

Evaluating the stabilization susceptibility of active rock glaciers in the French Alps

Marcet et al

The paper has improved since its initial submission. I thank the authors for their very detailed response to my reviews. I have some additional comments that are primarily focused on the introduction and methods. There are also a number of spelling and grammatical errors throughout that should be addressed. I have pointed out a number of them but not all.

We thank the reviewer for this valuable revision of our manuscript. We are glad that previous changes were appreciated and we are glad of this new revision. We agree with most of the comments provided. The manuscript has surely improved. Our English native speaker co-author did a detailed revision of grammar and spelling mistakes.

Abstract

The abstract is much improved, it is clear and concise.

P1L4 ... as a support tool...

Corrected

P1L11 ...model performance was good...

Corrected

P1L19 suggest: The occurrence of permafrost degradation is dependent on the ground properties, snow cover interactions and ground ice content () and is therefore a heterogeneous phenomenon.

Thank you for the suggestion, text modified accordingly

P1L20 suggest: loss in strength

Accepted suggestion.

P2L3 Therefore, there is a growing...

Corrected

P2L4 ... to allow for a targeted risk...

Corrected

P2L11 "...destabilization consists on the onset"? Suggest you reword this sentence

Sentence modified to (P2L11):

"This suggests that the destabilization occurrence is caused by a basal sliding process over the normal creep of the rock glacier"

P2L13 creep-driven sections and sliding sections

Corrected

P2L13 Change the word exceptionally, doesn't make sense here

Changed to *"In very rare circumstances"*

L17 Reword sentence, doesn't work as is

Thank you for noticing. The sentence was not well located. Now we changed to a topic sentence to introduce the paragraph (P2L18):

"The destabilization process can be triggered either by a mechanical forces or changes in climate"

L20 ... leading to destabilization...

Corrected

L21 Sentence does not flow, reword to strengthen the point

Changed to (P2L19-21):

"A warmer climate may also trigger a destabilization crisis as increasing temperatures may cause permafrost degradation of the rock glacier. This process may result in the onset of water saturated shear layers where sliding occurs, triggering the crisis"

L25 – 29 I do not understand what you are trying to present in these sentences.

The sense of the sentences is to point out that the terrain predisposition to destabilization occurrence is fundamental. The sentences are now changed (P2L25-29):

"Although triggers are necessary to the destabilization occurrence, not all rock glaciers subjected to these external forces destabilize. For example, permafrost degradation in rock glaciers mainly causes permafrost thaw and results in inactivation (Scapozza et al., 2010). Destabilization can be triggered only if there is a local topographical predisposition of the rock glacier to this process, such as steep slopes (Roer et al., 2008; Delaloye et al., 2013). Therefore, the terrain attributes of the rock glaciers to the onset of a destabilization phase are a critical parameter in the process occurrence."

Last paragraph of the introduction should be cleaned up to make the point clearer. Also the introduction also does not include any details on the type of model being used. This should be included and should be mentioned in the abstract as well.

This paragraph has been rewritten and point is made more clear. The GAM is now mentioned in the introduction (P3L9)

P3L25 XX century?

Corrected

L27 ..was compiled...

Corrected

L32 20th century has something off with the superscript

Corrected

P4L2 ...similar to ...

Corrected

L4 Provide context for the Laurichard Rock Glacier, where is it? Linked to increasing temperature? Be direct, is this the phenomenon you are talking about?

Sentence modified accordingly (P4L4-5):

“Increasing air temperature was also addressed to be responsible for the acceleration since the late 1990s of the active Laurichard rock glacier located in the Combeynot massif of the French Alps (Bodin et al., 2009).”

L4 Remove sentence...at the same time....

Removed

L3-11 I don't see how the specifics of these examples are pertinent to your study. I would suggest stating that there have been a number of important changes associated with rock glaciers i.e. destabilization due to increasing temperatures, increases in the development of crevasses, and that these changes can/have led to risks in a number of regions. Summarize these examples more effectively.

These examples were required by RC1, as it was requested to specify the link between permafrost and climate change in the region. We nevertheless accept the comment and presented the paragraph in a more succinct form. Please find the new version of the paragraph at P3L32 – P4L9

L33 You state you used all three available orthoimages to ensure that you were mapping surface disturbances and not just compression features. Due to the large temporal gaps how does mapping from the three mosaics help? Are you using the temporal images to identify if new crevasses have formed and hence a surface disturbance? Please clarify this section.

In this section is described the surface disturbances mapping. Here, multiple orthoimages are used to overcome the challenges of using a single image in mapping (as snow cover, bad lightning). Observing the evolution of surface disturbances is a methodology for the destabilization rating.

P5L7 recurrence of features on destabilized rock glaciers...

“Recurrent” was deleted as meaningless and misleading in this sentence.

L8-29 This section presents too many examples without clearly laying out why they are presented. How does past analysis of rock glaciers help you assign destabilization ratings? How did you use the three temporal periods and changes you might have mapped when assigning ratings? This is the type of information that should be highlighted. One or two past examples that you may have used to inform how you interpreted changes is fine but this sections needs to be much more concisely written

We agree that these paragraph were not properly presented. Please note the substantial revision at P5L6-27

To answer the questions:

This section is needed to define how we made the link between destabilization and features observable on multiple images PL6:

“Assigning a rating to quantify the degree of destabilization of a rock glacier required the definition of the characteristics of the “typical” destabilized rock glacier that can be observed on multiple orthoimages. To do so, we investigated the features of destabilized rock glaciers reported in the literature that could be observed by orthoimagery interpretation”

The use of the three orthoimages is now better defined at P5L26 :

“A comparison of the available IGN multi-year orthoimagery was used to observe the temporal evolution of the surface disturbances and surface deformation patterns.”

L30 on P4, L17 you say you split the glaciers into three categories cracks, crevasses, scarps, here you say you are splitting them into two categories...

On P4L17 we are talking about the type of surface disturbances. On P5L30 we are talking about the distinction in two separated categories of rate 3 rock glaciers. The reason why we create two categories of rate 3 rock glaciers is because most of previously known cases of destabilization report the occurrence of both crevasses and scarps (next sentence in text).

P6L18 What predictor variable represents climatic characteristics?

The elevation, as proxy of air temperature, and (partially) the PISR.

P8L15 evidence

Not sure what is meant here by the reviewer. We changed to “evidence of permafrost occurrence”

P9L25 suggest .. m a.s.l, and slope angles ranging....

Suggestion accepted

L28 PISR

Corrected

L28 Based on the figure there doesn't appear to be an increase in destabilization predisposition around 2000 kWh/m2. Please explain.

Thank you for noticing. This is a leftover from the previous version of the model before the major revision. Now the sentence has been deleted.

L30 How did you explore the relationship between PTP and destabilization?

It is now clarified at P9L26-28:

“The relation between PTP and destabilization was also explored by including this predictor variable in the model instead of elevation. Although the PTP caused lower model performance, it could be observed that the PTP was positively correlated with the destabilization.”

P10L1 The susceptibility map models rock glacier stability which you are using as a proxy to identify permafrost areas susceptible to destabilization correct?

Yes correct.

L5 This statement should be followed by some reasoning as to why “The susceptibility map predicted high destabilization susceptibility in areas belonging to stable rock glaciers”

This is defined in the discussion (section 4.3, P12L17) , as in this section are reported only the results.

P12L8 How was PTP found to be a significant predictor of potential destabilization? It wasn't included in the model. What statistics were done to measure significance?

We now avoid to talk about significance. It is made clear that the relation between PTP and rock glacier stability is explored by a separate model where PTP is used instead of elevation (P9L26, see comment above)

Where the map didn't perform well should be discussed. In the results you say "The susceptibility map predicted high destabilization susceptibility in areas belonging to stable rock glaciers" Why?

This is discussed in the dedicated section 4.3

Figure 1

Caption - Identification of the study area.

Corrected

In the legend what does "active production areas are found" mean? It would be useful to include another inset in the bottom left corner with a zoomed in image of one of the mountain ranges. It is difficult to see how the PFI scales with elevation on the map as it is.

The legend is the one of the PFI map, it is now specified the reference of the PFI. This map refers to permafrost conditions at production areas of active rock glaciers. A zoom of the map has been inserted.

Figure 2

What years are the orthoimages that are presented? It would be good if you actually included what you would have mapped on each orthoimage as it is quite difficult to see the features.

The years are added (all 2013). A polygon in each image has been added showing what was actually mapped on these orthoimages.

Figure 7

y-axis is very difficult to see. I would make it clear that you are presenting all variables however PTP wasn't included in the final model.

Axes label fonts have been increased. It is now made clear in the caption that the PTP is not included in the final model.

Figure 8

Is there a full susceptibility map for the entire study area? This may be of interest to many and should be included as a supplementary figure. Even better would be to include it in the paper and then have figure 8 as an inset.

Yes there is a map of the region and is provided as supplementary material. We prefer not presenting it as figure here as it would be almost impossible to see the susceptible zones in such figure (see for example your comment on the figure 1).

Tables

Table 4 Destabilization typo in column 1

Corrected

Table 5 Not called DEFROST susceptibility anymore right? Also based on the low surface area in the 3a class does it make sense to combine 3a and 3b into one class? Also please reorder 1, 2, 3a, 3b

Thank you, DEFROST deleted. Classes are separated for consistency. Rates reordered, also in previous tables.

Evaluating the destabilization susceptibility of active rock glaciers in the French Alps

Marco Marcer^{1,2}, Charlie Serrano^{1,2}, Alexander Brenning³, Xavier Bodin², Jason Goetz³, and Philippe Schoeneich¹

¹Institut d'Urbanisme et Géographie Alpine, Université Grenoble Alpes, Grenoble, France

²Laboratoire EDYTEM, Centre National de la Recherche Scientifique, Université Savoie Mont Blanc, Le Bourget-du-Lac, France

³Department of Geography, Friedrich Schiller University Jena, Jena, Germany

Correspondence: Marco Marcer (marco.marcer@univ-grenoble-alpes.fr)

Abstract. In ~~the present study~~ this study, we propose a methodology to estimate the spatial distribution of destabilizing rock glaciers, ~~focusing with a focus~~ on the French Alps. ~~At first, using recent orthoimages (2000 to 2013) covering the study region, we mapped the~~ We mapped geomorphological features that can be typically found in cases of rock glacier destabilization (e.g. crevasses and scarps) ~~. This database was then used as support tool to rate rock glaciers destabilization. The destabilization~~ using orthoimages taken from 2000 to 2013. A destabilization rating was assigned by taking into account the evolution of ~~the~~ these mapped destabilization geomorphological features ~~and, and by observing~~ the surface deformation patterns of the rock glacier, observable by comparing also using the available orthoimages. ~~The~~ This destabilization rating served then as database input to model the occurrence of rock glacier destabilization in relation to terrain attributes ~~and to, and to spatially~~ predict the susceptibility to destabilization at the a regional scale. Significant evidence of destabilization could be observed in 46 rock glaciers, i.e. 10% of the total active rock glaciers in the region. ~~Modelling the occurrence of destabilization suggested~~ Based on our susceptibility model of destabilization occurrence, it was found that this phenomenon is more likely to occur in elevations around the 0°C isotherm (2700 – 2900 m.s.l.), on ~~north-exposed, steep north-facing slopes, steep terrain~~ (25° to 30°) and flat to slightly convex topographies. Model performance ~~were was~~ good (AUROC \doteq 0.76), and the susceptibility map ~~reproduced well the observable patterns also performed well at reproducing observable patterns of destabilization~~. About 3 km² of creeping permafrost, ~~i.e. or~~ 10 % of the surface occupied by active rock glaciers, had a high susceptibility to destabilization. Considering ~~we observed~~ that only half of this surface is these areas of creep are currently showing destabilization evidence, we ~~suggested that a significant amount of rock glaciers are candidates for future destabilization~~ suspect there is a high potential for future rock glacier destabilization within the French Alps.

1 Introduction

Warmer mean annual air temperatures (IPCC , 2013) are linked to a general trend of increasing permafrost temperature (e.g. Harris et al., 2003) and its water content (e.g. Ikeda et al., 2008) causing permafrost degradation, a phenomenon widely observed in the European Alps (Haeberli et al., 1993, 2010; Springman et al., 2013; Bodin et al., 2015). ~~Permafrost degradation~~

~~occurrence~~ The occurrence of permafrost degradation is dependent on the ground properties, snow cover ~~interactions~~ and permafrost ice content (Scherler et al., 2013) and is therefore an heterogeneous phenomenon. Permafrost grounds affected by degradation experience a loss in ~~stiffness~~ strength due to the increasing ice ductility and reduced internal friction caused by the warmer ice and increasing water content (Davies et al., 2001; Haeberli et al., 1997; Harris and Davies, 2001; Nater et al., 2008; Huggel et al., 2010). Abnormal rockfall activity at high elevations (e.g. Ravanel and Deline, 2010) and increasing rock glaciers displacement rates (Delaloye et al., 2008) are often assumed as indicators of this change of state in the mountain permafrost. These processes may trigger mass movements that, in specific topographic conditions, may represent ~~an~~ a hazard to alpine communities. Therefore, there is a growing need to understand the occurrence of these phenomena at a regional scale to allow for a targeted risk assessment and land use planning (Haeberli et al., 2010).

