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INFLUENCE OF LOCAL *VS.* REGIONAL SETTINGS ON GLACIATION PATTERNS IN THE FRENCH ALPS

ABSTRACT: COSSART É., *Influence of local* vs. *regional settings on glaciation patterns in the French Alps*. (IT ISSN 0391-9838, 2013).

To complement the work led by glaciologists, geographers should explain the distribution of glaciers at different scales. Indeed, various local effects can interfere with regional climatic parameters to generate variations in glacier sensitivity. In this paper, we propose a method to explore the influences of various parameters (topography, relative location, topoclimate, etc.) on glacierisation, at two complementary scales (regional and local). Firstly, the level of equilibrium line altitude (ELA) of 217 glaciers located in the French Alps is explained by coupling a F-test on the influence of region belonging with a multiscalar principal component analysis (PCA). Secondly, the variables identified as influencing the ELA at a local scale (longitude, curvature and incoming solar radiation) are integrated into a geographically weighted regression (GWR) to predict the altitude of instantaneous glacierisation (AIG) at any given point. AIG is then mapped all over the French Alps, and partial correlation maps between AIG and explanatory variables are also provided. Finally, it is useful to identify the structures of spatial organisation, which show a subdivision between glaciers evolving under the influence of a humid climate (Belledonne-Grandes Rousses and Mont-Blanc), and other glaciers, set in drier conditions, and where local effects (curvature and incoming solar radiation) partly compensate for the low-level of precipitation.

KEY WORDS: Glaciers, Equilibrium line altitude, Local settings, Geographically weighted regression, The French Alps.

INTRODUCTION

Studies related to global warming provide a wealth contemporary research for physical geographers. This is particularly true in Alpine environments where global change directly affects the cryosphere and in turn the availability of such a major natural resource as water. As a consequence, glaciers are observed, monitored and mapped, through two distinct approaches.

On the one hand, glaciologists have compiled long-term records in many specific places: they acquire very precise geometric measurements to quantify mass-balances of glaciers and model the relationships between glaciers and climate. Mass-balance modelling is furthermore required by all specialists of mountainous environments as glaciers are a unique proxy of poorly-documented climate at high altitudes (Ohmura & *alii*, 1992), and are also a proxy for palaeoclimate reconstructions (Federici & *alii*, 2008, 2012; Mîndrescu & *alii*, 2010). However, one problem is that glacier distribution is also affected by non-climatic factors (Arnold & *alii*, 2006), so that measurements and modelling provided from one single glacier are not necessarily representative at regional scales, especially because each glacier may be characterised by its own sensitivity (Kuhn & *alii*, 1985; Braithwaite & Zang, 2000; Chenet & *alii*, 2010). This problem is particularly relevant in the French Alps, where surveyed glaciers were often chosen at the end of the 19th century not in terms of their scientific interest, but in terms of their accessibility.

On the other hand, geographers have highlighted that the consequences of climate change on glaciers can be highly variable due to local settings (topography, aspect, glacier position, etc.; Carrivick & Brewer, 2004; Evans, 2006 a & b; Carrivick & Chase, 2011; Cossart, 2011). In turn, geographers try to explain glacier distribution at various spatial scales. At the local scale, a first global model of local asymmetry of glaciation has been defined (Evans & Cox, 2005), but «*understanding of glacier distribution remains qualitative rather than quantitative*» (Evans, 2006a). Indeed, glaciation levels are sensitive to local settings, which were identified in early glacier surveys (Rabot, 1902): they correspond to factors that can create glaciation asymmetry at scales ranging from one to tens of kilometres, such as snow-drift (Evans & Cox, 2005), snow-avalanching (Cossart, 2011), shading effects (Evans, 2011),

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etc. However, it is still necessary to quantify as precisely as possible the relationship between glacier distribution and these local factors. At a regional scale, explanatory factors correspond, for instance, to the influence of latitude on temperatures and, in turn, on glacier ablation, as well as the distance from glaciers to wet sources, which influences glacier accumulation (Zemp & *alii*, 2007). Other authors also highlight the role of the glacier position within the overall atmospheric circulation pattern (Federici & *alii*, 2008; Six & *alii*, 2001). Due to this complex interplay between local and regional influences, many questions remain unresolved by geographers. How can we improve models of regional glacier distribution from local observations (Haeberli & Hoelzle, 1995)? To what extent do local settings, combined with regional climate patterns, influence glacier behaviour and distribution (Carrivick & Brewer, 2004)? Finally, to what extent can non-climatic factors influence glacier sensitivity?

In this paper, we aim to decipher the specific influences of local and regional settings in present-day glacier distribution, in order to propose synthetic maps of glaciation patterns at the regional scale. We focus on the French Alps, where we identify and describe 217 glaciers through aerial photographs and field investigations: in particular we assess the equilibrium line altitude (ELA) which is considered here as a key indicator of glaciation patterns (Porter, 2001; Meierding, 1982), and is thus a variable that should be explained. First, we apply a method derived from multiscalar, multivariate statistical analysis (Grasland & *alii*, 2000; Mathian & Piron, 2001) to enhance to what extent the ELA can be explained by regional or local influences and to provide a typology of glaciation patterns. Second, we apply the results of the multiscalar analysis to map the spatial variations of ELA at the scale of the French Alps within a GIS. This map corresponds to an interpolation of the altitude of instantaneous glacierisation (AIG), an index derived from ELA (Lie & *alii*, 2003), from data acquired on each glacier. A discussion on the best method to implement this interpolation is also required. Finally, our results provide an analysis of present-day glacier distribution in the French Alps, but also a methodological discussion on glacierisation modelling.

PRESENT-DAY GLACIATION IN THE FRENCH ALPS

In the French Alps, the current glaciated area is about 250 km^2 (according to the *Institut Géographique National*), subdivided into five main regions, from north to south: Mont-Blanc, Vanoise, Belledonne-Grandes Rousses, Massif des Ecrins, and finally a larger region including small southern glaciers (Queyras, Ubaye; fig. 1A, tab. 1). Some ELA measurements were made to compare the spatial distribution of glaciers at French Alps scale, during the 1970s and the 1980s. The first insights on spatial patterns of regional distribution were then documented (Vivian, 1975; Julian, 1980; Chardon, 1984; Francou, 1988; Chardon, 1989). ELA seems to reach its minimum altitude in the western part of the Mont-Blanc area (2700 m). From this zone, two main gradients are often highlighted. The most significant corresponds to a west-east gradient, due to a decrease in precipitation (climate continentalisation): along

TABLE 1 - Main characteristics of each region

	ELA	Longitude	Latitude	Slope	Curvature	ISR
Sud	3015	6.84	44.50	0.64	70	1568
Ecrins-Oisans	3018	6.32	44.90	0.81	39	1774
Belledonne	2906	6.09	45.19	0.68	70	2152
Vanoise	3090	6.93	45.41	0.67	71	1757
Mont-Blanc	2928	6.92	45.91	0.78	32	1604

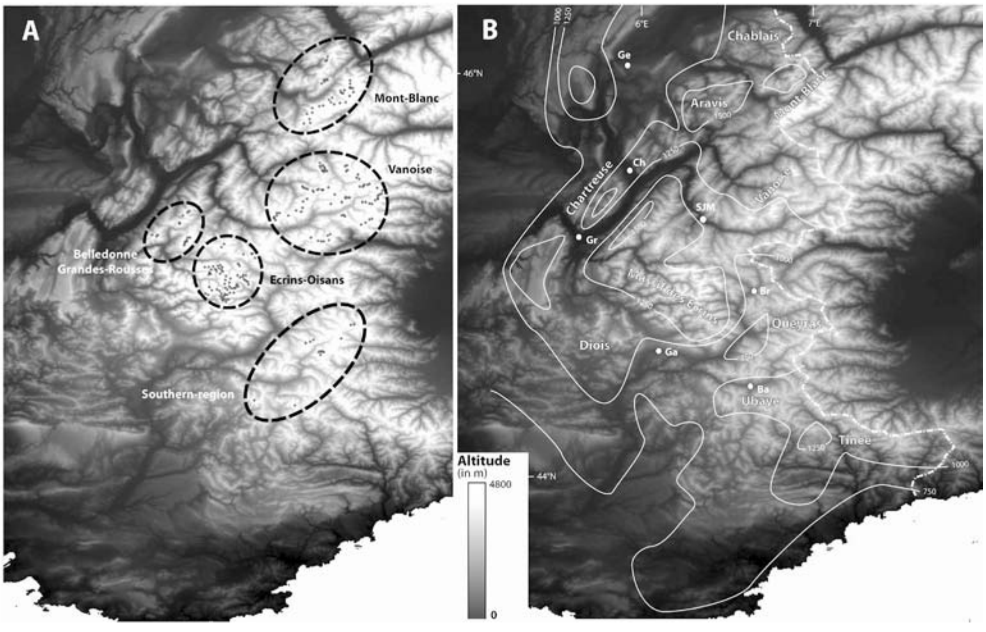

FIG. 1 - Physical setting of the study area. A: Location of glaciers, and the five main regions studied here. B: Precipitation patterns in the French Alps (according to Meteo-France data, calculated from 1981 to 2010).

