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Projecting Climate Change Impacts on Mountain Snow Cover in Central Scotland from Historical Patterns

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Abstract

Cumulative days of seasonal snow cover at Ben Lawers National Nature Reserve, a mountain site in Scotland, are related to altitude, temperature, and precipitation using a 45-year record from a nearby climate station. Multiple linear regression is used to model interannual variation in snow cover duration as a function of winter mean daily temperature and monthly precipitation. Snow cover duration is closely linked to temperature, while precipitation contributes a positive effect among winters of similar temperature mode. Snow cover duration at mid to upper altitudes (600–900 m) responds most strongly to variation in mean daily temperature. A 1 °C rise in temperature at the station corresponds to a 15-day reduction in snow cover at 130 m and a 33-day reduction at 750 m. The empirical relationship is applied to climate change scenarios from the HadRM3 regional climate model. Under a 'low' greenhouse gas emissions scenario, snow cover in the 2050s is projected to be reduced by 93% at 130 m, 43% at 600 m and 21% at 1060 m, while under a 'high' emissions scenario these reductions are projected to be 100%, 68%, and 32%, respectively. The potential impact of snow cover reduction on snow-dependent vegetation is modeled. The results suggest a future decline in climax vegetation of international conservation importance.

Introduction

Snow and ice cover play a major role in global climate, hydrology, and ecology. Continental and hemispheric climates are influenced by seasonal variations in snow and sea ice cover (Barry, 2002). For example, the recent decline in wintertime snow cover over Eurasia, resulting in a reduced surface albedo and warmer surface temperatures, has been linked to enhancement of the Arabian Sea summer monsoon and ocean productivity (Goes et al., 2005). At a regional scale, mountain snow cover and duration are major controlling factors on a range of environmental systems (Beniston et al., 2003a). The timing and intensity of snow melt influences the seasonality of low and high stream flows (López-Moreno and Nogués-Bravo, 2005) and can contribute to flooding (Bell and Moore, 1999). Snow protects dormant plants from frost damage (Oke, 1987; Beniston et al., 2003a) while snow melt acts as a signal for many alpine and subalpine plants to begin their growth cycle (Post and Stenseth, 1999; Keller et al., 2000; Dunne et al., 2003). Snow cover duration and minimum temperature also determine the survival rates of many alpine plants (Körner, 1994). Changes in snow cover duration are predicted to alter the composition of plant communities in the alpine zone (Heegaard and Vandvik, 2004; Keller et al., 2005).

Snow cover in mid-latitude mountain regions is highly sensitive to climatic variations, especially temperature (Beniston et al., 2003b). Studies in the Alps (Hantel et al., 2000; Beniston et al., 2003b) and Scotland (Harrison et al., 2001) have shown that temperature controls snow depth and duration. The North Atlantic Oscillation (NAO) exerts a strong influence on the variation in winter temperature and precipitation in western Europe (Hurrell and van Loon, 1997; Hurrell et al., 2001) and thus influences snow cover duration (Beniston, 1997) and depth (Mysterud et al., 2000). The negative effect of temperature on snow cover is complicated by precipitation, which tends to increase in warm, high NAO index winters. At high altitudes, where the mean winter temperature remains below freezing point, this extra precipitation falls as snow, compensating for the reduction caused by increased temperature. The crossover point above which warm, wet weather results in increased snow cover occurs at about 1500 m in the Swiss Alps (Beniston et al., 2003a) but 400 m in Norway where the correlation between winter climate and the phase of the NAO is particularly strong (Ottersen et al., 2001). Research in the Alps (Beniston, 1997; Martin and Durand, 1998; Hantel et al., 2000) has found that snow cover is most sensitive to variation in winter weather at 500–2500 m while Harrison et al. (2001) found this to occur at about 400 m in Scotland. Thus the relationship between snow cover and climate varies with altitude and geographical location (affecting the degree of oceanicity or continentality).

In the northern hemisphere, the last century appears to have been the warmest for a millennium (Folland et al., 2001). The

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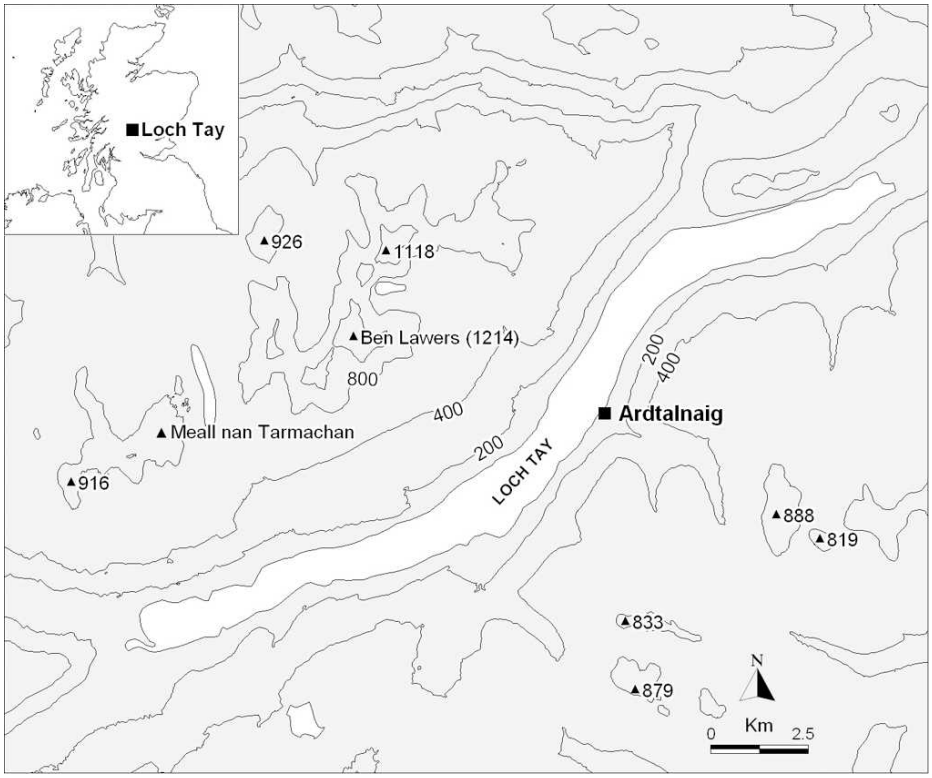

FIGURE 1. Location of the study site at Loch Tay, central Scotland. Altitudes in meters.

largest recent warming has been in winter in the extra-tropical northern hemisphere (Folland et al., 2001) and has been linked to an upward trend in the NAO index (Hurrell et al., 2001). Between 1966 and 1999 snow cover extent in the northern hemisphere decreased by 10% (Folland et al., 2001). Substantial declines in low altitude snow cover have occurred in the Alps (Mohnl, 1994, *cited in* Hantel et al., 2000; Beniston, 1997) and Scotland (Harrison et al., 2001) while increasing precipitation has resulted in little or no reduction in snow cover at high altitudes.