In this context, rock glaciers experiencing destabilization ~~recently gained~~ have recently become of interest. While active rock glaciers commonly present moderate interannual velocity variations that correlate with the ground temperature (Delaloye et al., 2008; Kellerer-Pirklbauer and Kaufmann, 2012; Bodin et al., 2009), destabilized rock glaciers are characterized by a significant acceleration that can bring the landform, or a part of it, to abnormally high velocities (Delaloye et al., 2013; Roer et al., 2008; Scotti et al., 2016; Lambiel, 2011; Eriksen et al., 2018). During this acceleration phase, morphological features typical of sliding processes, such as crevasses and scarps, appear and grow on the rock glacier surface. This suggests that the destabilization ~~consists on the onset of~~ occurrence is caused by a basal sliding process over the normal creep ~~of the rock glacier~~ movment of rock glaciers (Roer et al., 2008; Schoeneich et al., 2015). In this sense, crevasses and scarps are interpreted as the possible transition between ~~the~~ creep-driven ~~and the~~ sections and sliding sections of the landform (Roer et al., 2008). This ~~acceleration~~ destabilization phase, also referred as a "surge" (Schoeneich et al., 2015) or a "crisis" (Delaloye et al., 2013), may last decades and it ~~commonly resolves usually results~~ in a deceleration or inactivation of the landform. ~~Exceptionally~~ In very rare circumstances, destabilized rock glaciers may reach complete failure and collapse in a landslide (Bodin et al., 2016).

~~Since destabilization and increased displacement rates may precondition significant mass movements that in particular topographic setting may represent an hazard (Kummert and Delaloye, 2018), it is relevant to understand its genesis and occurrence~~ The destabilization process can be triggered either by a mechanical forces or changes in climate. An overload on the glacier surface caused by a landslide or glacio-isostatic uplift can cause a compressive wave that propagates through the landform increasing its displacement rates ~~and consequent~~ leading to destabilization (Delaloye et al., 2013; Roer et al., 2008). ~~Warmer climate and linked permafrost degradation on the other hand, is assumed to cause an increase of water content in the permafrost body and the~~ A warmer climate may also trigger a destabilization crisis as increasing temperatures may cause permafrost degradation of the rock glacier. This process may result in the onset of water saturated shear layers where sliding ~~may occur, possibly occurs~~, triggering the crisis (Lambiel, 2011; Schoeneich et al., 2015; Eriksen et al., 2018). The onset of crevasses and scarps can also increase the predisposition of the landform to trap ~~meteoric~~ water percolating into the permafrost body, causing a positive feedback process of destabilization (Ikeda et al., 2008). ~~Nevertheless~~ Although triggers are necessary to the destabilization occurrence, not all rock glaciers ~~experiencing permafrost degradation or mechanical overload are, or will be, destabilized. Permafrost degradation generally subjected to these external forces destabilize. For example,~~ permafrost degradation in rock glaciers mainly causes permafrost thaw ~~in the landform and consequent~~ and results in inacti-

vation (Scapozza et al., 2010). Destabilization ~~was observed only in rock glaciers presenting a topographical predisposition to mass movements, can be triggered only if there is a local topographical predisposition of the rock glacier to this process, such as steep slopes and flow across a convex section (Roer et al., 2008; Delaloye et al., 2013). This suggests that there is a terrain predisposition (Roer et al., 2008; Delaloye et al., 2013). Therefore, the terrain attributes~~ of the rock glaciers to the onset of a
 5 destabilization phase are a critical parameter in the process occurrence.

The purpose of this study was to obtain regional-scale insights into the issue of destabilizing rock glaciers in the French Alps. ~~In this region periglacial environment is abundant and occurrence of rock glacier destabilization was observed (Echelard, 2014; Bodin et al., 2015). Periglacial hazards therefore may exist and, given the dense urbanization of this region, the need for tools allowing a comprehensive risk assessment is crucial (Bodin et al., 2015). To do so, the present study proposed a two step methodology to~~
 10 Destabilization has been observed by several studies in the region (Echelard, 2014; Bodin et al., 2016; Serrano, 2017; Schoeneich et al., 2018); however, there has not yet been a comprehensive assessment of this phenomenon. This was done by (i) identify-identifying
the rock glaciers showing evidence of destabilization and, in order to provide an assessment of destabilized landforms, and
by (ii) model-modeling the occurrence of this phenomena in relation with local terrain attributes. At first, geomorphological
features observed in destabilization cases, here called "surface disturbances" were mapped phenomenon, in order to spot rock
 15 glaciers susceptible to incoming destabilization. Destabilized rock glaciers identification was performed by multi-temporal
 aerial image interpretation based on expert field knowledge (Section 2.2). ~~Surface disturbances were then used as support tool~~
The geomorphological features typically occurring on destabilized landforms such as scarps and crevasses, here called "surface
disturbances", were mapped and used to assign a destabilization rating ranging from 0 to 3 to each active rock glacier (Section
 2.2.1). Rock glaciers ~~classified attributed~~ with higher destabilization rating ~~presented-have~~ typical geomorphological charac-
 20 ~~teristics reported in known cases of destabilization, as-including~~ pronounced surface disturbances that increased by number
 and size in the past decades. These rock glaciers were suggested to be potentially destabilized while ~~, on the other hand,~~ rock
 glaciers not presenting surface disturbances were classified with lower ratings of destabilization (i.e. stable rock glaciers).
~~Evidence of presence/absence of rock glacier destabilization was used to model rock glacier stability in relation to terrain~~
~~parameters-~~
 25 The following step, i.e. modeling the destabilization occurrence, was performed by using a statistical approach ~~similar to~~
~~landslide science (Goetz et al., 2011) (that has been used for mapping landslide susceptibility (Goetz et al. (2011); Section~~
 2.3). ~~This allowed~~ Potentially destabilized rock glaciers were used as destabilization evidence and their relation with terrain
attributes (e.g., slope angle and elevation) was modeled using a Generalized Additive Model (GAM). This model can be applied
to better understand the relationship-relation between destabilization occurrence and terrain predisposition, and to compute a
 30 destabilization susceptibility map, which provides an overview of potentially destabilizing landforms at the-a regional scale
 (Section 2.3.1). Strengths and limitations of the methodology are widely discussed in the manuscript, as well as the contribution
 of the study to ~~the knowledge concerning enhancing our knowledge~~ rock glacier destabilization.

2 Methods

2.1 Study area and rock glacier inventory

The French Alps cover an area approximately 50-75 km wide and 250 km long, located between 44° and 46°S-N and 5.7° to 7.7°W (Figure 1). Apart from the noticeably high Mont Blanc massif (peaking at 4810 m.a.s.l.), mountain ranges commonly peak between 3000 and 4000 m.a.s.l.. The lithology is heterogeneous across the region. The Northern French Alps can be roughly divided into the West side, dominated by granite and gneiss (ranges of Mont Blanc, Belledonne, Ecrins and Grandes Rousses), and East side, where ophiolites and schists are more common (ranges of Vanoise, Thabor and Mont Cenis). In the Southern French Alps ophiolites, limestone and mica schists are the most common lithology (ranges of the Ubaye), while the crystalline range of Mercantour can be found at the southernmost end of the region. Dominant geology is described the BRGM (2015) at 1/ 1 000 000 scale, and the vectorial version of this map is used in this study to observe destabilization occurrence in relation to lithology.

In this region permafrost ~~is was~~ estimated to cover up to 770 km² (Boeckli et al., 2012; Marcer et al., 2017). The 0°C annual isotherm at the end of ~~XX-the 20th~~ century ranged from 2500 m a.s.l. in the ~~Southern-ranges-down-south~~ to 2300 m a.s.l. in the ~~Northern-sectors-north~~ (Gottardi , 2009). The periglacial landforms of the region were inventoried by the "Office national des forêts" (ONF: the National Forest Office) (Roudnitska et al., 2016). ~~This inventory, and revealed the high presence of active rock glacier in the region (i.e. 493 mapped rock glaciers). This inventory was~~ compiled between the years 2009 – 2016 by inspecting aerial imagery ~~in-Geographical-Information-System-(GIS)-and revised by Marcer et al. (2017), revealed the high incidence of active rock glaciers in the region (i. e. 493 landforms)-~~. This inventory was used in the present study to identify active rock glaciers locations and ~~to~~ investigate the occurrence of destabilization.

According to Auer et al. (2007), mean annual air temperature increased by up to 1.4°C in the ~~European-French~~ Alps during the ~~20th-th~~ century, and this rate has been increasing in recent decades. This ~~climatic-climate~~ warming is suspected to have caused some ~~quantifiable-noticeable~~ effects on the permafrost characteristics in the region. The only deep permafrost borehole in the region, located in the Ecrins massif in temperate permafrost (-1.3°C) with low ice content, showed a temperature increase rate of 0.04°C per decade between 2010 and 2014 (Schoeneich et al., 2012), ~~similarly-similar~~ to others sites in Switzerland where data series are longer (PERMOS , 2016). ~~The-increase-of-the-Increasing air temperature was also addressed to be responsible for the acceleration since the late 1990s of the active~~ Laurichard rock glacier ~~velocity-since-the-late-1990s-is also-suggested-to-be-linked-to-this-phenomenon-(Bodin-et-al.,-2009). At-the-same-time, several-located in the Combeynot massif of the French Alps (Bodin et al., 2009). Several~~ cases of rock glacier destabilization were ~~observed-In-2006-the-also observed in the region, as the collapsed~~ Berard rock glacier ~~collapsed-causing-a-landslide-of-250-000 m³, a very exceptional event that was possibly linked to the rare characteristics of this site, e.g. uncommonly fine grained debris (Bodin et al., 2016)-Echelard (2014)-identified-another-case-of-a-striking-destabilization-(Bodin et al., 2016) and~~ the Pierre Brune rock glacier ~~which-was-developing-a-series-of-deep-crevasses-while-also-accelerating. In-2015, a debris-flow-that-was-triggered-by-a concentrated-flow-at-the-front-of-a-destabilized-rock-glacier, the Lou-rock-glacier, reached-the-town-of-Lanslevillard, damaging some infrastructures (Schoeneich et al., 2017). In-a-first-attempt-to-get-a-regional-overview,(Echelard , 2014). Serrano (2017)~~

mapped destabilized rock glaciers in the Maurienne valley, Vanoise national park and Ubaye valley, highlighting the high incidence of destabilized rock glaciers in these areas.

2.2 Mapping rock glacier destabilization

The first step to identify destabilized rock glaciers was mapping surface disturbances on rock glaciers. Previous studies that described destabilized rock glaciers showed that these landforms present a wide variety of geomorphological features (e.g. Roer et al., 2008). Here, we followed a methodology similar to Serrano (2017), which consisted of defining a catalogue of typical surface disturbances that can be found on destabilized rock glaciers. Surface disturbances on rock glaciers were classified in three distinct categories, depending on their morphology and triggering causes: cracks, crevasses and scarps. Surface disturbances are described in detail in Table 1 and illustrated in Figure 2.

In this study, surface disturbances were mapped for the inventoried rock glaciers based on interpretation of a set of multi-temporal high-resolution aerial imagery for the French Alps. This orthoimagery collection was obtained from the Institut géographique national (IGN, National Institute of Geography), which is freely available from the official website (www.geoportail.fr) or can be accessed as a Web Mapping Service (IGN, 2011a, 2013). The IGN orthoimagery collection consists of orthomosaics covering all of France for three different collection periods. The first orthomosaic is composed of images taken from 2000 to 2004, the second from 2008 to 2009, and the third from 2012 to 2013. All images are of high-resolution: 50 cm x 50 cm for the most recent mosaic and slightly lower values (1 m x 1 m at its lowest) for the older mosaics, depending on the location. This resolution was sufficient to identify the smallest features to be mapped, i.e. the surface cracks (Figure 2a). Nevertheless, several limitations during the mapping process were encountered, as image distortion or illumination, and will be discussed in section 4.4.1.

Using a single orthoimage to map surface disturbances can lead to misinterpretations in the case of poor illumination of the terrain and snow patches covering the ground (Serrano, 2017). Indeed, as the surface morphology of a rock glacier is naturally shaped according to spatially varying creep patterns, it is easy to mistake actual surface disturbances related to compression features, such as furrows, depending on image quality. Therefore, surface disturbances, i.e. those morphological features not related to the creeping of the ice-rich permafrost, were mapped using all three available orthoimages in order to check that actual strain occurred where surface disturbances were located and to overcome limitations related to poor quality of an individual image.

