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Glacier development and topographic context

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Abstract

This paper analyses the topographic context of the remaining glaciated areas in the Maladeta Massif (Central Spanish Pyrenees). These ice-covered surfaces have been incorporated into a geographic information system (GIS) in an attempt at correlating the presence of ice with a range of topographic variables obtained from a digital elevation model. The use of generalized additive models and binary regression tree models enabled us (i) to quantify the spatial variability in the distribution of glaciers attributable to characteristics of the local terrain, (ii) to investigate the interaction between the variables that account for the ice cover distribution and (iii) to map the probability of glacier development. Our results show that although the development of glaciers depends on regional climate conditions, the topographic context is of paramount importance in determining the location, extent, shape and recent evolution of each glacial body. Thus, the joint effect of altitude, exposure to incoming solar radiation, slope and mean curvature is able to explain more than 70 per cent of the observed variance. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: glaciers; topographic context; generalized additive models; binary regression tree models; Maladeta Massif; Central Spanish Pyrenees

Introduction

Glaciers, especially smaller ice bodies, respond rapidly to slight oscillations in precipitation and temperature (Nesje and Dahl, 2000; Carrivick and Brewer, 2004). Thus, monitoring the evolution of glaciers provides useful information for researchers examining climate variability and change. The presence of a glacier depends on the snow accumulation-melt balance, which is related to the regional climate characteristics that control precipitation and temperature (in particular, latitude and air masses). However, local topography has considerable importance for the development of ice bodies at this more local scale and it is this that accounts for noticeable variations in the equilibrium line altitudes (ELAs) of different glaciers in the same region (Brozovic *et al*., 1997; Reinwarth and Escher-Vetter, 1999; Benn and Lehmkuhl, 2000; Carrivick and Brewer, 2004). In areas where the conditions for the presence of glaciers are particularly restrictive, small differences in topography account for (i) the presence or absence of small glaciers and (ii) their evolution (Allen, 1998; Kaser *et al*., 2004). A better understanding of how climate characteristics at the regional scale are modified by the topographic context is needed in order to improve the interpretation of the impact of climate variability on glacier evolution in a given area.

Here, we assess the way in which topographic conditions affect glacier development, using as an example the ice masses in the Maladeta Massif in the Spanish Pyrenees, where the southernmost cases of active glacial bodies in Europe are to be found. The extent of ice masses in this area has progressively decreased since the end of the Little Ice Age (LIA), when ice covered approximately 2000 ha. In recent decades, glacier shrinkage has accelerated as a consequence of climate evolution (Chueca *et al*., 2004). Today, glaciers remain as a residual phenomenon (554 ha) distributed in ten sectors of the Pyrenees. Of these, the Maladeta Massif has the largest ice-covered surface, with

12 glaciers or glacierettes that vary greatly in surface area, shape and level of conservation. It would appear that such heterogeneity reflects the particular terrain characteristics of each glacial cirque. The aims of this study are (i) to analyse the influence of terrain characteristics on the current presence of ice covered areas (glaciers or glacierettes) and (ii) to obtain probability maps of ice cover in the study area using two non-linear regression models. The probability maps enable us to assess the robustness of the response of the glaciers to the predictor variables introduced by the models and should be useful in estimating the conditions of conservation of the glacial bodies and their future evolution.

Study Area

The Maladeta Massif is the highest sector in the Central Spanish Pyrenees (Figure 1). It is formed from the crystalline rocks of the Maladeta batholith, which extends in an E–W direction. The massive nature and resistance of the granite and granodiorite materials give the area its particular morphology and are responsible for altitudes that rise well over 3000 m a.s.l. (Aneto, 3404 m; Maladeta, 3308 m, Tempestades, 3290 m; Alba peak, 3118 m).

Although the glaciers in this area have recorded a noticeable shrinkage since the LIA (Chueca *et al*., 2003, 2005), 197 ha still remain covered by ice, forming the largest glacial complex in the Pyrenees. The glaciated surface comprises the following 12 glaciers or glacierettes: Western (6·1 ha) and Eastern (48·4 ha) Maladeta glaciers, Aneto glacier (90·4 ha), Barrancs glacier (10·8 ha), the Western Tempestades glacier (14·3 ha), the Central (7·0 ha) and Eastern (2·1 ha) Tempestades glacierettes, the Coronas glacier (3·0 ha), the Western (6·5 ha) and Eastern (5·6 ha) Salenques glacierettes, and the small Alba (1·1 ha) and Cregüeña (1·9 ha) glacierettes.