At regional to national scales several studies have projected future change in seasonal snow cover based upon relationships between recent climate and snow cover duration (Hantel et al., 2000; Harrison et al., 2001; Beniston et al., 2003a). These studies suggest climate change will lead to increased liquid precipitation at low altitudes and an increase in solid precipitation at medium to high altitudes where temperatures remain below freezing. Thus snow cover duration is expected to decrease at low to medium altitudes but increasing precipitation may lead to increased snow cover at higher altitudes.

Few studies have looked at the potential effects of climate change on mountain snow cover at local scales, equivalent to individual nature reserves and ski resorts. A 45-year record of snow cover and weather is used to assess the climatic sensitivity of snow cover in the mountains surrounding Loch Tay in central Scotland. Regional climate scenarios are then used to assess the potential effects of climate change on snow cover duration. We test the hypotheses that increasing temperature will result in decreased snow cover at low altitudes, but at high altitudes this effect will be limited by increased precipitation.

The study site includes the Ben Lawers Special Area of Conservation, which contains high altitude plant communities, such as subarctic *Salix* spp. scrub and siliceous alpine and boreal grasslands (JNCC, 2004). A reduction in snow cover at high altitudes could have a significant impact on these internationally recognized habitats. Vegetation maps are used to determine the relationship between the altitudinal snow cover gradient and a climax plant community that depends upon late-lying snow cover. This model is then used to investigate the effect of snow cover change on vegetation distribution. The climatic factors driving the national scale distribution of this plant community are also examined.

Data and Methods

The study area encompasses the mountains surrounding Loch Tay in the central Highlands of Scotland (Fig. 1), including the Ben Lawers National Nature Reserve, named after the highest peak in the range (1214 m a.s.l.). Since 1958 daily weather has been recorded by Mervyn Browne at Ardtalnaig climate observation station (56.528°N, 4.110°W; 130 m a.s.l.) on the southern shore of Loch Tay. Since 1954, daily observations of snow cover from October to May on the mountains surrounding Ardtalnaig have been made as part of the Meteorological Office's Snow Survey of Great Britain. Snow cover is estimated within 150-m altitudinal bands up the mountains and an average for several mountains is recorded. Snow is recorded as present if 50% or more of the land within each altitudinal band is covered in snow. On days when the mountains are obscured by clouds the position of the snow line is interpolated from clear days before and after. Snow cover has an ephemeral and dynamic nature in Britain (Bell and Moore, 1999) with virtually all snow cover occurring during October–May. This study follows Harrison et al. (2001) in using the total days of snow cover between October and May as opposed to the duration of continuous snow cover at observation stations used in studies at higher altitudes or latitudes (Hantel et al., 2000; Beniston et al., 2003a). Snow cover may continue into the summer in discrete snow patches at sheltered, high-altitude locations where wind-blown snow accumulates (Watson et al., 1994). Late season snow cover records are therefore dependent on the presence and size of these snow patches.

A snow index was calculated for each month and October–May season by multiplying the number of days of snow cover

TABLE 1

Spearman's rank correlation coefficients between Ardtalnaig station and seven other nearby climate stations using monthly data for the period 1959–1999.

Station	Distance from Ardtalnaig (km)	Maximum temperature		Minimum temperature		Total precipitation	
		r_s	N	r_s	N	r_s	N
Dall Rannoch School	20.0	0.997	382	0.985	379	0.944	342
Drummond	25.8	0.995	353	0.994	354	0.915	358
Balquhidder	26.2	0.992	121	0.996	121	0.943	176
Faskally	29.8	0.995	486	0.990	487	0.886	452
Callander	32.6	0.994	225	0.988	224	0.882	217
Loch Venacher	34.7	0.995	212	0.989	213	0.894	451
Gleneagles	35.5	0.992	147	0.979	148	0.830	144

For all correlations: $P < 0.01$; N = number of months of data.

within each of the eight altitudinal bands by a number from 1 to 8. The weighting factor was a surrogate for the distance of each altitudinal band from the summit. Days with snow cover at 150 m were weighted by a factor of eight while days when snow only covered the highest peak (1200 m) were weighted by a factor of one. The resulting daily values were summed to give monthly and seasonal totals (snow indices). Months or seasons with a low average snowline were thus given a higher snow index than those in which the average snowline was higher.

Meteorological data were obtained from the British Atmospheric Data Centre (http://www.badc.nerc.ac.uk). The degree to which the Ardtalnaig observation station represented regional weather patterns was tested using correlations with monthly data from seven other stations within a 36 km radius. The correlations between winter weather conditions and the phase of the NAO were tested using NAO data from the Climatic Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm).

Surface-based air temperature lapse rates for the area were calculated using data from two automatic weather stations (at 673 and 310 m) in the Balquhidder experimental catchment (Johnson and Simpson, 1991), 30 km southwest of Ardtalnaig. These lapse rates were applied to the Ardtalnaig data in order to estimate air temperature at different altitudes in the study site. Pepin (2001), working in the Pennines of northern England, found that surface-based air temperature lapse rates calculated from a pair of weather stations agreed well with those calculated using data from 22 stations across the region.

Pearson's correlation and forward stepwise multiple regression were used to relate variations in total snow cover duration among years to winter (October–May) average meteorological conditions for the period October 1959 to May 2004. Forward stepwise multiple regression was used in order to assign variation in snow cover to the independent variables (Tabachnick and Fidell, 1996). Data from all available years of observations were used in order to capture as much variation in recent climate as possible. This allowed better projection of snow cover under future climate conditions based upon the empirical relationship.

The regression models formed the basis for projecting snow cover under climate change scenarios. The scenarios data were the result of climate change experiments conducted by the Hadley Centre for Climate Prediction and Research and were obtained from the United Kingdom Climate Impacts Programme (UKCIP; http://www.ukcip.org.uk). The experiments used a "double-nested" method in which output from the coupled ocean-atmosphere model, HadCM3, provided the boundary conditions to drive a high resolution model of the global atmosphere (HadAM3H), which in turn drove a high resolution (~50 km) regional model of the European atmosphere (HadRM3) (Hulme et al., 2002). HadCM3 has a stable and realistic present-day climate (Collins et al., 2001). HadRM3 provides a reasonable representation of the observed pattern of extreme rainfall over the U.K. (Ekstrom and Jones 2003). According to Hulme et al. (2002), "these models have a 20-year history of development [and] have been carefully analyzed and evaluated over many model generations." The UKCIP data have been used in a number of national and regional climate impact studies in the U.K. (e.g. Berry et al., 2005; McEvoy et al., 2006).