2.2.1 Rating the degree of destabilization

After the rock glacier surface disturbances were mapped, a rating of the degree of destabilization was assigned to each rock glacier. This rating was given not only to provide some insight to the observed levels of destabilization in the French Alps, but also to provide a confidence rating to describe a rock glacier as stable or unstable for the spatial distribution modelling of rock glacier destabilization.

Assigning a rating to quantify the degree of destabilization of a rock glacier required the definition of the characteristics of the “typical” destabilized rock glacier that can be observed on multiple orthoimages. To do so, we investigated the

recurrent features of destabilized rock glaciers reported in the literature that could be observed by orthoimagery interpretation. The Berard rock glacier showed a crevasse since 1947, which did not evolve until the early 2000s (Bodin et al., 2016). In 2003 the crevasse seemed to deepen and a new one formed a few tens of meters further east of the original. The rock glacier collapse took place where these crevasses were located. In At first, it was observed that the presence of surface disturbances was a necessary but not sufficient condition to the occurrence of destabilization, as rock glaciers may present surface disturbances but be stable for decades. For example, in the Pierre Brune (Figure 2b), Roc Noir (Figure 2a) and Hinteres Langtarkar rock glaciers a series of scarps and crevasses cut the whole body and divided the rock glacier into two zones with different velocities (Echelard, 2014; Serrano, 2017; Roer et al., 2008). Although surface disturbances, although crevasses could be observed in aerial imagery since the 1940s to the 1960s (Figure, destabilization occurred only in the late 1990s (Echelard, 2014; Serrano, 2017; Roer et al., 2008). Second, the destabilization process can be linked to an increase of surface disturbances occurrence (see Figure 3) evolution in terms of quantity and size were linked to the increased displacement speed of the sectors of the rock glacier downstream the surface disturbances, which occurred since the 1990s. Earlier, the rock glacier seemingly crept uniformly. A similar pattern was observed on the). Also, surface disturbances on destabilized landforms were observed to create a discontinuity in the creep pattern. For example, the Plator, Grosse Grabe and Gänder rock glaciers, where a scarp marked the have gone through a sharp transition from displacement speeds in the order of 0.1 – 0.9 m/y to displacements speeds of the order of several meters per year (Scotti et al., 2016; Delaloye et al., 2008).

These observations suggested that the presence of surface disturbances was a necessary but not sufficient condition to the occurrence of destabilization, as rock glaciers may present surface disturbances but be stable for decades. Also, high speeds. Finally, a high displacement rate may not be a necessary feature, as some destabilized rock glaciers, e.g. Lou and Furggwanghorn, moved at a “normal” rate of around 2 m/yr (Schoeneich et al., 2017; Roer et al., 2008). On the other hand, the agreement between the discontinuity of the surface

These observations suggest that destabilization may be spotted in orthoimages if the landform has surface disturbances increasing overtime time by frequency and/or magnitude, as well as if disturbances also create a strong discontinuity in the deformation pattern of the rock glacier and the surface disturbances was suggested to be a key pattern in destabilization. The co-occurrence of these two conditions was found in every known case of destabilization here analyzed. Considering landform. Nevertheless, rock glaciers were observed to show a wide variety and combination of these features, making it unrealistic to construct a binary classification of stable versus destabilized landforms. In order to acknowledge this, we proposed a rock glacier destabilizing rating destabilization rating based on four rates that varied from 0 (stable rock glaciers) to 3 (rock glaciers potentially destabilized), explained in which is explained in more detail in Table 2. For each active rock glacier, a rating of the degree of destabilization was assigned by observing the combination of surface disturbances and a qualitative assessment of recent deformation patterns. This rating was applied using a standardized workflow (Figure 4). Temporal evolution was assessed by observing the IGN orthoimagery collection. A comparison of the available IGN multi-year orthoimagery was used to observe the temporal evolution of the surface disturbances and surface deformation patterns.

Potentially destabilized rock glaciers were ultimately then classified into two different categories according to the type of surface disturbances observed. Most of the destabilization cases observed by previous studies described rock glaciers charac-

terized by surface disturbances that may reach several meters of depth, i.e. crevasses and scarps, and therefore suggested to split the permafrost body. These surface disturbances ~~can be~~ were mostly observed in coarse grained (i.e. blocky, sensu Ikeda and Matsuoka (2006)) rock glaciers. Nevertheless, in the French Alps many active rock glaciers are fine grained, and some destabilization cases, e.g. the Lou (Schoeneich et al., 2017) and Iseran (Serrano, 2017) rock glaciers, were observed to be
5 characterized by the presence of cracks only. These surface disturbances are shallower than crevasses and scarps ~~and~~, and are therefore suggested to affect only the upper layer of the rock glacier. As these observations were relatively recent, at present there is still not enough knowledge concerning the significance of these shallow cracks in the context of rock glaciers destabilization. We therefore decided to separate rock glaciers showing shallow surface disturbances from rock glaciers showing deep surfaces disturbances ~~into two distinct classes in order~~. This distinction was made to make the reader aware of this gap in
10 knowledge.

2.3 Modelling rock glacier stability

Modeling the rock glacier stability aims to identify the terrain attributes that may precondition rock glacier destabilization. The modelling followed a statistical approach similar to previous ~~spatial prediction~~ studies on landslides (Goetz et al., 2011) and arctic permafrost slope failures (Rudy et al., 2017) that used the Generalized Additive Model (GAM) with logistic link
15 function (R package "mgcv"). The GAM was selected because of its flexibility in modelling non-linear interactions between dependent and predictor variables. The logistic link function allows us to model the occurrence of a categorical response variable as a function of continuous variables (predictor variables). All numeric predictors were represented using spline-based ~~smooths~~ smoothing, for which we chose a maximum basis dimension of 4 in order to limit their flexibility and reduce overfitting. The actual degree of smoothness of the ~~spline smooths is~~ splines were determined by a generalized cross-validation procedure
20 (Wood, 2017).

In this study, rock glacier stability was hypothesized to be preconditioned by a series of local terrain attributes. In particular, rock glacier destabilization grouped by either presence or absence ~~, was~~ was used as the response variable, while terrain attributes describing local topography and climate were used as predictor variables. ~~The multiple~~ Multiple variable models were computed using different combinations of predictor variables. Different models were compared using the Akaike Information Criterion (AIC), which is a measure of goodness of fit that penalizes more complex models. The best multiple variable
25 model was selected by iterating a backward-and-forward stepwise variable selection, aimed to identify which combination of predictors ~~was~~ were better at describing the response variable by means of a lower AIC. Finally, the best model performance was estimated using the Area Under the Receiver Operating Characteristic (AUROC) (Hosmer and Lemeshow, 2000). The AUROC estimates the ability of the model to discriminate stable and unstable areas.

30 The predictive power of the model was estimated by spatial cross-validation (R package "sperrorest"). The method selected was the k-means clustering, which consisted ~~in dividing the database of~~ dividing the our mapped data in k spatially contiguous clusters (Ruß and Brenning, 2010a). All but one ~~clusters~~ cluster were used to train the model, while the remaining cluster was used to test the predictive power of the model. This process was repeated until each cluster was used at least once in both training and test sets. Here, we divided the database into $k = 5$ clusters of equal size per run and used 100 repetitions.

Performance indicators were evaluated on the respective test sets, and the overall model performance was evaluated using the average and standard deviation over all partitioning clusters.

The variable importance was assessed using permutation-based variable importance embedded in the spatial cross-validation (Ruß and Brenning , 2010b). This method consisted of permutating the values of each predictor variable one at a time and calculating the reduction in model performance caused by the permutations. One thousand permutations were performed for each spatial cross-validation repetition. Predictor variables causing higher deviations while permutated were considered the most important ones in the model.

2.3.1 Model response variable

Surface disturbances of potentially destabilized rock glaciers were used as evidence of creeping permafrost destabilization. This was done under the hypothesis that surface disturbances were the geomorphological expression of rock ~~glaciers~~ glacier destabilization. Although, many surface disturbances could be observed on rock glaciers that were classified as unlikely destabilized or as suspected of destabilization, potentially destabilized rock glaciers could be observed to increase surface disturbances ~~in~~ over time by number and size, creating a discontinuity in the deformation pattern, ~~suggesting a~~ which provided stronger evidence of destabilization. Therefore, only surface disturbances located in potentially destabilized rock glaciers were considered as solid evidence of rock glacier destabilization.

As surface disturbances were digitized as linear features, they were buffered and merged into an “unstable areas” polygon database. A buffer distance of 30 m was chosen. The model was found to be insensitive to changes in buffer size up to 90 m. All remaining areas within the polygons of stable and likely stable rock glaciers were used as “stable areas”. Polygons of both unstable and stable areas were sampled using a 25 m x 25 m point grid in order to assign the response variable to the modelling database. The point values were then used as binary response variable with values of 0 for stable areas of (likely) stable rock glaciers, while 1 was assigned for unstable areas of potentially destabilized rock glaciers in the modelling stage.

Since the rock glacier inventory counted a relatively small number of potentially destabilized cases (46 individuals), selecting only one point per rock glacier would have caused large uncertainty in the model outcome. ~~It was therefore performed~~ Therefore, a simple exploratory analysis ~~aimed was performed~~ to identify a suitable ~~amount number~~ of points per rock glacier to be used ~~in for~~ modeling. Multiple points ~~from one to ten~~ were randomly selected within each rock glacier perimeter and used to compute a model. This was repeated ten times per each point sample size ~~in order to~~ measure the variability of the model performance in relation to the point sample size. Since the model performances were found to stabilize for more than five points selected per rock glacier, ~~this the~~ number of points ~~was randomly extracted per rock glacier for modelling used~~ for modelling was five. Overall, the model was computed using 225 points with evidence of instability and 1785 points with evidence of stability.

2.3.2 Model predictor variables

Terrain attributes used in modelling needed to be selected to ~~represent as proxies the~~ act as proxies for processes that precondition destabilization. Although destabilization is found to occur in different conditions, some topographical features seem to

be recurrent. Destabilization ~~is~~has been observed to occur on steep slopes, as high slope angles tend to increase the internal shear stress (Delaloye et al., 2013). Surface disturbances are often located in convex ~~bedrock~~shaped bedrock surfaces, which causes an extensive flow pattern and a thinning of the permafrost body (Delaloye et al., 2013). Solar exposure also may be significant in the destabilization occurrence ~~as, for example~~since all known cases of destabilized rock glaciers in the French Alps are ~~North~~north facing. Solar exposure can also be a proxy of the snow cover duration, as ~~north-facing~~north-facing slopes are more prone to conserve longer snow patches through the summer ~~, making meltwater~~making melt water available through the summer. Elevation ~~as well is a proxy of snow cover duration as well as~~and mean annual air temperature ~~, possibly affecting~~can also be proxies of snow cover duration that have the possibility to affect permafrost characteristics. Considering this, slope angle, profile curvature, potential incoming solar radiation (PISR) and elevation were tested as predictor variables.

Terrain attributes were derived from the BD Alti DEM, 25 m × 25 m spatial resolution (IGN , 2011a). Slope angle and downslope curvature (Freeman , 1991) were evaluated using the Morphometry Toolbox in SAGA GIS (version 2.2.2, Conrad et al. 2015). Negative values of curvature indicate concave topography, while positive values indicate convex topography. Also PISR was calculated using the Terrain analysis toolbox in SAGA as the sum of the computed direct and diffusive components of the radiation (Wilson and Gallant , 2000). Clear-sky conditions, a transmittance of 70 %, and absence of a snow cover were assumed in the calculation of the annual total PISR.

Finally, it was decided to evaluate the relation between rock glacier destabilization and the spatial distribution of degrading permafrost in order to give an insight on the significance of the warming climate with respect to the destabilization phenomena. The spatial distribution of degrading permafrost was evaluated following the method already presented by other studies (Hoelzle and Haeberli , 1995; Lambiel and Reynard , 2001; Damm and Felder , 2013), which consisted ~~in~~of artificially shifting a permafrost map proportionally to the estimated climate warming ~~occurred~~occurring between the period of validity of the map and the current climate. Here, ~~as permafrost distribution map of the region we used the~~we used a Permafrost Favourability Index (PFI) map (Marcer et al., 2017) ~~.The~~to acts as a permafrost distribution map for the region. The PFI map was calibrated using active rock glaciers as ~~permafrost evidence~~evidence of permafrost occurrence, and it represents the permafrost conditions during the cold episodes of the Holocene, e.g. Little Ice Age (LIA). The climate warming between the years 1850-1920 and 1995-2005 was determined using the HISTALP database (Auer et al., 2007) over the region. A permafrost distribution map was then recomputed taking into account ~~of~~ these temperature variations and represented the theoretical permafrost distribution in equilibrium with the current climate. By comparing this theoretical permafrost distribution and the PFI, ~~it was obtained a~~map of the Potential Thawing Permafrost zone (PTP, i.e. the so-called “melting area” in Lambiel and Reynard (2001)) ~~was~~obtained. In order to use the PTP as predictor variable, it was represented by an index ranging between 0, i.e. no thaw expected, and 1, i.e. potential thaw.