The extent of the glacial phenomena in this area is attributable to the fact that (i) a considerable surface area is located around the 0 °C annual isotherm altitude, usually related to the location of the regional ELA – for the study area this isotherm has been estimated (by linear regression between altitude and mean temperatures of neighbouring observatories) at around 3000 m a.s.l. (Chueca and Julián, 2004), (ii) the disposition of the massif (NW–SE) facilitates the presence of a large surface exposed to the NE (this orientation has been considered as being prone to the development of glacial activity in the Pyrenees (García-Ruiz *et al*., 2000)) and (iii) the glaciated area stands out above the surrounding relief features. This accounts for a high annual precipitation, especially on the leeward slopes of the NW–SE axis. Rijckborst (1967) estimated that, at the altitude of these glaciers, precipitation exceeded 2500 mm,

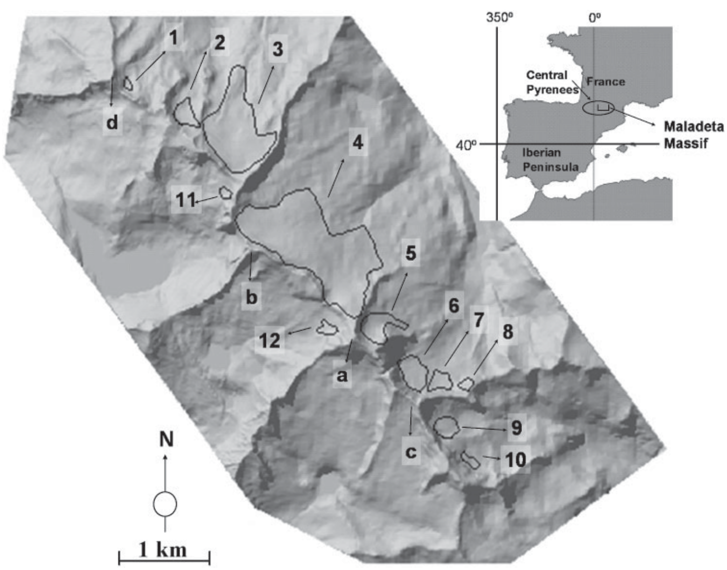

Figure 1. Study area. (a) Aneto peak, (b) Maldito peak, (c) Salenques peak, (d) Alba peak. (1) Alba glacierette, (2/3) Western–Eastern Maladeta glaciers, (4) Aneto glacier, (5) Barrancs glacier, (6) Western Tempestades Glacier, (7/8) Central–Eastern Tempestades glacierettes, (9/10) Western–Eastern Salenques glacierettes, (11) Cregüeña glacierette, (12) Coronas glacierette.

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and during December, February and April up to 400 cm of snow accumulated. These data point to the magnitude of the snow accumulation processes that usually occur from October to June.

Methods

Data

The glaciated surfaces were mapped from an aerial photography survey carried out by the *Gobierno de Aragón* between 1997 and 2000 (D.G.A. flight, approximate scale 1:20 000, colour). This information has been supplemented with photographs obtained from the project *Estudio de la dinámica de los glaciares del Pirineo aragonés* [*A Study of the Dynamics of the Aragonese Pyrenean Glaciers*] (Julián *et al*., 2001).

A 10 m cell-size digital elevation model (DEM; scale 1:10 000) was used. It was obtained from digital altitudinal data (Mapa Topográfico Nacional Series, sheet 180-I-II, scale 1:25 000; 10 m contour line equidistance). This enabled us to obtain detailed information about the relief of the study area. The topographical variables considered in this study were derived from the DEM and include (i) altitude (ALT); (ii) slope (S), (iii) mean curvature (MC) and (iv) mean annual radiation (AR). These variables were selected as they are widely considered as being the most significant in accounting for glacier development and/or the altitude of the ELA (Allen, 1998; Carrivick and Brewer, 2004; Chueca and Julián, 2004). Additional predictor variables, including planar and profile curvatures and mean solar radiation during summer, were also obtained. However, these are not discussed below given that, after a backward selection procedure (see Wood and Augustin, 2002), they were found to be poor indicators of glacial development. Digital coverage of annual mean incoming solar radiation under clear sky conditions was created using a MiraMon geographic information system (GIS) (Pons, 1998) in line with Pons (1996). This method considers the effect of terrain complexity (shadowing and reflection), the trajectory of the sun throughout the day (hourly), the earth–sun distance (monthly), atmospheric extinction and daily solar position. In contrast with other studies (Allen, 1998; Anderton *et al*., 2004), we did not introduce modelled exposed/sheltered areas as predictor variables since in this area there is no clear wind pattern.