The scenarios are categorized according to time period—2011 to 2040 (labeled the 2020s), 2041 to 2070 (the 2050s), and 2071 to 2100 (the 2080s)—and IPCC greenhouse gas emissions scenario—B1 (labeled Low Emissions), B2 (Medium-Low Emissions), A2 (Medium-High Emissions), and A1F1 (High Emissions). The study area falls at the corner of four 50-km grid cells, with the Ardtalnaig observation station in the southwest cell. Each 50-km grid cell in the HadRM3 model uses the average characteristics of the terrain being represented. The four cells vary in terms of mean altitude (range: 202–619 m). Taking an average change scenario for the four cells might, therefore, be more appropriate than using the value from just the southwest cell. However, precipitation declines greatly from west to east across the region (simulated annual average precipitation: 262–59 mm) due to the influence of the mountainous terrain on moist westerly airflows. Therefore, climate change data for the station's grid cell and the cell to the north were averaged and then applied to the 1961–1990 mean monthly observations at the station to produce future climate change projections. The simulated 1961–1990 daily mean air temperature produced by the regional climate model differs from daily mean air temperature observed at climate stations (the average of the minimum and maximum thermometers); however, this error was assumed to be small relative to the climate change projections. Projected climate variables were used with the empirical snow-climate regression models to project future snow cover. Uncertainty in the empirical relationship between snow cover and climate was accounted for using standard errors for the regression model coefficients. However, the scientific uncertainty associated with using only one climate model (Hulme et al., 2002) was not considered in this analysis.

Habitat distribution maps for the nature reserve had been produced by a previous survey (Smith et al., 2003), which followed the methods of the National Vegetation Classification scheme for British plant communities (Rodwell, 1991a, 1991b, 1992, 1995). The distribution of the predominant snow-dependent community, *Nardus stricta–Carex bigelowii* grass-heath (coded as U7 by Rodwell, 1992), was extracted from a Geographical Information

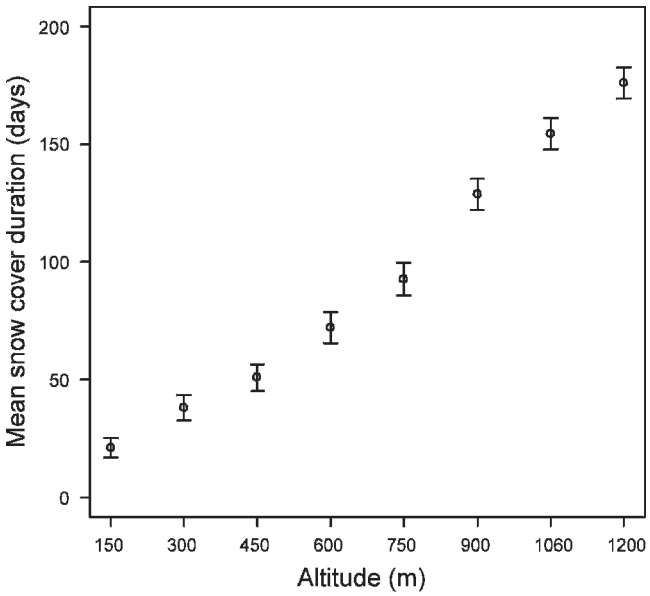

FIGURE 2. Mean and 95% confidence intervals of total snow cover days during October–May on the mountains surrounding Loch Tay, central Scotland, for the period 1954–2003.

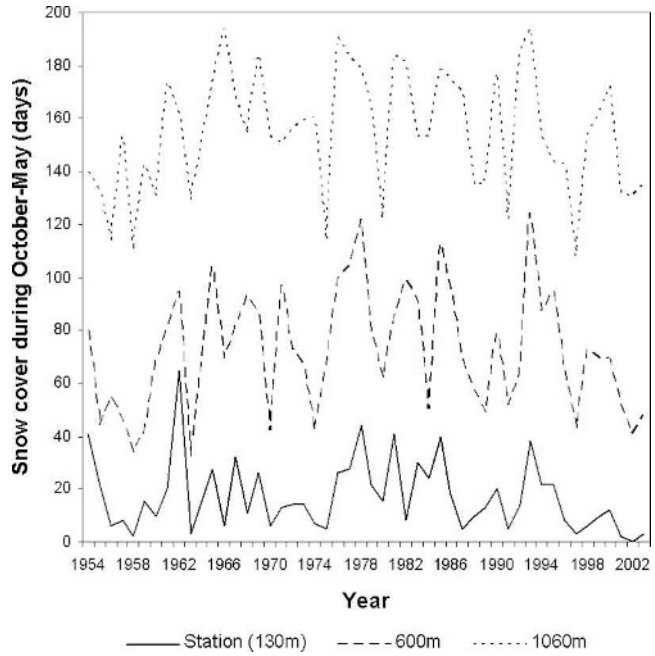

FIGURE 3. Time series of the total snow cover days during October–May at three altitudes in the mountains surrounding Loch Tay, central Scotland.

System (GIS). Polygons were amalgamated for its two subcommunities—Typical (U7b) and *Alchemilla alpina–Festuca ovina* (U7c)—covering 244 and 839 ha, respectively. Altitude data were extracted from a 50-m digital elevation model (DEM) of the area using IDRISI GIS. The presence/absence of the community along the altitudinal snow cover gradient was investigated using a generalized additive logistic model (GAM; Hastie and Tibshirani, 1990) in the R statistical environment (R Development Core Team, 2004). The model was trained on a random sample of 70% of GIS pixels and evaluated on the remainder. The empirical snow cover-climate model was then used to estimate future snow cover gradients using polynomial equations for snow cover duration in relation to altitude. The GAM was then run on these gradients to project the future locations of the community.

The current U.K. distribution of the grass-heath was digitized from a published map at 10-km grid resolution (Averis et al., 2004). The presence/absence of the community in the grid cells was modeled in relation to gridded climatic and soils data using a GAM. The five predictor variables used were (1) absolute minimum temperature over a 20 year period (T_{min}); (2) maximum annual temperature (T_{max}); (3) growing degree days above a 5 °C threshold (GDD); (4) accumulated annual soil moisture surplus (SMS); and (5) soil moisture deficit (SMD). These variables are thought to have direct physiological effects on plants and have been used in previous investigations of the potential effects of climate change on species distributions in the U.K. (Pearson et al., 2002). The model was trained on a random 70% subset of the data using a backward stepwise variable selection algorithm based upon Akaike's Information Criterion (Wintle et al., 2005). It was then run using the variables adjusted for the UKCIP scenarios of future climate.