It ~~is~~should be emphasized that PTP is only a proxy of permafrost degradation, which occurs at all the elevations, while the PTP zone consists ~~in~~of a belt of 250 to 300 meters ~~elevations~~in elevation that affects about 50% of the lower margins of the permafrost zone (Figure 5). PTP is used under the hypothesis that degradation is more intense at the lower margins of the permafrost zone ~~as permafrost may be~~where permafrost conditions may be more temperate, richer in water, and more sensitive to climate variations.

2.3.3 Susceptibility modelling

The model ~~was of rock glacier stability was also~~ used to predict the occurrence of degrading permafrost over the French Alps ~~obtaining the by producing a~~ susceptibility map (e.g. Goetz et al., 2011). This was done using the R package RSAGA and the raster images of the predictor variables maps, which allowed ~~to extrapolate~~ extrapolating the relationships between rock glacier stability and terrain attributes at the landscape scale. ~~It is emphasized that, being the model calibrated~~ We would like to highlight that since the model is constructed using data on destabilized rock glaciers, the susceptibility map ~~is significant only for the~~ applies mainly for processes relative to destabilization of ice-rich debris slopes. Therefore, in areas where creeping permafrost does not exist ~~the map was extrapolated and it may fail or be meaningless,~~ the extrapolated susceptibility may have high uncertainty. The model predicted a DEFROST index which was classified into five susceptibility zones using the 50, 75, 90, and 95 percentiles (Rudy et al., 2017; Goetz et al., 2011). These zones described very low (<50), low (50 – 75), medium (75 – 90), high (90-95) and very high (>95) susceptibility to permafrost destabilization.

3 Results

3.1 Destabilized rock glaciers inventory

More than 1300 surface disturbances were digitized, involving 259 active rock glaciers (Figure 6). Overall, more than the 50% of the active rock glaciers may be affected by some degree of destabilization as 46 rock glaciers (9.7%) showed potential destabilization, 86 (17.0%) were suspected of destabilization and 127 (25.7%) were unlikely destabilized. Only 13 potentially destabilized rock glaciers presented deep surface disturbances.

Potentially destabilized rock glaciers were mainly located in in the Vanoise National Park and in the Queyras and Ubaye mountain ranges. In these areas, densely jointed lithologies ~~, as (i.e., ophiolites and schists,)~~ dominate. Rock glaciers in crystalline lithologies ~~, (i.e., gneiss and granite, were found showing)~~ were found to have low rates of destabilization, ~~i. e.,~~ That is, only two rock glaciers were rated as possibly destabilized over a population of 55 (Table 3).

The predominant surface disturbance observed were cracks, which were present ~~on in~~ 187 of the active rock glaciers (Table 4). Crack clusters also had a high number of observed cases (152), while the deep surface disturbances occurred in about 15% of all the examined rock glaciers. In general, the ~~occurrence~~ occurrences of surface disturbances were dependent on the destabilization rating. Scarps and crevasses were found in about 10% on unlikely destabilized landforms. The observation of each surface disturbance was highest for potentially destabilized rock glaciers with deep surface disturbances, indicating that in these landforms multiple surface disturbances coexist.

3.2 Modelling

Following a stepwise backward and forward selection, the chosen model included PISR, slope angle, elevation and curvature as predictors. The mean cross-validated AUROC was 0.76 on the test set, indicating a good performance (Hosmer and Lemeshow

, 2000). The predictors having most influence on the response variable were the PISR (AUROC change = 0.162), curvature (AUROC change = 0.068), slope angle (AUROC change = 0.031) and elevation (AUROC change = 0.018).

The model transformation functions revealed the relations between terrain attributes and rock glacier stability (Figure 7). ~~Surface disturbances were~~ Higher predisposition to destabilization was more likely to occur in an altitudinal range between 2700 and 2900 m a.s.l. ~~Slope and slope~~ angles ranging between 25 and 30° ~~were associated with higher predisposition to destabilization~~. Slightly negative to positive curvature was also favourable to destabilization. PISR was negatively correlated with the destabilization probability, indicating that rock glacier destabilization was more likely to occur on north-facing slopes. ~~For higher PSIR, i.e. around 2000 kWh/m² destabilization predisposition is found to grow again. Although not used in the final model and therefore reported for exploratory purposes only.~~ The relation between PTP and destabilization was also explored by including this predictor variable in the model instead of elevation. Although the PTP caused lower model performance, it could be observed that the PTP was positively correlated with the destabilization.

3.3 Susceptibility map

The susceptibility map highlights creeping permafrost areas susceptible to destabilization based on regional-scale model predictions (examples shown in Figure 8). The susceptibility map reproduced well the previously known cases of destabilization. The destabilized areas of the Iseran, Roc Noir and Pierre Brune were predicted to ~~be at~~ have a high susceptibility to destabilization ~~coherently to,~~ which matches field observations. In some cases, the susceptibility map predicted high destabilization susceptibility in areas belonging to stable rock glaciers.

Rock glacier surfaces were investigated with respect to each susceptibility class (Table 5). About 75% of the creeping permafrost was found at low or very low susceptibility to destabilization. Creeping permafrost at high and very high susceptibility to destabilization accounted 10% of the total creeping permafrost surface, i.e. 2.9 km². While about one third of this surface was located in potentially destabilized rock glaciers, more than 1.4 km² of stable and unlikely destabilized rock glaciers were found at high and very high destabilization susceptibility.

4 Discussion

4.1 Rating rock glacier destabilization

The present study provided the first comprehensive assessment of rock glacier destabilization for the French Alps, ~~suggesting the and indicates the potentially~~ high prevalence of ~~the phenomena in this area~~ this phenomenon. Destabilized rock glaciers were more likely located in the Vanoise, Queyras and Ubaye ranges. In these areas the densely jointed lithology was suspected to generate mainly pebbly rock glaciers (Matsouka and Ikeda, 2001; Ikeda and Matsuoka, 2006). This ~~suggested~~ indicates that destabilization may be more likely to develop in pebbly rock glaciers, as observed in the Berard, Roc Noir and Lou rock glaciers. Also, ~~no rock glacier developed~~ rock glaciers in crystalline lithology ~~showed~~ did not show signs of potential destabilization. However, recognizing surface disturbances on pebbly rock glaciers may be easier than in “blocky” rock glaciers,

as smaller cracks are more evident. This may create a bias, which should be studied ~~more in in more~~ detail by investigating geomorphological features of destabilization occurring on blocky rock glaciers.

The majority of rock glaciers showing potential destabilization were characterized by shallow cracks (33 cases versus 13). Although, this is suggested to be partially due to the high incidence of rock glaciers located in densely jointed lithology, there ~~is are~~ a number of questions that still need to be answered in this context. At present, we are unsure about the significance of these surface disturbances in the context of destabilization. Cracks may either be a "mild" evidence of destabilization as they affect only the upper layer of the landform, or a typical surface disturbance occurring on destabilized pebbly rock glaciers. In the first case, using cracks as destabilization evidence could lead to an over-interpretation of the destabilization severity of the landform. On the other hand, it was observed that destabilization may occurred when only these type of surface disturbances occurred (Schoeneich et al., 2017; Serrano , 2017). Concerning this issue, this study suggested that these landforms deserve more attention due to their high incidence on the regional territory.

Overall, rock glacier destabilization rating can be a relevant tool for the local authorities to focus monitoring efforts related to periglacial risks assessment, as we identified all rock glaciers presenting signs of destabilization in the region. The destabilization rating, if ~~jointed with displacement rates assessment~~ combined with an assessment of displacement rates and landform connectivity, could ~~suggest indicate~~ the severity of the potential hazard and ~~can be used to~~ help identify actions that should be undertaken to deal with the problem. In general rock glaciers with low destabilization rating are currently evolving slowly or are stable, and consequently monitoring based on remote sensing may be sufficient. Suspected or potentially destabilized rock glaciers require more caution and in-situ monitoring is recommended.

4.1.1 Uncertainties in rating rock glacier destabilization

A potential source of uncertainty in this study was the subjectivity that can occur while mapping surface disturbances and rating the degree of destabilization. These activities were based on expert knowledge; however, it is possible that mapping and rating results vary depending on the operator. For example, the operators in charge of the digitization process were requested to interpret surface features that in many cases have small dimensions with respect to the resolution of the orthoimages, making the identification challenging. Orthoimages can have varying illumination from one year to another, causing surface disturbances to change their appearance. Orthoimages may also be distorted, creating unrealistic deformation patterns of the rock glaciers surface. Also, although surface disturbances were inventoried into the catalogue in an attempt to standardize the classification, destabilized rock glacier morphology is complex, and its identification requires intense training. In many cases the boundaries between the different typologies proposed were not sharp. Personal knowledge of the process evolved through the inventory compilation, requiring various iterations to review the work.

Another issue was that the operator's metrics of judgment was subjected to the "prevalence induced concept change" (Levari et al., 2018), as the classification might get stricter (or looser) when the operator deals with a series of destabilized (or stable) rock glaciers. The ratings were compiled and revised by different operators in an attempt to mitigate these effects. Some cases were subject of debate, highlighting significant individual biases. These biases can influence the resulting susceptibility model (Steger et al., 2016). It is therefore strongly recommended to integrate the inventory with in situ observations when possible

and to maintain a critical attitude towards the data. ~~At present time~~ Currently, France does not have a LiDAR-based high-resolution DEM covering the study region. Such data could be used to revise in the inventory in the future in order to reduce errors due to poor quality of the orthophotos. In particular, having high resolution DEM could allow us to avoid issues related to the differentiation between isolated crack and crevasse, as the judgment based on orthoimages may vary depending on the lightning.

Although observing aerial orthoimagery or high resolution DEMs could not replace the relevance of a proper in-situ survey, it provides us with data and resulting insights that would normally not be possible with in-situ surveys alone, a characteristic that fitted with the aim of the study. Additionally, the use of orthoimagey has been ~~proved~~ proven to be a useful approach for mapping rock glacier surface disturbances by Serrano (2017), where the results of field observation were compared to observations from orthoimagery. Although Serrano (2017) investigated a limited number of sites, those results were encouraging, showing that the method was relevant. The use of multiple orthoimages was believed to successfully reduce issues related to subjectivity and poor image quality in most of the cases. Observing the movements of the landforms was a valuable decision support tool, as surface disturbances could be related or not to discontinuities in a pronounced displacement field. Also, the use of multiples orthoimages reduced potential errors due to bad lighting that may enhance features that may be unrelated to destabilization processes (Serrano, 2017).

4.2 Modelling the predisposition to rock glacier destabilization

Despite the various limitations of the ~~database, data, the~~ results were encouraging. The spatially cross-validated model had a good performance, suggesting that the method is valuable in the context of modeling rock glacier stability. The relationships with predictor variables were found to be consistent with topographic settings observed in known cases of destabilization. High slope angles are suggested to increase internal shear, making the landform more susceptible to destabilization (Schoeneich et al., 2015). Convex slopes cause an extensive flow pattern as creep velocity is higher downslope the convexity (Delaloye et al., 2013). This ~~is suggested to cause~~ suggests that a thinning of the permafrost body and the generation of traction forces ~~that may enhance~~ may intensify the occurrence of surface disturbances. ~~The PTP was found to be a significant predictor of potential destabilization. In particular, increasing potential in permafrost thaw was linked to increase susceptibility of destabilization, indicating that destabilization was more likely to occur where the permafrost zone was expected to be thawing. This seems to be consistent with the relation between destabilization and elevation, as potentially destabilized rock glacier as more often located around 2800 m.a.s.l., which roughly coincides with the lower margins of the regional permafrost zone.~~

PISR had the most importance in the model, suggesting that rock glacier destabilization was primarily more likely to occur on north facing slopes. We cannot offer a convincing explanation of this phenomenon ~~assince~~ since, at the present state of the art, there is no systematic study comparing rock glacier characteristics in relation to their solar exposure. Nevertheless, we suggest that a possible explanation resides in the variability of ~~meltwater~~ melt water input of the rock glaciers with respect to solar exposure. Ikeda et al. (2008) suggest that high water input can boost destabilization by reducing internal friction. Considering that snow patches tend to last longer in ~~North exposed slopes, meltwater~~ north-facing slopes, melt water inputs may be more significant than in ~~south exposed~~ south-facing slopes.

