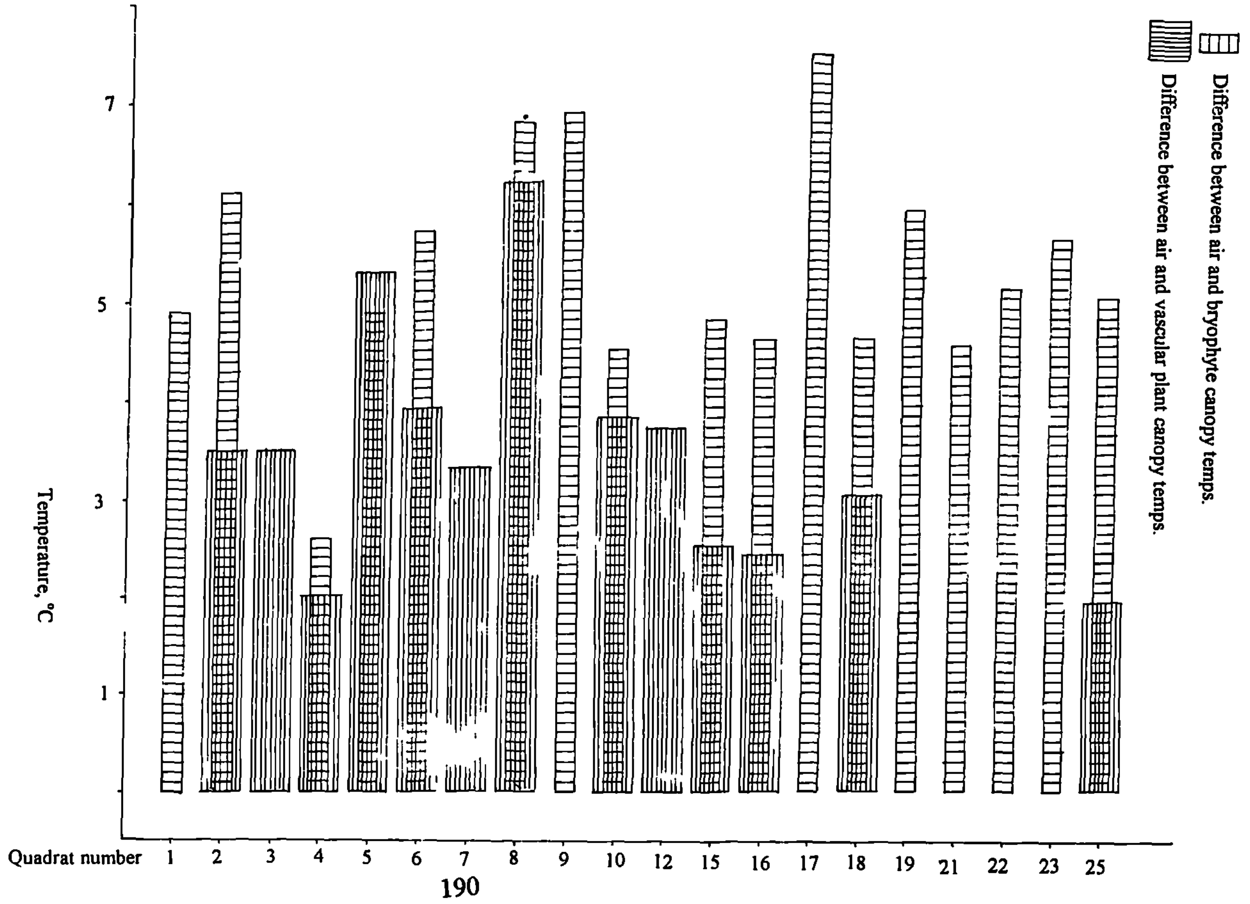


FIGURE 6.6b

DIFFERENCE BETWEEN AIR TEMPERATURE AND CANOPY TEMPERATURE.



23 and 25) show a significant drop in all temperatures, related to exposure to the south-westerly wind. Thus high wind speeds will adversely affect the ability of the plants to maintain a high ambient temperature, this being particularly true for the summit area where the cover may be more broken, and emphasises the importance of exposure in determining which species can survive. The ability of the vegetation to trap energy and retain a higher ambient temperature than the overlying air is apparent in all the figures, with the bryophyte canopy, being closed and much closer to the ground (and therefore sheltered from the wind), experiencing the greatest temperature enhancement. Breaks in the vegetation cover made by wind erosion, the action of herbivores or erosion generated by humans are therefore important in the effect that this break will have on the temperature of the vegetation immediately surrounding it. A reduction in the performance of vegetation surrounding a break in the canopy could contribute to the extension of that break.

The ability of the vegetation to trap heat in this way must positively affect its performance by ameliorating the adverse effects of the severe climate and providing a growth environment which is less hostile within the vegetation canopy, thereby giving some protection to young shoots from damaging frosts and wind chill. It also demonstrates that the use of air temperature, and particularly air temperature measured at screen or station level as a measure of growth capacity does not reflect the real situation experienced by the plants themselves. In the two cases where comparison with the Aonach Mor AWS data is possible, it can be seen that the air temperature over the site, measured just above the vegetation canopy, is greater by several degrees than that recorded at the AWS. Inaccurate measurement by the instrument used could explain this difference, though the amount of error makes this unlikely. Therefore it is probable that for daytime temperature in the summer months the warmth experienced by plants at the site is, on average, a little higher than that recorded by the AWS, greater on sunnier days than cloudy ones, and adversely affected by high winds. The greater impact of high wind on temperature in the summit quadrats, as opposed to quadrats located downslope from the plateau, further enhances the steepness of the environmental gradient between these locations.

The vegetation and substrate environment do show positive responses to radiation inputs through the summer months and experience generally higher temperatures than that of the overlying air, particularly in windy conditions. The heat store in the substrate is apparent and is likely to contribute positively to the prolongation of the growing season, at least for the bryophytes.

6.1.3 Vegetation.

The combination of vascular plants and bryophytes with different growth patterns found in almost all quadrats, plus the generally non-wintergreen strategy of vascular plants, produced a different record for each quadrat visit. The data for all visits was combined to give an overall, time-independent picture of quadrat constituents. The summary of quadrat data is given in Table 6.2 using Domin values for each species; absences are left blank for ease of viewing. Values for bare ground and percentage cover of herbs and mosses are given at the bottom of the table. It is important to note that all the individuals of *Deschampsia cespitosa* seen in the back corrie, and certainly all the specimens located within the quadrats, showed no signs of being ssp. *alpina,* with no viviparous reproduction observed. Additionally, the species of *Pohlia* expected by the National Vegetation Classification would appear to be *P. wahlenbergii*

TABLE 6.2

TABLE OF QUADRAT VEGETATION DATA, GIVING DOMIN VALUES FOR EACH SPECIES PRESENT

Species	Quadrat																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Deschampsia cespitosa	5	7	6	8	5	5	9	8		3		10			1		3		1			3	4		
Festuca vivpara				1											3	4	3	4	2	1			2		4
Carex bigelowii															5	6		4							2
Luzula spicata															3	3		2		2					1
Galium saxatile							3																		
Gnaphalium supinum																	3								
Salix herbacea															2										
Saxifraga stellaris	1	2	2		1	1							1				1		1		2		3	1	1
Huperzia selago															3										
Andraea nivalis																		5						3	
Anthelia sp.		3			4				1				2												
Dicranum fuscescens								1										4	4					2	5
Kiaeria starkei	3		6	5	4	3		3	3	5			4	4			5		4			8	8	3	5
Pohlia ludwigii	8	3	6	1	3	8		3	5	4	10		6	7							9	4	4	8	
Polytrichum alpinum		1	3	2			2	3		2					2	2			4		2				
Polytrichum sexangulare	5	4		5	4	3			3	5			3	4		1	5		4		3	4	5	3	3
Racomitrium fasciculare															6	6	5	4	3	6					4
Racomitrium heterostichum			1																						
Racomitrium lanuginosum																7		3							
Rhytidiadelphus squarrosus			1	1			4					4													
Sphagnum sp.		7					1																		
Marsupella sp.		1	1	2									2								3			3	
Moerkia blyttii				2																					
Scapania sp.	2			1				1		1												1			
Bare ground	4	4			5			3	9	6	4		8	7	4		6	8	9	7	5	6	4	6	5
Percentage herb cover	20	50	30	65	20	20	95	70	0	3	0	95	0	0	25	30	5	5	2	2	1	2	5	1	5
Percentage moss cover	95	95	85	40	80	85	20	60	15	70	85	10	30	65	80	100	70	25	30	50	85	70	95	70	80

var. *glaciale* not *P. ludwigii*, as already mentioned. Although not all areas could be sampled, a sample deemed representative by appearance of all the *Pohlia* found in each quadrat was removed and examined under a microscope. A small portable microscope was also used to check for similarities between different patches. On no occasion was *P. wahlenbergii* var. *glaciale* found and all samples examined were interpreted as being *P. ludwigii*. Great care was taken to ensure correct identification of all the major, diagnostic species.

The following general observations of the performance of species were made. The vascular plants generally displayed rapid growth as soon as snow cover was removed and temperatures rose. No observations were made which suggested that any species, but particularly *Deschampsia cespitosa*, were able to develop new shoots beneath a covering of snow, unlike the observations made by Billings and Bliss (1959) and Kimball, Bennett and Salisbury (1973). The reason for this is not clear, though it should be noted that the observations of shoot growth beneath snow cover would appear, from the literature, to be exceptional, rather than the norm.

Vascular plants also flowered rapidly, with *Carex bigelowii* producing inflorescences by mid-June and *Deschampsia cespitosa* by late June. The period of ripening took at least 60 days, with few quadrats able to produce ripe seed in any species by the time the plants died back at the end of August. Although seed was observed in *Carex bigelowii* and *Luzula spicata*, it was observed to be still attached and not shed in 1993, whereas quadrats 15 and 16 both produced mature seed in 1992. *Festuca vivipara* showed the ability to produce mature viviparous plants on inflorescences in quadrats 15 (successful in both years), 16 (partially successful in 1992, not in 1993), 18 (successful in 1992, not in 1993), 20 (no record for 1992, not shed in 1993) and 25 (loss of peg in this case makes it impossible to ascertain success in 1992, successful in 1993). Quadrats 17 and 19 both contained individuals of *F. vivipara* but no inflorescences were produced.

These results show a gradation in performance of sexual reproduction in all grasses, rushes and sedges with increasing failure as snow-lie increases. All of the species mentioned above demonstrated rapid and vigorous growth typical of arctic-alpine graminoids (Chapin 1983), however, die-back observed in all species of vascular plants except *Saxifraga stellaris* indicates that these particular ones are still relatively sensitive to temperature, unlike the conclusions drawn by Chapin (1983), or that they pursue strategies of programmed tissue death, which may differ from their normally observed strategy, as in *Deschampsia cespitosa.*

The bryophytes demonstrated a very different regime, as described by Rincon and Grime (1989). Little growth of new shoots or vigour returning to existing ones took place until they had been exposed for several days. There was no evidence of growth beneath snow cover. Once growth was initiated, all species showed vigour right through to the end of each recording season, except for *Pohlia ludwigii*, which became very brown and eventually desiccated with complete removal of the snowbed and consequent loss of an adequate moisture supply. Vigour in all bryophytes did, however, seem to suffer no damage when early snow and ice covered some of the quadrats in August 1992. There was also evidence that some species, such as *Kiaeria starkei* and *Racomitrium fasciculare*, may be able to carry capsules through a winter season, to be released on exposure the following year.

Capsules in all species and in each year showed abundant growth right through to mid- to late-October and demonstrated, along with vigorous shoot growth in all species where irrigation was sufficient, an ability to utilise periods of the year when vascular plants no longer sustain live tissue above the surface. Capsules were most common in *Kiaeria starkei* and *P. ludwigii*, with many quadrats producing fruits in both seasons. *Racomitrium fasciculare* also showed an ability to fruit, but *Polytrichum sexangulare* and *P. alpinum* were much less successful at fruiting.

The performance of *Deschampsia cespitosa* and bryophytes is shown in Tables 6.3 and 6.4. The performance of different species gives an indication of how close to the margins of their tolerance the environment in which they are located is. The performance of *Deschampsia* is particularly important since it is hypothesised that it is excluded from the snowbed core by its inability to tolerate the reduction in growing season generated by the snowbed. By observing the performance of the bryophytes it is also possible to indicate how optimal conditions are for them, and whether they inhabit the snowbed community because they are particularly suited to its environmental niche, or because they are forced to by competition with *Deschampsia* at the snowbed margins.

Contour plots of all the data from *Deschampsia cespitosa, Pohlia ludwigii* and *Kiaeria starkei* are shown in Figures 6.7 to 6.14, with general snowlie shown in Figure 6.2 , and snow-lie for 1993 in Figure 6.15. The impact of grazing on *Deschampsia cespitosa* shoots can be observed as shoot length declines through the season. However, no attempt was made to alter the length actually recorded since all quadrats demonstrated some level of grazing, with the proportion of shoots affected approximately the same throughout the site. Therefore it was assumed that the impact of grazing was the same in all areas of the site.

TABLE 6.3

TABLE SHOWING *Deschampsia* DATA

Date						1992	1993								
quad	2.7	31.7	10.8	5.9	16.9	10.10	9.6	24.6	10.7	20.7	3.8	14.8	27.10		
7	9.9	9.3	11.1	9.8	10.0		■	6.6	nr	11.7	13.4	12.8		A	SHOOT LENGTH
12	10.8	12.5	13.0	13.0	12.6		■	9.8	10.1	13.4	13.5	12.8			
2	10.2	7.9	6.4	8.1	8.4	8.3	■	-	-	7.9	10.0	8.9		B	
1	8.0	10.8	8.6	8.2	8.3		■	-	6.1	6.2	6.5	nr			
3	9.4	11.0	9.8	8.5	9.0	8.6	■	-	-	7.8	8.7	8.5			
5	3.4	5.1	6.2	5.2	5.4		■	1.4	3.8	4.1	4.0	4.1			
6	11.0	8.7	9.0	7.4	7.2		■	4.9	9.1	12.6	9.7	10.8			
8	8.5	8.8	9.1	5.8			■	4.0	6.1	9.8	nr	9.9			
10	5.2	nr	nr	nr	nr		■	2.0	3.8	4.1	4.3	4.1			
22	3.4	3.6	2.0	3.5	2.4		■	-	-	3.0	3.2	3.3			
4	10.2	9.8	7.4	7.6	8.0		■	3.8	5.1	7.0	8.4	8.1		C	
17	4.2	4.4	4.2	4.8	4.8		2.7	3.2	3.4	4.8	5.2	5.2	■		
19	-	2.5^2	2.7^4	2.8^4	▨	-	-	-	3.0^1	3.0^1	-	-	■		
23	2.3	2.5	2.4	2.6	■		■			3.1	3.8	3.2	■		
15	-	-	-	-	-	-	-	-	-	5.2	5.1			D	
7	-	16.4	17.8	17.0	16.7	ss	■	10.4	nr	11.9	16.9	17.1	s	A	INFLORESCENCE LENGTH AND STATE
12	8.9	17.4	18.2	18.0	18.3	ss	■	-	-	18.9	12.6	22.9	ss		
2	-	-	4.8	10.0	9.6	9.7^u	■	-	-	-	-	4.6	8.4^u	B	
1	-	-	-	4.9^2	-	-	■	-	-	-	-	-	-		
3	-	-	>20	>20	>20	u	■	-	-	-	-	6.4^c	-		
5	-	-	15.0	c	c	c	■	-	-	-	-	-	-		
6	-	11.1					■	-	-	-	15.0	15.2	u		
8	-						■	-	-	10.4	nr	11.0	u		
10	-						■	-	-		5.0^2	4.8^1	c		
22	-	-	-	5.3^2	-	-	■	-	-	-	-	-	-		
4	-	15.1	15.4	15.2	14.8	u	■	-	-	-	-	6.2	7.2^u	C	
17	-	-	-	7.0^1	7.1^1	u	-	-	-	-	-	-	■		
19	-	-	-	-	▨	-	-	-	-	-	-	-	■		
23	-	-	-	-	■	-	■	-	-	-	-	-	■		
15	-	-	-	-	-	-	-	-	-	-	-	-	-	D	
7				50	50	80	■				10	50	80	A	PERCENTAGE OF SHOOTS DEAD (%)
12			20	45	50	80	■				20	20	80		
2		20	50	60	75	95	■			50		20	100	B	
1				40	50	50	■						100		
3				50	60	80	■					15	100		
5				20	50	60	■	80				20	100		
6				25	35	50	■	20				20	50		
8				50	75	100	■	40				20	80		
10				nr	nr	60	■	65					80		
22					25	80	■						80		
4	20	20	20	50	50	85	■	50	50	20	20	40	80	C	
17				20	50	60		75			35	35	■		
19					▨								■		
23				30	■	50	■				10	25	■		
15											50	90	90	D	

LEGEND

Shoots - all measurements in centimetres. Shoot lengths averaged for 10 readings. Superscript numbers indicate fewer than 10 readings available in quadrat.

Inflorescences - all meaasurements in centimetres. Length averaged for 5 readings. Superscript numbers indicate fewer than 5 readings available in quadrat. Superscript or normal font letters indicate state of seeds: C = panicle closed U = unripe SS = some seed shed S = all seed shed

nr = no record

A = U13 B = *Deschampsia* - rich *Pohlia* snowbed

C = *Kiaeria - Polytrichum sexangulare* snowbed

D = transitional area

■ Quadrat covered

▨ Quadrat partially covered

TABLE 6.4

TABLE SHOWING THE PRESENCE OF BRYOPHYTE CAPSULES IN QUADRATS.

			Date															
			1992						1993									
		QUAD.	2.7	31.7	10.8	5.9	16.9	10.10	27.4	10.5	26.5	9.6	24.6	10.7	20.7	8.8	14.8	27.10
Deschampsia-rich *Pohlia* snowbed	*Ks*	1							■	■	■	■	■	▨		a4	nr	b3
		3		c1	c1	c1			■	■	■	■	■	nr	a2	b1	b1	c1
		5	b2	c1	c1+a1	c1+a2	c1+a2		■	■	■	■	b3	b3	b3	b3	b2	c2
		8							■	■	■	■	b2	b2	b2+a3	nr	b4	b+c4
		10		nr	nr	nr	nr		■	■	■	■	a4	a3	b3	c2		
		22							■	■	■	■	■		a2	b2	b2	c1
	Pl	6	a2	a3	a4	b4	a+b4	c4	■	■	■	■				a1		
		10		nr	nr	nr	nr		■	■	■	■			a1	a1	a4	c4
		22		a2					■	■	■	■	■					
	Ps	5							■	■	■	■			a2	a1	a1	b2
		22		a1					■	■	■	■	■				a1	b1
Pohlia snowbed	*Ks*	13	▨	a3	a3	b4	b+c4	c4	■	■	■	■	■	■	■	■	a4	b4
		14		nr			nr		■	■	■	■	■	■	■		a1	a2
		24							■	■	■	■	■	■	■	a4	a3	b3
	Pl	9		a2	a2	a2	b2	c1	■	■	■	■	■		a4	a4	a4	b+c4
		24		a1	a1	b1	b1		■	■	■	■	■	■	■	a1	a2	c2
		21			a2	a2			■	■	■	■	■		a4	a3	b3	b3
Kiaeria-*Polytrichum sexangulare* snowbed	*Ks*	17	c1	c1	c1+a2	b1		a1	■	■	■	a4	b4	b4	b4	c4		
		19	a2	b2	b2+a2	b3	▨	a3	■	■	■	b3	b3	b3	b3	c2		■
		23	b2	c1			■	a4	■	■	■	■	■	b4	b4	b+c4	c2	■
	Pl	23		a1	b3	b3	■	c2	■	■	■	■	■					■
	Ps	17							■	■	■		a2					
		19							■	■	■						a1	■
	Pa	15											a4	b4	b+c4	c2		
Transitional area	*Rf*	18			a4	nr	nr	a4	a3	b3	c2	c1		a1	a1	b1		
		25				nr	nr	a1	a4	nr								
		15				a4	a4	a4	b4	b4	c4	c3						
		16	nr	nr		a4	nr	b4	c4							b1		
		20	nr	nr	nr	nr	nr	a4	c3		c2	c2	c2	a4	a2	b2	b2	b1

LEGEND

■ Quadrat covered
▨ Quadrat partially covered

a = young, immature capsules	b = mature, closed capsules	c = open (unlidded) capsules
1 = few (<20)	2 = 20-50 3 = 50-100	4 = many (>100)

Kiaeria starkei	*Ks*	*Polytrichum sexangulare*	*Ps*			
Pohlia ludwigii	*Pl*	*Polytrichum alpinum*	*Pa*	*Racomitrium fasciculare*	*Rf*	nr = no record

FIGURE 6.7

Contour Plot of Deschampsia shoot lengths 1992.

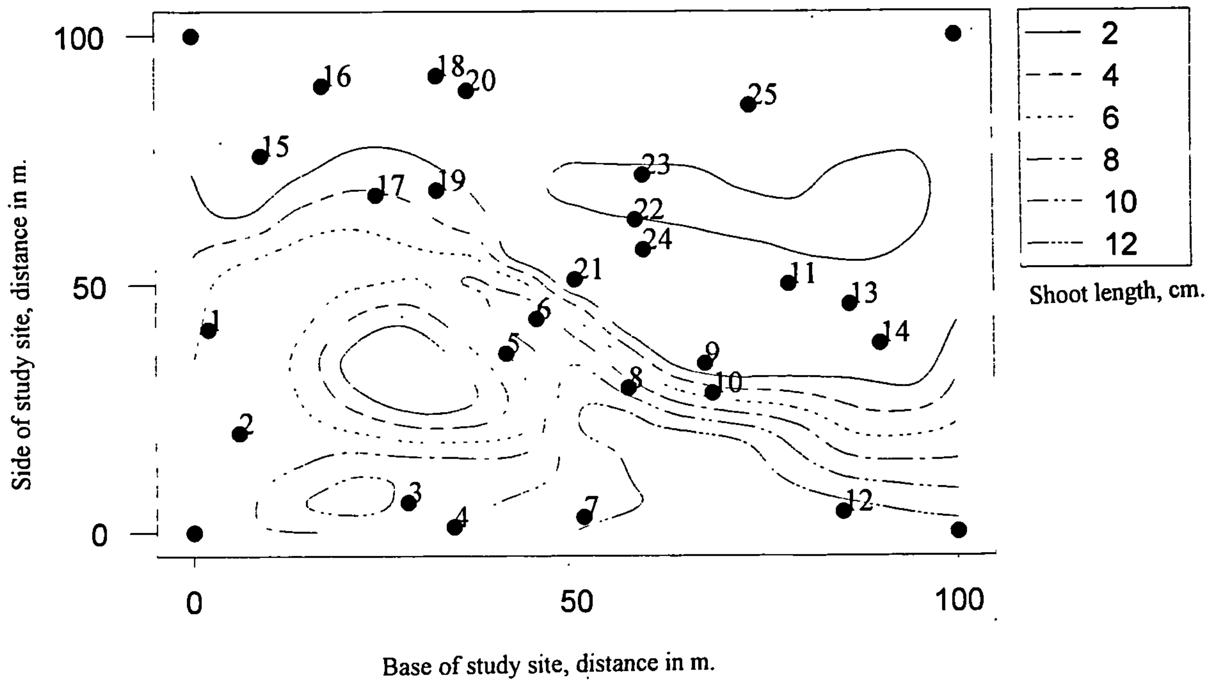


FIGURE 6.8

Contour Plot of Deschampsia shoot lengths 1993.

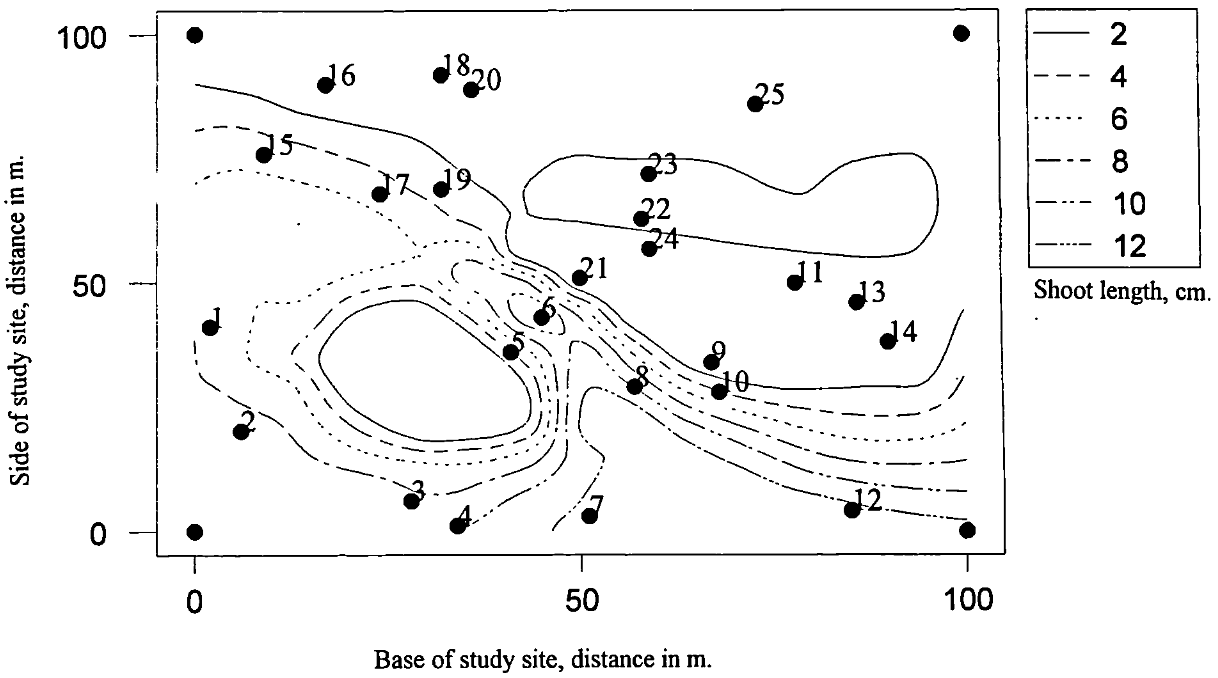


FIGURE 6.9

Contour Plot of Deschampsia inflorescences 1992.

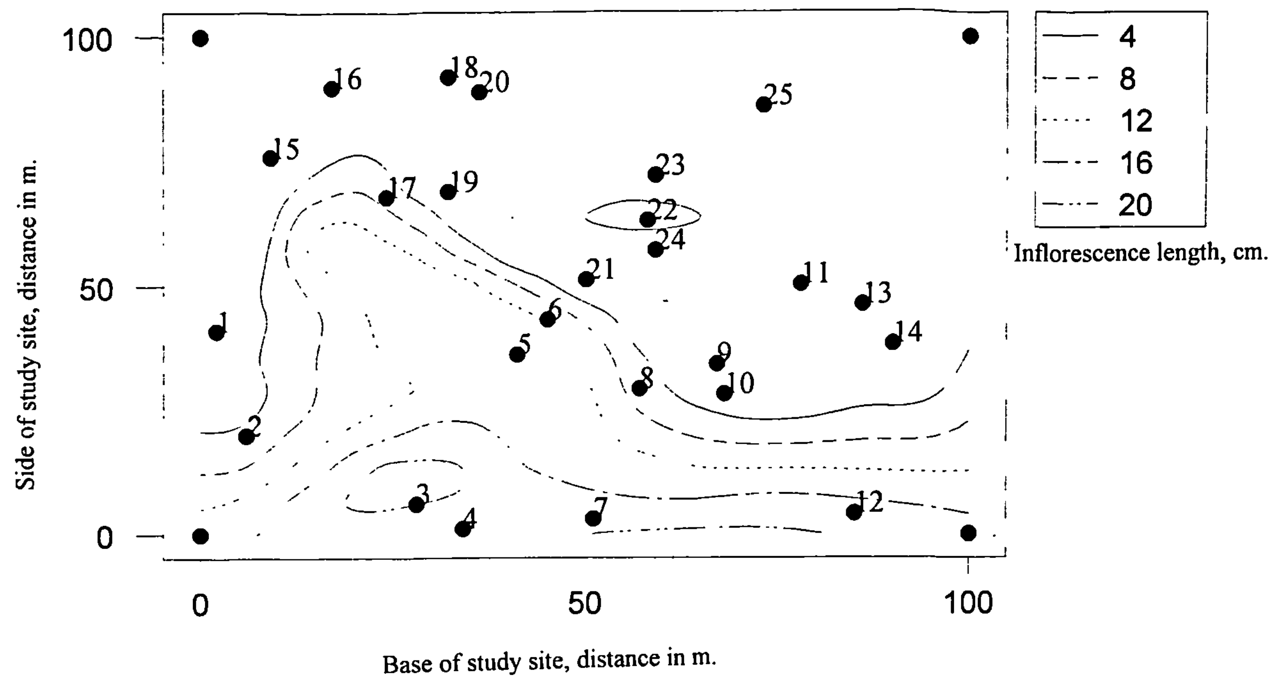


FIGURE 6.10

Contour Plot of Deschampsia inflorescence lengths 1993.

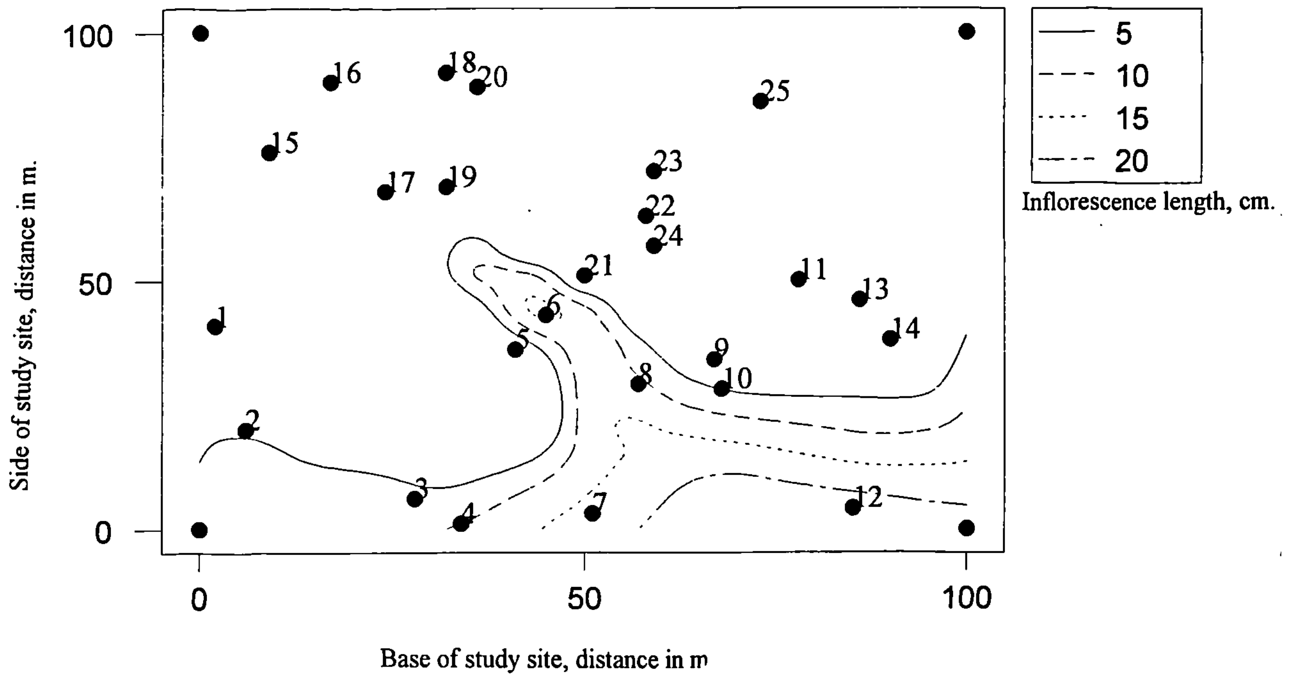


FIGURE 6.11

Contour Plot of Deschampsia seed success 1992.

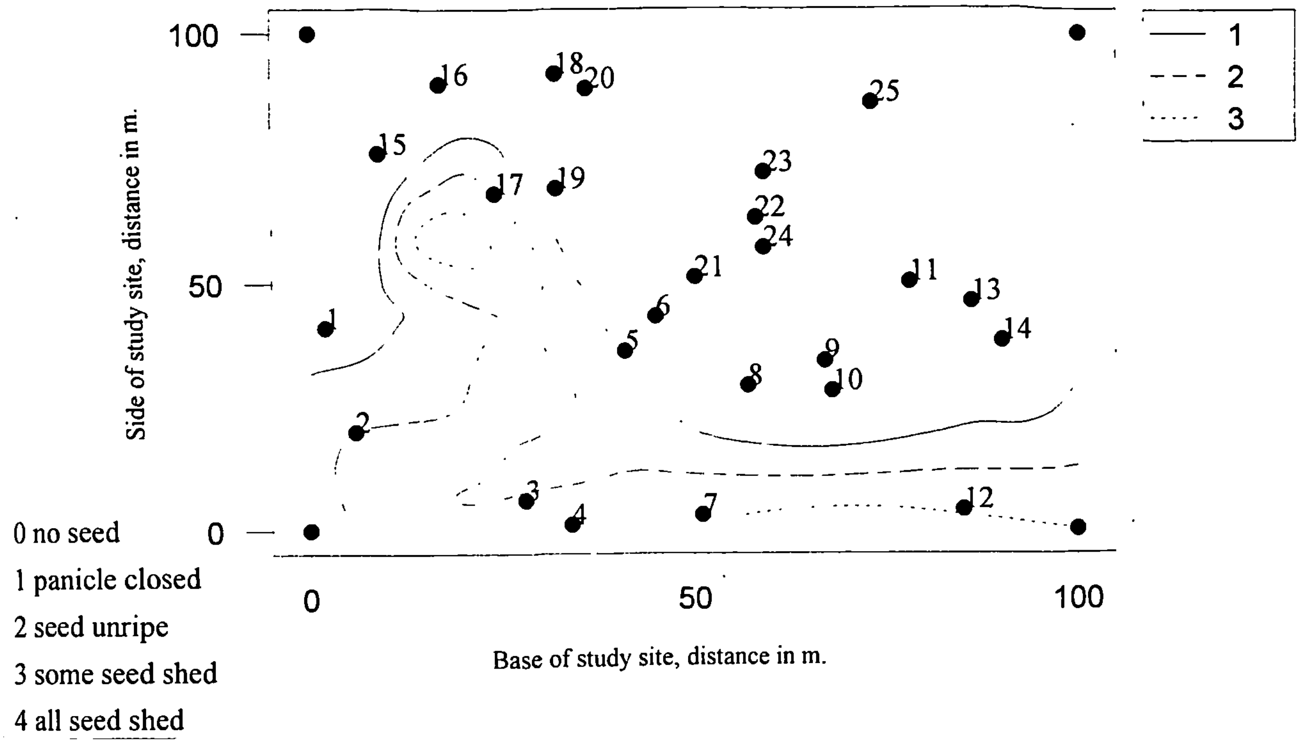


FIGURE 6.12

Contour Plot of Deschampsia seed success 1993.

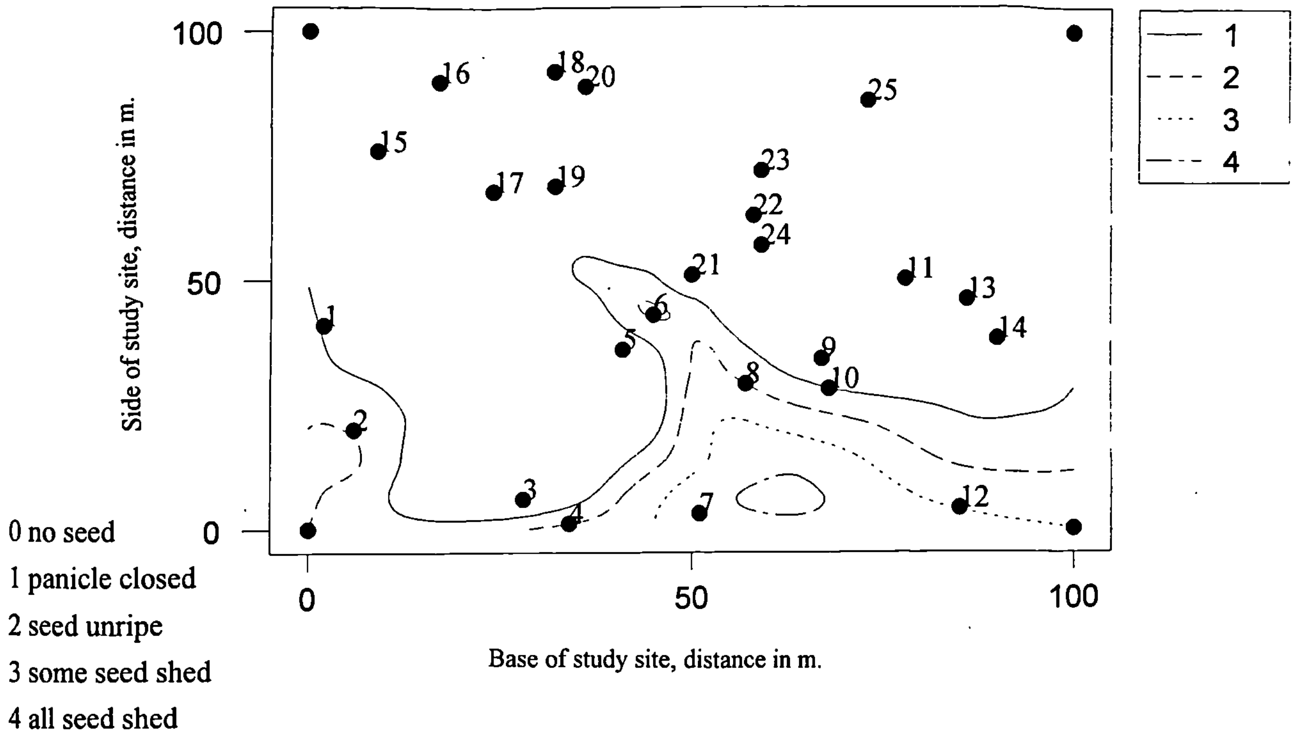
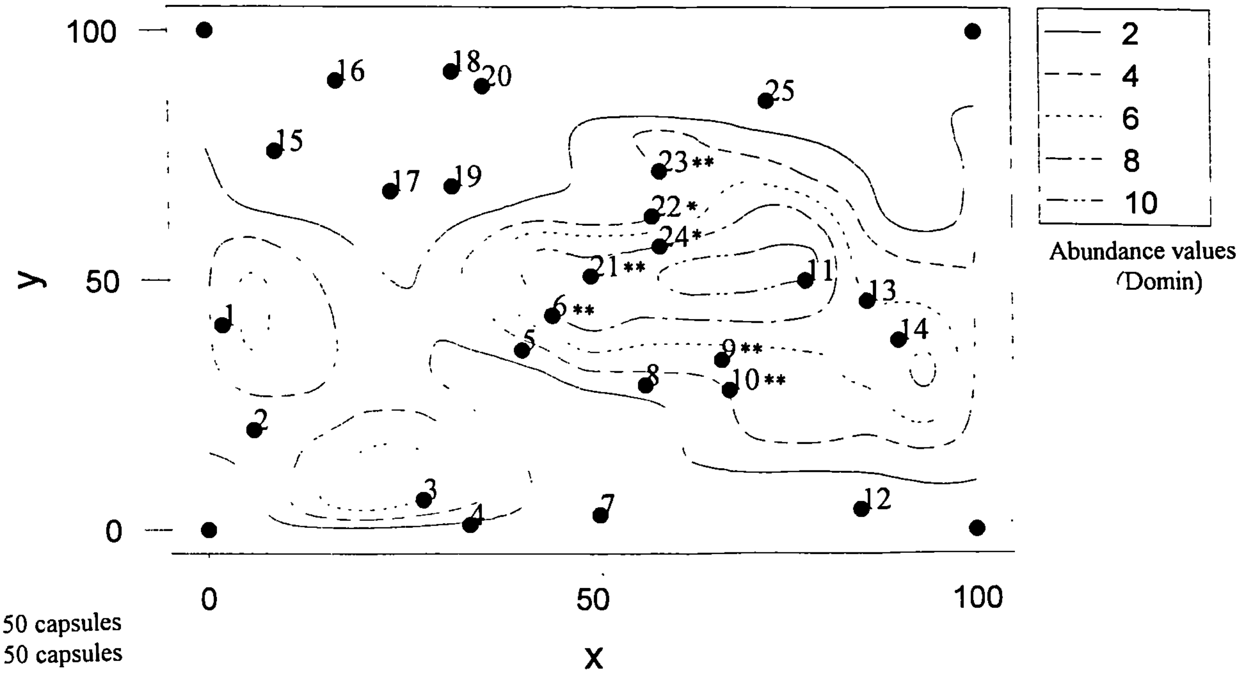


FIGURE 6.13

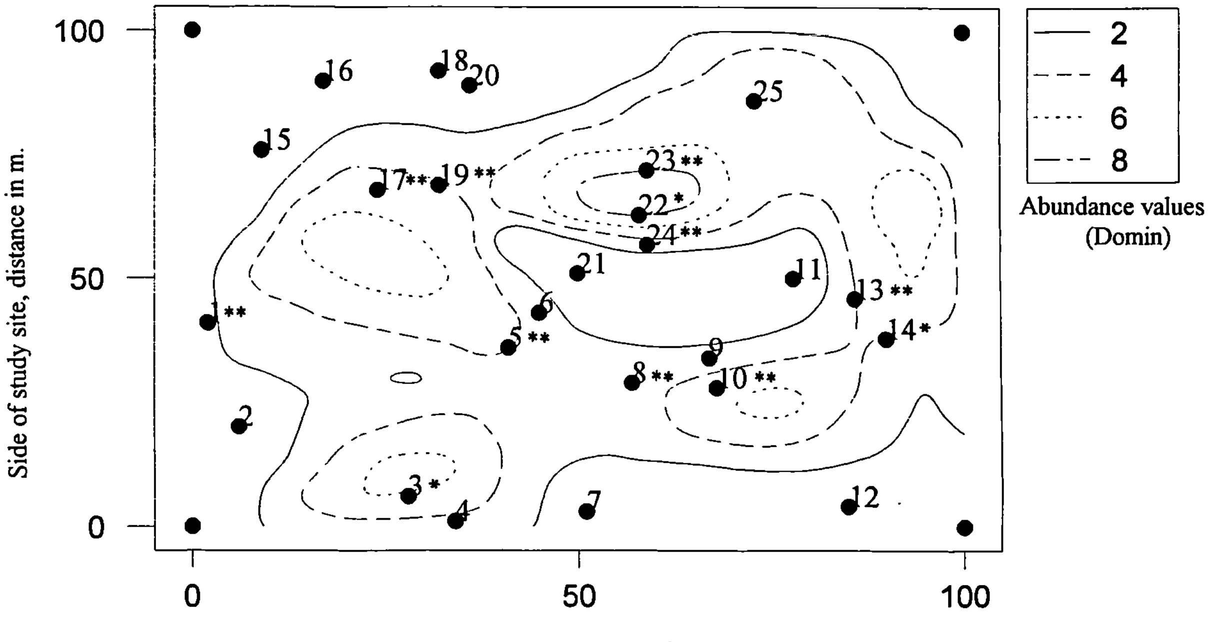
Contour plot of *Pohlia ludwigii* abundance values and capsule success.



* < 50 capsules
** > 50 capsules

FIGURE 6.14

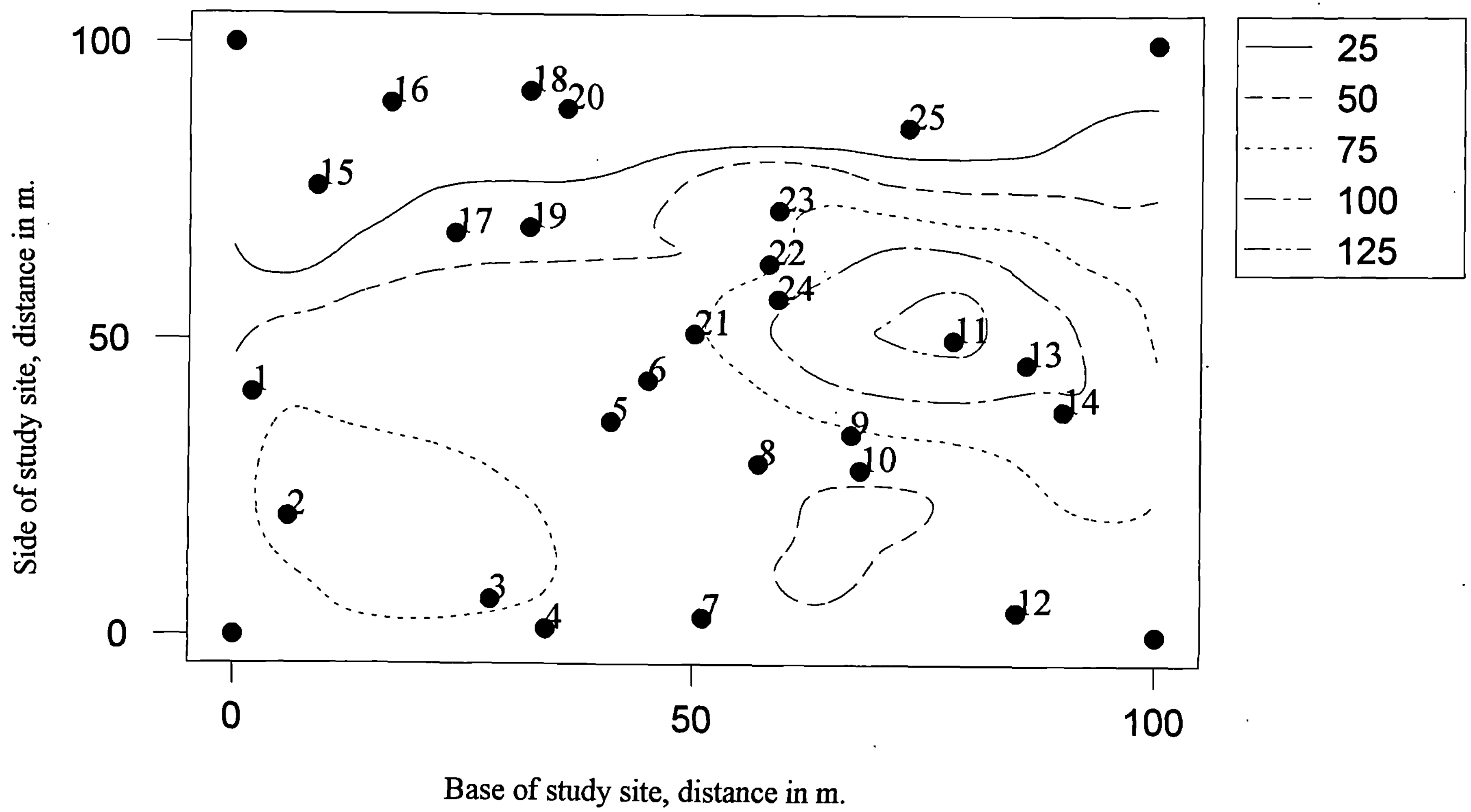
Contour plot of *Kiaeria starkei* abundance values and capsule success.



* < 50 capsules
** > 50 capsules

FIGURE 6.15

Contour Plot of snowlie duration in number of days beyond May 1st in 1993.



The *Deschampsia* contour plots show that shoot length is closely inversely related to the snowlie plot below the plateau edge. The area around quadrats 5, 6 and 8, where a gap develops, splitting the snowbed in two early in the summer, coincides with an extension of the higher shoot values otherwise confined to the lowest part of the site. The pattern is repeated in both years. The pattern of *Deschampsia* inflorescence shoot lengths in 1993 is very similar to the snowlie and shoot length patterns, showing that shoot lengths of 6cm or less do not coincide with inflorescence shoots of 5cm or more. However, the 1992 inflorescence and seed pattern is rather different and requires further examination.

The feature which distinguishes 1993 from 1992 is the extent of snowlie with 1992 becoming snow-free generally earlier than 1993. The split in the snowbed does, however, occupy the same position, as can be seen from Figure 6.15 which shows a plot of the number of days elapsing after May 1st before the area was observed to become free of snow. The snowlie contour plot for both years contains data from the whole of 1993 from April onwards, but in 1992 observations did not commence until the beginning of July. The snowlie observations made from the photographic material suggest that the left hand section of the snowbed in the vicinity of quadrats 2, 3 and 5 may have melted slightly earlier in relation to the right hand portion than in 1993, but remained longer over these quadrats than over quadrats 4, 7 and 12. The longer inflorescences in quadrats 2, 3 and 5 are also coincident with shorter shoot lengths, with records indicating that grazing was not particularly heavy in these quadrats and therefore not an explanatory factor. None of these three quadrats have very dense stands of *Deschampsia cespitosa* and are not typical of the other more productive quadrats, numbers 4, 7 and 12. Wetness levels are, however, lower in 2, 3 and 5 in

1992 than 1993, as would be expected with earlier melting and it is suggested that the earlier removal of snow cover than is probably normally experienced by these quadrats allowed growth to take place, with a larger proportion of resources being invested in inflorescences than is normal for other individuals in the area. Good irrigation and an absence of water-logging would have promoted better growth and the plant response may therefore represent an optimal response to an abnormally resource-rich year. It is also possible that the results given are not significant or are the result of the low resolution of data within the 100x100m site.

To ascertain how important this difference was, a correlation matrix was devised for the variables involved, which is shown in Table 6.5. Quadrats number 15, 16, 18, 20 and 25 were initially included in this analysis, but the very different regime experienced by these quadrats, the apparent importance of factors other than snow-lie duration, such as exposure to wind, and the different species occupying the plateau quadrats obscured the pattern relating snow-lie and its associated factors to vegetation composition and performance. Therefore these quadrats were removed from the analysis relating to the snowbed variables.

Correlation coefficients between all the *Deschampsia* variables are significant at the 99.5% or 99.9% level, while the correlation coefficients between the snow number (data from both years used to create the snow contour plot) and *Deschampsia* variable are all significant at the 90 to 98% level but not at the statistically significant 99% or 99.9% levels. Further analysis using least squares linear regression between the two data sets gave results given in Table 6.6. Data including the top quadrats is included for comparative purposes, indicating how important it is to remove these from the analysis. The absence of *Deschampsia cespitosa* from the plateau quadrats upsets the

TABLE 6.5
CORRELATION MATRIX AND SIGNIFICANCE LEVELS FOR *Deschampsia cespitosa* DATA

SIGNIFICANCE LEVELS: 95% * 99% ** 99.9% ***.
QUADRATS 15, 16, 18, 20 AND 25 EXCLUDED.

	snow no	Des shoots 92	Des inflor 92	Des seed 92	Des shoots 93	Des inflor 93	Des seed 93
Des shoots 92	**-0.559***						
Des inflor 92	**-0.505***	**0.833*****					
Des seed 92	**-0.469***	**0.672****	**0.811*****				
Des shoots 93	**-0.556***	**0.963*****	**0.801*****	**0.699*****			
Des inflor 93	-0.425	**0.816*****	**0.727*****	**0.602****	**0.860*****		
Des seed 93	-0.415	**0.738*****	**0.634****	**0.646****	**0.836*****	**0.895*****	
slope	0.425	**-0.567****	**-0.600****	**-0.492***	**-0.568****	**-0.529***	**-0.478***

TABLE 6.6

RESULTS OF LEAST SQUARES LINEAR REGRESSION FOR *Deschampsia* AND ENVIRONMENTAL VARIABLES

Response	Predicator	Ratio of sample variances (F)	value of p <
Deschampsia inflor. 92	*Deschampsia* shoots 92	88.26	**0.001*****
Deschampsia seed 92	*Deschampsia* shoots 92	38.51	**0.001*****
Deschampsia shoots 93	*Deschampsia* shoots 92	284.09	**0.001*****
Deschampsia shoots 92	snow number[1]	0.32	0.579
Deschampsia shoots 93	snow 93[1]	0.48	0.495
Deschampsia shoots 92	snow number	8.18	**0.010****
Deschampsia inflor. 92	snow number	5.47	**0.033***
Deschampsia seed 92	snow number	5.07	**0.037***
Deschampsia shoots 93	snow number	8.05	**0.011***
Deschampsia inflor. 93	snow number	3.97	0.062
Deschampsia shoots 93	snow 93	6.86	**0.017***
Deschampsia shoots 92	slope	8.55	**0.009****
Deschampsia inflor. 92	slope	9.00	**0.008****
Deschampsia seed 92	slope	5.73	**0.028***
Deschampsia shoots 93	slope	8.55	**0.009****
Deschampsia inflor. 93	slope	7.00	**0.016***
Deschampsia seed 93	slope	5.33	**0.033***

[1] denotes analysis undertaken with all 25 quadrats. Unless denoted, quadrats 15, 16, 18, 20 and 25 not included in analysis

TABLE 6.7

CORRELATION MATRIX (PEARSON'S) AND LEAST SQUARES LINEAR REGRESSION RESULTS FOR BRYOPHYTE AND ENVIRONMENTAL DATA FROM QUADRATS

PARTIAL CORRELATION MATRIX FOR BRYOPHYTE AND ENVIRONMENTAL VARIABLES:

	Pohlia shoots	*Kiaeria* shoots	*Pohlia* capsules	*Kiaeria* capsules
Kiaeria shoots	-0.115			
Pohlia capsules	0.343	0.197		
Kiaeria capsules	-0.077	**0.553***	-0.101	
snow	**0.762*****	-0.059	0.058	-0.091
wetness	**0.790*****	-0.255	0.292	-0.145
slope	**0.451***	-0.186	-0.015	-0.024

Additional correlation co-efficients:
wetness - snow **0.469***
slope - snow 0.425
slope - wetness 0.378

LEAST SQUARES LINEAR REGRESSION BETWEEN BRYOPHYTE AND ENVIRONMENTAL VARIABLES

Response	Predictor	ratio of sample variances (F)	value of p <
Pohlia shoots	snow-lie	24.99	**0.001*****
Pohlia shoots	wetness	29.94	**0.001*****
Pohlia shoots	slope	4.58	**0.046***
Kiaeria shoots	snow-lie	0.06	0.805
Kiaeria shoots	wetness	1.25	0.278
Kiaeria shoots	slope	0.64	0.433
Pohlia capsules	snow-lie	0.06	0.805
Pohlia capsules	wetness	1.68	0.212
Kiaeria capsules	snow-lie	0.15	0.704
Kiaeria capsules	wetness	0.39	0.543
wetness	snow-lie	3.26	0.088

trend for the performance and abundance of this species to decline with increasing snow-lie, since these quadrats have the least duration of snow-lie and the reason for the absence of *D. cespitosa* is very different. Their very different species composition and snow-lie regime, reflecting the acutely steep environmental gradient around the plateau edge, obscures the relationship being examined around the snowbed when included in the statistical analysis.

The results show that the positive relationship between shoots and inflorescences in both years is significant at a very high level and therefore the observed differences in pattern of location of the longer *Deschampsia* inflorescences in 1992 is not significant. The results also confirm the inverse relationship between duration of snowlie and the performance of *Deschampsia cespitosa* which supports the hypothesis that *D. cespitosa* is excluded from the snowbed because it cannot tolerate the prolonged period of snowlie and that as snowlie reduces downslope of the snowbed, so the performance of *D. cespitosa* improves. The occupation of the area where the snowbed splits in two around quadrats 6 and 8 also indicates that it is sensitive to a reduction in snowlie and might therefore be able to readily exploit any long-term changes in the average duration of the snowbed. This may have been the case for the observed difference in shoot and inflorescence lengths in 1992 although the difference is not statistically significant.

The strong inverse correlation between slope angle and *Deschampsia cespitosa* variables also suggests that this environmental variable either directly, or indirectly, is an important factor governing the distribution and performance of this species. The strong correlation between slope angle and snowlie, plus the absence of data on other environmental variables such as solifluction, makes it impossible to determine which are the causal factors, and which resultant. The presence of a strong rooting system will reduce solifluction, so rather than solifluction determining the presence or absence of *D. cespitosa*, it may be that the plant's presence or absence determines the level of solifluction. The relative importance of snow-lie and slope angle is difficult to ascertain without more detailed investigation. Other research, primarily observations made by McVean and Ratcliffe (1962), Rodwell (1992) and Rothero (1989) indicate that *D. cespitosa* is excluded from core snowbed vegetation, and secondarily Grime, Hodgson and Hunt (1988) state that *D. cespitosa* is not abundant on slopes of more than 40° but is not totally excluded from such sites either. It is more likely that snowlie is a more important factor in governing the distribution of *Deschampsia cespitosa* in this situation than slope angle, although the influence of slope angle cannot be ruled out and needs to be taken into consideration.

The bryophyte data collected were more qualitative than the *D. cespitosa* data and the only quantitative measures taken were the cover values for each quadrat, plus the type and number of capsules present for each species. The capsule data is summarised in Table 6.4. The cover values and capsule data were correlated and regressed in the same way as the *Deschampsia cespitosa* data and the results given in Table 6.7. Figures 6.13 and 6.14 show the performance of *Pohlia ludwigii* and *Kiaeria starkei* in both cover values and capsule density. The cover value of *Pohlia ludwigii* is clearly related to snowlie and wetness, with slope angle of secondary importance. *Kiaeria starkei*, on the other hand, is apparently unrelated to any of the factors examined, even the presence or absence of *P. ludwigii*, and even when the core snowbed quadrats of 11, 13 and 14 are removed from the data set, the results of both correlation and regression for *K. starkei* continue to give no significant association with other variables.

Pohlia ludwigii is, according to Hill, Preston and Smith (1994), particularly characteristic of late snowbed bryophyte-dominated vegetation but is also found along springs and streams on sandy and gritty soils, mainly at higher altitudes. Therefore it is not wholly confined to late snowbed vegetation but is most common there. However, it fruits very rarely, indicating that the population at the Aonach Mor site is located in near-optimal conditions. The absence of fruits from the snowbed core quadrats 11, 13 and 14, suggests that under the longest-lying snow conditions are less optimal than in slightly more peripheral areas where irrigation is more important and consistent. This is indicated by the presence of the species along bryophyte-dominated spring-lines not necessarily associated with late snowlie, although certainly within the montane zone (Watson, 1981; Hill, Preston and Smith, 1994).

Kiaeria starkei is another species characteristic of late snowbed vegetation (Rothero, 1989; Hill, Preston and Smith, 1992; Woolgrove and Woodin, 1994), but also occurs among boulders and scree and is typical of detrital soils, especially where slabs of rock are thinly covered with a layer of grit (Hill, Preston and Smith, 1992). The lack of correlation found in the Aonach Mor data, leads to the conclusion that it may be the solifluction associated with irrigation over steep slopes and skeletal soils which accounts for its presence, rather than any particular preference for the overlying late snow cover. Slope angle on the site is related very closely to snowlie and is also likely to be strongly positively correlated with solifluction, as the angle between gravitational pull and the surface is reduced. Downslope movement will be enhanced by levels of wetness, although the correlation between slope angle and wetness is not statistically significant, being only 90%. However, solifluction is a complex process and observations made of the quadrats and their surroundings suggest that *Kiaeria starkei* is associated with the downslope movement of gravel and bits of bryophyte mat. It is therefore concluded that some other factor may be important at this location for the distribution of *Kiaeria starkei* which has not been identified, but is likely to be related to movement of substrate and inundation with gravel and plant parts associated with the late snowbed environment.

According to the hypothesis presented, core snowbed species should exhibit optimum performance in the zone where vascular plant cover has been reduced to a low level, rather than in the centre of the snowbed. To a certain extent this appears to be true, but both *Kiaeria starkei* and *Pohlia ludwigii* show their best performance where vascular plant cover is almost completely absent, rather than where it merely reaches low values. On the other hand, neither species displays best performance in the snowbed core. It is also apparent from the data that both species, while apparently limited to the snowbed by the competition of a vascular plant cover, being completely absent from the *Deschampsia* grassland, are also affected by factors other than snow-lie, notably irrigation and slope stability. *Pohlia ludwigii* demonstrates the closest relationship with snow-lie, whereas *Kiaeria starkei* does not perform in a way that can be explained by late snow-lie duration. These results contradict those of Woolgrove and Woodin (1994) who propose that *Kiaeria starkei* is the most representative snowbed bryophyte, but follow the descriptions of Hill, Preston and Smith (1991, 1992).

Although the cover values for *Polytrichum sexangulare* were generally small, never exceeding 5, multiple linear regression analysis of all environmental variables as predictors of *Polytrichum sexangulare* was undertaken. Although a snowbed species, as described by Hill, Preston and Smith (1992), attaining maximum luxuriance of growth in snowbed core locations, snow-lie, wetness and slope angle were all unsuccessful predictors of its abundance. Significant at the 95% level, however, was bare ground, indicating that this species is less strongly associated with snow-lie than was originally thought, and is more associated with ground instability and erosion. Further work needs to be done with all the snowbed bryophytes to establish exactly the nature of the relationship between snow-lie duration, abundance and performance, since the results here conflict with some of those found by other researchers into snowbed species.

Qualitative data of the bryophytes included a note of how vigorous the shoots of each species were on each visit. Generally there was a delay between removal of snow cover and rehydration of the shoots, of up to 3 weeks, while *Polytrichum sexangulare* would sometimes take up to a month to produce an open rosette of leaves. None of the bryophytes displayed any tissue death, though some species such as *Scapania* spp. and *Marsupella* spp. showed desiccation when irrigation was reduced and *Pohlia ludwigii* became a dull reddish-green colour towards the end of the season, before shrivelling to a desiccated state. All displayed vigorous growth during the period of hydration.

Deschampsia cespitosa, however, showed a peculiar and, it is believed, unrecorded habit of die-back in its leaves. This species is normally wintergreen but at this location between 50 and 100% of all leaves would be brown and desiccated by September. Its location on Aonach Mor at 1150-1180m is high for this country; Grime, Hodgson and Hunt (1988) gives its altitudinal limits as 1130m. Freezing injury to tissues at the end of the season is also a possible explanation but would not agree with the observation of

PLATES 20 AND 21

PHOTOGRAPHS OF THE SITE ON 27.10.93, SHOWING SOME 50% DIE-BACK IN *Deschampsia cespitosa.*

gradual die-back from August onwards (see Table 6.3) as shown in Plates 20 and 21. taken on 27.10.93 and showing some live tissues and some die-back near the left-hand side of the site, around quadrat 2. Therefore the observed die-back may be an acclimation response to an environment to which it is not normally adapted, by removal of carbohydrate stores from above-ground tissues to below-ground tissues to prevent freezing injury late in the season.

Observations of tissue growth in *Deschampsia cespitosa* following the removal of snow cover show a gradual decrease in response time as snow cover increases in duration, so that individuals located nearer the snowbed core respond more quickly to the removal of snow than do the plants found in the dense *Deschampsia* grassland of quadrats 4, 7 and 12. Further evidence of early growth response of *D. cespitosa* was recorded in the pot experiment detailed later, where the growth of long, pale shoots was observed as soon as the area was free of snow, though growth then slowed and took longer to complete than the plants from the *Deschampsia* grassland. If energy stores are removed from above-ground tissues and stored in the roots and rhizomes instead, then new leaves must be grown at the beginning of the new season, which is an expensive strategy for a plant which is not normally physiologically adapted to this strategy. However, if the alternative is to lose the bulk of above-ground tissues to freezing injury, and with them the energy reserves stored in them, then an acclimation response of removal of energy stores from leaves to roots, causing die-back, is a reasonable strategy. This would follow the suggested strategy of a stressful environment where growth is uncoupled from resource intake (Grime, 1977; Grime, Hodgson and Hunt, 1988).

Deschampsia cespitosa is defined by Grime, Hodgson and Hunt (1988) as intermediate between C-S-R and stress-tolerant competitor; it has certain attributes which indicate an element of stress-tolerance, such as limited lateral vegetative spread and longevity (often more than 30 years), but with a normally wintergreen strategy, and long-lived leaves it also demonstrates competitive strategy. However, the foliar levels of N, P and Ca are not high (Grime, Hodgson and Hunt, 1988) which suggest that the transition from a wintergreen strategy to a deciduous strategy is not as costly as it might seem.

The die-back observed in *Deschampsia cespitosa*, which appears to be a deliberate strategy adopted by this species, is therefore interpreted as an indication of adaptation to a stressful environment and thus, along with the reduction in shoot length, inflorescence length and seed success, density and dominance, leads to the conclusion that the species is unable to penetrate further into the snowbed area owing to excessive stress and an inability to maintain sustainable levels of growth. Any change of the stress levels in space, such as a reduction in the average dimensions of the snowbed, would therefore ultimately lead to a spread of *D. cespitosa*. Although the species is a coloniser of artificial habitats according to Grime, Hodgson and Hunt (1988), it is proposed that the spread of *D. cespitosa* would not be rapid, given the apparent lack of seed production, the acknowledged restriction on vegetative reproduction and the longevity of individuals.

A lack of resolution of data for snowbed communities in the National Vegetation Classification (Rodwell, pers. comm.) and the small number of works undertaken so far in their study provided the opportunity to examine the community relationships between the different vegetation types observed. Although the sample of quadrats is small, nonetheless a contribution could be made by examining the classification and ordination results of these 25 samples. Initial analysis using Spearman's Rank correlation coefficients was undertaken to examine those species which displayed strong positive or negative associations in their distributions. The data was ranked owing to the large percentage of zero values and the non-normal distribution of all values. The results of the analysis, giving coefficients significant at 95% or above, is shown in Table 6.8.

Five obvious groupings of species emerge from this analysis, based on positive correlations with each other and negative correlations with species in other groups. The groups are:

1. *Festuca vivipara, Carex bigelowii, Luzula spicata, Salix herbacea, Huperzia selago, Racomitrium fasciculare, Racomitrium lanuginosum*, dry, low slope angle, no snow.

2. *Deschampsia cespitosa, Galium saxatile, Rhytidiadelphus squarrosus, Sphagnum* spp., not bare.

3. *Polytrichum sexangulare, Kiaeria starkei, Gnaphalium supinum, Scapania* spp., *Moerkia blyttii, Saxifraga stellaris*, (though these last three also have affinities with groups 2 and 4). High slope angles.

4. *Pohlia ludwigii, Marsupella* spp., snow.

5. *Dicranum fuscescens*, bare ground.

The first group of plants are largely found in the transitional and plateau quadrats, 15, 16, 18, 20 and 25, as indicated by the low slope angle, dryness and lack of snow. The second group is characteristic of the grassland quadrats 2, 4, 7, 8 and 12. The third

TABLE 6.8

TABLE OF SPEARMAN'S RANK CORRELATION COEFFICIENTS OF ABUNDANCE VALUES FOR VEGETATION DATA AND ENVIRONMENTAL DATA.