various cross-sections, precipitation decreases by 30-50% (1100 mm in Grenoble at 400 m asl *vs.* 730 mm in Briançon at 1320 m asl; 950 mm in Chambéry at 270 m asl *vs.* 750 mm in Saint-Jean-de-Maurienne at 600 m asl; fig. 1B). Francou (1988) estimated a consequent rise in ELA of about 10 m/km from west to east. The other gradient is oriented N-S and probably lower and irregular (Chardon, 1984, 1989). This gradient corresponds to the increase of incoming solar radiation (ISR) to the south and therefore to increased ablation of glaciers.

Beyond these two gradients linked to current climate settings, many local irregularities appear: their influence has not yet been fully understood. First of all, each region is differentiated by lithological and topographical parameters. In short, regions that belong to external crystalline massifs of the western Alps (Ecrins, Belledonne-Grandes Rousses, and Mont-Blanc) are roughly characterised by granitic or gneissic bedrocks, in which deep cirques, characterised by steep faces, were excavated (fig. 2). Vanoise and the southern glaciated areas mostly belong to the internal massifs, where schists, limestones and sandstones alternate. As a consequence, glacial erosion imprints are less marked and cirques are often characterised by quite low depth and concavity (fig. 3). Secondly, in each region, local contexts create some contrasts: two neighbouring glaciers can be characterised by very different ELAs (the ELA in areas separated by a ridge can differ by 150-200 m; Cossart, 2011); the distance to humid sources (*i.e.*, the Atlantic Ocean) is, for instance, perceptible within the Ecrins (Cossart, 2011) or Vanoise (Kaiser, 1988) massifs. Furthermore, topoclimate also influences local glaciation patterns through incoming solar radiation (and slopes) and through glacier position within a concavity (that may efficiently trap cold air in case of thermal inversion, and snow provided by avalanches).

In summary, many parameters that interplay at various scales may influence glacier distribution in the French Alps. Here we aim at deciphering the precise role of these various parameters.

ELA, DEFINITIONS AND CONCEPTS: STATE OF ART

A geographical approach to glacierisation requires a survey of a large number of glaciers, and the measurement of a parameter that can be easily calculated from remote-sensing or field measurements. The ELA is considered as a useful parameter to quantify the glaciation pattern, and it has been widely used to measure the influence of climatic variability on glaciers, even in the case of past climatic conditions (*e.g.*, Andrews, 1975; Porter, 1975, 1977; Federici & *alii*, 2008, 2012). The ELA is the theoretical boundary between the ice accumulation zone (upstream area of the glacier where snow accumulates to transform gradually into ice) and the ice ablation zone (area where the downstream loss of ice by melting or sublimation is dominant). At the end of the glacier ablation period (summer in the Alps, for example), the ELA coincides with the

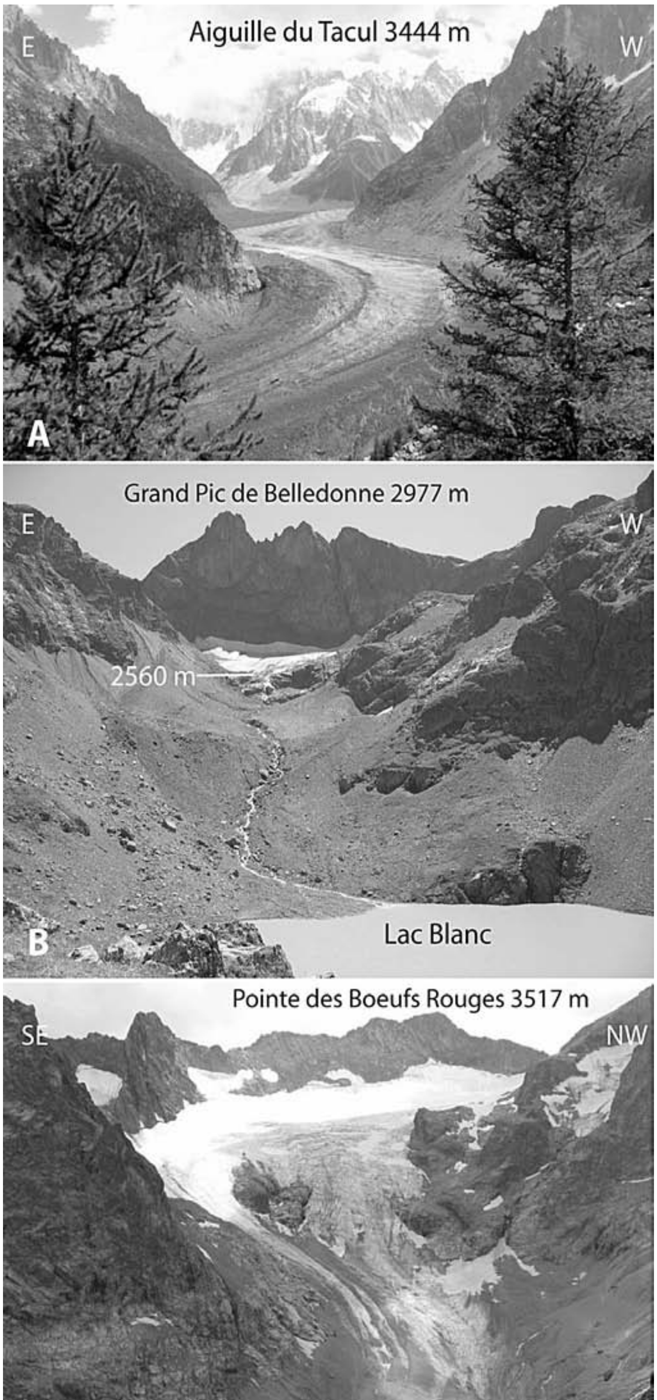

FIG. 2 - Examples of three glaciers located in crystalline massifs. A: Mer de Glace (Mont-Blanc). B: Glacier de Freydane (Belledonne). C: Glacier du Sélé (Ecrins-Oisans). Note the well-shaped concave cirques, characterised by steep free faces that may shelter the glacier from the sun and can be prone to snow-avalanching. Photographs taken by E. Cossart.

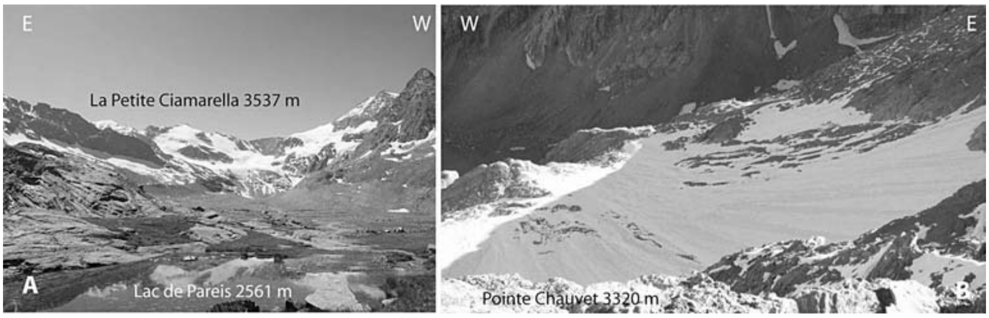

FIG. 3 - Examples of two glaciers located in internal massifs. A: Glacier des Evettes (Vanoise). B: Glacier du Chauvet (Upper Ubaye valley). Cirques here are poorly shaped (low concavity, low relief and low slope gradients). Photographs taken by E. Cossart.

snowline. As the altitude of the ELA varies over time, and especially following seasonal cycles, steady state ELA is often estimated and will be considered here. The steady state ELA corresponds to a theoretical balanced mass budget (Braithwaite & Muller, 1980), and is empirically calculated through «orometric» methods, based upon the altitudinal distribution of a glacier area. Richter (1885) suggested that the ELA divides the accumulation and ablation areas according to a definite ratio and suggested a value of 8/1. Currently, an area ratio of 2/1, corresponding to an accumulation area ratio (AAR) of 0.67, is considered as a good approximation of the steady state ELA in the case of alpine glaciers under present-day climatic conditions (Gross & *alii*, 1976; Meierding, 1982). This method is applied in this paper.