Statistical approaches

In this study a generalized additive model (GAM) and a binary regression tree model were used to investigate the relation between topographic context and the presence of glacial ice. Both provide information about the non-linear relationship between the predictor variables and the presence of ice. In addition, they allow us to draw probability maps of glacier development.

GAMs (Hastie and Tibshirani, 1987; Guisan and Zimmerman, 2000; Wood and Augustin, 2002) are a regression technique that supports non-Gaussian error distributions and non-linear relationships between predictor and response variables. In this case, the response variable is binomial, stressing the presence or otherwise of ice cover. GAMs are extensions of linear model regressions that apply non-parametric smoothers to each predictor and additively calculate the component response.

A GAM is expressed by

$$g(E(Y)) = \alpha + s_1(X_{1i}) + s_2(X_{2i}) + \ldots + s_p(X_{pi})$$

where g is the link function that relates the linear predictor with the expected value of the response variable Y, X_{pi} is a predictor variable and s_p a smoothing function. The splines used to relate each environmental variable to glacier presence were simplified to reduce the complexity of the adjusted splines (Wood and Augustin, 2002). A logistic link function was used to relate response and predictor variables. To evaluate the relative role of each predictor variable in the final model, the change in total deviance explained was calculated when each term was dropped (Wood and Augustin, 2002).

Binary regression tree models are non-parametric methods based on the recursive splitting of the information from the predictor variables in order to minimize the sum of the squared residuals obtained in each group (Breiman *et al*., 1984). To apply a regression tree model, the size of the tree must first be selected since fitted trees may be more complex than is warranted by the data available (Anderton *et al*., 2004). An excessive number of nodes hinders the environmental interpretability of data splits. Here, we considered that the inclusion of a new node should contribute to a reduction in unexplained variance by at least 5 per cent. Regression Tree Models also provide an alternative to the assumption of linearity in relationships between the response variable and the physical characteristics of the terrain (Elder *et al*., 1998; Erxleben *et al*., 2002; Anderton *et al*., 2004; Molotch *et al*., 2005).

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Validation procedure and accuracy estimation

The following procedure was adopted in order to ensure that the models obtained were not over-fitted. First, 10 per cent of the cells were randomly extracted from the whole of the study area. Then, we split the data in two groups: the first (70 per cent of the sample) was used to calibrate the model, while the second (30 per cent of the sample) was used to validate it (Guisan and Zimmermann, 2000). Continuous probability maps were obtained after applying the statistical models obtained in the calibration process to the whole area. Kappa values, K, were used to assess the predictive capacity of the models. The kappa statistic allows the evaluation of model efficacy by assessing the extent to which models predict occurrences that are better than chance occurrences (Fielding and Bell, 1997; Manel *et al.*, 2001). For example, a kappa of 0·85 means there is 85 per cent better agreement than by chance alone. Kappa values are drawn from a confusion matrix obtained from the validation data set. The confusion matrix contains information about observed and predicted of glaciers presence or absence done by a classification system. Kappa values can then be categorized as predicted and observed, not predicted and not observed, not predicted but observed and not observed and not predicted classes (Fielding and Bell, 1997). Different threshold probabilities to obtain kappa values (0·1, 0·2, 0·3, 0·4, 0·5, 0·6, 0·7, 0·8 and 0·9) were used in order to obtain a more robust validation and to avoid problems such as prevalence (Forbes, 1995). Kappa values vary between 0 and 1. K values $< 0{\cdot}4$ are considered as being poor; $0{\cdot}4 < K < 0{\cdot}75$ are accepted as being good, while K values $> 0{\cdot}75$ are excellent (Landis and Koch, 1997).

Results

Relationship between topographic variables and ice cover

Table I shows the fall in variance (per cent) as each predictor variable was omitted in turn from the GAM that included the other three predictor variables. 72·99 per cent of the variance was explained when the four predictor variables were included in the model. Altitude (ALT) was the variable that contributed most in explaining the presence of ice cover, with a fall of (51·4 per cent) when it was removed from the model. Solar radiation (AR), slope (S) and mean curvature (MC) represented 30·2 per cent, 16·6 per cent and 11·7 per cent respectively of the explanation of variance.