Results

OBSERVED WEATHER AND SNOW COVER PATTERNS

There was a strong degree of correlation between Ardtalnaig and seven other climate observation stations within the region in terms of temperature maxima and minima and precipitation (Table 1). The degree of correlation of monthly precipitation amount declined with distance from the study site (Pearson's $r = -0.849$, $P = 0.016$, $N = 7$). It is, therefore, justifiable to use data from just the Ardtalnaig station to investigate the relationship between snow cover on the mountains and other weather variables.

During 1954–2003 mean snow cover duration from October to May on the mountains surrounding Ardtalnaig increased approximately linearly with altitude at 15 days 100 m^{-1} ($r^2 = 0.984$, $P < 0.005$; Fig. 2). Both October–May mean temperature and mean precipitation at Ardtalnaig station increased during the 1959–2003 period (correlation with year: $r = 0.43$, $P = 0.003$, and $r = 0.48$, $P = 0.001$, respectively). There was no trend in the number of days with snow falling at the station during 1954–2003 ($r = 0.03$). There was no long-term trend in snow cover across altitudes in the mountains over the same period (Fig. 3). However, considering the latter half of the time series, a declining trend in snow cover was detected, which was significant at three out of nine altitudes (Table 2).

At all altitudes the duration of snow cover was negatively correlated with the phase of the winter NAO (the mean index for December to March), significantly so at and below 300 m (Table 3). However, snowfall did not correlate with winter NAO while the snow index (a high index indicating a lower snow line) was only weakly negatively correlated with the NAO (Table 4). Snowfall and snow cover on the mountains (as measured by the snow index) were negatively correlated with winter temperature

TABLE 2

Pearson's correlation coefficients between total days of snow cover from October to May and year, for 1979–2003.

Altitude (m)	130 (station)	150	300	450	600	750	900	1060	1200
r	−0.55**	−0.44*	−0.38	−0.39	−0.37	−0.37	−0.42*	−0.32	−0.26

* $P < 0.05$, ** $P = 0.005$.

TABLE 3

Pearson's correlation coefficients between snow cover at increasing altitudes and the phase of the winter NAO index, for 1954–2003.

Altitude (m)	130 (station)	150	300	450	600	750	900	1060	1200
r	−0.32*	−0.36*	−0.28*	−0.18	−0.16	−0.19	−0.19	−0.11	−0.03

* $P < 0.05$.

but not correlated with precipitation. Winters with a high NAO index were associated with higher daily mean temperature, monthly precipitation, and mean wind speed at the station.

The residuals from linear regression models of snow cover on daily mean temperature at the station within each altitudinal band correlated with monthly mean precipitation (Fig. 4). Forward stepwise multiple regression using daily mean temperature and monthly mean precipitation as independent variables enabled the variation in snow cover at each altitude to be represented as a function of these two climate parameters (Table 5). Higher mean temperature resulted in less snow cover while higher precipitation resulted in greater snow cover at all altitudes, all relationships being highly significant. The regression coefficients show that the sensitivity of snow cover to these two variables increased with altitude, with the greatest sensitivity being at about 750 m. A rise in October–May daily mean temperature of 1°C above the long-term mean corresponded with declines in snow cover of c. 16 days at the station and c. 33 days at 750 m. A 100-mm increase in October–May mean monthly precipitation above the long-term mean corresponded with an increase of 16 days at the station and 41 days at 750 m.

The relationship between snow cover, altitude, and October–May daily mean air temperature can be illustrated by comparing snow cover in the warmest (>90-percentile: 1988, 1989, 1997, 2001) and coldest (<10-percentile: 1962, 1978, 1985, 1993) years from the 1959–2003 frequency distribution (Fig. 5). The increase in snow cover with altitude was linear in cold winters, but became non-linear in warm ones, due to the persistence of snow in late-lying snow patches. The greatest deflection from cold to warm winters was at around 750 m, the zone of greatest sensitivity of snow cover to climatic variation. Surface-based daily mean air temperature lapse rates have been calculated from the Balquhidder catchment. Temperatures during 1982–1992 at the Balquhidder climate observation station closely matched those at Ardtalnaig (temperature maxima: $r = 0.977$, $P < 0.005$; minima: $r = 0.969$, $P < 0.005$). Assuming that lapse rates do not vary between warm and cold winters, these can be applied to the Ardtalnaig air temperatures to produce estimates of the possible air temperatures experienced at each altitude (Fig. 6). In cold winters (December–February) daily mean air temperatures above 300 m would tend to fall below 0°C, whereas in warm winters mean air temperatures would fall below 0°C above about 750 m. It is, however, unlikely that lapse rates do not vary between warm and cold winters (Pepin, 2001), but the available high altitude temperature data set is not long enough for this to be tested.

FUTURE SNOW COVER PROJECTION

Future climate scenarios from the HadRM3 regional climate model can be represented as deviations from the 1961–1990 baseline climate (Fig. 7). Monthly mean precipitation during the October–May period is projected to increase slightly, but this increase is small relative to the interannual variation observed at Ardtalnaig in the 1959–2003 period. Daily mean air temperature, however, is projected to exceed observed 1961–1990 conditions by the 2050s under the High Emissions scenario. The range of snow cover projections produced by using these climate scenarios in the empirical snow-climate relationship are illustrated in Figure 8 and, for the 2050s, are given in Table 6. Snow cover is projected to decline at all altitudes under all climate scenarios. Under a High scenario there may be no snow cover below 900 m by the 2080s.

SNOW-BED PLANT COMMUNITY DISTRIBUTION

Local Scale

The distribution of *Nardus stricta–Carex bigelowii* grass-heath within the nature reserve was analyzed with respect to the altitudinal snow cover gradient using a GAM with 3 degrees of freedom. The area under the receiver operating characteristic curve (AUC) was 0.95, indicating good model discrimination between presence and absence sites. The community is most common between approximately 800 and 1000 m and reaches its greatest extent at 900 m (Fig. 9). In the future, the projected distribution pattern shifts upwards as snow cover declines, with the optimal occurrence at 1100–1200 m, i.e. the summits.

National Scale

The projected future climate of the 10-km cells which are currently suitable for the community does not go beyond the range of climates currently observed in the U.K., i.e. future projections were not made beyond the range of the training data. Figure 10 presents the current observed and simulated distribution of the grass-heath in the U.K. The simulated distribution was given by a GAM with a maximum of three smoothing splines, which included T_{max}, GDD, and SMS; however, the T_{max} term was only

TABLE 4

Pearson's correlation coefficients for mean October–May climate parameters for 1959–2003.