Steady state ELA is supposed to vary mainly in accordance with two climatic parameters: temperature and precipitation, which may reflect ablation during the summer season and the accumulation of snow during the winter season, respectively. Accumulation is known to be influenced by both the regional distribution of precipitation as snow and the local redistribution of snow by wind and avalanching (Sissons & Sutherland, 1976; Sutherland, 1984). In addition, topography (slope, altitude, curvature, etc.) of glacier surroundings (impluvium) may also have a local influence on ice accumulation and thus on the ELA (Nesje, 1992; Dahl & *Alii*, 1997; Nesje & Dahl, 2000; Federici & *alii*, 2012). Ablation is influenced by multiscalar factors as well, more precisely latitude at the regional scale, and aspect or shading effects at the local scale (Evans, 2006a).

Due to these multiscalar influences, Zemp & *alii* (2007), following Lie & *alii* (2003), consider both a local (topographic) ELA and a regional (climatic) ELA, to distinguish between glacier ELAs reflecting the general winter precipitation and ablation season temperature in a region and glacier ELAs that are influenced by local factors (fig. 4). They also formulated the need for a theoretical approach to calculate a glaciation threshold in presently non-glaciated areas, to investigate the potential lowering of the regional ELA necessary to induce glacierisation, or more generally to provide diachronic maps of glacierisation variations at regional scales, even if some glaciers disappeared. Consequently, a theoritical index, called Altitude of Instantaneous Glacierisation (AIG), is calculated and considered as the minimum altitude of areas climatically suited for glacier formation (fig. 4). It is often interpolated from ELAs measurement or from glacier mass-balance through regression models (Lie & *alii*, 2003).

METHODS OF SPATIAL ANALYSIS

To explain the present-day glacier distribution, we compiled a database at the French Alps scale, gathering glaciological data (especially ELA measured for each identified glacier) and explanatory variables (topography, etc.). This database was then analysed using multiscalar analysis methods to decipher at what scale each explanatory variable may act. Finally, a model of present-day glacier distribution was defined, by interpolating AIG thanks to the explanatory variables previously identified as being influential.

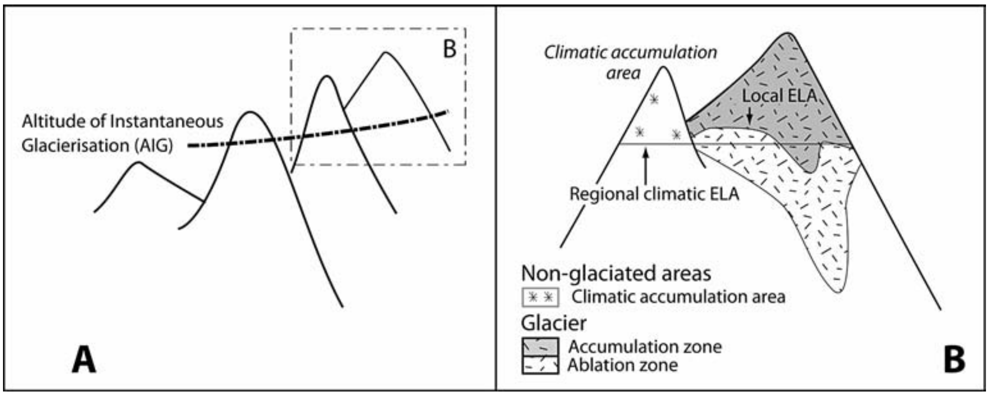

FIG. 4 - Indicators of glacierisation. A: At a regional scale, altitude of instantaneous glacierisation can be estimated at any given point. B: At a finer scale a climatic ELA can be defined by smoothing a local ELA measured in areas covered by glaciers.

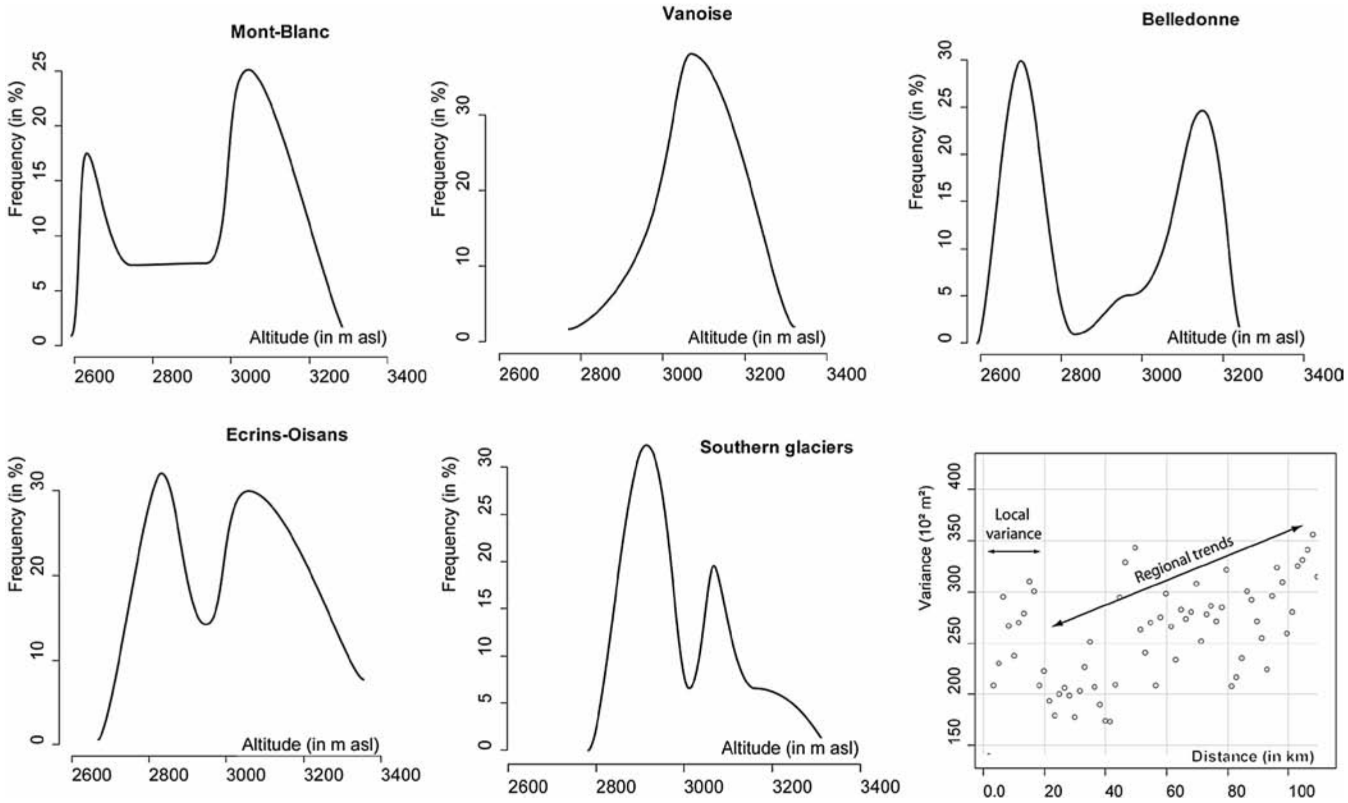

FIG. 5 - Characteristics of each region. A to E: Frequency diagrams of ELA in each region. F: Variogram of the ELA at French Alps scale.