Figure 2 shows the response curves of each topographical variable to the presence of glacial ice provided by the GAM. The plots show the smoothed predictor variable values on the X axis against the partial residuals on the Y axis, illustrating the nature of the relationship between the predictor and the residualized dependent variable values. The Y axis shows the name of the dependent variable with the degrees of freedom of the spline, indicating their degree of complexity.

The probability of glacier development increased noticeably with altitude (ALT). The smoothed line exhibits a threshold above 3200 m a.s.l., which implies an inversion in the tendency, with probability falling after this point. Solar radiation showed a negative relationship with the probability of the presence of ice. As annual incident radiation (AR) increased, the probability of ice cover fell slowly until a threshold of around 2000 MJ m^{-2} day^{-1} was reached. Annual radiation (AR) above this value brought about a marked acceleration in the fall in probability. Slope was also found to be an important factor in explaining the presence of ice cover. Probability remained relatively high in places with a slope (S) between 0 and 30°, reaching a maximum probability in areas with a slope around 20°. Steeper slopes than these tended to be less favourable for the development of glaciers. Finally, concave or plane areas were found to be suitable for the presence of ice cover. Probability fell rapidly when the cells presented positive values, i.e. convex places, and, thus, the lowest levels of probability of glacier development in the massif were recorded in these sectors.

Table I. Reduction of the explained variance when each predictor variable is removed from the model

Variables	Percentage of explained variance
All predictor Variables used	72·9
MC removed from the model	61·3
S removed from the model	56·4
AR removed from the model	42·7
ALT removed from the model	21·6

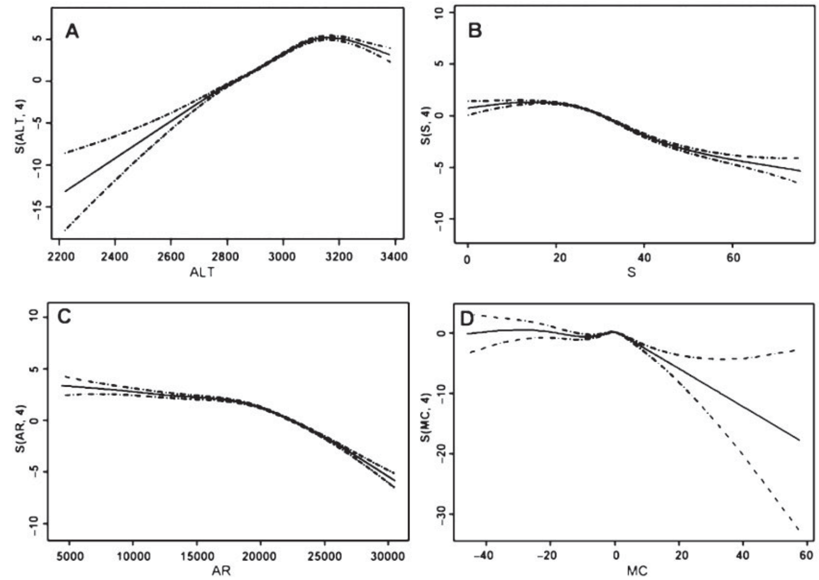

Figure 2. Response curves of the topographic variables to the probability of ice cover existence. (A) Altitude, (B) slope, (C) mean annual radiation, (D) curvature. Dotted lines represent the confidence intervals.

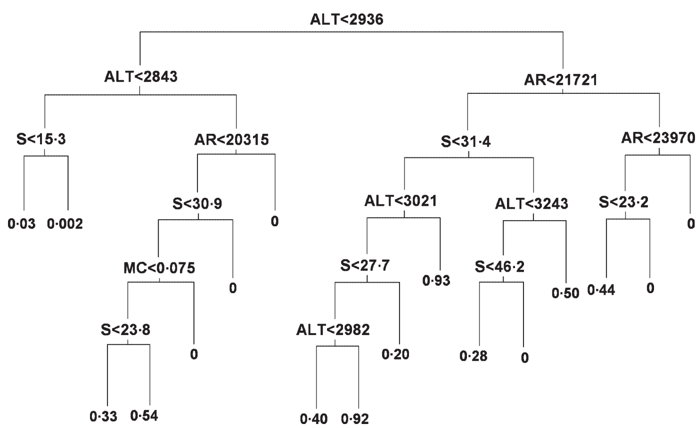

Figure 3. Regression tree model. Right branches group the cases that exceed the splitting thresolds. Left branches group the cases that are below the thresholds. Terminal nodes indicate the probability of ice cover.