	NAO	Temperature	Precipitation	Wind speed	Sunshine	Snowfall
Winter (DJFM) NAO index						
Daily mean temperature	0.48**					
Monthly mean precipitation	0.63**	0.40**				
Wind speed[a]	0.86**	0.33	0.80**			
Sunshine duration (hours)[b]	−0.07	0.01	−0.26	0.01		
Snowfall at station (days)	−0.10	−0.70**	0.01	−0.14	−0.12	
Snow Index	−0.24	−0.84**	−0.04	−0.22	−0.12	0.84**

[a] Based on 16 years of data.
[b] Based on 27 years of data.
** $P < 0.005$.

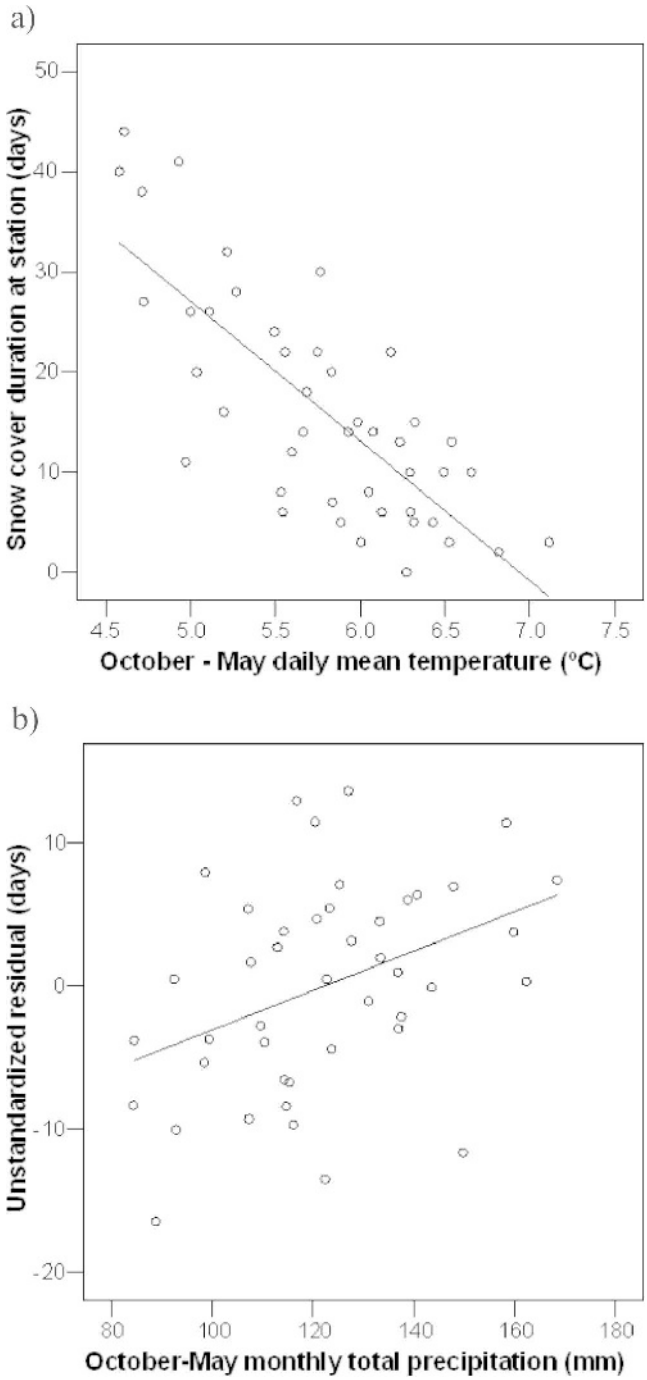

FIGURE 4. (a) The relationship between daily mean temperature during October–May and the duration of snow cover at Ardtalnaig station, 130 m; linear regression: $r^2 = 0.59$, $P < 0.001$, $N = 44$. (b) The relationship between October–May monthly total precipitation and residuals from the regression of snow cover on temperature; linear regression: $r^2 = 0.16$, $P = 0.008$, $N = 44$.

marginally significant. The distribution of the community was negatively related to growing season temperature variables and positively related to the soil moisture. The model had a high level of discrimination between presence and absence sites (AUC = 0.97). Although the model tended to overestimate the current distribution it was well calibrated (Miller's calibration slope = 1.03; Wintle et al., 2005). The future suitable climate space indicated a contraction of range in the 2050s (Figs. 10c and 10d). Of the 153 10-km grid cells currently occupied, 42 (27%) became unsuitable under the Low emissions scenario, and 80 (52%) became unsuitable under the High scenario. At the extent of the study site, all four of the 10-km grid cells encompassing the site had predicted current suitable climate space, agreeing with the observations. Projecting into the 2050s, one square lost suitable climate space under the Low scenario, while all four were unsuitable under the High scenario (Fig. 10).

Discussion

The modeling of both past and potential future snow cover duration has been based upon weather records from one climate station, Ardtalnaig, which is north-facing and close to the thermal reservoir of Loch Tay. Analysis shows, however, that Ardtalnaig is climatically representative of the region and provides the best prediction of the observed variation in snow cover on the nearby mountain range.

Total seasonal snow cover increases linearly with altitude by 15 days 100 m^{-1} (Fig. 3), agreeing with the estimate of 15–20 days 100 m^{-1} for Scotland (Harrison, 1997).

The interannual variation in snow cover is primarily controlled by temperature as shown in previous studies (Beniston, 1997; Hantel et al., 2000; Harrison et al., 2001). Among winters of a particular temperature mode (e.g. warm winters), precipitation modifies snow cover duration, as observed in the Alps (Beniston et al., 2003b). Thus a warm, wet winter has greater snow cover than a warm, dry one. Since the 1970s, the NAO has tended to be in its positive phase (Hurrell et al., 2001), associated with an increase in westerly airflow over Scotland, bringing warm, wet weather in the winter (Mayes, 1996; Harrison, 1997). This has been associated with a decline in snow cover in the study area (Table 2), particularly at low altitudes, which agrees with the findings of Harrison et al. (2001). The increased precipitation in warm years has not resulted in greater snow cover at higher altitudes compared with cold years, in contrast with patterns observed above 400 m in Norway (Mysterud et al., 2000) and 2000 m in the Swiss Alps (Beniston et al., 2003a), implying that the mountains of central Scotland are neither cold enough nor high enough for this to occur.