Interpretation of aerial photographs and the GIS database

Thanks to aerial photographs from the *Institut Géographique National*, 217 glaciers were identified and mapped all over the French Alps. Aerial photographs were acquired in August and September 2006, so that snow cover is at a minimum and glaciers can be easily delineated. Delineation has been carried out manually: shape layers were drawn through Google Earth® interface and then integrated within a GIS software (SAGA GIS®). Field investigations in particular places (Mont-Blanc, the Upper Maurienne area in Vanoise, Belledonne, Ecrins and Queyras) were also conducted from 2006 to 2010 to verify some observations. Glaciated areas were coupled with a 50 meter-resolution DEM to generate a hypsometric curve, and then assess the ELA through the AAR method (ratio 0.67, as mentioned above).

To explain the level of the ELA, and to further predict the AIG, we first estimate, at the location of each glacier, geographical parameters that may have a regional influence on glacierisation. The longitude, revealing the position from Atlantic humid sources, and latitude that may influence ablation, were assessed.

Second, we define the local settings of each glacier, to eventually explain the local variability of ELA. The impluvium was delineated automatically through a SAGA GIS® procedure, and its characteristics were assessed through topoclimatic parameters. Curvature, slope and incoming solar radiation (ISR), all derived from the DEM, were calculated and mapped. Curvature (and more precisely concave landforms) may particularly favour cold air trapping under stable weather conditions; moreover, well-shaped (concave) cirques are prone to snow accumulation through avalanches on the cirque floor. Slope gradients influence the frequency of avalanches on free faces, and in turn snow accumulation. Incoming Solar Radiation measurements reveal the shading effect due to rugged terrain that can partly hamper ice/snow ablation. Finally, each glacier was attributed to one of the five main glaciated regions previously defined: the region is thus considered as a qualitative variable within our database. The influence of this qualitative variable on ELA and predictors should be statistically tested to decipher whether each region is significantly different from the others or not. If this is the case, regional parameters could influence present-day glaciation. Otherwise, local parameters could be more important in explaining present-day glaciation.

Multiscalar analysis

This analysis is organised in two steps. First of all, a F-test is applied to estimate whether the ELA and predictor variability can be explained by regional belonging. Secondly, multiscalar principal component analysis (PCA) is applied to describe the relationships between ELA and explanatory variables at two scales (the French Alps and within regions), to highlight at what scale the relationship between ELA and each predictor is statistically relevant.

The F-test in one-way analysis of variance is used here to assess whether the ELA and explanatory variables values within a region differ from other regions. The null hypothesis is that the differences between regions are not significant. The method is based upon the calculation of «between-group variability», and «within-group variability», where a group is here a region. «Between-group variability» corresponds to the sum of squared differences between the centre of gravity (defined as a mean value) of each region and the centre of gravity (as a mean value) of the whole population (SSDb), so that:

$$SSDb(X) = \Sigma_r\ d[X(G), X(G_r)]^2 \qquad \text{(Eq. 1)}$$

where r is a region, X the considered variable, X(G) the centre of gravity of the population of glaciers (considering the variable X), $X(G_r)$ the centre of gravity of the region (considering the variable X), and d the distance.

"Within-group variability" corresponds to the sum of squared differences between an observation made on a glacier, and the centre of gravity of the region to which the glacier belongs (SSDw), so that:

$$SSDw(X) = \Sigma_r\ \Sigma_{g\epsilon r}\ d[X_{gr}, X(G_r)]^2 \qquad \text{(Eq. 2)}$$

where X_{gr} is the observation made on glacier g, on a variable X, in region r.

Comparisons between SSDb and SSDw, and ratios between these values and the entire variability, is a first step in deciphering the influence of local *vs.* regional settings. Nevertheless, a statistical test is needed in order to reject or not the null-hypothesis and finally the F-value can be assessed as follows:

$$\text{F-value} = [SSDb/(R-1)] \,/\, [SSDw/(N-R)] \qquad \text{(Eq. 3)}$$

where R is the number of the region (here 5) and N the population of glaciers (here 217). The F-value is compared to the F-distribution with R-1, N-R degrees of freedom under the null hypothesis: if F-value > F-distribution, then the null hypothesis is rejected.

Once the importance of both «between-» and «within-region variability» is assessed, the relationships between ELA and explanatory variables should be described. A multiscalar PCA is thus applied. First of all, a PCA is applied from all observations made on the glaciers. Secondly, a PCA is applied by considering the region to which a glacier belongs. The PCA is then calculated relative to the centre of gravity of each region. Indeed, the differences between the values observed on a glacier and the mean values (values of the centre of gravity) of the regions to which the glacier belongs are implemented within the PCA (Mathian & Piron, 2001). The aim of this method is to describe whether the combinations of variables are different at both scales: regional (first step) and local (second); if so, this allows the correlations between ELA and explanatory variables that are significant at each scale to be identified. Finally, the multiscalar PCA and F-test are coupled to describe the predictors which influence glacierisation at the scale of the French Alps (generating regional differentiation and significantly correlated with ELA in the PCA) and at the local scale (reinforcing local differentiation).

Interpolation of AIG

Here, we assume that a model of present-day glacier distribution can be revealed through the AIG estimation in any location of the study area. Such an estimation at any given point is particularly necessary in glaciology, as glaciers have shrunk since the Little Ice Age (LIA): in unfavourable areas (south-faced mountain slopes, for instance) large LIA glaciers have been subdivided in many little glaciers during the 20th century (Vivian, 1975). A study based upon ELA, and thus on each glacier, would be statistically influenced on the large number of glaciers in such unfavourable settings and would provide erroneous conclusions. A continuous representation, that overcomes glaciers location, of a theoretical altitude necessary for glacier development can be assessed, so that a spatial organisation could be consequently highlighted.

Such an estimation of AIG could be done through ELA kriging (Matheron, 1970; Cossart & *alii*, 2010) or a multiple regression (Joly & *alii*, 2003; Cossart, 2011). Nevertheless, these two methods are global ones as they assume that the processes being examined are constant over space. However, processes of glacierisation may be intrinsically different over space (Evans, 2006a and b, 2011), especially according to the region to which a glacier belongs. Furthermore, a misspecification of individual local effects can cause high residuals in global models; a problem often highlighted in climatological studies, especially in mountainous environments where local variability is high (Gottardi & *alii*, 2008; Joly & *alii*, 2008, 2009). To solve these problems, geographically weighted regression (GWR) can be applied to model processes that vary over space. GWR provides different regression coefficients for each location of the study area. First, for each given glacier (located at longitude X, latitude Y) of the study area, we perform a regression analysis estimating the value of ELA (noted $ELA'_{X,Y}$) from the predictors $V_i(x,y)$ which are estimated at surrounding glaciers location (x,y). A more important weight is given to a glacier (x,y) that is close to the survey point (X,Y) by a gaussian kernel smoothing, so that V_i must be indexed by (x,y). The formula would be:

$$ELA'_{X,Y}(x,y) = \beta_{0\,X,Y} + \beta_{1\,X,Y} * V_1(x,y) + ... + \beta_{n\,X,Y} * V_n(x,y) \qquad \text{(Eq. 4)}$$

where X,Y are the coordinates of a glacier on which the ELA' prediction is made; (x,y) are the coordinates of all surrounding glaciers, β_0, β_1, and β_n are coefficients that vary over space (β_0 is the intercept; β_1 and β_n are regression coefficients of predictors) and V_1 and V_n are explanatory variables (*i.e.*, predictors). This equation can be fitted by least squares to give an estimate of the parameters at the location (X,Y) and then calculate the predicted value ELA'. As explained before, data nearer (X,Y) is given a stronger influence on the model than data further away: parameters of this equation thus vary over space, and is different at each glacier location.

By extending the ELA' prediction to unglaciated areas, an estimation of AIG can be made: the regression equation is then applied to any unglaciated point (X,Y):

$$AIG(X,Y) = ELA'_{X,Y}(X,Y) \qquad \text{(Eq. 5)}$$

$$AIG(X,Y) = \beta_{0\,X,Y} + \beta_{1\,X,Y} * V_1(X,Y) + \ldots + \beta_{n\,X,Y} * V_n(X,Y) \qquad \text{(Eq. 6)}$$

This method is repeated for each survey point (X,Y) of the zone (including unglaciated areas) so that an estimated value of AIG is provided at any point in the study area.