However, the low frequency of places with high mean curvature (MC) values resulted in confidence intervals that point to a high degree of uncertainty in the response curve.

The regression tree (Figure 3) shows how the combination of the four terrain variables generated 17 different environments (each node) to explain the variance in glacier distribution. The role of each variable in the occurrence of glacial ice agrees with the response shown by the smoothed lines provided by the GAM.

The first split distinguishes between sectors located above and below 2936 m a.s.l. According to the following splits, below that altitude only the plane or concave cells (MC < 0·075) that received low incident radiation (20 315 MJ m^{-2} day^{-1}) and that presented a slope lower than 30·9° had a probability of being covered with glacial ice: 0·54 where the slope was less than 23·8°, and 0·33 where the slope angle was steeper.

Sectors over 2936 m a.s.l. that received an incident radiation between 21 721 and 23 970 MJ m^{-2} day^{-1} only presented a probability of ice cover when the slope did not exceed 23·18°. In these sectors the probability was 0·44.

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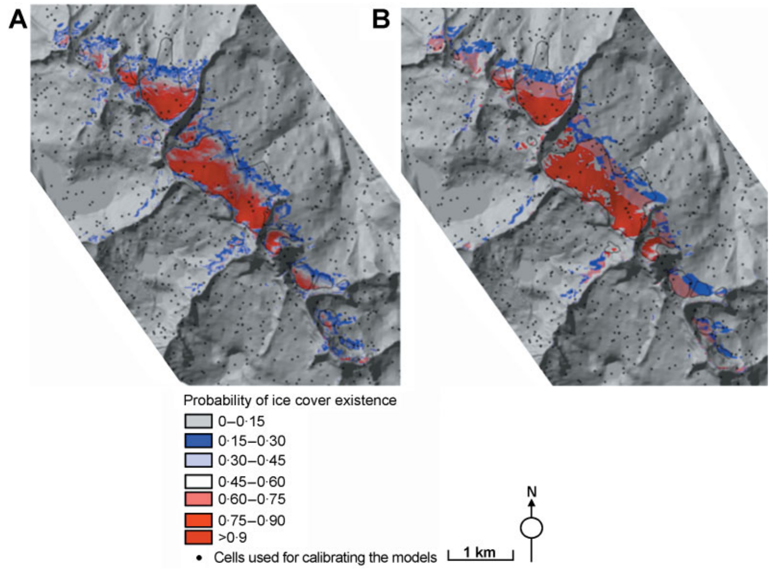

Figure 4. Probability maps of ice cover existence provided by GAM (A) and regression tree model (B). This figure is available in colour online at www.interscience.wiley.com/journal/espl

The highest areas receiving low solar radiation (AR < 21 721 MJ m^{-2} day^{-1}) were split in two groups: with a slope angle above or below 31·4°. The former areas extending up to 3243 m, as long as their slope angle did not exceed 46·2°, presented a probability of 0·28. Sectors with a slope angle below 31·4°, a low incident radiation and with an altitude above 3021 m presented the highest probability of glacier development. Different combinations of slope and altitude in areas below 3021 m presented probabilities of ice cover between 0·2 and 0·92.

Ice cover probability maps

Figure 4 shows the probability maps of glacier development in the massif according to the topographic context. Figure 4(A) shows the map provided by the GAM, which uses the smoothed response of each terrain variable to predict the probability value for a cell. Figure 4(B) is the prediction provided by the regression tree model. Given the specific characteristics of each model, GAM predicts in continuous units, while the tree model provides 17 discrete units (the number of terminal nodes).

Both regression models predicted a similar probability distribution of glacier development. Maximum probabilities of ice cover in the massif (0·8, 0·9) were recorded in the upper sectors where today's largest glaciers lie (the Maladeta, Aneto and Barrancs glaciers). Slightly lower probability levels (0·5–0·7) were typically predicted in the mean or lower sectors of these glaciers, or in the upper cells of the ice bodies of lesser significance (i.e. the Tempestades and Salenques glaciers and glacierettes). In several sectors, the models predictions were somewhat equivocal: assigning high probabilities in currently unglaciated areas (i.e. around Alba Peak, Portillones Ridge, around the Coronas glacier, below Llosas Ridge), and assigning low probabilities in currently glaciated sectors (i.e. Eastern Maladeta and the Coronas glacier, Cregüeña glacierette).