Variations in temperature and precipitation have increasing effects on total snow cover duration as altitude increases up to c. 750 m and then the sensitivity to climate diminishes with altitude. In contrast, Harrison et al. (2001) found the most sensitive altitude to be 400 ± 100 m. They primarily used data from a number of climate stations below 400 m as well as data on ski lift operations above 700 m. The difference in approach by the two studies may explain the difference in the estimate of the zone of maximum climatic sensitivity. In the Alps the position of the snow line is most sensitive to climatic variability below 2500–3000 m according to research using remote sensing (Wunderle et al., 2002, *cited in* Beniston et al., 2003b), while modeling has shown that snow duration in the French Alps is most sensitive to temperature variation below 2000 m (Martin and Durand, 1998).

Estimates of the potential air temperatures at different altitudes suggest a reason for the zone of greatest climatic sensitivity to occur at c. 750 m. Surface-based air temperature lapse rates were calculated using data from two weather stations at Balquhidder, 30 km from the site. The annual mean lapse rate of 7.4°C km^{-1} broadly agrees with results from previous studies in Britain (Harding, 1978; Harrison, 1994; Pepin, 2001). Applying a lapse rate to the winter (December–February) daily mean air temperature at Ardtalnaig indicates that the maximum altitude at which winter temperatures reach above freezing point in warm years is at c. 750 m. This freezing point threshold may determine

TABLE 5

Coefficients and constants from multiple linear regressions of October–May snow cover on daily mean temperature (α) and monthly mean precipitation (β) at different altitudes for the period 1959–2003.

	α	β	Constant	Adjusted r^2	F
Snowfall at station[a]	−15.38 ± 1.83	0.19 ± 0.05	96.56 ± 10.10	0.62	35.36
Snow cover at:					
Station 130 m[a]	−15.86 ± 1.75	0.16 ± 0.05	88.46 ± 9.89	0.65	41.00
150 m[a]	−17.07 ± 2.16	0.16 ± 0.07[b]	100.21 ± 12.18	0.59	31.44
300 m	−23.97 ± 2.50	0.23 ± 0.08[b]	149.91 ± 13.77	0.67	46.51
450 m	−26.58 ± 2.98	0.29 ± 0.09	169.88 ± 16.41	0.64	39.95
600 m	−30.70 ± 3.42	0.41 ± 0.11	201.09 ± 18.81	0.64	40.44
750 m	−33.12 ± 3.86	0.41 ± 0.12	234.37 ± 21.27	0.62	36.80
900 m	−31.59 ± 3.52	0.40 ± 0.11	264.01 ± 19.42	0.64	40.16
1060 m	−29.18 ± 3.47	0.40 ± 0.11	276.29 ± 19.09	0.61	35.50
1200 m	−23.70 ± 4.03	0.36 ± 0.13[b]	271.53 ± 22.22	0.43	17.41

For all models $P < 0.005$; and for all coefficients $P < 0.005$, except[b].

[a] The unusually severe winter of 1962/1963 was removed as an outlier: Cook's distance, $D = 0.71$.

[b] $P < 0.05$.

the altitude of greatest sensitivity of snow cover to climatic variability, which in previous warm winters has resulted in a non-linear increase in snow cover with altitude (Fig. 5). Above c. 750 m temperature variation among years has less effect on snow cover duration, perhaps because the temperature remains below freezing point. An alternative explanation could be that high altitude snow patches created by drifting snow resist melting and persist longer, reducing the sensitivity of snow cover duration to climate. Both of these effects may act to maintain snow above about 750 m.

This study has attempted to project the potential future duration of snow cover under different scenarios of climate change based upon the relationship between snow cover and climate observed over the last 45 years. The HadRM3 regional climate model projects that October–May mean temperature and precipitation will both increase under all scenarios of greenhouse gas emissions, with temperature increasing proportionately more than precipitation. The empirical snow-climate model projects a decrease in snow cover under all scenarios (Fig. 8, Table 6). Under a High Emissions scenario in the 2080s (2071–2100), snow cover may be completely absent from altitudes below 900 m.

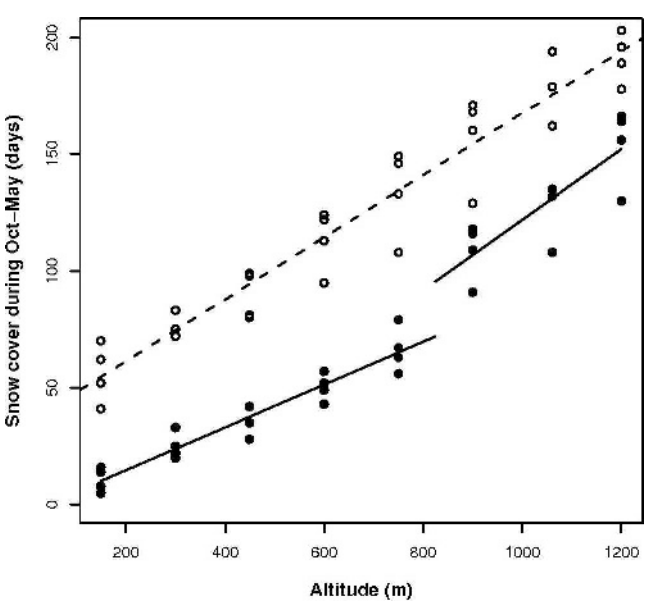

FIGURE 5. Snow cover duration in warm (closed circles) and cold (open circles) years from the 1959–2003 period. Dashed trend line for cold years: $r^2 = 0.94$; solid trend lines for warm years: 150–750 m, $r^2 = 0.92$; 900–1200 m, $r^2 = 0.69$.

The more persistent nature of snow cover above 750 m results in the presence of the *Nardus stricta–Carex bigelowii* (U7) grass-heath community above this altitude. This community contains rare bryophytes and lichens and falls within the 'siliceous alpine and boreal grasslands' habitat, which is considered to be in need of conservation at the European level (JNCC, 2004). Similar vegetation occurs in western Scandinavia and the Faroes (Averis et al., 2004). The projected decline in snow cover at high altitudes at this site indicates that late-lying snow may not occur as frequently in the future. This results in a projected upward shift in peak occurrence of snow-bed vegetation from 900 m to the summits of the mountains, above 1000 m (Fig. 9). However, the modeling approach taken did not include the effects of wind exposure, which results in removal of snow from the summits. Therefore, the summits are unlikely to be suitable for snow-bed communities in the future. Furthermore, the reduction in land area as altitude increases means that the potential areal extent of habitat will decline. Thus, the future potential distribution of snow-bed vegetation is more likely approximated by the area of overlap between the current distribution curve and future curves.