This GWR is thus implemented on a regular grid: each explanatory variable is a raster layer, so that the final results and the spatial variation of the estimated regression coefficients can be examined as raster maps. Such regression coefficients can be considered as partial derivatives of AIG ($\partial AIG/\partial ISR$; $\partial AIG/\partial Curvature$; $\partial AIG/\partial Longitude$) and reveal the sensitivity of AIG to each predictor at any point in the study area. The higher the partial coefficient of a predictor at one point, the higher its influence on AIG, as local (even tiny) variations of the predictor may generate significant variations of the AIG. Finally, the associated maps may be used to highlight the spatial organisation of AIG (*i.e.*, gradients, discontinuities, etc.), but also where each predictor is particularly influential.

MULTISCALAR INFLUENCES OF PREDICTORS ON ELA

According to our database, the ELA is at a maximum in the Vanoise area (3090 m asl), and at a minimum in the areas of Mont-Blanc and Belledonne-Grandes Rousses (about 2900 m asl). Ecrins-Oisans and the southern glaciers are in an intermediate configuration (about 3000 m asl). The ELA differences between the five regions (fig. 5, tab. 2) are significant according to the F-test but a first examination also highlights a very high local «within-region variability» that represents 85% of the total inertia. So, a double influence (local *vs.* regional), also well recorded by the variogram (fig. 5), is highlighted. On one hand the maximal variance is measured locally, over a short distance (less than 10 km); on the other hand over a longer distance, no sill appears, but a trend. This firstly confirms the non-stationarity of ELA and, secondly, that a regional trend influences the variability of ELA. This double scale influence reinforces the idea that multiscalar PCA and locationally dependent methods of interpolation (such as GWR) are required to identify what predictors are influent locally and/or regionally.

TABLE 2 - Summary of variables used within the database. Decomposition of the inertia according to the region. ELA is expressed in metres (asl), latitude and longitude in decimal degrees, slope in m/m, incoming solar radiation (ISR) in kW/m², curvature index is in %. The sums of squared differences (SSD) are calculated in squared units

	ELA	**Longitude**	**Latitude**	**Slope**	**Curvature**	**ISR**
Mean value	3024	7	45	0.73	54	1754
SSD between regions	882920	22	33	0.98	61500	3653736
SSD within Sud	115943	0	0	0.20	216464	1997203
SSD within Ecrins-Oisans	2127949	0	0	0.54	1085243	32483867
SSD within Belledonne	699133	0	0	0.09	27353	3064887
SSD within vanoise	904005	2	1	1.27	484422	20176390
SSD within Mont-Blanc	1211426	0	0	0.56	332056	20734876
SSD within	5058457	3	2	2.66	2145539	78457223
SSD Total	5964812	23	33	4	2208421	82329670
F obs	9.34	406.41	959.1	19.61	1.53	2.491
F threshold (0,01)	2.99	2.99	2.99	2.99	2.99	2.99
% SSD within	85%	12%	6%	74%	97%	95%
% SSD inter	15%	92%	95%	27%	3%	4%

Curvature and incoming solar radiation

Curvature and incoming solar radiation act at all scales (fig. 6). At the scale of the French Alps, they act together to influence ELA and are moreover positively correlated. The concavity/convexity of free faces is associated with the shading effect at this scale, and hence reduces glacier ablation. If the curvature index decreases, cirque concavity decreases, and the ELA rises. Furthermore, in rugged areas, deep and concave cirques (*i.e.*, higher curvature index) are more frequent, and concomitantly shading-effects are reinforced. Even if curvature and ISR are not significantly different between regions, slight variations of ELA can be noticed between some regions. Firstly, between regions characterised by high ELAs (*i.e.*, Vanoise and the southern region), Southern region glaciers are set within more concave cirques compared to the Vanoise glaciers. As a consequence, ELA is slightly lower compared to the Vanoise glaciers. Second, among the other regions, concavity is higher in the Belledonne-Grandes Rousses area and may generate a slight decrease in terms of ELA there.

At the local scale, within regions, incoming solar radiation remains highly correlated with ELA and is furthermore the best predictor. Curvature also remains correlated with ELA, but it may be noted that curvature and incoming solar radiation are not significantly correlated. At the local level, the role of aspect is enhanced: glaciers may occur within cirques of similar concavity, but characterised by opposite aspects, and thus by different incoming solar radiation. This shows that relationships are scale-dependent in terms of glacierisation. Nevertheless, the influence of both predictors is strengthened at local scales, within each region (fig. 6).

Geographic position

A first hypothesis explains ELA differences between regions, and especially the highest ELAs in Vanoise and the southern regions, by the position of each region (latitude and longitude) and its influence on the regional climate: for instance, Vanoise is in an eastern position, far from Atlantic humid sources; the southern region is characterised by higher angles of incidence. However, the PCA highlights a very low correlation between position and ELA at the alpine scale (fig. 6).

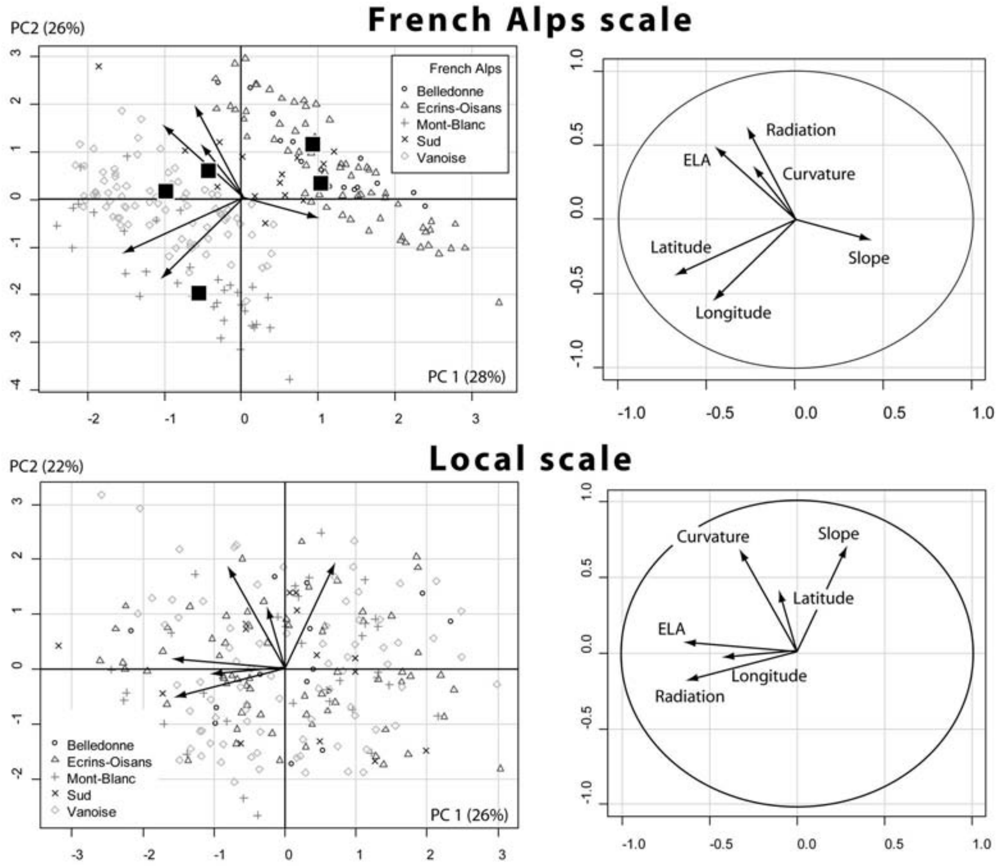

FIG. 6 - Results of the multiscalar PCA. Above: results of the PCA undertaken at the French Alps scale. Below: results according to the region concerned. Note that ISR remains correlated with ELA at all scales, and (at a lesser extent) curvature as well. Slope acts at regional scale, while longitude only incluences ELA at local scale (within region).

Nevertheless, the influence of the distance to the Atlantic Ocean on ELAs acts locally, within each region. This pattern reveals the strong constraint that creates, within a mountain region, the asymmetry (of precipitation) due to rugged relief. When separated by a ridge, mountain slopes facing humid fluxes (west in the French Alps) and mountain slopes sheltered from humid fluxes (east) are highly different in terms of glacierisation. This means that precipitation distribution and then glacier accumulation vary much more according to this local setting than to regional climatic trends (especially continentalisation).