Modeling rock glacier destabilization using PTP instead of elevation revealed that an increasing potential in permafrost thaw was linked to an increase in susceptibility to destabilization, indicating that destabilization was more likely to occur where the permafrost zone was expected to be thawing. This seems to be consistent with the relationship between destabilization and elevation, as potentially destabilized rock glaciers are more often located around 2800 m.a.s.l., which roughly coincides with the lower margins of the regional permafrost zone.

4.3 Susceptibility map

Overall, permafrost destabilization was adequately described, as indicated by the cross-validated performance, in most of the observed cases of destabilization. Although cases of potential destabilization were inventoried, rock glaciers that have a low rating of destabilization and are located in areas with high susceptibility should be identified as having a high potential of showing future destabilization. Results indicated that these rock glaciers had a large area of high predisposition to destabilization and should be monitored for risk assessment, suggesting that there is a high potential for future destabilization in the region. The map therefore may be used to spot rock glaciers that present a predisposition to develop destabilization. In particular, the Laurichard rock glacier is a site currently under monitoring which was found to present a low to medium susceptibility to destabilization in this study (Bodin et al., 2008). The comparison of the future evolution of this landform with respect to the DEFROST-susceptibility map is therefore recommended.

5 Conclusions

The present study aimed to give insights into the extent of the phenomenon of destabilizing rock glaciers in the French Alps. This was done by mapping Mapping and modelling rock glacier destabilization in the region using this region was conducted using an orthoimagery collection, a 25 m x 25 m resolution DEM, and statistical modelling. This methodology carried several limitations, due to subjectivity and modelling issues. Therefore, absolute model performance and the appearance of the susceptibility map may not be exact, and further work is strongly encouraged. Integrating the observations with high resolution LiDAR DEM and with new field-observations could spot possible systematic biases in the destabilization rating attribution and significantly reduce uncertainty.

Despite the limitations of this methodology, the study contributes to the knowledge related to permafrost degradation in the French Alps. Rock glacier destabilization potentially involves 46 active landforms, uniquely located in non-crystalline lithologies, which are typically densely jointed as ophiolites and schist. Shallow surface disturbances (i.e. cracks) had the highest incidence in potentially destabilized rock glaciers. At present, there are several questions concerning the destabilization of pebbly rock glaciers presenting these shallow surface disturbances, as only few studies tackled the subject. Therefore, considering the high incidence of these landforms in the region, it is suggested to dedicate more attention to the issue these issues in the future.

The destabilization of creeping permafrost was found to be a widespread phenomenon which involves more than 10% of the total surface of active rock glaciers, i.e. 3 km² ca. Only half of this surface was attributed to rock glaciers currently showing

a relevant degree of destabilization, suggesting that several stable rock glaciers have a significant degree of susceptibility to experience destabilization in the future. Rock glacier destabilization was found to ~~be more likely~~ more likely occur at the lower margins of the permafrost zone, i.e. ~~were~~ where permafrost thaw due to climate warming is expected to be more intense. This suggests that climate warming may have increased the predisposition of creeping permafrost to slope failure. In this context, the present study contributes by having mapped potentially destabilized rock glaciers and areas considered susceptible to destabilization, allowing to focus future monitoring efforts. In this sense, we suggest that the modelling framework proposed is relevant and further efforts to better acknowledge the phenomena are strongly encouraged.

Code and data availability. The R code to model rock glacier stability and database is available and built in RGUI version 3.4.4. Shape files for surface disturbances (one file per feature type. Data are in .shp format) and PTP and DEFROST susceptibility maps are available (.tiff format). Data are in referenced in EPSG : 2154.

Competing interests. Herby we declare that no competing interests is present for this study

Acknowledgements. The present study was funded by the region Auvergne-Rhone Alpes through the ARC-3 grant and by the European Regional Development Fund (POIA PA0004100) grant. The Lanslebourg - Val Cenis municipality also contributed to the present study by funding internships within the PERMARISK project.

References

- Auer, I., Reinhard, B., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., ... Gerhard, M. (2007). HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region. *International Journal of Climatology*, 27, 17–46. doi:10.1002/joc
- Avian, M., Kaufmann, V., and Lieb, G. K. (2005). Recent and Holocene dynamics of a rock glacier system: The example of Langtalkar (Central Alps, Austria). *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*, 59(2), 149–156. doi:10.1080/00291950510020637
- Barboux, C., Delaloye, R., Lambiel, C., Strozzi, T., & Collet, C. (2013). Surveying the activity of permafrost landforms in the Valais Alps with InSAR. *Jahrestagung Der Schweizerischen Geomorphologischen Gesellschaft*, 7–19.
- Bodin, X., Schoeneich, P. and Jaillet, S. (2008). High-Resolution DEM Extraction from Terrestrial LIDAR Topometry and Surface Kinematics of the Creeping Alpine Permafrost: The Laurichard Rock Glacier Case Study (Southern French Alps). *proceedings, Ninth International Conference on Permafrost*, June 29 – July 3, Fairbanks, Alaska.
- Bodin, X., Thibert, E., Fabre, D., Ribolini, A., Schoeneich, P., Francou, B., Reyanud, L. and Fort, M. (2009). Two Decades of Responses (1986 – 2006) to Climate by the Laurichard Rock Glacier, French Alps. *Permafrost and Periglacial Processes*, 344(June), 331–344. <https://doi.org/10.1002/ppp>
- Bodin, X., Schoeneich, P., Deline, P., Ravanel, L., Magnin, F., Krysiecki, J. M., and Echelard, T. (2015). Mountain permafrost and associated geomorphological processes: recent changes in the French Alps. *Journal of Alpine Research*, 103-2, doi:10.4000/rga.2885.
- Bodin, X., Krysiecki, J., Schoeneich, P., Roux, O., Lorier, L., Echelard, T., Peyron, M. and Walpersdorf, A. (2016). The 2006 Collapse of the Bérard Rock Glacier (Southern French Alps). *Permafrost and Periglacial Processes*. 28: 209–223. doi: 10.1002/ppp.1887.
- Boeckli, L., Brenning, A., Gruber, S. and Noetzi, J. (2012). Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. *The Cryosphere*, 6(4), 807–820. doi:10.5194/tc-6-807-201
- Brenning, A. (2008). Statistical geocomputing combining R and SAGA: The Example of Landslide susceptibility Analysis with generalized additive Models. *SAGASecods Out*, 19, 23–32.
- BRGM (2015). *BD Million-Géol: Carte Géologique à 1/1 000 000 Métropole, Image et Vecteur*. Available online at: http://www.brgm.fr/sites/default/files/plaquette_million2015.pdf
- Damm, B., and Felderer, A. (2013). Impact of atmospheric warming on permafrost degradation and debris flow initiation – a case study from the eastern European Alps. *textitE&G Quaternary Sci. J.* 62(2), 136-149. doi:10.3285/eg.62.2.05
- Davies, M.C.R., Hamza, O. and Harris, C. (2001): The Effect of Rise in Mean Annual Temperature on the Stability of Rock Slopes Containing Ice-Filled Discontinuities. *Permafrost and Periglacial Processes*, 12: 137–144.
- Delaloye, R., Perruchoud, E., Avian, M., Kaufmann, V., Bodin, X., Hausmann, H., Ikeda, A., and Käab, A., Kellerer-Pirkelbauer, A., Krainer, K., Lambiel, C., Mihajlovic, D., Staub, B., Roer, I., and Thibert, E.: Recent interannual variations of rock glacier creep in the European Alps, *9th International Conference on Permafrost*, 28 June–3 July, 2008, Fairbanks, Alaska, 1, 343–348, 2008.
- Delaloye, R., Morard, S., Barboux, C., Abbet, D., Gruber, V., Riedo, M., and Gachet, S. (2013). Rapidly moving rock glaciers in Mattertal. *Jahrestagung Der Schweizerischen Geomorphologischen Gesellschaft*, (i), 21–31.
- Durand, Y., Giraud, G., Laterneser, M., Etchevers, P., Merindol, L. and Lesaffre, B. (2009). Reanalysis of 44 yr of climate in the French Alps (1958–2002): methodology, model validation, climatology, and trends for air temperature and precipitation. *J. Appl. Meteorol. Climatol.* 48, 429–449. doi: 10.1175/2008JAMC1808.1
- Echelard, T. (2014). *Contribution à l'étude de la dynamique des glaciers rocheux dans les Alpes françaises par interférométrie radar différentielle (D-InSAR)*. PhD Thesis, Laboratoires PACTE et GIPSA-lab, Université Joseph Fourier, Grenoble, France.

- Eriksen, H. Ø., Rouyet, L., Lauknes, T. R., Berthling, I., Isaksen, K., Hindberg, H., et al. (2018). Recent acceleration of a rock glacier complex, Adjat, Norway, documented by 62 years of remote sensing observations. *Geophysical Research Letters*, 45. <https://doi.org/10.1029/2018GL077605>
- Freeman, G.T. (1991): Calculating catchment area with divergent flow based on a regular grid. *Computers and Geosciences*, 17:413-22
- 5 Gardent, M. (2014). *Inventaire et retrait des glaciers dans les Alpes françaises depuis la fin du Petit Age Glaciaire*. PhD Thesis, University of Grenoble-Alpes.
- Goetz, J. N., Guthrie, R. H., and Brenning, A. (2011). Integrating physical and empirical landslide susceptibility models using generalized additive models. *Geomorphology*, 129, 376–386. doi:10.1016/j.geomorph.2011.03.001
- Gottardi, F. (2009). *Estimation statistique et réanalyse des précipitations en montagne Utilisation d'ébauches par types de temps et assimilation de données d'enneigement Application aux grands massifs montagneux français*. PhD Thesis, Institut National Polytechnique de Grenoble - INPG.
- 10 Kääb, A. and Haeberli, W. (2001). Evolution of a High-mountain Thermokarst Lake in the Swiss Alps. *Arctic, Antarctic and Alpine Research*, 33, 385–390.
- Kaufmann, V., and Ladstädter, R. (2003). *Quantitative analysis of rock glacier creep by means of digital photogrammetry using multi-temporal aerial photographs : two case studies in the Austrian Alps*. In Permafrost, Phillips, Springman & Arenson (eds) (pp. 526 – 530).
- 15 Kummert, M. and Delaloye, R. (2018). Mapping and quantifying sediment transfer between the front of rapidly moving rock glaciers and torrential gullies. *Geomorphology*, 309, 60-76. doi: 10.1016/j.geomorph.2018.02.021
- Hand, D.J. and Till, R.J. (2001). A Simple Generalisation of the Area Under the ROC Curve for Multiple Class Classification Problems. *Machine Learning*, 45: 171. doi:10.1023/A:1010920819831
- 20 Haeberli, W., Guodong, C., Gorbunov, A. P. and Harris, S. A. (1993). Mountain Permafrost and Climatic Change. *Permafrost Periglac. Process.*, 4: 165-174. doi:10.1002/ppp.3430040208.
- Haeberli, W., Wegmann, M. and Vonder Mühll, D. (1997). Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps Slope stability problems related to glacier shrinkage and permafrost. *Eclogae Geol. Helv.*, 90, 407–414.
- Haeberli, W., Noetzi, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M. and Phillips, M. (2010). Mountain permafrost: Development and challenges of a young research field. *Journal of Glaciology*, 56(200), 1043-1058. doi:10.3189/002214311796406121
- 25 Harris C. and Davies M., E. B. (2001). The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate. *Permafrost and Periglacial Processes*, 12(1), 145–156. doi:10.1002/ppp.376
- Harris, C., Vonder Mühll, D., Isaksen, K., Haeberli, W., Sollid, J.L., King, L., Holmund, P., Dramis, F., Guglielmin, F., Palacios, D., 2003. Warming permafrost in European mountains. *Global and Planetary Change* 39, 215–225.
- 30 Hilbich, C., Hauck, C., Hoelzle, M., Scherler, M., Schudel, L., Völksch, I., Vonder Mühll, D. and Mäusbacher, R. (2008), Monitoring mountain permafrost evolution using electrical resistivity tomography: A 7-year study of seasonal, annual, and long-term variations at Schilthorn, Swiss Alps. *J. Geophys. Res.*, 113, F01S90, doi:10.1029/2007JF000799.
- Hoelzle, M. and Haeberli, W. (1995). Simulating the effects of mean annual air-temperature changes on permafrost distribution and glacier size: An example from the Upper Engadin, Swiss Alps. *Annals of Glaciology*, 21, 399-405. doi:10.3189/S026030550001613X
- 35 Hosmer, D. W. and Lemeshow, S. (2000). *Applied Logistic Regression*. John Wiley & Sons., New York.
- Huggel, C., Salzmann, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W. and Wessels, R. (2010). Recent and future warm extreme events and high-mountain slope stability. *Phil. Trans. R. Soc.*, 368, 2435–2459. doi: 10.1098/rsta.2010.0078