ALL COEFFICIENTS WITH SIGNIFICANCE OF 95% OR HIGHER ARE SHOWN

Deschampsia cespitosa	*Luzula spicata*	-0.439 *
Deschampsia cespitosa	*Sphagnum* spp.	0.399 *
Deschampsia cespitosa	*Dicranum fuscescens*	-0.445 *
Deschampsia cespitosa	*Rhytidiadelphus squarrosus*	0.625 ***
Deschampsia cespitosa	*Racomitrium fasciculare*	-0.409*
Deschampsia cespitosa	bare ground	-0.661 ***
Pohlia ludwigii	*Festuca vivipara*	-0.669 ***
Pohlia ludwigii	*Carex bigelowii*	-0.495 *
Pohlia ludwigii	*Luzula spicata*	-0.565 **
Pohlia ludwigii	*Marsupella* spp.	0.389 *
Pohlia ludwigii	*Racomitrium fasciculare*	-0.699 ***
Pohlia ludwigii	wetness	0.890 ***
Pohlia ludwigii	slope	0.636 ***
Pohlia ludwigii	snow	0.738 ***
Kiaeria starkei	*Luzula spicata*	-0.384 *
Kiaeria starkei	*Polytrichum sexangulare*	0.626 ***
Polytrichum sexangulare	*Luzula spicata*	-0.437 *
Polytrichum sexangulare	*Gnaphalium supinum*	0.422 *
Polytrichum sexangulare	*Scapania* spp.	0.391 *
Polytrichum sexangulare	slope	0.395 *
Festuca vivipara	*Carex bigelowii*	0.727 ***
Festuca vivipara	*Luzula spicata*	0.738 ***
Festuca vivipara	*Marsupella* spp.	-0.404 *
Festuca vivipara	*Racomitrium fasciculare*	0.860 ***
Festuca vivipara	*Racomitrium lanuginosum*	0.524 **
Festuca vivipara	wetness	-0.716 ***
Festuca vivipara	slope	-0.574 ***
Festuca vivipara	snow	-0.746 ***
Carex bigelowii	*Luzula spicata*	0.884 ***
Carex bigelowii	*Huperzia selago*	0.488 **
Carex bigelowii	*Salix herbacea*	0.488 **
Carex bigelowii	*Racomitrium fasciculare*	0.715 ***
Carex bigelowii	*Racomitrium lanuginosum*	0.706 ***
Carex bigelowii	wetness	-0.575 **
Carex bigelowii	slope	-0.612 ***
Carex bigelowii	snow	-0.599 ***
Luzula spicata	*Huperzia selago*	0.466 *
Luzula spicata	*Salix herbacea*	0.466 *
Luzula spicata	*Racomitrium fasciculare*	0.848 ***
Luzula spicata	*Racomitrium lanuginosum*	0.617 ***
Luzula spicata	wetness	-0.689 ***
Luzula spicata	slope	-0.689 ***
Luzula spicata	snow	-0.691 ***
Salix herbacea	*Racomitrium fasciculare*	0.394 *
Salix herbacea	*Huperzia selago*	1.000 ***
Galium saxatile	*Sphagnum* spp.	0.662 ***
Galium saxatile	*Rhytidiadelphus squarrosus*	0.510 **
Gnaphalium supinum	*Moerkia blyttii*	0.662 ***
Saxifraga stellaris	*Marsupella* spp.	0.454 *
Racomitrium fasciculare	*Huperzia selago*	0.394 *
Racomitrium fasciculare	*Racomitrium lanuginosum*	0.482 *
Racomitrium fascilculare	*Andraea* spp.	0.455 *
Racomitrium fasciculare	wetness	-0.772 ***
Racomitrium fasciculare	slope	-0.510 **
Racomitrium fasciculare	snow	-0.781 ***
Racomitrium lanuginosum	wetness	-0.429 *
Racomitrium lanuginosum	slope	-0.471 *
Racomitrium lanuginosum	snow	-0.433 *
Dicranum fuscescens	*Andraea* spp.	0.572 **
Dicranum fuscescens	bare	0.514 *
Rhytidiadelphus squarrosus	*Racomitrium heterostichum*	0.422 *
Rhytidiadelphus squarrosus	*Moerkia blyttii*	0.422 *
Rhytidiadelphus squarrosus	bare	-0.581 **
Scapania spp.	*Moerkia blyttii*	0.386 *
wet	slope	0.710 ***
wet	snow	0.751 ***
slope	snow	0.680 ***

group is one type of snowbed, distinct from the snowier group 4, and is characteristic of many of the quadrats, notably 5, 10, 17, 19 , 22 and 23. The *Pohlia ludwigii* quadrats overlap with those where *Kiaeria starkei* and *Polytrichum sexangulare* are dominant, such as 1, 3, 6, 9, 10, 13, 14 and 22, but the analysis suggests that there is some fundamental difference between the two types. The only quadrats which obviously fall into group 4 are 11 and 21. Group 5 represents the preference of *Dicranum fuscescens* for dry, stony ground and the occurrence of that species in quadrats 18, 19 and 25 with their high percentage of bare ground. The strength of the groupings suggest a degree of clustering in the data which encourages the use of more complex methods of analysis.

Cluster analysis of observations (MINITAB) was used on the data to obtain an hierarchical agglomerative measure of groupings within the data. The distance measure used was Euclidean and the linkage method single to produce the dendrogram shown in Figure 6.16. By changing the linkage from single, where the nearest-neighbour method of determining distance is used, to complex, where the furthest-neighbour method is used and is therefore in this sense the opposite of single linkage (Sneath and Sokal, 1973) the complementary dendrogram in Figure 6.17 is generated. Similarities between the two trees are obvious, particularly the separation of the plateau quadrats (15, 16, 18, 20 and 25) from the other and the consistency of similarity between most of the quadrats, such as 17 and 19, 7 and 12, but the position of some of the quadrats does differ, particularly quadrats from the snowbed areas, and the distinction of groupings changes, with the complex linkage method showing the most obvious distinction between 4, or 5 groups within the data.

FIGURE 6.16

CLUSTER ANALYSIS USING SINGLE LINKAGE AND EUCLIDEAN DISTANCE.

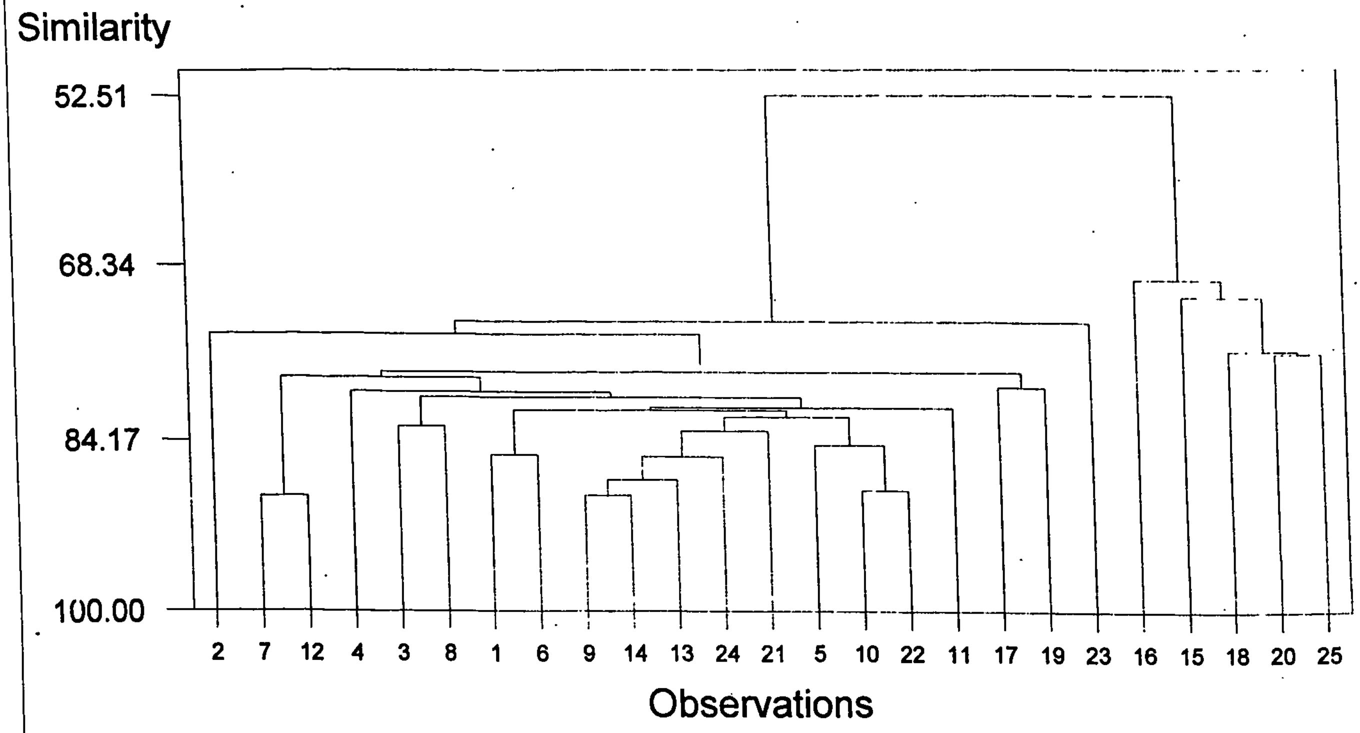
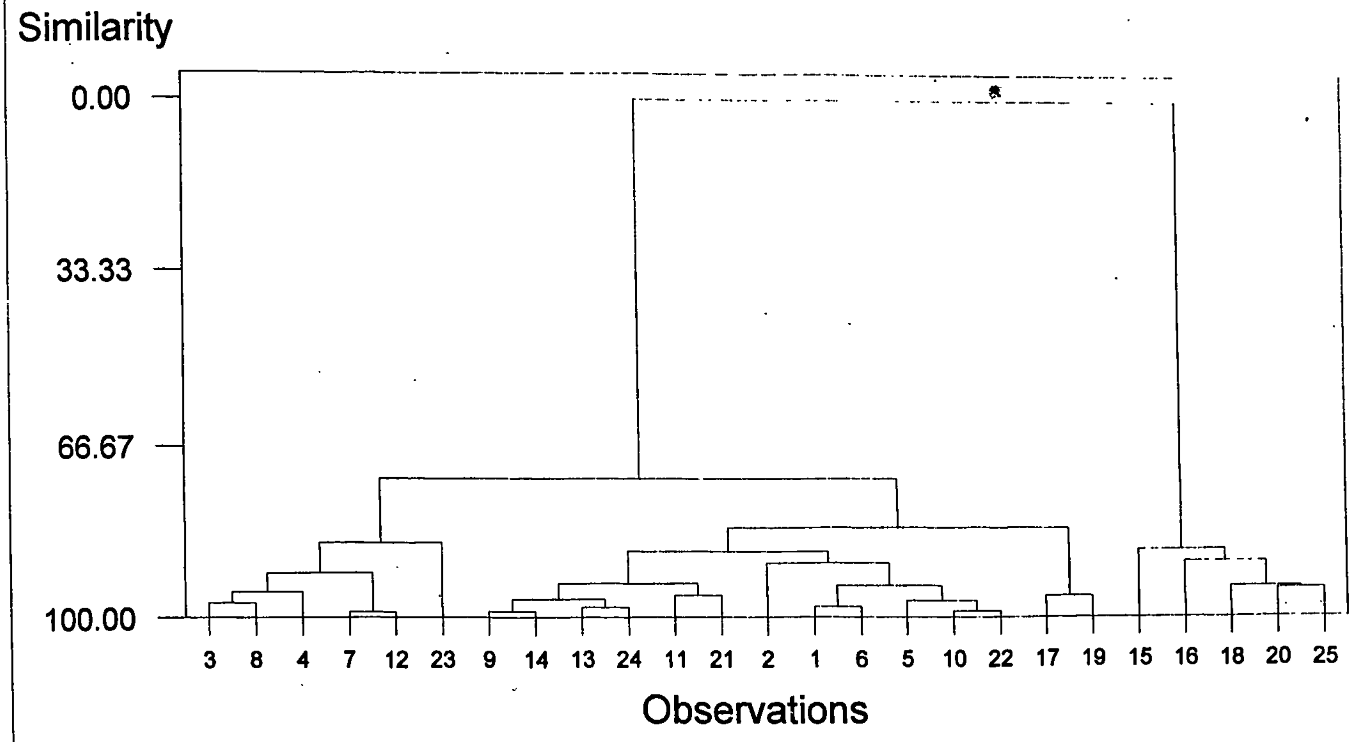


FIGURE 6.17

CLUSTER ANALYSIS USING COMPLEX LINKAGE AND SQUARED EUCLIDEAN DISTANCE



Further investigation of the relationships between the species occurring in the 25 quadrats involved the use of a classification technique, Two-Way Indicator Species Analysis, (TWINSPAN, Hill *et. al.*, 1975; Hill, 1977; Hill, 1979b) and an ordination technique, Detrended Correspondence Analysis (DECORANA, Hill, 1979a; Hill and Gauch, 1980). Comparison between the output for these quadrats and other work has focused on two sources, the National Vegetation Classification (Rodwell, 1992), and the communities proposed by Rothero (1989). Rothero's work is much more detailed than the NVC, but has no scope beyond this set of plant communities. Therefore a proportion of the quadrats surveyed will not be covered by his work. However, where his work covers the sort of communities found at this site, his classification is considered as a possible substitute for the NVC.

Classification methods group sets of samples into classes on the basis of their attributes, or floristic composition (Kent and Coker, 1992) and is a method of cluster analysis. The similarity of species composition between samples in the same class should be high and enables communities of differing affinities to be recognised. TWINSPAN is a polythetic divisive technique, that is all the data available are used to divide the whole population into progressively smaller groupings, and is based on the same concept of partitioning ordination space (Roux and Roux, 1967; Kent and Coker, 1992) as the cluster analysis used above, but operates from the whole group down, rather than combining from the individual level upwards. Pseudospecies are used to represent the presence of species at certain cover value levels, and are then used in presence/absence form to make the classification (Kent and Coker, 1992). No species was down-weighted for the classification. The classification table produced by TWINSPAN is shown in Table 6.9. According to this method, the data divide into 5

TABLE 6.9

FINAL TABLE OF TWINSPAN ANALYSIS OF 25 QUADRATS

Samples are in columns, species in rows.
Entries in the table are pseudospecies levels, not quantitave values.

```
Species name                  Species number          Sample number

                                     1|       12| 11212| 112|12112
                                    72|21356802|934411|4793|85560

Deschampsia cespitosa           477 44|43333422|------|4213|--1--    000
Galium saxatile                 610 2-|--------|------|----|-----    000
Rhytidiadelphus squarrosus     1940 33|--1-----|------|1---|-----    000
Sphagnum spp.                  2738 1-|4-------|------|----|-----    000
Racomitrium heterostichum      1931 --|--1-----|------|----|-----    0010
Scapania spp.                  2969 --|-2---111|------|1---|-----    0010
Pohlia ludwigii                1883 --|24324233|334444|1--3|-----    00110
Anthelia spp.                  2790 --|2--3----|12----|----|-----    00110
Marsupella spp.                2874 --|1-1-----|-2-2-2|2---|-----    00110
Gnaphalium supinum              644 --|--------|------|12--|-----    00111
Moerkia blyttii                2204 --|--------|------|2---|-----    00111
Saxifraga stellaris            1203 --|21211---|-1-1-2|-112|-1---    01
Kiaeria starkei                1641 --|-2332234|2332--|3334|-3---    01
Polytrichum alpinum            1890 2-|1-2--22-|-----2|2-3-|--22-    01
Polytrichum sexangulare        1896 --|33-32-33|2232-2|3333|-2-1-    01
Festuca vivipara                578 --|--------|------|1222|33231    10
Dicranum fuscescens            1633 --|--------|1--2--|--3-|33---    10
Andraea nivalis                2788 --|--------|---2--|----|3----    10
Racomitrium fasciculare        1930 --|--------|------|-32-|33333    1100
Luzula spicata                  811 --|--------|------|----|21222    1101
Huperzia selago                 821 --|--------|------|----|--2--    1101
Salix herbacea                 1171 --|--------|------|----|--2--    1101
Racomitrium lanuginosum        1932 --|--------|------|----|2--4-    1101
Carex bigelowii                 307 --|--------|------|----|3233-    111

                                    00|00000000|000000|0000|11111
                                    00|11111111|111111|1111|00111
                                      |00000000|000000|1111|
                                      |00000000|111111|    |
                                      |01111111|000011|    |
```

main groups, with a further sixth possible group of quadrats 11 and 21. Once again, the plateau quadrats 15, 16, 18, 20 and 25 are distinct from all the others, showing the importance of this division.

Quadrats 7 and 12 are distinguished from all others, as they are in the hierarchical method, indicating the distinctiveness of the dense *Deschampsia cespitosa* grassland, lacking in other species found elsewhere in the site, and displaying a much greater density of *D. cespitosa* and greater shoot elongation. The positions of quadrats 4 and 23 differ significantly between the hierarchical results and the TWINSPAN results. TWINSPAN readily combines these two quadrats with 17 and 19, the two of three transitional quadrats just below the plateau edge (the third being 23), which demonstrate relatively high diversity. Observation of the position and environmental data suggests that quadrat 4 is more closely related to 7 and 12, but has greater diversity with the presence of *Kiaeria starkei, Polytrichum sexangulare, Pohlia ludwigii, Scapania* spp. and *Marsupella* spp., none of which occur in 7 and 12. From the point of view of floristics, 4 and 23 are much more closely related than their position in the site might suggest. Quadrat 19 is floristically similar to 4 and 23, but 17 displays differences, more so to 4 and 23 than to 19, with its similar snowlie, slope angle and amount of bare ground. Given that the most important distinctions are floristic in a community classification and TWINSPAN divides samples into different communities on the basis of floristic similarity, it is more appropriate to select the TWINSPAN results in this instance than the hierarchical cluster analysis results, though the ordination results may not confirm this selection.

The TWINSPAN results agree well with the complex distance measure hierarchical results with regard to the snowbed core quadrats, combining 9, 11, 13, 14, 21 and 24 together into a distinct community, group 3 in Table 6.9 , while the single distancing method removes quadrat 11 from its adjacent position to the other quadrats, possibly on the basis that it contains only pure *Pohlia ludwigii*. The agreement of two of the three methods gives confidence in the designation of these six quadrats as one community, based largely on the dominance of *Pohlia ludwigii* and the related long duration of snowlie. TWINSPAN lumps together all the other quadrats (1, 2, 3, 5, 6, 8, 10 and 22) into one distinct group, group 2, whereas the other cluster methods divide them. The single distancing method has quadrat 2 by itself on the far left hand side, with other quadrats scattered in an apparently complex way around the snowbed core quadrats. The complex distancing method is visually much more distinct and satisfying, with quadrats 1, 2, 5, 6, 10 and 22 positioned on one side of the snowbed core quadrats and 3 and 8 combined with 4, 7, 12 and 23 on the other side, though this division of 1, 2, 3, 5, 8, 10 and 22 at a low level of similarity and failure to separate 7 and 12 from the others disagrees with the TWINSPAN results. It should be noted that the similarity levels in the complex distancing method are higher than those of the single distancing method, and that all combinations in the complex method agree with the divisions identified by TWINSPAN at the 95% level and above. The first disagreement of quadrat similarity between these two methods is the combination of quadrats 3 and 4 at the 94.97% similarity level.

Similarities between the TWINSPAN output and at least one of the hierarchical cluster models, suggest that the TWINSPAN divisions represented by the lines shown on the table are recognisable in the vegetation and are therefore identifiable communities. Comparisons between the TWINSPAN divisions and the NVC and Rothero's snowbed communities were made to further verify the validity of their assignation.

On the far right hand side of the table are quadrats 25, 15, 16, 18 and 20, in group 5. These are the plateau quadrats, dominated by *Carex bigelowii, Festuca vivipara* and *Racomitrium fasciculare*. *Racomitrium lanuginosum* occurs in only 2 of these quadrats, 16 and 18, and visually the vegetation here differs significantly from the *Racomitrium lanuginosum*-dominated areas of flatter, more central parts of the summit plateau. Therefore these quadrats do not appear to fit the NVC U10 description which clearly applies to other parts of the plateau, but with their slightly more sloping ground and a deeper snow cover, they may be sufficiently similar to assign to Rothero's *Carex bigelowii - Racomitrium* snowbed, which contains *Racomitrium fasciculare* and *Racomitrium heterostichum* and is described as occupying more mesic sites snow-free by June and of more open aspect on moderate slopes. Although in 1993 these quadrats became snow-free rather earlier than June, the comment in Rothero that this community is "virtually continuous for several kilometres on the Aonach Mor - Aonach Beag massif" (Rothero, 1989, p.16) indicates that these quadrats are most appropriately assigned to this community.

Moving left to group 4, quadrats 4, 17, 19 and 23 mostly lack *Pohlia ludwigii*, contain *Kiaeria starkei, Polytrichum sexangulare* and some *Polytrichum alpinum* but unlike the quadrats further left, also contain a persistent cover of *Festuca vivipara*. This group is possibly the most problematic, since the quadrats do differ quite markedly in general appearance, but generate similarities in TWINSPAN analysis. The presence of *Festuca vivipara* and the lower levels of snowlie set them apart from the other snowbed quadrats. However, they are not part of the plateau flora, nor the *Deschampsia* grassland. The community description which most closely fits these quadrats is the NVC's U11, which gives constancy and abundance values of *Festuca* *vivipara* as II (1-3), and *Deschampsia cespitosa* as V (1-8).

Left of these 4 quadrats are the two largest groupings, 2 and 3, with *Pohlia ludwigii* present in all samples at high cover values, but subdivided by the presence or absence of *Deschampsia cespitosa*. The community descriptions of these snowbed quadrats (1, 2, 3, 5, 6, 8, 10, 22, group 2, and 9, 11, 13, 14, 21 and 14, group 3,) are based on Rothero's snowbed communities, rather than those given by the National Vegetation Classification, after comparison with the classification and ordination given in Rothero (1989). The alternatives available in the NVC are M33, the *Pohlia wahlenbergii* var. *glacialis* spring and U11, *Polytrichum sexangulare - Kiaeria starkei* snowbed. A comparison of the floristics and environmental variables is given in Table 6.10 while Table 6.11 contains a review of the floristic of the quadrat data, arranged according to similarity.

The description for M33 indicates that *Pohlia ludwigii* may occur commonly but is only assigned a constancy value of IV and abundance values of 2-4. Instead, *Pohlia wahlenbergii* var. *glacialis* is dominant, with abundance values of 6-10, alongside *Deschampsia cespitosa* with abundance values of 1-4. There is no mention of *Kiaeria starkei* or *Polytrichum sexangulare* and given the regular occurrence of these species in the *Pohlia ludwigii*-dominated quadrats, along with the absence of *D. cespitosa*, gives rise to uncertainty about the allocation of quadrats 9, 11, 13, 14 and 24 to community M33. In contrast, Rothero's description of the *Pohlia* snowbed gives *Pohlia ludwigii* as by far the most abundant plant, with cover and abundance values of V (2-9), and with scattered individuals of *Deschampsia cespitosa* (III, 4-9) and *Polytrichum sexangulare* (II, 1-4). Where *D. cespitosa* is more or less dominant, Rothero assigns it to a *Deschampsia cespitosa* sub-community, which, with *Pohlia*

TABLE 6.10

COMPARISON OF NVC, THIS STUDY'S (*) AND ROTHERO'S COMMUNITY FLORISTICS.

Species	U11	*	Rothero	M33	*	Rothero
Agrostis capillaris	II (1-3)			I (3)		
Deschampsia cespitosa	V (1-8)	V (3-8)	I (1-4)	V (1-4)		III (4-9)
Deschampsia flexuosa	I (1-3)		II (1-6)			I (1)
Festuca rubra				I (2)		
Festuca vivipara	I (1-3)					
Nardus stricta	II (1-4)					
Poa annua				I (2-3)		
Carex bigelowii	III (1-8)		I (1-4)			
Juncus trifidus	II (1-8)		I (1-2)			
Alchemilla alpina	II (1-4)					
Cerastium cerastoides	I (1)			III (1-3)		I (4)
Chrysosplenium oppositifloium				III (2-4)		
Empetrum nigrum hermaphrodit.	I (1-3)					
Epilobium anagalladifolium				III (3)		
Galium saxatile	II (1-4)					
Gnaphalium supinum	III (1-6)		I (1-8)			
Montia fontana				I (4)		
Rumex acetosa				II (1)		
Salix herbacea	II (1-4)		I (3-8)			
Saxifraga stellaris	III (1-3)	III (1-2)	I (1-4)	IV (2-3)	III (1-2)	
Sibbaldia procumbens	II (1-6)					
Silene acaulis	II (1-3)					
Solorina crocea	I (1-4)					
Stellaria alsine				III (3)		
Veronica serpyllifolia				II (2)		
Voila palustris	II (1-3)					
Athyrium distentifolium	I (1)					
Blechnum spicant	I (1-3)					
Cryptogramma crispa	I (1-3)		I (4)			
Huperzia selago	III (1-3)		II (1-4)			
Andraea nivalis			I (7-8)		I (3)	I (6)
Bryum weigelii				II (1-3)		
Calliergon stramineum				II (6)		
Conostomum tetragonum	III (1-4)		II (1-6)			
Dicranella palustris				I (2-6)		
Dicranum fuscescens	I (1-3)	I (1)			I (2)	
Ditrichum zonatum			I (1-4)			I (1)
Drepanocladus exannulatus				I (2-4)		
Hygrohypnum luridum				II (2-3)		
Kiaeria falcata	I (1-6)		I (1-2)			
Kiaeria starkei	V (1-9)	IV (3-8)	V (1-9)		IV (3-4)	
Oligotrichum hercynicum	IV (1-4)		I (1-4)			I (1)
Philonotis fontana				III (1-7)		
Pleurozium schreberi	I (1-3)					
Pohlia drummondii	II (1-4)					
Pohlia ludwigii	I (1-6)	V (3-8)	II (1-4)	IV (2-4)	V (5-10)	V (2-9)
Pohlia nutans	II (1-3)		I (1-4)			
Pohlia wahlenbergii var. glacialis				V (6-10)		I (1)
Polytrichum alpinum	III (1-9)	III (1-3)	I (1-2)		I (2)	I (1)
Polytrichum sexangulare	IV (1-4)	IV (3-5)	V (1-9)		III (3-4)	II (1-4)
Racomitrium canescens	II (1-8)					
Racomitrium fasciculare	III (1-6)		I (1-4)			
Racomitrium heterostichum	II (1-6)	I (1)	III (1-8)			II (1-2)
Racomitrium lanuginosum	II (1-3)		I (1-2)			
Rhytidiadelphus loreus	II (1-4)					
Rhytidiadelphus squarrosus		I (1)				
Sphagnum squarrosum		I (7)		I (3)		
Anthelia julacea		II (3-4)	I (1-2)		II (1-2)	I (1)
Anthelia juratzkana	II (1-4)					
Barbilophozia floerkii	II (1-6)		IV (1-8)			
Cephalozia bicuspidata			II (1-4)			I (1)
Diplophyllum albicans			I (1-4)			I (1)
Gymnomitrium concinnatum			I (1-2)			
Lophozia sudetica	II (1-4)		III (1-6)			I (3-6)
Marchantia polymorpha				II (2-4)		
Marsupella alpina		II (1)	I (1-2)		III (203)	
Marsupella brevissima			II (1-4)			I (1)
Marsupella condensata			I (1-2)			
Marsupella emarginata	I (1-4)		I (1-4)			I (3-6)
Marsupella sphacelata			II (1-4)			I (1-4)
Marsupella stableri			I (1-2)			
Moerkia blyttii	II (1-4)		II (1-8)			
Nardia scalaris	III (1-4)		III (1-8)			III (1-6)
Pleurocladula albescens	II (1-4)		II (1-6)			
Scapania nemorosa		III (1-4)		I (4)		
Scapania undulata				II (1-2)		I (1-8)
Scapania uliginosum				II (1-4)		II (1-6)
Cetraria islandica	II (1-3)					
Cladonia bellidiflora	II (1-3)					
Cladonia pyxidata	I (1-3)					
Cladonia uncialis	I (1-3)					
Bare ground		IV (4-6)	II (1-7)		V (4-9)	I (4)
Number of samples	31	8	38	10	6	10

TABLE 6.11

VEGETATION SUMMARY FOR 25 QUADRATS USING SELECTED SPECIES.

	7	**12**	**4**	**8**	**2**	**3**	**5**	**10**	**22**	**23**	**1**	**6**	**13**	**9**	**14**	**21**	**24**	**11**	**17**	**19**	**25**	**18**	**16**	**20**	**15**
Deschampsia cespitosa	9	10	8	8	7	6	5	3	3	4	5	5							3	1					1
Festuca vivipara			1							2									3	2	4	4	4	1	3
Carex bigelowii																					2	4	6		5
Luzula spicata																					1	2	3	2	3
Galium saxatile	3																								
Gnaphalium supinum			1																3						
Salix herbacea																									2
Saxifraga stellaris					2	2	1			3	1	1	1			2	1		1	1	1				
Huperzia selago																									3
Andraea nivalis																	3					5			
Dicranum fuscescens														1			2			4	5	4			
Kiaeria starkei			5	3		6	4	5	8	8	3	3	4	3	4		3		5	4	5				
Pohlia ludwigii			1	3	3	6	3	4	4	4	8	8	6	5	7	9	8	10							
Polytrichum alpinum	2		2	3	1	3		2								2				4			2		2
P. sexangulare			5		4		4	5	4	5	5	3	3	3	4	3	3		5	4	3		1		
Raco. fasciculare																			5	3	4	4	6	6	6
Raco. heterostichum						1																			
Raco. lanuginosum																						3	7		
Rhytid. squarrosus	4	4	1			1																			
Sphagnum spp.	1				7																				
Anthelia spp.					3		4						2	1											
Marsupella spp.			2		1	1							2			3	3								
Moerkia blyttii			2																						
Scapania spp.			1	1				1	1		2														
Slope	32	31	33	35	40	34	36	38	38	28	40	38	39	43	42	37	40	42	39	40	10	8	9	10	18
Snow	4	4	4	5	7	6	5	5	7	6	6	5	8	6	8	6	7	9	3	3	1	1	1	1	2
Bare ground				3	4		5	6	6	4	4		8	9	7	5	6	4	6	9	5	8		7	4
Average wetness	2.8	2.8	3.0	3.0	3.4	2.9	3.3	3.2	3.2	3.0	4.5	4.7	3.9	3.1	3.7	4.4	3.4	3.7	2.6	2.8	2.3	2.1	2.2	1.6	2.3

ludwigii present in all the other snowbed quadrats and *Deschampsia cespitosa* achieving abundance values of 3-8 at constancy V, suggests that all the snowbed quadrats could be assigned to the *Pohlia ludwigii* community. In terms of succession, Rothero describes this community as occupying ground less wet than that occupied by *Pohlia wahlenbergii* var. *glacialis, Anthelia julacea - Sphagnum auriculatum* and *Philonotis fontana - Saxifraga stellaris* springs. This confirms that the community found here on Aonach Mor is not what the NVC describes as M33 but an example of Rothero's *Pohlia ludwigii* snowbed; were there any wetter areas, then perhaps examples of M33 might be present.

On drier ground of equivalent snowlie, with stable substrate Rothero suggest that a transition to a community dominated by *Kiaeria starkei* and *Polytrichum sexangulare* will take place. Although lacking in several important species, in terms of abundance and constancy, such as *Lophozia sudetica*, quadrats 1, 2, 3, 5, 6, 8, 10 and 22 in group 2, also have some striking similarities with this community, which is very similar to the NVC's U11, though lacking *Oligotrichum hercynicum*, as well as to the *Pohlia ludwigii* community. However, quadrats 8 and 3 lack any occurrence of *Polytrichum sexangulare* which has a constancy value of V in Rothero's classification. Meanwhile, quadrats 4 and 23 appear to fit in well with this community description. The assignation of these quadrats is therefore reserved until the ordination plot is examined.

Finally, on the far left, in group 1, quadrats 7 and 12 represent the NVC's U13, *Deschampsia cespitosa* grassland, a description which fits the data from these quadrats well, with the dominance of *D. cespitosa* and the presence of *Rhytidiadelphus*, though here it is *squarrosus* rather than *loreus*, and *Galium saxatile*.

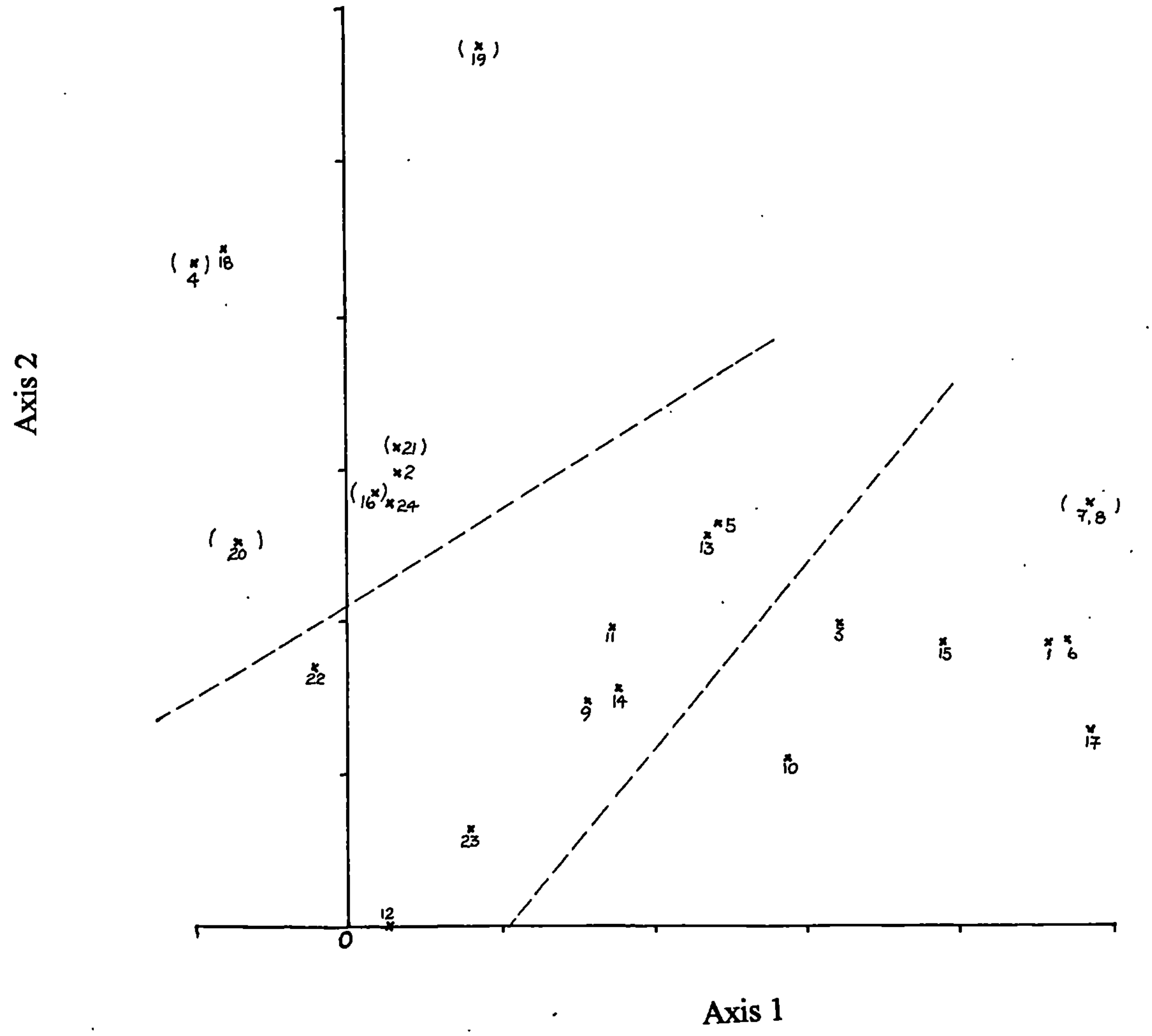
To assess the value of these divisions in the light of underlying environmental variables, and to examine further the classification of the snowbed quadrats, ordination of the data was also undertaken. Ordination techniques are part of gradient analysis, in which differences in species composition are related to underlying environmental variables, rather than classification which groups samples on the basis of floristic similarity. Indirect ordination techniques, examining variation within the vegetation data first, independently of the environmental variables, followed by comparison with the environmental variables, includes a widely-used technique called detrended correspondence analysis, available in the programme DECORANA (Hill, 1979a; Hill and Gauch, 1980; Kent and Coker, 1992). DECORANA produces two ordination plots, in sample space and in species space, which show floristic similarity between quadrats and similarities in the distribution of different species within the samples.

Looking at the species ordination diagram first, in Figure 6.18, those species represented in 2 or fewer quadrats have been marked with brackets. The two dotted lines represent the divisions between, on the left and higher on the y-axis, species characteristic of the *Deschampsia cespitosa* grassland, in the centre the snowbed species, and on the right the species characteristic of the plateau and transitional quadrats.

The sample ordination plot, shown in Figure 6.19, and ignoring the dotted lines for the present, displays some differences to the community divisions recognised by the TWINSPAN analysis. Quadrats 7 and 12 are definitely separated from any other quadrats containing *Deschampsia cespitosa* and thus the distinction between these two quadrats and the others by the cluster analysis and TWINSPAN is valid. Similarly, the plateau quadrats, 15, 16, 18 and 20 are also quite separate. However, the other

FIGURE 6.18

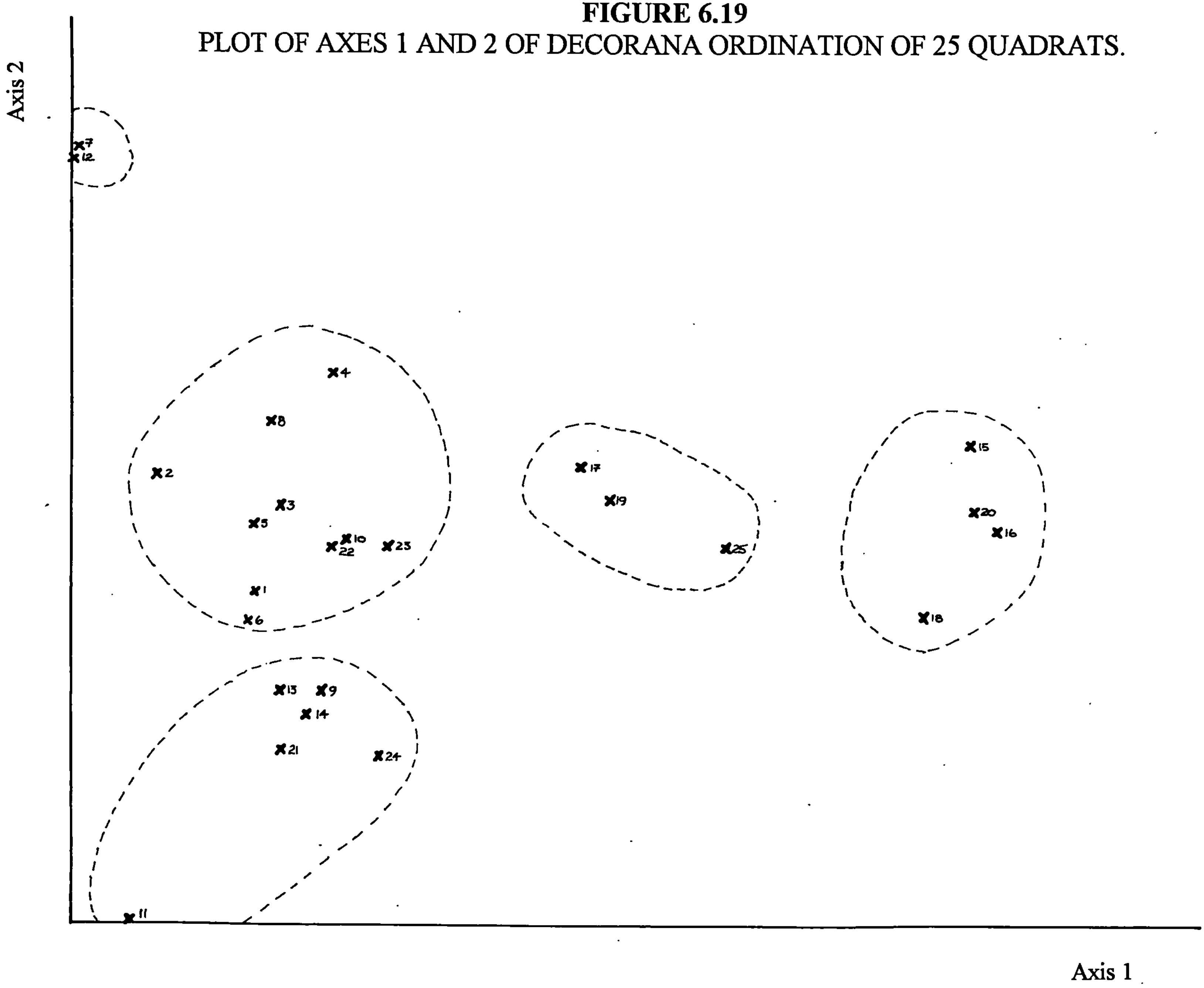
PLOT OF AXES 1 AND 2 OF DECORANA ORDINATION OF 24 SPECIES



Number	Species name	Number	Species name
1	*Carex bigelowii*	2	*Deschampsia cespitosa*
3	*Festuca vivipara*	4	*Galium saxatile*
5	*Gnaphalium supinum*	6	*Luzula spicata*
7	*Huperzia selago*	8	*Salix herbacea*
9	*Saxifraga stellaris*	10	*Dicranum fuscescens*
11	*Kiaeria starkei*	12	*Pohlia ludwigii*
13	*Polytrichum alpinum*	14	*Polytrichum sexangulare*
15	*Racomitrium fasciculare*	16	*Racomitrium heterostichum*
17	*Racomitrium lanuginosum*	18	*Rhytidiadelphus squarrosus*
19	*Moerkia blyttii*	20	*Sphagnum* sp.
21	*Andraea nivalis*	22	*Anthelia* sp.
23	*Marsupella* sp.	24	*Scapania* sp.

FIGURE 6.19

PLOT OF AXES 1 AND 2 OF DECORANA ORDINATION OF 25 QUADRATS.



divisions are not so distinct. Quadrats 17 and 19 occupy a position close to 25 but 4 is quite separate and much closer to 8 and to the bulk of the snowbed samples. The *Pohlia*-dominated quadrats lacking in *Deschampsia cespitosa* (13, 9, 14, 21 and 24) are a little separate from the others, with 11 quite distinctly on its own as the pure *Pohlia* quadrat. The other grouping of 1, 2, 3, 4, 5, 6, 8, 10, 22 and 23 is a more or less discrete cluster.

Examination of the position of the samples in the ordination should enable an assessment of the governing environmental variables to be made. Axis 2, with quadrats 7 and 12 so high and quadrat 11 so low, is most likely to be related to vegetation height, vascular plant content, or possibly pH. The presence or absence of *Deschampsia cespitosa* does not provide an adequate explanation, with the plateau quadrats too far from the zero value, yet containing none of this species. Vegetation height and vascular plant content are possible explanations for the distribution, though quadrats 9 and 14 also contain no vascular plants and have vegetation of similar height to quadrat 11, while numbers 21 and 24 both contain *Saxifraga stellaris* and yet are lower on axis 2 than 9 and 14. pH would seem to be a more likely explanation, with snowbed core quadrats lower than the bulk of the other quadrats, being irrigated immediately in the vicinity of the acid snowbed, while 7 and 12 experience the downslope reduced acidity observed in the pH measurements. Further work needs to be carried out to determine whether this interpretation is correct.

Axis 1 is most likely to reflect some measure of exposure, with the plateau quadrats well separated on the right-hand side, while the snowbed quadrats and downslope *Deschampsia* quadrats, which are heavily sheltered by the topography, are much lower on this axis. Snow-lie is not obviously incorporated into this axis, except in the coarsest way by differentiating between the scoured summit quadrats and the more heavily covered quadrats on the lee slope, since the snowbed quadrats are higher on this axis than quadrats 7 and 12. A more appropriate interpretation is for axis 1 to represent the degree of shelter and proximity to the windiest part of the site, on the summit plateau. Insufficient samples are present to justify an ordination of quadrats away from the plateau, that is excluding quadrats 15, 16, 17, 18, 19, 20 and 25. Further work is required to obtain more samples of vegetation across the snowbed which in ordination may produce results which indicate the importance of snow. It is supposed that in this case the snow gradient is obscured by the steeper environmental gradient related to exposure; examination of the snowbed gradient without the same extent of exposure gradient would give clearer results for the snowbed.

A revised vegetation summary table is shown in Table 6.11 which shows cover values for quadrats arranged according to the communities suggested in the ordination of samples plot by TWINSPAN and DECORANA, but assigning quadrat 4 to the snowbed quadrats and 25 to the transitional quadrats, with environmental data shown at the bottom. Quadrat 4 is combined with the larger of the two snowbed groupings on the strength of its distance from quadrats 17, 19 and 25 and proximity to 8 in the ordination diagram. Quadrat 25 is assigned to the transitional quadrats on the strength of the absence of *Deschampsia cespitosa,* the presence of *Carex bigelowii* and *Luzula spicata* and the high cover value of *Festuca vivipara.* It could be argued that, with high cover values for *Kiaeria starkei* and *Polytrichum sexangulare* (5 and 3 respectively), that 25 should be grouped with the snowbed quadrats. Equally, with a snowlie value of 1, low slope angle and wetness values, plus the presence of *Carex bigelowii* and *Festuca vivipara,* it could be assigned to the plateau quadrats, as suggested by the other analyses. Instead, it is preferred to allocate it an intermediate position, alongside quadrats 17 and 19, transitional between the snowbed vegetation and the summit plateau vegetation.

Thus the 25 quadrats are grouped in communities according to the dotted lines shown on the ordination plot. Quadrats 7 and 12 are grouped together as U13, the NVC's *Deschampsia cespitosa* grassland. Quadrats 15, 16, 18, and 20 are grouped together as Rothero's *Racomitrium - Carex* snowbed, in spite of the constant presence of *Festuca vivipara* which is not recorded in Rothero's work. 25, 17 and 19, although similar, fit best with the NVC's U11. Were it necessary to choose one of Rothero's communities for these three quadrats, for the sake of consistency, it would be difficult on the basis of floristics, but on the grounds of snowlie, it would be necessary to assign them to the *Racomitrium - Carex* snowbed, with its shorter duration of snowlie. For the other quadrats, 9, 11, 13, 14, 21 and 24 are assigned to Rothero's *Pohlia ludwigii* snowbed, sub-community B, or dense stands of *P. ludwigii,* but differ from the samples obtained by Rothero by having *Kiaeria starkei* present at constancy IV, abundance 1-4 and *Polytrichum sexangulare* at constancy IV, rather than III. Quadrats 1, 2, 3, 4, 5, 6, 8, 10, 22 and 23 are more difficult to assign. They have:

Pohlia ludwigii with constancy V, abundance 1-8
Kiaeria starkei with constancy IV, abundance 4-8
Polytrichum sexangulare with constancy IV, abundance 3-5
Deschampsia cespitosa with constancy V, abundance 4-8.

Rothero's communities have the following constancy and abundance values:

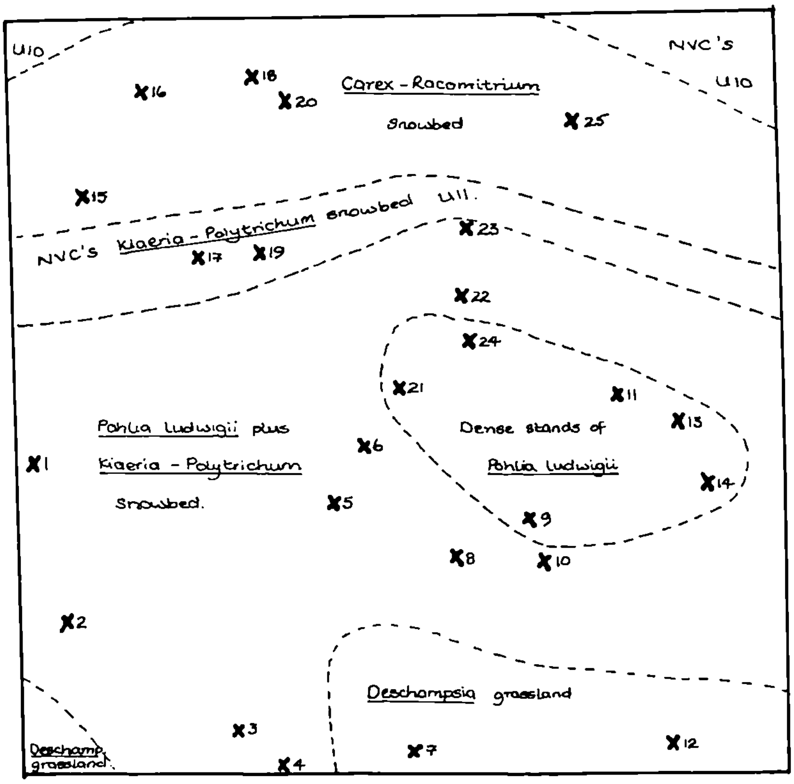
	Pohlia ludwigii snowbed	*P. ludwigii* dense stands	*Deschampsia*-rich facies of *P. ludwigii* snowbed	*Kiaeria starkei-Polytrichum sexang*. Snowbed
Pohlia ludwigii	V 2-9	V 7-9	V 1-9	II 1-4
Poly. sexangulare	II 1-4	III 1-4	I 1	V 1-9
Kiaeria starkei	-	-	-	V 1-9
Desch. cespitosa	III 4-9	I 1	IV 5-9	I 1-4

The differences between these quadrats and the communities offered by Rothero is probably due to the fine nature of the mosaic of species found in the snowbed area, largely obscured using larger quadrat sizes, plus the relatively small number of samples. For these snowbed core quadrats, where bryophytes are the dominant form of vegetation, it is proposed that an area of only .25 m^2 should be used in future work, rather than the $1m^2$ which was actually used. The larger size appears to have trapped both communities within its area, or if that is not the case, then an additional community exists containing all four of the species given above at high levels of constancy and abundance. The expertise of Rothero, and the poor resolution of this study for some species, particularly the liverworts, indicate that the former is true. Therefore these snowbed quadrats are given a combination of both the *Pohlia ludwigii Deschampsia*-rich facies community and the *Kiaeria starkei - Polytrichum sexangulare* community.

As a result of the community assignations given above, plus observations of the vegetation within and around the study site made during the course of the research, the map shown in Figure 6.20 can be given for communities in the site area. The relationship between snowlie and the different communities found is apparent when this map is compared with the contour plot for snowlie, with the dense stands of

FIGURE 6.20

VEGETATION MAP OF THE STUDY SITE USING NVC AND ROTHERO'S SNOWBED COMMUNITIES.



Pohlia ludwigii occupying the area of longest snowlie. The combination community of *Kiaeria starkei - Polytrichum sexangulare* and *Pohlia ludwigii*, *Deschampsia* -rich facies surrounds the areas of very latest snowlie. Downslope the NVC's U13 *Deschampsia* grassland succeeds these communities on areas of less snowlie while upslope the NVC's U11 *Kiaeria - Polytrichum* snowbed is found. Transitional onto the community of the plateau core, U10, lies an area of *Carex - Racomitrium* snowbed, dominated by *Racomitrium fasciculare* and *R. heterostichum* alongside *Carex bigelowii* and *Festuca vivipara.*

The need for a greater number of samples of late snowbed vegetation and the more peripheral communities has been made clear with the difficulties encountered on assigning the data from this study to either NVC communities, or Rothero's (1989) work. The relationship between environmental variables and vegetation patterns is also more complex than originally thought, with other factors in addition to snow-lie duration, particularly slope stability, irrigation and pH, likely to have a significant impact on the pattern of vegetation.

An appropriate tool to further the investigation of the relationship between snow-lie and snowbed species would be Geographical Information Systems (GIS). At the outset of this thesis appropriate software, such as ARCINFO, was not available for personal computers (PCs), nor were most PCs sufficiently powerful to operate such complex software. However, rapid advances in both the software and the hardware now make this a very real possibility for use in this instance. Using such software would allow the mapping of all the complex variables together, offering a greater insight into which variables interact most closely with each other, and which are more independent. This would allow further research priorities to be identified.

TABLE 6.12
TABLE OF *Deschampsia* POT EXPERIMENT RESULTS

Date	Pot 1	Pot 2	Pot 3	Pot 4	Pot 5	Pot 6	Pot 7	Pot 8	Pot 9
24.6.93	Some *Festuca, Rhytid.* otherwise dead.	Covered	Covered	Covered	Covered	Covered	Covered	Covered	Covered
10.7.93	*Des.* with shoots 1cm, *Fes.* same. Pale, not vig.	*Des.* with brown growth, 3-4cm, poor-looking	Covered	Covered	Covered	Covered	Covered	Covered	Covered
20.7.93	Same as previous visit	25% shoots green, to 5cm, vig. and healthy	Just emerged; little green on brown shoots.	Covered	Covered	Covered	Covered	Covered	Covered
3.8.93	Largely dead, some shoots (mostly dead) to 5cm.	2-3 shoots 6cm, bryos. starting but not emerged so identity unknown	Good growth, shoots 6-8cm, some inundation.	*Pohlia* taking over - creeping round edges. *Des* 6 shoots, av. 4cm	Snow 2m above pot - crushed. 2 tiny shoots, very pale.	Covered	Covered	Covered	Covered
14.8.93	Vig. growth, similar to surrounding grassland.	Gone.	12 shoots, av. 6cm, mostly vigorous and green	Good growth, shoots 5-6cm, green. Pot a little crushed.	Very crushed, some shoots but all dead.	Level with base of snow,3 green shoots, some dieback.	Crushed. Just emerged, v. spindly, long pale shoots	No growth, very crushed	Vig. growth in *Des.* but v. crushed
27.10.93	Still vig. growth!	Gone	Reasonably vig. with one mini panicle	Long shoots, now all dead	Largely crushed, a few dead shoots	V. crushed. Shoots there, all dead	Still vig. growth, sheltered below rocks	Now under new snow.	*Des.* now dead. V. crushed

6.1.4 *Deschampsia* Experiment.

The summary of results of the observed performance of *Deschampsia cespitosa* in the transplanted pots is shown in Table 6.12. The immediate growth response of *D. cespitosa* to snow removal is apparent in pots 2, 3, 4, 5, 6, 7 and 9, as is the delayed growth response of bryophytes, in pot 2. However, often the first few shoots appeared to be very pale and fragile, and it took some time before robust, vigorous growth was observed in the pots. Some pots demonstrated die-back while others did not, with pots 1, 3 and 7 showing vigorous growth in October. This suggests that die-back is programmed in the undisturbed grassland and that growth and photosynthesis are possible in near-freezing temperatures, necessary for the disturbed plants since their resource acquisition will have been disrupted by transfer to pots and a new location, and also by the change in snow-lie duration. Some pots, such as 1, 2, 5 and 6 demonstrated such poor performance that it is concluded the additional disturbance proved too stressful and that the individuals concerned were unlikely to survive.

The amount of substrate slippage became even more apparent during this experiment with many of the plastic pots used being totally crushed during the course of a year. The importance of this factor, which was observed but not quantified in any way, requires further investigation in conjunction with the other major factors of snow-lie and irrigation.

Poor performance of *Deschampsia cespitosa* in the pot experiment indicates increased levels of stress under greater duration of snow-lie. This is especially true for the lack of die-back observed in pots 1, 3 and 7 where photosynthetic tissue remained active much longer than in the more peripheral areas of the snowbed. It is concluded, therefore, that the die-back observed in *D. cespitosa* is an acclimation response to the environmental conditions, which can be reversed. However, the likely reasons behind die-back indicate that plants finding it necessary to suspend this response are experiencing high levels of stress and are therefore in very marginal situations. The fact that *D. cespitosa* does not occupy the snowbed core but in the short-term is apparently able to utilise the sub-optimal snow-free period at the end of the summer season suggests that in the longer term increased stress of longer snow-lie through the optimal part of the growing season is a limiting factor.

The potentially damaging effects of acid flush from the snowbed should now be a high research priority with regard to both vascular plants as well as bryophytes. It may well be that the stress of snowlie duration is intimately linked with the stress of acid irrigation, both of which are likely to have different threshold levels for vascular plants and bryophytes.

Summary points:

1. Patterns of wetness, snow-lie and species' performance and distribution were identified.
2. The abundance and performance of *Deschampsia cespitosa* decreased as snow-lie increased.
3. The bryophyte *Pohlia ludwigii* showed highest performance where snow-lie and irrigation were most persistent.
4. Other snowbed bryophytes (*Polytrichum sexangulare* and *Kiaeria starkei*) showed no relationship with snow-lie duration but demonstrated some correlation with

slope angle and substrate stability.

5. The presence of a vegetation cover dampened the amplitude of the vegetation temperature curve relative to air temperature beyond the vegetation canopy.
6. Die-back, programmed to take place in late August and interpreted as an acclimation response, was observed in *Deschampsia cespitosa*.
7. Classification of the communities observed on Aonach Mor was similar to that proposed by Rothero (1989), but differed significantly to that offered by the NVC.
8. The need for further samples of snowbed and other upland vegetation types included in the NVC was identified.

CHAPTER 7

THE CLIMATE SNOW-COVER LINK

7.1 Climate at the Aonach Mor AWS.

The climate data for Aonach Mor are given earlier in section 5.6. They demonstrate a two-season year in which 7 months, from mid-October to mid-May can be classed as "winter", with mean temperature for that period -1.5°C while "summer" lasts for the remaining 5 months and has a mean temperature of 5.4°C. The relatively low temperature for the summer season demonstrates a good environment for the long duration of snow-lie where the snowpack is deepest on lee slopes, while the winter temperatures show that on average precipitation will fall as snow rather than rain, enhancing the build-up of deep snowpacks. It should be remembered that the temperatures given by the AWS on Aonach Mor will not accurately reflect temperatures at the ground surface, where maxima will be a little higher and minima much lower. Without a consistent set of observations of temperature at the ground surface, it is not possible to make a direct correlation between the AWS data and snowpack development and decay, or between the AWS data and vegetation parameters, other than to demonstrate the two-part season and identify the onset of the main melt period and thus the potential growing season.

Wind conditions show relatively high levels of windiness in winter and although direction is not as consistent during winter as during summer, there is still a predominance of south-westerly winds, ensuring the consistent development of deep snowpacks in late snowbed locations and thus high late snowbed loyalty. High winds cause substantial damage to snow crystals being transported in the air or by saltation at the ground surface; the lower wind speeds experienced at Aonach Mor relative to Cairn Gorm thus improves the opportunities for the development of deeper snowpacks on Aonach Mor, although mean temperature and the incidence of rainfall and thaw events during winter are higher.

Further work should now be carried out at this site to establish a stronger link than can be provided by the data from this study between the climate parameters offered at the AWS and the development and decay of snowpacks at late snowbed locations. Such a study could offer a far better insight into how future climate change may affect the duration of late snowbeds and thus the survival of snowbed vegetation than is presently possible.

7.2 Data from Scottish Meteorological Stations.

The monthly data from the three selected Meteorological Stations, Cape Wrath, Tiree and Eskdalemuir gave 49 years data of wind direction and strength, pressure, air and ground frost, snowfall and snowlie, with which to examine the variation of Scottish climate with regard to those variables most closely related to snow-lie duration, and any indications of change.

Given the relative importance of the late winter and spring months up to and including May for the generation and summer survival of late snowbeds (Watson, Davison and French, 1994), rather than weather during the summer months, the data were combined into two three-month seasons in the winter half-year, December, January, February and March, April, May. This combination approach had the additional benefit of generating enough values in each of the categories of measurement to ensure that the data were normally distributed. Only in one or two instances for wind

TABLE 7.1
PEARSON'S CORRELATION COEFFICIENTS FOR CAPE WRATH WIND DATA, DECEMBER, JANUARY AND FEBRUARY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	**6-7** 0300	**4-5** 0300	**1-3** 0300	**Calm** 0300	**8+** 1500	**6-7** 1500	**4-5** 1500	**1-3** 1500	**Calm** 1500
N 0300	-0.133	0.028	0.147	-0.002	-0.071	-0.182	0.083	-0.014	0.127	-0.207
NE 0300	**-0.394****	-0.237	-0.070	**0.428****	0.013	**-0.397****	**-0.394****	0.067	**0.491*****	-0.252
E 0300	-0.271	-0.191	0.025	**0.314***	-0.164	-0.216	-0.194	0.051	0.201	0.051
SE 0300	**-0.369****	**-0.330***	-0.079	**0.409****	0.285	**-0.385****	**-0.362***	-0.014	**0.437****	0.174
S 0300	0.186	-0.040	-0.148	-0.009	-0.002	0.176	-0.039	-0.109	-0.023	0.049
SW 0300	**0.319***	0.141	0.061	-0.280	-0.136	0.258	0.251	0.068	**-0.390****	0.131
W 0300	**0.600*****	**0.444****	-0.066	**-0.552*****	-0.234	**0.590*****	**0.488*****	-0.219	**-0.459*****	-0.206
NW 0300	-0.288	0.211	0.221	-0.069	-0.018	-0.180	0.091	**0.309***	-0.129	-0.191
N 1500	-0.253	0.028	0.083	0.127	-0.130	-0.202	-0.073	0.096	0.157	-0.257
NE 1500	**-0.387****	-0.257	-0.105	**0.438****	0.113	**-0.387****	**-0.421****	0.096	**0.428****	0.006
E 1500	-0.262	-0.174	0.040	0.279	-0.138	-0.223	-0.167	0.085	0.191	-0.081
SE 1500	**-0.329***	-0.275	-0.075	**0.380****	0.190	**-0.352***	-0.291	-0.020	**0.376****	0.209
S 1500	-0.044	-0.198	-0.204	0.198	0.235	-0.071	-0.276	-0.185	**0.325***	0.073
SW 1500	**0.356***	0.119	0.140	**-0.399****	0.074	**0.312***	0.209	0.093	**-0.401****	0.031
W 1500	**0.513*****	**0.460*****	-0.036	**-0.473*****	**-0.408****	**0.539*****	**0.504*****	-0.098	**-0.517*****	-0.233
NW 1500	-0.172	0.122	0.191	-0.085	0.018	-0.172	0.105	0.075	0.037	-0.203

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS
OF WIND DIRECTION AND STRENGTH.

TABLE 7.2

PEARSON'S CORRELATION COEFFICIENTS FOR TIREE WIND DATA, DECEMBER, JANUARY AND FEBRUARY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	**6-7** 0300	**4-5** 0300	**1-3** 0300	**Calm** 0300	**8+** 1500	**6-7** 1500	**4-5** 1500	**1-3** 1500	**Calm** 1500
N 0300	**-0.322***	**-0.488*****	0.139	0.292	**0.304***	**-0.322***	**-0.310***	0.101	0.180	0.180
NE 0300	0.042	**-0.379****	-0.144	**0.300***	**0.316***	0.064	**-0.339***	-0.209	0.247	**0.313***
E 0300	0.001	-0.122	-0.029	0.087	0.045	-0.108	-0.044	0.092	-0.133	**0.369****
SE 0300	**0.385****	0.119	-0.125	-0.161	0.044	0.282	0.114	-0.177	-0.093	0.132
S 0300	0.054	0.160	0.122	-0.152	-0.259	0.168	0.080	-0.015	-0.028	-0.189
SW 0300	-0.053	**0.303***	-0.007	-0.085	**-0.397****	-0.085	0.286	0.156	-0.142	**-0.402****
W 0300	-0.053	**0.333***	-0.001	-0.106	**-0.377****	0.102	0.111	-0.023	0.066	**-0.433****
NW 0300	-0.168	-0.123	0.125	0.015	0.142	-0.162	-0.077	0.123	0.015	0.039
N 1500	-0.135	**-0.337***	0.157	0.092	0.288	-0.230	-0.248	0.162	0.087	0.123
NE 1500	**-0.394****	**-0.362***	0.030	**0.349***	0.250	-0.087	**-0.344***	-0.290	**0.432****	0.095
E 1500	0.108	-0.149	0.046	-0.014	0.06	-0.065	-0.094	0.205	-0.187	**0.374****
SE 1500	**0.397****	0.008	**-0.330***	0.071	0.122	0.267	0.058	-0.250	-0.006	0.143
S 1500	0.089	0.054	0.121	-0.108	-0.232	0.128	0.175	-0.055	-0.010	**-0.358***
SW 1500	-0.136	**0.420****	-0.008	-0.170	-0.265	0.044	0.217	-0.043	-0.004	**-0.360***
W 1500	-0.058	**0.346***	0.195	**-0.304***	**-0.311***	-0.019	0.260	0.189	-0.175	**-0.345***
NW 1500	-0.193	-0.155	-0.062	0.244	0.049	-0.162	-0.192	-0.009	0.237	-0.129

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS
OF WIND DIRECTION AND STRENGTH.

TABLE 7.3

PEARSON'S CORRELATION COEFFICIENTS FOR ESKDALEMUIR WIND DATA, DECEMBER, JANUARY AND FEBRUARY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	**6-7** 0300	**4-5** 0300	**1-3** 0300	**Calm** 0300	**8+** 1500	**6-7** 1500	**4-5** 1500	**1-3** 1500	**Calm** 1500
N 0300	**-0.328***	**-0.377****	**-0.438****	**0.531*****	-0.062	-0.046	**-0.419****	**-0.491*****	**0.582*****	-0.039
NE 0300	-0.047	**-0.383****	**-0.457*****	**0.432****	0.054	-0.192	**-0.355****	**-0.341***	**0.350***	0.109
E 0300	-0.097	**-0.322***	**-0.449****	**0.369****	0.099	-0.253	**-0.352***	-0.261	**0.341***	0.029
SE 0300	0.187	0.189	-0.006	-0.116	0.041	0.133	0.060	0.153	-0.139	-0.023
S 0300	0.137	**0.331***	0.187	0.038	**-0.369****	-0.003	0.119	0.277	-0.042	**-0.350***
SW 0300	0.095	**0.405****	**0.573*****	-0.207	**-0.453****	0.089	**0.352***	**0.566*****	**-0.372****	**-0.324***
W 0300	0.205	0.286	**0.629*****	**-0.308***	**-0.327***	0.270	**0.502*****	**0.479*****	**-0.398****	**-0.298***
NW 0300	**-0.313***	-0.132	0.129	0.231	**-0.321***	-0.033	-0.130	-0.042	0.238	-0.239
N 1500	-0.291	**-0.298***	**-0.452****	**0.337***	0.147	-0.001	**-0.344***	**-0.448****	**0.480*****	-0.001
NE 1500	-0.119	**-0.375****	**-0.596*****	**0.403****	0.217	-0.242	**-0.377****	**-0.486*****	**0.411****	0.205
E 1500	-0.221	**-0.377****	**-0.410****	**0.488*****	-0.054	-0.168	**-0.434****	**-0.344***	**0.529*****	-0.128
SE 1500	0.071	0.069	-0.055	0.064	-0.076	-0.034	-0.015	0.104	0.098	-0.273
S 1500	0.180	**0.369****	0.233	-0.074	**-0.319***	0.068	0.101	**0.322***	-0.082	**-0.340***
SW 1500	0.131	**0.350***	**0.463*****	-0.200	**-0.344***	-0.015	**0.327***	**0.490*****	**-0.356***	-0.238
W 1500	0.085	0.255	**0.561*****	-0.264	**-0.295***	0.230	**0.404****	**0.338***	**-0.305***	-0.207
NW 1500	-0.108	-0.191	0.203	-0.061	0.008	0.154	0.047	0.090	-0.021	-0.111

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS
OF WIND DIRECTION AND STRENGTH.

TABLE 7.4

PEARSON'S CORRELATION COEFFICIENTS FOR CAPE WRATH WIND DATA, MARCH, APRIL AND MAY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	**6-7** 0300	**4-5** 0300	**1-3** 0300	**Calm** 0300	**8+** 1500	**6-7** 1500	**4-5** 1500	**1-3** 1500	**Calm** 1500
N 0300	-0.041	-0.129	0.047	0.072	-0.081	-0.039	-0.129	0.043	0.065	-0.130
NE 0300	-0.157	-0.123	-0.211	0.201	0.250	-0.122	-0.044	-0.201	0.234	0.151
E 0300	-0.018	-0.002	-0.023	0.123	-0.226	0.049	0.055	-0.020	0.004	0.095
SE 0300	-0.242	**-0.313***	-0.039	0.219	0.141	-0.172	-0.266	0.010	0.123	**0.391****
S 0300	-0.187	-0.156	-0.211	**0.375****	-0.100	-0.122	-0.180	-0.101	0.178	0.081
SW 0300	0.266	**0.515*****	**0.551*****	**-0.648*****	**-0.476*****	0.180	**.0467*****	**0.421****	**-0.567*****	**-0.582*****
W 0300	**0.454****	**0.423****	0.238	**-0.468*****	-0.282	**0.407****	**0.315***	0.166	**-0.390****	**-0.518*****
NW 0300	-0.036	0.063	0.138	-0.215	0.169	-0.185	0.064	0.100	-0.044	-0.004
N 1500	-0.001	-0.025	0.015	0.041	-0.097	-0.034	-0.009	-0.060	0.108	-0.118
NE 1500	-0.125	-0.051	-0.215	0.200	0.147	-0.109	0.112	-0.209	0.195	0.158
E 1500	-0.053	-0.052	0.007	0.109	-0.166	-0.021	-0.010	0.095	0.018	-0.019
SE 1500	-0.195	-0.269	-0.145	0.225	0.260	-0.083	-0.203	-0.098	0.179	**0.363***
S 1500	-0.135	-0.225	-0.277	**0.367****	0.105	-0.111	-0.212	-0.161	0.260	0.147
SW 1500	0.106	0.191	**0.388****	**-0.364***	-0.280	0.054	0.143	**0.433****	-0.257	**-0.528*****
W 1500	**0.484*****	**0.484*****	0.118	**-0.384****	**-0.325***	**0.460****	**0.384****	0.124	**-0.364***	**-0.447****
NW 1500	-0.046	-0.037	0.056	-0.112	0.229	-0.159	0.039	-0.053	0.053	0.098

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS OF WIND DIRECTION AND STRENGTH.