Slope

Three elements suggest that the slope of free faces has a great influence at the French Alps scale (fig. 6, tab. 1). Firstly, if we exclude latitude and longitude, only the slope of free faces is significantly different between regions. Secondly, PCA at the alpine scale suggests a good negative correlation between ELA and slope: the greater the slope, the lower the ELA. Thirdly, this correlation does not appear at the local scale and cannot explain a local differentiation between ELAs. As a consequence, this confirms that each region is characterised by its own topographic setting (especially the slope gradient of free faces), creating significant differentiation. For instance, PCA highlights that Vanoise and the southern regions are differentiated from others by low slope gradients and higher ELAs. Indeed, high slope gradients are known to be prone to snow avalanching, and thus supply snow to glaciers. Such a supplementary supply of snow is probably less efficient in Vanoise and the southern regions, due to their topography and, in turn, to their lithological characteristics. On the other hand, the Ecrins-Oisans region is characterised by the steepest slopes, thus lowering the ELA there.

Locally, the influence of slope on ELA is low (r close to 0; fig. 6). This suggests that even if slope may vary inside a region, such variations do not have any significant influence on glacierisation: curvature, ISR and longitude are more efficient in differentiating ELAs.

AIG INTERPOLATION

Description and validation of results

GWR was conducted; considering the influence of local variability, the selected predictors are the three explanatory variables that act at the local scale: ISR, curvature and longitude. Indeed, a GWR including all variables had been tested, but the adjusted coefficient of determination is better with the three predictors mentioned above (tab. 3). GWR gives statistically significant results: AIG is estimated to range from 2630 m asl to 3280 m asl (fig. 7 A

TABLE 3 - Selection of predictors by a backward stepwise GWR regression. Adjusted r^2 is at maximum with three predictors: Curvature (C), Longitude (Lg) and Incoming Solar Radiation (ISR). Slope (S) and Latitude (Lat) are progressively excluded

Predictors	**R^2**	**Adjusted R^2**	**RMSE**
ISR C Lg Lat S	0.46	0.29	85
ISR C Lg S	0.44	0.34	82
ISR C Lg	0.41	0.37	88

and B), with a mean of 2915 m asl. More precisely, the distribution is bipolar (maximal frequencies at 2830 m asl and 3050 m asl), revealing differentiation between south-facing and north-facing glaciers (fig. 7B). R^2 varies in space, but remains satisfactory (fig. 8A). It ranges from 0.2 in non-glaciated areas (especially on the piedmont, where it is difficult to fit the model because of the lack of relief and glaciers) to 0.47 next to the Ecrins-Oisans or Vanoise regions (where the model can be fitted by close and numerous glaciers). The calculated RMSE is about 88 m: the distribution of residuals fits a Gaussian law, and even if some high values are observed locally (-280 m in Belledonne; +275 m in eastern Vanoise), 70% of the glaciers show residuals comprised between –88 and +88 m (fig. 9). This result is indeed slightly better than recent models (±100 m; Carrivick & Brewer, 2004), and not so far from AIG estimations made on smaller areas (±60 m in Massif des Ecrins; Cossart, 2011). RMSE is also close to the classical inaccuracy of methods of ELA estimation (±50 m in Meierding, 1982; ±45 m in Bate, 2008). Furthermore, a variogram constructed from residuals does not highlight any spatial trend within the residual distribution. Thus, the model efficiently integrates both regional and local trends (fig. 9B).

Model implications

The GWR highlights that the influence of predictors on AIG can vary in space, confirming the non-stationarity of the glacierisation process. Yet, even if all predictors are positively correlated with AIG (fig. 8 B to D), the partial derivatives between AIG and predictors (∂AIG/∂ISR; ∂AIG/∂Curvature; ∂AIG/∂Longitude) vary (fig. 8 B to D) and can be used to identify the spatial organisation and specificities of each region.

In the Mont-Blanc region, ELA reaches its minimum. Another specificity of this area is a high ∂AIG/∂Curvature

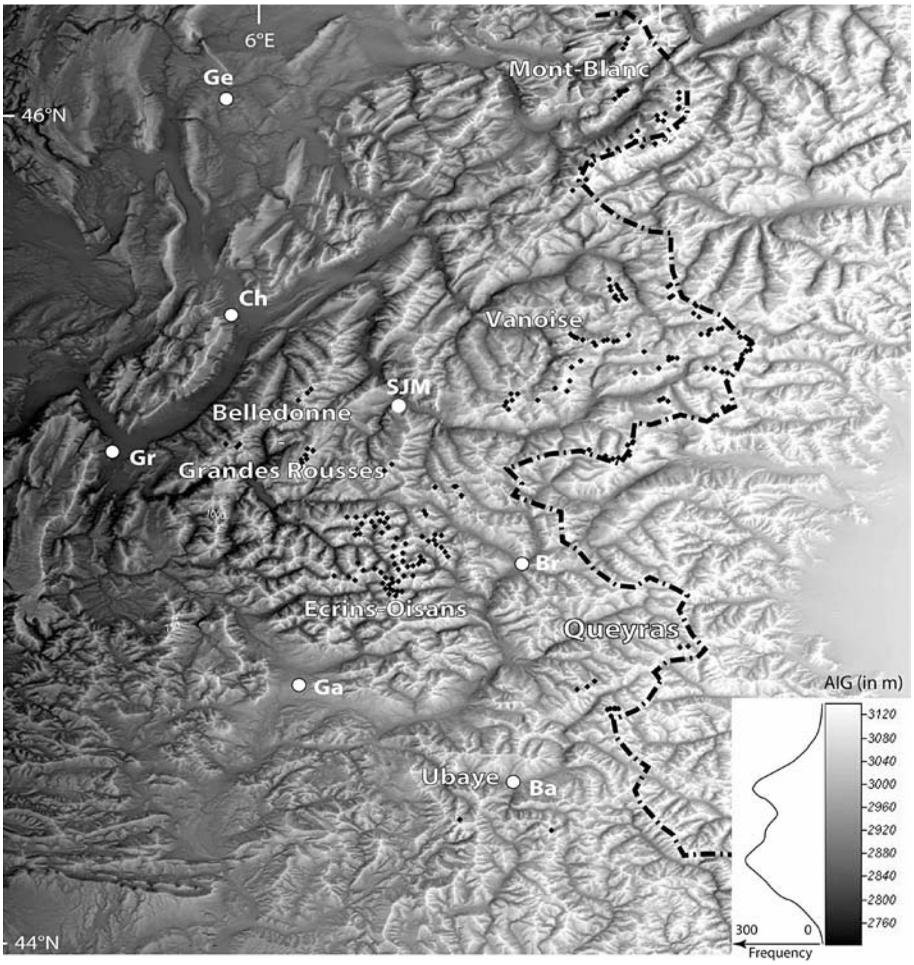

FIG. 7 - Altitude of instantaneous glacierisation (AIG), estimated from the GWR. The frequency (number of pixels) of each AIG value is plotted: note the bipolar repartition.