The distribution model for the grass-heath community created at a coarse (10 km) scale was not based directly on snow cover duration. The most important factors correlated with the occurrence of the community were GDD (negatively) and SMS (positively), with T_{max} a lesser factor. Snow cover duration and the length of the growing season are correlated and so the inclusion of GDD in the model would be expected. Also, the high winter precipitation in montane regions in the U.K. would result in a large soil moisture surplus. The vegetation is characterized by being saturated by meltwater in spring and early summer (Averis et al., 2004). It is interesting that T_{min} was not found to be an important variable. This could be an artifact of the correlation between the three temperature input variables. Alternatively, it might be related to the insulating effect of snow cover against subzero winter air temperatures. The coarse scale model projects the loss of between a quarter and a half of this community's suitable climate space across the U.K. in the 2050s (Fig. 10). This result at the national scale supports the local findings.

Species respond individualistically to climate change (Huntley, 1999) and so modeling the distribution of a plant community

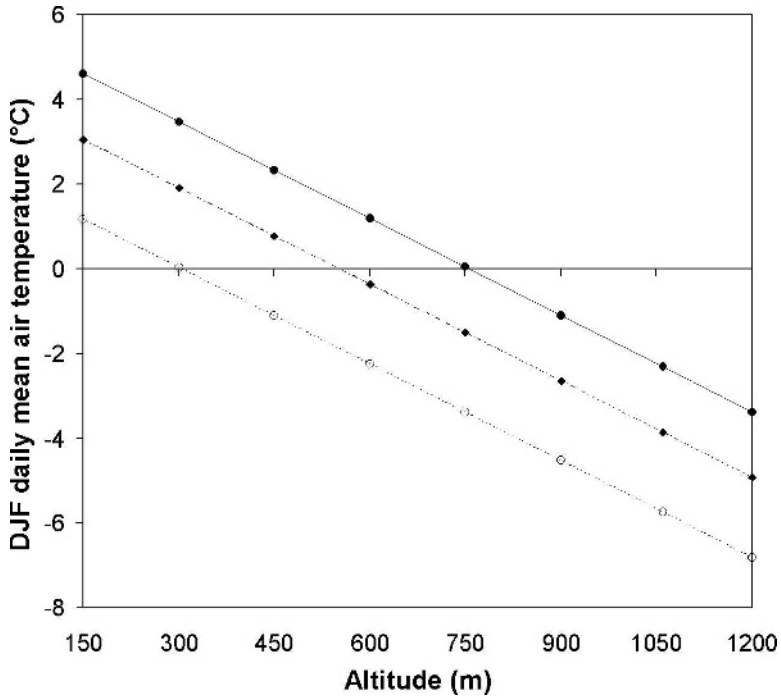

FIGURE 6. Predicted December–February daily mean air temperature at different altitudes in warm (closed circles) and cold (open circles) winters compared to the 1961–1990 mean (closed diamonds), based upon December–February mean lapse rates from Balquhidder.

as a single entity, as in this study, may not give accurate predictions. Future changes may entail increased abundance of species favored by reduced snow cover (Keller et al., 2005) and invasion of snow-bed communities by more competitive species from lower altitudes (Callaway et al., 2002), eventually resulting in a shift in community composition (Heegaard and Vandvik, 2004), perhaps to a sward more dominated by low shrubs such as *Calluna vulgaris* and *Vaccinium myrtillus*. Another possibility is that the tussocks of *Nardus stricta* will thicken up, making establishment by other species harder (A. Averis, personal communication). These changes could adversely affect the rare species found in this community.

Snow records used in this study came from the Snow Survey of Great Britain. This is a subjective measure of snow cover averaged over several mountains at each site and suffers at the daily scale from the problem of low clouds obscuring the mountains from the observer's view. This study used data recorded by the same observer over a 50-year period and so avoided the problem associated with changes of observer, which may have occurred at other sites. However, the strength of the Snow Survey is its spatial scale, encompassing many of Britain's mountain areas. It would be informative to carry out a study on a larger set of Snow Survey sites, thereby incorporating wider climatic variability, in order to make more accurate projections of snow cover change using a temperature-precipitation matrix similar to that suggested by Beniston et al. (2003a). This might shed further light on the variability in the position of the zone of greatest climate sensitivity and the effect of increasing precipitation at higher altitudes.

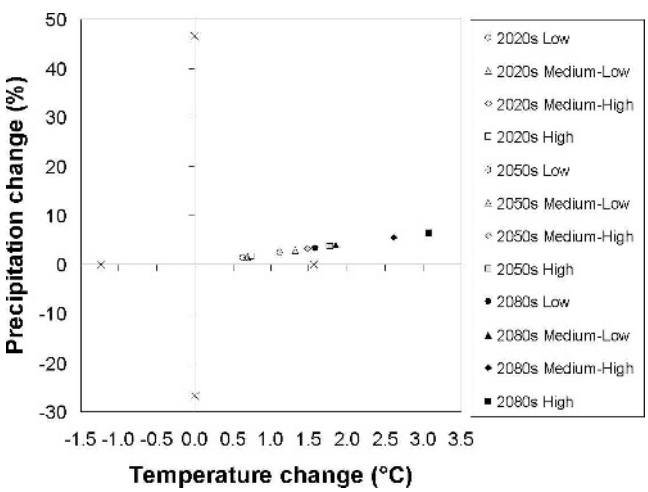

FIGURE 7. Projected change in October–May monthly mean precipitation and daily mean temperature from the 1961–1990 mean for Ardtalnaig station, based upon HadRM3 model output. Observed 1961–1990 mean lies at the origin, and 1959–2003 minima and maxima are represented by crosses on the axes.

The Snow Survey does not specifically measure snow patches, but they are included in the overall estimates of snow cover. Specific predictions for snow patches are difficult since the vegetation cover, slope, aspect and shelter of the terrain affect the degree of insolation and exposure to wind, which in turn influence the duration of snow patches at local scales (Watson et al., 2002; Geddes et al., 2005). At such a fine scale, further accuracy would be achieved by using physically-based snow-melt models coupled with information on species' responses (e.g. Keller et al., 2005), but this depends upon detailed weather, topographic and spatial snow cover data as well as knowledge of the physiological responses of alpine plants to changes in snow cover duration. Unfortunately, no measurements of snow depth and weather at different altitudes and exposures existed for this site. It would, therefore, have been difficult to parameterize and test

TABLE 6

Projected percentage reduction in snow cover duration under different climate change scenarios for the period 2041–2070.