TABLE 7.5

PEARSON'S CORRELATION COEFFICIENTS FOR TIREE WIND DATA, MARCH, APRIL AND MAY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	**6-7** 0300	**4-5** 0300	**1-3** 0300	**Calm** 0300	**8+** 1500	**6-7** 1500	**4-5** 1500	**1-3** 1500	**Calm** 1500
N 0300	**-0.394****	-0.270	**0.427****	-0.024	-0.190	**-0.298***	-0.181	**0.464*****	-0.241	-0.023
NE 0300	-0.057	-0.067	-0.202	**0.297***	-0.214	0.032	-0.080	-0.136	0.201	-0.140
E 0300	0.268	0.265	-0.136	-0.268	**0.407****	**0.361***	0.004	0.246	0.062	**0.471*****
SE 0300	-0.011	-0.230	0.074	0.104	-0.016	0.238	-0.199	-0.076	0.172	-0.039
S 0300	-0.026	-0.020	0.018	0.084	-0.205	0.028	0.000	0.200	-0.138	-0.239
SW 0300	**0.301***	**0.432****	-0.181	-0.115	-0.168	-0.127	**0.414****	-0.265	-0.002	-0.097
W 0300	0.125	0.050	-0.132	0.133	-0.207	0.003	0.168	-0.130	0.062	**-0.300***
NW 0300	-0.195	-0.164	0.259	0.039	-0.268	**-0.322***	-0.015	**0.330***	-0.199	-0.168
N 1500	**-0.295***	**-0.332***	0.123	0.210	-0.118	-0.181	**-0.301***	0.279	0.003	-0.090
NE 1500	0.111	-0.140	-0.005	0.178	-0.264	-0.009	-0.090	-0.014	0.118	-0.207
E 1500	0.197	**0.346***	-0.113	**-0.330***	**0.419****	**0.318***	0.012	-0.102	-0.083	**0.553*****
SE 1500	0.137	-0.070	-0.032	-0.061	0.270	**0.403****	-0.147	-0.180	0.161	0.162
S 1500	-0.155	-0.112	0.031	0.175	0.258	-0.036	0.032	0.042	0.013	**-0.332***
SW 1500	**0.376****	**0.328***	-0.260	-0.048	-0.046	-0.034	0.286	**-0.310***	0.122	-0.152
W 1500	0.142	0.261	-0.053	-0.069	-0.197	-0.113	**0.322***	-0.029	-0.139	-0.178
NW 1500	**-0.405****	-0.216	**0.340***	-0.036	-0.071	**-0.438****	0.002	**0.334***	-0.210	-0.086

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS OF WIND DIRECTION AND STRENGTH.

TABLE 7.6

PEARSON'S CORRELATION COEFFICIENTS FOR ESKDALEMUIR WIND DATA, MARCH, APRIL AND MAY.

SIGNIFICANT COEFFICIENTS IN BOLD, * 95% LEVEL, ** 99% LEVEL, ***99.9% LEVEL.

	8+ 0300	6-7 0300	4-5 0300	1-3 0300	**Calm** 0300	8+ 1500	6-7 1500	4-5 1500	1-3 1500	**Calm** 1500
N 0300	-0.270	-0.278	**-0.461*** **	**0.318***	0.041	-0.205	-0.291	-0.049	0.195	-0.156
NE 0300	0.074	0.024	0.288	-0.024	-0.174	0.173	-0.122	-0.089	0.069	0.138
E 0300	0.001	-0.197	0.239	0.092	-0.211	-0.046	-0.135	**-0.525*** **	**0.363***	**0.513*** **
SE 0300	0.093	-0.001	**0.364***	0.153	**-0.407** **	-0.061	-0.051	**-0.298***	0.219	0.224
S 0300	0.029	0.045	0.246	**0.359***	**-0.558*** **	0.017	-0.009	**0.305***	-0.151	**-0.401** **
SW 0300	0.286	**0.296***	**0.357***	0.104	**-0.427** **	0.212	0.281	0.160	-0.196	-0.189
W 0300	0.093	0.274	0.247	-0.137	-0.089	0.102	0.275	-0.057	-0.076	0.101
NW 0300	-0.133	-0.143	-0.016	**0.420** **	**-0.364***	0.004	-0.149	0.145	0.051	**-0.482*** **
N 1500	-0.206	-0.053	-0.261	-0.015	0.210	-0.118	-0.090	-0.137	0.152	-0.009
NE 1500	-0.073	0.084	0.024	-0.180	0.157	0.083	0.016	-0.036	-0.037	0.219
E 1500	-0.044	**-0.488*** **	-0.106	0.253	-0.085	-0.122	**-0.369** **	**-0.496*** **	**0.463*** **	**0.356***
SE 1500	0.039	-0.109	-0.082	0.056	0.018	-0.032	-0.088	**-0.423** **	**0.328***	0.240
S 1500	-0.038	0.135	-0.165	-0.025	0.104	-0.031	0.097	**0.[illegible]0***	-0.179	**-0.415** **
SW 1500	0.218	0.091	0.180	0.230	**-0.391** **	0.044	-0.035	0.172	-0.076	-0.235
W 1500	-0.008	**0.308***	0.170	-0.136	-0.042	0.092	**0.388** **	0.214	-0.269	-0.194
NW 1500	-0.094	-0.106	0.130	-0.104	0.056	-0.047	-0.002	**0.298***	-0.203	-0.182

CORRELATION MADE BETWEEN FREQUENCY OF OBSERVATIONS OF WIND DIRECTION AND STRENGTH.

strengths of 8+ at Eskdalemuir were the data not normally distributed.

Correlations between wind direction and strength, using Pearson's Product Moment correlation coefficient, were made. The results of the correlations can be seen in Tables 7.1 to 7.6. Significant correlations at the 95%, 99% and 99.9% level are marked and indicate the following relationships:

1. December, January and February.

Gales and winds of up to Force 6 at **Cape Wrath** most often occur in south-westerly, westerly and north-westerly air streams, while light winds come from the north-east, east or south-east.

At **Tiree** gales are positively related to south-easterly airflow at 0300 hours and negatively to northerly or north-easterly airflow, while these last two directions are positively correlated to light winds. Force 6-7 winds correlate negatively with north and north-easterly airflow and positively with westerly and south-westerly flow.

At **Eskdalemuir** the data for gales are not normally distributed, with winds of such force rare at this station. However, Force 6-7 winds are negatively correlated to north, north-east and easterly flow and positively to south-west and westerly flow. The same pattern is observed for Force 4-5 and reversed for light winds.

2. March, April and May.

Cape Wrath has positive correlation between the frequency of gales and westerly winds, and between Force 6-7 and westerlies and south-westerlies. Force 6-7 is also negatively correlated to south-easterlies at 0300 hours. Force 4-5 is positively correlated to south-westerlies, while south-westerlies and westerlies are negatively correlated to light winds and calm weather. Thus high wind speeds are associated with westerly flow.

Tiree has most gales from the south-west at 0300 hours, but by 1500 the preferred directions are east and south-east. Meanwhile fewest gales come from the north and north-west. For Force 6-7 westerly and south-westerly flow is positively correlated, with northerly flow negatively related, while at Force 4-5 this relationship is reversed. Light winds generally come from the east or north-east.

There is no correlation for gales at **Eskdalemuir** during the spring, but strong winds are predominantly westerly and south-westerly in direction, and not easterly. Moderate winds in the afternoon may come from the south or north-west, and light winds from the east and south-east, while in the morning moderate winds are predominantly south-easterly and south-westerly and light winds northerly, north-westerly or southerly.

There is broad general agreement between Cape Wrath and Tiree on which directions produce the strongest winds, but the situation at Eskdalemuir is slightly different, with some anomalous values, such as the difference in wind direction for moderate and light winds from morning to night. Tiree and Cape Wrath were specifically chosen because of their coastal and unsheltered locations, affording the best possible record of wind speed and direction through time, unaffected by topography and changes in land use such as have been described for Eskdalemuir. This last station was chosen because of its southerly and upland location, but problems with changes in the instrumentation used and land use in the surrounding area do exist. The station is also topographically sheltered, to a certain extent, though the degree of sheltering of the wind vane and anemometer has changed since it was moved from the top of the Observatory and placed in more open country (Mike Porter, 1997, Met. Office, pers. obs.). Therefore the relationship between wind direction, wind strength and other variables at this station should be treated with caution, as should any changes which may be observed in the 49 years of data. The strong effect of sheltering is apparent in terms of windiness. As an upland station, Eskdalemuir should experience stronger winds than its lowland counterparts, but both Tiree and Cape Wrath are windier. Thus the level of sheltering at Eskdalemuir must be very high. The snow data and pressure are least likely to be affected and may be used with more confidence.

Correlations between snowfall, wind direction and strength are not shown in their entirety, but the statistically significant correlations (for the same station unless otherwise stated) are given in Table 7.7. There is a strong association at all stations between snowfall and high winds, and between snowfall and north-easterly winds at Tiree. The correlation with high winds, which generally are positively correlated themselves with zonal flow, suggests that much snowfall comes from westerly quarters, though the variability in actual direction may have obscured the association. The correlation with high winds does, however, confirm the importance of drift during precipitation events and indicates that accumulation areas which become late snowbeds are offered a consistent and substantial supply of snow whenever precipitation takes place.

Correlations between snow-lie, air and ground frost are too numerous to mention individually, but significant values consistently occur between the snow and frost data and north-easterly winds at Tiree at 1500 hours, and calm weather at Eskdalemuir at 1500 hours. Negative values are achieved for south-westerlies at Eskdalemuir at 1500

TABLE 7.7

STATISTICALLY SIGNIFICANT CORRELATIONS BETWEEN SNOWFALL, WIND DIRECTION AND WIND STRENGTH FOR CAPE WRATH, TIREE AND ESKDALEMUIR.

VARIABLE 1	VARIABLE 2	Correlation co-efficient.
CW snowfall	CW 0300 8+	0.307*
CW snowfall	CW 0300 6-7	0.295*
CW snowfall	CW 0300 1-3	-0.325*
CW snowfall	TIR 1500 NE	0.304*
TIR snowfall	TIR 0300 8+	0.296*
TIR snowfall	TIR 1500 8+	0.327*
TIR snowfall	TIR 0300 6-7	0.391**
TIR snowfall	TIR 1500 6-7	0.403**
TIR snowfall	TIR 0300 1-3	-0.342*
TIR snowfall	TIR 1500 NE	0.297*
ESK snowfall	ESK 0300 4-5	0.298*
ESK snowfall	ESK 0300 1-3	-0.302*
ESK snowfall	ESK 1500 1-3	-0.296*
ESK snowfall	ESK 1500 CALM	0.295*
ESK snowfall	TIR 1500 NE	0.360*

hours in relation to air and ground frost. The pressure level at Cape Wrath also shows a strong negative correlation for snowfall at Tiree and Eskdalemuir, indicating that low pressure to the north of Scotland, rather than further south, is largely responsible for falls of snow in the southern part of the country.

The information obtained from the Snow Survey of the level of snowlie on Ben Nevis and Creag Meagaidh from 1953 onwards was averaged for each of the months in which it was recorded (October to May) and correlated with wind data from Cape Wrath, Tiree and Eskdalemuir. For the December, January and February period, the mean level of snowlie was correlated strongly and positively with westerly winds at Tiree, and negatively with northerly, north-easterly and easterly winds. At Cape Wrath the positive correlations were with gale force winds and south-westerlies, and negative with northerlies, while at Eskdalemuir the positive values were for south-westerlies and negative for south-easterlies. The snowlie figures are higher for higher snow lines, so low snow lines produce negative correlation in this analysis. The standard deviation of snowlie for each month showed a very similar pattern of correlation, with high variability of snow line, as well as generally high snow lines most associated with windiness and winds from westerly quarters, and low snow lines and variability with easterlies. In the spring period the pattern changes, with southerly and south-easterly winds responsible for high snow lines and high variability of snowlie, and westerly through to northerly winds keeping snow lines low and less variable.

This shows a fundamental difference between the precipitation of snow and its durability. Snow falls most often, according to the correlation above, on high winds, but these high winds are also largely responsible for the removal of snow by melting. The crucial factor for the permanence of snowlie is therefore low temperature associated with wintertime easterlies and spring northerlies, and also moderate or light rather than strong winds, especially at night to allow radiative cooling, since strong winds are largely westerly and south-westerly and are milder than easterlies or northerlies. In spring low winds are more strongly associated with high snow lines, more probably from the higher daytime temperatures which can build up during the longer hours of daylight under such conditions. The springtime association between low snow lines and westerlies is interesting, since it indicates that these moist and generally mild air flows bring more snow to the hill in spring, rather than removing it. This is not, however, the case in the winter. The difference in the altitudinal lapse rate, being at its steepest in spring, must be responsible for the change in the influence of westerlies, with snow falling in spring at lower altitudes than in winter on a westerly air streams.

The connections between snowfall, snow-lie and climate are thus established, centred on the occurrence and strength of westerly, zonal flow and the seasonal variations in lapse rates. Lack of data from higher levels and difficulties in assessing the depth of snow accumulation at different sites and on different aspects makes the connection between climate and specifically the late snowbeds harder to establish, but consistency in prevailing winds and thus the location of the late snowbeds reduces the level of uncertainty somewhat. More information is still needed on the development of the snowpack at late snowbed sites, particularly in the western Highlands, before the relationship between climate and late snowbeds can be firmly established for the winter half-year. A programme of survey of snow depth and morphology is therefore recommended.

The implications of the climate - snow link are important if there is any identifiable shift towards a more strongly zonal flow over Scotland during the winter and spring months. Mayes (1996) shows how the enhanced vigour of the mid-westerly circulation is changing the seasonal distribution of precipitation, with higher values in the winter half-year, particularly in the north-west of Britain, and lower values in the summer. This is consistent with many of the global models for future climatic change (Houghton *et. al.*, 1996). According to the relationships outlined above, stronger zonal circulation with more westerly flow and less easterly flow and light winds, will increase the amount of snowfall in the west and north of Britain, but may reduce the duration of snowlie, at least at lower levels, in the winter. An interesting aspect of this is that at higher levels, where snowlie is more consistent (Watson, Davison and French, 1994; Pottie, 1994), greater accumulations may form, particularly on eastern slopes, and therefore the distribution of snow melt may change, showing greater variability with decreasing altitude and also on different aspects at the same altitude. In spring, instead of the snow line being raised by a continuation of the strong zonal flow, its effect reverses, bringing snow lines down and keeping them down. This hypothesis of a shift in the snow regime from winter to spring is apparent in the observations made by Green (1975), identifying a two-part snowlie half-year, with thaws in January and a possible shift of the whole snow season to slightly later in the winter and spring.

In order to identify any trends within the data collected, least squares linear regression analysis of the data against year number was undertaken. The results for the winter and spring quarters of the year for wind direction and strength for 49 years of data are given in Table 7.8. A number of significant changes can be observed, most particularly in the incidence of calm weather and different wind speeds in general, plus changes in

TABLE 7.8

VALUES OF THE RATIO OF SAMPLE VARIANCES (*F*) AND SIGNIFICANCE OF LEAST SQUARES LINEAR REGRESSION FOR WIND FREQUENCY DATA AT CAPE WRATH, TIREE AND ESKDALEMUIR, 0330 AND 1500 hours.
THE DIRECTION OF THE TREND IS INDICATED BY THE SYMBOL IN THE BOTTOM RIGHT-HAND CORNER OF THE CELL.

* = 95% confidence level ** = 99% confidence level *** = 99.9% confidence level

D, J, F	N	NE	E	SE	S	SW	W	NW	Calm	8+	6-7	4-5	1-3
CW 0300	0.64 0.429	3.85 0.056	0.25 0.617	0.01 0.922	1.62 0.209	0.66 0.422	**4.59 + 0.037	**9.84 – 0.003	0.71 0.402	***22.01 + 0.000	*6.93 + 0.011	**9.34 – 0.004	*4.54 – 0.038
CW 1500	2.67 0.109	2.49 0.121	0.35 0.557	0.10 0.752	0.11 0.741	0.09 0.760	3.56 0.065	2.36 0 131	0.57 0.454	***18.20 + 0.000	**8.07 + 0.007	**12.21 – 0.001	2.94 0.093
TIR 0300	*4.26 – 0.044	1.11 0.297	1.33 0.254	0.06 0.809	0.18 0.677	2.93 0.094	1.30 0.259	2.63 0.111	***14.98 – 0.000	2.53 0.118	2.48 0.122	3.14 0.083	1.12 0.295
TIR 1500	1.39 0.245	0.66 0.419	1.12 0.294	0.05 0.833	0.09 0.768	0.02 0.893	1.74 0.194	3.17 0.081	3.21 0.080	0.77 0.383	1.78 0.189	*4.29 + 0.031	2.33 0.134
ESK 0300	3.14 0.083	0.62 0.434	1.37 0.247	0.71 0.403	**10.51 + 0.002	0.06 0.805	0.42 0.520	0.73 0.398	**7.93 – 0.007	0.02 0.879	0.04 0.852	0.90 0.349	2.24 0.141
ESK 1500	2.59 0.114	0.75 0.392	0.00 0.992	0.10 0.745	***14.24 + 0.000	0.46 0.503	0.01 0.926	0.52 0.476	**8.65 – 0.005	0.00 0.961	2.01 0.163	1.48 0.229	1.92 0.172
M, A, M	N	NE	E	SE	S	SW	W	NW	Calm	8+	6-7	4-5	1-3
CW 0300	1.18 0.282	1.16 0.286	0.09 0.765	0.01 0.906	1.15 0.288	0.80 0.375	**9.20 + 0.004	**9.89 – 0.003	0.91 0.344	**9.27 + 0.004	3.41 0.071	1.08 0.305	0.30 0.589
CW 1500	2.02 0.162	0.35 0.559	0.00 0.990	0.26 0.611	0.00 0.974	3.81 0.057	*5.84 + 0.020	0.70 0.407	1.70 0.198	***11.73 + 0.001	1.37 0.248	**9.22 – 0.004	0.33 0.567
TIR 0300	1.84 0.182	1.36 0.249	0.30 0.585	2.07 0.157	0.32 0.572	0.00 0.985	0.37 0.546	0.23 0.636	3.18 0.081	2.88 0.096	1.58 0.215	3.19 0.081	1.45 0.234
TIR 1500	1.31 0.259	0.03 0.854	0.29 0.591	2.72 0.106	0.11 0.742	0.75 0.390	0.40 0.532	1.35 0.251	0.79 0.378	0.09 0.760	1.71 0.197	*6.88 + 0.012	**10.98 – 0.002
ESK 0300	***33.90 + 0.000	***20.44 – 0.000	***14.95 – 0.000	**9.31 – 0.004	*4.98 + 0.030	**7.58 – 0.008	**7.75 – 0.008	**8.68 + 0.005	*5.34 0.025	*5.34 0.025	*4.89 – 0.032	***11.59 – 0.001	3.33 0.074
ESK 1500	2.59 0.114	0.10 0.750	0.83 0.368	0.01 0.936	***12.51 + 0.001	1.84 0.182	2.07 0.157	0.14 0.705	3.54 0.066	*6.48 0.014	*4.07 – 0.049	2.17 0.147	0.00 0.953

westerly and north-westerly winds at Cape Wrath in both quarters, and southerly winds at Eskdalemuir in winter. Significant changes also take place at Eskdalemuir in wind direction at 0300 in spring, but this pattern is not reflected in the data for 1500, except for southerlies. The direction of change, either an increasing or decreasing trend, needs to be examined before any conclusions about the origin of these changes can be drawn.

Trend analysis using a linear or quadratic model for the wind directions and strengths which show significant change through the regression analysis was performed. The analysis used was the MINITAB Time Series Trend Analysis which fits a particular type of trend line - linear, quadratic, growth curve or S-curve - to a time series. The fitted trend equation is shown at the top of every trend graph while three values of accuracy are also shown: MAPE (Mean Absolute Percentage Error), expressed in percent; MAD (Mean Absolute Deviation) using the same units as the data; and MSD (Mean Squared Deviation) which is similar to mean squared error and uses a common denominator, n, which allows comparison between different models.

Some of the linear models were unsatisfactory, with poor fit at one end of the time series, so where appropriate, a quadratic model was used. On two occasions neither model gave a good visual fit and a 5-year moving average was added to the data to present some indication of trend.

Graph plots of the data gave the opportunity to observe any non-gradual changes which may have occurred as a result of changes in instrumentation, although personal assurances from staff at the Met. Office indicated that these would not be apparent in data of as low resolution as monthly totals. Trend analysis graphs for all the statistically significant trends are given in Appendix II. The first data to be investigated were those from Eskdalemuir, since the trends are confined to 0300 hours at that station alone and occur for all directions. It is also the station which is most likely to be affected by changes in nearby afforestation, changes in the siting of instruments in 1965 and the introduction of digital logging equipment in 1980 (Young, 1985). Step changes in the graphs are quite obvious in the following cases for March, April and May:

0300 hours	SE, NW, calm, Force 6-7
1500 hours	Force 6-7

The other graphs do show, in some instances, a high degree of non-linearity and, in the case of easterly winds, a step change at a different time, in 1971; although it is likely that some of these trends reflect real changes in the winds experienced over a wide area, the difference of the shape of some of the graphs, and knowledge that afforestation could be affecting the data in the same way, though less identifiably, it seems prudent to discard the Eskdalemuir data unless at a later stage it is necessary to use it to support data from the other two stations, unaffected by nearby changes in land use.

A further data problem illuminated by the Eskdalemuir spring data for winds of Force 4-5 at 0300 hours, is that the trend observed in the whole data set by regressions analysis is largely driven by the first ten years of data. Removal of those years reduces the significance of the trend to a 95% confidence limit from the 99.9% limit for the full 49 years. This problem is much more severe in spring wind speed data from Tiree and Cape Wrath; Tiree 1500 hours Force 4-5 trend is driven by exceptionally low values in years 3, 4, and 5. Removal of the first five years and regression of the remaining data reduces the value of the ratio of sample variances (F) to 0.54 and increases p to <0.468. For Cape Wrath Force 4-5 0300 hours removal of the first 4 years reduces F to 1.44 and increases p to <0.236, while for 1500 hours removal of the first eight years makes $F = 0.29$ and $p < 0.592$.

Similarly, Force 1-3 at Cape Wrath, the trend is driven by the last four years of data. Removal of these changes the 0300 hour statistics to $F = 0.00$ and $p < 0.951$ and the 1500 hour statistics to $F = 0.03$ and $p < 0.856$. It is thus possible to conclude that a significant change in light winds in spring at Cape Wrath has taken place over the latter part of the 1980's and early 1990's, after a long period without change. The trend data for Force 4-5 at Cape Wrath and Tiree does not provide any evidence of change in the past 40 years.

Relatively few of the records for December, January and February are affected by the problems found in the spring quarter outlined above. The south-east and north-west data from Eskdalemuir which demonstrate the most significant effects of the resiting of the instruments in 1965 are not statistically important, nor do they demonstrate the same step changes observed in the spring data. The reasons for this are not clear, but although the implication is that resiting may not be as crucial a factor in the trends observed, it is considered unwise not to discard the spring data. Change in the type of instrument used does, however, affect the calm weather data from Eskdalemuir for the winter period, and therefore the trend indicated by regression is also discarded. This is because the new digital anemometer is less responsive to very light winds than the old-style instrument; once moving, it can maintain movement very effectively in very light winds, but it takes gusts of about 6 knots to actually start moving (Met. Office, pers.

comm.).

In summary, many of the statistically significant trends indicated by regression analysis are not considered to be valid, but a number do still stand out as being apparently unaffected by extraneous factors. These include, for the winter quarter-year, an increase in westerly winds and high winds at Cape Wrath, and a decrease in north-westerlies and moderate or light winds. These changes are more apparent at 0300 hours and represent an intensification of zonal flow as shown by Mayes (1996). A similar pattern is repeated in spring for the same station, though the change is less strong. The pattern is not repeated at Tiree or Eskdalemuir.

Another way of looking at changes in zonal flow, and particularly an intensification of depressions, is to examine the pressure data. These are the monthly averages and have been examined on a month-by-month basis. Significant changes have taken place in March and April. Linear trend models for pressure in March at Cape Wrath, Tiree, Eskdalemuir and the difference between Cape Wrath and Eskdalemuir are shown in Figures 7.1 to 7.4, with least squares linear regression values for changes through time as follows:

Cape Wrath	$F = 10.54$,	$p <$ **0.002****
Tiree	$F = 8.43$,	$p <$ **0.006****
Eskdalemuir	$F = 6.71$,	$p <$ **0.013****

The linear trend for the pressure difference between Cape Wrath and Eskdalemuir is shown, which, although not significant in regression analysis, shows a definite trend to increase, with the negative trend at Cape Wrath stronger than that at Eskdalemuir.

FIGURE 7.1

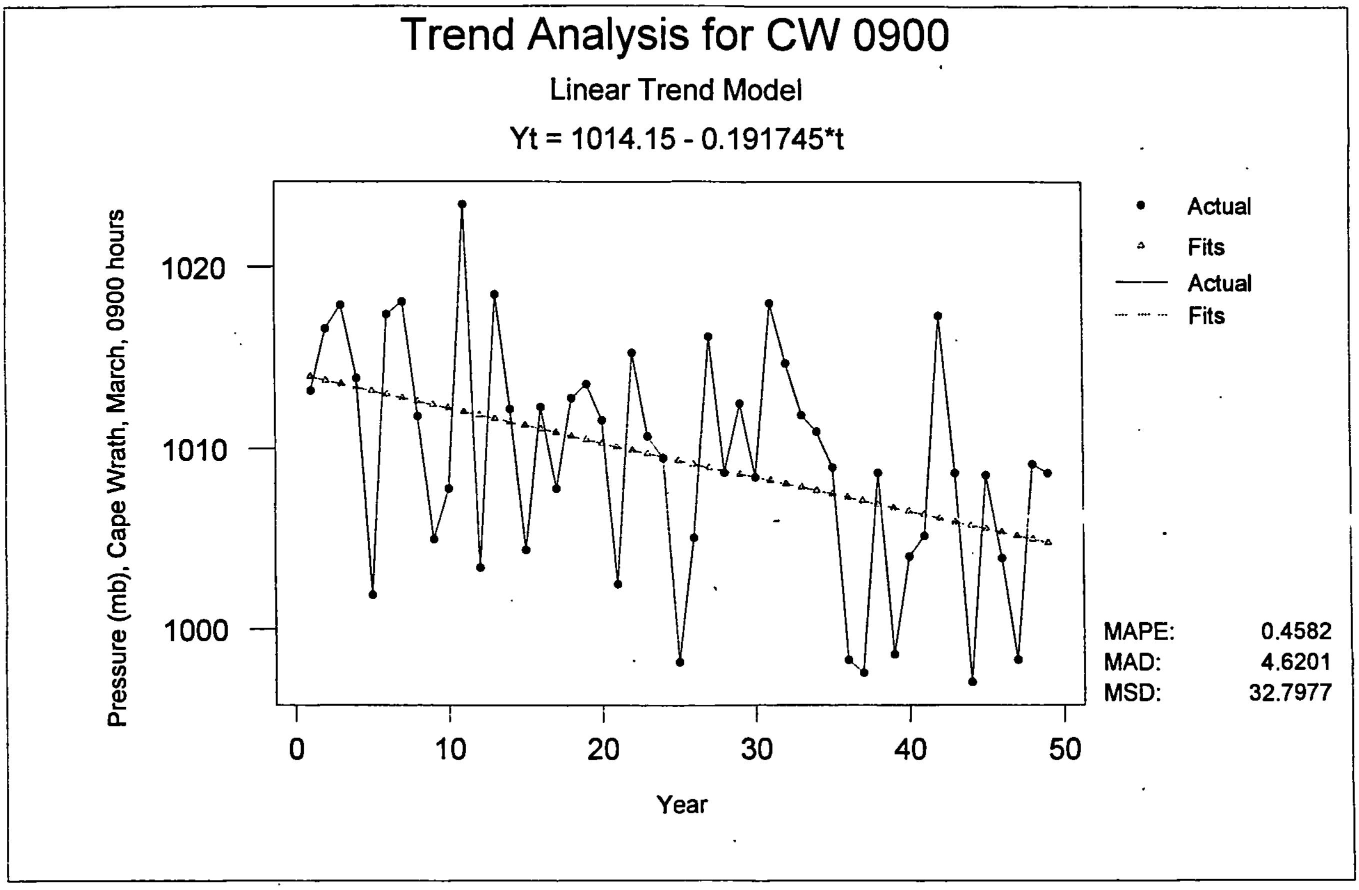


FIGURE 7.2

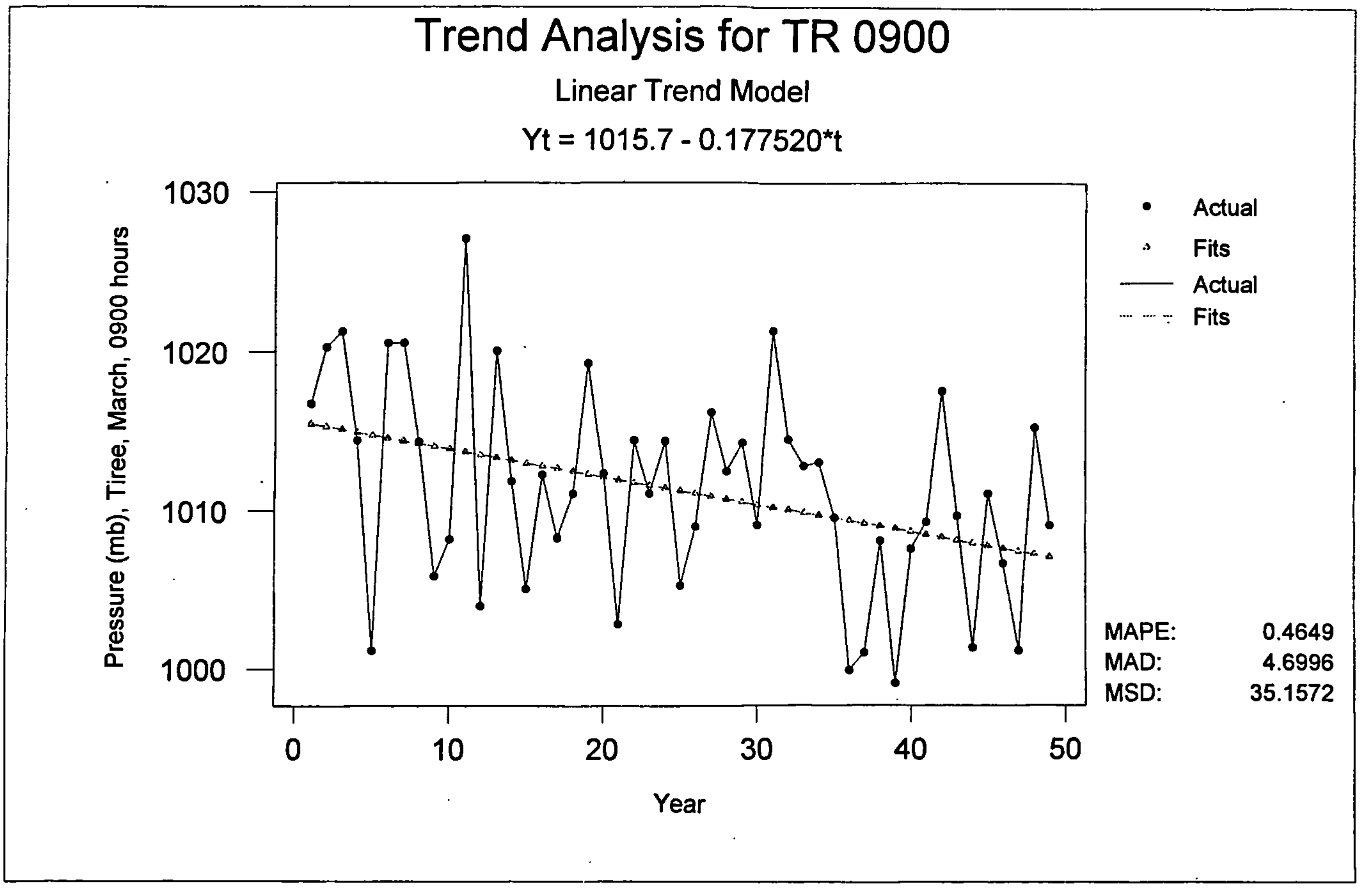


FIGURE 7.3

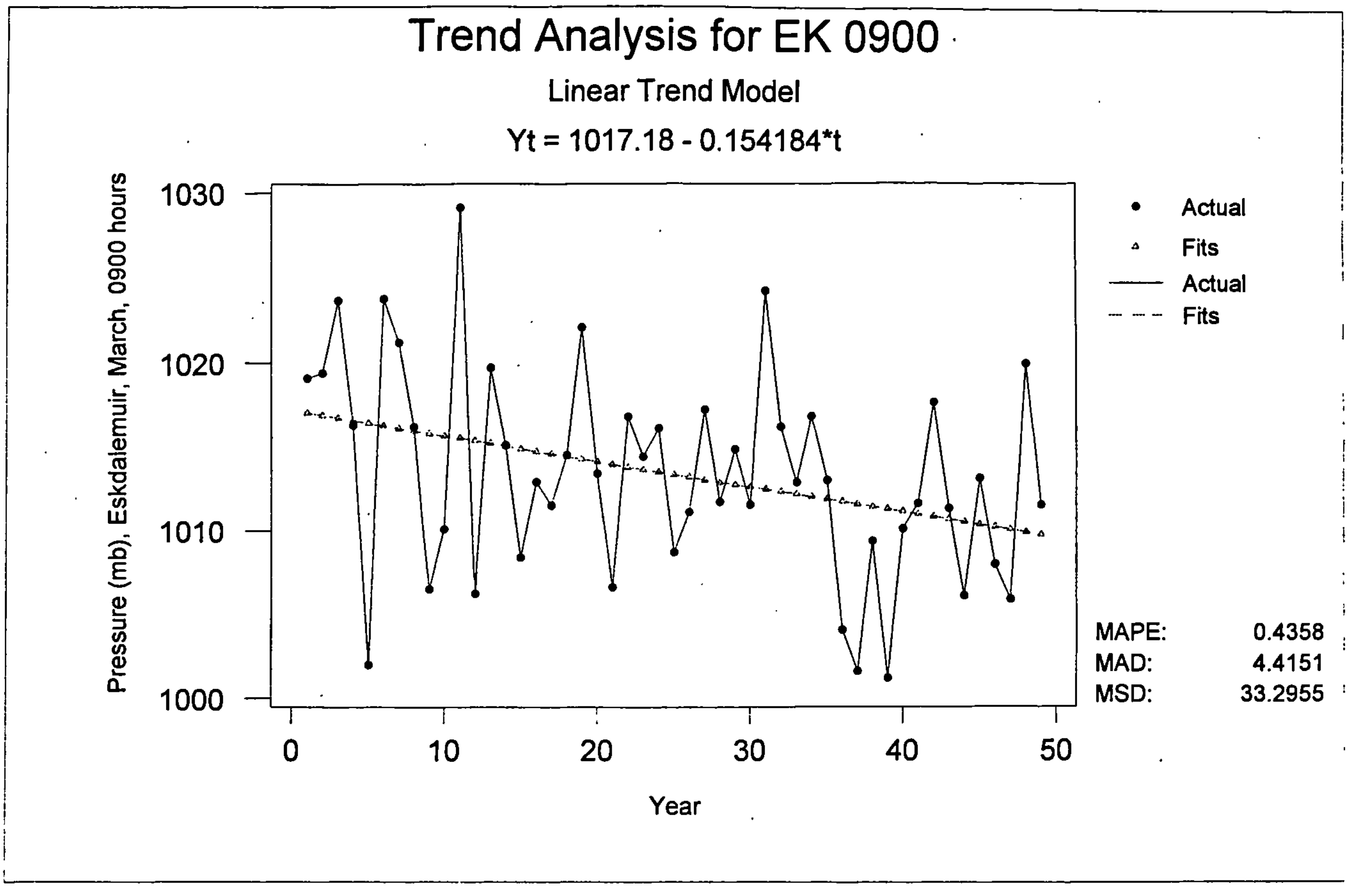


FIGURE 7.4

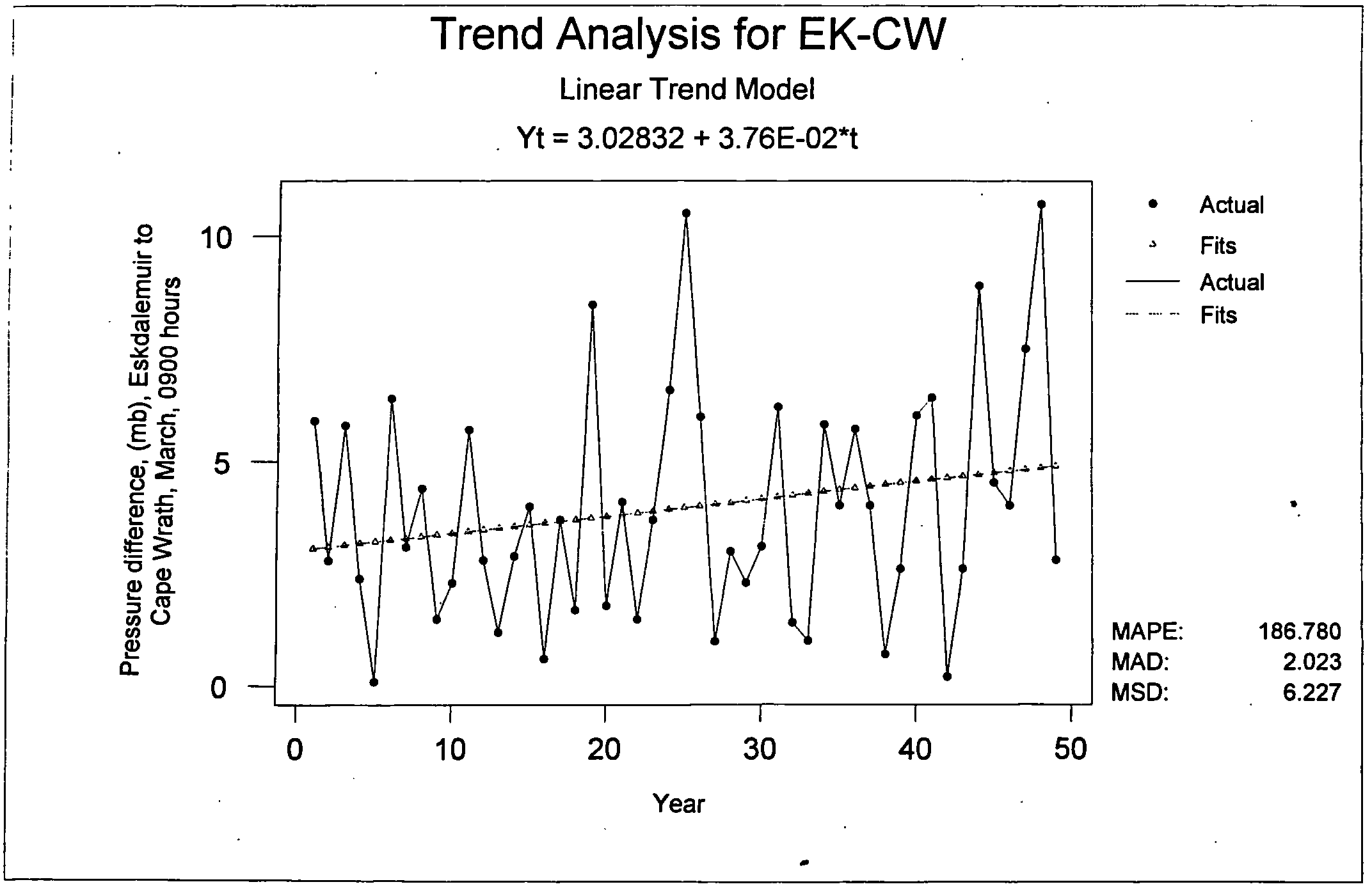
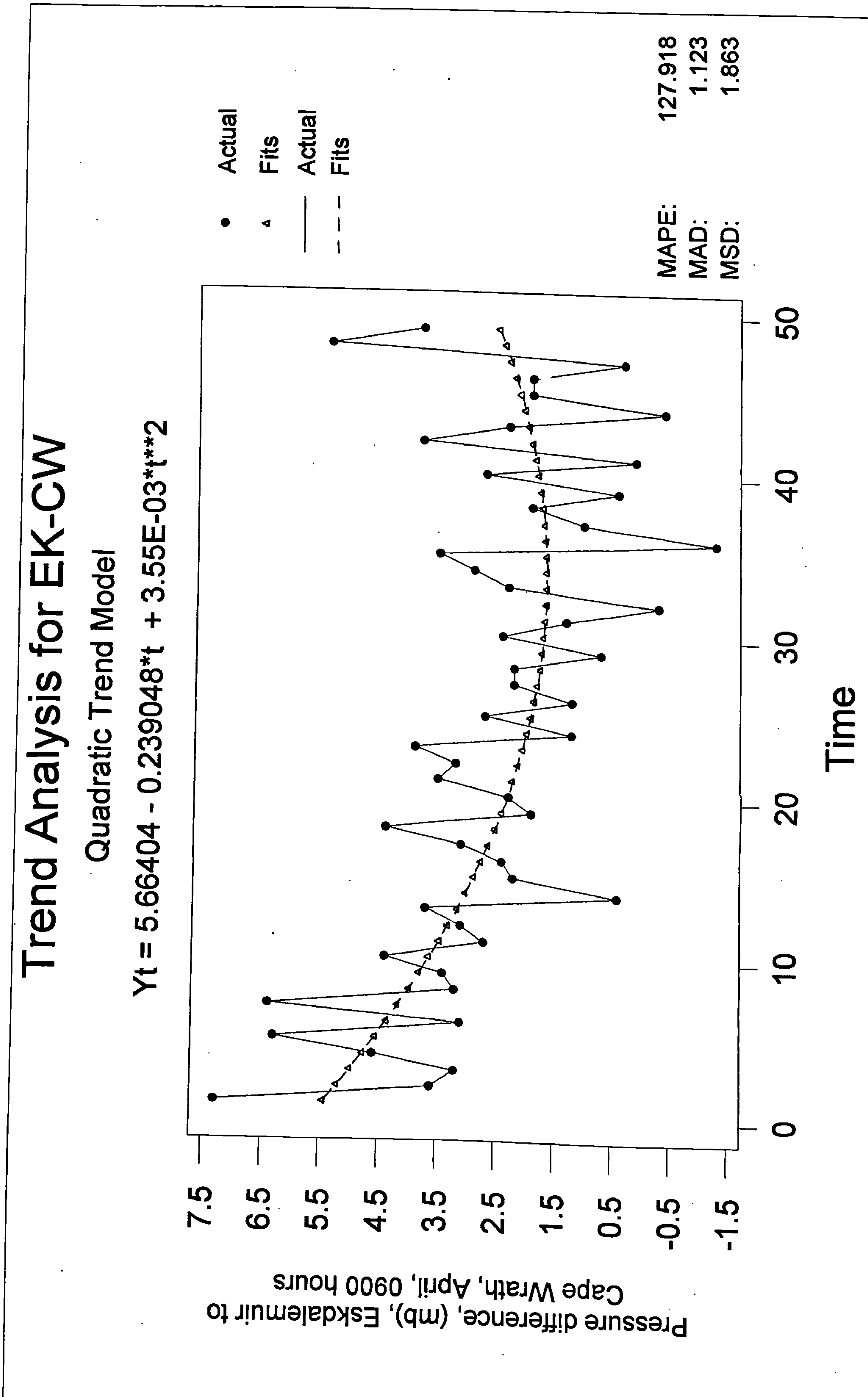


FIGURE 7.5


Trend Analysis for EK-CW
Quadratic Trend Model
Yt = 5.66404 - 0.239048*t + 3.55E-03*t**2
Actual
Fits
Actual
Fits
MAPE: 127.918
MAD: 1.123
MSD: 1.863
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
Pressure difference, (mb), Eskdalemuir to Cape Wrath, April, 0900 hours
0
10
20
30
40
50
Time

This can be seen from the equation describing the line of trend: Eskdalemuir has the equation Yt = 1017.18 - **0.154*t** while Cape Wrath data generate the equation Yt = 1014.15 - **0.192*t** (bold indicates the values describing the steepness of the line).

The pattern in April is a little different, with no significant trends for Tiree and Eskdalemuir as individual stations, but Cape Wrath shows a definite decrease in pressure and the pressure difference between stations is significant, as follows:

Cape Wrath	$F = 3.79$,	$p <$ **0.057**	negative trend
Tiree - Cape Wrath	$F = 3.03$,	$p <$ **0.088**	negative trend
Esk'muir - Cape W.	$F = 15.59$,	$p <$ **0.0001*****	negative trend

The quadratic trend graph for the pressure difference is shown in Figure 7.5, which indicates that the negative trend observed from 1943 to approximately 1980 has been replaced by a rising trend in recent years. This reversal in trend will have reduced the value of F in the regression analysis from a higher value which would be given for the period 1943 - 1980, giving even greater significance to the trend.

These changes in the strength of the pressure gradient between Eskdalemuir and Cape Wrath in March and April are further indications of a strengthening of zonal flow during spring and explain the increases in westerly and high winds observed for this period at Cape Wrath. No changes in pressure were found for December, January or February, in spite of the observed pattern of increased westerlies and high wind speeds at Cape Wrath. The change in westerlies here, though, is taking place at the expense of north-westerlies, indicating that there may be a shift in the latitude of zonal flow, rather than in its intensity. A northwards shift in the Polar Front at this period of the

TABLE 7.9

VALUES OF THE RATIO OF SAMPLE VARIANCES (F) AND p FOR LEAST SQUARES LINEAR REGRESSION OF MONTHS DECEMBER, JANUARY, FEBRUARY AND MARCH AGAINST TIME

0300 hours	**value of *F***	**value of $p <$**	**1500 hours**	**value of *F***	**value of $p <$**
CW SW	9.45	**0.003****	CW SW	2.71	0.102
CW N	16.35	**0.001*****	CW N	29.50	**0.001*****
CW NW	4.61	**0.033****	CW NW	3.75	0.055
TIR SW	4.60	**0.033****	TIR SW	3.62	0.059
TIR W	10.87	**0.001*****	TIR W	6.63	**0.011***
TIR NW	0.16	0.693	TIR NW	0.12	0.733
CW 8+	23.02	**0.001*****	CW 8+	20.33	**0.001*****
CW 6-7	8.97	**0.003****	CW 6-7	13.96	**0.001*****
CW 4-5	0.32	0.570	CW 4-5	0.12	0.732
CW 1-3	14.94	**0.001*****	CW 1-3	27.29	**0.001*****
TIR 8+	1.81	0.180	TIR 8+	1.01	0.317
TIR 6-7	0.21	0.644	TIR 6-7	0.23	0.635
TIR 4-5	0.31	0.576	TIR 4-5	0.86	0.356
TIR 1-3	0.90	0.344	TIR 1-3	0.01	0.913

Other statistically significant or near-significant values of F (ratio of sample variances) are:

Cape Wrath snowfall	$F = 3.44$	$p < 0.065$
Cape Wrath ground frost	$F = 3.40$	$p < 0.067$
Eskdalemuir snowfall	$F = 5.84$	$p <$ **0.017***

year and consequent increase in temperature could account for the difference in the effect of high winds and westerlies on snow lines on the higher hills, whereas the same shift in spring, shown by a similar pattern of north-westerly replacement with westerly, with steeper lapse rates, has the reverse effect on snow lines. However, the changes in wind direction and speed are not found at Tiree (ignoring the Eskdalemuir data) in the periods examined so far. Examination of four months, December, January, February and March together does, however, generate the same responses in south-west, west and north-west winds at Tiree as for Cape Wrath. The changes in wind speed are not represented at Tiree, though the changes at Cape Wrath are strong. Table 7.9 gives the values of F and p for regression against year number for these variables.

The changes in zonal flow are therefore having a marked effect during the coldest four months, more so in the far north than further south, and this change is increasing the amount of snowfall in the far north. It is possible that this change may affect more southern areas in the Highlands, with further increases in spring snowfall consequently likely at higher altitudes, but an increase in mid-winter thaws at lower altitudes.

The data available for snow-lie at all altitudes must now be examined to assess whether this trend is reflected in changes in the snow-lie regime as recorded by the Snow Survey of Great Britain.

7.3 The Snow Survey and Other Sources of Snow-lie Data.

Some of the snow data collected through the Snow Survey has already been used in the monthly weather statistics, usually the Ben Nevis and Creag Meagaidh data monthly means and standard deviation. Other snowlie data for the stations examined has also been processed but unless stated otherwise, significant relationships between these and other variables of wind and pressure were not found. Correlations between snowfall, snowlie, ground frost and air frost produced no unexpected relationships. Days with snowfall were not well correlated with snowlie, or either measures of frost, whereas snowlie, air and ground frost correlated together well. There are indications of an increase in snowfall and groundfrost at Cape Wrath, and snowfall at Eskdalemuir (this latter at the 95% level) but otherwise trends were not discovered for either winter or spring.

The data from Creag Meagaidh and Ben Nevis are shown visually in Figure 7.6 which gives graphs of each year for the duration of snow-lie at different altitudes. Curves which are steeper and further to the left indicate years with relatively little snow. These include, most dramatically, the winters of 1963-4, 1975-6, 1984-5 and 1991-2. Investigation of these curves was made by measuring the gradient between the start and end points, then plotting it against year number using MINITAB's LOWESS command, which generates a smoothed curve between the data given. This plot if shown in Figure 7.7. The plot shows a significant downwards trend in the gradient of the snow line, indicating a reduction in the duration of snowlie averaged over all altitudes, after an increase from the 1940's to the early 1950's.

Least squares regression between the gradient and year number generated an F-statistic of 17.07, significant at the 99.9% level. Therefore it is possible to conclude that snowlie duration averaged over all altitudes on Creag Meagaidh, at least, has decreased from the early 1970's to the early 1990's.

The altitudinal diagrams giving daily snow-lie data in the Snow Survey were carefully examined to give values for the level of the snow line for every day during each winter.

FIGURE 7.6

NUMBER OF DAYS WITH SNOW LYING EACH WINTER, CREAG MEAGAIDH, 259 - 1128m.

SOURCE: THE SNOW SURVEY OF GREAT BRITAIN, MET. OFFICE.
1969-70 MISSING OWING TO INSUFFICIENT DATA.

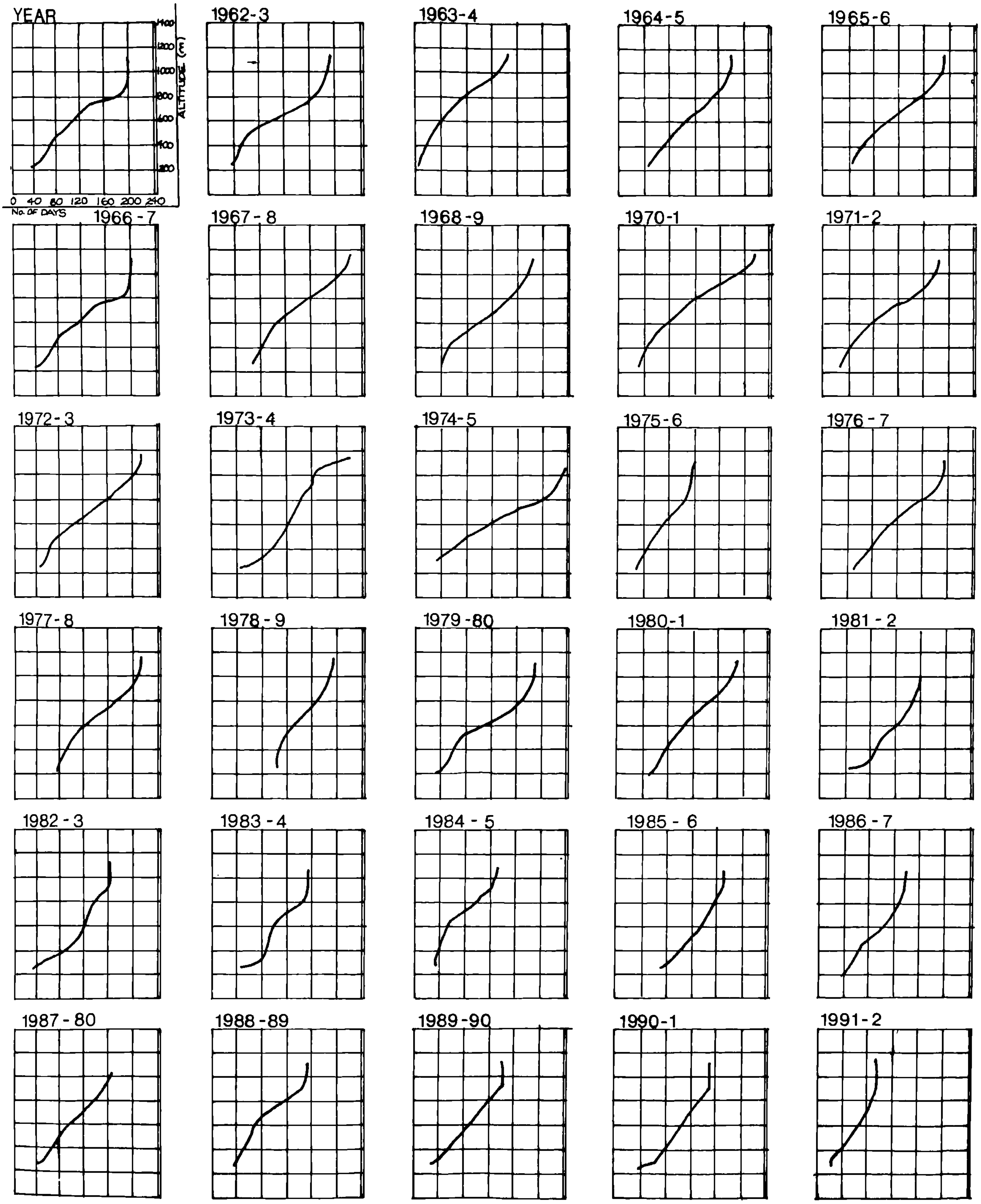
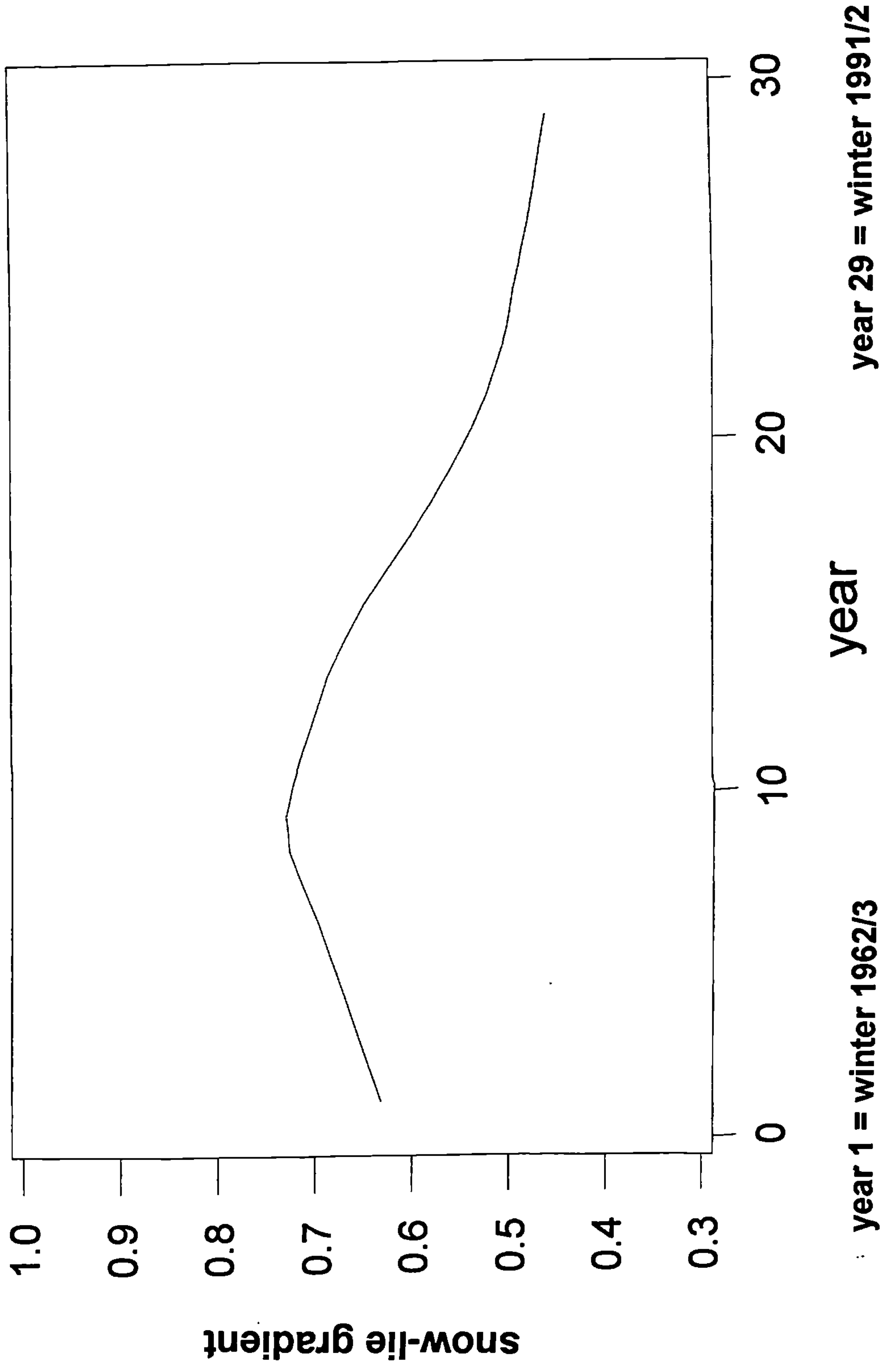


FIGURE 7.7

LOWESS SMOOTHED CURVE OF SNOWLIE GRADIENT
FOR BEN NEVIS / CREAG MEAGAIDH DATA.

snow-lie gradient measured as the average angle of line for number of days with snow lying shown in Figure 7.6



These figures were then reproduced as graphs and are displayed in Appendix III. The index along the *x* axis shows the year numbers from 1 (1953-4) to 39 (1991-2) while the *y* axis gives the observed altitude of the snow line. The altitudes change from feet to metres in the winter of 1966-7.

The extreme years (poor snow years 1963-4, 1971-2, 1975-6, 1984-5 and 1991-2; good snow years 1954-5, 1969-70, 1978-9 and 1981-2) are shown in graphs 11, 19, 23, 32 and 39 for poor years and 2, 17, 26 and 29 (high years). In poor snow years although snowfall is frequent, the removal of snow is both rapid and frequent, giving a more ephemeral snowlie rather than an increase in altitude to which snowfall initially takes place. These winters did not experienced any prolonged spell of cold weather. The year with poorest snow cover is 1991-2, which had some snowfall throughout the year, but snowlie of extremely short duration. In contrast, 1963-4 experienced snowfall within a much shortened time-period in comparison with a normal winter, though this snow remained on the ground for a much longer period.

With the good snow years, graph number 26 (1978-9) shows a late move into winter but a prolonged period of observation-level snow-lie with little thaw during the main part of winter, and a late rise towards spring. Graph 17 shows a bias owing to lack of data from the latter part of the season and although the data which is available indicates that it was probably a reasonably snowy year, it would not have been recorded as an extreme year were it not for the shortage of data. The other two extremely good snow years show slightly different patterns, though all show prolonged periods of snow-lie at low levels; number 2 (1954-5) shows a late decline to winter and a relatively early move to spring, though only late snowfall is recorded. The middle of the winter also shows a fair amount of variability with several thaw incidents. Number

29 (1981-2) is, conversely, very consistent with low-level snow-lie during the main part of winter with only one incident of thaw to summit level, but the winter ends during April, rather than enduring into May. The main difference between these extreme years appears to be the incidence of thaw during the winter and also the length of the winter season. However, the general pattern which is observed is a winter of about 5 months with periodic snowfall interspersed with periods of thaw, when snow-lie can regularly recede to summit level, that is by 1000m, in a matter of a very few days. This illustrates weather patterns found during the passage of Atlantic weather systems of relatively southerly derivation, with warm fronts followed by cold, and then replaced by another warm front as the next depression approaches.

Although these data are useful for indicating snowy and unsnowy years, the depth of accumulated snow is not measured, nor is there any useful information about the distribution of snow at the highest levels. The connections between climate, snowfall and late snowbed accumulation suggest that reductions in snow-lie duration at lower altitudes, particularly in spring, do not necessarily mean a reduction in accumulation at the late snowbed sites, but rather may lead to a steepening of the snow-lie gradient over altitude. Therefore, it is reasonable to conclude that areas of snow accumulation on the western hills which generate the latest-lying snowpatches may benefit positively from years when snowfall is high and the variation in the altitude of the snow line (and thus the standard deviation of snow-lie) is also high. This situation implies a persistence of westerly rather than easterly flow, generating a high degree of loyalty in snowbed accumulation. Although periods of warmer weather intersperse snowfalls, and much of the new snow may disappear, substantial amounts will have accumulated in the snowbed sites on the strong winds which accompany westerly flow in winter.

These warm periods may introduce a thaw to the snowbed sites above 1000m, but removal of the upper snow layers through melting (largely evaporation or sublimation into the warm air stream flowing over it) may be more than compensated for by an increase in snow density caused by melt-freeze metamorphism. Thus although, except in very barren years, the snow line may be variable and prolonged periods of cold weather absent, accumulation for the uppermost late snowbeds, such as the site on Aonach Mor, may be enhanced.

Although conditions are expected to vary considerably between the east and the west of the Highlands, correlation between snowlie at Braemar and the snow line on Ben Nevis/Creag Meagaidh proved to be significant and using Braemar snowlie as a predictor of the BN/CM snow line gave $F = 6.83$ and $p <$ **0.013****. This may be the result of much of the variation in snow line caused by a high degree of westerliness being lost in the monthly averaging and that therefore this relationship represents nothing more than a similarity in temperature; cold months in Braemar are also cold months on the hill.

Snowfall and snow-lie both show considerable variability through time. Recent trends, since the 1970's, show an increase in the variability of snow-lie and the altitude of the snow line. This is accompanied, more recently, by an increase in zonal flow in winter and snowfall at the higher altitudes of the Scottish Highlands.

At present it is concluded that high-altitude snowbeds in the Scottish Highlands may be experiencing an increase in duration rather than a decrease as is apparent at lower altitudes. This would be the result of greater amounts of precipitation in increased zonal flow, leading to greater drifting and therefore increased accumulation, though this may be taking place over a shorter time period with mid-winter thaws common. Periodic thawing of the snowpack may also lead to an increase in snowpack density and a reduction in the rate at which a snowbed melts. At lower altitudes short-term accumulation may also be substantial but snow-lie duration is reduced and accumulations rapidly thaw in the shorter and more variable winter season.

At present the late snowbeds at highest altitudes in the Scottish Highlands may experience an increase in the variability of snow-lie but average duration does not appear to be affected. Changes apparent since the late 1980's, which indicate reduced snow-lie, are too recent and observed for too short a duration for any assessment to be made of their significance.

Summary points:

1. The data from Scottish Meteorological Stations indicated an increase in westerly, zonal flow during the winter and spring months, with snowfall strongly correlated to westerly flow and high wind speeds.

2. Wind data from Eskdalemuir was considered to be unsuitable following changes in the site characteristics and the siting of instruments.

3. Pressure data from all three stations showed a decreasing trend, and the difference in pressure between Cape Wrath and Eskdalemuir has decreased, significant at the 99.9% level.

4. The Snow Survey of Great Britain showed a general increase in the average altitude of snowlines during the last twenty years, but no information is available for the site-specific snowbeds.

CHAPTER 8

THE IMPACT OF CLIMATE CHANGE.

Climate is demonstrated to be changing, and is expected to continue to change for many centuries, as a result of the increase in atmospheric proportions of gases and particles generated by industrial and agricultural activity undertaken by humans (Houghton *et. al.*, 1996). Most significant are the so-called "greenhouse gases", the most notorious of which is carbon dioxide, produced by the burning of fossil fuels. These act like a greenhouse, inhibiting outgoing long-wave radiation while being transparent to incoming short-wave radiation.

Identifying actual changes in climate is becoming easier as the length of reliable records increases, but natural variability is high and isolating trends which are a direct result of radiative forcing by greenhouse gases is very difficult. Therefore, although predictions of future climate change are largely based on the effects of anthropogenic radiative forcing, the current definition embraces any climate change, whether as a result of human activity or not (Houghton, Jenkins and Ephraums, 1990).

Predicting future changes is extremely complex, since all aspects of the climate system need to be taken into account and our understanding of the workings of different parts of the system are incomplete (Houghton *et. al.*, 1996). As a result of improvements in monitoring, the level of understanding is constantly changing; this, in conjunction with continual improvements in computing, gives rise to constant improvements in the modelling of climate change, such as the inclusion of improvements on the radiative effects of aerosols in the model results reported in Houghton *et. al.*, (1996). It is within this framework of uncertainty that some of the better-known Global Climate Model (GCM) predictions are presented, derived from the most recent Intergovernmental Panel on Climate Change scientific report (Houghton *et. al.*, 1996). The models used in the IPCC summaries are given in Table 8.1 with the institutes producing models and results in Table 8.2.

Where possible, regional-scale predictions are given, though it is apparent that the errors, or bias, increase as the region being modelled decreases in size. With an area only the size of the Scottish Highlands, its proximity to the North Atlantic where the nature of change is not certain (Houghton *et. al.*, 1996), and the experimental stage of the nested models used to generate regional predictions, the results must be approached with caution.

Although global temperature is rising, and is predicted to continue to rise, the distribution of changes in temperature are not uniform. In general, high northern latitudes are expected to warm relatively more than low latitudes, mainly due to reduced sea ice cover, and the warming is most likely to take place in late autumn and winter as a result of the slower formation of sea ice, rather than summer when it becomes negligible (Houghton *et. al.*, 1996). Land masses are predicted to warm more than oceans due to the positive feedback of reduced snow cover and albedo over land in winter and spring, plus greater evaporative cooling over the oceans than over land surfaces, and the diurnal range of temperature over land is expected to reduce (Houghton *et. al.*, 1996). The introduction of better resolution of the effects of aerosols has reduced the extent of maximum winter warming in high latitudes and also reduced the warming expected for the mid-latitudes in the Northern Hemisphere (Houghton *et. al.*, 1996).

Reductions in the mid-latitude warming with improved aerosol information have led two experiments to generate areas of net cooling in mean surface air temperature over eastern China, the Middle East and eastern North America (Roekner *et. al.*, 1995; Taylor and

TABLE 8.1
TABLE OF TRANSIENT COUPLED GCM EXPERIMENTS
FROM THE IPCC REPORT OF WORKING GROUP 1, 1995

Centre	Reference	Flux adj?	Scenario	Warming at x2 CO_2	Equ^m Warming
BMRC	Power et. al. 1993, Coleman et.al. 1993.	No	1%/yr.	1.35	2.1
CCC	G. Boer (pers.comm.)	Yes	1%/yr.	-	3.5
COLA	E. Schneider (pers. comm.)	No	1%/yr.	2.0	-
CSIRO	Gordon and O'Farrell, 1996	Yes	1%/yr.	2.0	4.3
GFDL	Stouffer (pers.comm.)	Yes	0.25%/yr.	2.6	3.7
"	Stouffer (")	Yes	0.5%/yr.	2.4	3.7
"	Manabe et. al. 1991, 1992	Yes	1%/yr.	2.2	3.7
"	Stouffer (pers.comm)	Yes	2%/yr.	1.8	3.7
"	Stouffer (")	Yes	4%/yr.	1.5	3.7
GISS	Russell et.al. 1995, Miller & Russell 1995.	No	1%/yr.	1.4	-
IAP	Keming et. al. 1994	Yes	1%/yr.	2.5	-
MPI	Cubasch et. al. 1992, 1994; Hasselmann et.al. 1993; Santer et.al. 1994	Yes	IPCC90A	1.3	2.6
"	Cubasch et.al. 1992; Hasselmann et.al. 1993; Santer et. al. 1994	Yes	IPCC90D	na	2.6
"		Yes	IPCC 90A	1.5	-
MPI	Hasselmann et.al. 1995	Yes	IPCC90A	na	2.6
"	Hasselmann et.al. 1995	Yes	Aerosols	na	2.6
MRI	Tokioka et.al. 1995	Yes	1%/yr.	1.6	-
NCAR	Washington & Meehl 1989	No	1%/yr.	2.3	4.0
"	Washington & Meehl 1993, 1996; Meehl & Washington 1996	No	1%/yr.	3.8	4.6
UKMO	Murphy 1995; Murphy & Mitchell 1995	Yes	1%/yr.	1.7	2.7
"	Johns et.al. 1996; Keen 1995	Yes	1%/yr.	1.7	2.5
"	Johns et.al. 1996;Tett et.al. 1996; Mitchell et.al. 1995; Mitchell & Johns 1996	Yes	1%/yr.	na	2.5
"	as above	Yes	Aerosols	na	2.5

TABLE 8.2

TABLE OF INSTITUTES PRODUCING IPCC 1995 GCM RESULTS

CENTRES:	
BMRC	Bureau of Meteorlogical Research Centre (Australia)
CCC	Canadian Centre for Climate
COLA	Centre for Ocean, Land and Atmosphere
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
IAP	Institute of Atmospheric Physics
MPI	Meteorological Research Institute (Japan)
NCAR	National Centre for Atmospheric Research (USA)
UKMO	United Kingdom Meteorological Office

TABLE 8.3

STATISTICALLY SIGNIFICANT LINEAR REGRESSION RESULTS FOR JUNE, JULY AND AUGUST FOR CAPE WRATH, TIREE AND ESKDALEMUIR.

FREQUENCY OF WIND DIRECTION AND STRENGTH WERE REGRESSED AGAINST YEAR NUMBER.

