Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

12th Oct 20

Dear Dr Marcer,

Please allow me to apologise for the long delay in sending a decision on your manuscript titled "Regional scale investigation on rock glacier destabilization and links with climate change". It has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Authors, Dear Editor,

I am happy to see a study, which carries out an area covering analysis of collapsing rock glaciers and extraordinary accelerations of these landforms. This is an important field of permafrost research and has relevant socio-economic implications.
The basic approach chosen in this study is sound. However, there are still major changes necessary before the work can be published.
Major issues are:

1. The language and mode of expression. This should be checked by a native speaker.

2. The precision and correctness of statements. The authors are much too often unclear, ambiguous or unprecise which sometimes results in simply false statements.

3. The structure of the manuscript is currently a big mess. Information on methods, datasets or other specifications are distributed over all of the sections. They do not appear in a logical order, allowing the reader to follow the presented analysis. Why are methods written after results and discussion??

4. The methods are partly suboptimal or insufficient and the solidity of the results could be improved by adapting them. This aims especially on the little dataset on which deformation rates and accuracy analysis are based on (see detailed comments). If the authors stick to their methods, they must at least provide a sensitivity analysis how the low number of records effect their results.

5. The physical interpretation of the results is incomplete and partly misleading as well as based on outdated literature. There must be a better literature review considering the large number of publications on rock glacier dynamics of the last 10 years.

I made a lot of detailed comments in the attached PDF of the manuscript that will give clear evidence for the 5 points above.

I am looking forward for an improvement and successful publication of the work!

All the best
Robert Kenner

Reviewer #2 (Remarks to the Author):

Review of
Title: Regional scale investigation on rock glacier destabilization and links with climate change
Authors: Marco Macer, Alessandro Cicoira, Diego Cusinqui, Xavier Bodin, Thomas Echelard, Renée Obregon, Philippe Schoeneich

Communications Earth & Environment (an open-access journal from Nature Research)
Manuscript Number: COMMSENV-20-0319-T

Editor-in-Chief: Joe Aslin

The present review is based on a revised version of the original paper and on the comments of three anonymous reviewers.

The paper deals with change detection of rock glacier kinematics in the French Alps and with an attempt to explain the observed changes (rock glacier speed-up and surface disintegration) with climate change, i.e. temperature increase. Similar studies (other regions, local sites, shorter observation periods) have been published focusing either on pure rock glacier flow measurements or on pure mathematical modelling of rock glacier flow/deformation. The present paper tries to link rock glacier flow velocity and observed strain rates with temperature (change). This analysis is complicated by the fact that the surface topography is very much influencing the flow behavior. Steeper terrain will cause an increase of flow velocity. If strain rates exceed a critical limit crevasses/cracks may occur. In case the rock glacier is moving in steeper terrain eventually landsliding will take place. This phenomenon is called “destabilization”, which means that the previously compact permafrost body gets disintegrated. The research question is whether acceleration of rock glaciers flow and observed rock glacier destabilization (in some cases) is a matter of climate change, i.e. atmospheric warming.

The three reviewers have thoroughly discussed the original manuscript and provided valuable comments for improving the paper. The reviewer expressed doubts about the novelty of the work presented, missing answers to possible research questions (What is triggering destabilization?), and some statistical issues.

The authors have addressed all remarks provided by the three reviewers and changed the original manuscript accordingly. The modifications refer to both text and figures.

The abstract is now fully concise and it provides the reader with all relevant details (definition, research question, possible answer). The speciality of the present paper is that the authors have investigated a large region, i.e. the entire French Alps, which is unique. Moreover, their analysis covers also a large time span, i.e. seven decades. Similar research is mostly on test sites comprising only one rock glacier or a group of rock glaciers, at most.

The reviewer thinks that the annex of the manuscript highlighting all 18 rock glaciers locations with “destabilization” characteristics is a great value not only to the very expert but also to the interested reader. The reviewer (belonging to the first group) liked to browse the annex.
The introduction provides an exhaustive review of the research question and its scientific background. They explain the terminology of “destabilization”. Maybe, this word is somehow misleading but it is used in the scientific community. The authors clearly state all possible causes (bedrock topography, climatic forcing, etc.) for the onset of “destabilization”. The authors once again highlight that they provide a regional scale systematic analysis of rock glacier displacement rates and destabilization onset over the past seven decades (1948-2018).