	Emissions scenarios			
Altitude (m)	Low	Medium-Low	Medium-High	High
130 (station)	93	100	100	100
600	43	51	57	68
1060	21	24	27	32

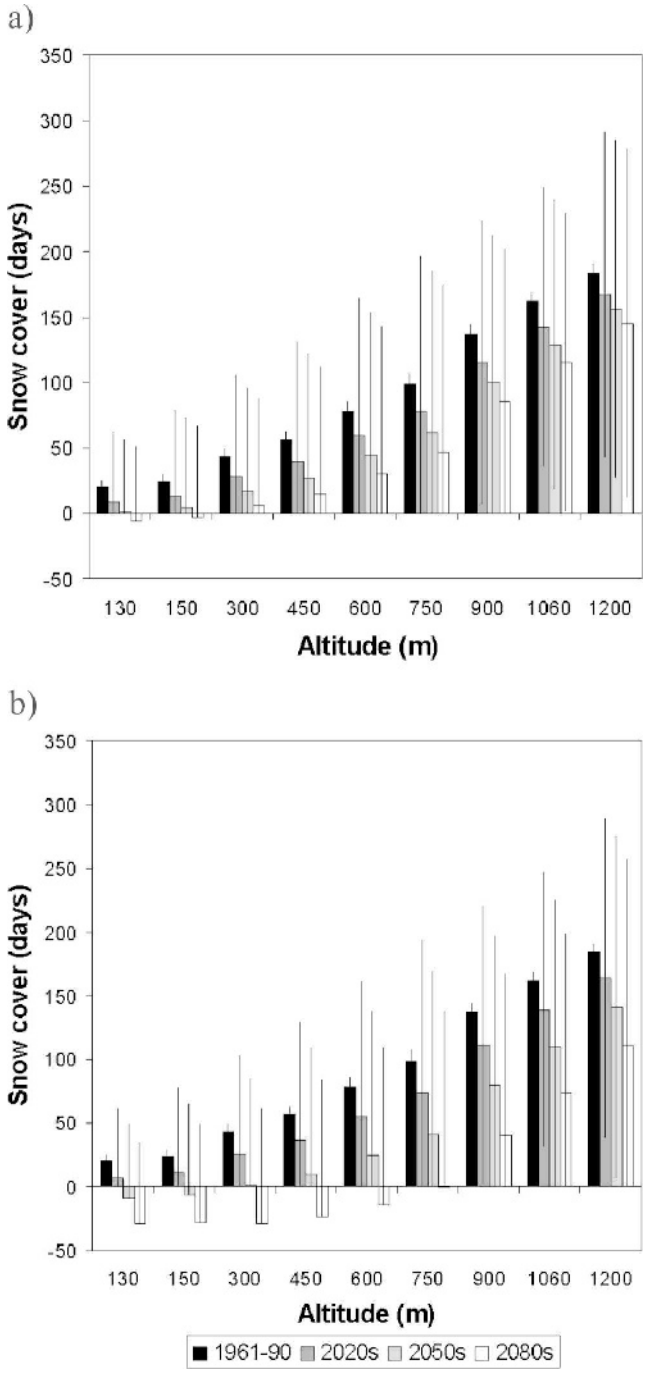

FIGURE 8. Observed snow cover duration and projections for the 2020s, 2050s, and 2080s under two greenhouse gas emissions scenarios: (a) Low and (b) High. Negative values for snow cover have been left in, but equate to zero days. Error bars represent error in the observed snow-climate relationship.

a physically based snow model. This study aimed to estimate the effect of climate change on the duration of snow cover at the scale of an entire nature reserve. The Snow Survey records provided a valuable source of information at the correct scale for this purpose.

Conclusions

Analysis of a 50-year observational record of daily winter-season snow cover on mountains in Central Scotland shows that

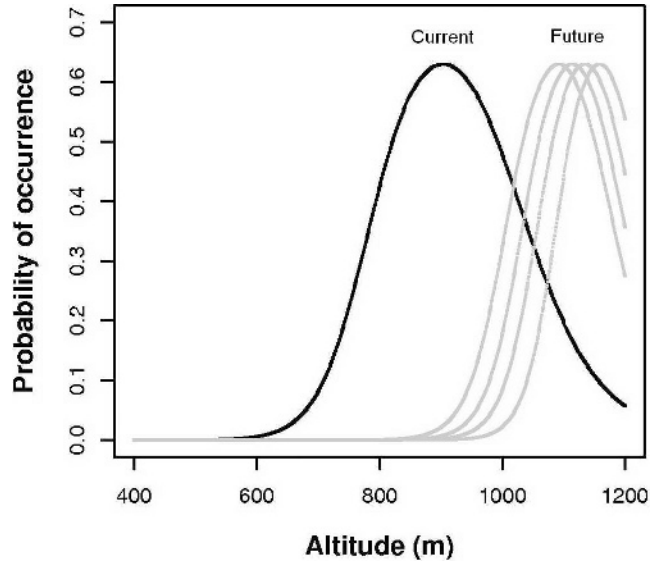

FIGURE 9. Observed current (black dots) and potential future (gray dots) distribution of *Nardus stricta–Carex bigelowii* grass-heath along an altitudinal gradient. Curves are fitted to observed presence/absence data using a GAM. Future curves are projected for the 2050s, from left to right: Low, Medium-Low, Medium-High, and High Emissions scenarios.

snow cover at low altitudes has declined, reflecting previous research at a national scale (Harrison et al., 2001). Projection of an empirical snow-climate model into the future shows that some snow cover will be lost at all altitudes under all future climate change scenarios for the U.K. The natural treeline at this site falls between approximately 600 and 650 m (D. Mardon, personal communication), above which occur arctic-alpine plant communities of national and international importance (Ratcliffe, 1977; JNCC, 2004), which can be strongly influenced by the duration of snow cover (Körner, 1999). Some plants are adapted to live in persistent snow patches (Körner, 1999). A decrease in snow cover at upper altitudes, as our results indicate, could therefore have a significant impact on these plant communities. This research has not looked specifically at snow patches. However, snow patches in this region are less abundant after warm winters and springs (Watson et al., 1994). Therefore, our projected overall declines in snow cover at all altitudes under climate change would imply reduced snow patch duration and size.

Further research using data from other Snow Survey of Great Britain sites as well as more detailed data on snow patches and their associated vegetation is warranted by our finding that snow cover at upper altitudes, at least in this region, appears more sensitive to climate change than previously suggested, with potentially significant impacts on habitats of high conservation interest.

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FIGURE 10. (a) Observed distribution of *Nardus stricta–Carex bigelowii* grass-heath (Averis et al., 2004). (b) Current suitable climate space. (c and d) Projected suitable climate space under 2050s Low and High scenarios, respectively.

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