Data type and source	**F - statistic**	**p - values**
CW 0300 W	6.00	**0.018***
CW 1500 W	9.18	**0.004****
TIR 0300 W	4.95	**0.031***
TIR 0300 W	4.33	**0.002****
ESK 0300 W	11.24	**0.043***
EKS 1500 W	0.28	0.600
CW 0300 6-7	20.92	**0.000*****
CW 1500 6-7	24.19	**0.000*****
CW 0300 1-3	9.82	**0.003****
CW 1500 1-3	1.99	0.165
TIR 0300 calm	10.67	**0.002****
TIR 1500 calm	2.01	0.163

Penner, 1994). More importantly, most models show a reduction in the strength of the North Atlantic meridional circulation, from 10-30%, due to decreased salinity resulting from higher precipitation and inhibited sinking and mixing (Murphy and Mitchell, 1995). The reduction in ocean circulation produces very reduced warming or, in some cases, cooling in the region of the North Atlantic south of Greenland (Mitchell *et. al.*, 1995(b)). The implications of such a reduction in warming are increased if there is also an increase in zonal flow, as is shown later, since an increased proportion of the total air masses passing over Britain will be passing across an area of relatively cold water before arriving at the British Isles, thus reducing the impact of generally higher temperatures elsewhere.

Increased precipitation is a common feature of all the models reported in Houghton *et. al.*, 1996). Apart from the Goddard Institute for Space Studies (Russell *et. al.*, 1995; Russell, Miller and Rind, 1995), which shows a cooling in the Norwegian Sea and therefore reduced precipitation in this area (Houghton *et. al*, 1996), all models show increased winter half-year precipitation at high latitudes, extending in many cases southwards to the mid-latitudes.

The increases in precipitation in the region of the northern North Atlantic and north-western Europe are related in the UKMO (United Kingdom Meteorological Office) slab model, plus the UKMO AOGCM (atmosphere-ocean Global Circulation Model) to an intensification and poleward shift in the Northern Hemisphere mid-latitude storm tracks (Hall *et. al.*, 1994; Carnell *et. al.*, 1996). The area of most intensification lies in the eastern North Atlantic and thus affects western Europe, with the British Isles bearing the brunt of the increase in cyclonicity. Difficulties in predicting the degree of change in zonal circulation of the mid-latitudes centre on two conflicting effects. With high latitudes warming more at the surface than the sub-tropics, the thermal gradient which drives the zonal circulation is decreased; but increased latent heat released at upper levels in the tropics counteracts this (Houghton *et. al.*, 1996).

The predictions of increased zonal flow are now appearing to be registered by climatic conditions currently being experienced in northern and western Britain (Bardossy and Caspary, 1990; Mayes, 1991; Murray, 1993; Mayes 1994, 1996; Harrison, 1997), including the findings of this volume. Winters (August to March) have become more progressive while early summer (April and May) has become more blocked (Mayes, 1994, 1996), increasing the seasonal cycle and partitioning (Mayes, 1996).

Precipitation during the winter, and particularly in January and March, has increased as a result of the increase in zonal flow, though this is only for 1961-90 relative to the period 1941-70 (Mayes, 1996). This coincides with an increase in westerly airflow since the mid 1970's (Mayes, 1991; Smith, 1995), similar to higher levels of flow experienced at the peak of westerly flow in the 1920's and 1930's (Lamb, 1972); changes in the levels of precipitation in Scotland between 1916-1950 and 1961-1990 do, however, show differences, mainly in the increased seasonality found in the most recent period and in particularly high levels of precipitation in March (Mayes, 1996). Recent years have been particularly anomalous, with an almost unbroken run of mild, warm or exceptionally warm winters since 1987-88 (with the exception of the averagely-severe winter of 1991-92) and high winter rainfall, especially in the north-west of Scotland (Smith, 1995; Harrison, 1997). The focus of increased precipitation over areas of high ground also imply an increase in the orographic component of rainfall with upland sites recording greater increases than their lowland counterparts (Mayes, 1996). A general decrease in summer precipitation and increased incidence of blocking is not true of the north-west, where precipitation increases since 1980 are most likely to be associated with increased summer westerlies resulting from the northwards displacement of depressions by blocking conditions further south (Mayes, 1996).

Data from Cape Wrath, Eskdalemuir and Tiree would support the increase in westerlies suggested by Mayes (1996); wind direction and strength data for all three stations for the period June, July and August give the regression results given in Table 8.3. The direction of change is for an increase in westerlies at all stations, a decrease in light winds and calm weather and increase in high winds, associated with the increase in westerlies.

The pressure data do not, however, support the increase in westerlies with a decreasing trend in pressure, except in the last ten years. Increasing trends, significant at the 95% level for Cape Wrath and Tiree, and the 99% level for Eskdalemuir, are found by regression analysis, but plots of pressure at Cape Wrath and Eskdalemuir using the LOWESS (locally-weighted scatterplot smoother) in MINITAB command, given in Figure 8.1 and Figure 8.2, show that the increase in pressure given by the regressions results is only true for the first forty years, and that since approximately 1981 (year 38) pressure has been decreasing at these stations. Since the increase and decrease is similar at both stations, there is no change found in the pressure difference between Cape Wrath and Eskdalemuir; it may be necessary to examine the pressure difference over a greater distance by using a more southerly station to establish the presence of blocking conditions to the south.

An increase in westerly flow over the Highlands could have important effects on the duration of late snowlie, by increasing cloudiness (and thereby reducing radiation receipts) and keeping air temperatures low. However, it has been shown that typical westerly flow with moderate to high wind speeds and not fully saturated, causing

FIGURE 8.1

LOWESS SMOOTHED CURVE OF PRESSURE,
CAPE WRATH, 0900 HOURS, JUNE, JULY AND AUGUST.

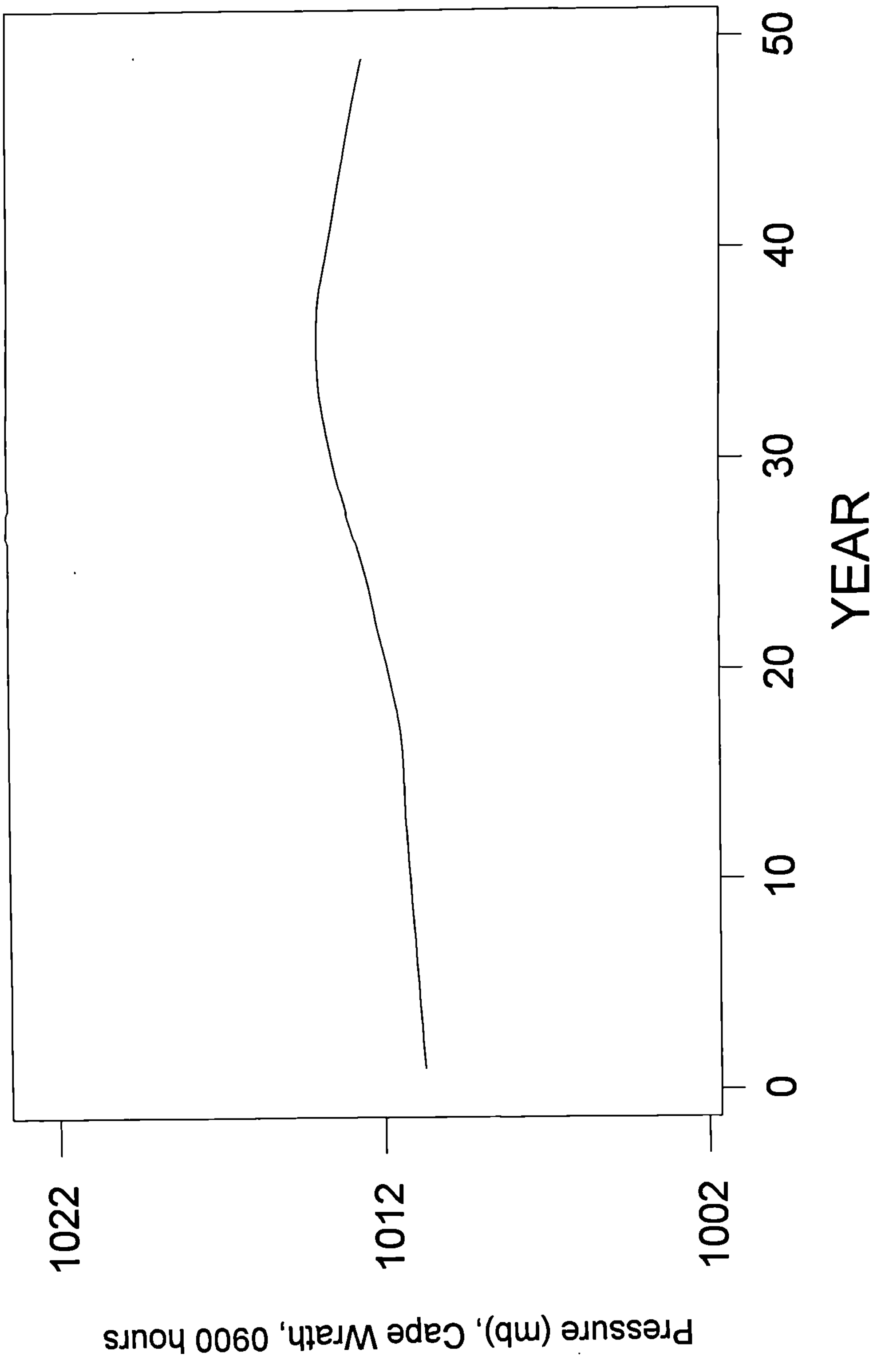
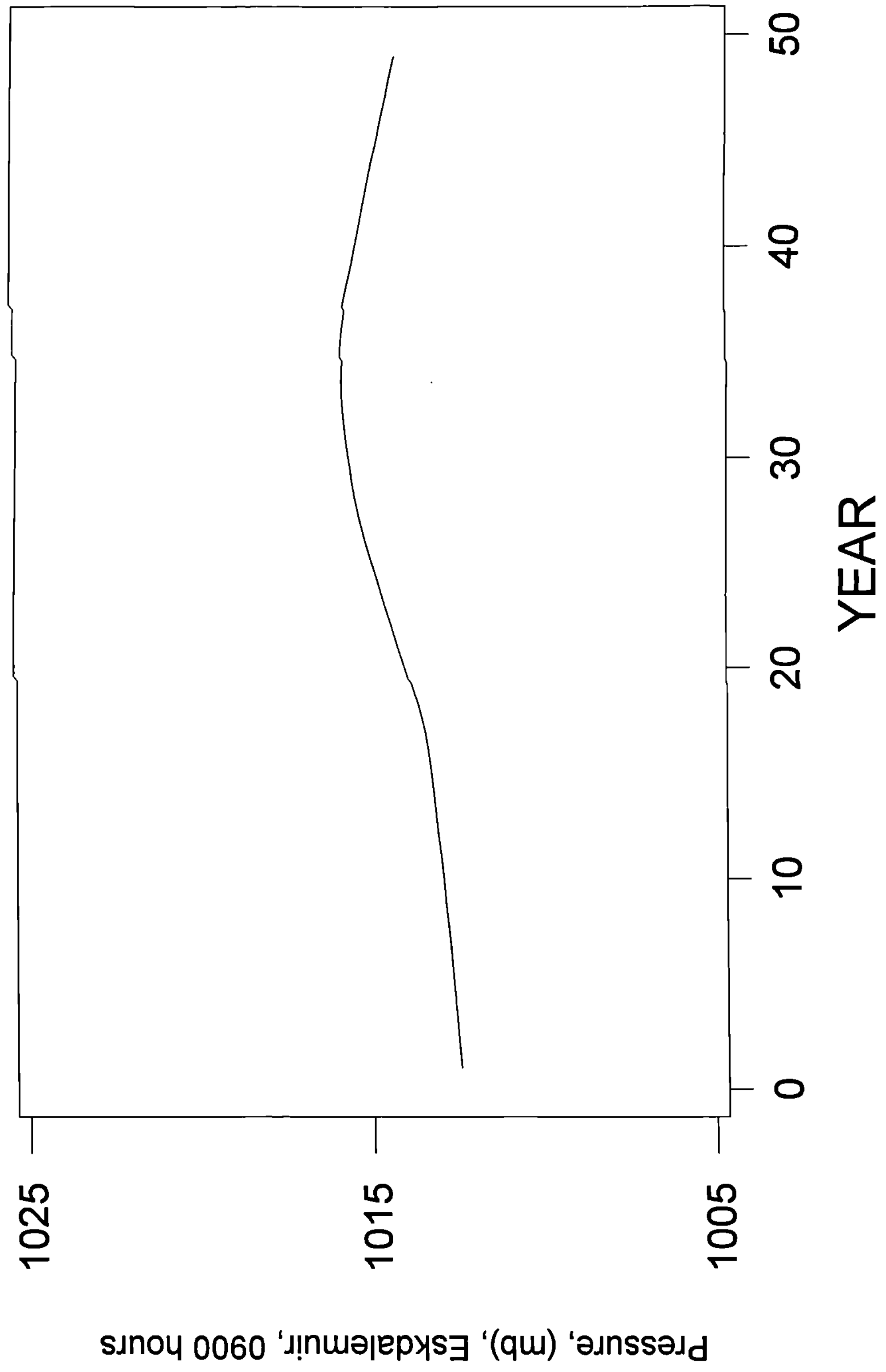


FIGURE 8.2

LOWESS SMOOTHED CURVE OF PRESSURE, ESKDALEMUIR, 0900 HOURS, JUNE, JULY AND AUGUST.



constant replacement of the air over a snowpatch can create conditions for extensive melt. Although important, it has also been shown that the most crucial factor for summer survival of snowbeds is the accumulation of snow during winter and spring, rather than summer temperatures (Watson, Davison and French, 1994).

An increasing westerly component of airflow during winter and early spring has been observed in the present study at Cape Wrath, and in the pressure difference across Scotland, in concert with the findings of Mayes (1991, 1994, 1996) and Harrison (1997). The increase in precipitation in January and March (Smith, 1995) is of particular significance since in these months temperatures are low at high altitude, with temperature at all altitudes low in January and with steep lapse rates in March keeping temperature in the hills low, indicating that at least over 1200m, snowfall and snow accumulation is not decreasing (Harrison, 1997) and even possibly increasing. The high incidence of westerly flow will also enhance the "loyalty" of snowbeds to particular patches. The possibility that snowlie may not decrease at higher levels in the future, may provide the mechanism for a positive feedback in the further survival of snow on the Scottish hills. With spring lapse rates shown to be highest in westerly flow and an increased thermal gradient related to reduced snow accumulation at lower levels and increased accumulation at higher levels, lapse rates may possibly increase more. This situation could explain why during the Holocene climatic maximum, some snowbed species, at least, did not become extinct in Britain as shown by their continued presence in the British flora.

Such changes may increase snow accumulations in the locations of interest, where late snowbeds may be found in the summer. This is the single most important factor in their survival through the summer and it is therefore likely that although snowlie may become more ephemeral at lower altitudes, and also possibly on certain aspects at higher altitudes, the duration of late snowbeds on easterly and northerly aspects at the highest levels (over 1000m) will be unchanged, at least in the immediate future. If, however, lapse rates remain as they are at present, or become less steep, especially in winter and spring and thus generating a snow-lie gradient which is also less steep, then it seems probable that some of the late snowbed bryophytes and snowbed vegetation as a community type could become extinct in Britain in the next 50-100 years.

The snowbed vegetation examined here is dominated by bryophytes and a few long-lived vascular plants. None are true competitors and all display a degree of stress-tolerance. Their longevity and high investment in survival rather than reproduction means that they will be relatively slow to respond to changes in their microenvironment (Sparks and Carey, 1995), even allowing for the possible preferential use of their immediate surroundings by plastic clonal growth forms (Oborny, 1994). It is unlikely that any other species not currently associated with the snowbed could exploit such a lag in response. Such growth forms are also particularly prone to extreme events, from which they may take years to recover (Sparks and Carey, 1995). Therefore, should snowlie at the site change its average duration over the next few decades, the response from *Deschampsia cespitosa*, the most dominant potential invader, is not likely to be very rapid. The gradients of vegetation and snowlie which currently exist suggest that the snowbed would need to achieve complete melting on average by the beginning of June rather than mid-to-late July to allow the invasion of vascular plants such as *Deschampsia cespitosa* and the consequent elimination of the specialist snowbed bryophytes such as *Pohlia ludwigii, Kiaeria starkei* and *Polytrichum sexangulare*. This reduction would require significantly higher temperatures in late spring and early summer than at present to melt a deep snowbed, or the reduction in the depth of build-up of snow from an estimated 3-5 metres at greatest depth to an estimated 30 centimetres. In the light of the predictions for changes in summer temperatures at this location, which are not as high as for changes in winter temperatures, and given the likely increased "loyalty" of snowdrift to such a location on an easterly slope, together with increased wintertime precipitation, this ten-fold decrease in snow build-up seems unlikely to be realised until well into the next century, if then. The likelihood of a reduction of warming in the eastern and northern North Atlantic further decreases the chances of a loss of late snowlie at the highest levels in the western Highlands by reducing the long-term warming experienced over northern Britain relative to other parts of Europe, and thus possibly introducing a return to colder winter conditions associated with increased blocking and reduced zonal flow over the country relative to other parts of Europe.

It therefore seems appropriate to conclude that future climate change, as predicted by models such as the Hadley Centre Model (UKMO), may generate a variable response according to altitude, with snow-lie at low altitudes decreasing in response to warmer temperatures and a greater proportion of precipitation falling as rain as opposed to snow, but at higher altitudes a less obvious decrease, perhaps grading into an area at the highest altitudes where snow-lie actually increases, in particular the accumulated depths on lee slopes. This steepening of the altitudinal gradient of snow-lie may be accompanied by a change in the longitudinal gradient across the Highlands, with more snow falling in the west in increased zonal conditions in winter, and smaller accumulations in the east, which experiences the rain-shadow effect (Weston and Roy, 1994). The area of greatest snowiness may therefore move from the Cairngorms

(Watson, 1992), to the hills around Ben Nevis, generating a shift in the location of snowbed vegetation from its current stronghold in the Cairngorms towards the western hills. This change in location of optimum conditions for snowbed vegetation enhances the need to identify areas in Lochaber and throughout the western Highlands where snowbed vegetation would benefit from protection and active conservation measures.

It should also be remembered that the climatic optimum for the current Holocene period was on average 2°C warmer than today (Price, 1983), but snow-lie did not, during that period, become sufficiently reduced in the late snowbeds to cause the loss of the snowbed bryophytes from the Scottish flora. It may be that some of the vascular plants present in the Scandinavian snowbeds became extinct at that time, but the bryophytes have remained, with one or two species, such as *Pohlia ludwigii* and *Pohlia wahlenbergii* var. *glacialis* being absent from any other vegetation type.

Summary points:

1. Most transient coupled GCMs predict increasing temperature at sea level, accompanied by an increase in winter-time precipitation for the British Isles.

2. Sea surface temperature predictions for the North Atlantic indicate that the area south of Greenland, which is important in generating weather systems approaching the British Isles, may not warm relative to surrounding areas, which would dampen the current trend of increased zonal flow.

3. The possibility of changes in the lapse rate make the predictions difficult to transpose to the upland areas of Britain, though the continued presence of snowbed vegetation in the British flora following the Holocene climatic optimum indicates that lapse rates may well have differed then, allowing late snowbeds to survive.

CHAPTER 9

DISCUSSION.

The two hypotheses addressed by this study are that late snowbeds have high loyalty to location but have variable duration of cover, and that late snowbed vegetation is dominated by stress-tolerant species in a sub-optimal environment, surrounded by vegetation of more competitive species who are unable to tolerate the reduced growing season afforded by the late snow-lie duration of the snowbed core. Should climate change lead to a substantial reduction in snow accumulation and therefore snow-lie duration, then the snowbed core species would therefore be lost as the more competitive peripheral species invade.

The loyalty to location of the snowbed has been demonstrated through the literature and from the data collected from the Aonach Mor site to be applicable to the whole of the Scottish Highlands. The duration of snow-lie has also been shown to be highly variable in the western Highlands, allowing the first hypothesis to be accepted.

The second hypothesis, in its different parts, is more complicated. It has been shown that the relationship between snow-lie duration and the vegetation is more complex than originally thought, with slope stability and meltwater acidity identified as two key variables affecting the snowbed bryophytes and possibly also the surrounding vascular flora, which require further investigation. However, it is also apparent that the vegetation found downslope from this particular location is excluded from the snowbed core by increases in stress associated with the more prolonged snow-lie, showing a decrease in size and performance as snow-lie duration increases and demonstrating a loss of acclimation response in the form of die-back when transplanted into the snowbed core. The upslope vegetation displays a very rapid transition into chionophobous types whose dominant environmental factor is exposure and here the gradient of snow-lie is too steep to allow satisfactory investigation of the hypothesis concerning snowbed vegetation. Investigation of the performance of the snowbed bryophytes indicates that for some, particularly *Pohlia ludwigii*, the late snowbed environment is optimal with best performance located closer to the core than the zone of reduced cover of competitive vascular plants, allowing this aspect of the stated hypothesis to be rejected and further indicating that the preferences in terms of temperature of bryophytes are significantly different from vascular plants, as demonstrated by Furness and Grime (1982b). The two other dominant snowbed bryophytes, *Kiaeria starkei* and *Polytrichum sexangulare*, displayed little relationship with snow-lie duration and are more likely to be affected by slope stability and possibly other factors not yet identified. This would concur with the presence of *Kiaeria starkei*, at least, in a number of chionophobous situations (Rodwell, 1992).

It seems likely that the snowbed core, which may not melt in some years but which normally is snow-free for approximately 4-10 weeks, is not apparently optimal for any of these snowbed specialists. It is therefore anticipated that a reduction in snow-lie duration in the region of 10-20 days on average will generate a shift of the optimal areas for the snowbed bryophytes towards the snowbed core accompanied by a gradual invasion of the more peripheral areas by vascular plants, thus restricting further the area occupied by the snowbed bryophytes, but still offering an area of optimal or near-optimal conditions.

Snowbed loyalty in the Scottish Highlands is high, mainly a result of the dominance of prevailing winds from westerly quarters. Snow-lie duration is more variable as a result of the effects of mid-winter thaws in westerly flow. However, the variability in snow-lie duration decreases with increasing altitude and snow depth. Although no data are available to confirm this, it therefore seems likely that over the late snowbeds where the influence of snow drift is greatest, variability in accumulation and snow cover is least. The most important variable governing late snowbed duration is the amount of accumulation, associated with winter and spring temperature. With lapse rates steepest in spring, although snow-lie at lower altitudes shows a decreasing trend, it is not clear whether accumulation over the late snowbeds is decreasing as a result of increased zonal flow. It is possible, with the greater incidence of westerly flow and the consequently maximised steepness of lapse rates, that the gradient of snow-lie over altitude will actually steepen with changing climate, leading to the greatest change in snow-lie concentrated at lowest altitudes and minimal change at the highest altitudes. With variability in snow accumulation least over the late snowbeds, there may also be a change in the temporal distribution of snow-lie at any given altitude, with areas of least snow accumulation becoming snow-free much earlier, but with the effect reducing as snow accumulation increases. Thus the areas of montane vegetation least likely to be affected by a reduction in snow-lie could, perversely, be the late snowbeds. It therefore seems prudent to examine vegetation which is strongly associated with snow-lie of lesser duration, such as some of the dwarf shrubs, in concert with any monitoring of late snowbed vegetation.

In due course, with improved prediction tools, it should become more certain how climate change will affect an area as small as the Scottish Highlands and in a location as sensitive as the western seaboard of Northern Europe. The reduction of uncertainty about how much temperature change is likely to take place, how precipitation is likely to be affected, and the seasonal distribution of these changes will vastly improve our ability to anticipate how vegetation at all altitudes will be affected, which at present is no more than speculative.

A substantial gap in the knowledge of upland climate will also be filled with the longer-term operation of the Aonach Mor AWS, which will provide invaluable data describing the climate of the western Highland hills. It is anticipated that in ten years' time, a far more accurate assessment of climate change and its impact on snow-lie duration on the Scottish hills could be made using this information, in conjunction with data from sea level stations. It is also desirable that more research be undertaken into the rate of decrease in temperature with altitude, its seasonal and spatial distribution and the nature of the line describing its decrease, whether linear or more complex.

The degree of change in snow accumulation necessary to elicit a change in the vegetation beneath the late snowbeds is large which, given the above, makes it unlikely that the specialist snowbed bryophytes will disappear entirely from locations like the one on Aonach Mor. The uncertainty about accumulation over the late snowbeds, with an increase possible in periods of increased spring-time zonal flow and a dramatic decrease extremely unlikely, means that this habitat does not appear to be threatened by changing climate, as was proposed earlier in the thesis, thereby justifying time and resources spent on the conservation of snowbed vegetation habitat. However, it is also very apparent that a programme of monitoring of snow accumulation over sites such as this is a high priority, to firmly establish the link between climate and snow accumulation and duration at higher altitudes. This should not be confined to east or west, but should encompass examples of mountains from across the Highlands, such as sites in the Mamores, on Aonach Mor, Creag Meagaidh, Ben Alder, Ben Dearg or Seana Bhraigh (Inverlael), the Glenshee hills, the Cairngorms and Lochnagar. Such a programme should be established to identify the effects of any changes as soon as possible, concentrating on measuring the depth of accumulation at different sites, the performance of key species in known snowbed locations, and the temporal distribution of snow-lie at altitudes over 900m in the Scottish Highlands. This relatively simple programme would complement the work being undertaken by climate modellers and offer some linkages with climate as measured at lower altitudes by the Met. Office. It could easily be combined with a programme of remote sensing and should concentrate on identifying similarities and differences between sites and between years, with the ultimate objective of constructing an accurate model of snow accumulation and depletion in given weather conditions.

The need for investigation into different aspects of snowbed vegetation is clear. The pattern of vegetation, community composition and distribution and the suite of environmental factors governing that distribution all require further research. Initially it is proposed that a comprehensive survey of the snowbed and associated peripheral communities in the Scottish Highlands be undertaken, at a resolution comparable to the NVC into which it may then be incorporated, but with a much greater number of samples and using surveyors with specific expertise in snowbed bryophytes. This should bridge the gap between the excellent work done by Rothero (1989) on the snowbed bryophytes and the more general approach adopted by the NVC.

The need for further samples is not merely restricted to the snowbed communities but appears to apply to all the montane communities of the NVC. Ultimately it is hoped that a gradual accumulation of information and samples will lead to a revision of the montane communities, with the possibility of making a geographical distinction between upland communities in England, Wales and Scotland should the differences between them merit it. The steepness of all the climatic gradients in the British Isles indicates that this may be a very real need, rather than trying to lump together very disparate communities and locations. It is not suggested that the framework of the NVC be abandoned, but that with time and greater information, appropriate revisions may be made. More accurate and informative comparisons could then be made between the British upland flora and that of other arctic-alpine areas, in particular Scandinavia and, possibly, Iceland.

A further research priority is to establish the relationship between meltwater pH and species distribution, including both vascular plants and bryophytes. It seems likely that for *Deschampsia cespitosa*, at least, and possibly some of the snowbed bryophytes, meltwater pH is an important limiting factor affecting species distribution. In the western Highlands it is not envisaged that this factor will achieve increased importance, with increased zonal flow bringing less polluted snowfall than that found under easterly flow. It is also proposed that the importance of acid deposition in the eastern Highlands under conditions of greater zonal flow may not increase, even though air quality over Europe may decrease, as the incidence of the appropriate easterly air flow depositing pollutants over the eastern Highlands is likely to fall. However, the relatively high levels of pH causing damage to *Kiaeria starkei* in the research undertaken by Woolgrove and Woodin (1996), and the occurrence of very acid snowfalls in the eastern Highlands indicate that research into other species must be a priority.

The importance of the snowbed bryophytes in the montane zone in Scotland is emphasised by both Carey *et. al.* (1994), and Brown, Horsfield and Thompson (1993). Since their presence in the Scottish flora does not appear to be immediately threatened, it seems appropriate that an effort is now made to clarify the associations between the species, and between species and environmental variables. If this were to be undertaken, then it would be possible to set the snowbed flora in an international context, especially relative to the Scandinavian snowbeds. Establishing the position of Scottish snowbed vegetation within the framework of the circumpolar arctic-alpine flora would allow research into the Scottish situation to be predictive of how other, less sensitive areas climatically, will respond to future changes in climate. The same argument can be applied to the whole suite of montane flora in Scotland, making this an important area for monitoring and research in future years.

Summary points:

1. The hypothesis that snowbed loyalty to location is high and duration very variable between years is valid for both the western and eastern Highlands.

2. The hypothesis that the snowbed bryophytes are restricted to a sub-optimal environment in the snowbed core by more competitive peripheral species, which in turn cannot tolerate the stress of late-lying snow is partly accepted and partly rejected, it having been established that some snowbed bryophytes are optimally placed in the snowbed core area.

3. Slope stability and meltwater pH are identified as two other important factors affecting snowbed core and peripheral vegetation.

4. The uncertainty of lapse rates relative to future climate change makes it difficult to make predictions concerning snowbeds and their vegetation, though it seems likely that the impact will be less than originally thought.

5. Research priorities identified include:

    a) mountain climate and lapse rates

    b) snow accumulation and depletion

    c) snowbed vegetation and other chionophilous communities

    d) the whole range of montane vegetation in the British Isles

    e) meltwater pH and associated species distribution.

REFERENCES AND APPENDICES

REFERENCES

Aizen, V.B. and Aizen, E.M. (1993). Glacier runoff estimation and simulation of streamflow in the peripheral territory of Central Asia. International Association of Hydrology Publications, 218: 167-179.

Aleksandrova, V.D. (1980). *The Arctic and the Antarctic: their Division into Geobotanical Areas.* Cambridge University Press, New York, N.H.

Aleksandrova, V.D. (1988). *Vegetation of the Soviet polar deserts.* Cambridge University Press, Cambridge.

Amen, R.D. (1965). Seed dormancy in the alpine rush, *Luzula spicata*, L. Ecology, 46: 361-364

Anderson, J. G. C. (1935). The Marginal Intrusions of Ben Nevis. Transactions of the Geological Society of Glasgow, 19: 225-269.

Anon. (1960-87). *Arctic Flora of the USSR.* Vols. 1, 1960 and 4, 1963, Publishing House of the USSR Academy of Science, Moscow, Leningrad: Vols. 2, 1964, 3, 1966 and 5, 1966, Nauka, Moscow, Leningrad: Vols. 6, 1971, 7, 1975, 8-1, 1980, 8-2, 1983, 9-1, 1984, 9-2, 1986 and 10, 1987, Nauka, Leningrad.

Babb, T.A. and Whitfield, T.W.A. (1977). Mineral nutrient cycling and limitation of plant growth in the Truelove Lowland ecosystem. In Bliss, L.C. (ed.) *Truelove Lowland, Devon Island, Canada: a high arctic ecosystem.* University of Alberta Press, Edmonton. 589-606.

Baier, J.D., Bazzaz, F.A., Bliss L.C. and Boggess, W.R. (1972). Primary production and soil relations in an Illinois sand prairie. American Midl. Nat. 88: 2002-08.

Bailey, E. B. (1960). *Geology of Ben Nevis and Glen Coe.* 2nd edition (1st edition Bailey, E. B. and Maufe, H. B., 1915). Memoirs of the Geological Survey of Scotland. HMSO.

Baldwin, H. and Smithson, P.A. (1979). Wind chill in upland Britain. Weather, 34: 294-306.

Ballantyne, C.K. (1983). Precipitation gradients in Wester Ross, North-west Scotland. Weather, : 379-387.

Bardossy, A. and Caspary, H.J. (1990). Detection of climate change in Europe by analysing European atmospheric circulation patterns from 1881-1989. Theoretical Applied Climatology, 42: 155-167.

Barry, R. G. (1992). *Mountain Weather and Climate.* 2nd edition. Routledge.

Barry, R. G. and Chorley, R. J. (1987). *Atmosphere, Weather and Climate.* Fifth edition. Routledge.

Barton, J.S. (1984). Observing mountain weather using an automatic station. Weather, 39: 140-145.

Barton, J.S. (1987). Weather observations on Cairn Gorm summit. Meteorological Magazine, 116: 346-353.

Bell, K.L. and Bliss, L.C. (1979). Autecology of *Kobresia bellardii*: why winter snow accumulation limits local distribution. Ecological Monographs, 49: 377-402.

Billings, W.D. (1974). Adaptations and origins of alpine plants. Arctic and Alpine Research, 6: 129-142.

Billings, W. D. and Bliss, L. C. (1959). An alpine snowbank environment and its effects on vegetation, plant development, and productivity. Ecology, 40(3), 388-397.

Billings, W.D. and Mooney, H.A., (1968). The ecology of arctic and alpine plants. Biological Reviews, 43: 481-530.

Birks, H.J.B. (1973). *Past and Present Vegetation of the Isle of Skye - a Palaeoecological Study.* Cambridge University Press.

Birks, H. J. B. (1988). Long-term ecological change in the British uplands. In Thompson, D. B. A. and Usher, M. B. (eds) *Ecological Change in the Uplands.* Blackwell Scientific Publications, Oxford.

Birks, H.J.B. and Ratcliffe, D.A. (1981). *Upland Vegetation Types: a list of National Vegetation Plant Communities.* Nature Conservancy Council, Peterborough.

Birse, E.L. (1971). *Assessment of Climatic Conditions in Scotland, 3. The Bio-climatic Sub-Regions.* Map and explanatory pamphlet, The Macaulay Institute for Soil Research, Aberdeen.

Bjarnason, A.H. (1983). *Islensk Flora.* UNN, Reykjavik.

Bliss, L.C. (1956). A comparison of plant development in microclimates of arctic and alpine tundras. Ecological Monographs, 26: 303-337.

Bliss, L.C. (1962). Adaptations of arctic and alpine plants to environmental conditions. Arctic, 15: 117-144.

Bliss, L.C. (1966). plant productivity in alpine microhabitats on Mount Washington, New Hampshire. Ecological Monographs, 36: 125-155.

Bliss, L.C. (1971). Arctic and Alpine plant life-cycles. Arctic, 15: 117-144.

Boecher, T.W. (1972). Evolutionary problems in the arctic flora. In Valentine, D.H. (ed.) *Taxonomy, Phytogeography and Evolution.* Academic Press, London.

Boecher, T.W., Fredskild, B., Holemn, K. and Jakobsen, K. (1978). *Gronlands Flora.* 3rd edition. Haase, Copenhagen.

Braun-Blanquet, J., Emberger, L and Molinier, R. (1947). *Instructions pour l'etablissement de la Carte des Groupements Vegetaux.* C.N.R.S. Service de la Carte des Groupements Vegetaux de le France, Montpellier.

Brazel, A.J., Tempe, F., Chambers, D. and Kalkstein, L.S. (1992). Summer energy balance on West Gulkana Glacier, Alaska, and linkages to a temporal synoptic index. Zeitschrift fur Geomorphologie, N.F Suppl.-Bd. 86: 15-34.

Britton, M.E. (1966). Vegetation of the arctic tundra. In Henson, H.P. (ed.) *Arctic Biology*. 67-130. Oregon State University Press, Corvallis.

Brown, A., Birks, H.J.B. and Thompson, D.B.A. (1993). A new biogeographical classification of the Scottish Uplands. II. Vegetation - environment relationships. Journal of Ecology, 81: 231-251.

Brown, A. Horsfield, D. and Thompson, D.B.A. (1993). A new biogeographical classification of the Scottish Uplands. I. Description of vegetation blocks and their spatial variation. Journal of Ecology, 81: 207-230.

Browning, K.A. and Hill, F.F. (1981). Orographic rain. Weather, 36: 326-329.

Browning, K.A., Hill F.F. and Pardoe, C.W. (1974). Structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. Quarterly Journal of the Meteorological Society, 100: 309-330.

Browning, K.A., Hill F.F. and Pardoe, C.W. (1975). The nature of orographic rain at wintertime cold fronts. Quarterly Journal of the Meteorological Society, 101: 333-352.

Buchan, A. (1890). The meteorology of Ben Nevis. Transactions of the Royal Society of Edinburgh, 34.

Buchan, A. and Omond, R. (1902). The meteorology of the Ben Nevis observatories. Part II. Transactions of the Royal Society of Edinburgh, 43.

Buchan, A. and Omond, R. (1905). The meteorology of the Ben Nevis observatories. Part III. Transactions of the Royal Society of Edinburgh, 43.

Buchan, A. and Omond, R. (1910). The Meteorology of the Ben Nevis Observatories. Part IV. Transactions of the Royal Society of Edinburgh, 44.

Burrows, C.J. (1977). Alpine grassland and snow in the Arthur's Pass and Lewis Pass regions, South Island, New Zealand. New Zealand Journal of Botany, 15: 665-686.

Burt, T.P. (1980). *A Study of Rainfall in the Southern Pennines.* Dept. of Geography, Huddersfield Polytechnic, Occasional Paper no. 8.

Carey, P.D., Dring, J.C.M., Hill, M.O., Preston, C.D. and Wright, S.M. (1994). *Biogeographical zones in Scotland.* Scottish Natural Heritage, Research, Survey and Monitoring Report no. 26.

Carlsson, B.A. and Callaghan, T.V. (1990). Effects of flowering on the shoot dynamics of *Carex bigelowii* along an altitudinal gradient in Swedish Lapland. Journal of Ecology, 78: 153-166.

Carlsson, B.A. and Callaghan, T.V. (1991). Positive plant interactions in tundra vegetation and the importance of shelter. Journal of Ecology, 79: 973-983.

Carnell, R.E., Senior, C.A. and Mitchell, J.F.B. (1996). An assessment of measure of storminess: simulated changes in Northern Hemisphere winter due to increasing CO_2. Climate Dynamics, (accepted).

Chandler, T.J. and Gregory, S. (1976). *The Climate of the British Isles.* Longman, London.

Chapin, F. S. III (1983). Direct and indirect effects of temperature on arctic plants. Polar Biology, 2: 47-52.

Chapin, F.S., Johnson D.A., and McKendrick, J.D. (1980). Seasonal movement of nutrients in plants of differing growth form in an Alaskan tundra ecosystem: implications for herbivory. Journal of Ecology, 68: 189-209.

Chapin, F.S. III, Miller, P.C., Billings, W.D. and Coyne, P.I. (1980). Carbon and nutrient budgets and their control in coastal tundra. In Brown, J., *et.al.* (eds.), *An Arctic Ecosystem; the Coastal Tundra at Barrow, Alaska.* U.S. IBP Synthesis Series 12. Stroudsburg, Pa.: Dowden, Hutchinson and Ross, 458-482.

Chester, A.L. and Shaver, G.R. (1982). Reproductive effort in cotton grass tussock tundra. Holarctic Ecology, 5: 200-206.

Cohen, J. (1994). Snow cover and climate. Weather, 49: 150-155.

Cohen, J. and Rind, D. (1991). The effect of snow cover on the climate. Journal of Climate, 4: 689-706.

Colman, A.R. and Moralee, S. (1991). Frequency of warm and cold days and nights, and snowfall at Southampton and Eskdalemuir 1937-1989. Journal of Meteorology, 16: 121-126.

Conway, H. and Raymond, C.F. (1993). Snow stability during rain. Journal of Glaciology, 39: 635-642.

Cox, J.E. and Larsen, D.W. (1993). Environmental relations of the bryophytic and vascular components of a talus slope plant community. Journal of Vegetation Science, 4: 553-560.

Craig, D. and Johnston, L.M. (1988). Acidification of shallow groundwaters during the spring melt period. Nordic Hydrology, 19: 89-98.

Crawford, R. M. M. (1989). *Studies in Plant Survival: ecological case histories of plant adaptation to adversity.* Blackwell Scientific Publications, Oxford.

Crawford, R.E.M. and Balfour, J. (1983). Female predominant sex-ratios and physiological differentiation in arctic willows. Journal of Ecology, 71: 149-160.

Crawley, M.J. (ed.) (1986). *Plant Ecology.* Blackwell Scientific Publications, Oxford.

Curran, J.C., Peckham, G.E., Smith, D., Thom, A.S., McCulloch, J.S. and Strangeways, I.C. (1977). Cairngorm summit automatic weather station. Weather, 32: 61-63.

Dahl, E. (1956). Rondane: mountain vegetation in south Norway and its relation to the environment. Skrifter Utgitt av det Norske Videnskaps-Akademi I Oslo I. Mat.-Naturvid. Klasse, 3: 1-374.

Daniels, F.J.A. (1994). Vegetation classification in Greenland. Journal of Vegetation Science, 5: 781-790.

Davies, T.D. and Tranter, M. (1989). Studies of snow chemistry in the Scottish Highlands. Proceedings of the 46th Eastern Snow Conference, Quebec, 1-13.

Davies, T.D., Tranter, M., Jickells, T.D., Abrahams, P.W., Landsberger, S., Jarvis, K. and Pierce, C.E. (1991). Heavily-contaminated snowfalls in the remote Scottish Highlands: a consequcnce of regional-scale mixing and transport. Atmospheric Environment, 26A(1): 95-112.

Davies, T.D., Tranter, M., Blackwood, I.L. and Abrahams, P.W. (1993). The character and causes of a pronounced snow-melt induced 'acidic episode' in a stream in a Scottish sub-arctic catchment. Journal of Hydrology, 146: 267-300.

Davison, R.W. (1985). *Winter Weather and the Supply of Snow in the Eastern Highlands of Scotland: 1954/5 to 1983/4.* Research Discussion Paper 21, University of Edinburgh Department of Geography.

Dewey, K.F. (1977). Daily maximum and minimum temperature forecasts and the influence of snow cover. Monthly Weather Review, 105: 1594-1597.

Douglas, C.K.M. and Glasspoole, J. (1947). Meteorological conditions in heavy orographic rainfall in the British Isles. Quarterly Journal of the Meteorological Society, 73: 11-38.

Elvebakk, A. (1994). A survey of plants associations and alliances from Svalbard. Journal of Vegetation Science, 5: 791-802.

Ferguson, R.I. (1984). Magnitude and modelling of snowmelt runoff in the Cairngorm mountains, Scotland. Hydrological Sciences Journal, 29: 49-62.

Ferguson, R.I. and Morris, E.M. (1987). Snowmelt modelling in the Cairngorms, NE Scotland. Proceedings of the Royal Society of Edinburgh, Earth Sciences, 78: 261-267.

Ferrier, R.C., Jenkins, A. and Elston, D.A. (1995). The composition of rime ice as an indicator of the quality of winter deposition. Environmental Pollution, 87: 259-266.

Flock, J.W. (1978). Lichen bryophyte distribution along a snow-cover soil-moisture gradient, Niwot Ridge, Colorado. Arctic and Alpine Rescarch, 10: 31-47.

Fohn, P.M.B. (1980). Snow transport over mountain crests. Journal of Glaciology, 26: 469-480.

Fox, J.F. (1983). Germinable seed banks of interior Alaska tundra. Arctic and Alpine Research, 15: 405-411.

Furness, S.B. and Grime, J.P. (1982a). Growth rate and temperature responses in bryophytes. I. An investigation of *Brachythecium rutabulum*. Journal of Ecology, 70: 513-523.

Furness, S.B. and Grime, J.P. (1982b). Growth rate and temperature responses in bryophytes. II. A comparative study of species of contrasted ecology. Journal of Ecology, 70: 525-536.

Gardner, J. (1969). Snowpatches: their influence on mountain wall temperatures and the geomorphic implications. Geografiska Annaler, 51: 114-120.

Gartner, B.L. Chapin, F.S. III and Shaver, G.R. (1983). Demographic patterns of seedling establishment and growth of native graminoids in an Alaskan tundra disturbance. Journal of Applied Ecology, 20: 965-980.

Gartner, B.L. Chapin, F.S. III and Shaver, G.R. (1986). Reproduction of *Eriophorum vaginatum* by seed in Alaskan tussock tundra. Journal of Ecology, 74: 1-18.

Gjaerevoll, O. (1956). *The Plant Communities of the Scandinavian Alpine Snow Beds.* Trondheim.

Glazyrin, G.E. (1970). Fazovoe sostoyanie osadkov v gorakh v zavisimosit ot prizemnoy temperaturiy vozdukha. Met. i Gidrol., 30-34. Quoted in Barry (1992).

Gloyne, R.W. (1957). *Problems of Surface Airflow and Related Phenomena in Agriculture, Horticulture and Forestry.* London: Air Ministry, Meteorological Research Committee (M.R.P. no. 1045).

Gloyne, R.W. (1967). Wind as a factor in hill climates. In Taylor, J.A. (ed.) *Weather and Agriculture.* Pergamon. 59-67.

Gloyne, R.W. (1971). A note on average annual mean of daily earth temperature in the United Kingdom. Meteorological Magazine, 108: 1-6.

Grainger, R.J. and Male, D.H. (1978). Melting of a prairie snowpack. Journal of Applied Meteorology, 17: 1833-1842.

Gray, D.M. and Male, D.H. (eds.) (1981). *Handbook of Snow.* Pergamon Press, Toronto.

Green, F.H.W. (1975). The transient snow-lie of the Scottish Highlands. Weather, 30: 226-235.

Green F.H.W. and Harding, R.J. (1979). The effects of altitude on soil temperature. Meteorological Magazine, 108: 81-91.

Green F.H.W. and Harding, R.J. (1980). Altitudinal gradients of soil temperatures in Europe. Transactions of the Institute of British Geographers, 5: 243-254.

Grime, J.P. (1977). Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. American Naturalist, 111: 1169-1194.

Grime, J.P. (1979). *Plant Strategies and Vegetation Processes.* Chichester: Wiley.

Grime, J.P., Hodgson, J.G. and Hunt, R. (1988). *Comparative Plant Ecology; a Functional Approach to Common British Species.* Unwin Hyman, London.

Hall, N.M.J., Hoskins, B.J., Valdes, P.J. and Senior, C.A. (1994). Storm tracks in a high resolution GCM with doubled CO_2. Quarterly Journal of the Royal Meteorological Society, 120: 1209-1230.

Harding, R.J. (1978). The variation of the altitudinal gradient of temperature within the British Isles. Geografiska Annaler, 60: 43-49.

Harding, R.J. (1979). Altitudinal gradients of temperature in the northern Pennines. Weather, 34: 190-201.

Harrison, S.J. (1974). Problems in the measurement and evaluation of the climatic resources of upland Britain. In Taylor, J.A. (ed.) *Climatic Resources and Economic*

Activity: a Symposium. David and Charles, Newton Abbot. 47-63. Aberystwyth Memoranda in Agricultural Meteorology no. 15.

Harrison, S.J. (1985). Spatial and temporal variation in the precipitation-elevation relationship in the maritime uplands of Scotland. Paper delivered to the International Seminar on Topoclimatology and its Possible Applications, Liege, March 1985.

Harrison, S.J. (1988). Numerical assessment of local shelter around weather stations. Weather, 43: 325-330.

Harrison, S.J. (1992). Global warming and winter road maintenance. Highways and Transportation,

Harrison, S.J. (1993). Differences in the duration of snow cover on Scottish ski-slopes between mild and cold winters. Scottish Geographical Magazine, 109: 37-44.

Harrison, S.J. (1997). Changes in the Scottish climate. The Botanical Journal of Scotland, 49(2): 287-300.

Harrison, S.J. and Kelly, I. (1996). A field-based index of topographic shelter and its application to topoclimatic variation. Applied Geography, 16: 53-63.

Haskell, G. (1952). Polyploidy ecology and the British Flora. Journal of Ecology, 40: 265-282.

Havlik, D (1968). *Die Hoehenstruefe maximaler Niederschlagssumen in den Westalpen.* Freiburger Geogr. Hefte, 7, Freiburg.

Hay, J.E. and Fitzharris, B.B. (1988). The synoptic climatology of ablation on a New Zealand glacier. Journal of Climatology, 8: 201-215.

Hendershot, W.H., Mendes, L. and Lalande, H. (1992). Soil and stream water chemistry during spring snow-melt. Nordic Hydrology, 23: 13-26.

Hewitt, A.D., Cragin, J.H. and Colbeck, S.C. (1991). Effects of crystal metamorphosis on the elution of chemical species from snow. Proceedings of the 48th Eastern Snow Conference, Guelph.

Hibberd, S. (1984). A model for pollutant concentrations during snowmelt. Journal of Glaciology, 30: 58-65.

Hill, M.O. (1977). Use of simple discriminant functions to classify quantitative data. In E. Diday, L. Lebart, J.P. Pages and R. Tomassone (eds.) *First International Symposium on Data Analysis and Informatics.* Vol. 1, Institute de Recherche d'Informatique et d'Automatique, Le Chesnay, 181-199.

Hill, M.O. (1979a). *DECORANA - a FORTRAN Program for Detrended Correspondence Analysis and Reciprocal Averaging.* Cornell University, Dept. of Ecology and Systematics, Ithaca, New York.

Hill, M.O. (1979b). *TWINSPAN - a FORTRAN Program for arranging Multivariate Data in an Ordered Two Way Table by Classification of the Individuals and Attributes.* Cornell University, Dept. of Ecology and Systematics, Ithaca, New York.

Hill, M.O. and Gauch, H.G, (1980). Detrended Correspondence Analysis, an improved ordination technique. Vegetatio, 42: 47-58.

Hill, M.O., Bunce, R.G.H and Shaw, M.W. (1975). Indicator species analysis, a divisive polythetic method of classification and its application to a survey of native pinewoods in Scotland. Journal of Ecology, 63: 597-613.

Hill, M.O., Preston, C.D. and Smith, A.J.E. (1991). *Atlas of the Bryophytes of Britain and Ireland. Volume 1: Liverworts.* Harley Books, Colchester.

Hill, M.O., Preston, C.D. and Smith, A.J.E. (1992). *Atlas of the Bryophytes of Britain and Ireland. Volume 2: Mosses (except Diplolepideae).* Harley Books, Colchester.

Hill, M.O., Preston, C.D. and Smith, A.J.E. (1994). *Atlas of the Bryophytes of Britain and Ireland. Volume 3: Mosses (Diplolepideae).* Harley Books, Colchester.

Holdgate, H.T.D. (1973). Rainfall forecasting for river authorities. Meteorological Magazine, 102: 33-38.

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds) (1990). *Climate Change: The IPCC Scientific Assessment.* Cambridge University Press, Cambridge.

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds) (1996). *Climate Change 1995. The Science of Climate Change.* Cambridge University Press, Cambridge.

Hulme, M. and Jones, P.D. (1991). Temperatures and windiness over the United Kingdom during the winters of 1988/9 and 1989/90 compared with previous years. Weather, : 126-136.

Hulten, E. (1968). *Flora of Alaska and Neighbouring Territories.* Stanford University Press, Stanford, U.S.A.

Jackson, M.C. (1977). A classification of the snowiness of 100 winters - a tribute to the late L.C.W. Bonacina. Weather, 32: 91-97.

Jackson, M.C. (1978). Snow cover in Great Britain. Weather, 33: 298-304.

Jenkins, A., Ferrier, R. and Waters, D. (1993). Melt water chemistry and its impact on stream water quality. Hydrological Processes, 7: 193-203.

Jickells, T.D., Davies, T.D., Tranter, M., Landsberger, S., Jarvis, K. and Abrahams, P. (1992). Trace elements in snow samples from the Scottish Highlands:

sources and dissolved/particulate distributions. Atmospheric Environment, 26A(3): 393-401.

Johnson, A.W. and Packer, J.G. (1965). Polyploidy and environment in arctic Alaska. Science, 148: 237-239.

Keddy, P.A. (1989). *Competition.* Chapman and Hall, London.

Kent, M. and Coker, P. (1992). *Vegetation Description and Analysis. A practical Approach.* Wiley, Chichester.

Kimball, S.L., Bennett, B.D. and Salisbury, F.B. (1973). The growth and development of montane species at near-freezing temperatures. Ecology, 54: 168-173.

Kirkpatrick, A.H. and Rushton, B.S. (1990). The oceanicity/continentality of the climate of the north of Ireland. Weather, 45: 322-326.

Knight, D.H., Rogers, B.R. and Kyte, C.R. (1977). Understorey plant growth in relation to snow duration in Wyoming subalpine forest. Bulletin of the Torrey Botanical Club, 104: 314-319.

Kohl, G. and Jordan, R. (1995). Sub-surface melting in a seasonal snow cover. Journal of Glaciology, 41: 474-482.

Lamb, H.H. (1972). British Isles weather types and a register of the daily sequence of circulation patterns, 1861-1971. Meteorological Office, Geophysical Memoir no. 116.

Langmuir, E (1970). Snow profiles in Scotland. Weather, 25: 205-209.

Laughlin, G.P. (1981). Minimum temperature and lapse rate in complex terrain: influencing factors and prediction. Archives for Meteorology, Geophysics and Bioclimatology, Series B, 30: 141-152.

Leck, M.A. (1980). Germination in Barrow, Alaska, tundra soils cores. Arctic and Alpine Research, 12: 343-349.

Linacre, E. (1982). The effect of altitude on the daily range of temperature. Journal of Climatology, 2: 375-382.

Lumb, P.E. (1983). Snow on the hills. Weather, 38: 114-115.

McConnell, D. (1988). The Ben Nevis Observatory log books. Weather, 43: 356-362 and 396-401.

McGraw, J.B. (1980). Seed bank size and distribution of seeds in cottongrass tussock tundra, Eagle Creek, Alaska. Canadian J. of Botany, 58: 1607-1611.

McGraw, J.B. and Shaver, G.R. (1982). Seedling density and seedling survival in Alaskan cotton grass tussock tundra. Holarctic Ecology, 5: 212-217.

McGregor, G.R. and Gellatly, A.F. (1996). The energy balance of a melting snowpack in the French Pyrenees during warm anticyclonic conditions. International Journal of Climatology, 16: 479-486.

McKendrick, J.D., Ott, V.J. and Mitchell, G.A. (1978). Effects of nitrogen and phosphorus fertilization on carbohydrate and nutrient levels in *Dupontia fisheri* and *Arctagrostis latifolia*. In Tieszen, L.L. (ed.) *Vegetation and Production Ecology of an Alaskan Arctic Tundra.* Ecological Studies 29. New York: Springer-Verlag, 509-537.

McVean, D.N. and Ratcliffe, D.A. (1962). *Plant Communities of the Scottish Highlands.* Monographs of the Nature Conservancy, No. 1, HMSO, London.

Malloch, A.J.C. (1988). *Vespan II. A computer package to handle and analyse multivariate species data and handle and display species distribution data.* Institute of Environmental and Biological Sciences, University of Lancaster, Lancaster.

Manley, G. (1936). The climate of the northern Pennines. Quarterly Journal of the Royal Meteorological Society, 62: 103-115.

Manley, G. (1942). Meteorological observations on Dun Fell, a mountain station in northern England. Quarterly Journal of the Royal Meteorological Society, 68: 151-165.

Manley, G. (1943). Further climatological averages for the northern Pennines, with a note on topographic effects. Quarterly Journal of the Royal Meteorological Society, 69: 251-261.

Manley, G. (1945). The effective of altitudinal change in temperate Atlantic climates. Geographical Review, 35: 408-417.

Manley, G. (1969). Snowfall in Britain over the past 300 years. Weather, 24: 428-437.

Manley, G. (1971). The mountain snows of Britain. Weather, 26: 192-200.

Mayes, J.C. (1991). Recent trends in summer rainfall in the United Kingdom. Weather, 46: 190-196.

Mayes, J.C. (1994). Recent changes in the monthly distribution of regional weather types in the British Isles. Weather, 49: 156-162.

Mayes, J.C. (1996). Spatial and temporal fluctuations of monthly rainfall in the British Isles and variations in the mid-latitude westerly circulation. International Journal of Climatology, 16: 585-596.

Miller, P.C. (1982). Environmental and vegetational variation across a snow accumulation area in montane tundra in central Alaska. Holarctic Ecology, 5: 85-98.

Mitchell, J.F.B., Johns, T.C., Gregory, J.M. and Tett, S.F.B. (1995a). Climate response to increasing levels of greenhouse gases and sulphate aerosols. Nature, 376: 501-504.

Mitchell, J.F.B., Davis, R.A., Ingram, W.J. and Senior, C.A. (1995b). On surface temperature, greenhouse gases and aerosols: models and observations. Journal of Climatology, 8: 2364-2386.

Mooney H.A. and Billings, W.D. (1960). The annual carbohydrate cycle of alpine plants as related to growth. American Journal of Botany, 47: 594-598.

Moran, M. (1988). *Scotland's Winter Mountains.* David and Charles.

Morris, E.M. and Thomas, A.G. (1985). Preferential discharge of pollutants during snowmelt in Scotland. Journal of Glaciology, 31: 190-193.

Murphy, J.M. and Mitchell, J.F.B. (1995). Transient response of the Hadley Centre coupled model to increasing carbon dioxide. II. Temporal and spatial evolution of patterns. Journal of Climate, 8: 57-80.

Murray, R. (1993). Bias in southerly synoptic types in decade 1981-1990 over the British Isles. Weather, 48: 152-154.

Namias, J. (1960). Snowfall over eastern United States: factors leading to its monthly and seasonal variations. Weatherwise, 13: 238-247.

Namias, J. (1962). *Influences of abnormal heat sources and sinks on atmospheric behaviour.* Proceedings International Symposium on Numerical Weather Prediction, Tokyo, 1960, Meteorological Society of Japan, 615-627.

Nordhagen, R. (1940). *Norsk Flora.* Olso.

Nordhagen, R. (1943). *Sikilsdalen og Norges fjellbeiter.* Bergens Museums skrifter, 22. Bergen.

Oborny, B. (1994). Growth rules in clonal plants and environmental predictability - a simulation study. Journal of Ecology, 82: 341-351.

Oke, T.R. (1987). *Boundary Layer Climates.* 2nd edition. Routledge, London.

Oksanen, L. and Ranta, E. (1992). Plant strategies along mountain vegetation gradients: a test of two theories. Journal of Vegetation Science, 5: 175-186.

Oliver, J. (1964). A study of upland temperatures and humidities in South Wales. Transactions of the Institute of British Geographers, 35: 37-54.

O'Reilly, J.O. and Page, S.E. (1990). *Ecology of Plant Communities.* Longman Scientific and Technical.

Pears. N.V. (1967). Wind as a factor in mountain ecology: some data for the Cairngorm mountains. Scottish Geographical Magazine, 83: 118-124.

Pearsall, W.H. (1950). *Mountains and Moorlands.* Collins, New Naturalist Series.

Pearson, M.G. (1973a). The winter of 1739-40 in Scotland. Weather, 28: 20-24.

Pearson, M.G. (1973b). Snowstorms in Scotland. Weather, 28: 195-201.

Pearson, M.G. (1975a). Never had it so bad. Weather, 30: 14-21.

Pearson, M.G. (1975b). 1779 - a year of remarkable weather in eastern Scotland. Weather, 30.

Pearson, M.G. (1976). Snowstorms in Scotland - 1729 to 1830. Weather, 31, 391-393.

Polunin, N. (1959). *Circumpolar Arctic Flora.* Oxford University Press, Oxford.

Poore, M.E.D. (1995). The use of phytosociological methods in ecological investigations. III. Practical application. Journal of Ecology, 43: 606-651.

Poore, M.E.D. and McVean, D.N. (1957). A new approach to Scottish mountain vegetation. Journal of Ecology, 45: 401-439.

Pottie J.M. (1994). Scottish snowbeds: records from three sites. Weather, 50: 124-129

Price, R.J. (1983). *Scotland's Environment during the last 30,000 years.* Scottish Academic Press, Edinburgh.

Purves, R.S. Barton, J.S. and Wright, D.S.B. (1994). Automated measurement of snow temperature profiles in the Cairngorm mountains, Scotland. Meteorological Applications, 2: 199-207.

Ratcliffe, D.A. (1977). *A Nature Conservation Review.* Cambridge University Press, Cambridge.

Ratcliffe, D.A. (1981). The Vegetation. In Nethersole-Thampson, D. and Watson, A. *The Cairngorms: their Natural History and Scenery.* Melven Press, Perth.

Ratcliffe, D.A. and Thompson, D.B.A. (1988). The British Uplands: their ecological character and international significance. In Usher, M.B. and Thompson, D.B.A. (eds.) *Ecological Change in the Uplands.* 9-36. Blackwell Scientific, Oxford.

Ratcliffe, R.A.S. and Murray, R. (1970). New lag associations between North Atlantic sea temperature and European pressure applied to long-range weather forecasting. Quarterly Journal of the Royal Meteorological Society, 96: 41-49.

Raunkier, C. (1934). *The Life Forms of Plants and Statistical Plant Geography.* Clarendon Press, Oxford.

Razzhavin, V.Y. (1994). Snowbed vegetation of far north-eastern Asia. Journal of Vegetation Science. 5: 829-842.

Reiter, E.R. (1963). *Jet-stream Meteorology.* Chicago, University of Chicago Press.

Richardson S.G. and Salisbury, F.B. (1977). Plant responses to light penetrating the snow. Ecology, 58: 1152-1158.

Rincon, E. and Grime, J.P. (1989). An analysis of seasonal patterns of bryophyte growth in a natural habitat. Journal of Ecology, 77: 447-455.

Roach, D.A. (1983). Buried seed and standing vegetation in two adjacent tundra habitats, northern Alaska. Oecologia, Berlin, 60: 359-364.

Roberts, E.H. (1972). Dormancy: a factor affecting seed survival in the soil. In Roberts, E.H. (ed.) *Viability of Seeds.* Syracuse University Press, Syracuse. 321-359.

Rodwell, J.S. (1991). *British Plant Communities.* Vol. 2. *Mires and Heaths.* Cambridge University Press, Cambridge.

Rodwell, J.S. (1992). *British Plant Communities.* Vol. 3. *Grasslands and Montane Communities.* Cambridge University Press, Cambridge.

Roekner, E., Siebert, T. and Feichter, J. (1995). Climatic response to anthropogenic sulphate forcing simulated with a general circulation model. In Charlson, R.J. and Heintzenberg, J. (eds.) *Aerosol Forcing of Climate.* Wiley, Chichester.

Rothero, G. (1989). *Snowbed Survey 1989. Analysis of communities.* Unpublished thesis, MPhil.

Rothero, G. (1990). *Snowbed Survey 1990. Site reports.* Unpublished thesis, MPhil.

Roux, G. and Roux, M. (1967). A propos de quelques methodes de classification en phytosociologie. Revue de Statistique Applique, 15, 59-72.

Russell, G.L., Miller, J.R and Rind, D. (1995). A coupled atmosphere-ocean model for transient climate change studies. Atmosphere-Ocean, 33: 4.

Salter, M. de C. S. (1921). *The Rainfall of the British Isles.* University of London Press, London.

Sayers, R.L. and Ward, R.T. (1966). Germination responses in alpine species. Bot. Gaz., 127: 11-16.

Schoendorf, T. and Herrmann, R. (1987). Transport and chemodynamics of organic micropollutants and ions during snow-melt. Nordic Hydrology, 18: 259-278.

Seaward, M.R.D. (1977). *Lichen Ecology.* Academic Press, London.

Shibata, O. and Nishida, T. (1993). Seasonal changes in sugar and starch content of the alpine snowbed plants, *Primula cuneifolia* spp. *Hakusanensis* and *Fauria crista-galli*, in Japan. Arctic and Alpine Research, 25: 207-210.

Smith, L.P. (1975). Change of weather factors with height. (Unpublished copy available in the National Meteorological Library, Bracknell).

Smith, R.B. (1982). A differential advection model of orographic rainfall. Monthy Weather Review, 110: 306-309.

Smith, K. (1995). Precipitation over Scotland, 1757-1992: some aspects of temporal variability. International Journal of Climatology, 15: 543-556.

Smith, S.G. (1983). The seasonal variation of wind speed in the United Kingdom. Weather, 38: 98-102.

Smithson, P.A. (1969). Effects of altitude on rainfall in Scotland. Weather, 24: 370-376.

Smithson, P.A. (1970). Influence of topography and exposure on airstream rainfall in Scotland. Weather, 25: 379-386.

Sneath, P.H.A. and Sokal, R.R. (1973). *Numerical Taxonomy.* Freeman, San Fransisco.

Sorenson, T. (1941). Temperature relations and phenology of the North-east Greenland flowering plants. Meddelelser von Gronland, 125: 1-305.

Sparks, T.H. and Carey, P.D. (1995). The responses of species to climate over two centuries: an analysis of the Marsham phenological record, 1736-1947. Journal of Ecology, 83: 321-329.

Spink, P.C. (1980). A summary of summer snows in Scotland, 1965-1979. Journal of Meteorology, 5: 105-111.

Spomer, G.G. and Salisbury, F.B. (1968). Eco-physiology of *Geum turbinatum* and implications concerning alpine environments. Botanical Gazette, 129: 33-49.

Stanton, M.L., Rejmanek, M. and Galen, C. (1994). Changes in vegetation and soil fertility along a predictable snowmelt gradient in the Mosquito Range, Colorado, U.S.A. Arctic and Alpine Research, 26: 364-374.

Stewart, R.E. (1985). Precipitation types in winter storms. Pure and Applied Geophysics, 123: 597-609.

Strong, D.R., Simberloff, D., Abele, L.G. and Thistle, A.B. (1985). *Ecological Communities; conceptual issues and the evidence.* Princeton University Press, Princeton, N.J.

Tabony, R.C. (1985a). The variation of surface temperature with altitude. The Meteorological Magazine, 114: 37-48.

Tabony, R.C. (1985b). Relations between minimum temperature and topography in Great Britain. Journal of Climatology, 5: 503-520.

Taylor, J.A. (1960). *Hill Climates and Land Usage with Special Reference to Highlands Britain.* Geography Department, UCW, Memo no. 3 (Aberystwyth).

Taylor, J.A. (1976). Upland Climates. In T.J. Chandler and S. Gregory (eds). *The Climate of the British Isles.* London: Longman. 264-287.

Taylor, P.A., Sykes, R.I. and Mason, P.J. (1989). On the parameterization of drag over small-scale topography in neutrally-stratified boundary layer flow. Boundary Layer Meteorology, 48: 409-422.

Taylor, K. and Penner, J.E. (1994). Climate system response to aerosols and greenhouse gases: a model study. Nature, 369: 734-737.

Terjung, W.H. (1966). Physiologic climates of the conterminous United States: a bioclimatological classification based on man. Annals of the Association of American Geographers, 56: 141-179.

Thom, A.S. (1974). Meteorological Report. In Parnell, B.K. (ed). *Aonach Mor. A planning report on the prospect of winter sport development at Fort William.* Scottish Tourist Board, Edinburgh.

Thompson, D.B.A. and Baddeley, J. (1991). Some effects of acidic deposition on montane *Racomitrium lanuginosum* heaths. In Woodin, S.J. and Farmer, A.M. (eds.) *Effects of Acid Deposition on Nature Conservation in Great Britain.* NCC, Peterborough.

Thompson, D.B.A. and Brown, A. (1992). Biodiversity in montane Britain; habitat variation, vegetation diversity and some objectives for conservation. Biodiversity and Conservation, 1: 179-208.

Thompson, D.B.A. and Sydes, C.S. (1991). The British Uplands. In I.G.F. McLean (ed.) *Our Natural Heritage.* Nature Conservancy Council, Peterborough.

Tieszen, L.L. (1972). The seasonal course of above-ground production and chlorophyll distribution in a wet arctic tundra at Barrow, Alaska. Arctic and Alpine Research, 4: 307-324.

Tout, D.G. (1976). Temperature. In Chandler, T.J. and Gregory, S. (eds.) *The Climate of the British Isles.* Longman, London. 96-128.

Tranter, M., Abrahams, P.W., Blackwood, I.L., Brimblecombe, P. and Davies, T.D. (1988). The impact of a single black snowfall on streamwater chemistry in the Scottish Highlands. Nature, 332: 826-829.

Troshin, A.S. (ed.) (1967). *The Cell and Environmental Temperature.* Pergamon Press, New York.

Vestergren, T. (1902). Om den olikformiga snobetackningens inflytande pa vegetationen I Sarek-fjallen. Bot. Not. Lund.

Wagner, A.J. (1973). The influence of average snow depth on monthly mean temperature anomaly. Monthly Weather Review, 101: 624-626.

Walker, D.A. (1985). *Vegetational and environmental Gradients of the Prudoe Bay Region, Alaska.* CRREL Report 85-14, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Walker, M.A., Daniels, F.J.A. and van der Maarel, E. (1994). Circumpolar arctic vegetation: introduction and perspectives. Journal of Vegetation Science, 5: 758-764.

Walsh, J.E. and Ross, B. (1988). Sensitivity of 30-day dynamical forecasts to continental snow cover. Journal of Climate, 1: 739-754.

Ward, R.G.W. (1981). *Snow avalanches in Scotland with particular reference to the Cairngorm mountains.* Unpublished PhD thesis, University of Aberdeen.

Watson, A. (1992). *The Cairngorms.* Scottish Mountaineering Club District Guide.

Watson, A., Davison, R.W. and French, D.D (1994). Summer snow patches and climate in Northeast Scotland. Arctic and Alpine Research, 26: 141-151.

Watson, E.V. (1981). *British Mosses and Liverworts.* Cambridge University Press, Cambridge.

Weston, K.J. and Roy, M.G. (1994). The directional-dependence of the enhancement of rainfall over complex topography. Meteorological Applications, 1: 267-275.