Table II shows the kappa values for both models. The GAM and regression tree provide very similar values, oscillating between 0·6 and 0·7, when predicted probabilities are below 0·5. According to Landis and Koch (1997), almost all of the K values obtained can be considered as good, indicating that the models predict robustly occurrences that are better than chance occurrences. For higher probability thresholds, kappa values progressively decrease, especially in the case of predictions using the GAM.

Discussion and Conclusions

In this paper, generalized additive and binary regression tree models have been used to investigate the topographic context of glaciers in the Maladeta Massif, Central Pyrenees. Both have been shown to be useful for (i) analysing the response of the predictors to the response variable and (ii) mapping the probability of glacier development in the area.

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Table II. Kappa values obtained in the validation procedure

	Kappa	
Probability	**GAM**	**Tree model**
0·1	0·60	0·66
0·2	0·66	0·70
0·3	0·67	0·65
0·4	0·63	0·65
0·5	0·61	0·65
0·6	0·58	0·52
0·7	0·52	0·50
0·8	0·45	0·50
0·9	0·22	0·50

During the last years, both statistical approaches have been used in environmental modelling, mainly in ecology and biogeography studies related to the prediction and explanation of distinct features of biodiversity: species presence/absence data or species richness (Yee and Mitchell, 1991; Bio *et al*., 1998; Lehmann *et al*., 2002) and snow distribution studies (Elder *et al*., 1998; Erxleben *et al*., 2002; Anderton *et al*., 2004; López-Moreno and Nogués-Bravo, 2005). However, they had not been applied yet for this field, so they can be considered as promising tools for further research on glaciology.

The non-linearity of both models has constituted a considerable advantage for the analysis, since all the predictor variables considered have shown abrupt changes in their response to the probability of ice cover occurrence. A further advantage of the two models is the way in which they facilitate the environmental interpretation of the established relationships between predictors and response. Thus, the response curves (GAM) and the tree model report similar responses of the predictor variables (ALT, S, AR and MC) to the presence of glacial ice (glaciers or glacierettes). Moreover, these responses can be easily related to the different processes that affect the glacier mass balance.

Altitude is a key factor in explaining the presence of ice. Its importance is due to the control that it exerts on (i) snow accumulation, since as precipitation in the Pyrenees increases following an altitudinal gradient around 75 mm/100 m (Rijckborst, 1967), and (ii) snow accumulation and ice melt as a consequence of the altitudinal gradient followed by temperature in the area. In the Pyrenees, the decrease in temperature has been estimated at 0·5–0·6 °C/100 m of increasing altitude (Del Barrio *et al*., 1990). Thus, the hypsometry of the glaciated sectors is of paramount importance for explaining the mass balance of the glaciers (Brocklehurst and Whipple, 2004; Reinwarth and Escher-Vetter, 1999; Brozovic *et al*., 1997). In the study area, the 0 °C isotherm is located around 3000–3100 m (Chueca and Julián, 2004), which explains why today glacial activity is restricted to a small portion of the surface area.

The annual incoming solar radiation also plays an important role in explaining the presence of ice in the area due to its impact on the ablation rate. Several authors stress the close relationship between solar radiation or slope aspect, on the one hand, and glacier development (Kruss and Hastenrath, 1987; Mölg *et al*., 2003a, 2003b; Chueca and Julián, 2004; Kaser *et al*., 2004) and other geomorphological processes typical of cold regions, such as permafrost (Schrott, 1991; Gruber and Hoelzle, 2001) and rock glacier distribution (Baroni *et al*., 2004), on the other. In the Pyrenees, García-Ruiz *et al*. (2000) concluded that most glacial cirques, and certainly the best developed, are to be found on the north and north-east slopes, because of the lower radiation rates recorded there. In the Maladeta Massif, Chueca and Julián (2004) observed a close relationship between the spatial distribution of incoming radiation and the shape and development of small cirque glaciers. Here, we have shown that glacier development occurs in areas that receive less than 2100 W m^{-2} $year^{-1}$. Above this value, the probability of the presence of glacial ice is practically null. In areas where precipitation is related to the arrival of fronts from a dominant direction, incoming radiation could be correlated with precipitation, making it difficult to separate the response of each variable (Benn and Lehmkuhl, 2000). In this sector, however, this possibility is negligible since the glaciers lie very close to the main watershed divide, and precipitation on both sides is very similar.