The authors put a lot of emphasis in gathering of the kinematic data needed for the analysis. They used all kinds of measurement techniques, from manual feature tracking, area-based orthophoto change detection using governmental data, re-evaluation of original aerial photographs applying modern structure-from-motion technology, and carrying out own UAV-based surveys. Such work is indeed laborious and time-consuming. Of course, in the long run we can think about high-precision orthophotos (10 cm resolution) and contemporaneous digital surface models (every orthophoto pixel gets a height) for high mountain regions to be provided by national mapping agencies, maybe for a three-years interval. Based on this data morphological changes of rock glaciers can be studied in full details, including 3D deformation analysis and analysis of mass balance (to answer the question of permafrost thawing/degradation due to atmospheric warming).

The results obtained are clearly stated. The statistical analysis is based on linear regression (correlation). Appropriate figures visualize the data used and the results obtained. The working hypothesis of the authors for the whole process of morphological change on the rock glaciers is summarized in Figure 1, which includes 4 phases, i.e. normal activity destabilization onset, destabilization peak and deceleration. This might be a nice takeaway for the interested reader.

The paper does not provide any information, but literature, on the mechanism of “destabilization”. High mountain environments are complex systems and thus difficult to understand. This paper is a good example to better understand rock glacier kinematics in the light of climate change based on excellent data (regional, accurate, long-term) and simple reasoning. The latter allows the inter-comparison of results obtained from other regions. The IPA (International Permafrost Association) Action Group “Rock glacier inventories and kinematics” supports this goal.

The paper is worthwhile to be published since it provides valuable new information/data on rock glacier kinematics and provides a working hypothesis about rock glacier surface disintegration as a function of flow velocity/strain rate and temperature over time.

Comments

Introduction:

Line 48: 1976;
Line 49: 1996;

Line 61 and elsewhere: Please use “kinematics” instead of “dynamics” if appropriate.
KAV/20

Reviewer #3 (Remarks to the Author):

I have carefully read the manuscript of Marcer et al. “Regional scale investigation on rock glacier destabilization and links with climate change "and I found it interesting, well written and properly organized.
I also read the authors 'responses to the first three reviewers' comments.
The manuscript has substantially improved following the modifications made by the authors and now I believe that there are no significant obstacles in proceeding towards its publication

The main problem that was raised concerned the novelty of the article topic.
Reading the article, in light of the changes made by the authors, I don't think this drawback still exists. The aim of the work is clearly to provide readers with a vision of how the analysis of regional and local data underlines the (already known) effects of air temperature increase on the destabilization of rock glaciers. To my knowledge observations on such a regional scale are not available in the rest of the European Alps.
Moreover, also the quantification of the non-homogeneity of the responses of rock glaciers to the increase of air temperature (in terms of pre and post destabilization behaviour) is in my opinion an analysis not present on a regional scale.
Finally, the considerations on how the behaviour of rock glaciers is modulated also by the geotechnical characteristics give to the paper the right degree of completeness in the understanding of a complex phenomenon such as the mechanical behavior of a detrital body of variable thickness, partially frozen, placed on a bedrock with variable geometry and subject to a time-variant climatic stress.
In other words, I believe that the topic of the paper has been dealt with in depth, focusing of course on a specific topic but also considering other variables. I think that this type of vision is a merit that is not always detectable in papers that are addressed to a wide audience such as the one interested in climate change vs geomorphic response.