Wijk, S. (1986). Performance of *Salix herbacea* in an alpine snow-bed gradient. Journal of Ecology, 74: 675-684.

Woolgrove, C.E. and Woodin, S.J. (1994). Relationship between the duration of snow-lie and the distribution of bryophyte communities in Scotland. Journal of Bryology, 18: 253-260.

Woolgrove, C.E. and Woodin, S.J. (1996). Effects of pollutants in snowmelt on *Kiaeria starkei*, a characteristic species of late snowbed bryophyte dominated vegetation. New Phytologist, 133: 519-529.

Young, W.K. (1985). Instrumentation at Eskdalemuir Observatory. Meteorological Magazine, 114: 202-211.

Young, T.P. and Peacock, M.M. (1992). Giant senecios and alpine vegetation on Mount Kenya. Journal of ecology, 80: 141-148.

APPENDIX I

COMMUNITY DESCRIPTIONS OF NVC,
IN PRE-PUBLICATION FORM,
AND ROTHERO (1989, 1990) USED IN THIS STUDY.

DESCRIPTION OF ROTHERO'S SNOWBED COMMUNITIES (Rothero, 1989).

"**Pohlia ludwigii snow bed.**

"Constant species *Pohlia ludwigii*

"Rare species *Cerastium cerastoides, Pohlia wahlenbergii* var. *glacialis*

"Description

"Typically this community has a dense deep green carpet in which *Pohlia ludwigii* is much the most abundant plant particularly in areas of latest snow lie; where it has just emerged from the snow the stems are red-brown with only a hint of green at the apex. Where it is well developed this community is usually the first to catch the eye as there are few other common species, and on some sites, notably on Aonach Mor and Garbh Coire, Braeriach, pure swards of the moss can cover in excess of 100m2. Characteristically however, there will be scattered plants of *Deschampsia caespitosa* (usually what used to be ssp. *alpina*) and *Polytrichum sexangulare* with hepatics like *Nardia scalaris* and *Scapania uliginosa* intimately mixed with *P. ludwigii*. Despite the close proximity of the *Marsupella brevissima - Lophozia sudetica* snow bed, these species and their associations are only occasional in this community and always of low cover value.

"*Deschampsia caespitosa* sub-community

"The grass is more or less dominant in this facies usually associated with *Pohlia ludwigii* and *Scapania uliginosa* and *S. undulata*; on more craggy ground the rare *Cerastium cerastoides* may occur in relative abundance.

"Habitat

"This community tends to be restricted to the areas of latest snow lie which are permanently irrigated either by meltwater or by seepages down crags or from springheads in the short period they are snow free. It can develop over permanently wet bedrock and here may be associated with *Andraea nivalis* and seems to prefer a coarse substrate and is absent from the gravels and sands subject to amorphous solifluction. It can cope with frequent inundations of sand and stems in excess of 15cm can be extracted from sites where layering in the soil suggests repeated burial.

"Succession

"This community exists in a mosaic of other snow bed types and its distribution depends largely on lateness of snow lie, irrigation and stability of substrate. On wetter sites it merges into spring communities, *Anthelia julacea - Sphagnum auriculatum, Philonotis fontana - Saxifraga stellaris* and *Pohlia wahlenbergii* var. *glacialis* springs or variants on these, normally being involved. On sites that are drier and often on a finer substrate this community merges into either the *Marsupella brevissima - Lophzia sudetica* or the *Polytrichum sexangulare - Kiaeria starkei* snow beds."

"***Polytrichum sexangulare - Kiaeria starkei* snow bed.**

"Constant species

"*Polytrichum sexangulare, Kiaeria starkei, Barbilophozia floerkii*

"Rare species

"*Pleurocladula albescens, Andraea nivalis, Marsupella condensata, Cephalozia bicuspidata* ssp. *ambigua*.

"Description

"This community has a coarser appearance than the hepatic dominated snow beds as it is usually dominated by one or both of the two mosses either in open patches or in dense swards. Packed tightly around the mosses in many cases are the dark green shoots of *Barbilophozia floerkii*, looking very different to the yellow-green plant in its more 'normal' habitat of more oceanic block screes. The hepatic 'understorey' also has varying mixtures of *Nardia scalaris, Lophozia sudetica* and *Cephalozia bicuspidata* and all of these can occasionally be dominant. The mosses Racomitrium heterostichum and *Conostomum teteragonum* are also frequent, often blackened if they are recently exposed. On wetter sites *Pohlia ludwigii* is often present but the feature here can occasionally be large patches of *Andraea nivalis*, more normally a species of dripping rocks and rocks in burns. This community can also contain large patches of the thalloid hepatic *Moerkia blyttii*, particularly on steeper, irrigated slopes below crags and on the sides of the meltwater channels. Vascular plants are infrequent, the most common being open swards of *Deschampsia flexuosa*, which are often conspicuous but give low cover values, *Huperzia selago* as isolated stems and the occasional rosette of *Saxifraga stellaris*. On drier sites there may be good patches of *Salix herbacea* and *Gnaphalium supinum*.

"Although sampling proved an intractable problem for block scree, observation suggests that most stands on block scree would fit into this community but with the addition of species like *Isopterygium elegans* and an elevation of the importance of *Diplophyllum albicans* and *Plagiothecium* species, the latter usually associated with fern litter. There are clear links here also with *the Athyrium distentifolium - Cryptogramma crispa* community of block scree sites.

"Habitat

"The bulk of the latest snow lie areas form the basis for this community, stability of substrate and at least intermittent irrigation, possibly being the most important requirements. Both *Polytrichum sexangulare* and *Kiaeria starkei* reach their highest cover values in lines of meltwater seepage which are not permanently wet, but both are present in much drier sites also. The community spreads onto coarse scree as long as there is some infill and, as mentioned above, fills the interstices of coarse block scree particularly on the more westerly sites on Aonach Mor, though *P. sexangulare* is infrequent on such sites.

"Succession

"On less stable sites with finer substrate, this community grades *into M. brevissima - L. sudetica* snow bed. On stable sites with a gravel substrate but which are snow free earlier, then there is a transition to the *Racomitrium - Carex bigelowii* snow bed. In coarse block scree where snow melts a little earlier the increasing frequency of the ferns *Athyrium distentifolium* and *Cryptogramma crispa* indicates a move towards that, less chionophilous community. On wetter sites of equivalent snow lie, *Pohlia ludwigii* becomes much more frequent or there may be a trend towards a vegetation in which *Andreaea nivalis, Anthelia julacea, Scapania undulata* and *S. uliginosa* are the principal components."

"*Racomitrium - Carex bigelowii* snow bed

"Constant species

"*Carex bigelowii, Racomitrium heterostichum, R. fasciculare, Polytrichum sexangulare, Barbilophozia floerkii, Salix herbacea.*

"Rare species

"*Anthelia luratzkana, Pleurocladula albescens, Marsupella condensata.*

"Description

"The distinguishing feature of this community is the presence of a greater number of vascular plants in the bryophyte turf, in which flat patches of *Racomitrium* spp. are a feature. *Carex bigelowii* and *Salix herbacea* are prominent, although they may have only low cover values. Other frequent vascular plants are *Huperzia selago, Gnaphalium supinum* with *Deschampsia caespitosa* and the odd rosette of *Saxifraga stellaris*, often with *Racomitrium fasciculare*, in the wetter spots. Small hepatics are only occasional here but some of the rare species still occur, however the robust *Barbilophozia floerkii* is usually abundant and sometimes dominant. Both *Polytrichum sexangulare* and *Kiaeria starkei* occur frequently but usually have a low cover value. The overall impression is still of a bryophyte community of reasonable diversity, with scattered vascular plants.

"Habitat

"This community is limited to more mesic sites which are free of snow by June in a normal year and often is best developed on sites on moderate slopes that have an aspect that is more open. Drainage can vary although none of the sites were very wet; another feature is the development of a skeletal organic soil which is largely absent from the more extreme communities. The stable 'aprons' at the bottom edges of slopes subject to solifluction and slumping, and slopes in hollows that are relatively early snow free and have a less extreme irrigation regime show the best development of this community. In late snow areas dominated by crags and scree, this community occurs on finer material in the scree away from the areas of latest snow lie and on the tops of rocky bluffs, which again are relatively early snow free. A variant on this snow bed occurs along the cornice line above steep slopes or crags where the cornice persists into June; this snow bed is virtually continuous for several kilometres on the Aonach Mor - Aonach Beag massif.

"Succession

"This is very much a transitional type between the *P. sexangulare - K. starkei* snow bed and the *Carex bigelowii - Dicranum fuscescens* sedge heath described below. In wetter sites there may be a rapid change to some form of *Deschampsia caespitosa* grassland but in general the more snow free margins tend to be drier and the cover of *Carex bigelowii* increases. On sites where a gravel substrate is prevalent, this snow bed may follow on from the *M. brevissima - L. sudetica* snow bed on easy angled slopes below scarps subject to solifluction, and may form a complex with the same community along the cornice line and in hollows in plateaux."

NATIONAL VEGETATION CLASSIFICATION
QUADRAT COMMUNITY DESCRIPTIONS

U10 *Carex bigelowii - Racomitrium lanuginosum* moss heath.

Constant species
Carex bigelowii, Deschampsia flexuosa, Festuca ovina/vivipara, Vaccinium myrtillus, Racomitrium lanuginosum, Cladonia uncialis.

Rare species
Artemisia norvegica, Diapensia lapponica, Koenigia islandica, Loiseleuria procumbens, Luzula arcuata, Minuartia sedoides, Sibbaldia procumbens, Aulacomnium turgidum, Hypnum hamulosum, Kiaeria starkei, Nephroma arctica.

Physiognomy
The *Carex bigelowii - Racomitrium lanuginosum* community takes in both continuous carpets of mossy heath and much more open vegetation in which *Racomitrium lanuginosum* remains an important distinguishing feature. In the closed swards included here, this moss is often truly dominant, forming an extensive, sometimes total, cover of densely-packed shoots, frequently curled over all in one direction by relentless winds, but growing together as a vigorous mat up to 5cm or so thick, which can be peeled off the rocky substrate beneath. From this kind of vegetation, which can stretch for many hectares over broad plateaus, there is a complete gradation through broken rocky ground with more patchy carpets, to almost barren stone-littered surfaces on which small clumps of *R. lanuginosum* are virtually the only cover.
Some other mosses play a more infrequent, but locally prominent, role in the community, though this variation is not of itself sufficient to characterize different kinds of *Carex - Racomitrium* heath (c.f. Poore 1955c, Huntley 1979). Most obvious among these is *Dicranum fuscescens* which is only occasional throughout but sometimes patchily abundant within masses of *R. lanuginosum*, often where there are slight depressions, perhaps just a few centimetres deep, which catch and hold a little snow in winter. Some of these spots are clearly transitional to late snow-beds, but often the effect of just to produce a mosaic within the moss carpet of what is otherwise fairly uniform vegetation. *Polytrichum alpinum* can behave in the same fashion, though it is rarely as extensive as *D. fuscescens*, and more locally, *Rhytidiadelphus loreus* and other bulky pleurocarps, or the rare *Kiaeria starkei*, can pick out sheltered places. Then, scattered through the carpet, there can be occasional shoots of *Dicranum scoparium, Hypnum cupressiforme, Polytrichum piliferum, P. alpestre, Campylopus paradoxus* and *Andreaea alpina.* Some other *Racomitrium* spp. may occur infrequently too: *R. heterostichum, R. fasciculare* and *R. canescens* have all been recorded here, the last once noted in abundance by McVean and Ratcliffe (1962) over an area where fresh sand had been blown among rocks, but having a very restricted role in general here compared with, say, Icelandic moss-heaths (McVean 1955). One particular sub-community also provides a locus for the rare montane mosses *Aulacomnium turgidum* and *Hypnum hamulosum*. Frequent hepatics are much less numerous than mosses but *Diplophyllum albicans* and *Anastrepta orcadensis* occur occasionally and assiduous searching, especially of damper places, sometimes

turns up uncommon taxa such as *Anthelia juratzkana* and *Gymnomitrion corallioides* (Watson 1925, Birks 1973)

Lichens are not usually of high cover in the carpet, although a number are found frequently throughout and in some stands there is marked local enrichment of this element in the flora. Most common are *Cladonia uncialis* and *Cetraria islandica*, with *Cladonia arbuscula, C. gracilis, Cornicularia aculeata* and *Sphaerophorus globosus* more occasional and uneven on their representation. Among a variety of infrequent lichen associates is the very rare foliose species *Nephroma arcticum* (McVean and Ratcliffe 1962) and a large number of saxicolous taxa, particularly of the genera Lecidea, *Lecanora, Parmelia* and *Umbilicaria*, including some strict Arctic-Alpines, growing on exposed rock fragments (Watson 1925). From these, James et. al. (1977) tentatively defined two rare montane associations of the *Rhizocarpion alpicolae* alliance.

Scattered through this ground, or dotted about in the whelter of rocks or moss clumps in the more open kind of vegetation, vascular plants are sometimes reduced to sparse wind-clipped individuals of a very few species. However, there is generally some *Carex bigelowii* and, though this is nothing like so luxuriant or floriferous as in flushed and less wind-swept situations, it can be quite abundant in the community, its rhizomes spreading protected in or beneath the moss mat. Then, there are frequent small tussocks of *Festuca ovina*, very often clearly *F. vivipara*, and, particularly towards lower altitudes, *Deschampsia flexuosa* with small sprigs of *Vaccinium myrtillus*. More occasional, or rather more unevenly distributed among the sub-communities, are *Galium saxatile, V. vitis-idaea, Agrostis canina, A. capillaris, Alchmilla alpina* and *Salix herbacea* and, where these become a little more frequent, together with *Carex pilulifera* and *Potentilla erecta*, the community begins to look transitional to the sort of grassy or sub-shrub heath that occurs in windswept places at lower levels. In other stands, towards the more exposed extreme to which the community penetrates, there can be a very striking enrichment, in what is often an open and heterogenous cover, with *Luzula spicata, Polygonum viviparum, Thymus praecox* and various cushion herbs, notably *Silene acaulis, Armeria maritima* and the rare *Minuartia sedoides* and *Sibbaldia procumbens*. It is in this kind of *Carex-Racomitrium* heath too, that another rarity, *Juncus trifidus,* is most often seen, usually on wind-blasted ablation surfaces, in vegetation which McVean and Ratcliffe (1962) described as a distinct *Juncus-Festuca ovina* nodum, but which can readily be accommodated here.

Three further extremely rare, and only fairly recently discovered, members of the British mountain flora are also found in more open, rocky stands of this moss-heath (Raven and Walters 1956). *Artemisia norvegica* a plant that is otherwise known only from parts of Norway and the Urals (Hulten 1954), occurs in this vegetation in numerous small colonies spread over three localities in Ross (Blakelock 1953, Perring and Farrell 1977), while *Diapensia lapponica*, an altogether more spectacular plant when in flower and one with a widespread Arctic-Subarctic range, is restricted to a single rocky crest near Fort William, where it is fairly plentiful but damaged by collectors and deer (Perring and Farrell 1977). *Koenigia islandica,* which occurs on Skye and Mull, is not restricted to *Carex-Racomitrium* heath, being found also in wet, stony *Carex-Koenigia* flushes, but some of its drier stations north of the Storr on Skye belong here (Birks 1973).

Habitat

The *Carex-Racomitrium* moss-heath is characteristic of wind-swept, cloud-ridden plateaus at moderate to very high altitudes through the cold, humid mountains of north-west Britain. It is strongly concentrated in the Scottish Highlands, where very large stands can be found over ridges and summits that are mostly blown clear of snow, but it also occurs more locally on moderately exposed cols and spurs, and can extend into situations where wind-erosion and bitter temperatures maintain some of the most inhospitable upland scenery in the country. In general, harsh climatic conditions make this a climax community, although stands at lower altitudes have sometimes been affected by grazing.

The combination of exposure to cold with high humidity is of great importance for the development of this kind of vegetation. It is largely a community of the low- to middle- alpine zones in our mountains, extending down to below 500m along the western edge of its range, where it is represented on the Isles from Skye down to Arran, but confined to progressively higher altitudes moving through the north-west Highlands into the Grampians: in Ross, for example, its base lies at around 750m, whereas in the central Highlands it is not found much below 900m but extends in fragmentary fashion to over 1200m (McVean and Ratcliffe 1962, Birse 1980). Throughout these regions, at these levels, the summers are brief and cool, with mean annual maxima usually below 21°C (Conolly and Dahl 1970). Outlying stations further south =, where the community is of local importance over summits in the Southern Uplands, the Lake District, the north Pennines and, in more attenuated form, in north Wales, are just a little warmer, with maxima of 23-23°C, but these still present some of the bleakest tracts of high ground outside the Highlands. Winter minima, on the other hand, and thus the annual range of temperatures, vary considerably across these parts of Britain, with the most bitter and more continental conditions being experienced over the higher summit plateaus of the east-central Highlands, the climate further west being noticeable more equable, particularly towards the lowest altitudinal limits of the community, over the spurs of the mountains along the Atlantic seaboard of Scotland (*Climatological Atlas* 1952).

Towards the former extreme, the *Carex-Racomitrium* heath only survives where there is some degree of shelter from the harshest exposure, its hold being increasingly tenuous the less oceanic the general climatic conditions: over the eastern slopes of the Cairngorms, for example, the lower limit of the community can be up to 250m below that on the more exposed western spurs (McVean and Ratcliffe 1962). In general, however, this is a vegetation type of open, relatively unsheltered conditions, being most extensive over tracts of flat or gently-sloping ground, on what Smith (1900b), in the first, classic account of the community, called "alpine plateaus". In such places, away from hollows and lee slopes, there is little relief from the strong, unrelenting winds that blow at these altitudes, so the ground is for the most part kept free of any but a patchy cover of snow through the winter. Over the range of the *Carex-Racomitrium* heath, the amount of snow can be substantial with over 100 days observed snow- or sleet-fall in some places (Manley 1940), but this is caught and held only very lightly and locally here, being mostly swept off into more sheltered situations. There can sometimes be a light covering of verglas over the moss carpet, with icy pennants frozen onto upstanding sedge and grass leaves (Poore 1955c), but generally speaking the vegetation and soils are fully exposed to the influence of fluctuating temperatures and to the drying effect of the wind on ground already deprived of much of its winter moisture by the redistribution of precipitation in snow drifted elsewhere.

Potentially, then the flora of such situations is likely to have a strong Arctic-Alpine character, consisting of plants adapted to the very short growing season and tolerant of bouts of bitter cold and desiccation alternating with drenching mist, and of the environmental instability resulting from freeze-thaw and solifluction. And, moreover, to be able to survive in soils that are often of a very fragmentary character and highly impoverished, locally in deep pockets, but often shallow and stony, usually sharply-draining and sometimes strongly podzolised and with at most a thin humic crust (Smith 1911b, Poore 1955c, Poore and McVean 1957, McVean and Ratcliffe 1962). What inhibits the expression of such a floristic aspect throughout the *Carex-Racomitrium* heath is the formidable competitive power of *Racomitrium lanuginosum* in all but the most exposed and disturbed situations here. Of all the many kinds of upland vegetation to which this moss contributes, it is in this community, characteristic of usually snow-free, but less continental conditions, and with little or no grazing, that its growth is most vigorous and effective in ousting montane species susceptible to being crowded out......

U11 *Polytrichum sexangulare - Kiaeria starkei* snow-bed.

Constant species

Deschampsia cespitosa, Kiaeria starkei, Oligotrichum hercynicum, Polytrichum sexangulare.

Rare species

Carex lachenalii, Cerastium cerastoides, Luzula arcuata, Sibbaldia procumbens, Conostomum tetragonum, Kiaeria starkei, Pohlia ludwigii, Polytrichum sexangulare, Anthelia juratzkana, Moerkia blytii, Pleurocladula albescens.

Physiognomy

The *Polytrichum seaxangulare-Kiaeria starkei* snow-bed brings together a variety of bryophyte-dominated vegetation in which the most consistent species are the montane rarities *Kiaeria starkei* and *Polytrichum sexangulare* together with *P. alpinum* and *Oligotrichum hercynicum*. *K. starkei* is usually the most abundant of these and, where snow lies particularly late, its yellowish-green shoots can form a virtually pure carpet, but other mosses and hepatics can be locally dominant. *Barbilophozia floerkii*, for example, is often quite abundant in the carpet and sometimes exceeds *K. starkei* in cover, forming extensive dark-green patches, and stands rich in *K. falcata* and the rare *Pohlia ludwigii* are also occasionally found. Another uncommon bryophyte, *Pleurocladula albescens*, can occur in some quantity too, the pale colour which gives it its name developing best, according to Watson (1925) where the plants are long deprived of air and light by snow. Both *Racomitrium heterostichum* and the rare *Conostomum tetragonum* can be moderately abundant, though these species are not so consistently important here as in the carious *Salix-Racomitrium* snowbeds.

Other bryophyte which generally contribute to the mat as scattered shoots and small patches include *Racomitrium fasciculare, R. lanuginosum, R. canescens. Pohlia drummondii, Nardia scalaris, Lophozia sudetica* (perhaps including some *L. wenzelii*) and, more locally, the rare hepatics *Anthelia juratzkana* and *Moerkia blyttii*. Lichens are much less numerous and never abundant, but *Cladonia bellidiflora* and *Cetraria islandica* are quite frequent and *Solorina crocea* is sometimes found.

Vascular plants are typically sparse, although the combination of frequent *Deschampsia cespitosa, Carex bigelowii, Omalotheca supina* and *Saxifraga stellaris* is very characteristic of this community, the pure white flowers of the last, emerging through the late-melting snow, being one of the most memorable sights of summer botanising in the Highlands. *Huperzia selago, Nardus stricta, Alchemilla alpina, Silene acaulis* and *Sibbaldia procumbens* are also occasional to common, and this kind of vegetation provides one locus for the rarities *Cerastium cerastoides, Carex lachenalii* and, sometimes straying from more exposed situations, *Luzula arcuata.* In contrast to the *Salix-Racomitrium* snowbed, *Salix herbacea* is only occasional and usually of low cover.

Habitat

The *Polytrichum-Kiaeria* community is strictly confined to very late snowbeds at high altitudes through the coldest parts of the Scottish Highlands. It occurs, generally as small stands, in hollows and corries and over sheltered slopes in almost all the major mountain ranges although, towards the more oceanic north-west of Scotland, stands become increasingly local.

This is a vegetation type of some of the highest slopes in the Highlands, characteristic of the middle-alpine zone from around 900m to over 1200m. At these levels, annual accumulated temperatures are at their lowest in the country, often less than 250 day-degrees C yr^{-1} (Page 1982), with short, cool summers, mean annual maxima being usually below 21°C (Conolly and Dahl, 1970), and long, bitter winters. These generally harsh conditions are reflected in the floristics of the community in the poor representation of the sub-montane plants and the occurrence of many Arctic-Alpines, like *C. bigelowii, C. supina, S. stellaris, Alchemilla alpina, Sibbaldia procumbens, Silene acaulis, Salix herbacea, J. trifidus, Cerastium cerastoides* and *Carex lachenalii*, and montane bryophytes such as *Kiaeria starkei, O. hercynicum, P. sexangulare, P. alpinum, C. tetragonum, Pohlia drummondii* and *Pleurocladula albescens.*

More particularly, however, this is one of the communities characteristic of more sheltered situations in our coldest mountains where snow is caught and held long into the spring. Across the range of the *Polytrichum-Kiaeria* vegetation, precipitation varies considerably, from not much over 1600mm with around 180 wet days per year in the Cairngorms to the east, to almost 3200mm with more than 220 wet days per year through the western Highlands (*Climatological Atlas* 1952, Ratcliffe 1968). But, at these altitudes, much of the winter share of this is received as snow, with over 100 days of snow- or sleet-fall over the higher ground (Manley 1049), and in the windy conditions this is swept from more exposed ground into sheltered places, accumulating thickly where the gathering grounds are large and persisting long over shaded north and east-facing aspects. Although detailed data are still lacking, this community seems to be found where such accumulations are deepest and most persistent, not finally melting in some years until well into June. And, although many of the slopes here are quite steep with the melt-waters draining away readily, the ground is generally stable and not much liable to the solifluction or downwash that characterizes some snowbeds (McVean and Ratcliffe 1962).

For some of the plants recorded here, the snow cover is important in providing shelter from the bitter temperatures and harsh winds of winter. The very occasional ferns such as *Blechnum spicant* and *Cryptogramma crispa*, for example, benefit from the protection from frost, although the ground is generally not sufficiently humic and bouldery for them to thrive in abundance, and snow-lie is altogether too long for the community to provide a locus for those oceanic bryophytes that can persist in less chionophilous heaths (Ratcliffe 1968). More important in this particular case are the redistribution of precipitation through the drifting and persistence of the snow, and the shortening of the growing season by the lengthy snow-lie and irrigation with frigid melt-waters. This combination of factors excludes plants which demand drier ground and/or a longer summer, giving an opportunity for more hygrophilous or competition-sensitive species to flourish. *Salix herbacea, Omalothece supina, Saxifraga stellaris* and cushion herbs like *Sibbaldia procumbens* and *Silene acaulis* are among the Arctic-Alpines here which favour more open conditions, while *Deschampsia cespitosa, Nardus stricta* and *Carex bigelowii* all tolerate the wet, mineral soils. The moist nature of the ground also enables *Alchemilla alpina* to persist in situations which would otherwise be inhospitable: over higher ground in the Cairngorms, for example, this plant is strongly concentrated around the better-draining sides of these snow-patches (Raven and Walters 1956).

It is a mixture of these species which give most of the character to the vascular element of the *Polytrichum-Kiaeria* community, but their contribution to the cover is strictly limited by the luxuriance of the snow-tolerant bryophytes of the community, the plants most obviously able to benefit from the particular environmental conditions here. Not all of the most abundant members of this group are confined to late snow-beds, but *Kiaeria starkei, K. falcata* and *Racomitrium heterostichum* rarely grow on soil, as opposed to rock surfaces, unless snow-lie is prolonged, and other species of the community, such as *Polytrichum sexangulare, Moerkia blyttii* and *Pleurocladula albescens* are virtually exclusive to patches of long-persistent snow (McVean and Ratcliffe 1962). However, some of these do occur in other kinds of chionophilous vegetation, notably the *Salix-Racomitrium* community and, where the vegetation types occur in close proximity, as in the snow-beds of the Cairngorms and Ben Lawers, it is not always clear what environmental factors distinguish them. Sometimes, though, the *Salix-Racomitrium* community does occupy ground where snow-lie is obviously not so deep or lengthy as here, and where the effects of solifluction are more pronounced (McVean and Ratcliffe 1962).

The effects of long-persistent snow overrides some of the influence of the underlying soils on the vegetation and the *Polytrichum-Kiaeria* community can be found over base-rich substrates, like the calcareous schists of some of the Breadalbane mountains, as well as more acidic ones.

Typically, though, with the strong leaching of the profiles, the soils are base-poor, indeed usually with signs of incipient podzolisation and there is sometimes gleying below where melt-waters produce intermittent waterlogging. A distinct humose top-soil can generally be seen and buried humic layers are sometimes found where wind-blown detritus has been deposited on the vegetation. With surface pH between 4.5 and 5.5, the flora is prevailingly calcifuge or indifferent, *C. bigelowii, O. supina, Saxifraga stellaris, Silene acaulis* and *Huperzia selago* being among the important montane species here with that kind of edaphic preference (McVean and Ratcliffe 1962).

U12 *Salix herbacea - Racomitrium heerostichum* snowbed

Constant species

Salix herbacea, Racomitrium heterostichum

Rare species

Luzula arcuata, Minuartia sedoides, Sibbaldia procumbens, Kiaeria starkei, Gymnomitrium corallioides, Cetraria delisei, Solorina croea.

Physiognomy

The *Salix herbacea - Racomitrium heterostichum* community includes a variety of carpets and crusts of bryophytes in which *Salix herbacea* is a constant feature. This tiny willow, rarely more than a couple of centimetres tall here, is sometimes quite abundant as a loose mat of prostrate shoots, their leaves and catkins appearing together in June as the last of the snow melts, or as late as August in the highest stands (Meikle 1984). In other cases, the cover of *S. herbacea* is patchy or generally sparse, when it is usually bryophytes which dominate, most commonly mixtures of *Racomitrium heterostichum* with one or other of *R. fasciculare, Gymnomitrium concinnatum* or the rare *Kiaeria starkei*, a moss that is locally abundant here, though not so consistently important as in the *Polytrichum - Kiaeria* community. *R. lanuginosum, Conostomum tetragonum, Oligotrichum hercynicum* and *Polytrichum alpinum* also occur frequently, though not usually with high cover, but *P. sexangulare* is only occasional. In some stands which are best included with this vegetation, the rare *Marsupella brevissima (=Gymnomitrium varians)* is strongly dominant, crowding out many of the associates, and another related rarity, *G. corallioides* occurs in this community in some places.

Other bryophytes recorded her include *Pohlia nutans, Nardia scalaris* and *Barbilophozia floerkii*, which are quite frequent, and *Diplophyllum albicans, Polytrichum piliferum* and *Lophozia sudetica*, which are more occasional. Lichens are typically of sparse cover, but *Cladonia bellidiflora, C. uncialis, C. pyxidata* and *Cetraria islandica* are fairly common and the community provides one locus for the rare *C. delisei* and *Solorina crocea.*

Apart from *Salix herbacea*, only *Carex bigelowii* and *Deschampsia flexuosa* occur frequently throughout this kind of vegetation and these are not generally more than moderately abundant. *D. cespitosa, Omalotheca supina* and *Huperzia selago* are occasionally found and there is sometimes a little *Festuca ovina/vivipara, Luzula spicata, Juncus trifidus* and *Alchemilla alpina.* Arctic-Alpine rarities that can find a place here include *Luzula arcuata, Sibbaldia procumbens* and *Minuartia sedoides.*

Habitat

The *Salix - Racomitrium* community is strictly limited to late snow-beds with some solifluction or downwash at high altitudes in the coldest mountains of Scotland. It is found, usually in small stands, over gentle to steep ground on snow-bound slopes and in sheltered hollows on plateaux through most of the Highlands north to Beinn Dearg and, in more fragmentary form, on Mull and in the Southern Uplands.

Like the *Polytrichum - Kiaeria* community, this is a vegetation type of some of the most inhospitable ground in the uplands, typical of the middle-alpine zone from about 900m to more than 1250m. The geographical boundaries of the *Salix - Racomitrium* community are drawn just a little wider than there, but the climate is still generally very harsh, with brief, cool summers with mean annual maximum temperatures usually below 22°C (Conolly and Dahl 1970) and long, bitter winters. As there, then, it is Arctic-Alpine plants that give the vegetation much of its general character, with such species as *S. herbacea, C bigelowii, L spicata, S. acaulis, J. trifidus, F. vivipara, A. alpina* and *O. supina*, and the high montane bryophytes *K. starkei, O. hercynicum, P. alpinum, C. tetragonum* and *G. concinnatum.*

As with the *Polytrichum - Kiaeria* community, however, it is the accumulation and persistence of snow that gives the *Salix - Racomitrium* vegetation much of its particular stamp. Precipitation is again very variable across the range, from around 1600mm with 180 wet days yr $^{-1}$ in the east-central highlands, to more than 3200mm with over 220 wet days yr $^{-1}$ to the wet (Climatological Atlas 1952) but much of this falls as snow, with more than 100 days observed snow- or sleet-fall over this higher ground (Manley 1940). The *Salix - Racomitrium* community is not so strictly associated as is the *Polytrichum - Kiaeria* vegetation with north- and east-facing slopes where snow accumulation is deepest and most long-lasting, but conditions are always sufficiently sheltered here as to catch some snow and for it to persist for lengthy periods. And, again, it seems to be the redistribution of precipitation, the shortening of the growing season and irrigation by melt-waters that are the important factors associated with snow-lie that influence the vegetation, favouring a predominance of snow-tolerant bryophytes with a scattering of competition-sensitive herbs.

Unfortunately, detailed information is still lacking, but McVean and Ratcliffe (1962) considered that the *Silene - Luzula* sub-community was characteristic of conditions closer to those favoured by the *Polytrichum - Kiaeria* vegetation, with the *Gymnomitrion* and *Marsupella* types somewhat less extreme, though still more chionophilous than, say, the *Carex - Polytrichum* moss heath. Additionally, although it is sometimes difficult to interpret the environmental preferences of these different kinds of late snow-bed when they occur in close proximity, they seem to favour ground with varying degrees of stability. The *Polytrichum - Kiaeria* community, though often found on steep slopes, is generally typical of stable situations, whereas the *Silene - Luzula* type of *Salix - Racomitrium* heath often occurs where melt and rain wash down finer detritus which completely buries the vegetation from time to time. The soils are more strongly gleyed here and, although surface humus is thin, there are often buried humic horizons in the profile.

The *Gymnomitrion* and *Marsupella* sub-communities are different again. here, the soils are kept permanently moist and, as the melt occurs, the thawed and saturated surface layers shift over the still frozen ground beneath. Drastic slumping and flow of material often obscures the finer effects of such amorphous solifluction but the puckered crust of leafy hepatics characteristic of these kinds of *Salix - Racomitrium* snow-beds is a very good indication of more subtle movements below. Such vegetation is thus generally found on much gentler slopes than those which the *Silene - Luzula* can colonise, and one very striking habitat for the *Gymnomitrion* sub-community is within the sinking centres of old, expanding *Juncus trifidus* tussocks around which the wind-blown and frost-heaved gravel is accumulating on fell-fields (Ingram 1958). Such situations are generally very exposed to fierce winds and bitter cold but even slight depressions can catch and hold a little snow which muffles the effect of the low temperatures.

U13 *Deschampsia cespitosa - Galium saxatile* grassland

Constant species
Agrostis capillaris, Deschampsia cespitosa, Galium saxatile, Hylocomuim splendens, Polytrichum alpinum, Rhytidiadelphus loreus.

Rare species
Cerastium cerastoides, Minuartia sedoides, Sibbaldia procumbens.

Physiognomy
The *Deschampsia-Galium* grassland comprises short or rather rank tussocky swards in which grasses and bulky hypnaceous mosses are the most important structural elements. The commonest and most abundant grass throughout is *Deschampsia cespitosa* and its coarse, densely-tufted habit often gives this vegetation its distinctive stamp. Sometimes, the plants are recognisably of the ssp. *Alpina*, which always has at least some proliferous spikelets, more or less smooth panicle branches and lemmas with a short awn set high on the back (Hubbard 1968, Tutin et. al. 1980), but in Scotland this taxon is morphologically less well-defined from ssp- *cespitosa* than in Scandinavia (Hedberg 1958). In some of the vegetation included here, *D. cespitosa* is so overwhelmingly dominant that little else can compete with its vigorous growth, but in general the swards are richer than this and a variety of other grasses often make a modest contribution to the cover. Most frequent among these are *Agrostis capillaris, Festuca ovina/vivipara, Nardus stricta* and *Deschampsia flexuosa*, with *Anthoxanthum odoratum, Festuca rubra* and *Agrostis canina* rather more unevenly distributed. *Carex bigelowii* is also quite common, though it does not usually have the abundance that it shows in the drier sedge- and moss-heaths with which this vegetation is often found. *Luzula multiflora* occurs occasionally and some stands have a little *L. sylvatica*, a plant which can increase its contribution very substantially where the *Deschampsia-Galium* grassland grades to the vegetation of ungrazed ledges.
Other herbs have a rather variable representation and, among these, only *Galium saxatile* is constant throughout. But *Rumex acetosa, Alchemilla alpina* and *Viola palustris* are very common and characteristic and there are occasional records for *Potentilla erecta, Oxalis acetosella, Cerastium fontanum, Euphrasia frigida* and *Huperzia selago*, with *Sibbaldia procumbens, Ranunculus acris, Diphasium alpinum, Saxifraga stellaris* and *Thymus praecox* sometimes occurring in the more diverse of the grassy swards. In general, though, smaller plants such as *Salix herbacea, Silene acaulis* and *Armeria maritima*, typical of more open vegetation, are very infrequent here, and stands with *D. cespitosa* and tall herbs, some of which McVean and Ratcliffe (1962) included in a species-rich facies of their *Deschampsietum*, are in this scheme places in the *Luzula-Geum* community. Finally, among the vascular associates, there is quite frequently a little *Vaccinium myrtillus*, very occasionally some *V. vitis-idaea*, but sub-shrubs are never a prominent component of this vegetation.
Often as abundant as the herbaceous companions, and sometimes exceeding even *D. cespitosa* in extent, are a number of mosses, among which *Rhytidialelphus loreus* is the most common and abundant, with *Hylocomium splendens, Pleurozium schreberi* and *R. squarrosus* also very common and sometimes having quite high local cover. *R. triquetrus*, however, is only occasional here and McVean and Ratcliffe's (1962) *Deschampsieto-Rhytidiadelphetum triquetrosum* is mostly subsumed in the *Festuca-Alchemilla-Silene* community. *Polytrichum alipinum* is constant and there is

frequently some *Racomitrium lanuginosum* and occasionally a little *Pohlia nutans*. *Kiaeria starkei* has sometimes been found here in very small amounts, but neither this nor mosses like *Polytrichum sexangulare, R. heterostichum, Oligotrichum hercynicum* or *Conostomum tetragonaum* are typical of even the most chionophilous vegetation included on the *Deschampsia-Galium* community.

Hepatics are much less numerous and extensive than mosses, but *Ptilidium ciliare* occurs quite commonly and there is very occasionally a little *Nardia scalaris*. Lichens, too, are few and sparse but *Cetraria islandica, Cladonia gracilis* and *Peltigera canina* are sometimes found.

Habitat

The *Deschampsia-Galium* grassland is characteristic of strongly irrigated and often snow-bound slopes are moderate to high altitudes through the wettest and coldest of our mountains. It is almost entirely confined to the Scottish Highlands, where it is particularly common and extensive in the more oceanic western ranges and, even there, it often shows a strong preference for those aspects where the cool and humid character of the regional climate is accentuated. Although mostly a natural climax community, it is possible that at least some stands have been derived by the influence of grazing.

It is the maintenance of moist ground conditions throughout the year that seems to be of prime importance for the composition and distribution of this kind of vegetation, although a number of factors are involved in meeting this requirement, and the ways in which these operate have quite an effect on floristic variation and habitat relations within the community. Of general significance, first, is high rainfall, because the *Deschampsia-Galium* grassland is strongly concentrated in the most consistently wet parts of Britain. Stands can be found throughout much of the Scottish Highlands wherever precipitation exceeds 1600mm (*Climatological Atlas* 1952), and in a very few far-flung localities over high ground further south where the climate is as wet as this, but the community is much more prominent in the mountains of west Scotland, where there is often more than 2400mm of rain annually and, more importantly, where there is a consistently high atmospheric humidity. For the most part, the range of the *Deschampsia-Galium* grassland falls within the 200 wet days per year line (Ratcliffe 1968) where there is a daytime cloudiness over the upper slopes that is frequently more than 80% (Page 1982), and it is through this region that stands are particularly common, widespread and extensive, often covering many hectares (McVean and Ratcliffe 1962).

The second point of importance is that, even in these wettest areas, there if a strong tendency for the community to be concentrated on north- and east-facing slopes where, in the shaded and sheltered conditions, evaporation is minimised. It is in such situations, too, that the impact of snow-lie is at its greatest for, though the *Deschampsia-Galium* grassland may not always be absolutely dependent on this factor, it is in general a chionophilous community. It has a broad altitudinal range occurring widely between 500 and 1000m, but at such levels, and especially towards the upper limits, much of the winter precipitation is received as snow, with often more than 100 days observed fall annually over the highest ground (Manley 1940). In western Scotland, the *Deschampsia-Galium* grasssland is one of the most extensive kinds of vegetation over slopes in the low- and middle-alpine zones where the snow is caught and held for relatively long periods, on more sheltered hillsides, over the flanks of deep, sunless corries, in the fairly late snow-beds that develop in shallow depressions and around the margins of really long-lasting fields. And it is shelter from frosty and the redistribution of precipitation that come with the drifting and persistence of snow that help the community maintain a hold over suitable topographies in those Scottish mountains with a drier and more bitter climate, like the east-central Highlands, where it is a local feature on cold slopes and in gullies around Caenlochan and Lochnagar (NCR 1977, Huntley 1979).

The third factor concerns the way in which climate and topography interact through the soils. The *Deschampsia-Galium* grassland occurs over a wide variety of parent materials although on calcareous rocks, like the Dalradian mica-schists of Breadalbane and locally lime-rich Moine schists and gneiss through the north-west Highlands, it tends to be replaced by some kind of *Luzula-Geum* vegetation, what McVean and Ratcliffe (1962) called the species-rich facies of their *Deschampsiaetum*. And the great scarcity of the community on the granite of the Cairngorms, where there are eminently suitable topographies, suggests that this particular substrate may be too base-poor or sharply-draining (McVean and Ratcliffe 1962). Between these extremes, the diversity of parent materials beneath the *Deschampsia-Galium* grassland generally weathers to fragmentary, though often quite humic rankers or, with the heavy rainfall, to some kind of podzolised profile, frequently with poor horizonation and with bleaching masked by the incorporation of organic matter. Surface pH is usually between 4 and 5 (McVean and Ratcliffe 1962). The slopes over which the community develops are often quite steep, mostly from 10-30°, but the ground is generally stable and there is little of the solifluction associated with really long snow-lie or extreme exposure. Most important of all, perhaps, is the fact that a combination of rainfall, snow-melt, flushing from springs, seepage-lines and dripping rock-faces, together with the low evaporation, keep the soils moist through the whole of the year. Some profiles show signs of impedence with gleying below, particularly where the parent materials are clayey and the slope more gentle, but drainage is typically rapid. Furthermore, with the quite late snow-melt and the mean annual maximum temperatures throughout the range of the community at 21° or less (Conolly and Dahl 1970), the plants experience a very short growing season while their roots are irrigated with what must be well-nigh frigid waters.

Much of the distinctive character of the *Deschampsia-Galium* grassland comes from the fact that *D. cespitosa* is so well able to capitalise on these conditions, perhaps especially ssp. *alpina*, although most of what we know about the behaviour of this grass in Britain relates to ssp. *cespitosa* (Davy 1980). The grass can survive on a wide variety of soil types and though, across the lowlands of Britain, it occurs mainly on profiles with mull or moder humus, it is well able to tolerate oligotrophic situations. It is, in fact, possible that some of the soils on which the *Deschampsia-Galium* grassland is found are not so impoverished as might appear, at least when compared with the profiles that support sub-shrub or sedge-heaths on similarly snow-bound ground. But, in any case, the grass has an internal system of nutrient-cycling from older to developing tillers which means that it can insulate itself somewhat against shortage of nutrients (Davy and Taylor 1974b, 1975). More important is its marked tolerance of very moist soils: it has well-developed root aerenchyma which, by lowering oxygen requirements in the tissues, can help maintain an oxidising environment around the roots, thus alleviating the impact of toxic reduced ions, like ferrous (Martin 1968, Davy and Taylor 1974a, Rahman 1978). This ability may be crucial for its vigorous growth here, where it can out-compete even plants like *Nardus*, an important grass in much moderately chionophilous vegetation, but one which prefers and oxidising environment in the upper soil layers in summer (Peasll 1950).

The rise to prominence of *D. cespitosa* on moist and moderately acidic soils in the uplands can already be seen to some extent in the *Festuca-Agrostis-Galium* grassland, the major plagioclimax pasture of the sub-montane north and west of Britain: where this extends onto higher slopes on cooler, wetter regions, both *D. cespitosa* and *Rhytidiadelphus loreus* become preferentially frequent. And, in its general floristics, the *Deschampsia-Galium* grassland, though it extends to far greater altitudes that the *Festuca-Agrostis-Galium* swards, has as much in common with them as most other high montane vegetation found around it over upper slopes and plateaus. Most stands of the community fall within the 21° mean annual maximum isotherm, which forms a crude boundary for many Arctic-Alpines in Britain (Conolly and Dahl 1970), but few of these plants find a place here. Indeed only *D. cespitosa* ssp. *alpina, F. vivipara, C. bigelowii, Alchemilla alpina* and *Polytrichum alpinum* find more than occasional representation through the community as a whole and much of the character of the vegetation comes from plants like *F. ovina, A. capillaris, Galium saxatile, Potentilla erecta, Hylocomium splendens, Pleurozium schreberi* and *R. squarrosus* which maintain a strong continuity with the Nardo-Galion grasslands on lower slopes. In large measure this is because many of the Arctic-Alpine plants of chionophilous communities need open ground, maintained by the very long snow-lie or downwash or solifluction processes that are infrequent here. And, of course, there is the very vigorous growth of *Deschampsia cespitosa* itself in many stands, highly effective in excluding more diminutive and competition-sensitive herbs. This may play some part, too, in the scarcity or low cover of snow-tolerant acrocarpous mosses, such as *Polytrichum alpinum* and *Dicranum fuscescens*, which become very important in the very late snow-beds of the drier mountains of the central and eastern Highlands.

Continuity with sub-montane swards is especially obvious on the *Anthoxanthum-Alchemilla* sub-community, which occurs throughout the range of the *Deschampsia-Galium* grassland, though with a preference for lower altitudes and steeper slopes. In the oceanic far-west of the Scottish Highlands, this kind of vegetation can be found below 400m, though most stands occur between 600 and 900m. Even at these altitudes, however, snow-lie does not seem to be so lengthy as over the *Rhytidiadelphus* sub-community, there is a somewhat longer and warmer growing season, and soil moisture perhaps depends as much on the high rainfall and seepage as on irrigation from melt-waters. Thus, though Arctic-Alpines such as *Sibbaldia procumbens, Diphasium alpinum* and *Saxifraga stellaris* find an occasional place here, the growth of *D. cespitosa* is very vigorous and the more striking preferentials are species like *Anthoxanthum, Rumex acetosa, Ranunculus acris, Festuca rubra,* and *Achillea millefolium*, which give the swards the look of a more mesophytic Nardo-Galion grassland. The soils here tend to be not so strongly podzolised and, where there is a small measure of base-enrichment from the irrigation waters, the flora begins to show strong continuity with that of the *Luzula-Geum* or *Alchemilla-Sibbaldia* communities.

The *Rhytidiadelphus* sub-community is more strongly chionophilous than the *Anthoxanthum-Alchemilla* type, characteristic of higher altitudes, generally between 700 and 1000m, on moderately steep slopes which catch and hold snow for long periods. With a shift to these conditions, the dominance of *D. cespitosa* becomes weakened, presumably by the longer snow-lie, and the representation of plants of sub-montane Nardo-Galion swards fades with the cooler climate. The increased prominence of *C. bigelowii*, *Polytrichum alpinum* and lichens give some similarity with the moderately late snow-beds of the eastern Highlands, but this kind of *Deschampsia-Galium* vegetation is only found in fragmentary form east of Creag Meagaidh and Ben Heasgarnich and provides a geographical replacement in the west for the *Carex-Polytrichum* sedge-heath. An abundance of *R. loreus* and other hypnaceous mosses is not unknown among chionophilous vegetation in regions with a drier and more bitter climate, but it tends to be seen at lower altitudes over moderately snow-bound slopes and in association with sub-shrubs which provide shelter and maintain high humidity. Increasingly, towards the west of Scotland, with its humid and more equable climate, the shade and shelter of north- and east-facing slopes, even up to very high altitudes and without a mantle of sub-shrubs, provide such conditions. Here, then, the *Rhytidiadelphus* sub-community may be among the most chionophilous vegetation types of the cloud-ridden upper slopes.

In most situations, and certainly in these extreme habitats, it is possible to account for the distinctive features of the *Deschampsia-Galium* vegetation in terms of these climatic and edaphic factors, but in certain places it is possible that there has been some anthropogenic influence, particularly on the grassier swards of the *Anthoxanthum-Alchemilla* sub-community. Rather striking, for example, are those places where species-poor vegetation of this kind, strongly dominated by *D. cespitosa*, gives way to richer and more luxuriant tall-herb assemblages of the *Luzula-Geum* or *Luzula-Vaccinium* communities, where the sole environmental difference seems to be that the latter are inaccessible to grazing stock occurring on ledges and over cliff-bound slopes. Certainly, compared with many of the plants in such vegetation, *D. cespitosa* is unpalatable and favoured by grazing, although in the uplands its herbage is less rough and poorer in silica that at lower altitudes (Horn 1935) and in deed in some countries it is regarded as providing quite good forage in mountain regions (Hitchcock and Chase 1950, Grummer 1968, Dale 1973). However, it is possible that the snow-lie regime and pattern of irrigation are different on ledges than on more open slopes and that the great abundance of *D. cespitosa* over that latter is largely natural (McVean and Ratcliffe 1962).

M33 - *Pohlia wahlenbergii* var. *glacialis*

Constant species

Deschampsia cespitosa, Saxifraga stellris, Pohlia ludwigii, P. wahlenbergii var. *glacialis.*

Rare species

Alopecurus alpinus, Cerastium cerastoides, Epilobium alsinifolium, Phleum alpinum, Pohlia ludwigii, P. wahlenbergii var. *glacialis.*

Physiognomy

Pohlia wahlenbergii var. *glacialis* can be found as an infrequent and low-cover associate in a variety of vegetation types of wet ground through the uplands of north-western Britain but, in the *Pohlietum glacialis*, it dominates in spongy carpets, often of quite small extent, but exceptionally covering up to 200m^2, of a brought apple-green colour that makes the stand readily recognisable from a distance. Few other bryophytes occur with any frequency and none is consistently abundant. There is commonly a little *Pohlia ludwigii* and *Philonotis fontana* sometimes attains a measure of prominence, though typically it is nothing like such high cover as in the *Philonoto-Saxifragetum*. Other bryophytes recorded occasionally are *Hygrohypnum luridum*, *Bryum weigelii, Calliergon stramineum, Scapania undulata, S. uliginosa, Dicranella palustris* and *Marchantia alpestris.*

In this carpet, vascular plants are few in number and typically of low cover. Only *Deschampsia cespitosa* (often ssp. *alpina* at the higher altitudes characterised by this community) and *Saxifraga stellaris* are constant, but the rare Arctic-Alpine *Cerastium cerastoides* is quite often found and there can also be some *Stellaria alsine, Chrysosplenium oppositifolium, Epilobium anagallidifolium, Veronica serpyllifolia* var. *humifisa* and *Rumex acetosa.* Other rare plants which find an occasional locus here are *Epilobium alsinifolium, Alopecurus alpinus* and *Phleum alpinum.*

Habitat

The *Pohlietum* is strictly confined to spring-heads associated with the late snow-beds of the higher reaches of the Scottish Highlands, where there is vigorous irrigation by cold, oligotrophic waters.

Although *P. wahlenbergii* var. *glacialis* occurs in small amounts over quite a wide range of altitudes through the uplands of north Wales, Cumbria and Scotland, it is found with the kind of dominance characteristic here only within the high montane zone, at altitudes generally above 850m, where mean annual maximum temperatures do not exceed 21°C (Conolly and Dahl 1970). Within this area, which includes the central and north-western highlands of Scotland, the community is further restricted to situations where snow lies longest. Precipitation is heavy throughout the region, with more than 1600mm annually (Climatological Atlas 1952) and, with the bitter winter temperatures at high altitudes, much of this falls as snow, persisting long everywhere but especially so over north- and east-facing slopes. The majority of the stands of the *Pohlietum* are from such aspects and the community is especially well-developed in association with those extensive late snow-beds found in the great sunless amphitheatres of the corries in the Cairngorms, Ben Alder and Creag Meagaidh in the central Highlands and, further north-west, in the Affric-Cannich hills and on Beinn Dearg.

Typically, in these localities and at other sites where the community occurs less extensively, as on Beinn Laoigh, Bidean nam Bian, around Lochnagar and in the Monar Forest (NCR 1977), the rocks from which the springs emerge are acidic and calcium-poor, usually schists, granulites and grits of the Moine series, granites or lavas and agglomerates. So the flushing waters, and the often sloppy, ill-structures mixtures of mineral and organic matter held beneath the moss carpet, are base-poor and oligotrophic. And it is these general climatic and edaphic features which determine the overall character of the community, with its cold-tolerant plants such as *Deschampsia cespitosa, Stellaria alsine, Chrysosplenium oppositifolium* and *Philonotis fontana,* and definite montane species like *Saxifraga stellaris, Cerastium cerastoides, Epilobium anagallidifolium* and *Bryum weigelii.* This much, and the noticeable lack of calcicolous plants, the *Pohlietum* shares with the *Philonoto-Saxifragetum.*

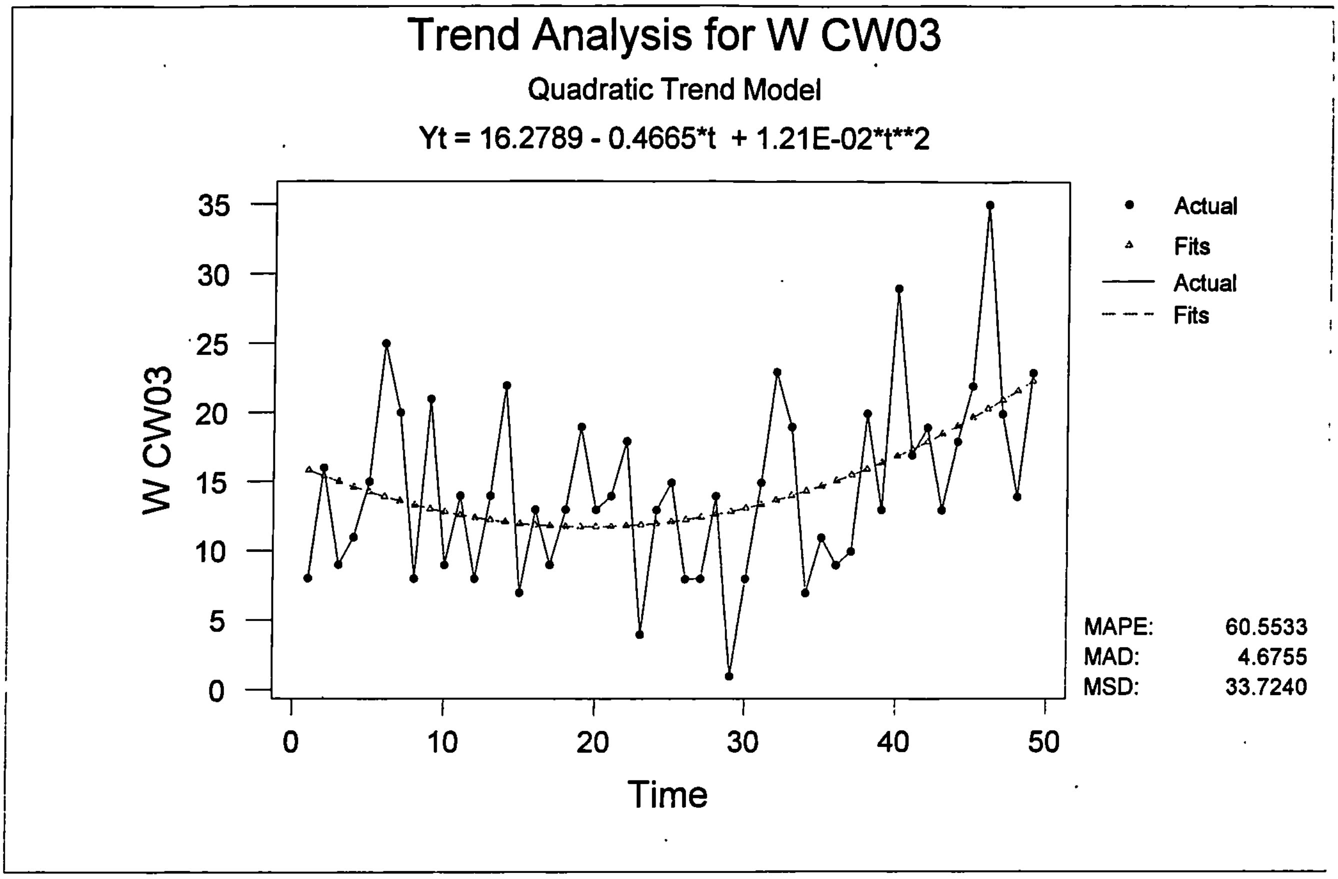
The difference between the two kinds of spring vegetation is best seen among the bryophyte element where there is a switch from dominance by *Philonotis fontana, Dicranella palustris* and *Scapania undulata* to *Pohlia wahlenbergii* var. *glacialis* and *P. ludwigii.* All these species are capable of luxuriant growth an vigorous oligotrophic springs, but the latter two become prevalent where the water temperatures are lower: not all cold springs have the *Pohlietum* but, in those which do, the water temperature is consistently below 4°C (McVean and Ratcliffe 1962). The *Philonoto-Saxifragetum* has a much broader geographical range that the *Pohlietum*, its mean altitude is some

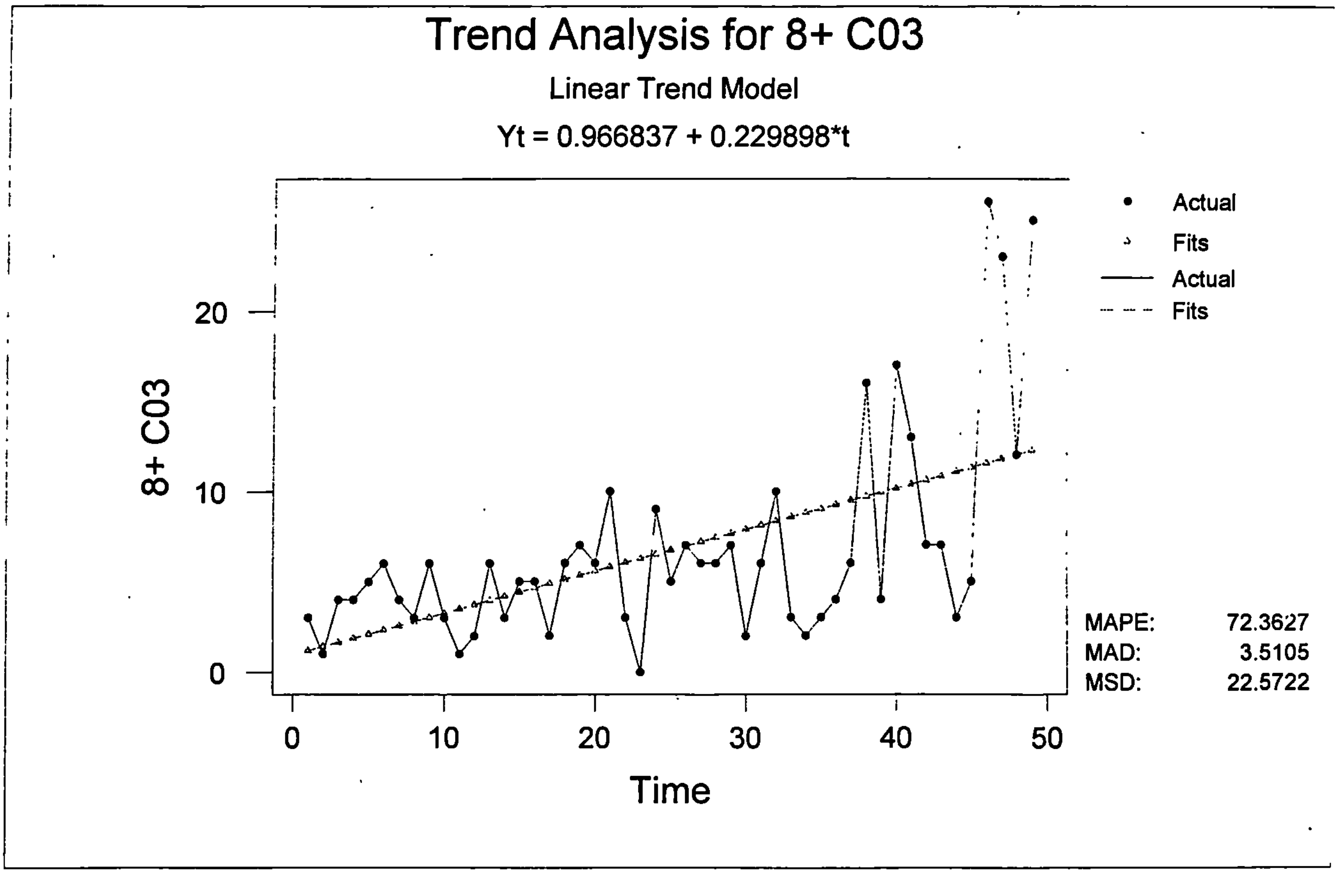
300m lower and, though it can be found in springs fed by melting snow, its association with that habitat is by no means exclusive as with the *Pohlietum*.

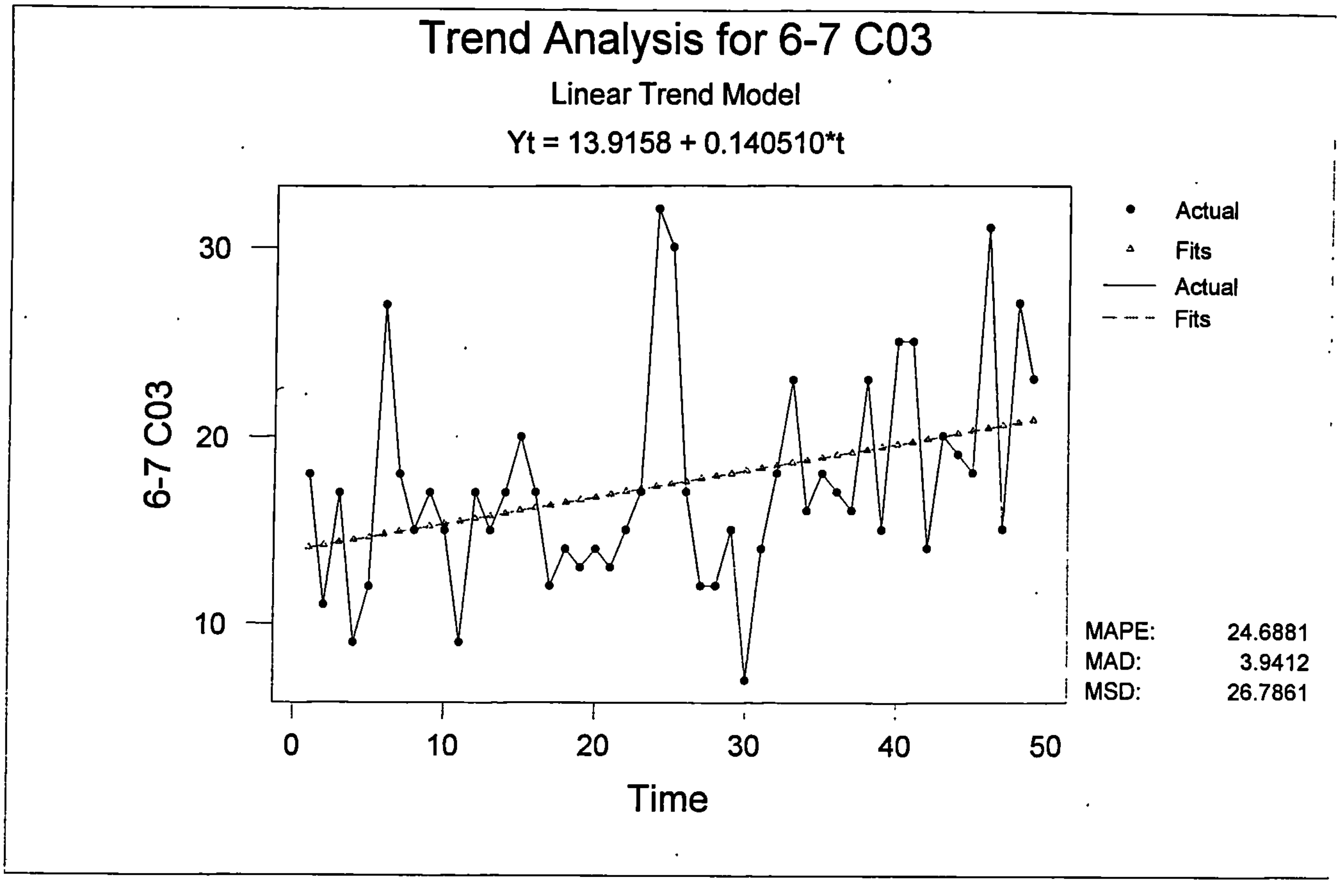
APPENDIX II

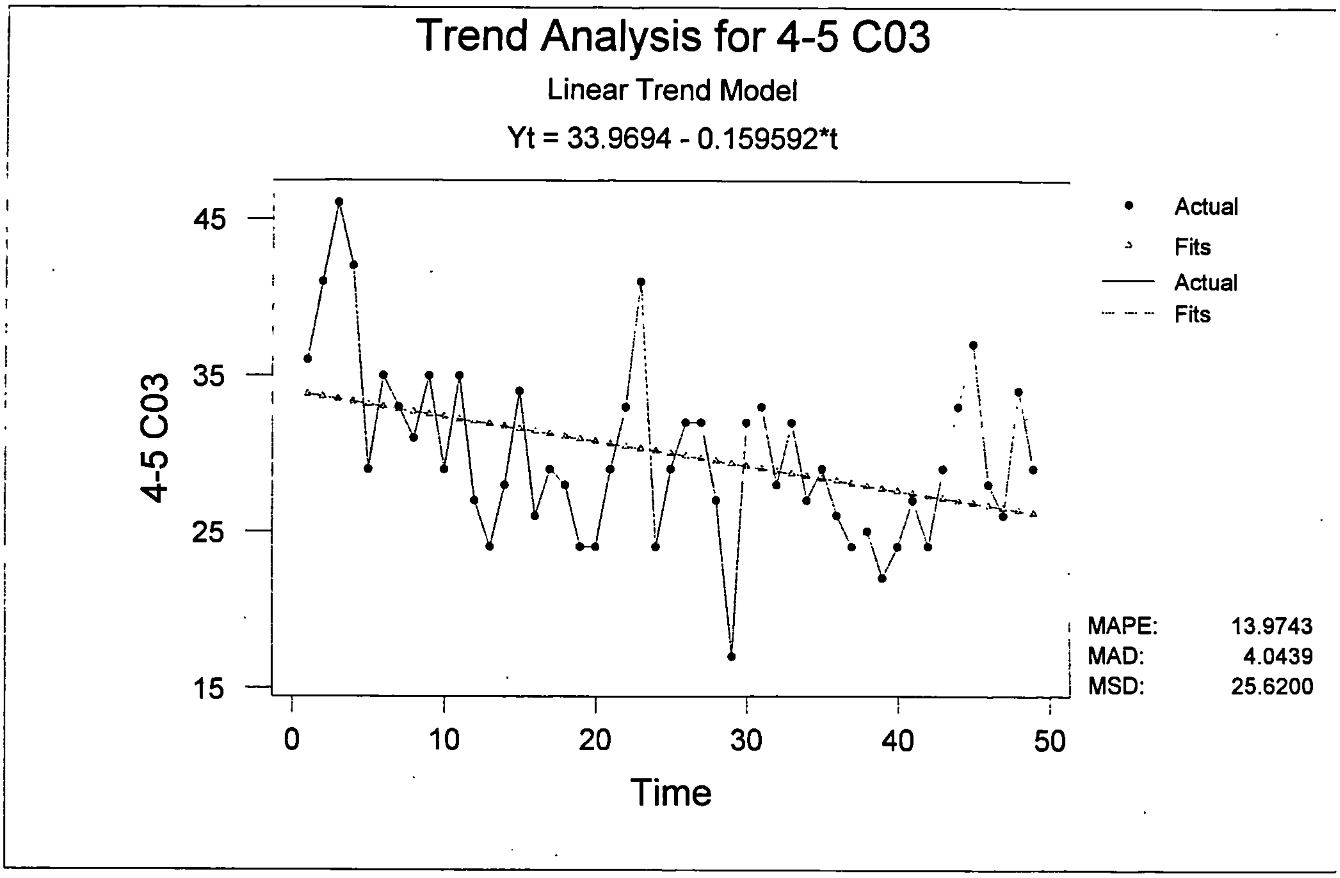
TREND ANALYSIS, BOTH LINEAR AND QUADRATIC DEPENDING ON APPROPRIATENESS OF FIT, OF STATISTICALLY SIGNIFICANT TRENDS GIVEN IN TABLE 4.23.