- IGN (2011a). *BD ALTI R, Version 2.0 - Descriptif de Contenu*. Available online at: http://professionnels.ign.fr/sites/default/files/DC_BDALTI_2-0.pdf.
- IGN (2011b). *BD Ortho R Historique - Descriptif de Contenu et Livraison*. Available online at: http://pro.ign.fr/sites/default/files/u136/DC_DL_BDORTHOHisto.Pdf
- 5IGN (2013). *BD Ortho R, Version 2.0, Ortho HR R, Version 1.0 - Descriptif de Contenu*. Available online at: http://professionnels.ign.fr/doc/DC_BDORTHO_2-0_ORTHOHR_1-0.pdf
- Ikeda, A. and Matsuoka, N. (2002). Degradation of Talus-derived Rock Glaciers in the Upper Engadin. *Permafrost and Periglacial Processes*, 13(April), 145–161. <http://doi.org/10.1002/ppp.413>
- Ikeda, A., Matsuoka, N. (2006). Pebbly versus bouldery rock glaciers: Morphology, structure and processes. *Geomorphology*, 73(3–4), 279–296. <https://doi.org/10.1016/j.geomorph.2005.07.015>
- 10 Ikeda, A., Matsuoka, N. and Kaab, A. (2008). Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps : An effect of liquid water. *Journal of Geophysical Research*, 113, 1–12. doi:10.1029/2007JF000859
- IPCC, 2013: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y.
- 15 Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.
- Kellerer-Pirklbauer, A., [and](#) Kaufmann, V. (2012). About the relationship between rock glacier velocity and climate parameters in central Austria. *Austrian Journal of Earth Sciences*, 105(2), 94–112.
- Lambiel, C. and Reynard, E. (2001). Regional modelling of present, past and future potential distribution of discontinuous permafrost based on a rock glacier inventory in the Bagnes-Hérémence area (Western Swiss Alps). *Norsk Geografisk Tidsskrift*, 55(4), 219–223. doi:10.1080/00291950152746559
- 20 Lambiel, C. (2011). Le glacier rocheux déstabilisé de Tsaté-Moiry (VS) : caractéristiques morphologiques et vitesses de déplacement. *La Géomorphologie Alpine: Entre Patimoine et Contrainte*, 3–5.
- Levari, D. E., Gilbert, D. T., Wilson, T. D., Sievers, B., Amodio, D. M., and Wheatley, T. (2018). Prevalence-induced concept change in human judgment, *Psychology*, 360, 1465–1467.
- 25 Marcer, M., Bodin, X., Brenning, A., Schoeneich, P., Charvet, R. and Gottardi, F. (2017). Permafrost Favorability Index : Spatial Modeling in the French Alps Using a Rock Glacier Inventory. *Frontiers in Earth Sciences*, 5(December), 1–17. doi:10.3389/feart.2017.00105
- Matsuoka, N. and Ikeda, A. (2001). Geological control on the distribution and characteristics of talus-derived rock glaciers. *Ann. Rep., Inst. Geosci.*, Univ. Tsukuba, (27), 11–16.
- 30 Nater, P., Arenson, L. and Springman, S. (2008). Choosing Geotechnical Parameters for Slope Stability Assessments in Alpine Permafrost Soils in Alpine Permafrost Soils. *In Proceedings of the 9th International Conference on Permafrost*, 29 June – 3 July 2008, Fairbanks, Alaska, Vol. 1, Fairbanks, AK, Institute of Northern Engineering, 1261–1266.
- PERMOS 2016. *Permafrost in Switzerland 2010/2011 to 2013/2014*. Noetzli, J. , Luethi, R., and Staub, B. (eds.), Glaciological Report Permafrost No. 12–15 of the Cryospheric Commission of the Swiss Academy of Sciences, 85 pp
- 35 Ravanel, L. and Deline, P. (2010) Climate influence on rockfalls in high-Alpine steep rockwalls: the north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the ‘Little Ice Age’. *The Holocene*, 21(2):357–365. doi:10.1177/0959683610374887
- Roer, I., Käab, A. and Dikau, R. (2005). Rockglacier acceleration in the Turtmann Valley (Swiss Alps): Probable Controls. *Norsk Geografisk Tidsskrift*, 59(July), 157–163. doi:10.1080/00291950510020655

- Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C., and Kääb, A. (2008). Observations And Considerations On Destabilizing Active Rock glaciers In The European Alps. *Ninth international conference on permafrost*, eds D. L. Kane and K. M. Hinkel (Fairbanks, AK: University of Alaska), 1505–1510.
- Roudnitska, S., Charvet, R., Ribeyre, C. and Favreaux B. L. (2016). *Les Glaciers- Rocheux De Savoie: Inventaire, Cartographie Et Risques Associés - Rapport Provisoire*. Chambéry: Office National des Forêts, Service de Restauration des Terrains en Montagne
- Rudy, A. C. A., Lamoureux, S. F., Treitz, P., Ewijk, K. Van, Bonnaventure, P. P. and Budkewitsch, P. (2017). Terrain Controls and Landscape-Scale Susceptibility Modelling of Active-Layer Detachments, Sabine Peninsula, Melville Island, Nunavut. *Permafrost and Periglacial Processes*, 28, 79–91. doi:10.1002/ppp.1900
- Ruß, G. and Brenning, A. (2010a) *Data mining in precision agriculture: Management of spatial information*. In Computational Intelligence for Knowledge-Based Systems Design; Springer: Berlin, Germany, 2010; pp. 350–359
- Ruß, G., and Brenning, A. (2010b). *Spatial Variable Importance Assessment for Yield Prediction in Precision Agriculture*. In Computational Intelligence for Knowledge-Based Systems Design; Springer: Berlin, Germany, 2010; pp. 184–195.
- Sattler, K., Keiler, M., Zischg, A. and Schrott, L. (2011). On the Connection between Debris Flow Activity and Permafrost Degradation : A Case Study from the Schnalstal , South Tyrolean Alps , Italy. *Permafrost and Periglacial Processes*, 265(May), 254–265. doi:10.1002/ppp.730
- Scapozza, C., Lambiel, C., Reynard, E., Fallot, J. M., Antognini, M. and Schoeneich, P. (2010). Radiocarbon dating of fossil wood remains buried by the piancabella rock glacier, Blenio valley (Ticino, Southern Swiss Alps): Implications for rock glacier, treeline and climate history. *Permafrost and Periglacial Processes*, 21(1), 90–96. https://doi.org/10.1002/ppp.673
- Scherler, M., Hauck, C., Hoelzle, M., and Nadine, S. (2013). Modeled sensitivity of two alpine permafrost sites to RCM-based climate scenarios climate scenarios, *Journal of Geophysical Research*, 118, 780-784. https://doi.org/10.1002/jgrf.20069
- Schoeneich, P., Echelard, T., Krysiecki, J.-M., Kergomard, F., Lorier L., Mingrat, L., Darricau, C., Jugnet, P., Cotoni, T., Mellan L., Huwald, H. and Berton, F. (2012). The borehole 2Alpes-3065 – a pilot installation for fiber optic DTS measurements in permafrost. *Tenth International Conference on Permafrost*, 20-27 Juin 2012, Salekhard. vol. 4/2, p. 507-508.
- Schoeneich, P. et al. (2015) *Velocity Changes of Rock Glaciers and Induced Hazards*. In: Lollino G., Manconi A., Clague J., Shan W., Chiarle M. (eds) *Engineering Geology for Society and Territory - Volume 1*. Springer, Cham
- Schoeneich, P., Ribeyre, C., Marcer, M., Bodin, X. and Brenguier, O. (2017). *Etude géomorphologique et géophysique du glacier rocheux du Col du Lou suite à la lave torrentielle du 14 août 2015*. Technical report, Grenoble.
- Scotti, R., Crosta, G. B. and Villa, A. (2016). Destabilisation of Creeping Permafrost: The Plator Rock Glacier Case Study (Central Italian Alps). *Permafrost and Periglacial Processes*, 28: 224–236. doi:10.1002/ppp.1917
- Serrano, C. (2017). *Analyse géospatiale des glaciers rocheux déstabilisés en Haute Maurienne - Vanoise et en Ubaye*. Master Thesis. University of Grenoble-Alpes, Department of Geography.
- Springman, S. M., Yamamoto, Y., Buchli, T., Hertich, M., Maurer, H., Merz, K., Gartner-Roer, I. and Seward, L. (2013). Rock Glacier Degradation and Instabilities in the European Alps: A Characterisation and Monitoring Experiment in the Turtmannal, CH. *Landslide Science and Practice*, 4(June), 329–333. https://doi.org/10.1007/978-3-642-31337-0
- Steger, S., Brenning, A., Bell, R. and Glade, T. (2016). The propagation of inventory-based positional errors into statistical landslide susceptibility models. *Natural Hazards and Earth System Sciences*, 16(December), 2729 – 2745. doi:10.5194/nhess-16-2729-2016
- Westermann, S., Langer, M., Boike, J., Heikenfeld, M., Peter, M., Etzelmüller, B. and Krinner, G. (2016). Simulating the thermal regime and thaw processes of ice-rich permafrost ground with the land-surface model CryoGrid 3, *Geosci. Model Dev.*, 9, 523-546. doi:10.5194/gmd-9-523-2016

Wilson, J. P. and Gallant, J. C. (2000). *Terrain Analysis - Principles and Applications*. New York: Jhon Wiley & Sons, Inc.

Wood, S.N. (2017) *Generalized Additive Models: An Introduction with R (2nd edition)*. Chapman and Hall/CRC Press.

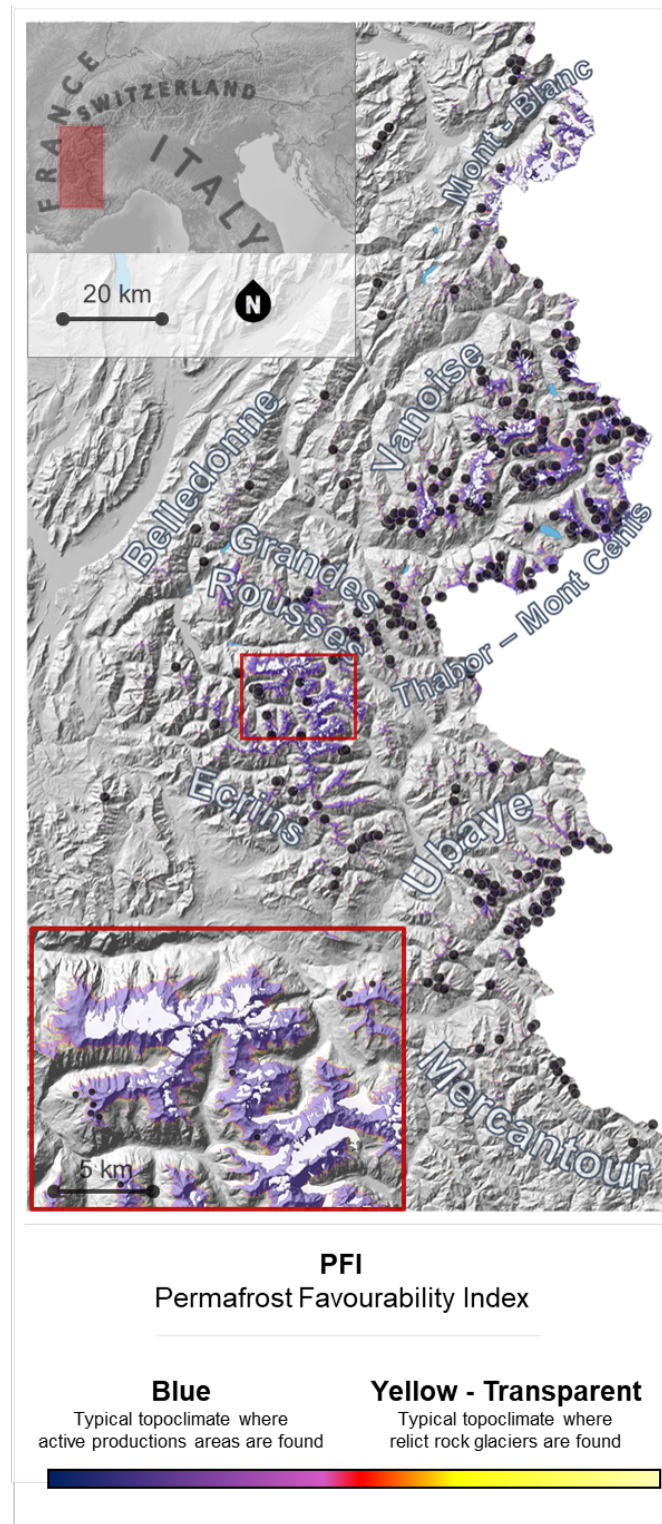


Figure 1. Identification of the study area in the European Alps and overview of the periglacial environment. Permafrost distribution is represented by the PFI map (Marcer et al., 2017). Black dots identify active rock glaciers locations (Marcer et al., 2017).