I think that in some places the text needs minor clarifications / changes (not substantial) (see annotated manuscript).
The illustrations are more than good, and part of the data/results is conveniently placed in the supplement material.
Hope this may help.
Best regards - Adriano Ribolini

Regional scale investigation on rock glacier destabilization and links with climate change

Marco Marcer[1,2,3], Alessandro Cicoira[4], Diego Cusicanqui[2,5], Xavier Bodin[2], Thomas Echelard[1], Renée Obregon[1], Philippe Schoeneich[1]

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Abstract

Rock glaciers are ice-rich creeping landforms typical ~~of~~ permafrost mountain ranges ~~that in~~ particular topographic settings can develop an anomalous behaviour, called "destabilization". This phenomenon consists ~~in~~ a landslide-like behaviour of the rock glacier, which develops strain failures on its surface (e.g. cracks and crevasses) and an increase in the displacement rates by one to two orders of magnitude. Although several studies explored ~~this~~ event, investigations are conducted only on few landforms and~~,~~ often~~,~~ on limited time spans. Here, we investigate the evolution of rock glacier ~~destabilization occurrence~~ over the past seven decades for ~~a large region, i.e.~~ the entire French Alps, providing for the first time a regional-scale analysis of this phenomenon ~~and covering the past seven decades~~. Our results show that rock glacier displacements are characterized by an acceleration since the 1990s, concurrent with the development of destabilization in 18 landforms (i.e. 5% of the 337 active rock glaciers in the region). We then perform a statistical analysis to evaluate the correlation between destabilization ~~occurrence~~ and air temperature variability, highlighting that the onset of this phenomenon is significantly correlated to the increase in regional air temperature ~~and confirming~~ the results of previous studies based on single-site analysis. Although site~~s~~ characteristics play a critical role for the onset of destabilization, atmospheric warming is likely a necessary condition for the occurrence of this phenomenon. We therefore suggest that warming air temperatures are causing not only rock glacier acceleration ~~at regional scale~~ but also rock glacier destabilisation.

KEYWORDS: ROCK GLACIER, DESTABILIZATION, CLIMATE CHANGE, PERMAFROST

Introduction

Rock glaciers are debris landforms typical of the dry-cold mountain environment (Wahrhaftig & Cox, 1959) and are gaining interest in the contexts of water resources availability (Jones et al, 2017), paleoclimatology (e.g., Frauenfelder et al, 2001) and, due to their movement, potential natural hazards (e.g., Schoeneich et al, 2015). These landforms are generated when internal stresses, due to gravity, trigger a creeping mechanism in permafrost debris slopes that possess a sufficiently large ice content to allow for internal deformations (Haeberli, 1985). The creeping process confers to rock glaciers a typical cohesive flow morphology consisting of ridges and furrows created by compressive and extending stresses in the surface deformation patterns, which are clearly distinguishable in the landscape (Haeberli 1985, Frehner et al., 2015). The displacement rate of rock glaciers has been addressed in several studies describing the connection between climate and creep at different scales, ranging from seasonal (Wirz et al, 2016), decadal (Bodin et al, 2009), centennial (Shroder, 1976: Scapozza et al, 2010; Sorg et al, 2015), and millennial (Barsch, 1996: Kerschner et al, 1999). Rock glaciers were found to be climate sensitive as their displacement rates vary at the seasonal and decadal scales due to fluctuations in ground temperature and local hydrology characteristics (Buchli et al., 2018; Delaloye et al., 2010, Bodin et al., 2009, Cicoira et al, 2019a, Cicoira et al, 2019b).

Until few decades ago, rock glacier displacement rates were thought to be limited to a few decimetres per year, but recent studies have shown that acceleration can take place, bringing displacement rates of some landforms up to several meters per year (e.g. Delaloye et al, 2008, Kellerer-Pirklbauer et al, 2018). This acceleration pattern was described to be similar to the exponential relation between ice viscosity and temperature (Mellor et al, 1969), and a link between climate change and rock glacier displacement rates at the decade scale is, therefore, generally accepted by the scientific community (Arenson 2005a, Kääb et al 2007). In the European Alps it was observed that this climatic dependence process leads to a synchronous response of the landforms at the regional scale, from pluri-annual to pluri-decadal climatic trends, to the point that rock glacier dynamics have been suggested to be used as indicators of climate change impacts on the cryosphere (Delaloye et al, 2018).