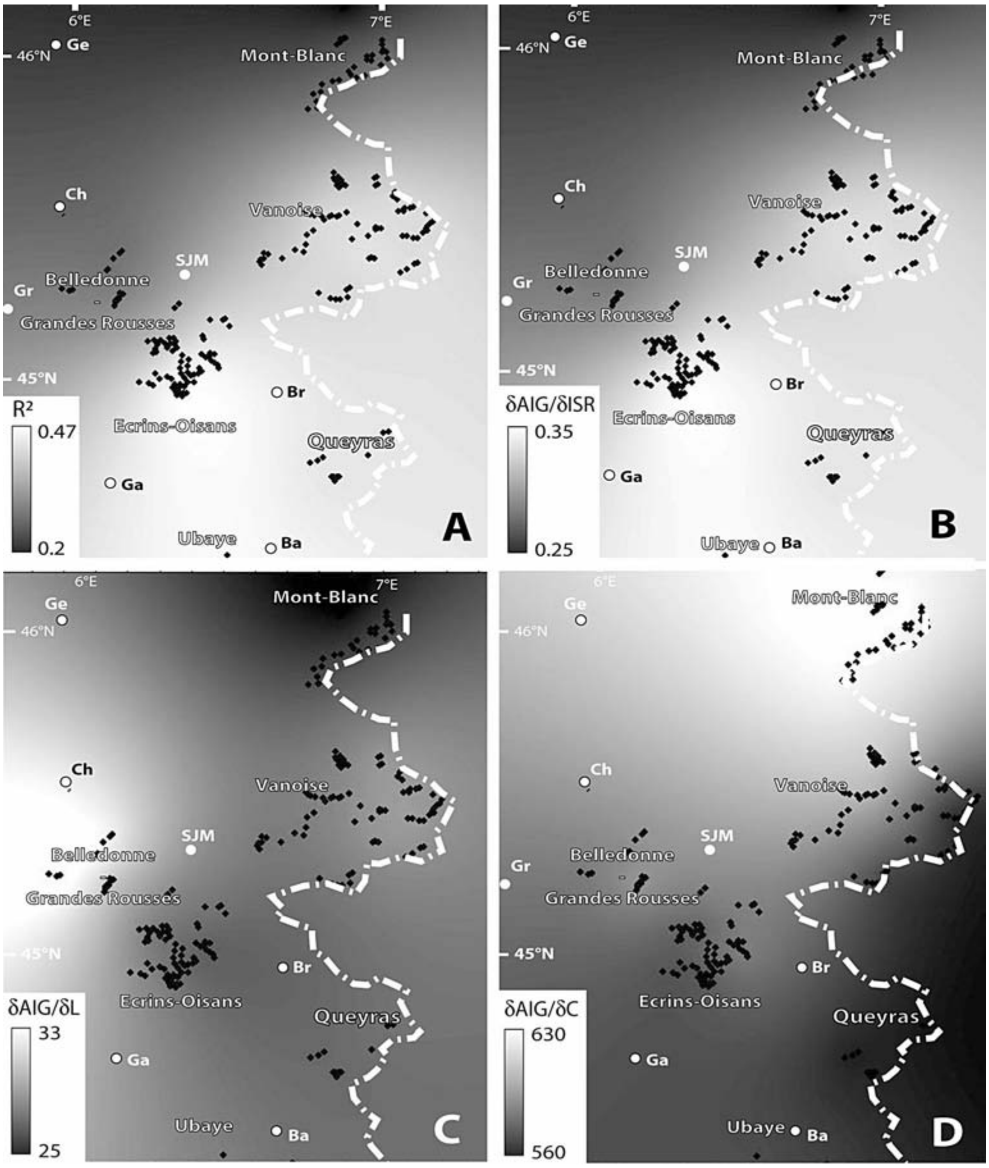

FIG. 8 - Grid maps of partial derivative coefficients and determination coefficient of the GWR. A: Determination coefficient. B: Incoming solar radiation partial coefficient; C: Longitude partial coefficient; D: Curvature partial coefficient. Note the complementary patterns between ISR and longitude partial coefficients.

that reaches its maximum here (fig. 8D), so that AIG decreases significantly when glacier cirques are concave (low curvature index). This suggests that most of the Mont-Blanc glaciers benefit from efficient cold air and snow trapping due to cirque shape. Conversely, ∂AIG/∂Longitude is low suggesting no specific increase in ice-accumulation towards the west. This fact can be due to the very particular topoclimatic setting of this region, entirely over the western part of the highest mountain ridge of the Alps. In this case, precipitation is abundant regardless of the position within the region, thus minimising the influence of longitude.

In the Vanoise region, ELAs are at their maximum, in spite of a quite northern position. It may be noted here that ∂AIG/∂Longitude is also high: more precisely, the local maximum of the coefficient is located in eastern Vanoise, so that AIG increases significantly eastward (fig. 8C). The precipitation distribution, especially in areas sheltered from humid fluxes, appears to be of prime importance. ∂AIG/∂Curvature is also quite high; as cirques in Vanoise are shallower, this in turn generates an AIG rise. This suggests that the shape of cirque glaciers here hampers ice-preservation (as there is less cold air and snow trapping). Nevertheless, the influence of ISR on glaciers is rather low here, or at least lower than in other areas.

Belledonne-Grandes Rousses is characterised by very low AIG. This pattern can be explained by the western position of this region, as ∂AIG/∂Longitude is at a maximum (fig. 8C): consequently, the level of AIG decreases rapidly westward. This suggests a very high influence of precipitation, which is indeed very abundant in such western areas, well exposed to humid, Atlantic fluxes. Furthermore, a high ∂AIG/∂Curvature coefficient is combined with well-shaped concave cirque glaciers (low curvature

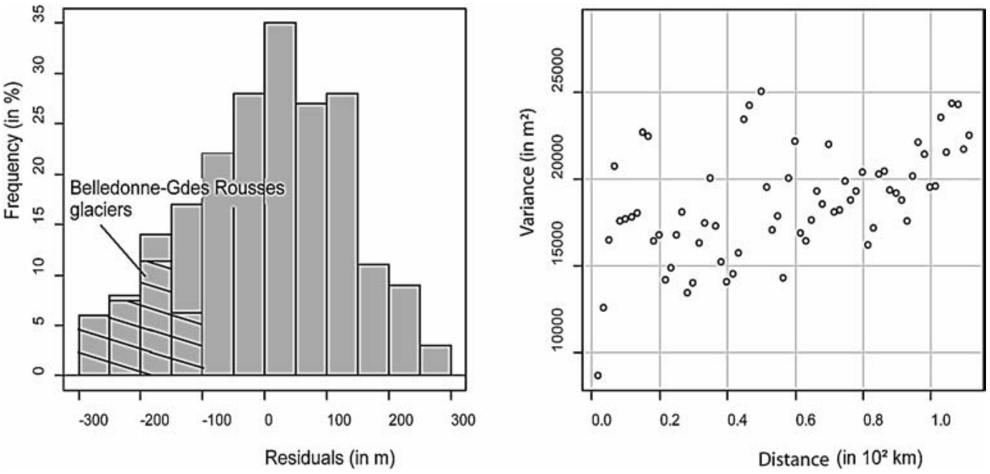

FIG. 9 - Residuals of the GWR results. A: Frequency diagram. B: Variogram. Note the Gaussian distribution of the residuals, and the concentration of Belledonne-Grandes Rousses glaciers in negative, extreme values.

index), especially in the Belledonne (western) area, which contribute to lower AIG.

The Ecrins-Oisans glaciers are in an intermediate position according to AIG values. Nevertheless, a main specificity appears through the ∂AIG/∂ISR ratio, which is at its highest (fig. 8B). As this predictor is highly variable at a local scale, it implies a variety of both AIG and glacier types in this area. Yet, contrasts between north-facing tongue-shaped glaciers (Glacier de la Pilatte and Glacier Coste with ELAs ranging from 2750 m asl to 2850 m asl, respectively) and small south-facing cirque glaciers (Glacier d'Ailefroide, ELA about 3250 m asl) have long been noticed (Rabot, 1902; Cossart & *alii*, 2006; Cossart, 2011) and may be explained by a high sensitivity of glacierisation to aspect.

Southern glaciers are characterised by an ELA quite lower than expected (*i.e.*, ELA is lower here than in the Vanoise region, for instance). Nevertheless, conditions for glacierisation seem poorer here than in Vanoise, as the estimated AIG is higher in this southern region (mean = 3070 m asl) than in the Vanoise region (mean = 3010 m asl). This pattern is due to the high ∂AIG/∂ISR ratio (fig. 8B), combined with exclusively north-facing, well-shaded glaciers. Indeed, as the altitude of topographical units is quite limited (summits above 3000 m asl are rare), conditions conducive to glacier development can only occur in well-shaded areas. Finally, these very specific settings imply a bias; low regional ELAs are artificially due to the lack of glaciers with southern aspects. ELA comparison here is insufficient to reveal the conditions in which glaciers develop: only the AIG may provide new insights.

These results highlight another benefit of this model: an estimation of the AIG at any point allows comparisons between regions gathering different numbers of glaciers. On the one hand, statistically, in regions with few glaciers, these glaciers occur under highly specific conditions conducive to ice-accumulation and ice-preservation, and thus involving a biased reduction of the ELA at a regional scale. On the other hand, this pattern does not occur in regions with many glaciers, often set in various contexts, which may or may not be conducive to ice-accumulation. In this case, AIG comparison (even in non-glaciated areas) prevents any bias.