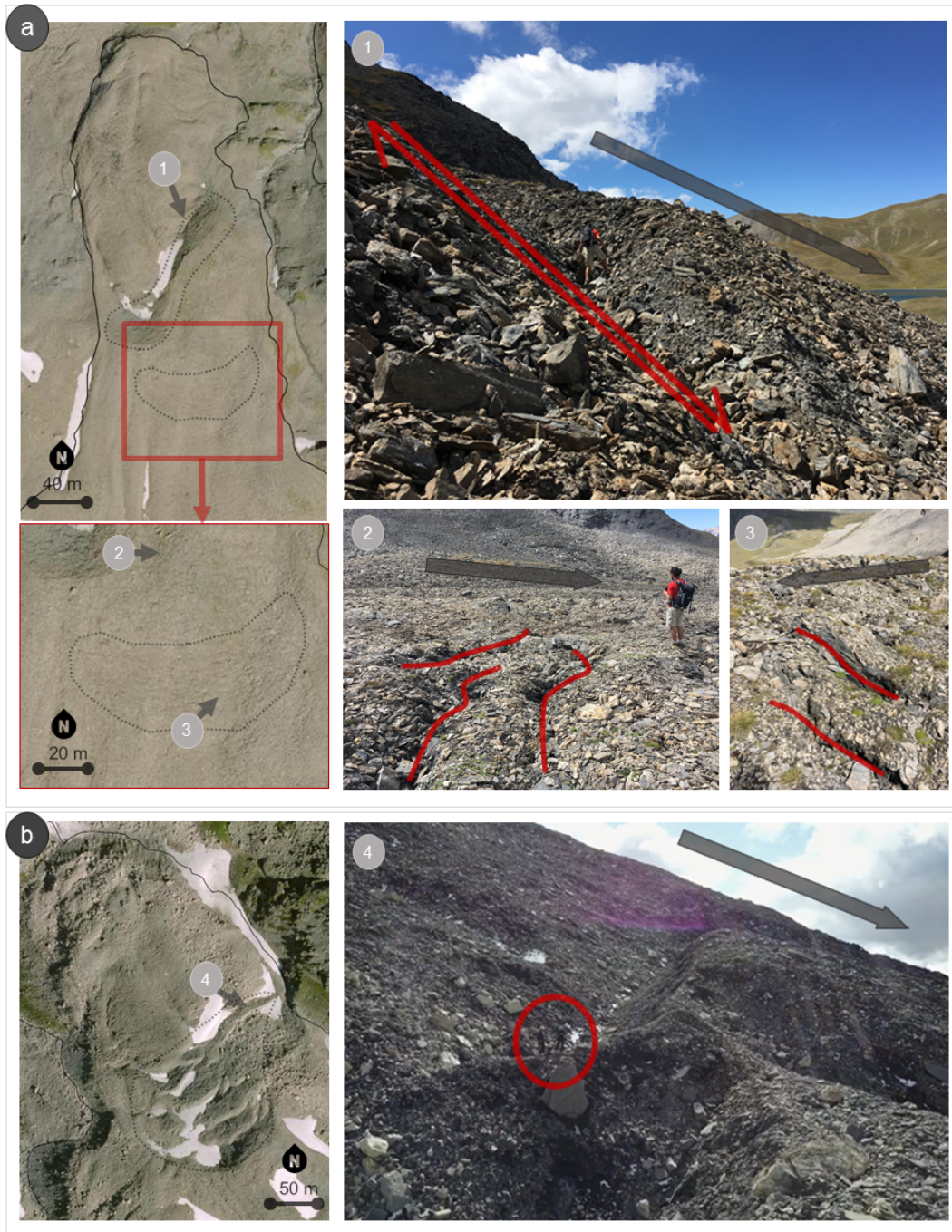


Figure 2. Examples of surface disturbances observable ~~on~~in the available orthoimages ~~of 2013~~ in comparison to field observations on (a) Roc Noir (Serrano , 2017) and (b) Pierre Brune (Echelard , 2014) destabilized rock glaciers. ~~Black~~The black arrows ~~on field pictures~~ indicate the rock glacier displacement direction. ~~On Roc Noir rock glacier are observable a~~A scarp (1) and cracks (2,3) .~~On Pierre Brune have been observed on the Roc Noir rock glacier~~are observable large. Large crevasses (4) can be seen on the Pierre Brune rock glacier. The dotted black lines indicate how the surface disturbances were mapped on these orthoimages.

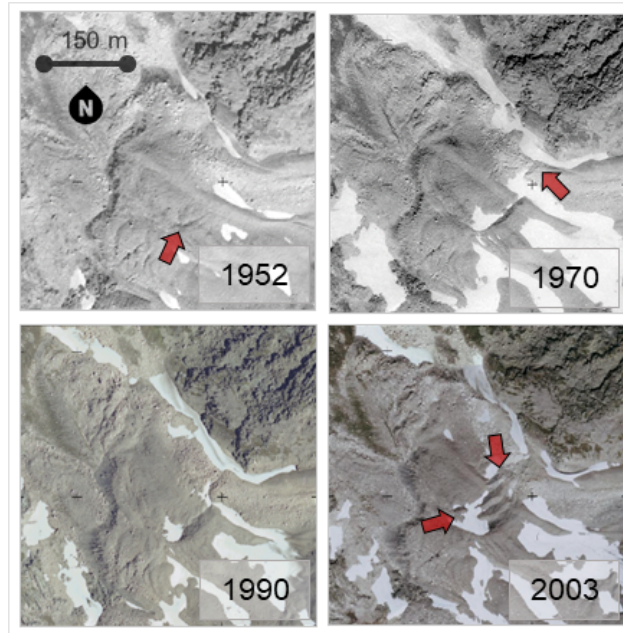


Figure 3. The evolution of the destabilization of the Pierre Brune rock glacier. The destabilization evidence, in this case a crack observable since 1952, evolved to a crevasse, observable in 1970. Afterwards, the landform was stable for 20 years as destabilization evidences did not further evolve. Between 1990 and 2003 the rock glacier experienced severe destabilization with the formation of new crevasses and a scarp in the location of the 1952 crack.

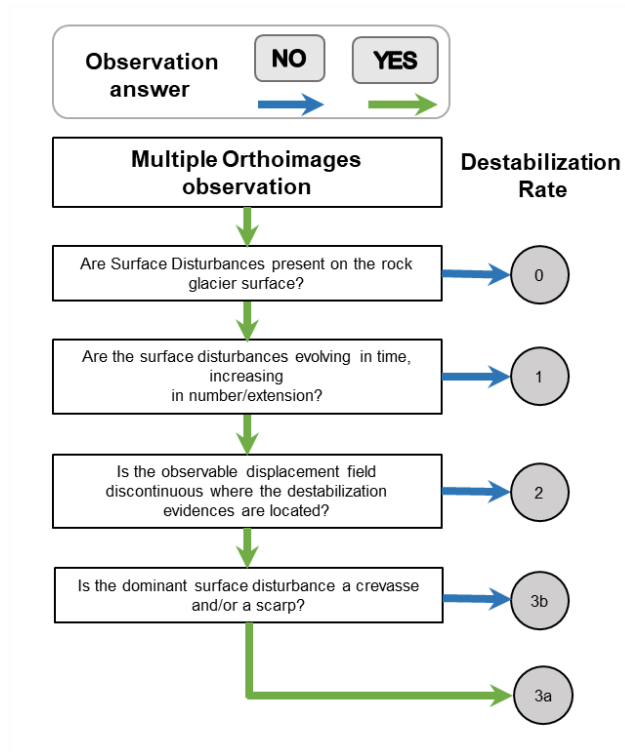


Figure 4. General pipeline used to rate rock glacier destabilization by observing surface disturbances and qualitative displacement field. Higher rates of destabilization indicate potentially unstable rock glaciers, while lower ratings indicate stable rock glaciers.

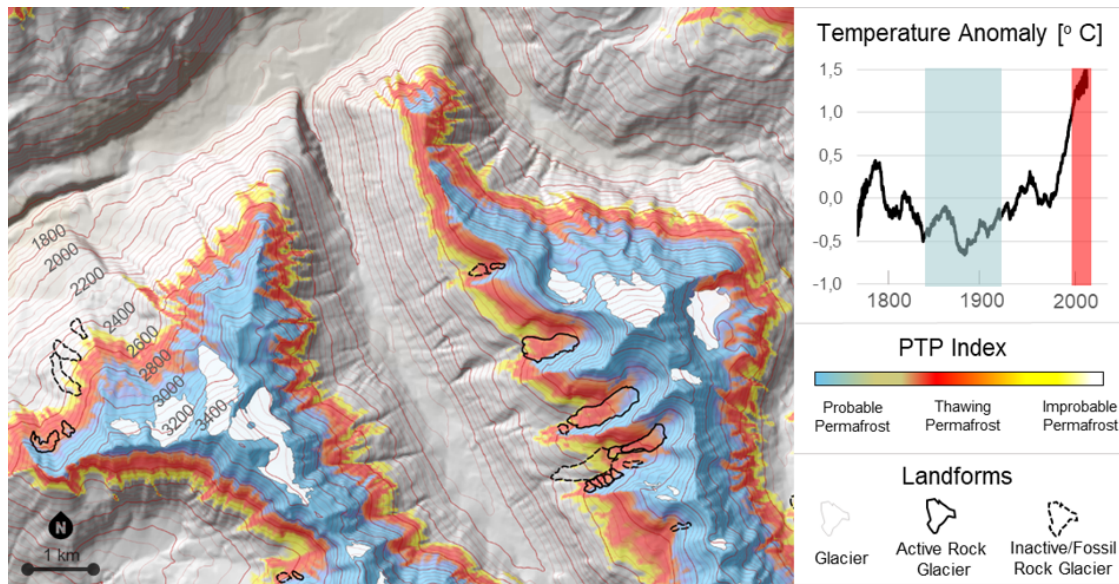


Figure 5. Example Map of Potential Thawing Permafrost (PTP) distribution in the Mont Cenis range, indicating the extent of the permafrost zone not in equilibrium with the present climate (red colored areas). Temperature warming to compute the map is evaluated using HISTALP data (Auer et al., 2008) between the end of the Little Ice Age (light blue shade period in the temperature anomaly plot) and the current climate (red shade period).