However, in the past decades a growing number of studies reported anomalous rock glacier behaviour commonly addressed as “destabilization” (Avian et al., 2005; Bodin et al., 2016; Delaloye and Morand, 2011; Delaloye et al., 2013; Eriksen et al., 2018; Lambiel, 2011; Roer et al., 2008; Scotti, Crosta, & Villa, 2016; Vivero & Lambiel, 2019; Marcer et al, 2020). Though no widely accepted definition has yet emerged, rock glacier destabilization is mostly defined as a landslide-like behaviour of the landform, consisting of a sudden acceleration of part of the landform, where the displacement rates increase up to two orders of magnitude (see Figure 1). Such phase can last a few years up to several decades and generally resolves in a sudden deceleration or inactivation of the landform (Delaloye et al., 2013), although structural collapse of the landform may exceptionally occur (Bodin et al., 2016). Destabilization onset is also characterised by the development of tensile geomorphological features on the rock glacier surface (i.e. crevasses, cracks and scarps) called “destabilization signs”. These features most likely play a crucial role in the destabilisation process as they allow large infiltration from meteoric and melt water into the landform, as well as increased thermal exchange with warm summer air, reducing internal resistance and boosting the landslide-like behaviour. Thus, there is therefore a positive feedback process between acceleration and destabilisation signs development that once initiated rapidly compromise the rock glacier stability (Ikeda and Matsuoka, 2006). The destabilization signs mostly develop in steep and convex areas where extending flow occurs. Although this topographical predisposition is critical to the destabilization onset (Delaloye et al., 2013; Marcer et al., 2019), destabilization does not occur for all rock glaciers presenting high topographical predisposition (Marcer et al., 2019), suggesting that other geotechnical factors (e.g. rock glacier internal structure, temperature, hydrology, stress conditions related to overloading input of rock mass) also control the onset of the destabilization (Delaloye et al., 2013; Yamamoto and Springmann, 2017, Buchli et al., 2018). Once the process is triggered, the landform becomes dynamically discontinuous since the areas downslope from the destabilization signs develop a different dynamical behaviour than the areas upslope. In particular, the downslope areas generally experience a stronger acceleration, whereas upslope the behaviour of the rock glacier remains unchanged.

Concerning its onset, destabilization has been suggested to be the possible result of external mechanical loading (Delaloye et al, 2013; Scotti et al, 2016) or climatic forcing (Roer et al, 2008; Lambiel 2011; Eriksen et al, 2018). The first hypothesis addresses as triggering process those phenomena which force a variation in the rock glacier mass distribution in relation to the bedrock topography. These processes involve the passage of a thick area of the rock glacier over a steeper section or external loading caused by a rockfall on the landform surface. These processes induce internal stresses on the landform, that are suggested to compromise its creeping mechanism and lead to a strong acceleration. This hypothesis is supported by several studies that report destabilization onset after the occurrence of such phenomena (Delaloye et al., 2013; Scotti et al., 2016). The second hypothesis considers destabilization as a process induced or favoured by climate change. Increasing air temperatures are responsible for permafrost degradation (i.e., interstitial ice thaw and increase of water content), making the landforms velocity more sensitive to temperature (Mellor et al, 1969, Arenson 2005b, Kääb et al, 2007) and decrease in its internal stress resistance (Arenson 2005a, Yamamoto et al, 2017). Degrading permafrost is more prone to fracturing and to the development of openings (i.e. destabilisation signs) in the rock glacier surface (Arenson 2006, Yamamoto 2017). These openings enhance permafrost degradation by modifying local hydrology, establishing the positive feedback process that can compromise the landform stability (Ikeda et al., 2008; Yamamoto & Springman, 2017). Overall, both external mechanical loading and climatic forcing hypothesis are based on a limited number of case studies, and it is challenging to identify the main controlling factors in destabilization.

Although some studies have investigated regional scale evolution of rock glaciers displacements rates (Delaloye et al, 2008; Kellerer-Pirklbauer et al, 2018; Kääb et al, 2020), to date there are no similar investigations focusing on destabilization. In order to provide to the alpine permafrost community a valuable base to tackle these issues, this study aims to provide a regional scale systematic analysis of rock glacier displacement rates and destabilisation onset over the past seven decades (1948 – 2018). The region chosen for this study are the French Alps, i.e. the surface of the European Alps within the French national borders. These mountains are known to be rich in rock glaciers with a high number of potentially destabilized landforms (Marcer et al., 2017, 2019). For the same study region, Marcer et al. (2019) classified all the creeping rock glaciers in five classes of "destabilization rating" depending upon their geomorphological characteristics. The study indicated that 10% (i.e. 46) of the creeping rock glaciers in the French Alps show potential destabilization (Figure 3), giving therefore the opportunity to investigate the destabilization process on a larger scale than previous studies that typically focused on few sites.