DISCUSSION

Spatial dependence of mechanisms

Mechanisms conducive to glacierisation are known to evolve in space, mostly because of climatic conditions, and more precisely because of exposure to humid fluxes: continental glaciers are assumed to be less sensitive than maritime glaciers to climate change (Oerlemans & Fortuin, 1992). More precisely, maritime glaciers are strongly related to western fluxes and then precipitation patterns (Nordli & *alii*, 2003; Nesje, 2009) while glaciers are more sensitive to incoming solar radiation in dryer areas (Francou, 1988; Evans, 2006a). This classical pattern is confirmed in the French Alps, as ∂AIG/∂ISR and ∂AIG/∂ Longitude ratios evolve in complementary ways (negative correlation, r = –0.54). On the one hand, the influence of longitude is stronger in wet conditions (*e.g.*, Belledonne-Grandes Rousses), so that the exposure to humid fluxes is of prime importance there. On the other hand, incoming solar radiation or curvature highly influences the ELA variability in sheltered (dryer) areas. This case occurs for instance in Ecrins-Oisans, where a quite low AIG is maintained by the influence of these two predictors. A same pattern is observed very locally in Southern region, in areas where glaciers remain. Yet, the Vanoise region remains the only region where the sheltering effect from humid fluxes cannot be fully compensated for by other predictors, derived from cirque morphometry.

Finally, in the French Alps the subdivision between humid influences and dryer areas mostly corresponds to the external crystalline massifs. On the one hand westward, the Belledonne-Grandes Rousses region is characterised by AIG asymmetry driven by exposure to humid fluxes. On the other hand, eastward, glaciers located in Vanoise, Ecrins-Oisans and the southern regions are sensitive to ISR and curvature, the AIG being lower only in particular settings (well-shaped concave cirques and highly shaded areas). Mont-Blanc area is in an intermediate setting.

Origin of residuals

While our model can explain nearly half of the ELA/AIG variability, residuals remain which should be explored in order to be further reduced. Three main limits are still encountered: firstly, the type of glacierisation and the position of the glacier within a cirque, secondly the different behaviour of debris-covered glaciers, characterised by reduced melting, and thirdly the wind-blown effect on snow (re)distribution.

The influence of lithology and topography on glacierisation has been previously highlighted, so that glaciers located in concave cirques have conditions conducive to ice-preservation (cold-air trapping) and to ice-accumulation (convergence of snow-avalanche fluxes). Consequently, cirque glaciers, well confined at the foot of free faces benefit more from this local effect, and may thus appear less influenced by the direct climate (Dyurgerov & *alii*, 1994; Dyurgerov, 2003; Cossart, 2011). Indeed, the reduction in the area of these glaciers has been tiny given the context of global warming. Meanwhile tongue-shaped glaciers have generally been subject to significant loss before eventually becoming cirque glaciers, by which time the influence of local settings is more important (Kaiming & *alii*, 2011). As a matter of fact, negative feedback may occur during the decay of a glacier: during glacial retreat, glaciers are progressively confined to the foot of free faces, so that they are progressively more influenced by the cirque concavity. In some cases, most of the glacier surface belongs to a cold air trap or to an avalanche area zone, so that the relative importance of snow supply by avalanches increases. As a consequence, the rate at which the ELA rises slows down when glaciers are progressively confined within a cirque (fig. 10). Glaciers have retreated all over the French Alps since the Little Ice Age (Vivian, 1975; Kaiser, 1988; Chardon, 1993; Cossart & *alii*, 2006), but during this decay most cirque glaciers have evolved slightly because of the topographic constraints of free faces, especially in Belledonne-Grandes Rousses and southern regions that encompassed only cirque glaciers during the Little Ice Age. This pattern probably partly explains the lower than expected ELAs in Belledonne-Grandes Rousses and southern regions, in comparison with other regions where glacier tongues were affected by higher rates of ELA rise (fig. 9A).

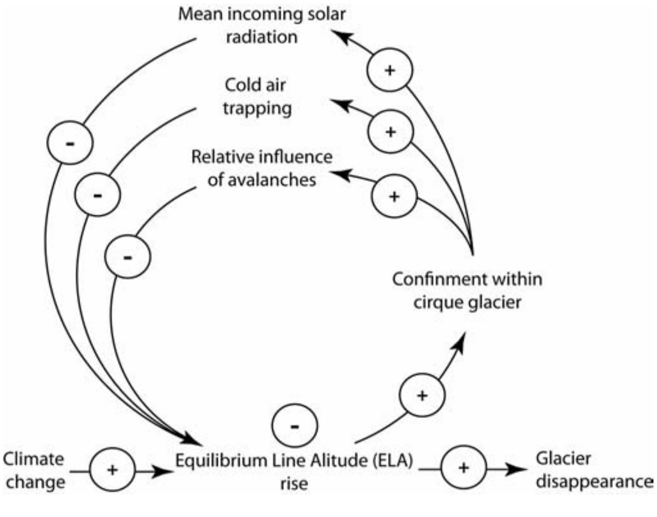

FIG. 10 - Negative feedback during glaciers decay. This feedback may explain why cirque glaciers can be less sensitive to increases in ELA, compared with tongue-shaped glaciers.

Debris cover is known to be an efficient shelter from the sun (Østrem, 1959; Nakawo & Rana, 1999), and may generate an abnormally low ELA (difference to the order of 100 m in Clark & *alii*, 1994; Cossart, 2011). It is nevertheless still difficult to integrate such a parameter within a spatial model, partly because debris cover may thicken or be reduced over time.

Wind-blown snow is a parameter whose influence on snow cover is cited, but only roughly measured because of the complexity of wind phenomena (variability of orientation, intensity, etc.). On a finer scale (Ecrins region), at which dominant winds can be assumed to have a single main orientation, some promising attempts to integrate wind redistribution were made through GIS modelling (Cossart, 2011). Unfortunately, at the French Alps scale, dominant winds are more complex to implement. There may be alternately west fluxes (northern Alps) or south-west fluxes (southern Alps), so that any modelling requires further investigation. Nevertheless, many authors consider that distance to humid sources is rather more important than snow redistribution by wind in all mid-latitudes (Evans, 2006b), with the wind-blown effect being more significant in the quite low relief of high latitudes (Evans, 2011).

CONCLUSION

The present study confirms that both local and regional settings interplay to explain present-day glacier distribution in the French Alps. Nevertheless, if some significant differences between regions are observed, the main variability of ELAs is due to local factors, within each region (about 85% of the total variability). A GWR model enables this local variability to be integrated and AIG to be evaluated at any given point of the area, ranging from 2730 m asl to 3140 m asl, with a mean of 2915 m asl. The non-stationarity of glacierisation is evidenced, discriminating glaciers more sensitive to precipitation (Belledonne-Grandes Rousses region) and others more sensitive to ablation (Vanoise, southern regions). The role of topography (especially curvature) is also of prime importance, as it reveals the possible influence of snow-avalanches on ice-accumulation and cold-air trapping on ice-ablation. Thus, well-shaped concave cirques lower the ELA (*e.g.*, in Belledonne-Grandes Rousses and in Mont-Blanc area, more slightly in Ecrins-Oisans). Another consequence is that Vanoise can be considered as a region where local settings collectively contribute to higher the ELA/AIG.

Finally, AIG can be estimated satisfactorily by GWR and allows the identification of various patterns of glacierisation sensitivity at the French Alps scale. Furthermore, we highlight that AIG estimations at any point prevent misinterpretation when different regions are compared. Indeed, some bias within regional ELA estimations can occur if only few glaciers exist, located in very specific settings, while AIG offers insights even in non-glaciated areas. This work could be built upon by coupling scenarios of climate change with the results of a glacier-distribution model, to better infer the possible consequences of climate change. Indeed, both climatologists and hydrologists have asked for such a regional approach, to better implement their models, defined on grids at the regional scale. Before this, a GWR model should be applied to different times in the past (LIA, various dates within the 20th century) to better document whether the spatial variability of mechanisms also occurred in the past, and more generally to understand how glacier behaviour may evolve.

Collectively, the results reflect that a geographical approach provides complementary insights into questions of glacier distribution and behaviour. Indeed, spatial analysis should be more often coupled with glaciological studies to better integrate the high variability of glacier responses due to local and regional settings.

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