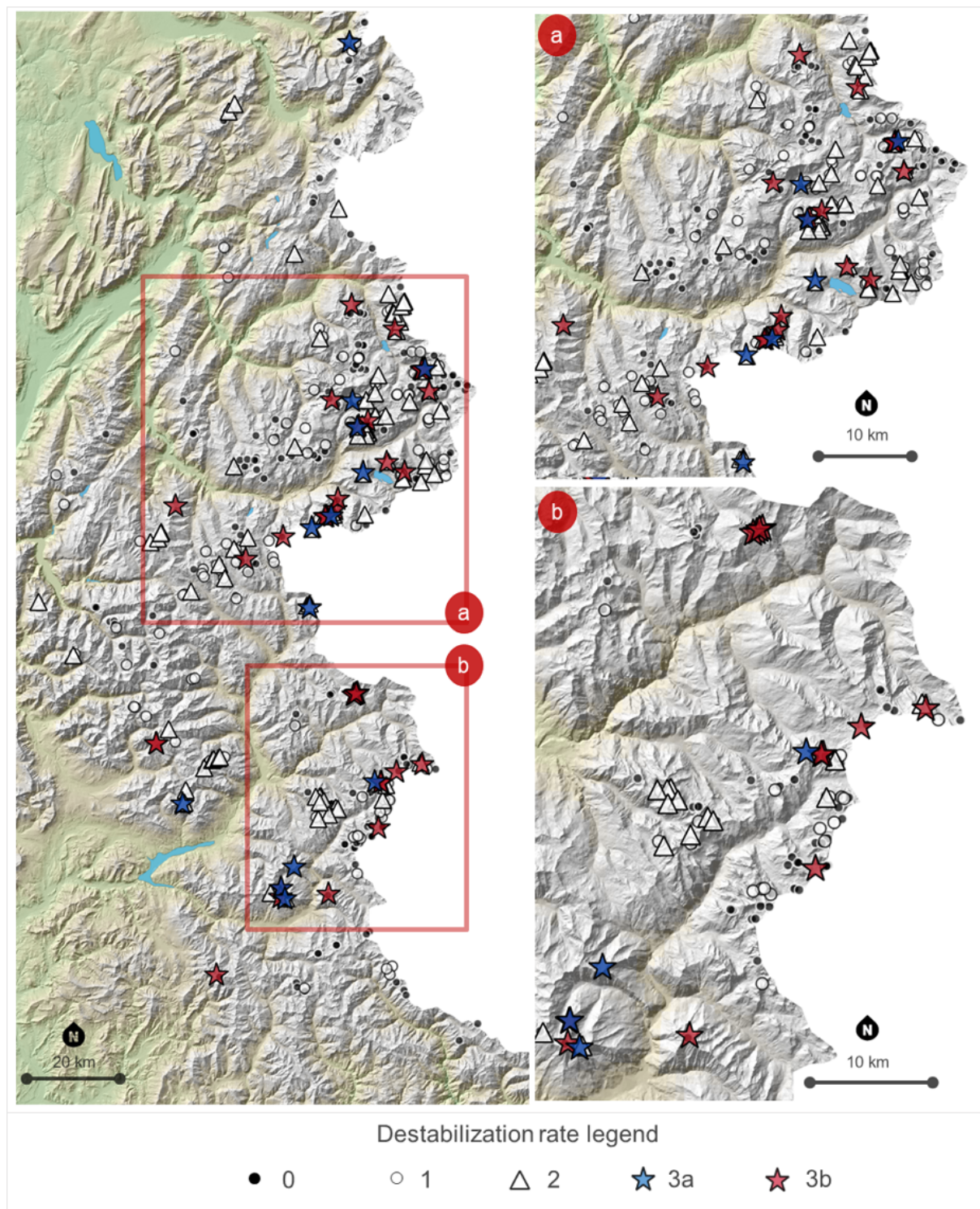


Figure 6. Map of active rock glaciers in France by rock glacier destabilization rating, with focus on the (a) Vaonise - Mont Cenis and (b) Ubaye ranges as most of potentially destabilized landforms were observed in these areas.

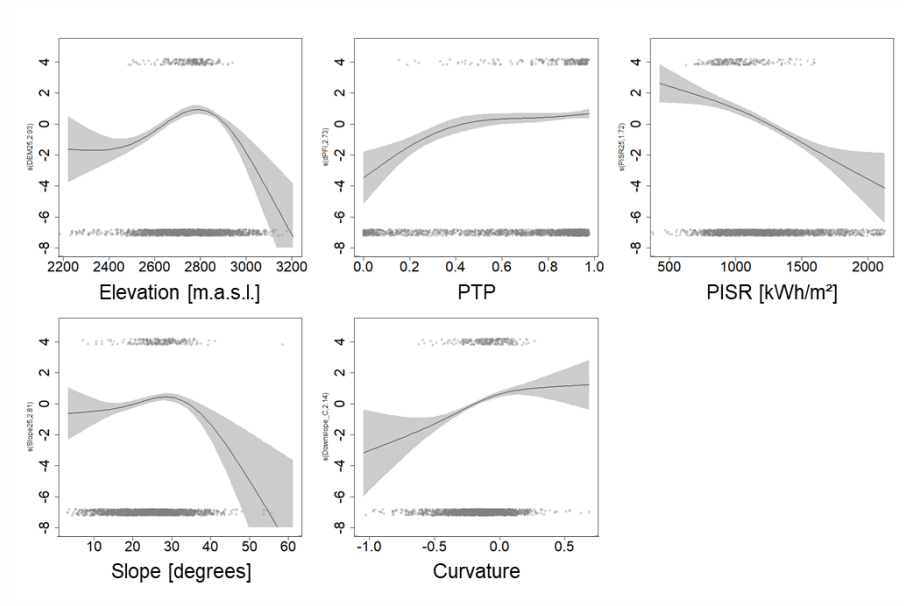


Figure 7. Transformation function plots of the GAM model showing the relationship between each predictor variable and destabilization occurrence. The data distribution with respect to predictor variables are indicated with dots on top (destabilization evidence) and on the bottom (stability evidence) of the plots. The y axis represents the transformation of the predictor variable by the GAM's spline, indicated here by " $s(\text{predictor})$ ". The effective degrees of freedom are also reported. The PTP is presented here for explanatory purposes, although it was not included in the final model.

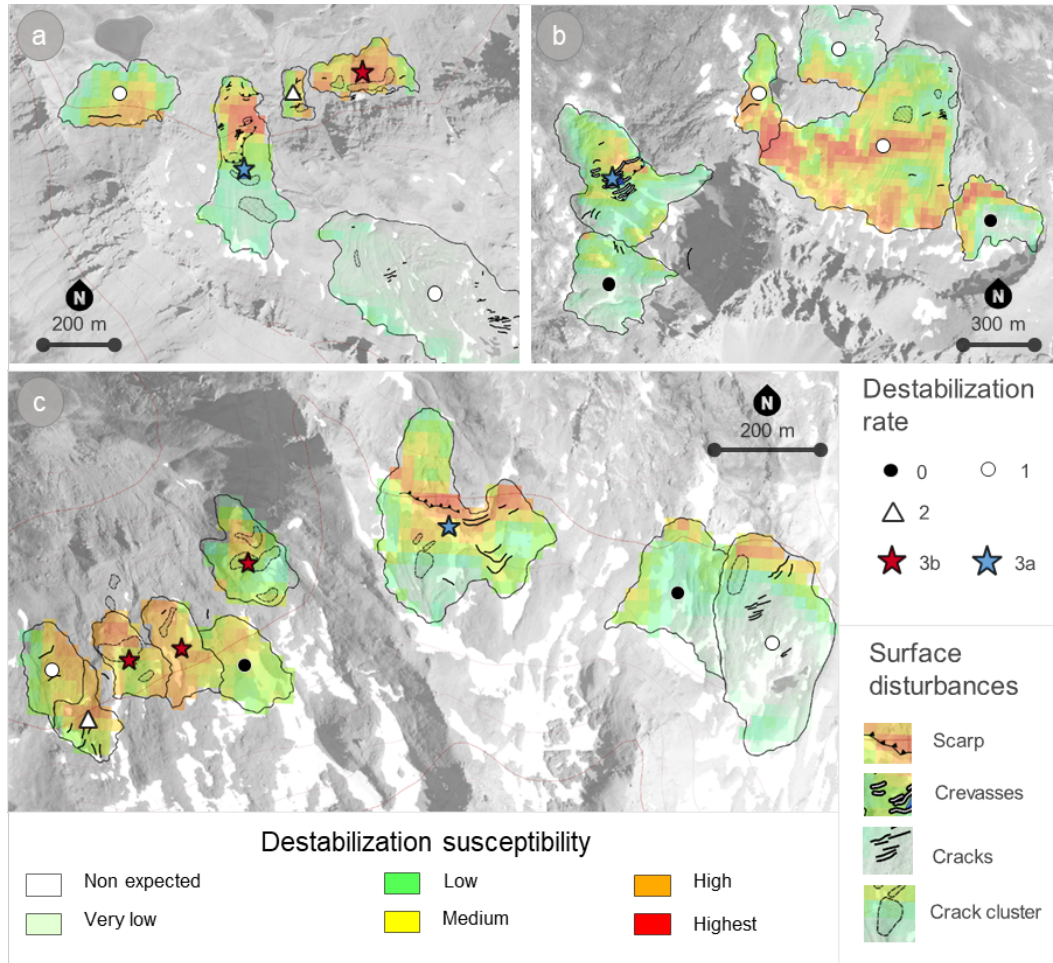


Figure 8. Examples of the susceptibility map in (a) Roc Noir, (b) Pierre Brune and (c) Iseran and Neighbouring rock glaciers. The susceptibility map successfully identifies instabilities observed on the potentially destabilized rock glaciers. Nevertheless, some predicted instabilities were observed in areas that appear stable by observing the orthomosaics.

Table 1. Description of surface disturbance features that could be observed in the field or from orthoimagery to identify signs of rock glacier destabilization

Feature	Description
Cracks	These are shallow linear incisions in the surface of an active rock glacier where a strain is applied (called “scars” in Roer et al. (2008)). Cracks can be several tens of meters long and occur either individually or in a great number, being spaced from each other of only <u>by only a</u> few meters. In this case we define the feature as a “crack cluster” (translated from Serrano (2017)). Their proximity and shallowness lead <u>led</u> to the assumption that they affect only the active layer of the landform. Nevertheless, this feature was found to be largely predominant on the Lou (Schoeneich et al., 2017), signal de l’Iseran (Serrano , 2017) and Tsate’-Mory (Roer et al., 2008; Lambiel, 2011) rock glaciers and therefore considered of interest in the context of the study.
Crevasses	These deep transverse incisions on the rock glacier surface can range in length from several meters to the entire landform width (Avian et al., 2005; Delaloye et al., 2008; Roer et al., 2008). Their depth is substantially larger than the active layer thickness, suggesting the presence of a shear plane sectioning the frozen body. Crevasses may be isolated or grouped. Spectacular crevasses can be found on Pierre Brune rock glacier (Fig. 1), where they are up to 7 m deep and 10 m wide, cutting across the entire landform (about 150 m). Similar dimensions are reported in the Furggwanhorn rock glacier (Roer et al., 2008).
Scarps	Described by Scotti et al. (2016) and Delaloye et al. (2008) as steep slopes (30 to 40°) several meters high cutting transversally the entire rock glacier. Scarps are associated with deep shear planes that disconnect the rock glacier into two bodies that creep at different speeds <u>rates</u> . Their activation is associated with a sudden acceleration of the downstream portion of the landform. One of the biggest scarp observable in the region is the one on Roc Noir rock glacier (Serrano , 2017). This S-shaped scarp, 20–30 m high and 40–45° steep, cuts transversally the whole landform (120 m) and the downstream lobe creeps about twice as fast as the upper part.

Table 2. Rating classes used to describe rock glacier destabilization

Rating	Label	Description
3	Potential destabilization, potentially destabilized rock glaciers	Surface disturbances are well recognizable and evolve in time, increasing in number and/or size. The deformation pattern of the rock glacier is discontinuous and some sectors move significantly faster than others. The source of the discontinuity may be located at the rock glacier's root and the whole landform may be affected by destabilization. Deformation pattern discontinuities are sharp and coincide with the presence of surface disturbances. Sectors moving appreciably faster may also present a series of surface disturbances. If the dominant surface disturbances are deep (i.e. crevasses and scarps), then it is attributed the rate 3a . If the dominant surface disturbances are shallow (i.e. crack and crack clusters) then it attributed the rate 3b
2	Suspected destabilization	In these landforms the surface disturbances are well recognizable and evolve in time, by increasing in number and/or size. The velocity field is continuous, i.e. there are no abrupt spatial differences in the velocity field. If there are sectors moving faster than others, their transition is smooth
1	Unlikely destabilization	In these landforms surface disturbances do not appear to evolve in time. The rock glacier presents a continuous deformation pattern, with no sectors moving substantially faster than others.
0	Non-observable destabilization	Active rock glaciers not presenting surface disturbances are considered as stable.

Table 3. Number of rock glaciers per dominant lithology in relation to destabilization rate.

Destabilization rate	Ophiolites	Schist	Sandstone	Mica-schist	Gneiss	Granite	Limestone	Totals
0	47	88	21	11	31	3	32	233
1	39	37	11	3	13	2	22	127
2	33	28	5	0	1	1	18	86
3b 3a	18 5	7 2	1	3 0	0	0	4 5	33 13
3a 3b	5 18	2 7	1	0 3	0	0	5 4	13 33

Table 4. Number of rock glaciers per destabilization rating showing a specific surface disturbance.

Destabilization <u>Destabilization</u> rating	Cracks	Crack clusters	Crevasses	Scarps
1	86	54	13	8
2	52	51	15	11
3b 23-29-0-0 3a	10	9	10	8
<u>3b</u>	<u>23</u>	<u>29</u>	<u>0</u>	<u>0</u>
Totals	187	152	40	27

Table 5. Active rock glacier area per class of destabilization susceptibility.

Destabilization Rating	Surface per susceptibility class [km ²]				
	<i>Very Low</i>	<i>Low</i>	<i>Medium</i>	<i>High</i>	<i>Very High</i>
0	8.09	3.21	1.70	0.43	0.37
1	4.03	2.16	1.29	0.42	0.38
2	2.18	1.50	0.93	0.34	0.30
3b 0.07 0.19 0.31 0.24 0.38 3a	0.17	0.27	0.17	0.05	0.05
<u>3b</u>	<u>0.07</u>	<u>0.19</u>	<u>0.31</u>	<u>0.24</u>	<u>0.38</u>
Cumulative Surface	14.54	7.33	4.41	1.47	1.48