Slope also significantly affects glacier distribution in the study area. GAM showed that slopes around 15–30° are particularly prone to ice cover occurrence. In steeper slopes, this probability falls rapidly. The landscape of the highest sector of the Maladeta Massif is dominated by ridges, cliffs and steep slopes, which hinder glacier development as

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here snow cannot accumulate properly, while avalanches transport the snow to lower sectors of the slopes (Mittaz *et al*., 2002). For this reason, Brozovic *et al*. (1997) claim that the existence of very steep slopes in the glaciated altitudinal range represents a drawback for glaciar development in the Northwestern Himalaya and Karakoram. Furthermore, a number of studies reveal that on very steep slopes ice thickness is reduced because of a faster ice flux (Hubbard, 1997). Thus, in periods of glacial shrinkage when the head of a glacier enters steeper areas, the de-glaciation processes become more rapid, while sudden detachment events might even be observed (Benn and Lehmkuhl, 2000). In the Maladeta Massif study area, a similar process was reported in the 1980s, when the surface area of the Tempestades glacier, located on a very steep slope, was reduced drastically following such a detachment.

The capacity of mean curvature to account for glacier development in the area was lower. However, both models indicated that convex up surfaces are not conducive to ice cover, which would appear to be due to the difficulty for snow to accumulate in such conditions and to the higher solar radiation rates recorded in convex sectors.

Although several studies have analysed the effect of certain characteristics of the terrain on glacier distribution and evolution, few consider the joint effect of the predictor variables or use this information for modelling glacial dynamics, and only a few exceptions can be found. Allen (1998) related the different topographic characteristics of glaciers to their accumulation–ablation ratio (AAR) and used linear models to discriminate between four forms of glaciers and perennial snowfields in the Rocky Mountains. Bishop *et al*. (2001) considered the morphological complexity of the landscape to obtain morphometric terrain parameters for mapping alpine glaciers.

Here, the combined effect of the four predictor variables taken into consideration enabled us to explain more than 70 per cent of the variance shown in the distribution of glaciers.

The kappa values point to the high degree of robustness and to the accuracy of these predictions. According to the relations established by the models between the terrain characteristics and the presence of ice cover, we were able to obtain ice cover probability maps for the massif. In general, the probabilities predicted by the models provide information about the degree of conservation of the glacial bodies. Thus, high probabilities coincide with the best conserved sectors of the most developed glaciers in the massif, whilst low probabilities coincide with the areas of the glaciers that are most exposed to melting. In some cases (e.g. Coronas Glacier), these low values of probability affect the whole of the glaciated surface. Thus, the probability values might be considered as being an indicator of the degree of exposure to ice calving in the near future if current climatic trends were to continue.

In spite of the high predictive capacity of the models, a number of significant deviances were observed between the probabilities predicted and the presence or absence of glacier ice cover. Generally, these errors were found in sectors in which the topographic context represents a limit situation for glacier development, and in which the specific characteristics of the location accelerate or delay the retreat velocity of the glaciers. Thus, cells that received an overoptimistic estimation of ice cover correspond to recently de-glaciated areas that today remain snow-patched for most of the year (Chueca *et al*., 2005). In fact, on the slopes of the Alba Peak, where high probabilities of glacier development were predicted, an active rock glacier has recently been detected (Serrano and Agudo, 2004). By contrast, the areas for which the model predicts low probabilities of coverage, but where ice is actually present, correspond in the main to (i) the lower area of the Eastern Maladeta Glacier, the only ice body to have developed a glacial tongue and where the ice cover is primarily due to the flux of ice and not to the topographic or climatic conditions, and (ii) the Coronas Glacier and Cregüeña glacierettes. However, both cases have suffered very rapid glacier retreat in recent decades (Chueca *et al*., 2003). This suggests that they are redoubts of ice bodies that developed under more favourable conditions, which today lie in areas that are little prone to glacial activity. Hence, we can expect them to disappear in the very near future.

According to our results, we can conclude that topography exerts a considerable influence on the distribution of ice cover in the Maladeta Massif, and determines the level of conservation of each glacial body. Thus, non-linear regression models would seem to be a useful tool for analysing the interactions between terrain characteristics and glacier development, facilitating the interpretation of the effects of climate variability on glacier surface extent at the local and regional scales.

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