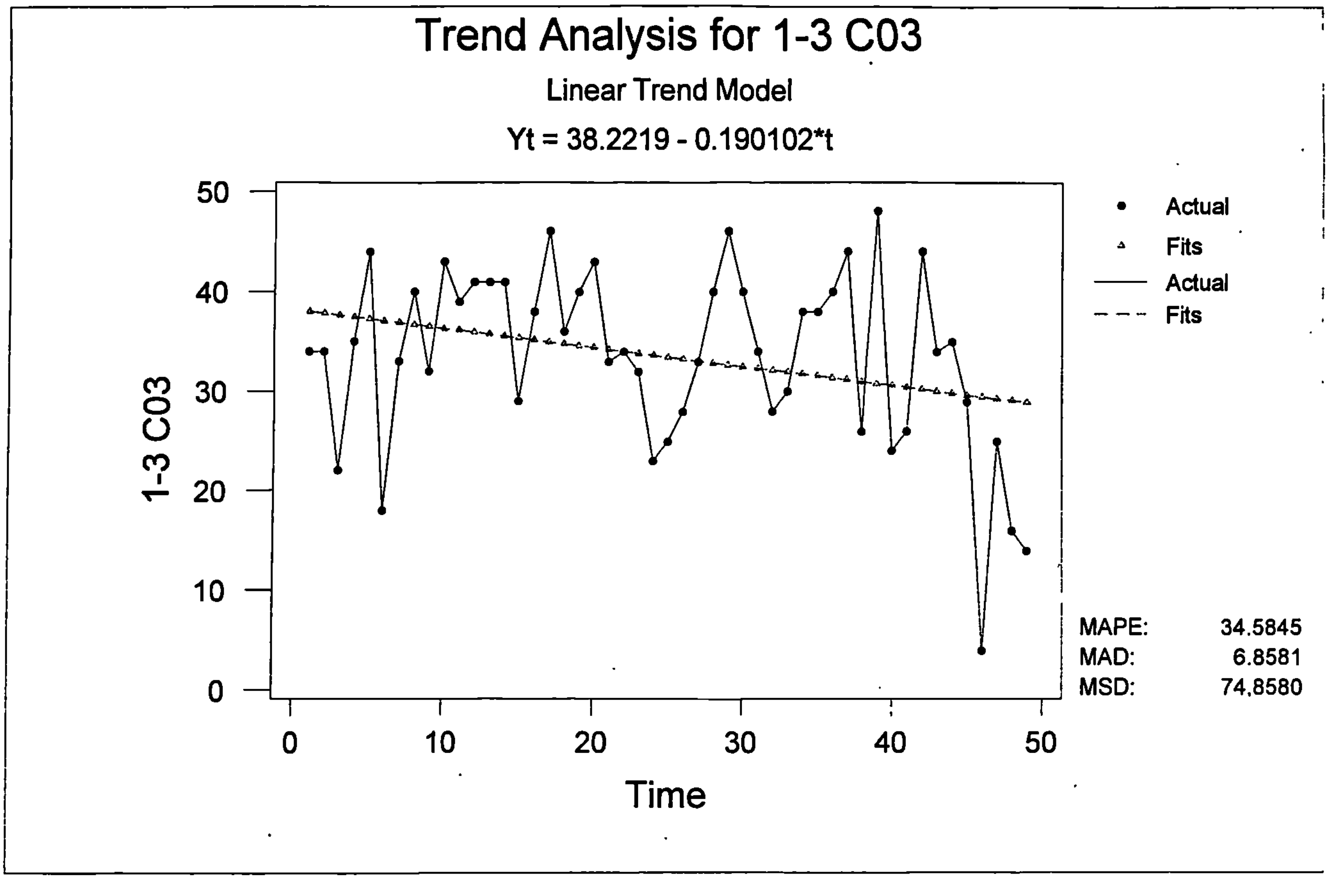
DATA FOR DECEMBER, JANUARY AND FEBRUARY

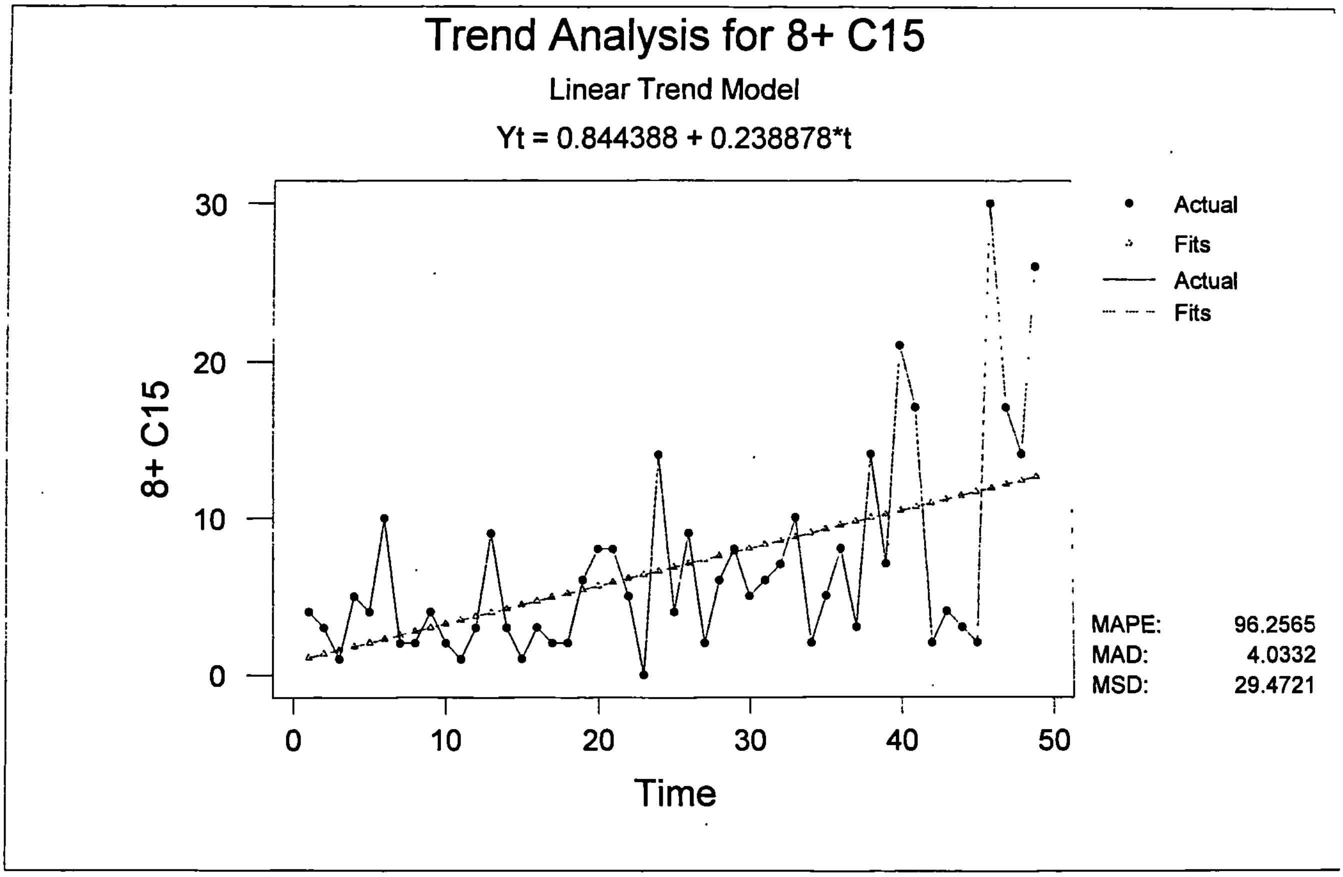

Trend Analysis for W CW03
Quadratic Trend Model
Yt = 16.2789 - 0.4665*t + 1.21E-02*t**2
W CW03
35
30
25
20
15
10
5
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 60.5533
MAD: 4.6755
MSD: 33.7240

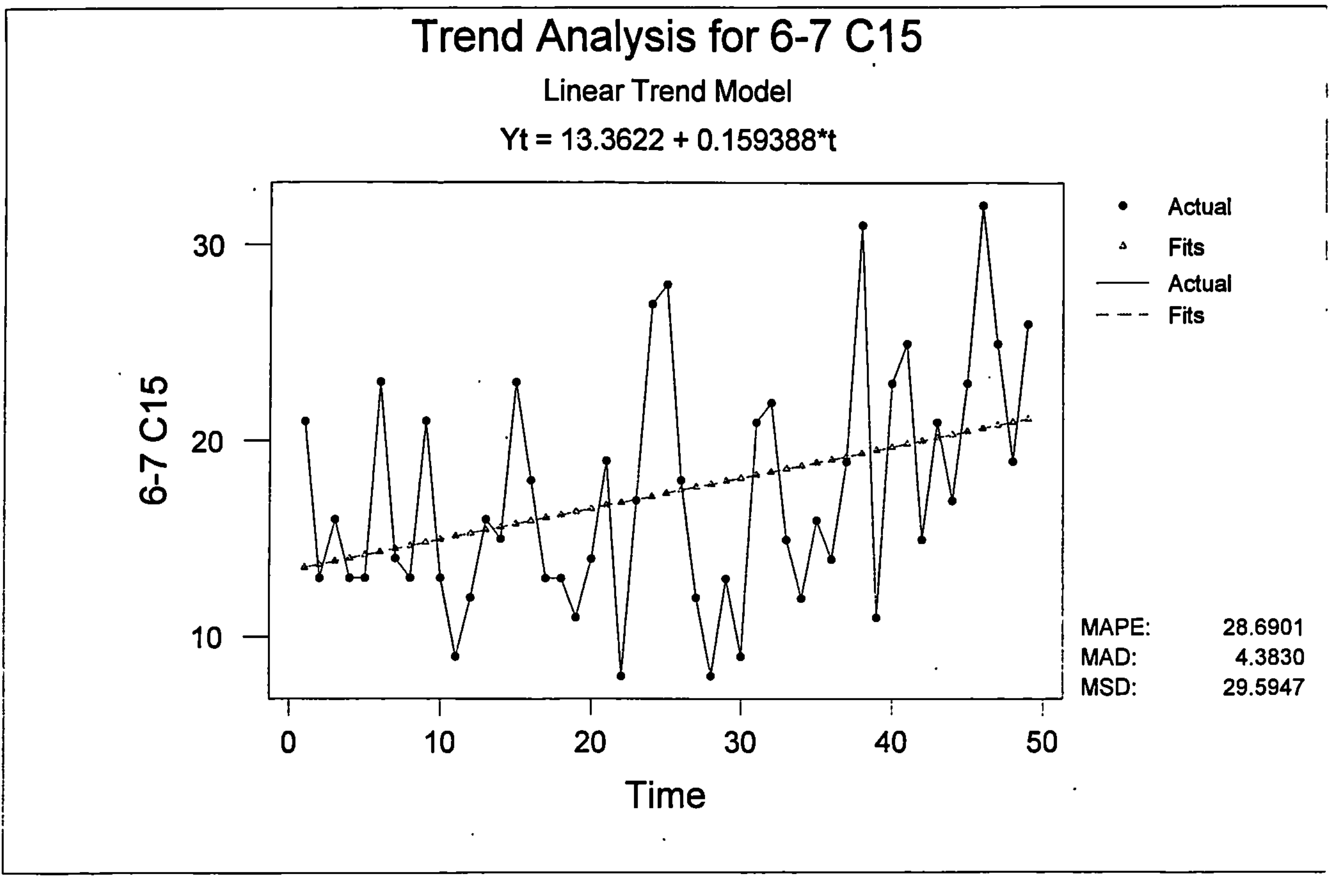

Trend Analysis for 8+ C03
Linear Trend Model
Yt = 0.966837 + 0.229898*t
8+ C03
20
10
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 72.3627
MAD: 3.5105
MSD: 22.5722

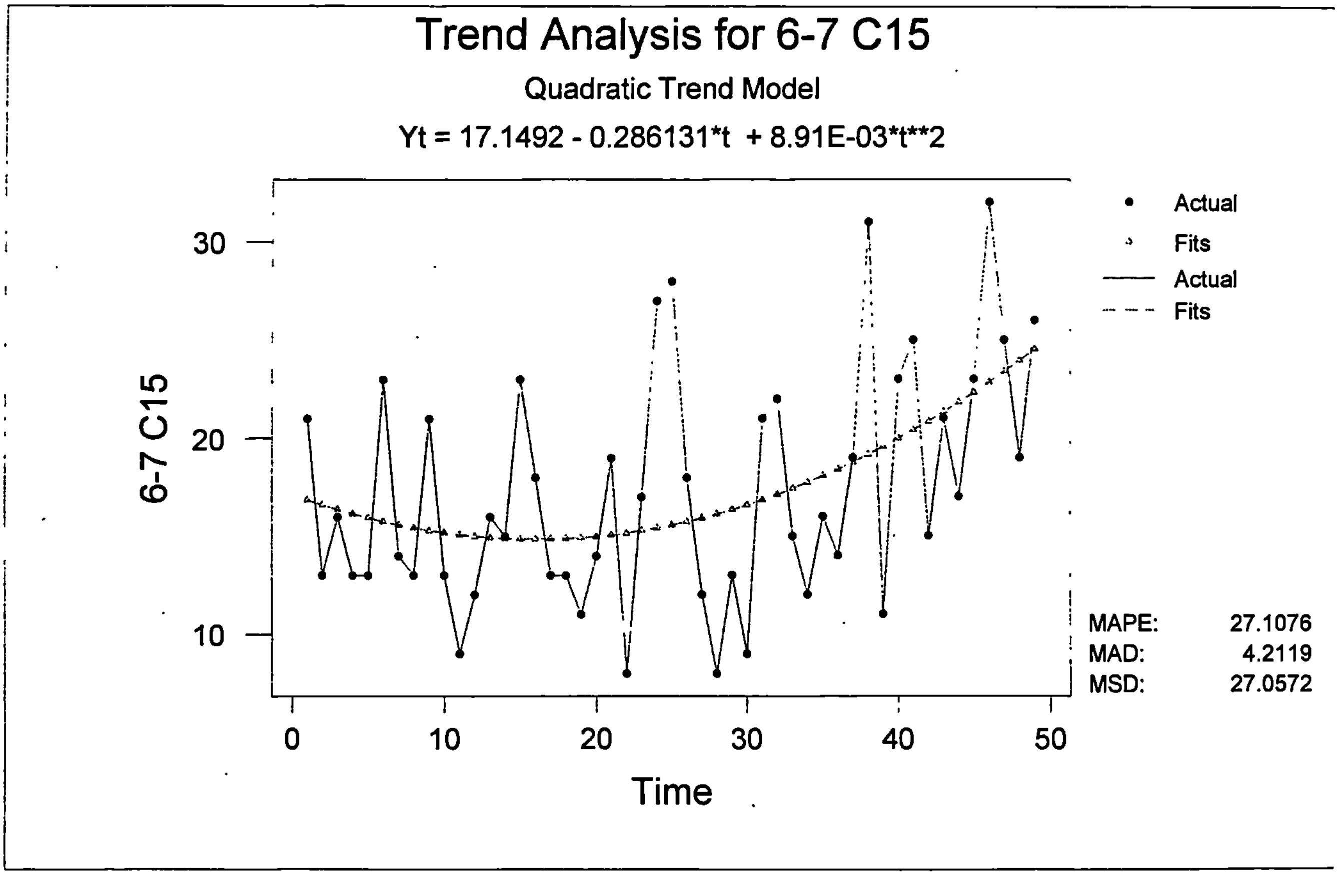

Trend Analysis for 6-7 C03
Linear Trend Model
Yt = 13.9158 + 0.140510*t
6-7 C03
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 24.6881
MAD: 3.9412
MSD: 26.7861

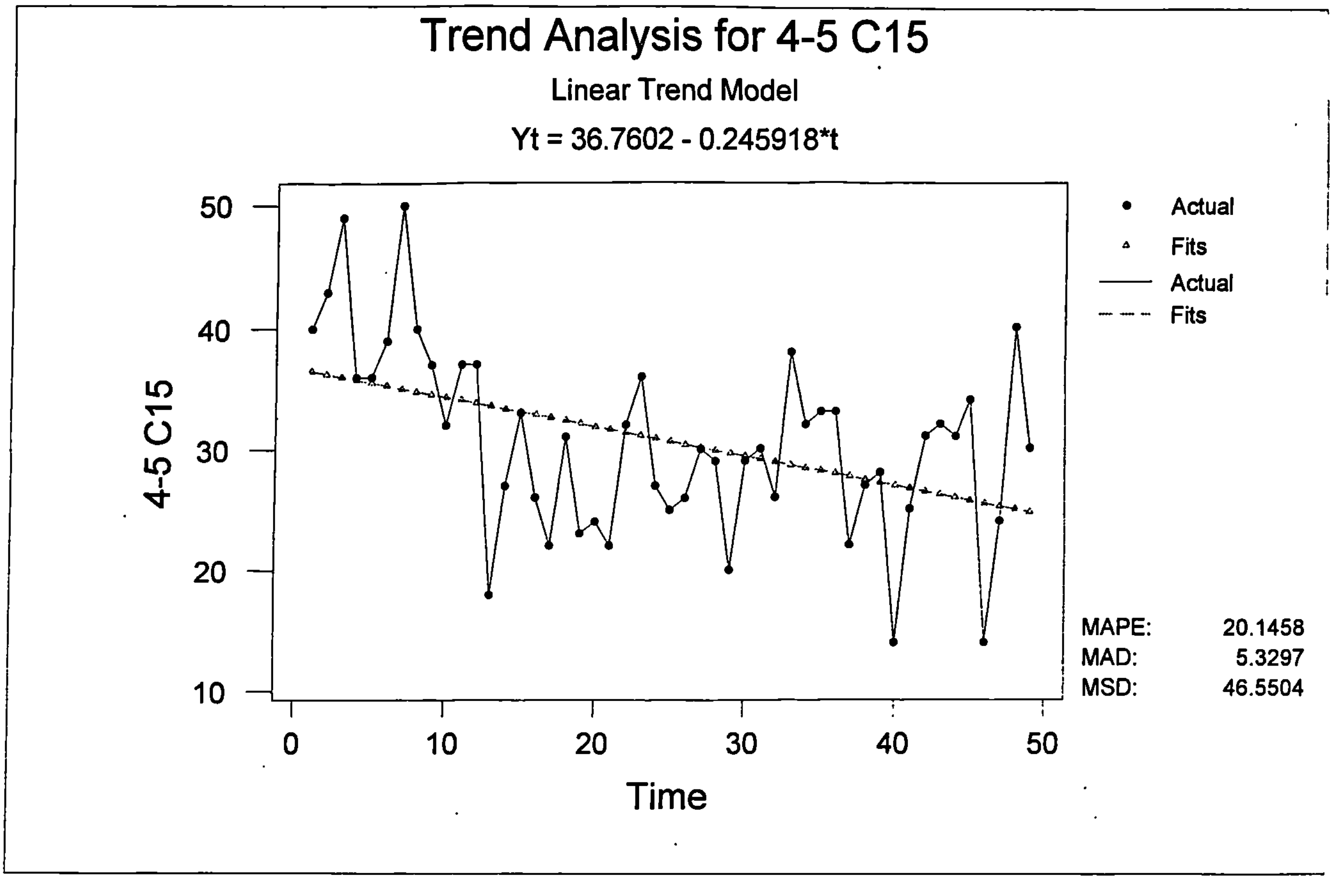

Trend Analysis for 4-5 C03
Linear Trend Model
Yt = 33.9694 - 0.159592*t
4-5 C03
45
35
25
15
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 13.9743
MAD: 4.0439
MSD: 25.6200

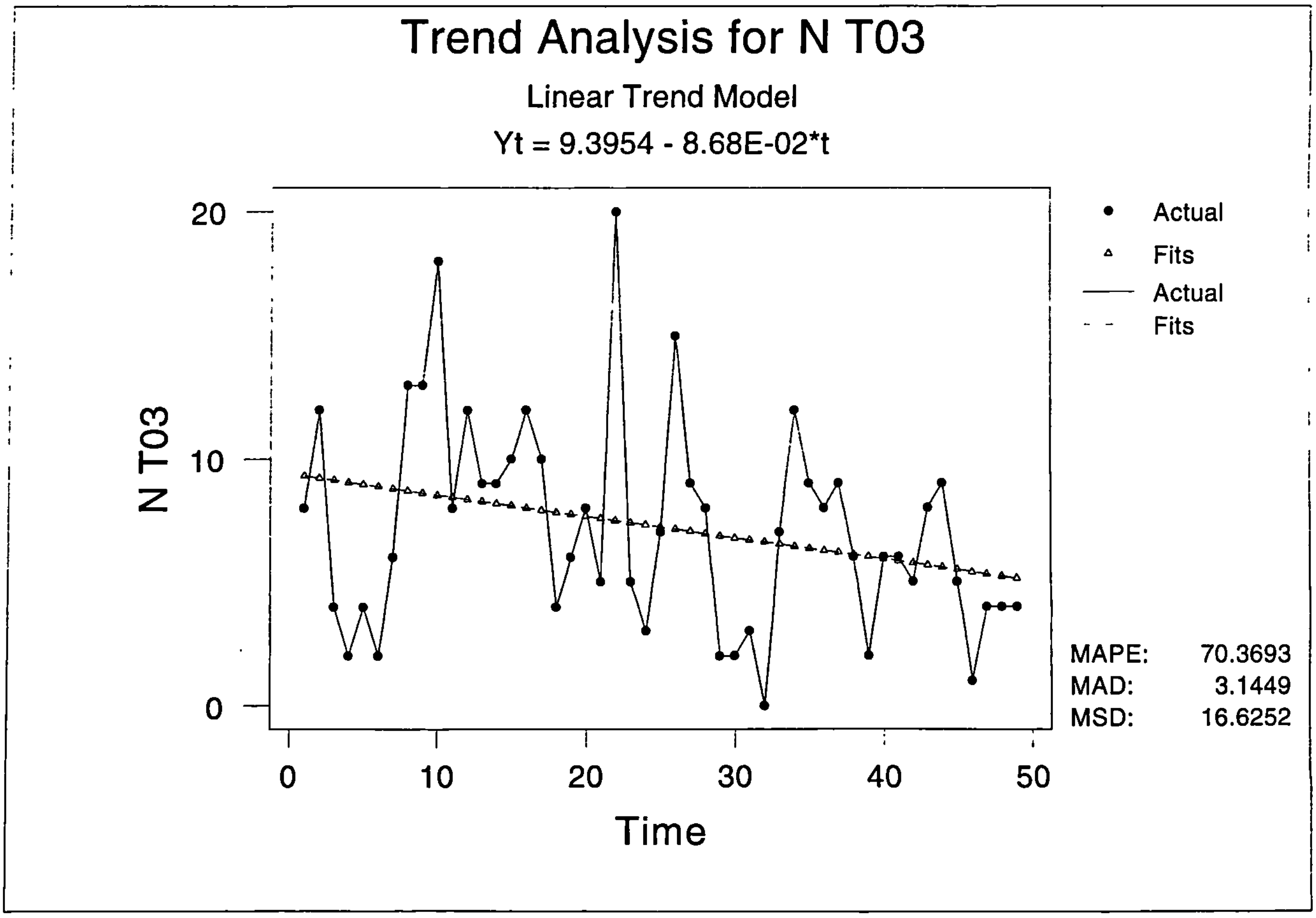

Trend Analysis for 1-3 C03
Linear Trend Model
Yt = 38.2219 - 0.190102*t
1-3 C03
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 34.5845
MAD: 6.8581
MSD: 74,8580

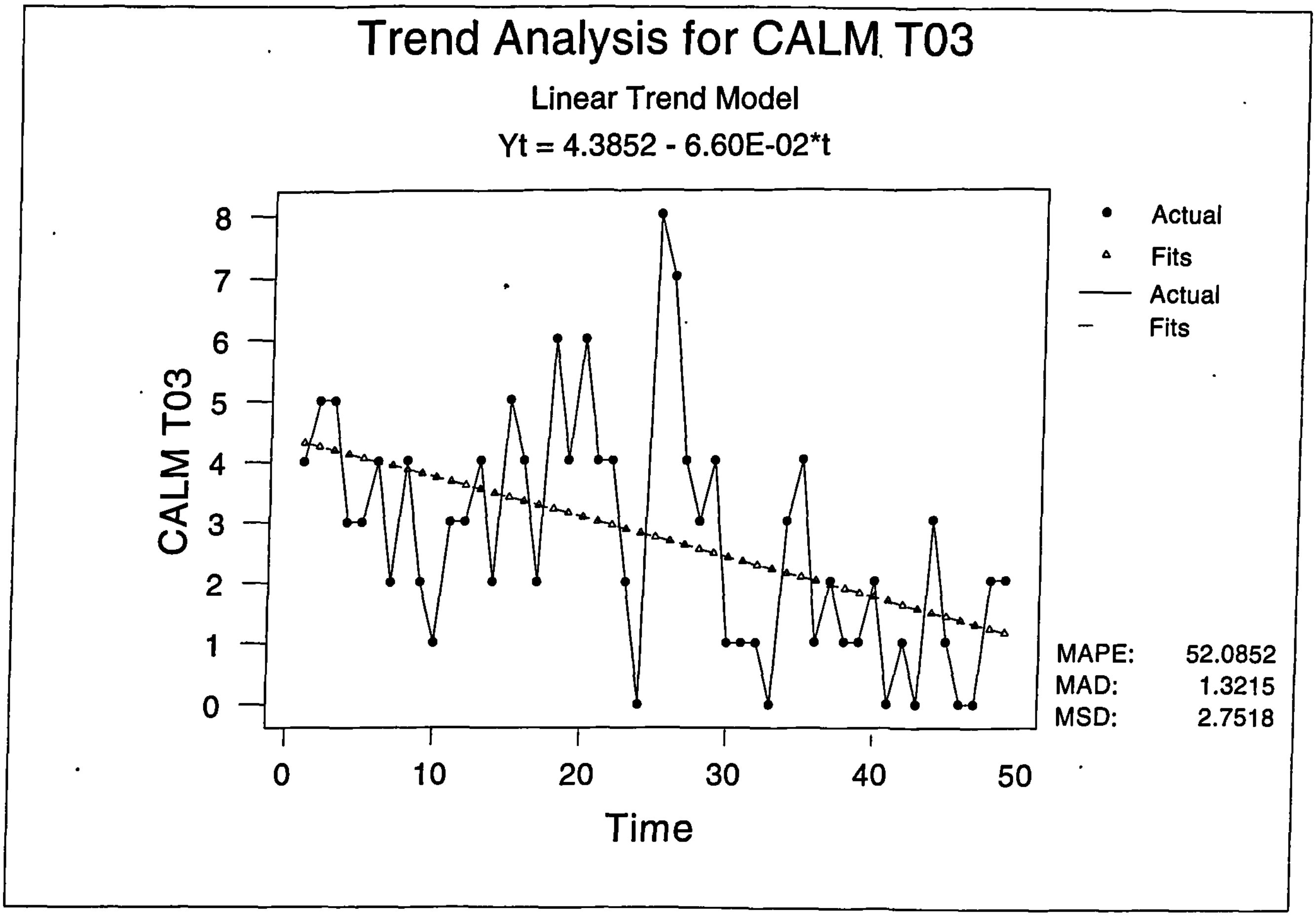

Trend Analysis for 8+ C15
Linear Trend Model
Yt = 0.844388 + 0.238878*t
8+ C15
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 96.2565
MAD: 4.0332
MSD: 29.4721

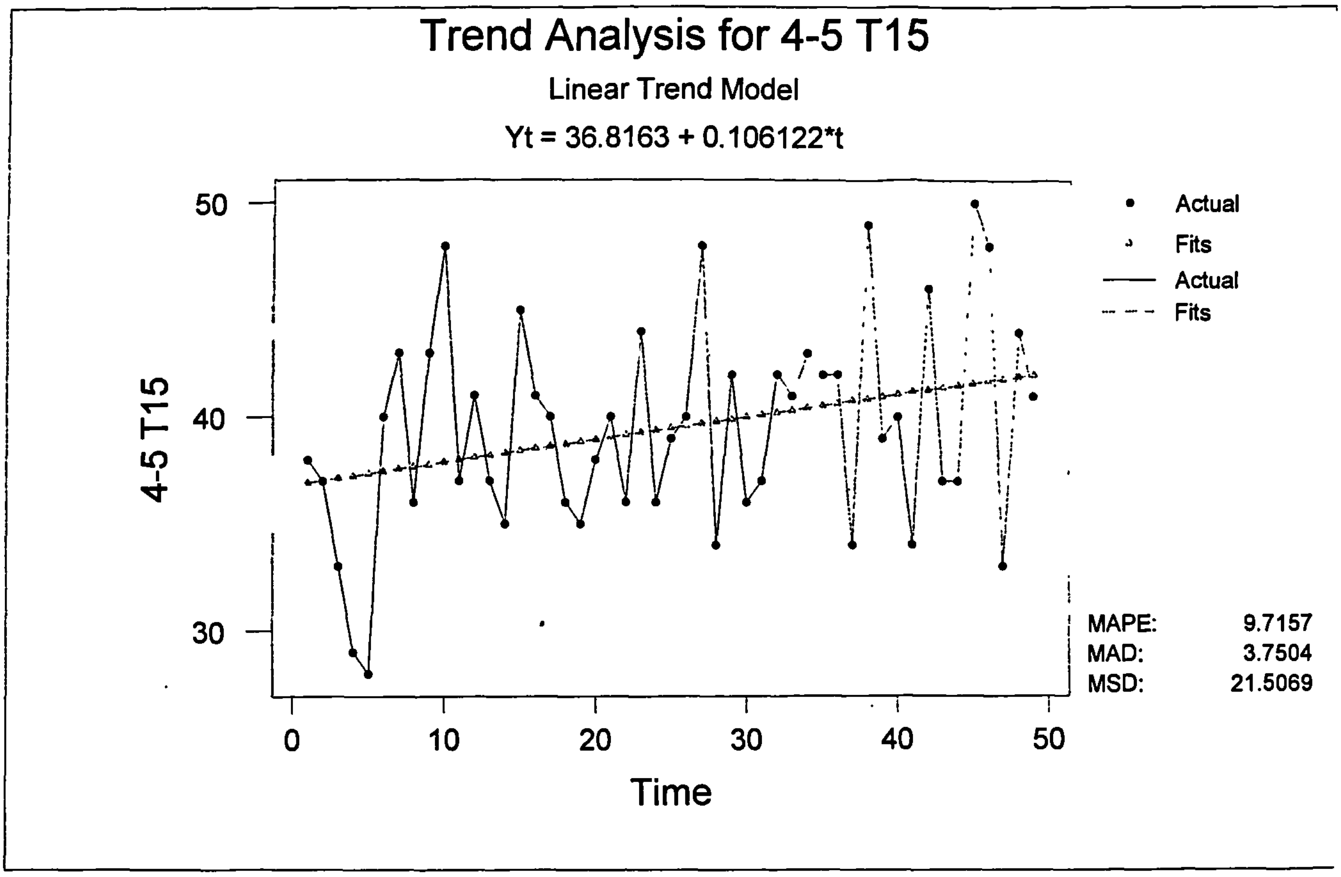

Trend Analysis for 6-7 C15
Linear Trend Model
Yt = 13.3622 + 0.159388*t
6-7 C15
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 28.6901
MAD: 4.3830
MSD: 29.5947

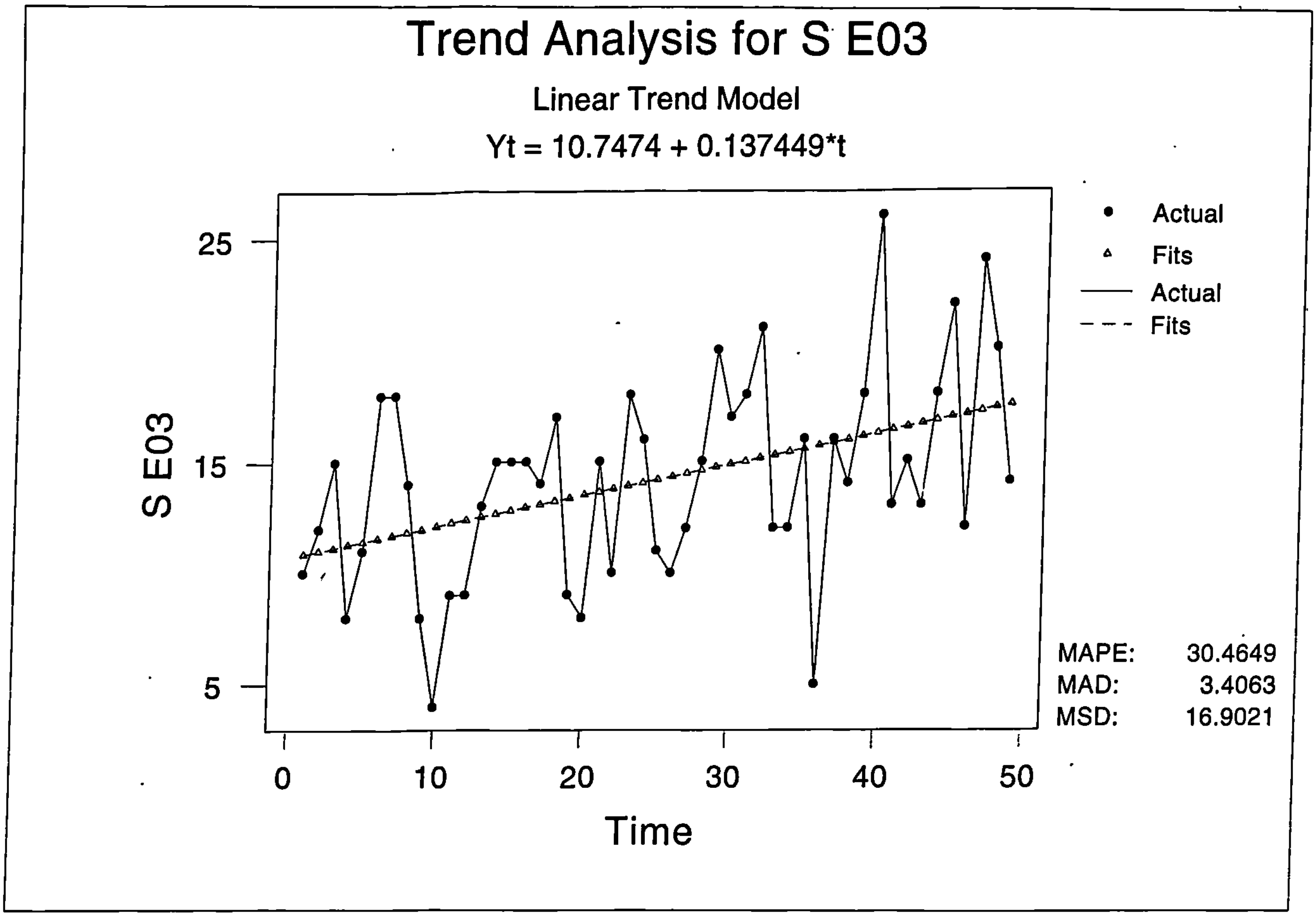

Trend Analysis for 6-7 C15
Quadratic Trend Model
Yt = 17.1492 - 0.286131*t + 8.91E-03*t**2
6-7 C15
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 27.1076
MAD: 4.2119
MSD: 27.0572

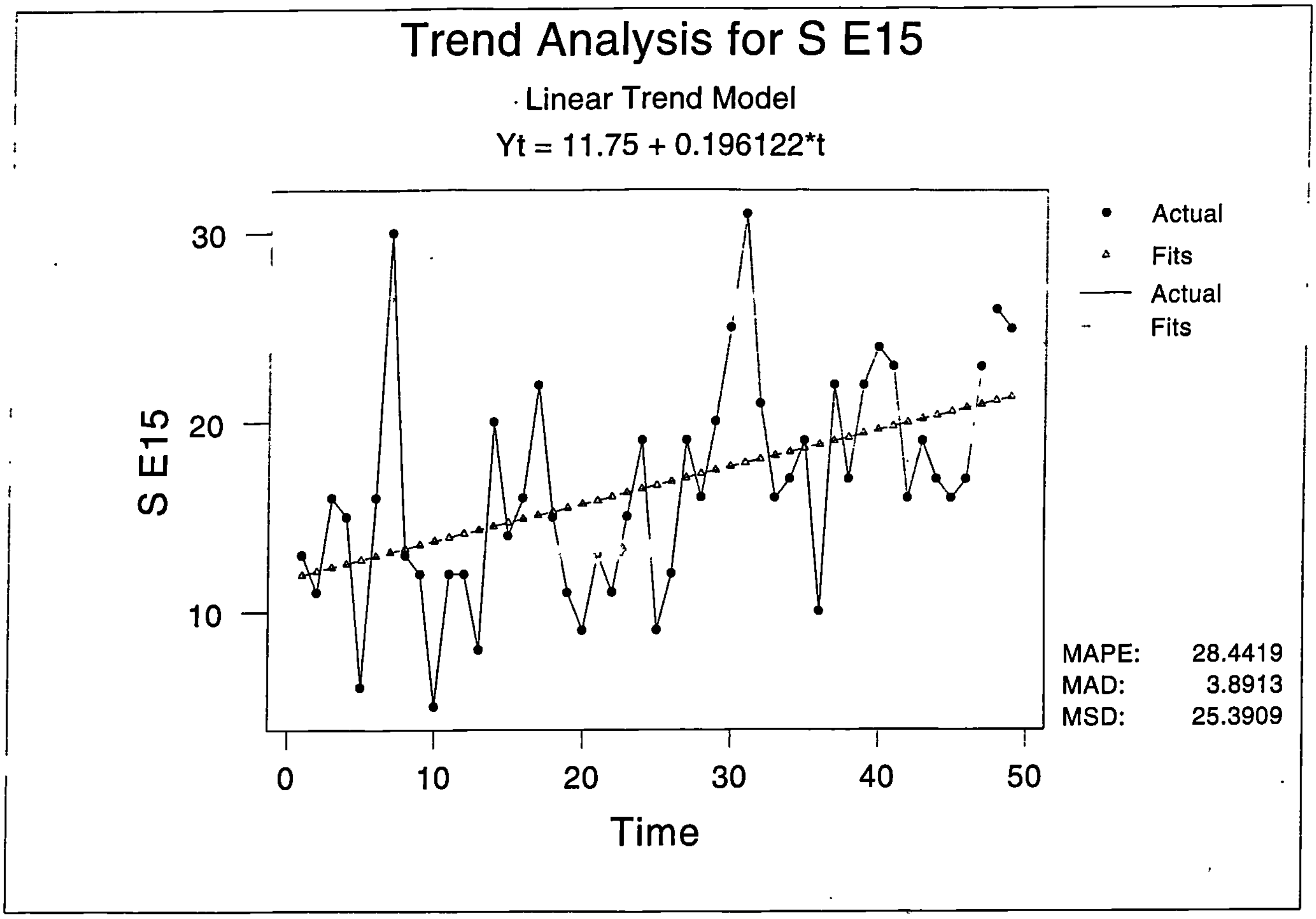

Trend Analysis for 4-5 C15
Linear Trend Model
Yt = 36.7602 - 0.245918*t
4-5 C15
50
40
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 20.1458
MAD: 5.3297
MSD: 46.5504

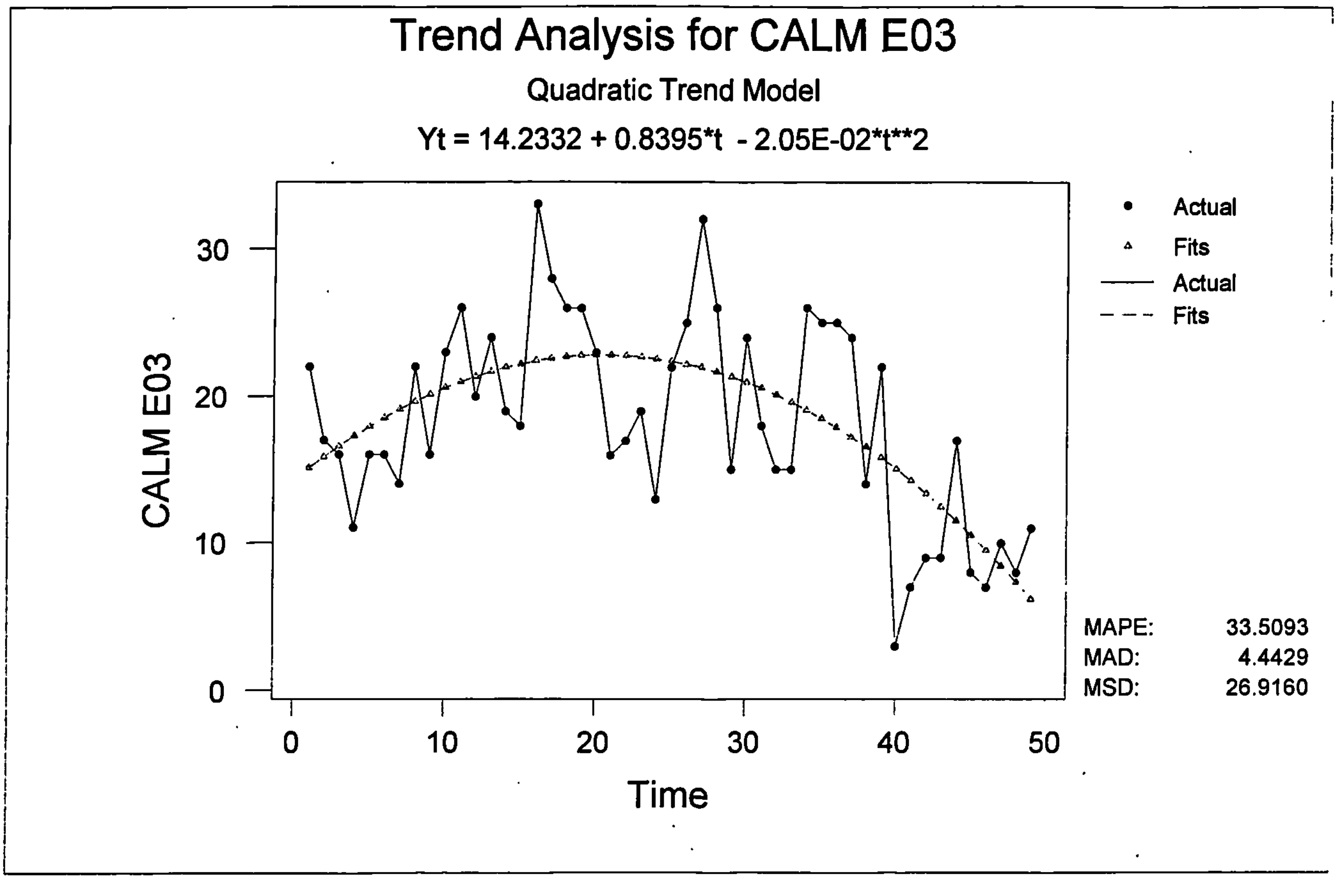

Trend Analysis for N T03
Linear Trend Model
Yt = 9.3954 - 8.68E-02*t
N T03
20
10
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 70.3693
MAD: 3.1449
MSD: 16.6252

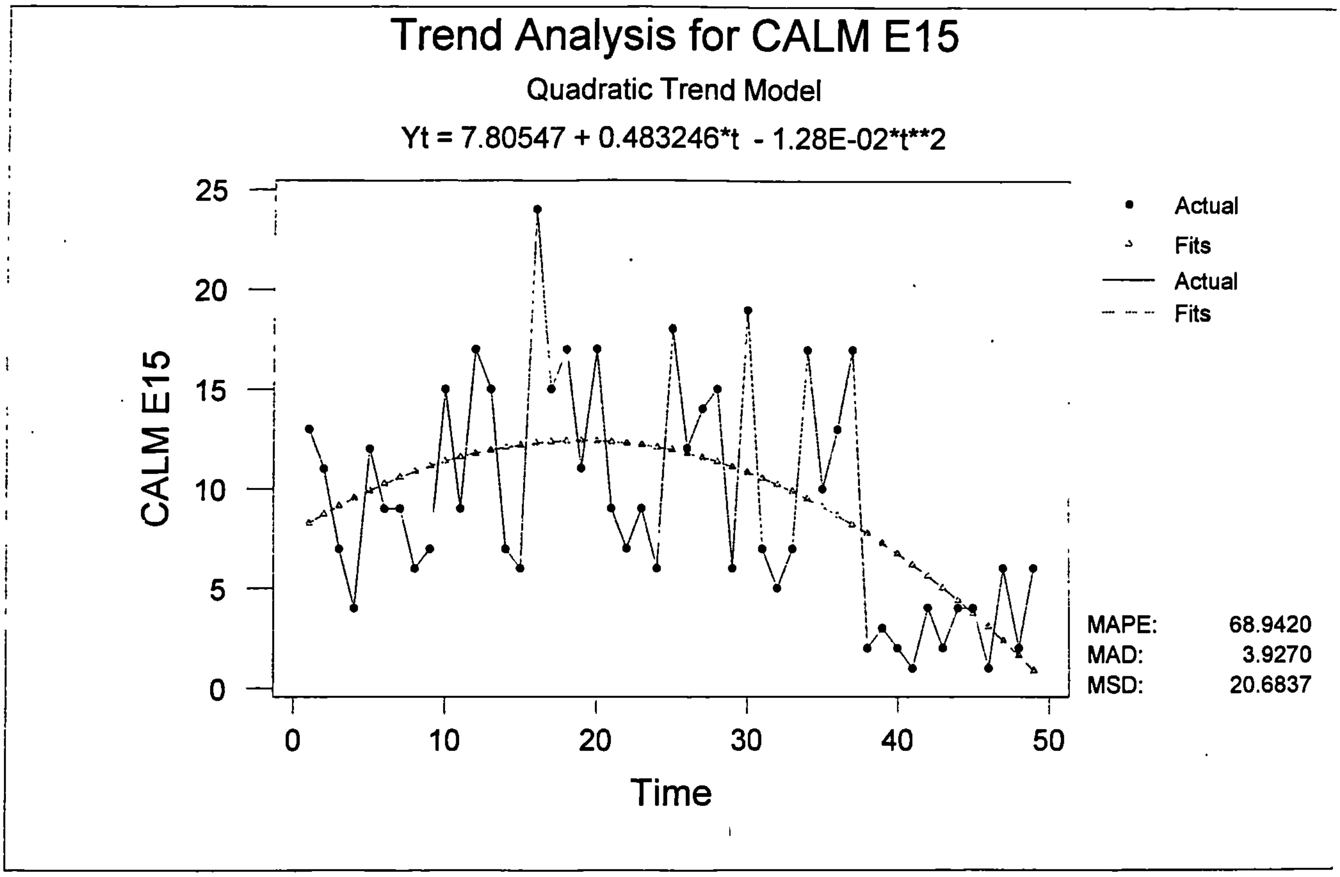

Trend Analysis for CALM T03
Linear Trend Model
Yt = 4.3852 - 6.60E-02*t
CALM T03
0
1
2
3
4
5
6
7
8
Time
0
10
20
30
40
50
Actual
Fits
Actual
Fits
MAPE: 52.0852
MAD: 1.3215
MSD: 2.7518


Trend Analysis for 4-5 T15
Linear Trend Model
Yt = 36.8163 + 0.106122*t
4-5 T15
30
40
50
Time
0
10
20
30
40
50
Actual
Fits
Actual
Fits
MAPE: 9.7157
MAD: 3.7504
MSD: 21.5069

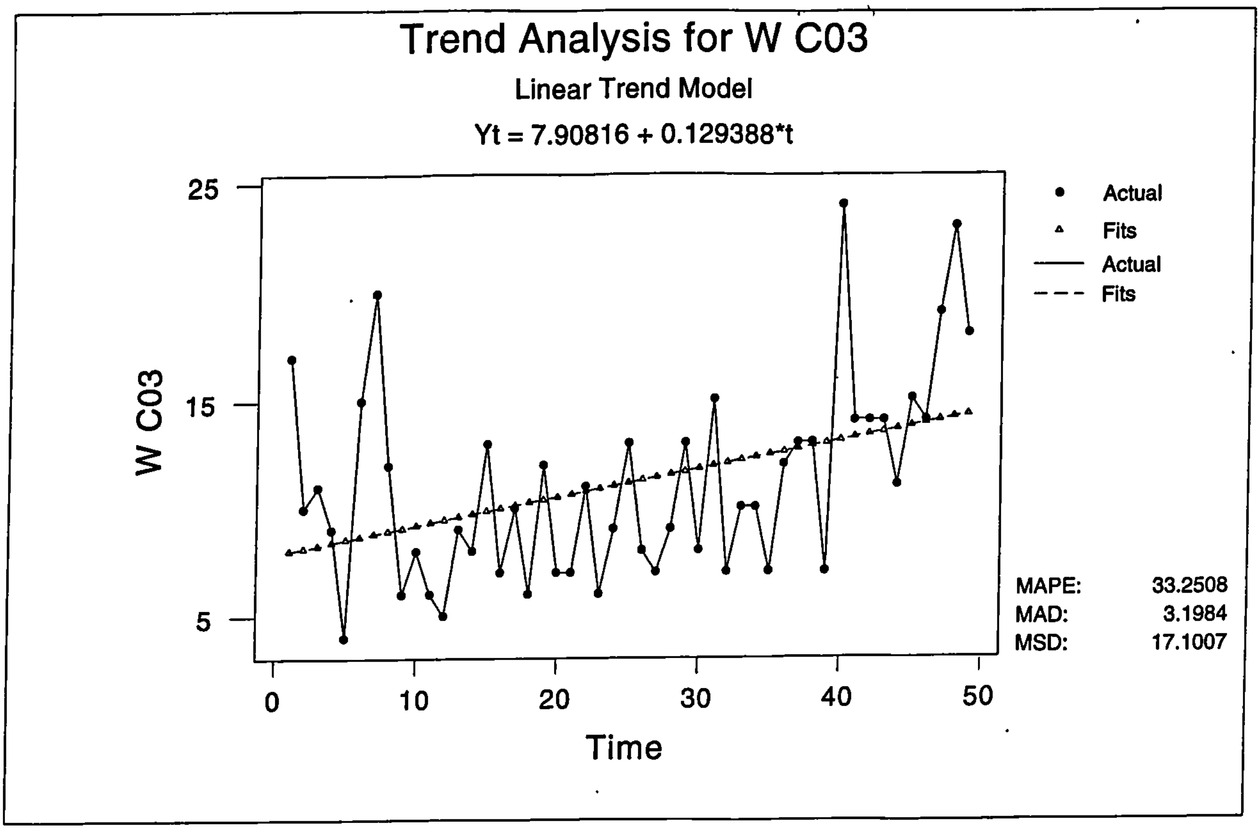

Trend Analysis for S E03
Linear Trend Model
Yt = 10.7474 + 0.137449*t
S E03
25
15
5
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 30.4649
MAD: 3.4063
MSD: 16.9021

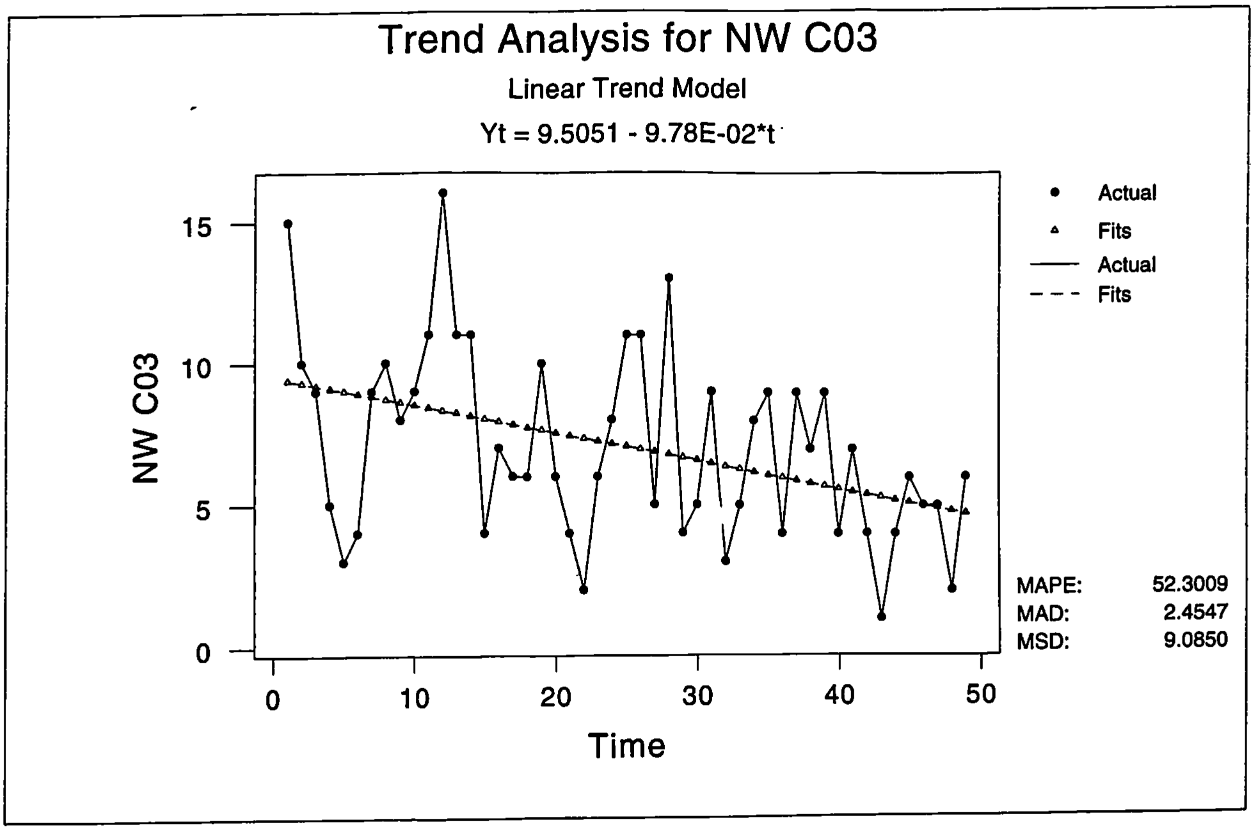

Trend Analysis for S E15
Linear Trend Model
Yt = 11.75 + 0.196122*t
S E15
30
20
10
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- Fits
MAPE: 28.4419
MAD: 3.8913
MSD: 25.3909

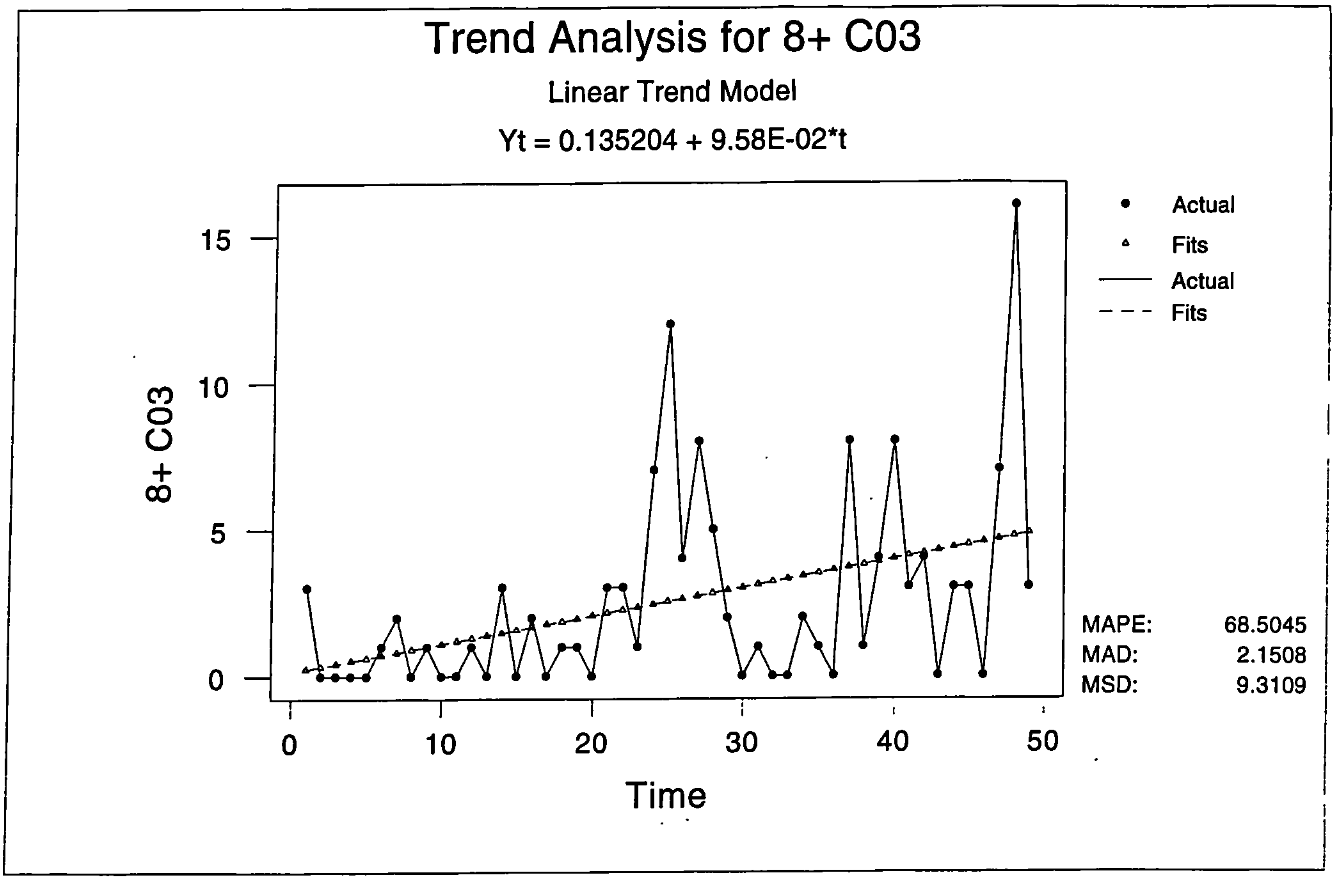

Trend Analysis for CALM E03
Quadratic Trend Model
Yt = 14.2332 + 0.8395*t - 2.05E-02*t**2
CALM E03
0
10
20
30
Time
0
10
20
30
40
50
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 33.5093
MAD: 4.4429
MSD: 26.9160

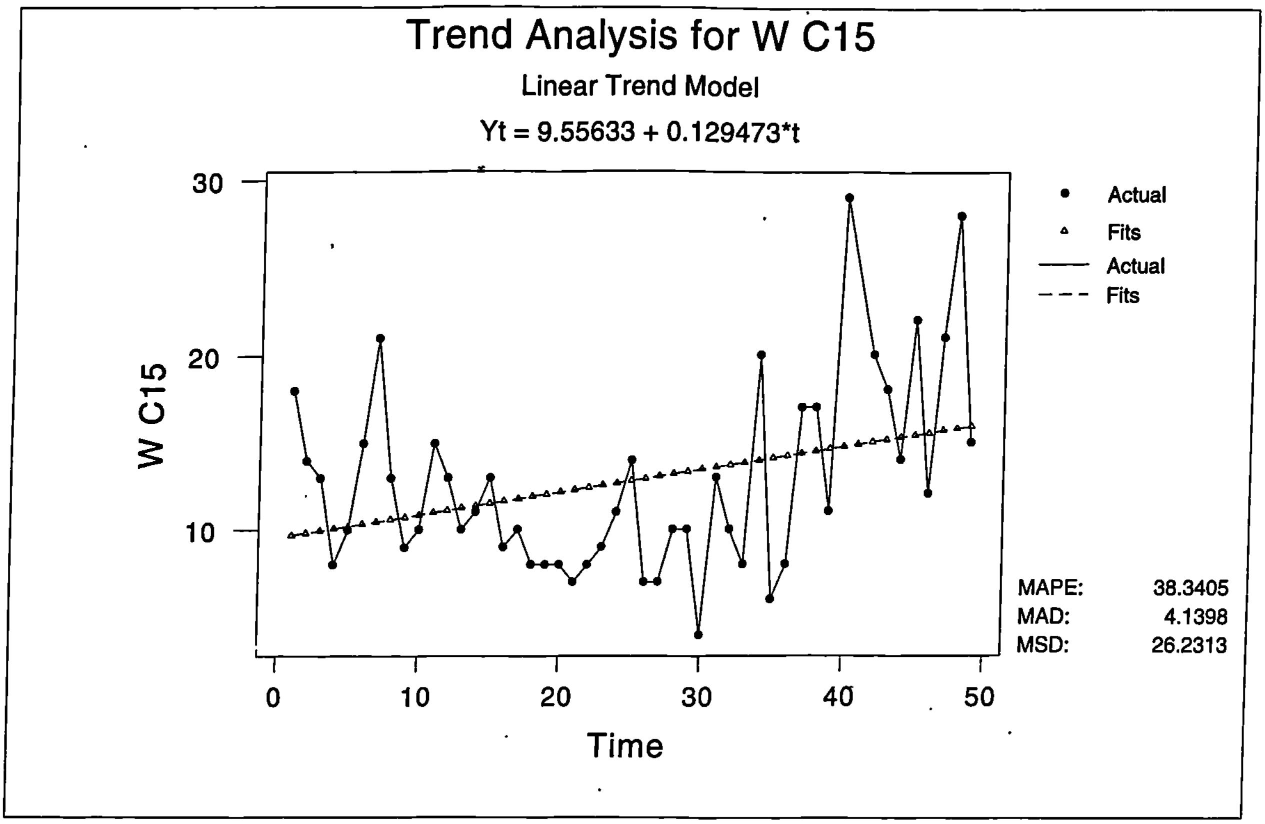

Trend Analysis for CALM E15
Quadratic Trend Model
Yt = 7.80547 + 0.483246*t - 1.28E-02*t**2
CALM E15
0
5
10
15
20
25
Time
0
10
20
30
40
50
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 68.9420
MAD: 3.9270
MSD: 20.6837

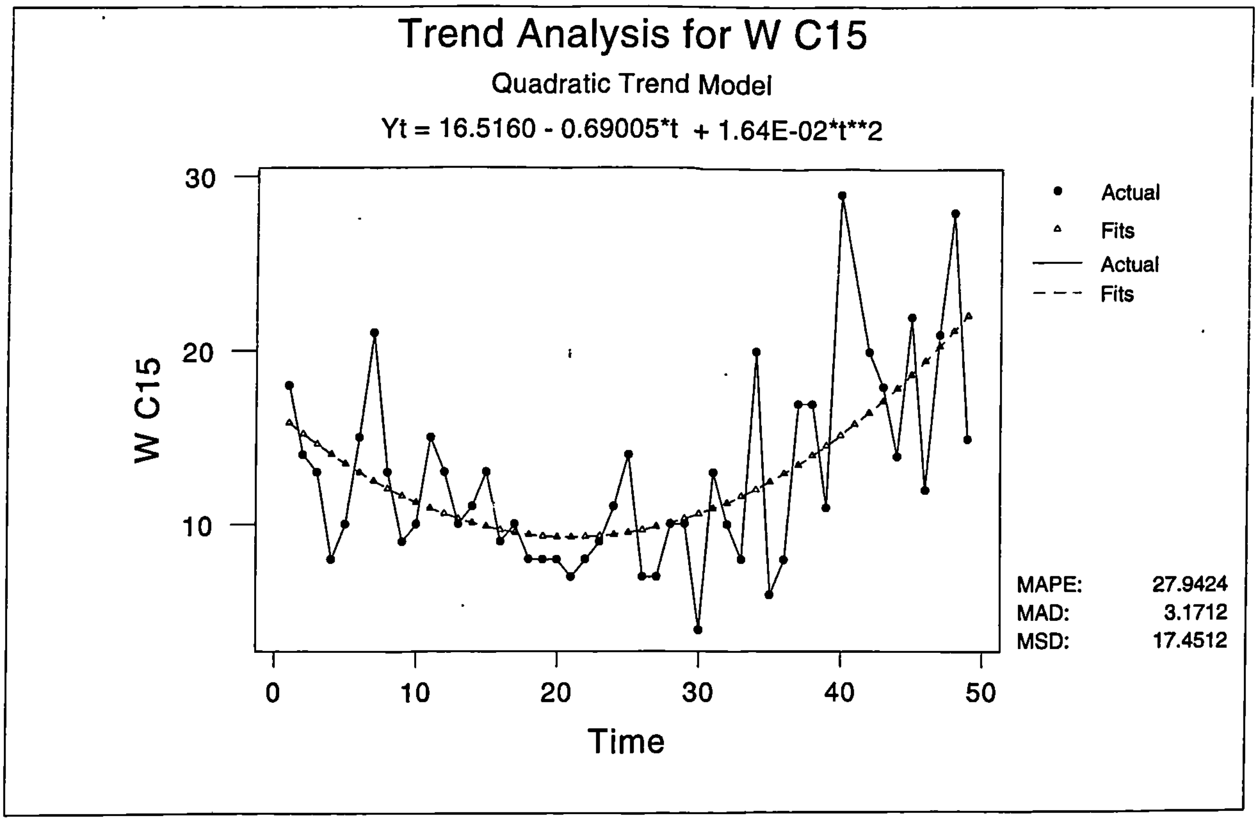
DATA FOR MARCH, APRIL AND MAY

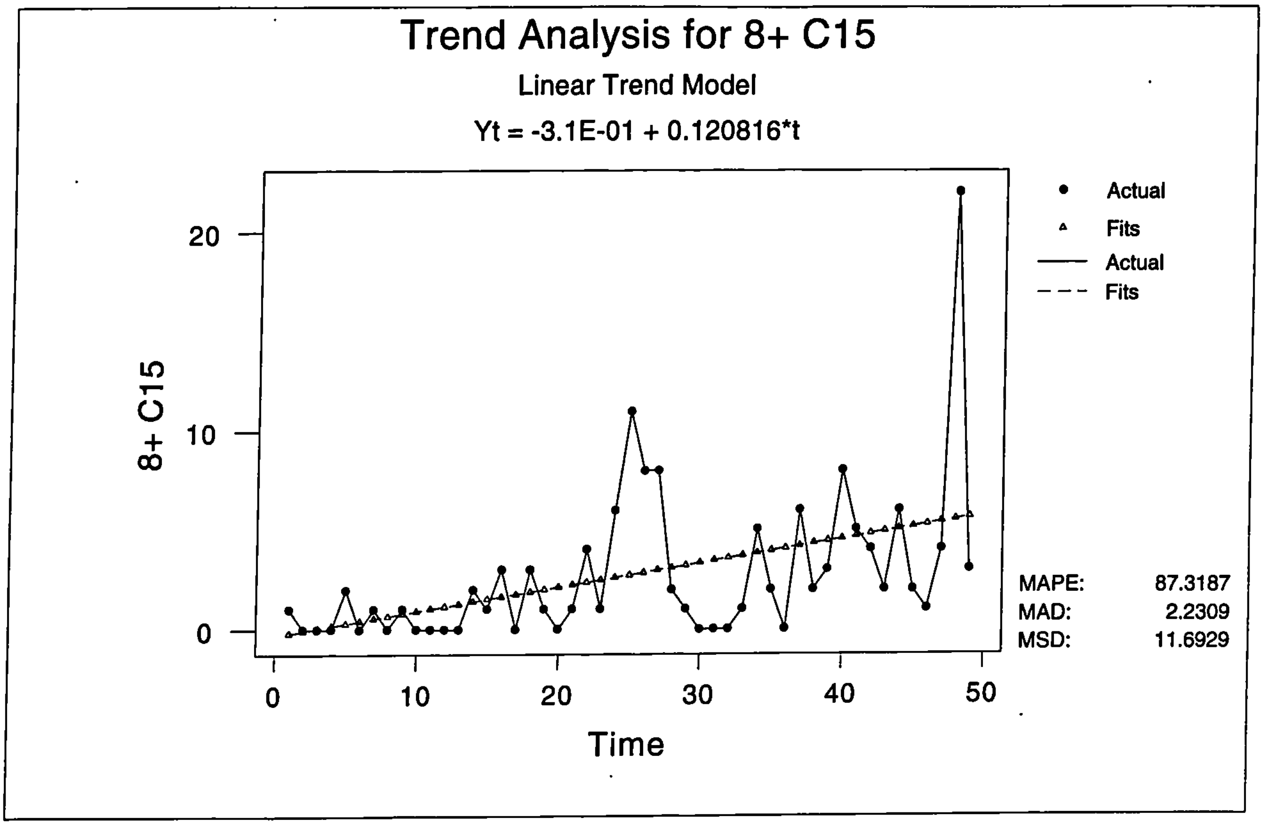

Trend Analysis for W C03
Linear Trend Model
Yt = 7.90816 + 0.129388*t
W C03
25
15
5
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 33.2508
MAD: 3.1984
MSD: 17.1007

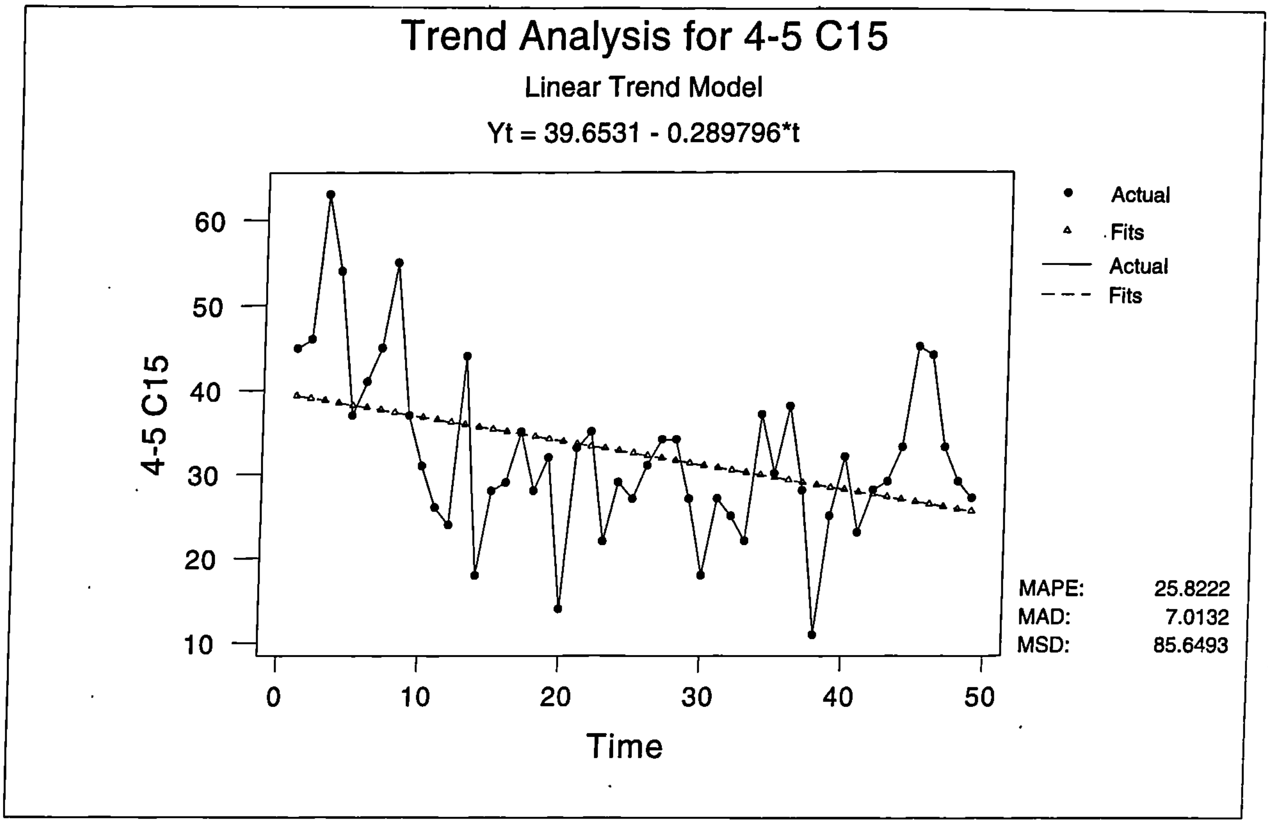

Trend Analysis for NW C03
Linear Trend Model
Yt = 9.5051 - 9.78E-02*t
NW C03
15
10
5
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 52.3009
MAD: 2.4547
MSD: 9.0850

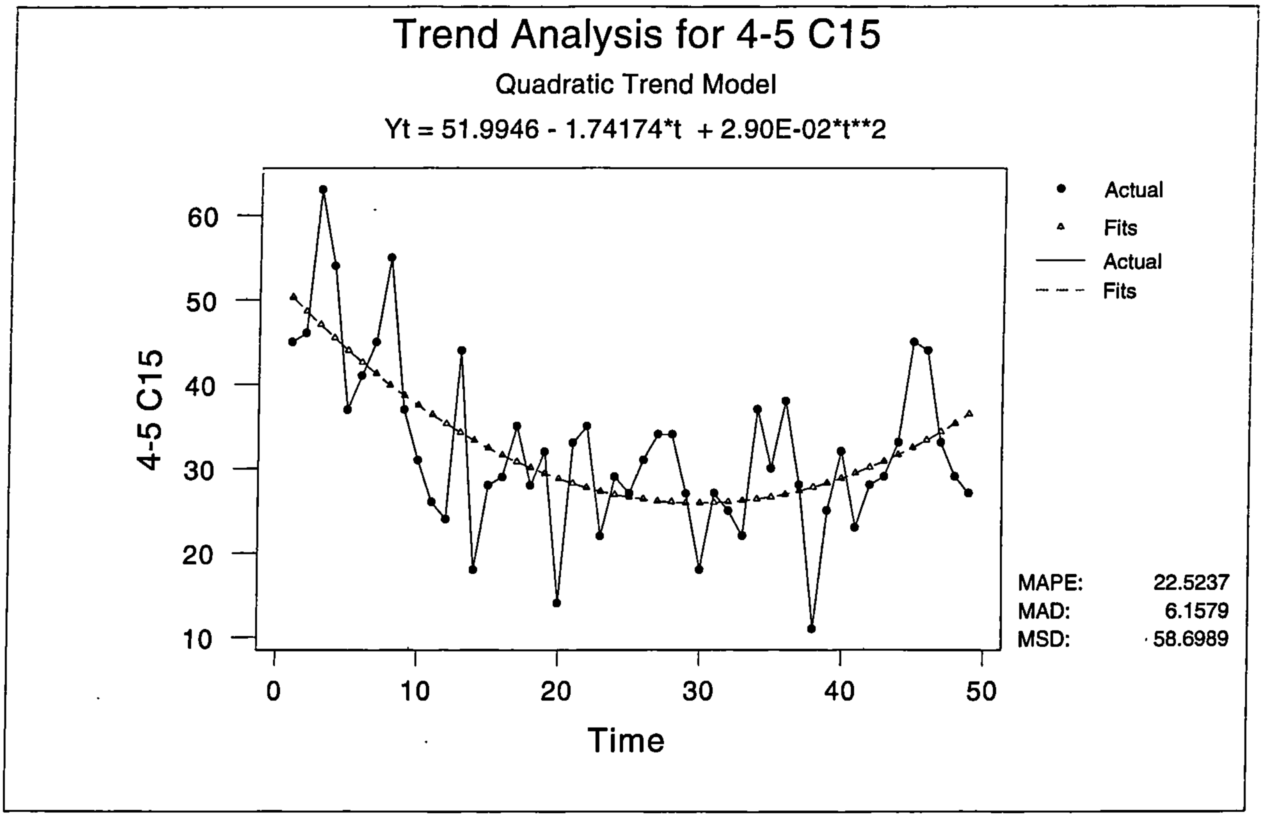

Trend Analysis for 8+ C03
Linear Trend Model
Yt = 0.135204 + 9.58E-02*t
8+ C03
0
5
10
15
Time
0
10
20
30
40
50
Actual
Fits
Actual
Fits
MAPE: 68.5045
MAD: 2.1508
MSD: 9.3109

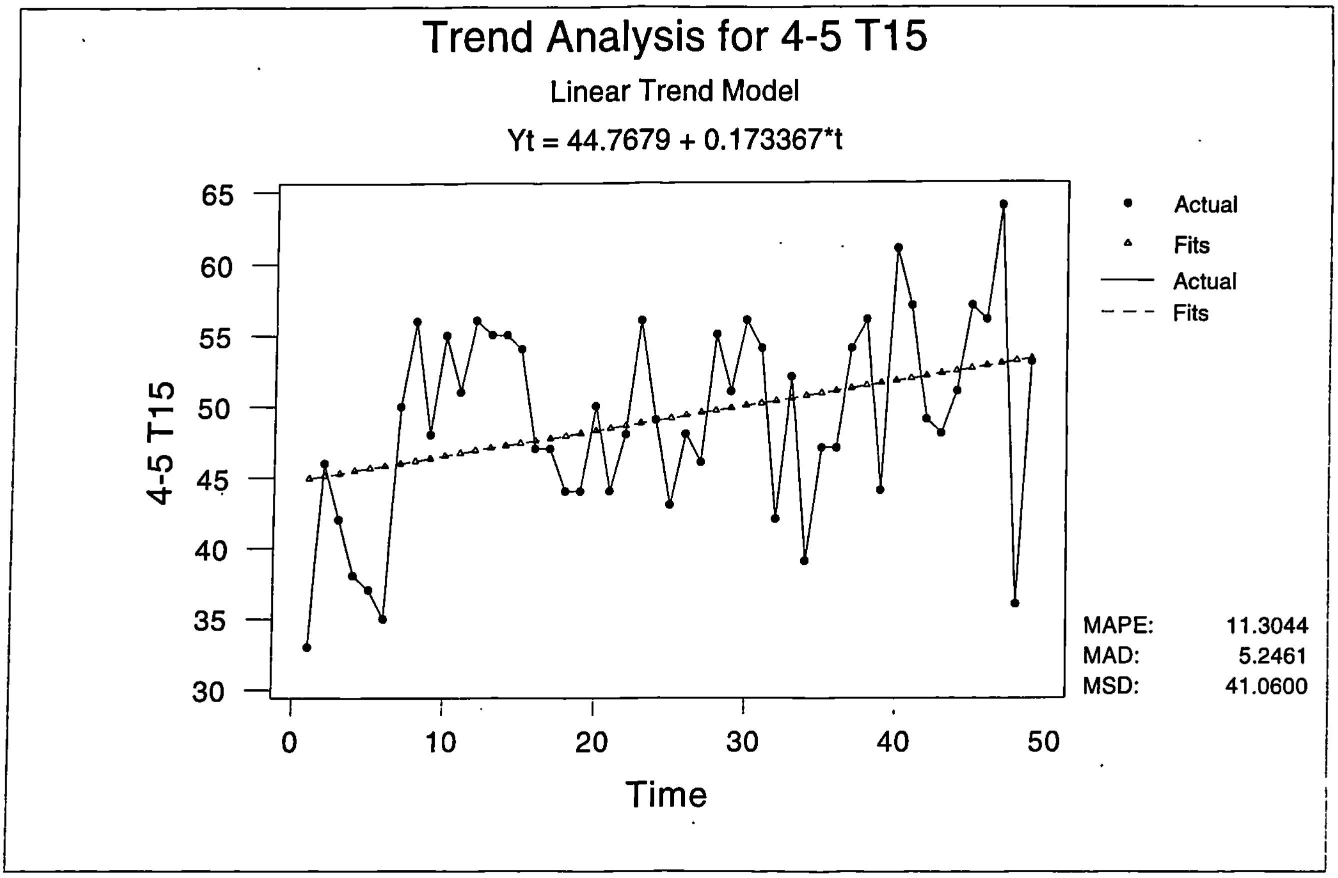

Trend Analysis for W C15
Linear Trend Model
Yt = 9.55633 + 0.129473*t
W C15
30
20
10
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 38.3405
MAD: 4.1398
MSD: 26.2313


Trend Analysis for W C15
Quadratic Trend Model
Yt = 16.5160 - 0.69005*t + 1.64E-02*t**2
W C15
30
20
10
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 27.9424
MAD: 3.1712
MSD: 17.4512


Trend Analysis for 8+ C15
Linear Trend Model
Yt = -3.1E-01 + 0.120816*t
8+ C15
0
10
20
Time
0
10
20
30
40
50
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 87.3187
MAD: 2.2309
MSD: 11.6929


Trend Analysis for 4-5 C15
Linear Trend Model
Yt = 39.6531 - 0.289796*t
4-5 C15
60
50
40
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 25.8222
MAD: 7.0132
MSD: 85.6493

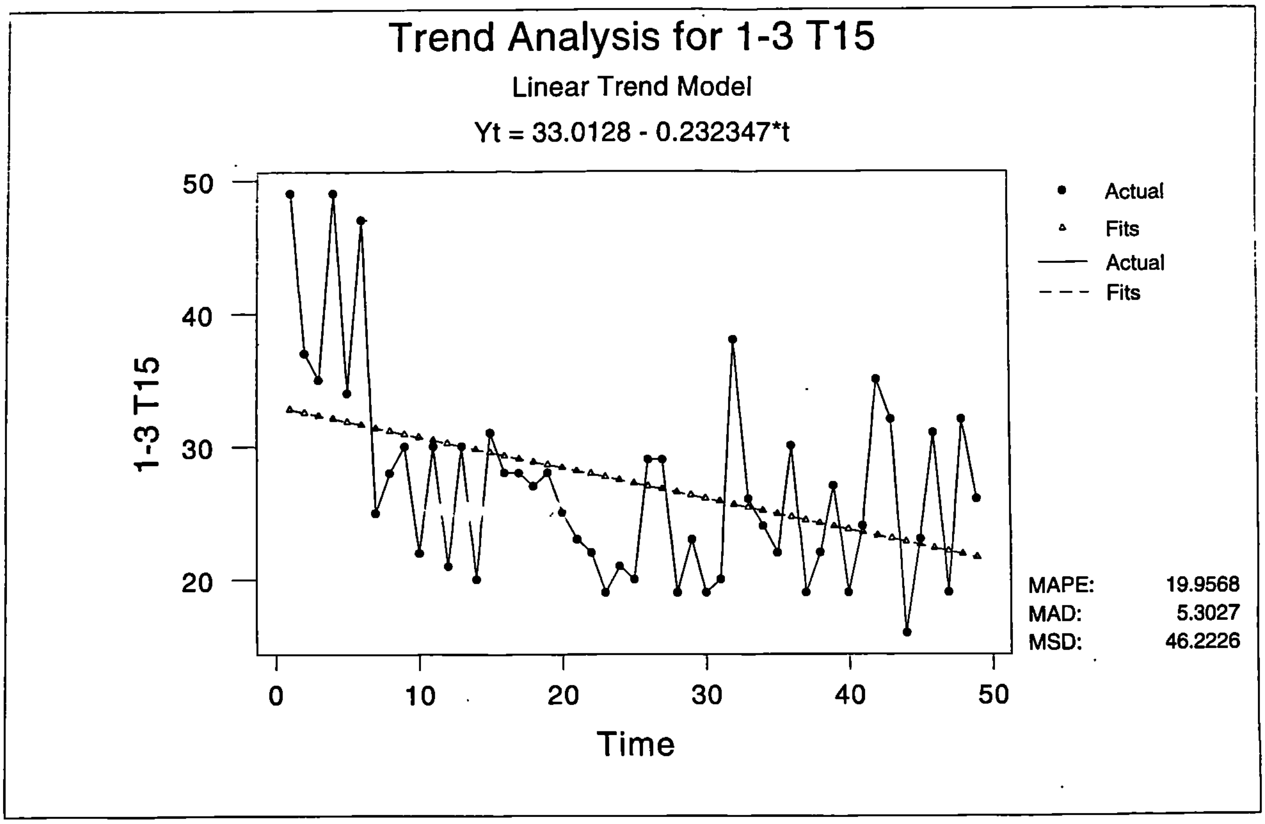

Trend Analysis for 4-5 C15
Quadratic Trend Model
Yt = 51.9946 - 1.74174*t + 2.90E-02*t**2
4-5 C15
60
50
40
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 22.5237
MAD: 6.1579
MSD: 58.6989



Trend Analysis for 4-5 T15

Linear Trend Model

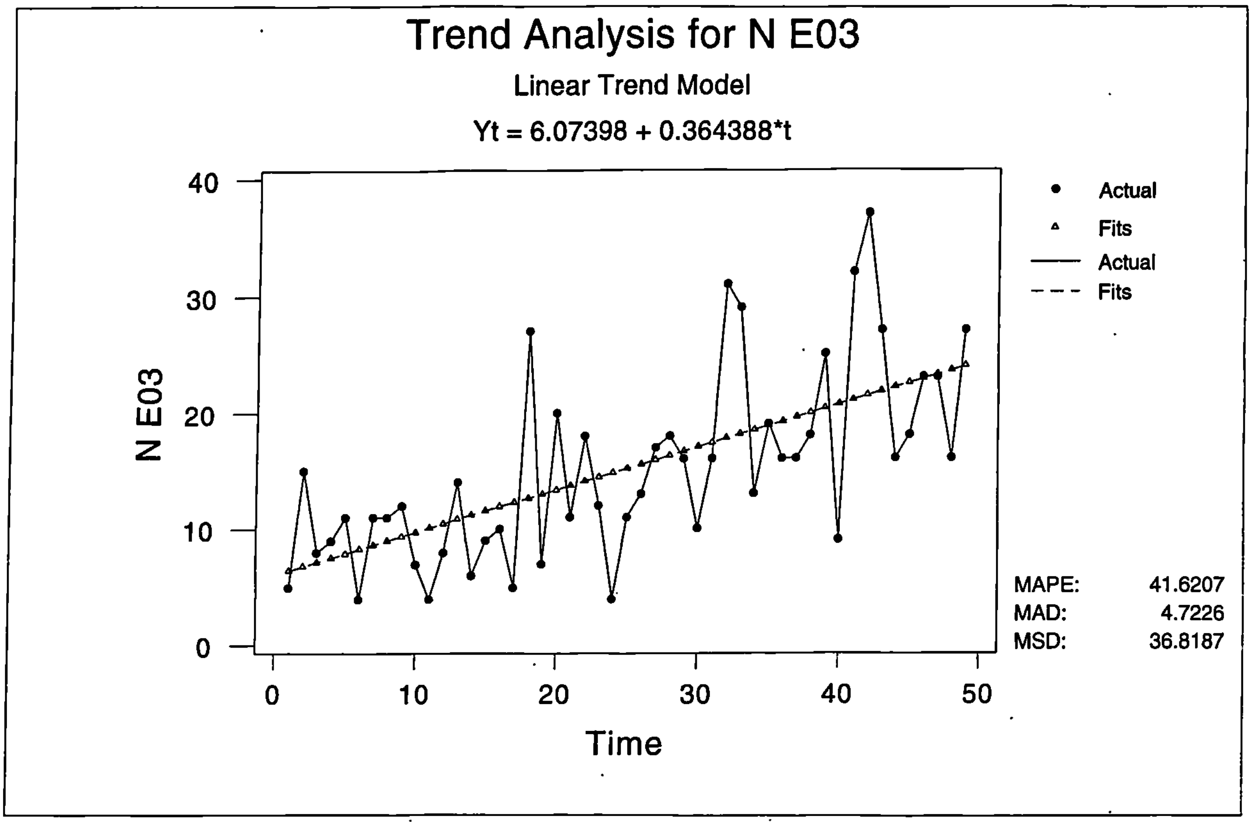
Yt = 44.7679 + 0.173367*t

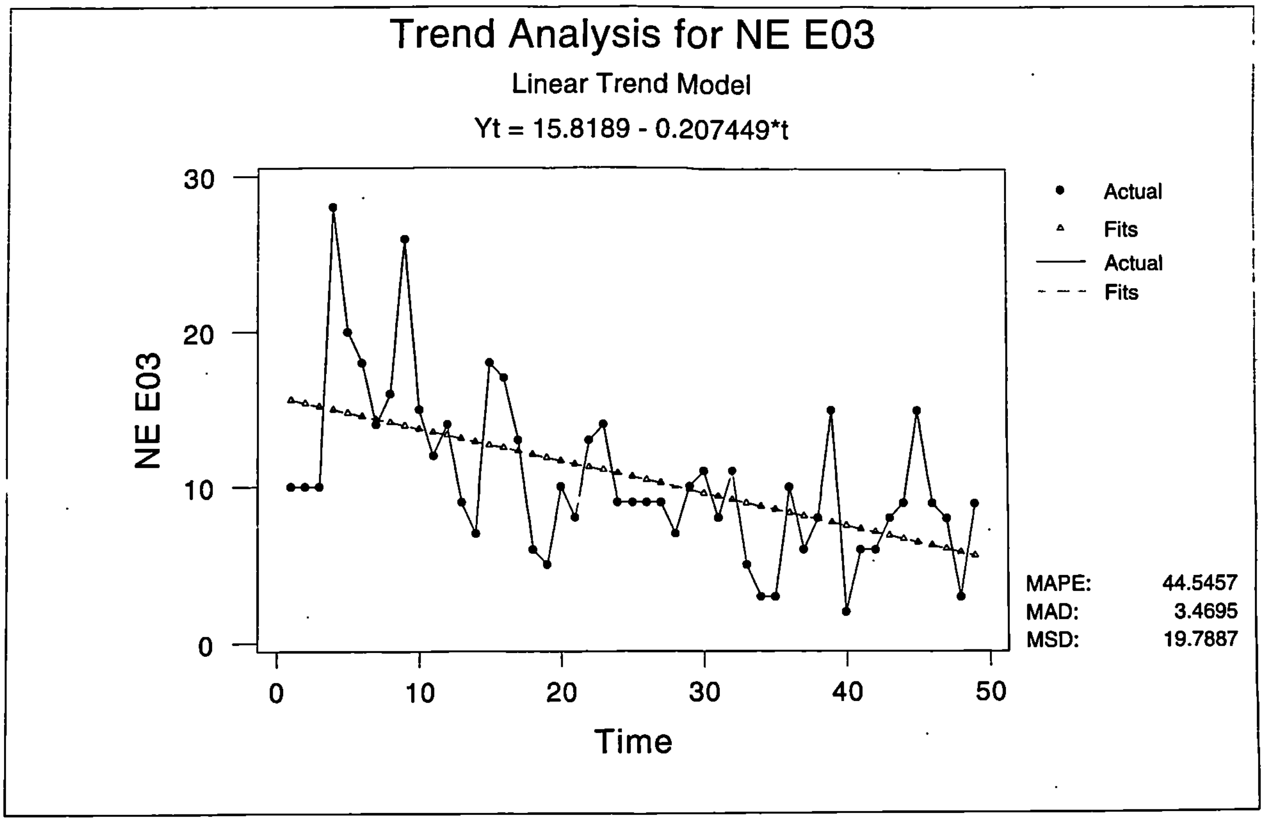


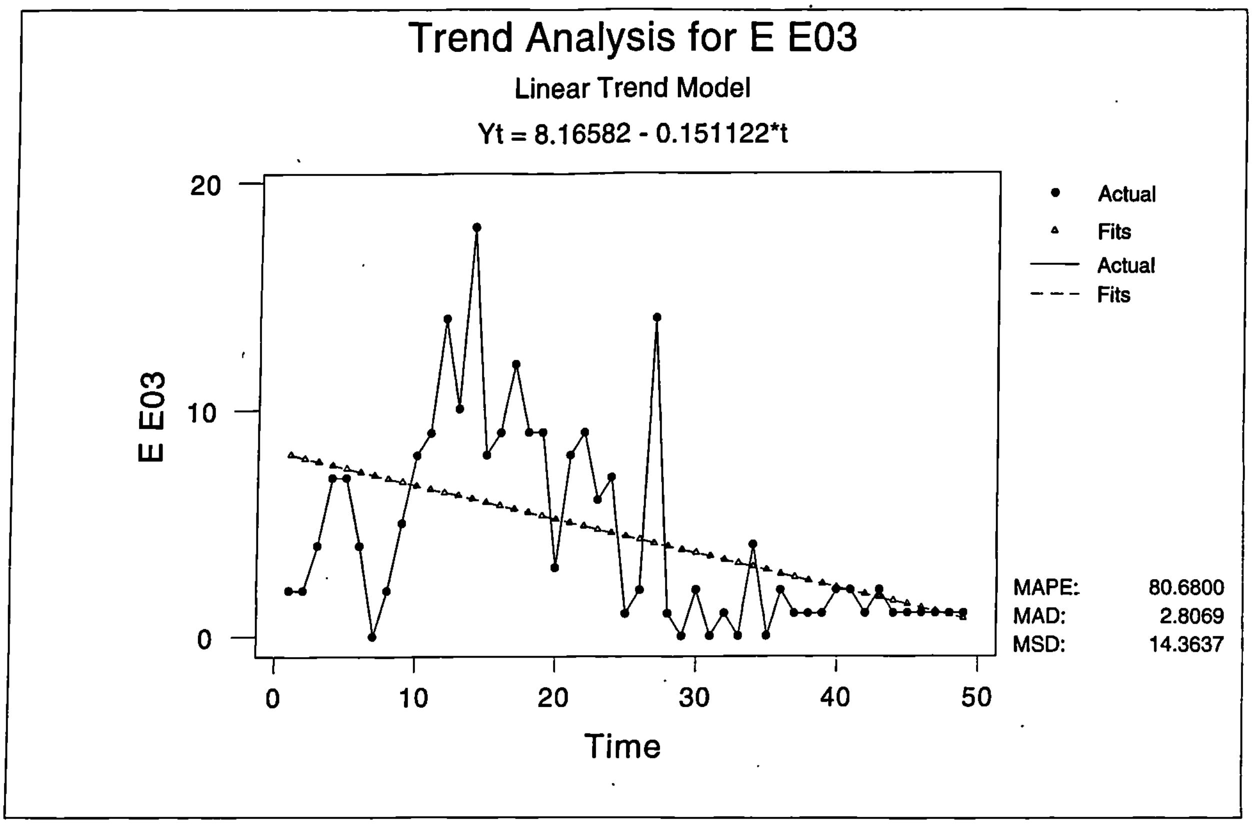
Trend Analysis for 1-3 T15

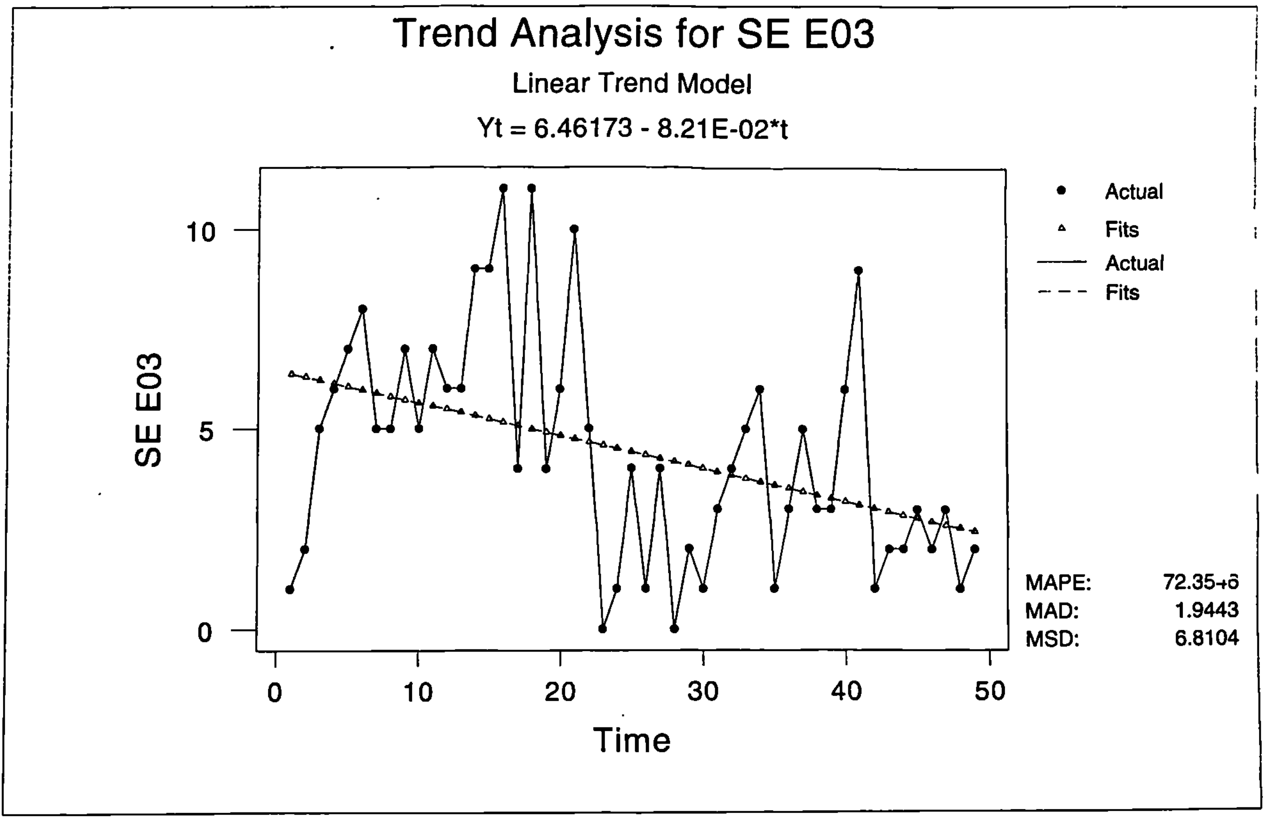
Linear Trend Model

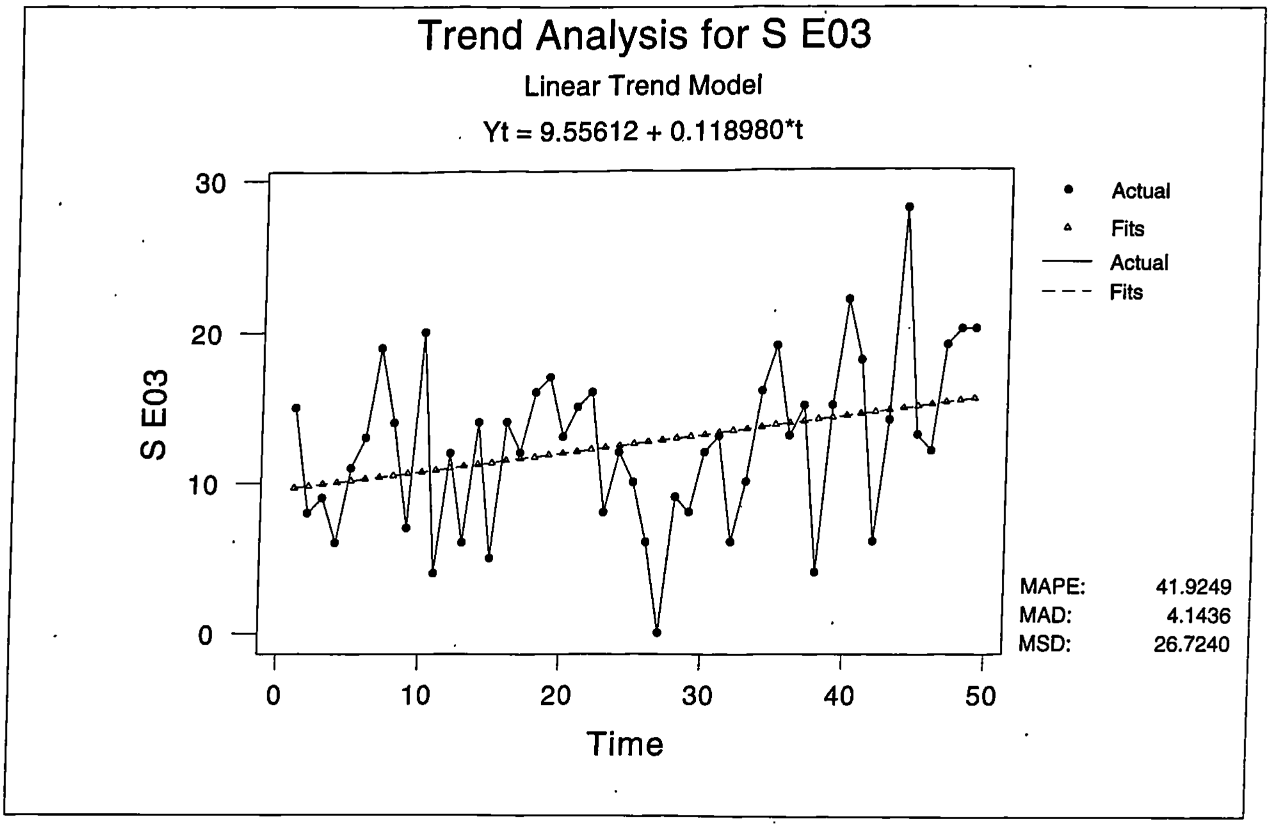
Yt = 33.0128 - 0.232347*t

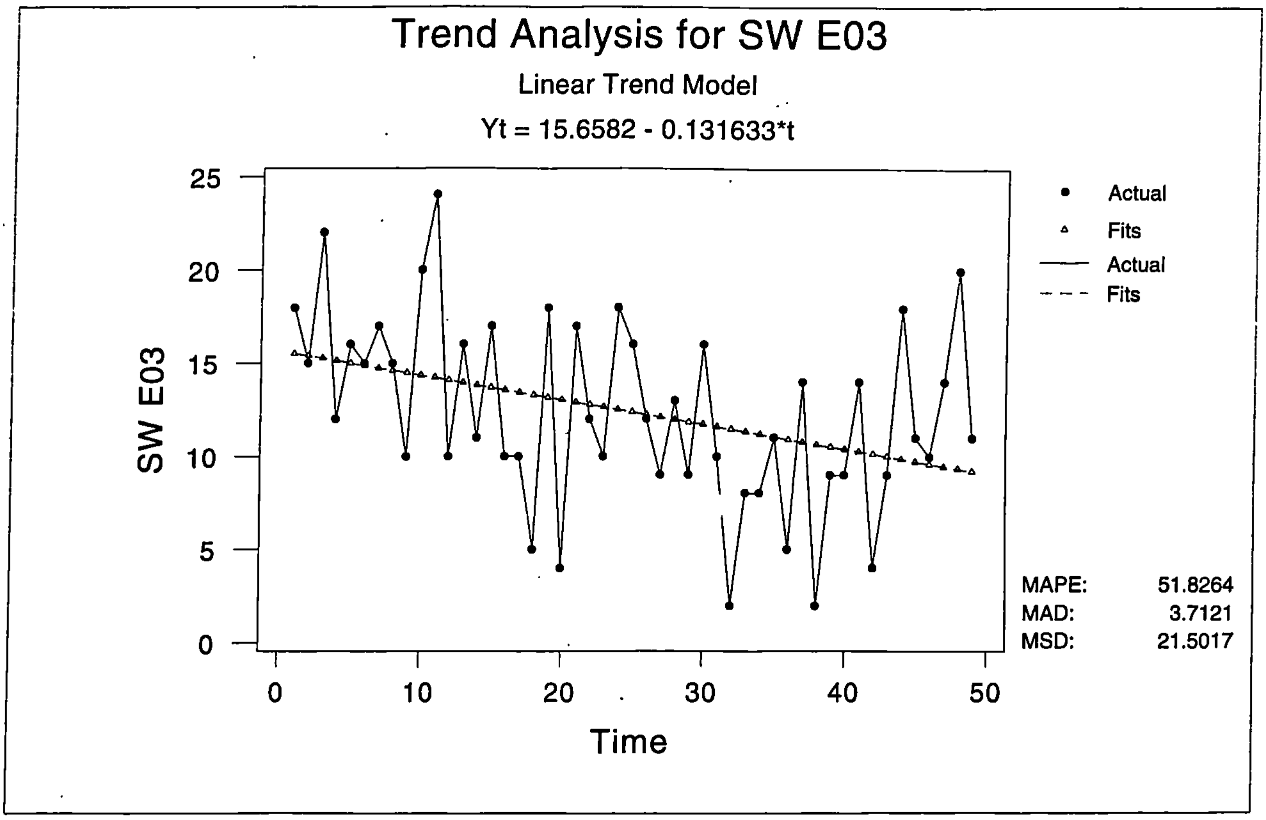

Trend Analysis for N E03
Linear Trend Model
Yt = 6.07398 + 0.364388*t
N E03
40
30
20
10
0
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 41.6207
MAD: 4.7226
MSD: 36.8187

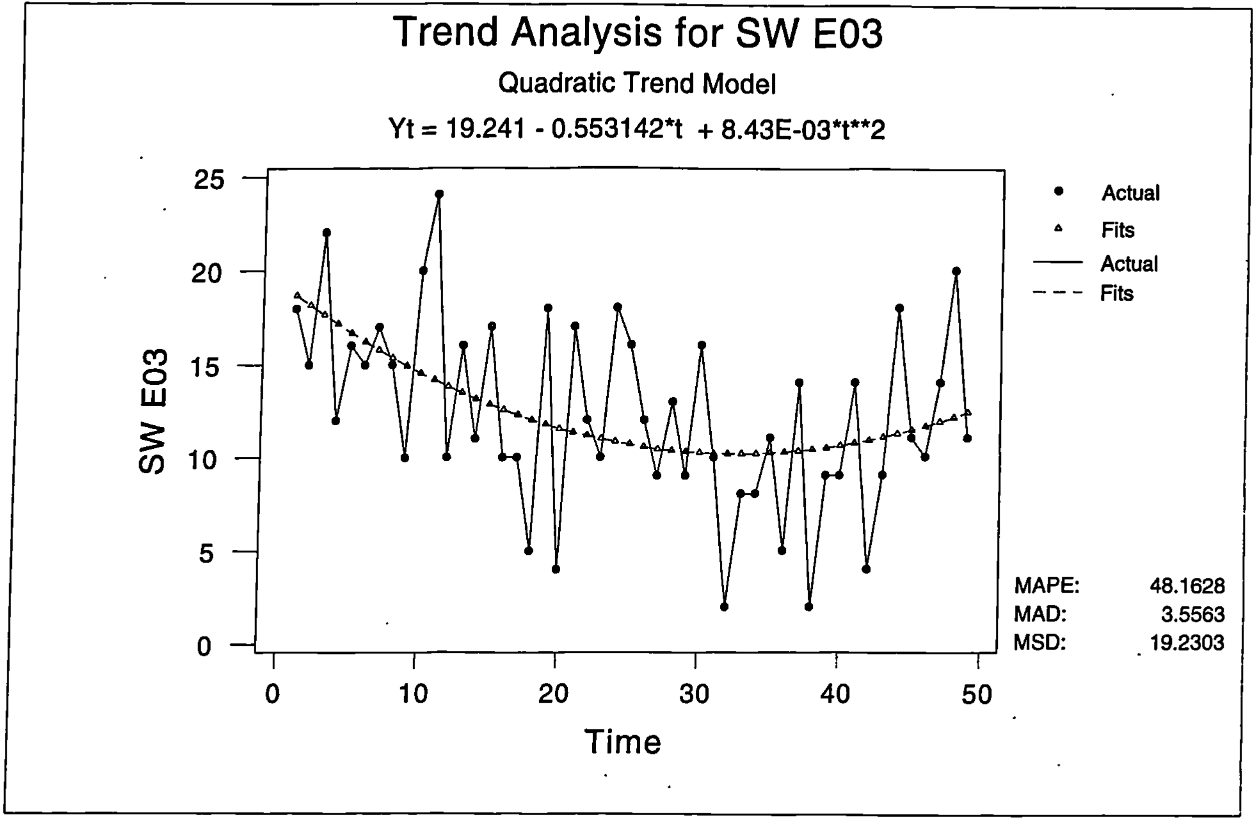

Trend Analysis for NE E03
Linear Trend Model
Yt = 15.8189 - 0.207449*t
NE E03
30
20
10
0
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 44.5457
MAD: 3.4695
MSD: 19.7887

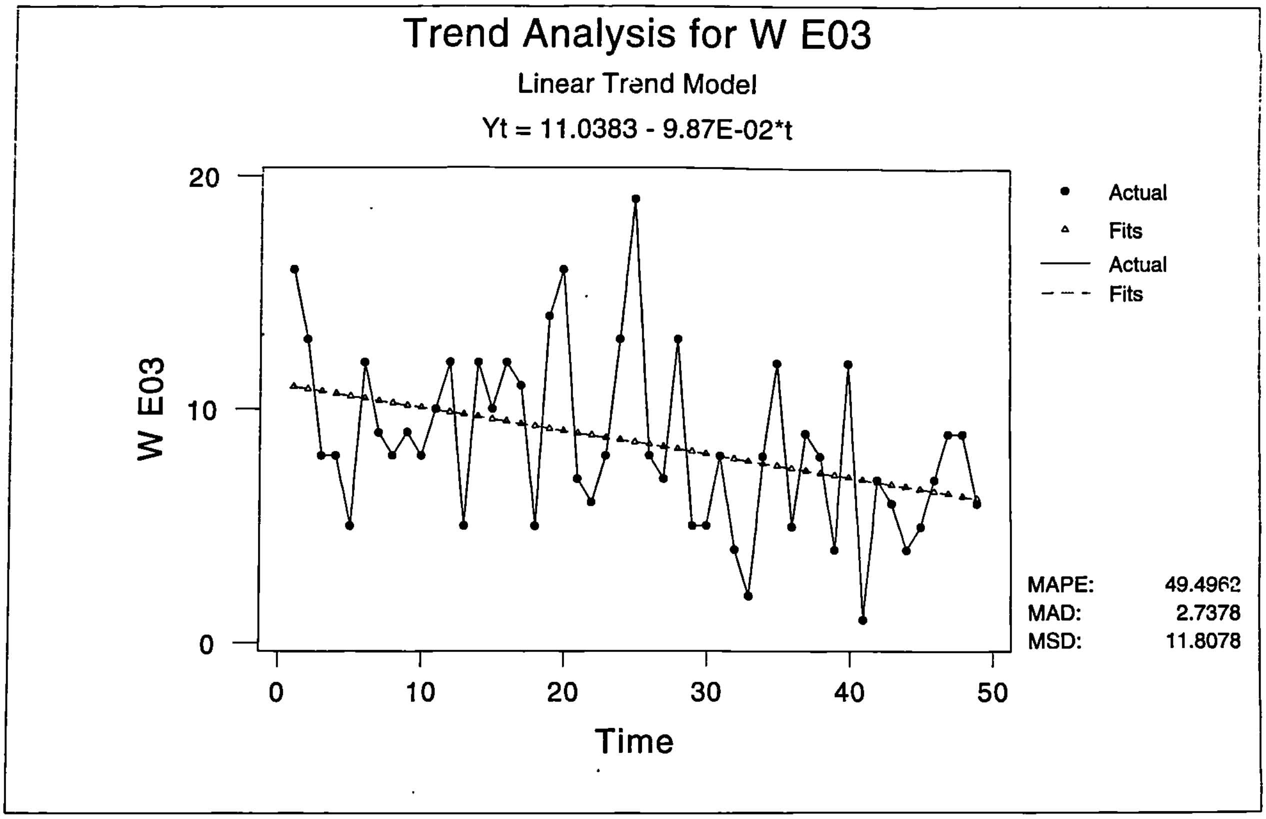

Trend Analysis for E E03
Linear Trend Model
Yt = 8.16582 - 0.151122*t
E E03
20
10
0
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 80.6800
MAD: 2.8069
MSD: 14.3637

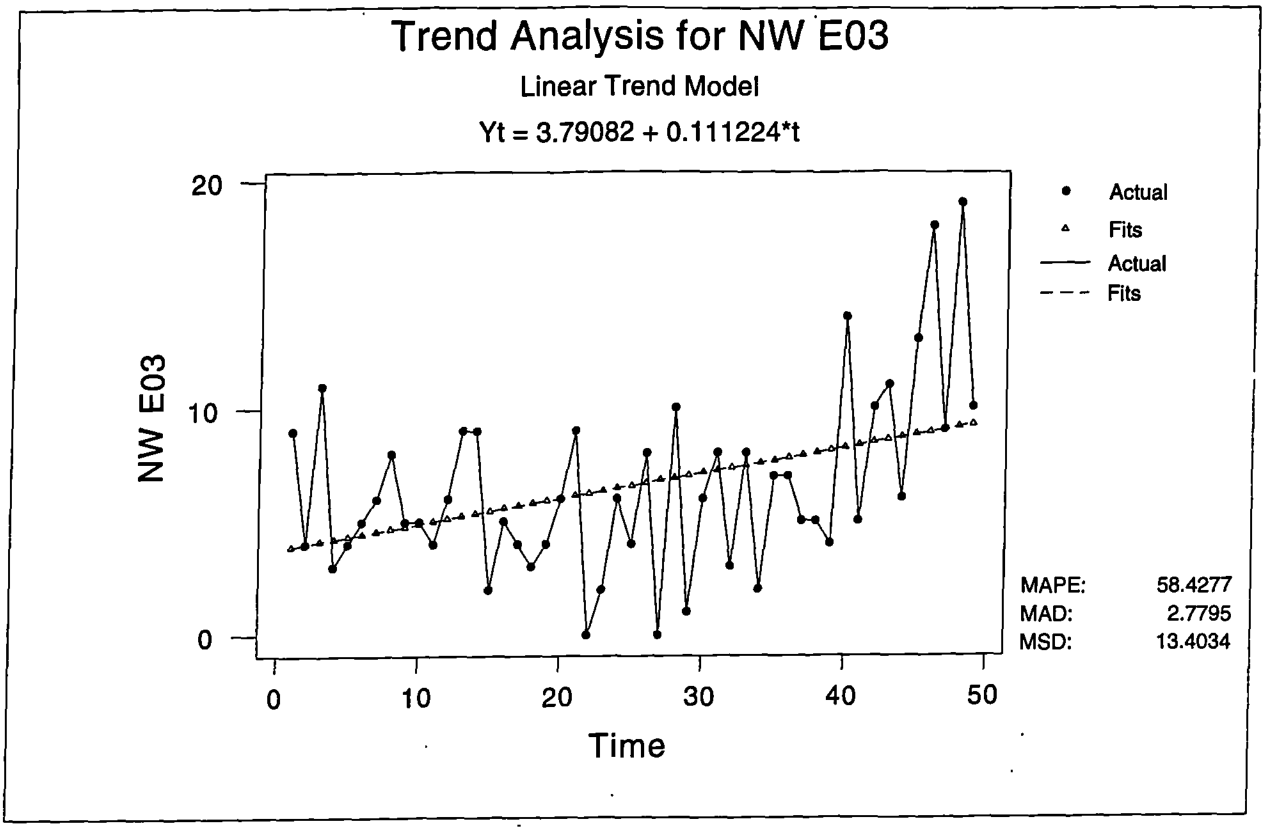

Trend Analysis for SE E03
Linear Trend Model
Yt = 6.46173 - 8.21E-02*t
SE E03
10
5
0
0
10
20
30
40
50
Time
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 72.3546
MAD: 1.9443
MSD: 6.8104

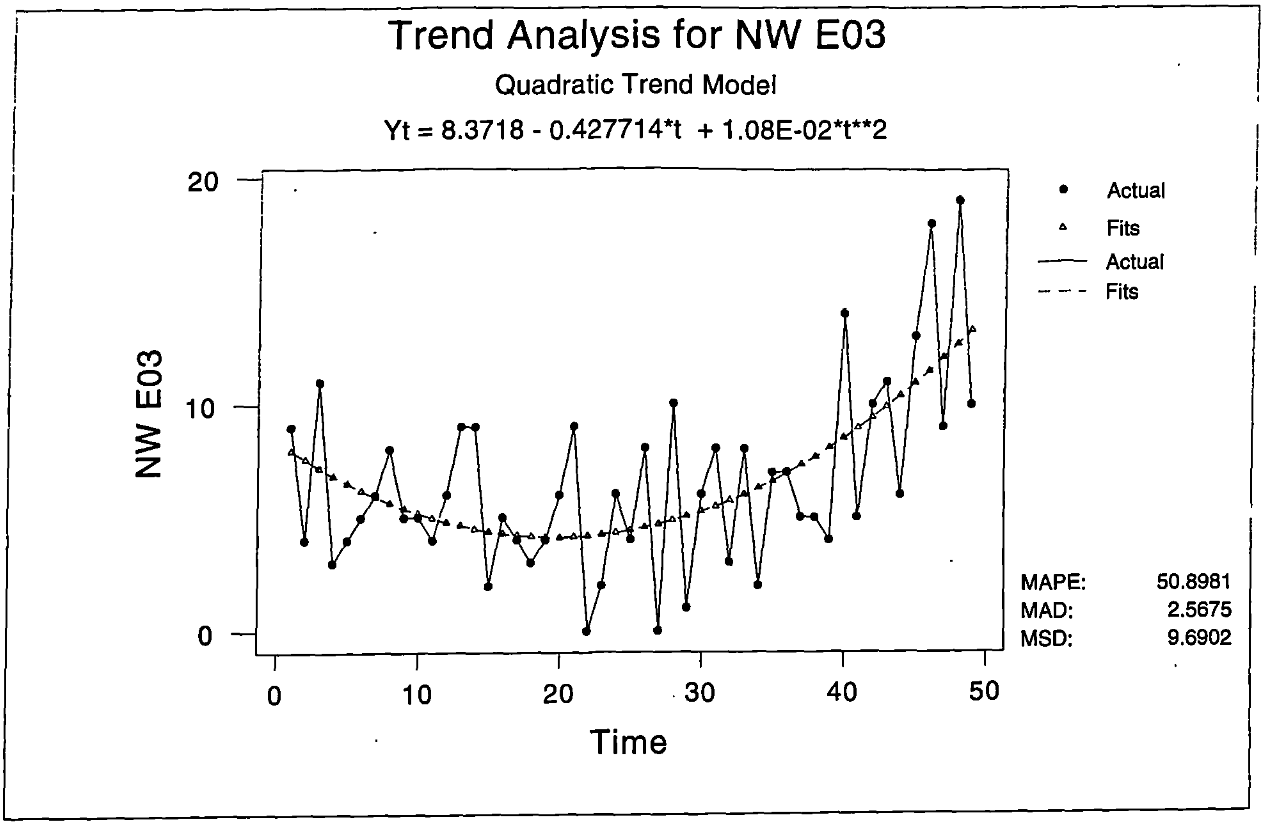

Trend Analysis for S E03
Linear Trend Model
Yt = 9.55612 + 0.118980*t
S E03
30
20
10
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 41.9249
MAD: 4.1436
MSD: 26.7240

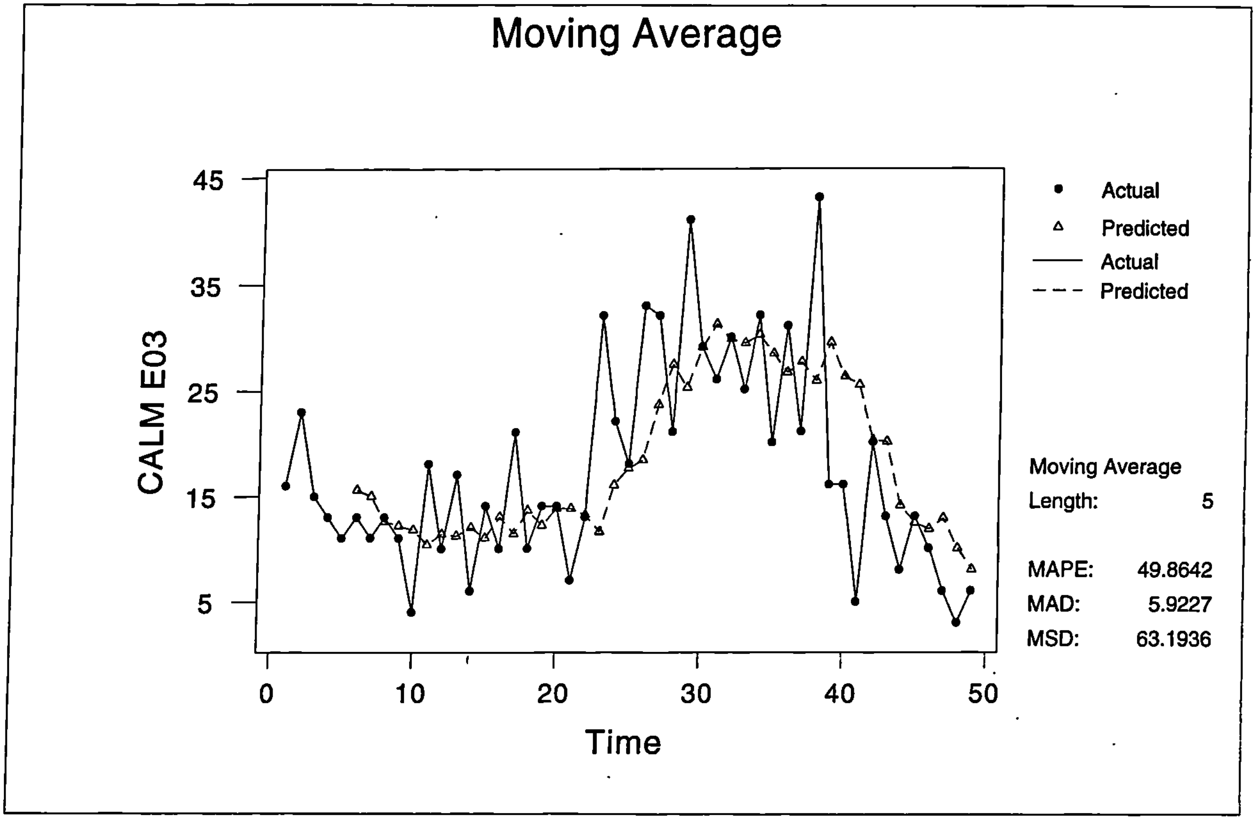

Trend Analysis for SW E03
Linear Trend Model
Yt = 15.6582 - 0.131633*t
SW E03
25
20
15
10
5
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 51.8264
MAD: 3.7121
MSD: 21.5017

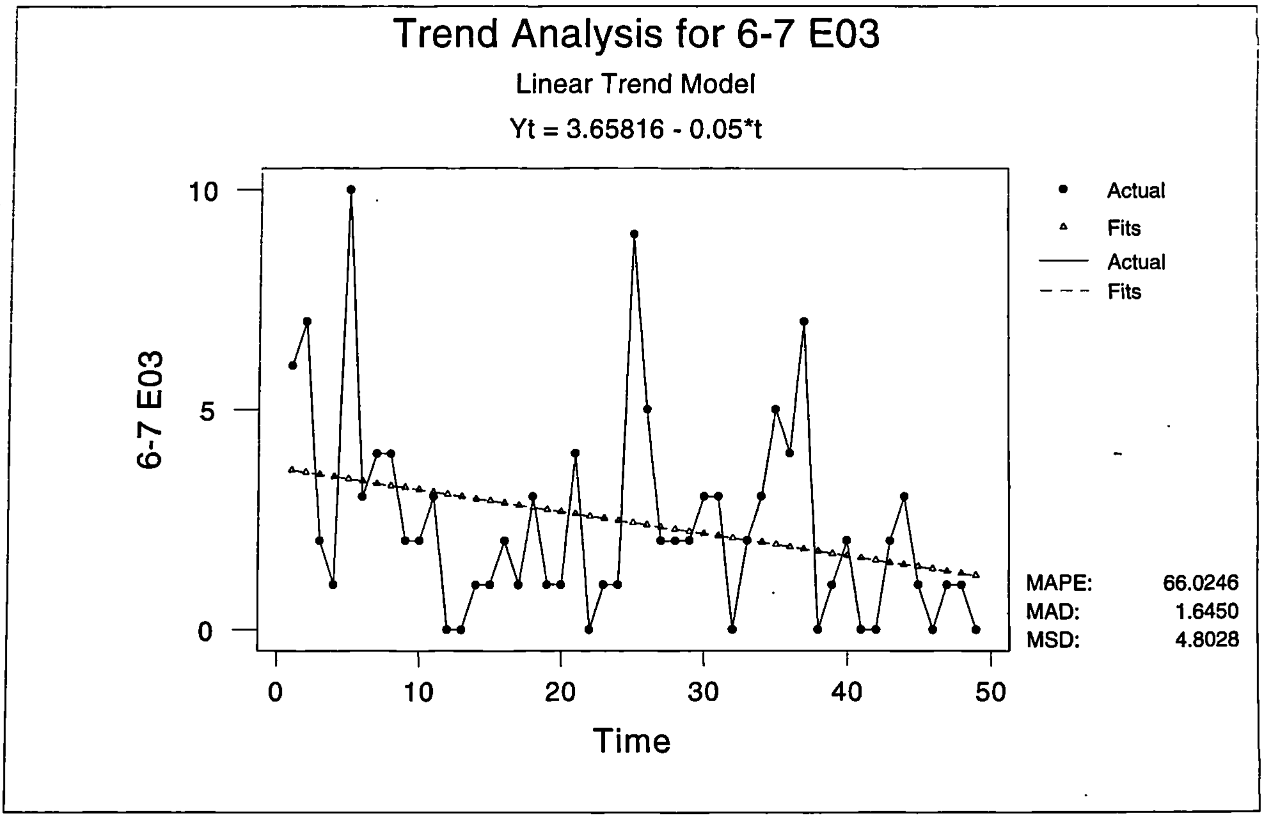

Trend Analysis for SW E03
Quadratic Trend Model
Yt = 19.241 - 0.553142*t + 8.43E-03*t**2
SW E03
25
20
15
10
5
0
Time
0
10
20
30
40
50
Actual
Fits
Actual
Fits
MAPE: 48.1628
MAD: 3.5563
MSD: 19.2303

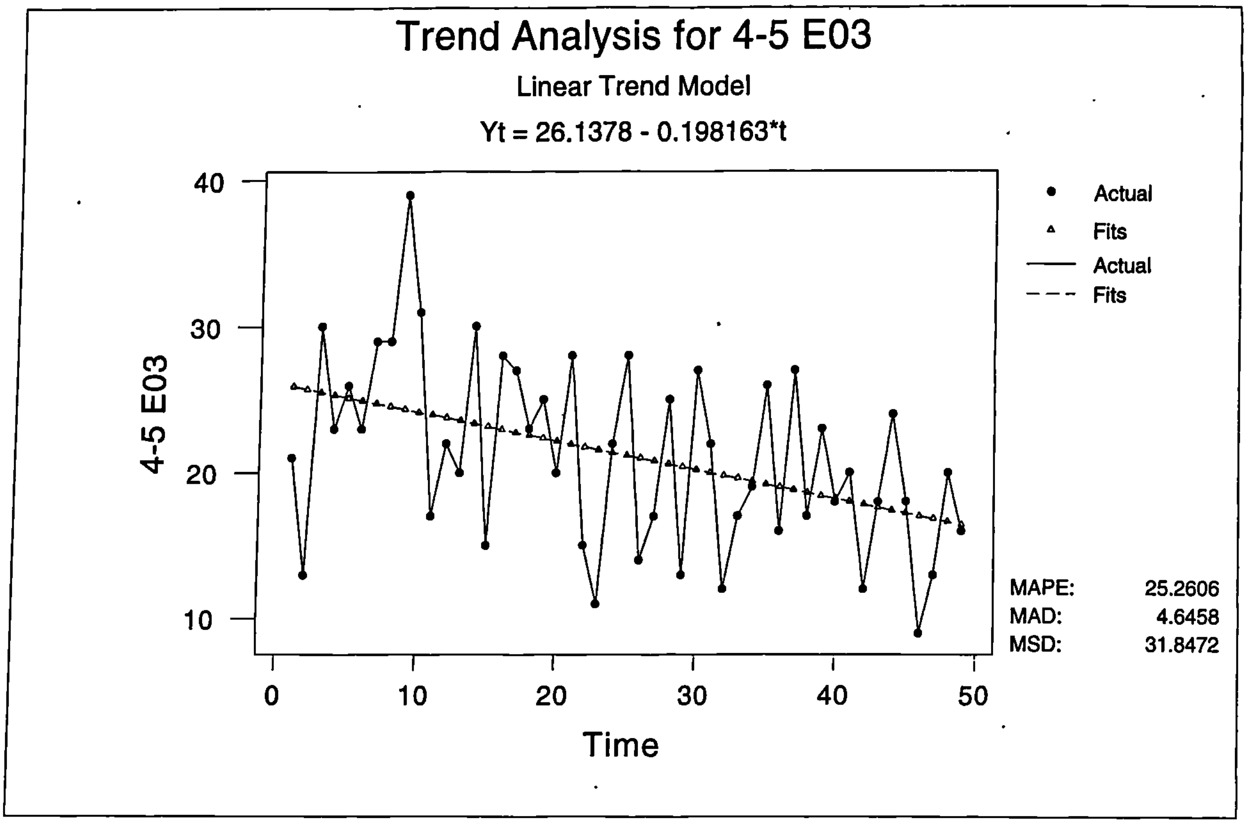

Trend Analysis for W E03
Linear Trend Model
Yt = 11.0383 - 9.87E-02*t
W E03
20
10
0
Time
0
10
20
30
40
50
Actual
Fits
Actual
Fits
MAPE: 49.4962
MAD: 2.7378
MSD: 11.8078

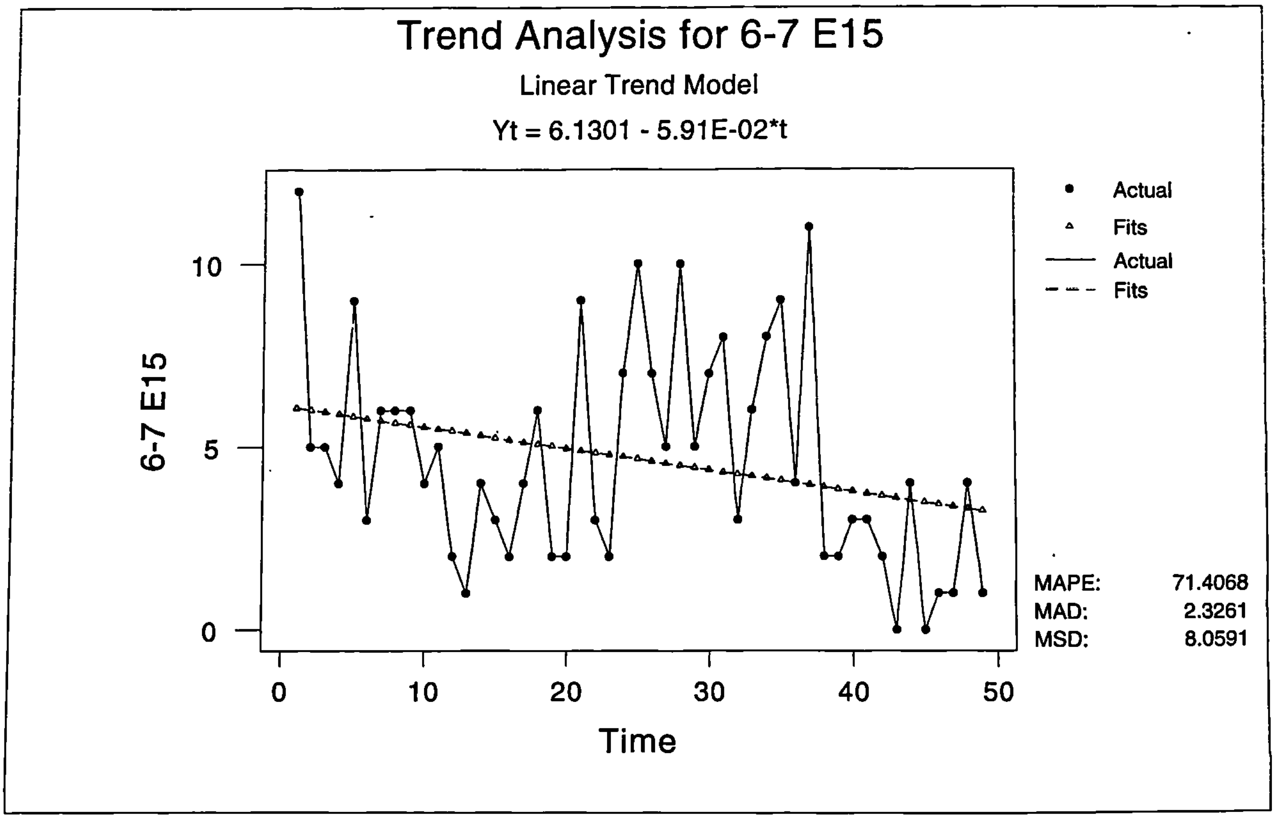

Trend Analysis for NW E03
Linear Trend Model
Yt = 3.79082 + 0.111224*t
NW E03
0
10
20
Time
0
10
20
30
40
50
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 58.4277
MAD: 2.7795
MSD: 13.4034


Trend Analysis for NW E03
Quadratic Trend Model
Yt = 8.3718 - 0.427714*t + 1.08E-02*t**2
NW E03
0
10
20
Time
0
10
20
30
40
50
● Actual
▵ Fits
—— Actual
- - - Fits
MAPE: 50.8981
MAD: 2.5675
MSD: 9.6902


Moving Average
CALM E03
45
35
25
15
5
0
10
20
30
40
50
Time
Actual
Predicted
Actual
Predicted
Moving Average
Length: 5
MAPE: 49.8642
MAD: 5.9227
MSD: 63.1936


Trend Analysis for 6-7 E03
Linear Trend Model
Yt = 3.65816 - 0.05*t
6-7 E03
10
5
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 66.0246
MAD: 1.6450
MSD: 4.8028


Trend Analysis for 4-5 E03
Linear Trend Model
Yt = 26.1378 - 0.198163*t
4-5 E03
40
30
20
10
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 25.2606
MAD: 4.6458
MSD: 31.8472


Trend Analysis for 6-7 E15
Linear Trend Model
Yt = 6.1301 - 5.91E-02*t
6-7 E15
10
5
0
0
10
20
30
40
50
Time
Actual
Fits
Actual
Fits
MAPE: 71.4068
MAD: 2.3261
MSD: 8.0591

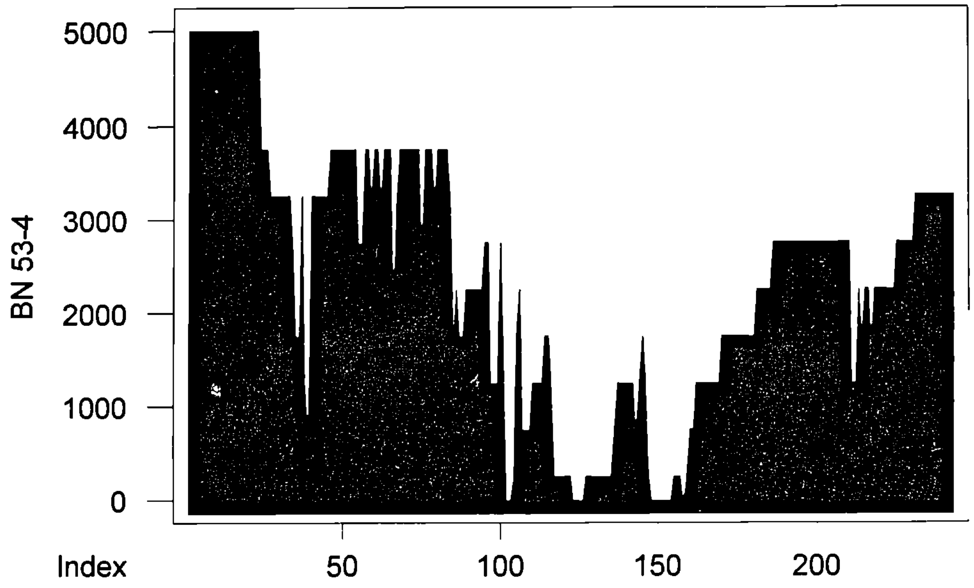
APPENDIX III

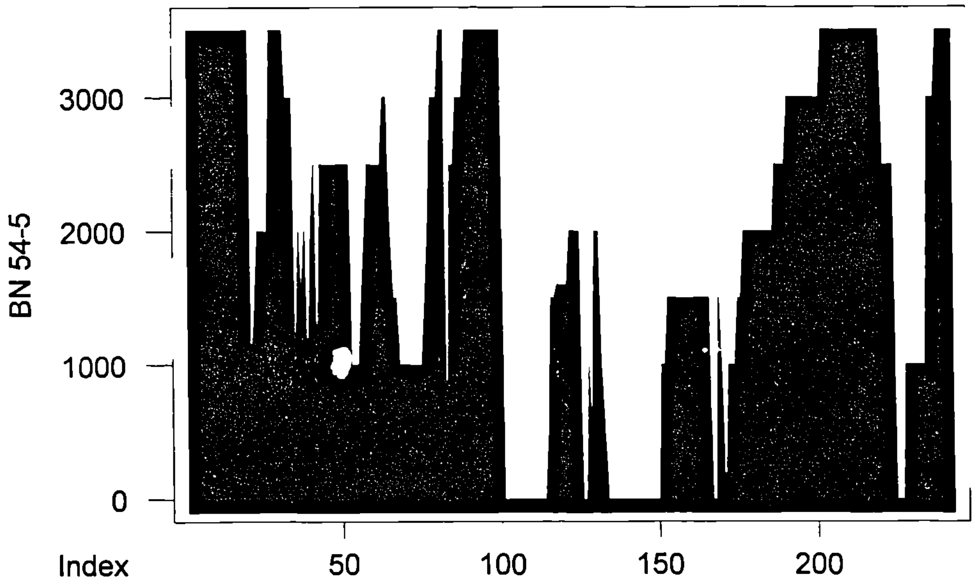
SNOW-LIE DIAGRAMS FOR BEN NEVIS AND CREAG MEAGAIDH THROUGH THE WINTER SEASON (OCTOBER - MAY) FROM 1953/4 TO 1991/2.

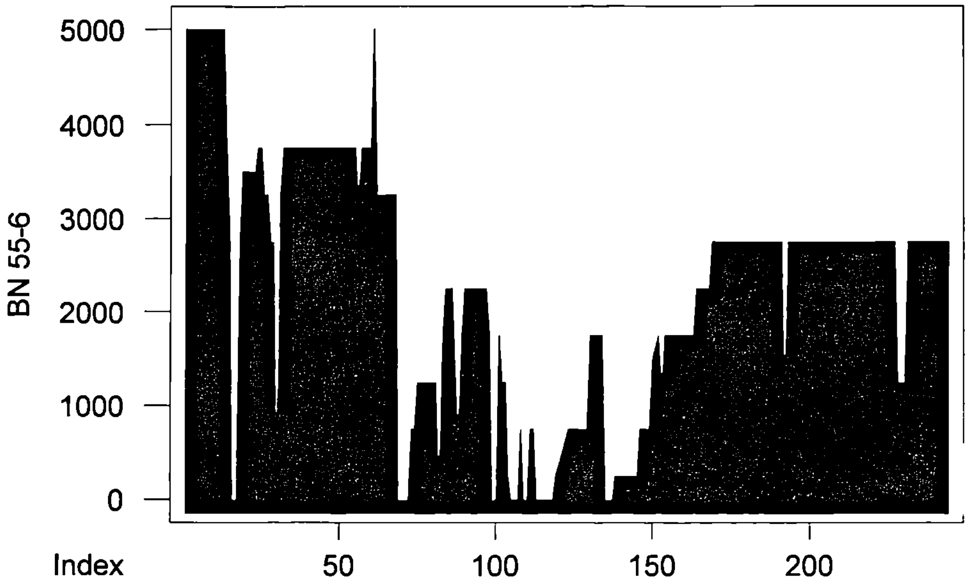
BLACK AREAS INDICATE SNOWFREE HILLSIDE, WHILE WHITE AREAS ARE SNOW COVERED.

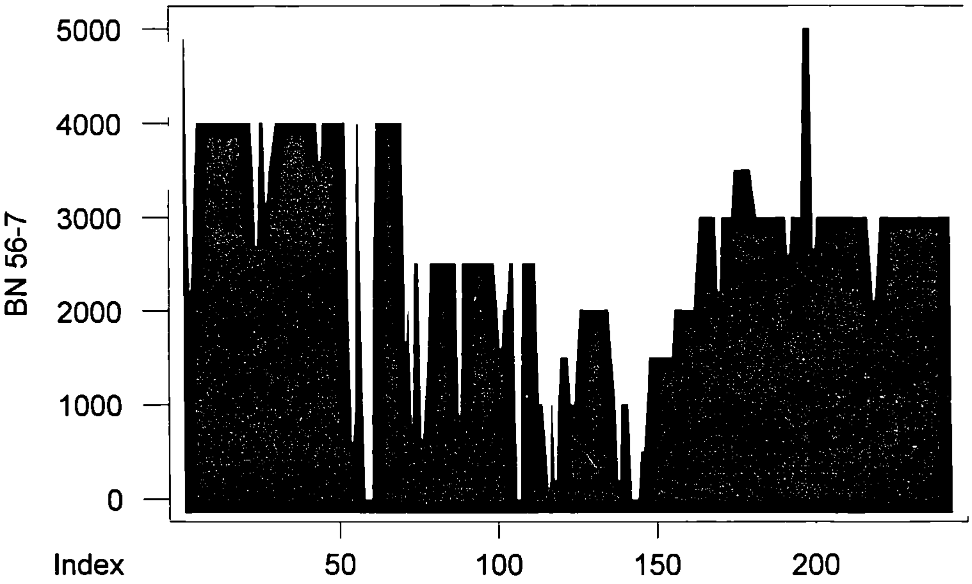
VERTICAL AXIS GIVES ALTITUDE IN FEET (1953/4 - 1965/6) OR METRES (1966/7 - 1991/2)

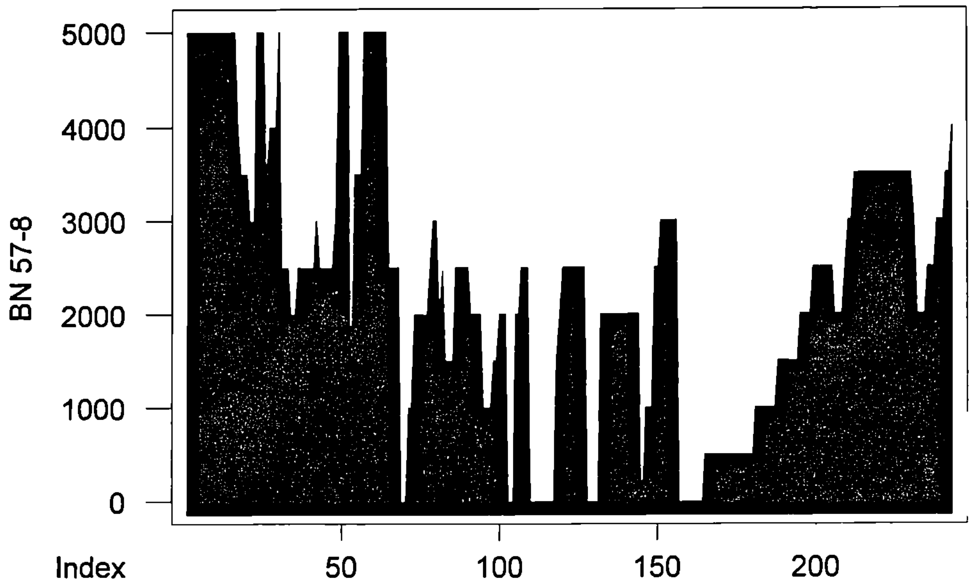
HORIZONTAL AXIS MEASURES NUMBER OF DAYS OF WINTER SEASON ELAPSED FROM 1/11 (DAY 1) TO 31/5 (DAY 273 OR 274).

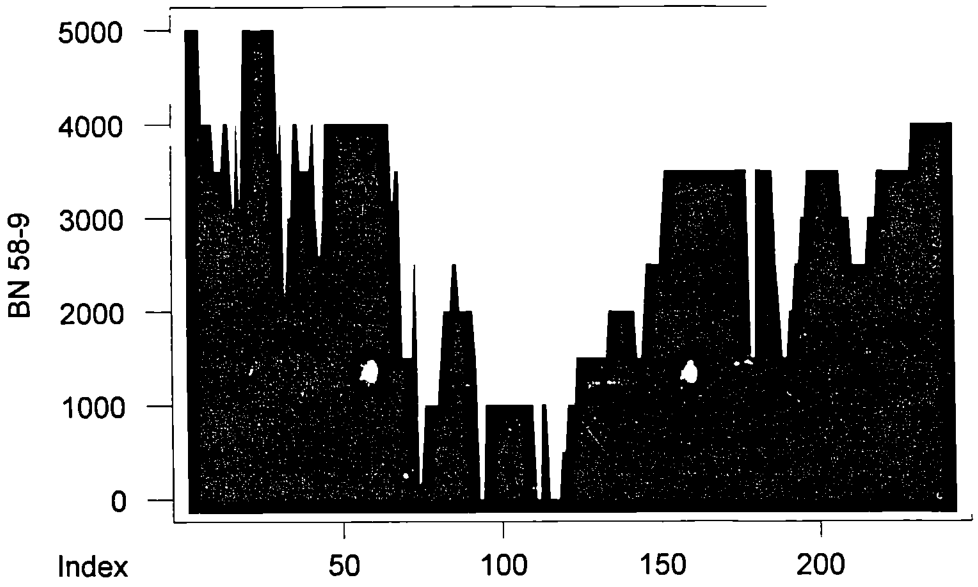

5000
4000
3000
2000
1000
0
BN 53-4
Index
50
100
150
200

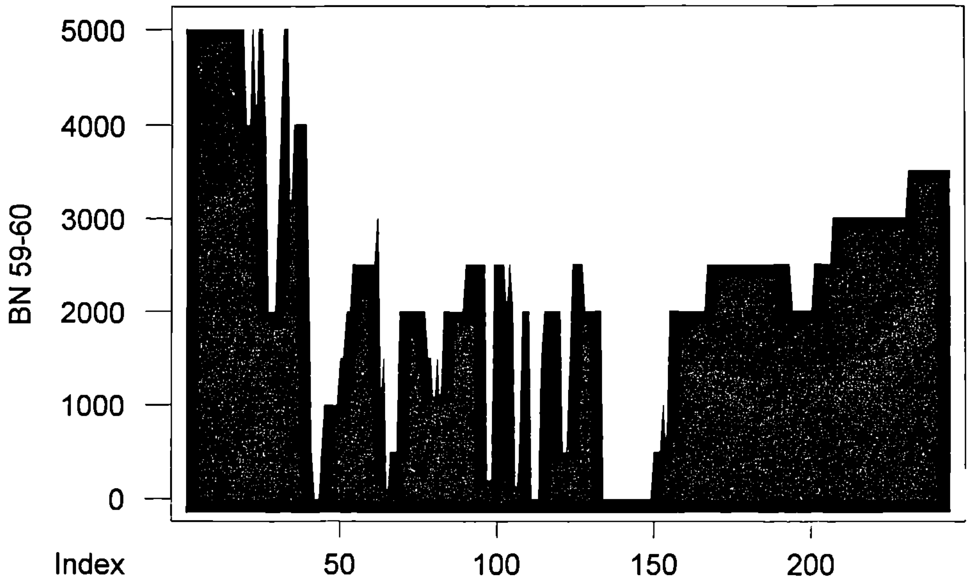

3000
2000
1000
0
BN 54-5
Index
50
100
150
200

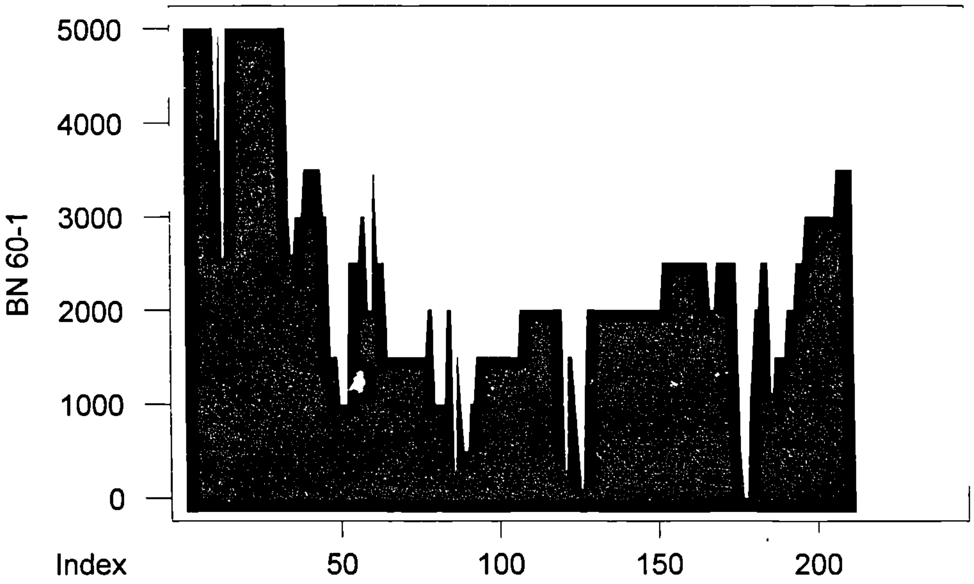

5000
4000
3000
2000
1000
0
BN 55-6
Index
50
100
150
200

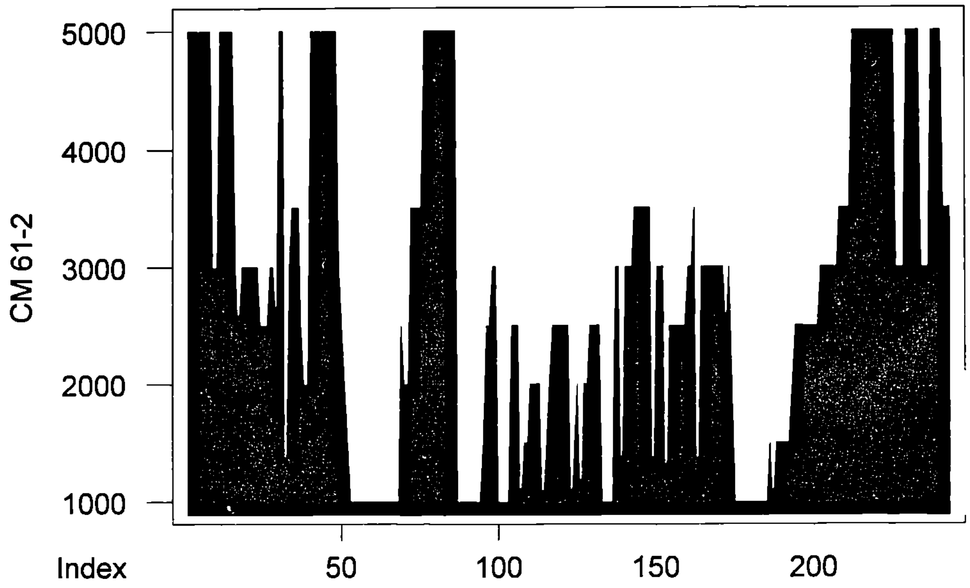

5000
4000
3000
2000
1000
0
BN 56-7
Index
50
100
150
200

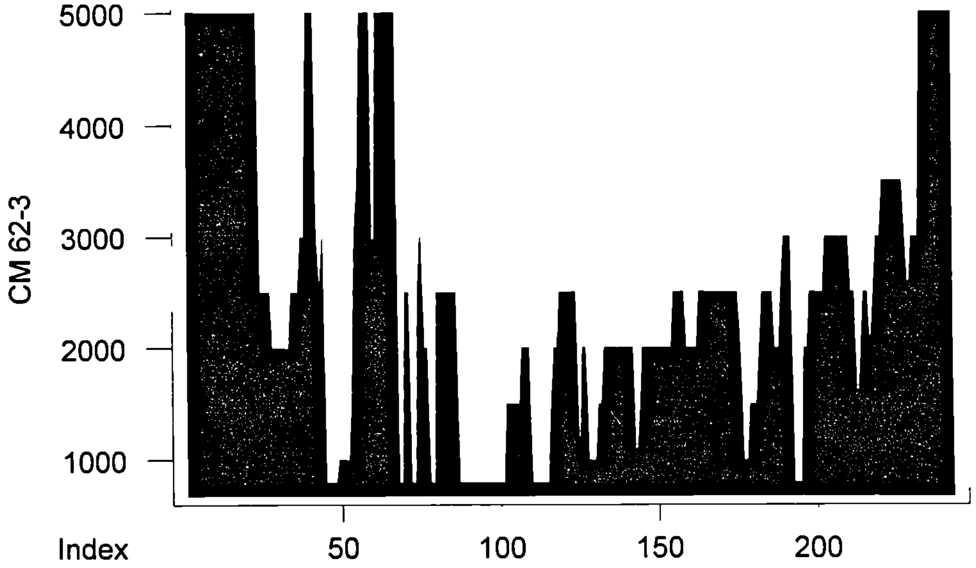

BN 57-8
5000
4000
3000
2000
1000
0
Index
50
100
150
200

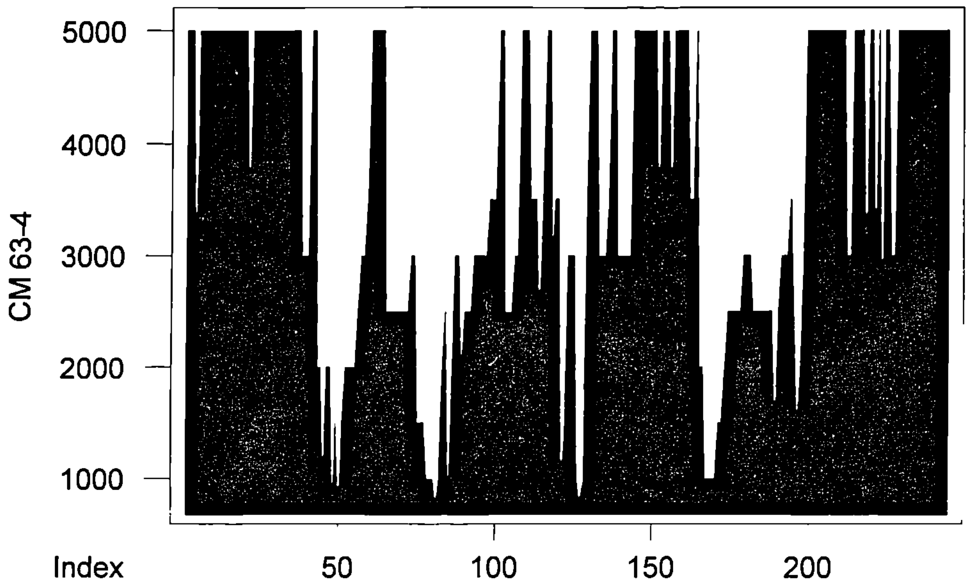

BN 58-9
5000
4000
3000
2000
1000
0
Index
50
100
150
200

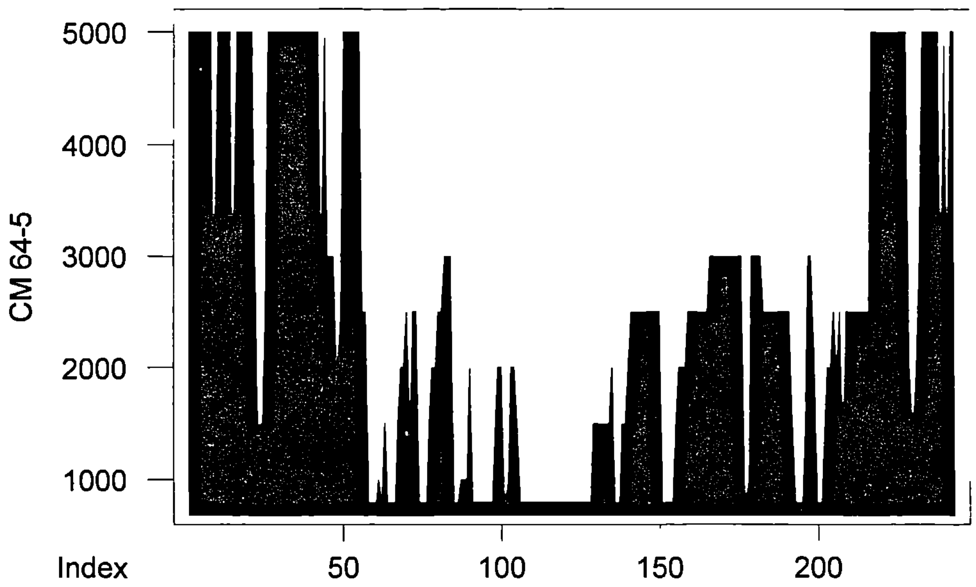

5000
4000
3000
2000
1000
0
BN 59-60
Index
50
100
150
200

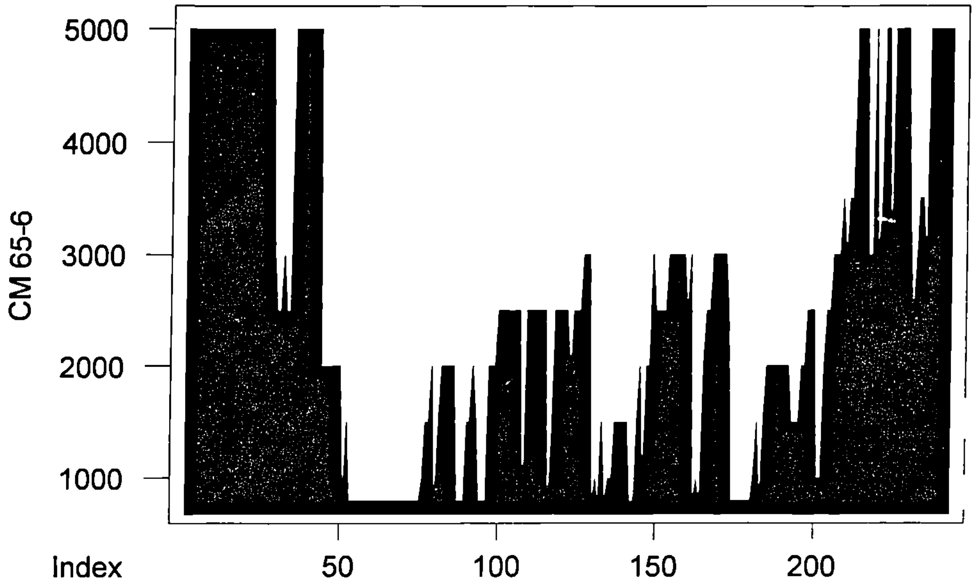

5000
4000
3000
2000
1000
0
BN 60-1
Index
50
100
150
200

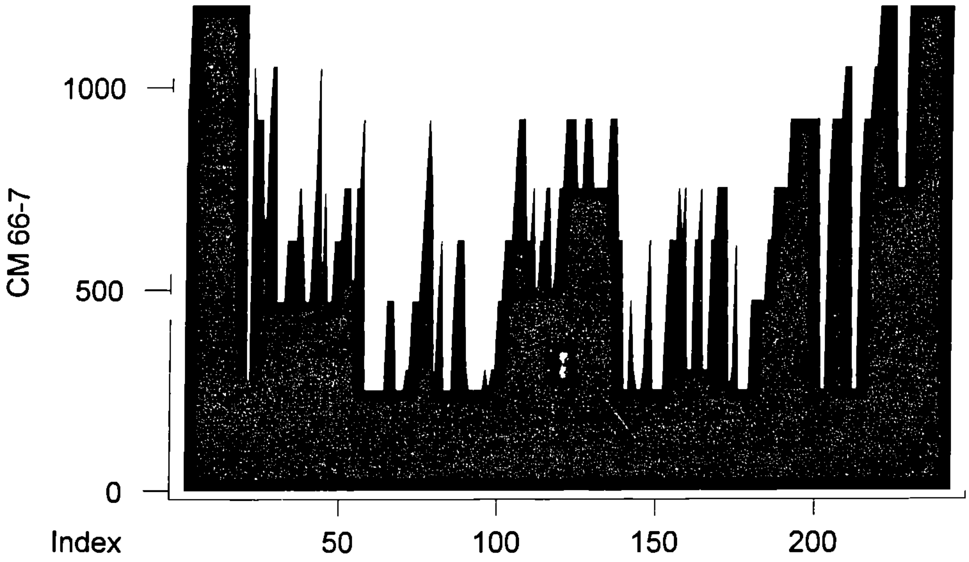

5000
4000
3000
2000
1000
CM 61-2
Index
50
100
150
200

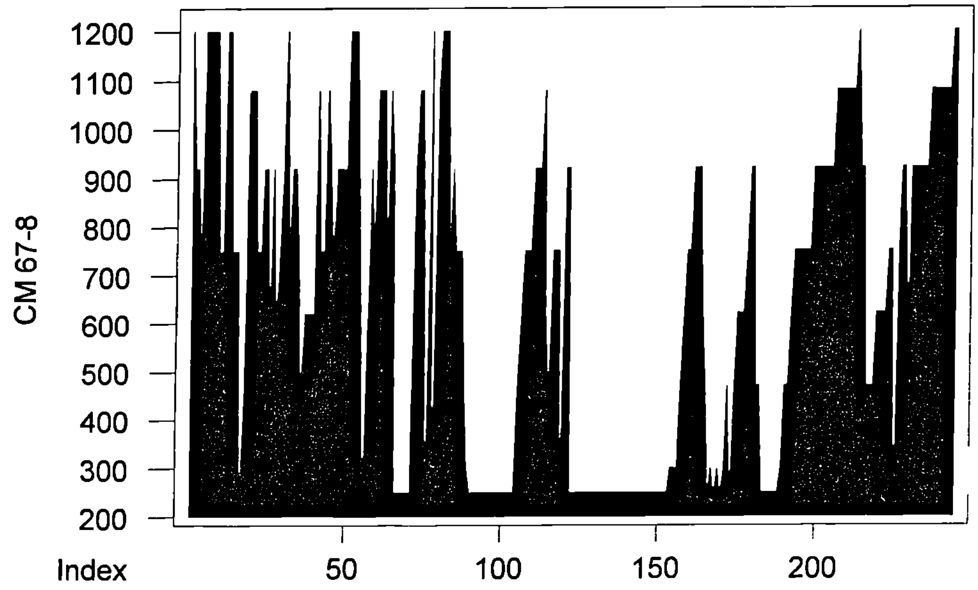

5000
4000
3000
2000
1000
CM 62-3
Index
50
100
150
200

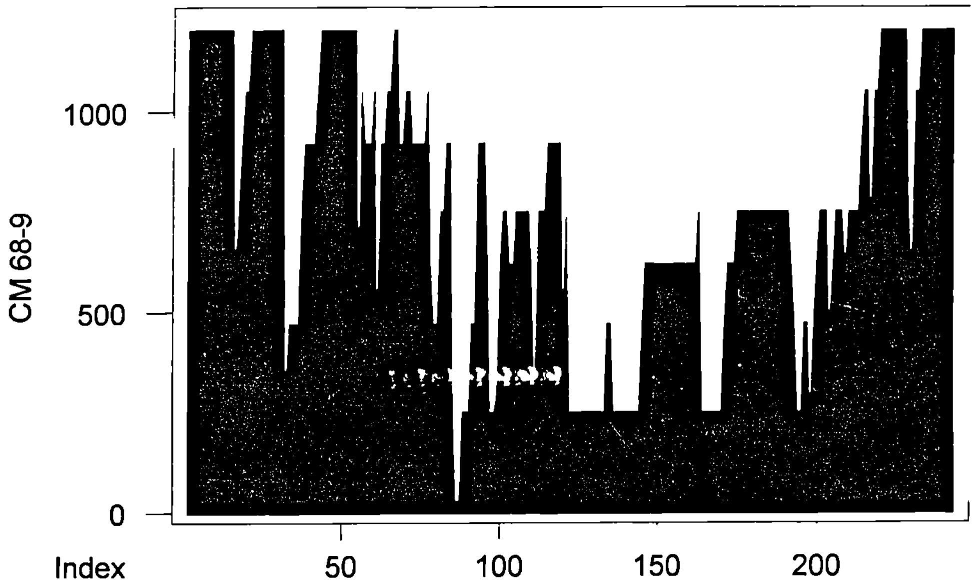

5000
4000
3000
2000
1000
CM 63-4
Index
50
100
150
200

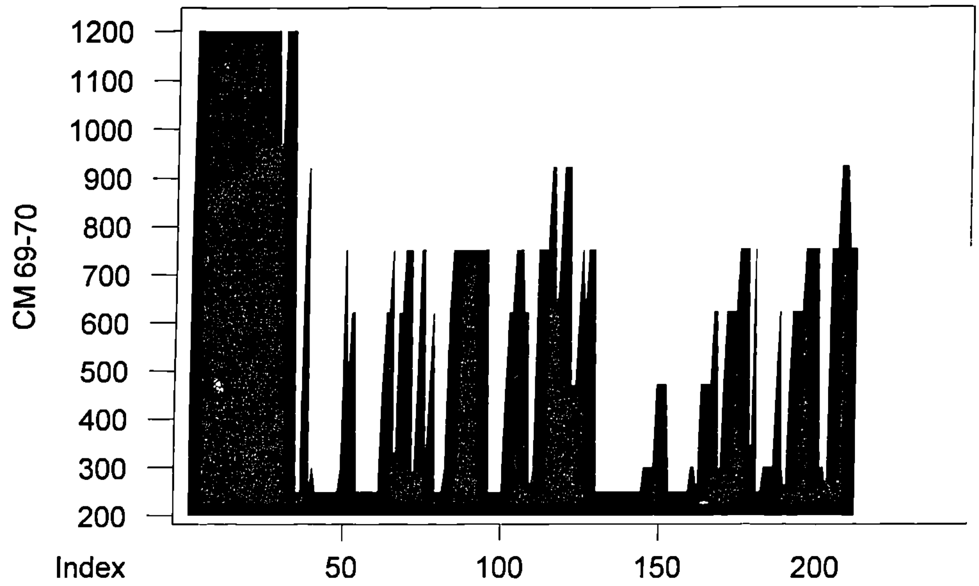

5000
4000
3000
2000
1000
CM 64-5
Index
50
100
150
200


5000
4000
3000
2000
1000
CM 65-6
Index
50
100
150
200

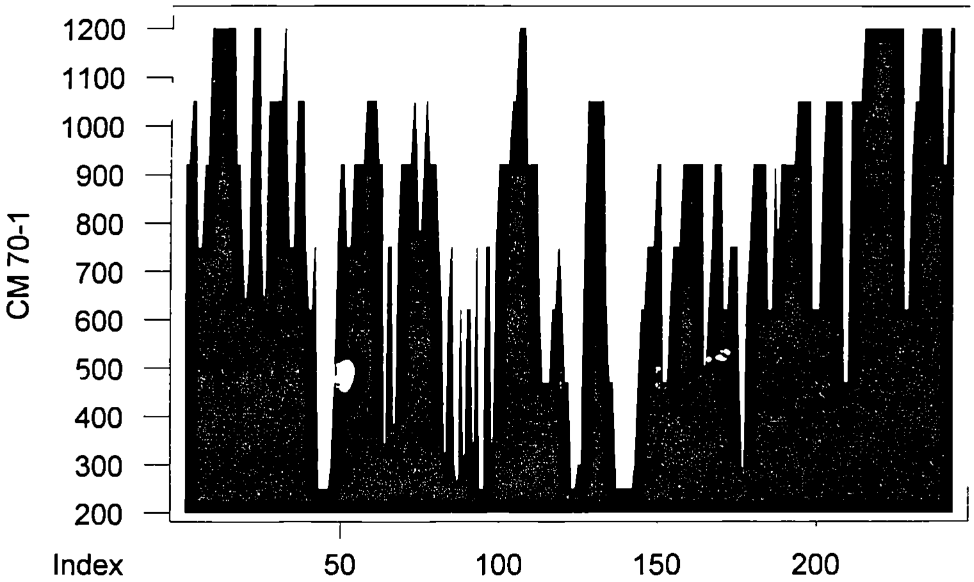

1000
500
0
CM 66-7
Index
50
100
150
200


1200
1100
1000
900
800
700
600
500
400
300
200
CM 67-8
Index
50
100
150
200

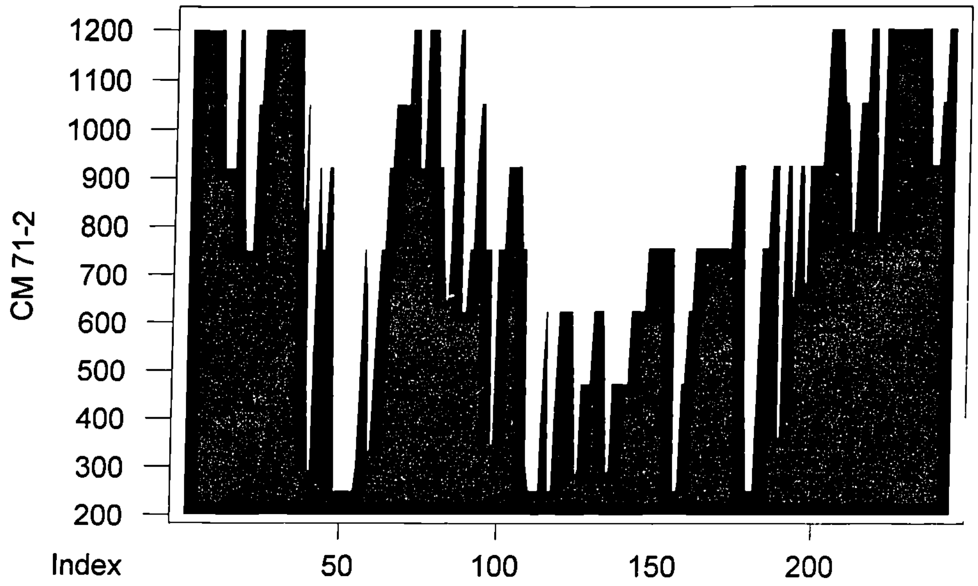

1000
500
0
CM 68-9
Index
50
100
150
200

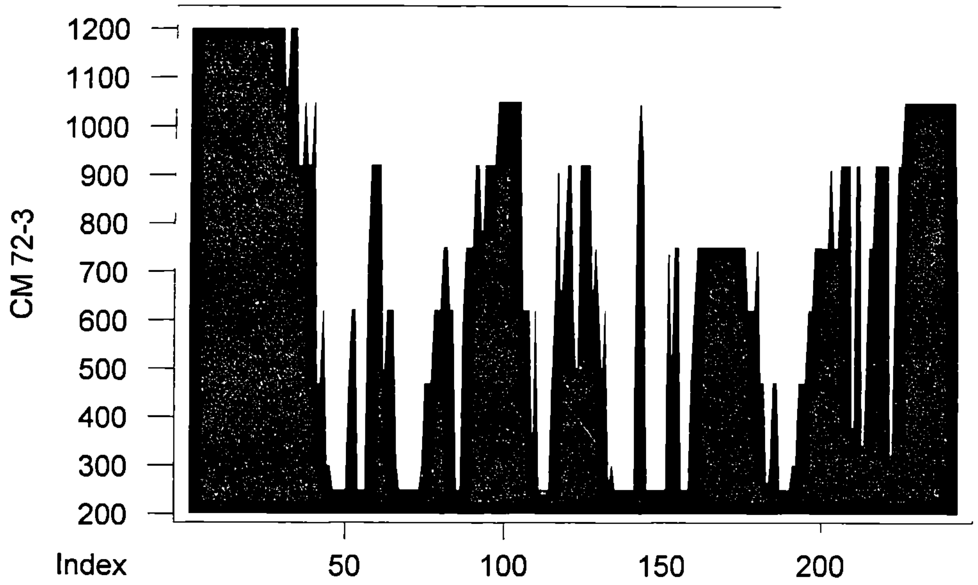


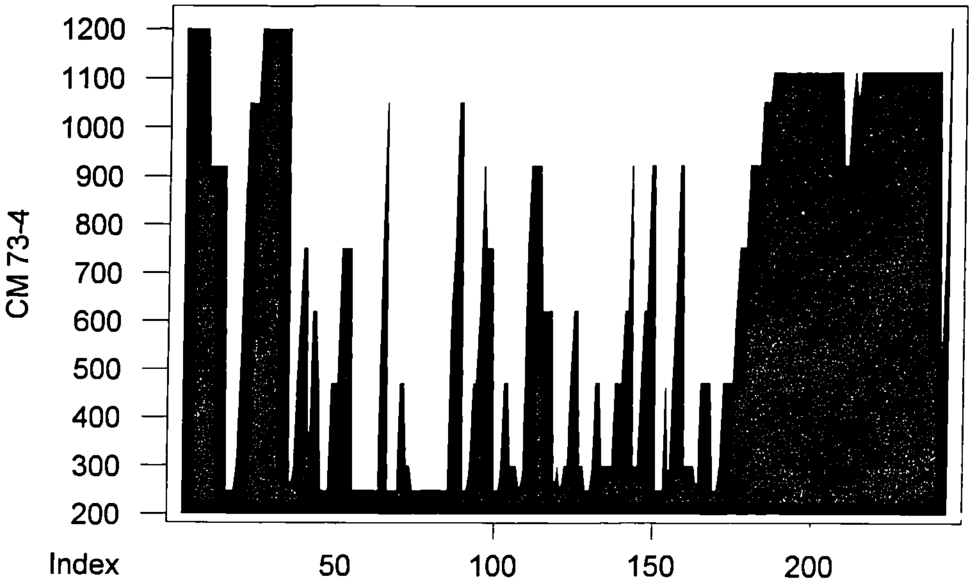
CM 69-70
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200

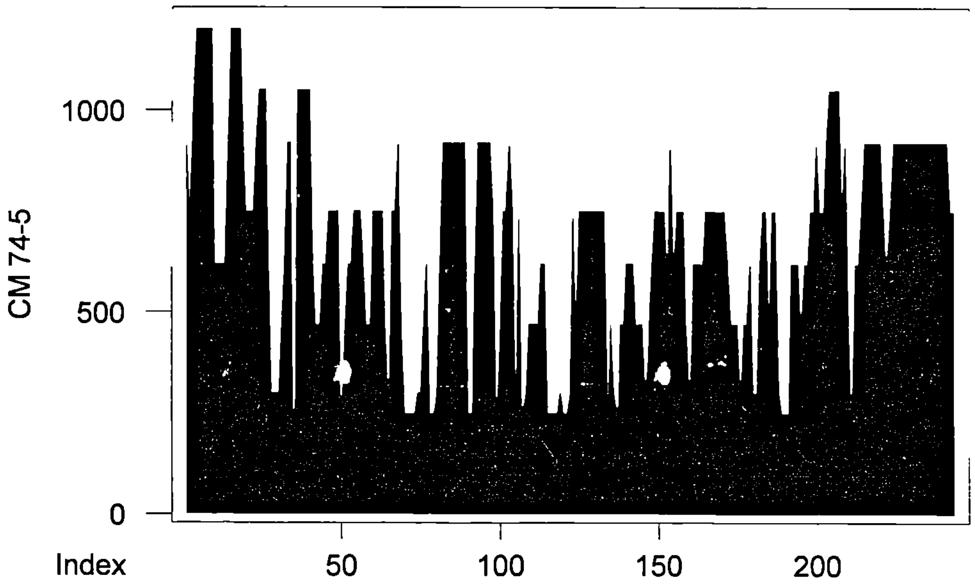


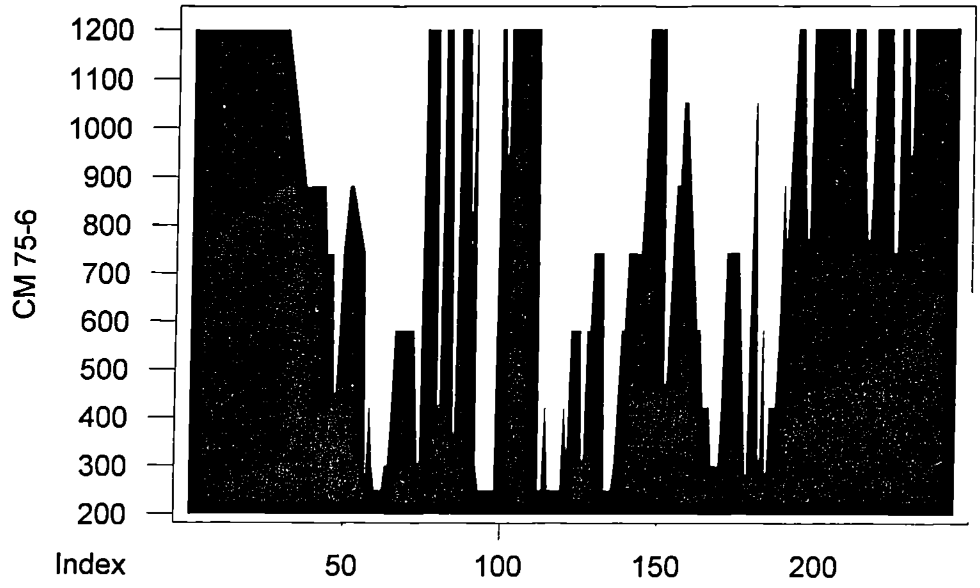
CM 70-1
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200


1200
1100
1000
900
800
700
600
500
400
300
200
CM 71-2
Index
50
100
150
200

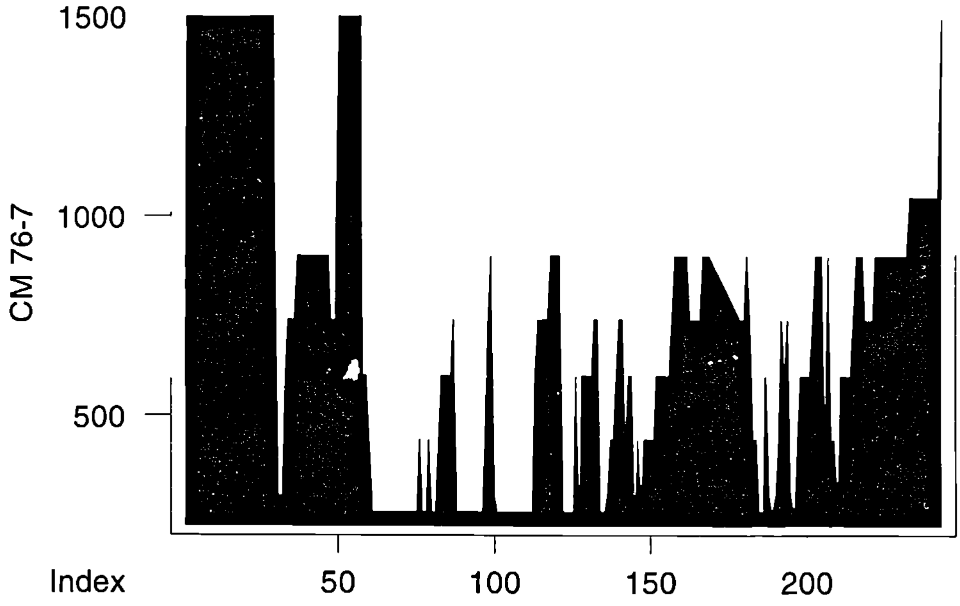

1200
1100
1000
900
800
700
600
500
400
300
200
CM 72-3
Index
50
100
150
200


1200
1100
1000
900
800
700
600
500
400
300
200
CM 73-4
Index
50
100
150
200

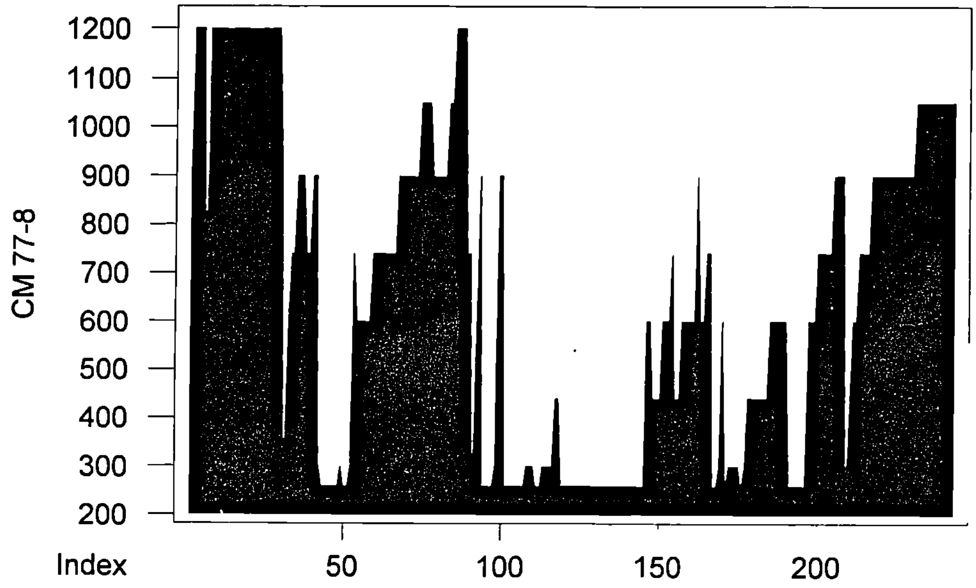

1000
500
0
CM 74-5
Index
50
100
150
200

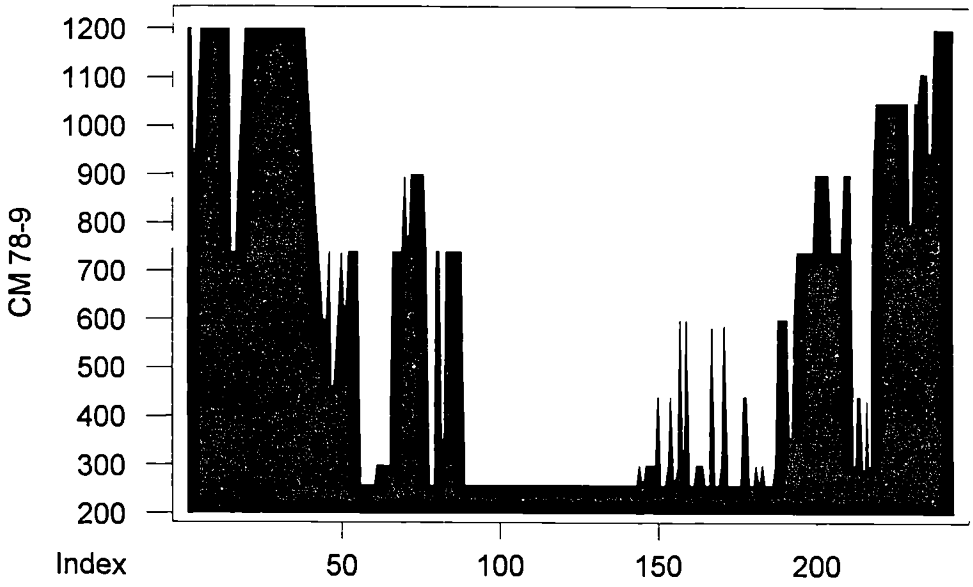


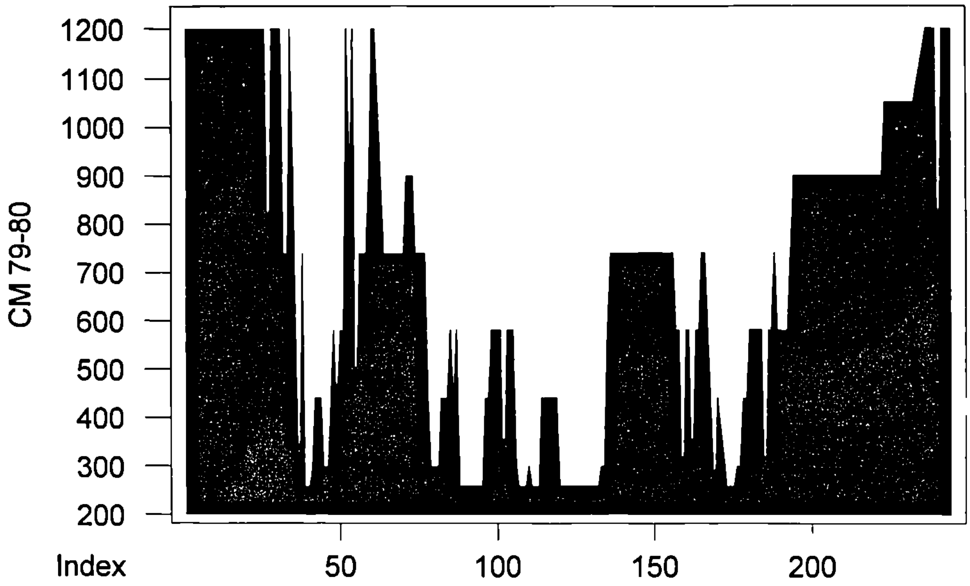
CM 75-6
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200

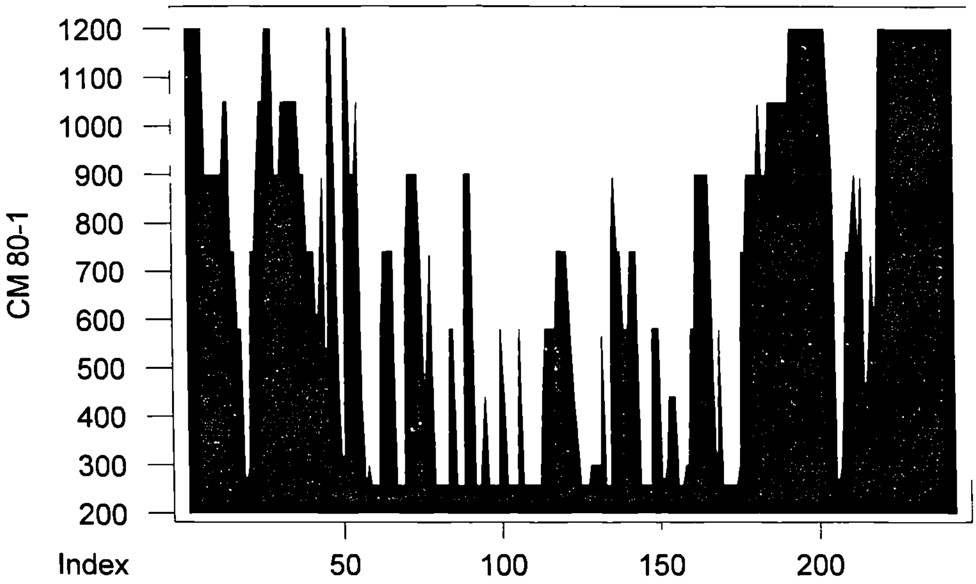


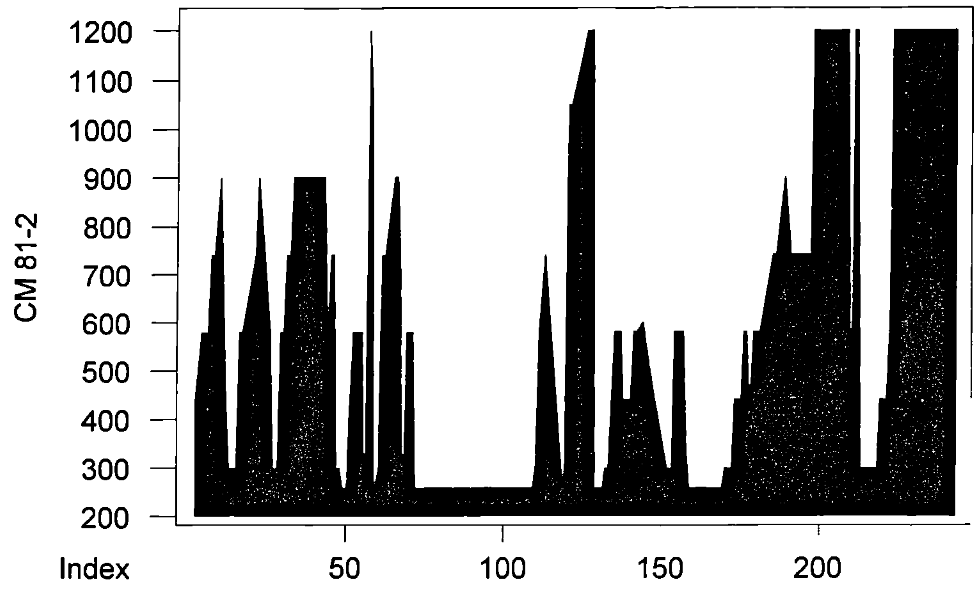
CM 76-7
1500
1000
500
Index
50
100
150
200

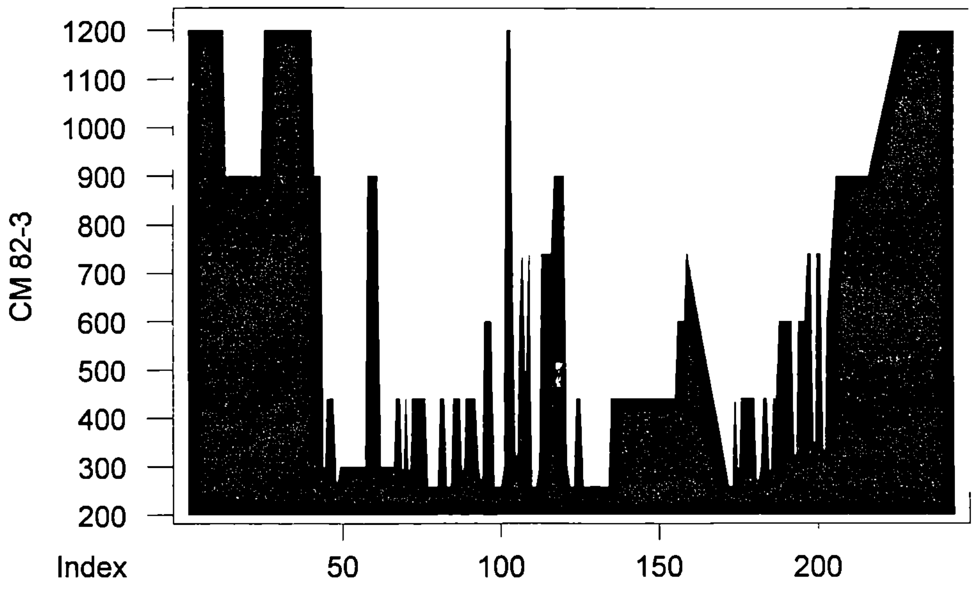

1200
1100
1000
900
800
700
600
500
400
300
200
CM 77-8
Index
50
100
150
200

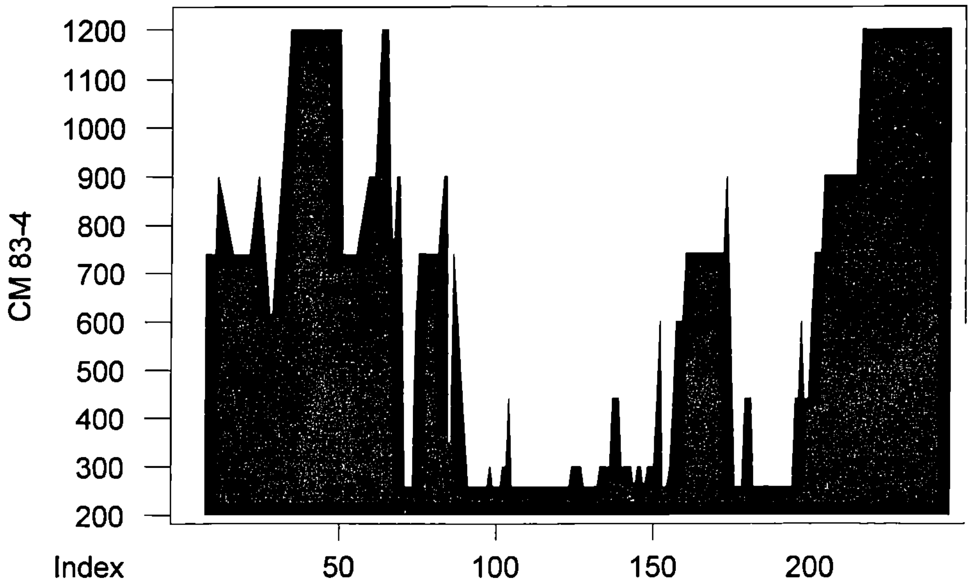

1200
1100
1000
900
800
700
600
500
400
300
200
CM 78-9
Index
50
100
150
200

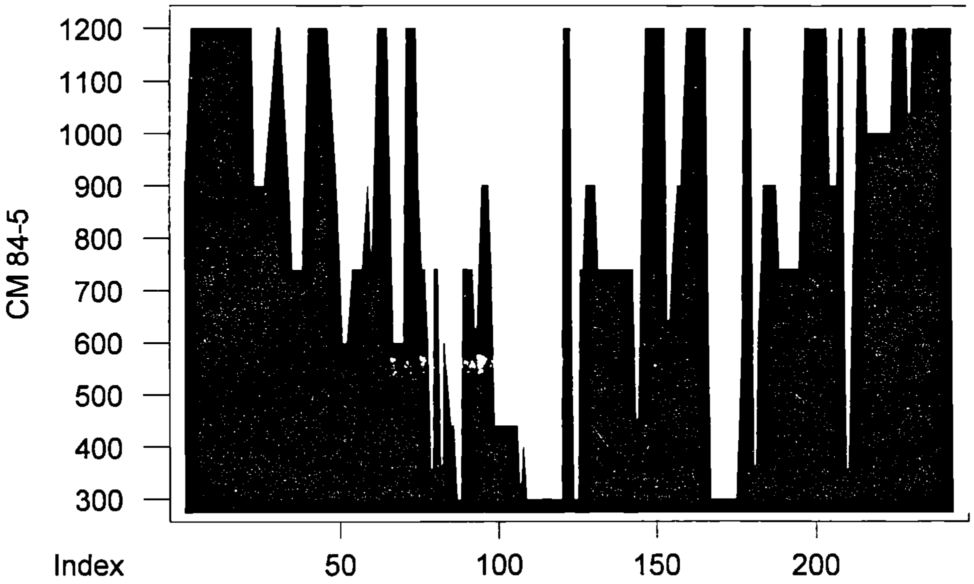

1200
1100
1000
900
800
700
600
500
400
300
200
CM 79-80
Index
50
100
150
200

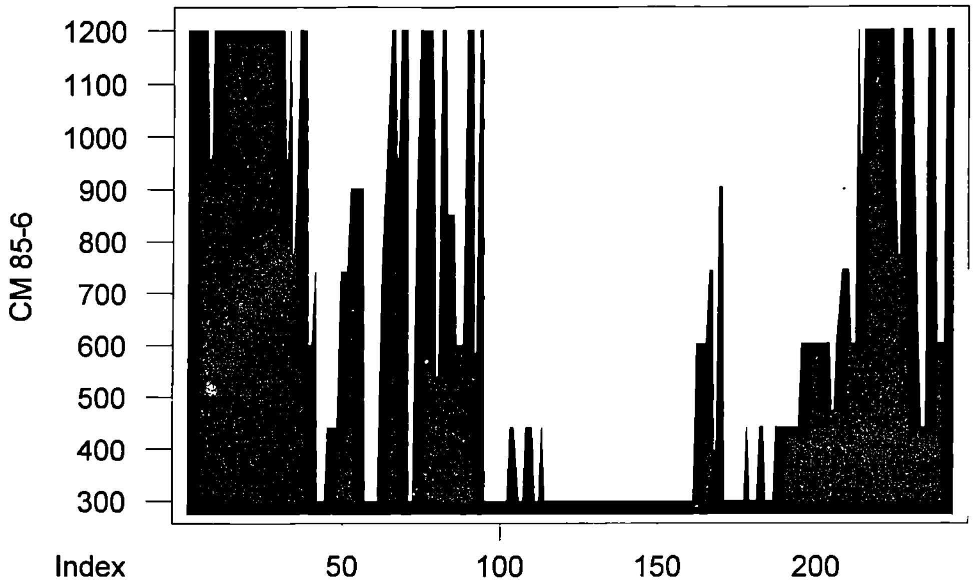

1200
1100
1000
900
800
700
600
500
400
300
200
CM 80-1
Index
50
100
150
200

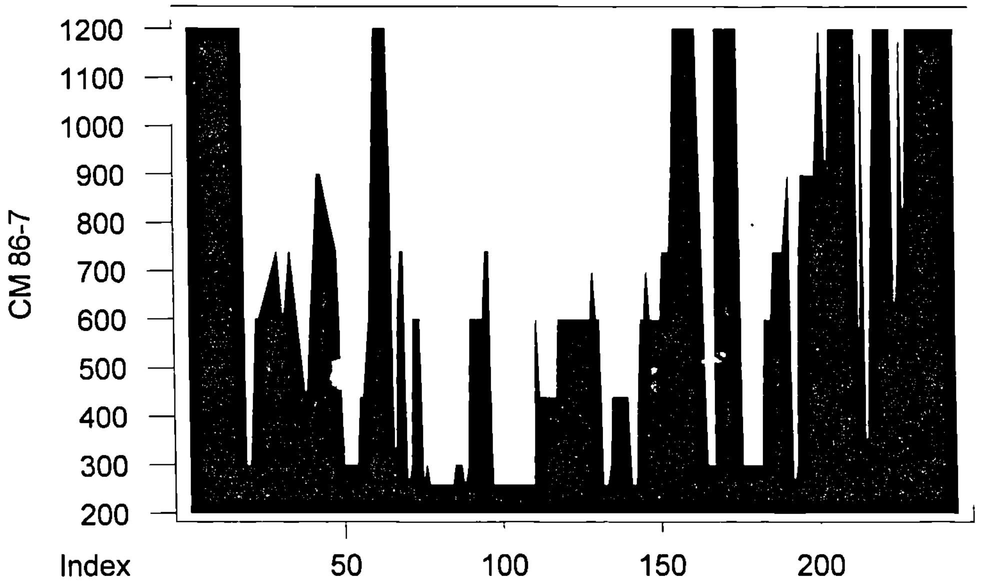

1200
1100
1000
900
800
700
600
500
400
300
200
CM 81-2
Index
50
100
150
200

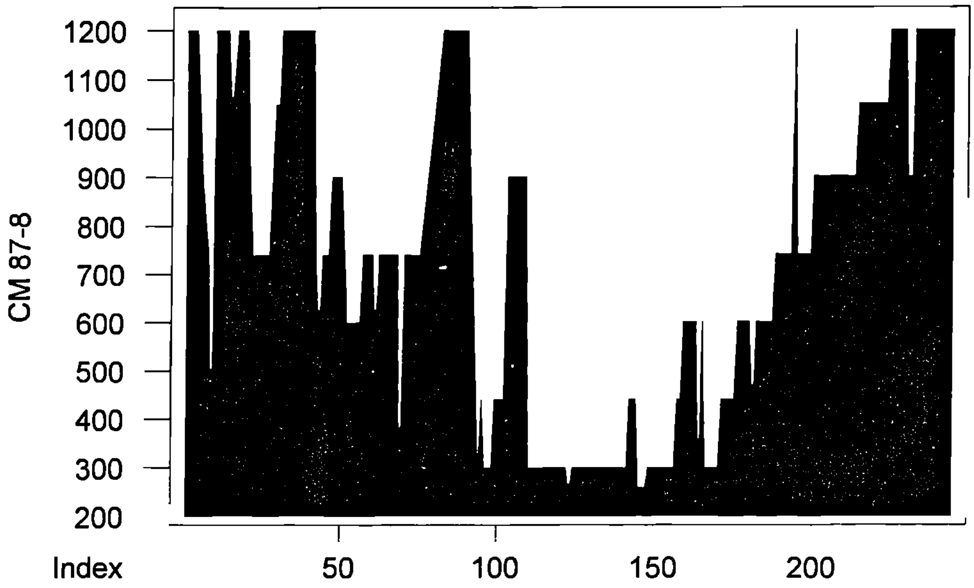

1200
1100
1000
900
800
700
600
500
400
300
200
CM 82-3
Index
50
100
150
200

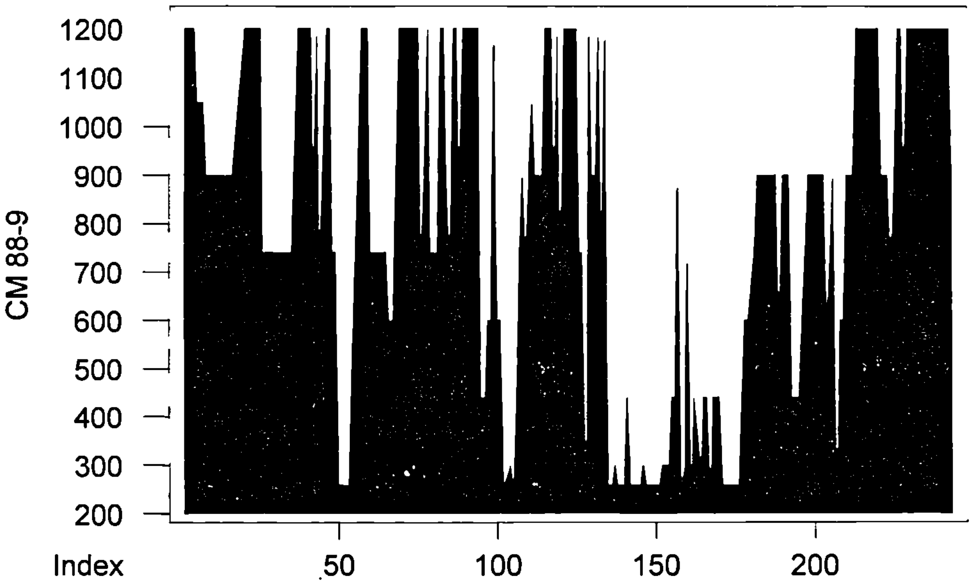

1200
1100
1000
900
800
700
600
500
400
300
200
CM 83-4
Index
50
100
150
200

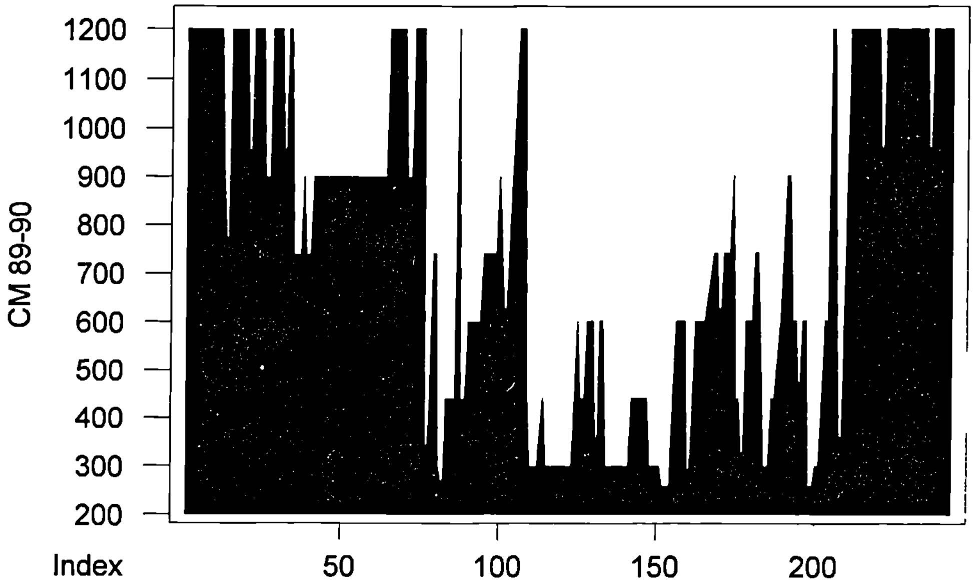

1200
1100
1000
900
800
700
600
500
400
300
CM 84-5
Index
50
100
150
200

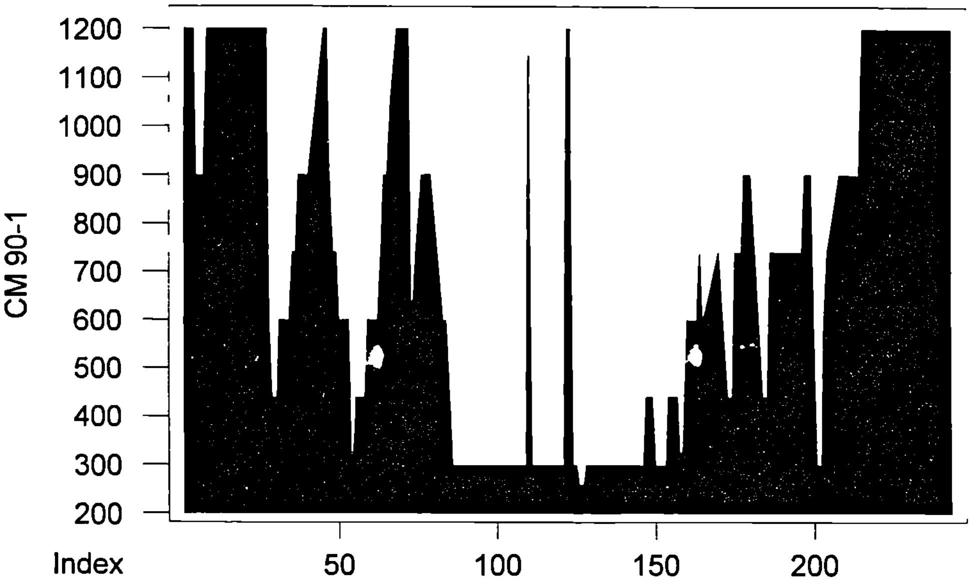

CM 85-6
1200
1100
1000
900
800
700
600
500
400
300
Index
50
100
150
200

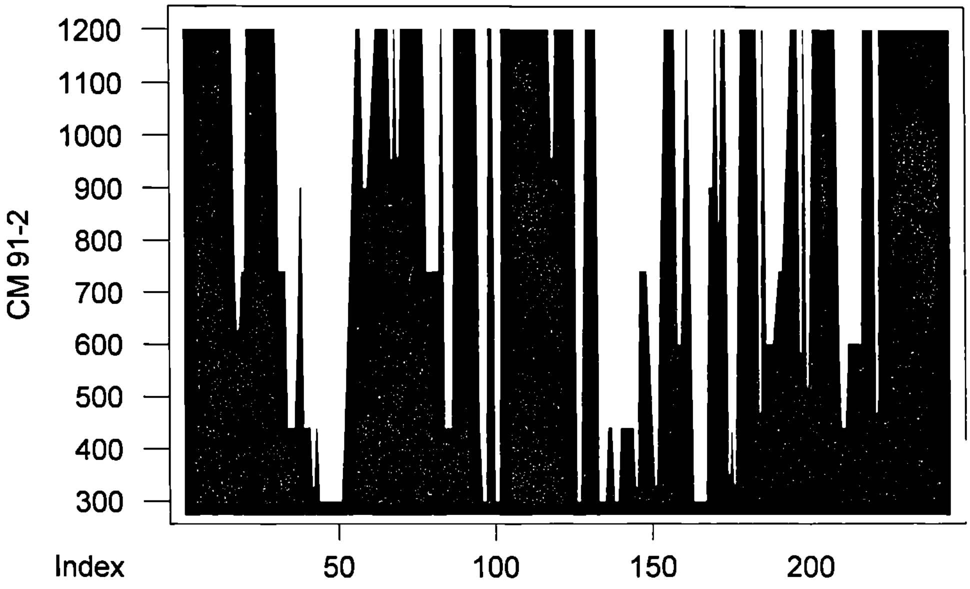

CM 86-7
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200


1200
1100
1000
900
800
700
600
500
400
300
200
CM 87-8
Index
50
100
150
200


1200
1100
1000
900
800
700
600
500
400
300
200
CM 88-9
Index
50
100
150
200


CM 89-90
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200


CM 90-1
1200
1100
1000
900
800
700
600
500
400
300
200
Index
50
100
150
200


CM 91-2
1200
1100
1000
900
800
700
600
500
400
300
Index
50
100
150
200


Coire Choille-rais
Allt Choille-rais
Allt Daim
Stob Coire an Fhir Dhuibh
Coire an Fhir Dhuibh
Creagan na Gabhar
Allt a' Chùl Choire
An Cùl Choire
Aonach an Nid
Coire an Lochain
Aonach Mòr
1221m
Seang Aonach Mòr
Aonach Beag
Coire Giubhsachan
Allt Coire Giubhsachan
Allt an t-Sneachda
Leac an t-Sneachda
22
19