The geomorphological observations provided by Marcer et al. (2019) are here combined with an analysis of the landforms horizontal displacement rates over the past seven decades, evaluated using manual feature tracking on aerial orthoimagery. This analysis is performed in three steps: regional scale assessment, site scale analysis and statistical analysis of the relationships with climatic conditions. At first, displacement rates of all active rock glaciers are estimated by manual feature tracking moving boulders on four orthomosaics provided by the French National Institute of Geography (IGN). The four orthomosaics are the result of the assemblage of orthoimages acquired during different periods: (i) 1948 to 1952, (ii) 2001 to 2004, (iii) 2008 to 2009 and (iv) 2015 to 2017, and allow to compute displacement rates over three time periods: period 1 from 1948-1952 to 2001-2004; period 2 from 2001-2004 to 2008-2009 and period 3 from 2008-2009 to 2015-2017. This analysis allows to obtain a rough estimation of the rock glacier dynamics in the region and its spatio-temporal evolution, and, most importantly, to identify the destabilized rock glaciers, i.e. presenting abnormally high displacement rates (> 3 m/y) and destabilization sings development (Study site localization in Figure 3; for a detailed site description of each landform see the annexed document “Destabilized rock glaciers in the French Alps”). The second step consists in a detailed analysis of displacement rates and geomorphological evolution of these destabilized landforms using a higher number of orthoimages. Additional to the destabilized landforms, three rock glaciers not presenting destabilization (from hereon referred as “stable”) are also investigated, in order to provide displacement rates evolution to be compared to the destabilized landforms. Additional orthoimages are computed for each site using the Structure from Motion approach (Smith et al., 2016) from aerial imagery that was acquired by the IGN since the 40s at pluriannnial frequency (generally, five to fifteen years) and recent UAV surveys. The orthoimages are also used to explore the relationship between strain rates and crevasse formation at the local sites, which have been widely investigated in the field of glaciology (e.g. Holdsworth, 1969). For the destabilized rock glaciers, the strain rates are calculated between the stable and the destabilized area, while for stable rock glaciers strain rates are evaluated between upper and lower moving target available.

Finally, since the database provided by this study is unique and it allows new insights on rock glacier destabilization, we propose a basic analysis of the link between this phenomenon and climate changes aimed to explore the hypothesis of a statistically significant correlation between climate and destabilization development. In particular we evaluate correlation significance between the dynamical evolution of both and destabilized rock glaciers and the air temperature anomaly evolution, extracted for each rock glacier site using the SAFRAN meteorological reanalysis (Durand et al., 2009) and HISTALP database (Auer et al., 2006).

Results

Regional scale assessment

Significant displacement rates in at least one of the periods were evaluated for 337 rock glaciers, while significant movements in all three periods were obtained for 114 rock glaciers (Fig. 3). Incomplete displacement rate series were mostly due to insufficient image quality in one or more frames, sometimes causing movements to be below the detectability thresholds. Because these thresholds are inversely proportional to the duration of the time period, slow rock glaciers are more easily detectable over longer time periods. On average for our data set, only rock glaciers moving faster than 0.52 m/y could be detected in the period 2008-2009 to 2015-2017, while in the period 1948-1952 to 2001-2004 this threshold was 0.10 m/y.

Our results show an increase in rock glaciers displacement rates during the past seven decades (Figure 4, Table 1) for the French Alps. Mean displacement rates increased from 0.30 m/y (period 1948-1952 to 2001-2004) to 0.97 m/y (period 2001-2004 to 2008-2009) and finally to 1.25 m/y (period 2008-2009 to 2015-2017). On average for the whole region, displacement rate in 2008-2009 to 2015-2017 is six times higher than in 1948-1952 to 2001-2004. Most of the acceleration occurred between the periods 1948-1952 to 2001-2004 and 2001-2004 to 2008-2009 (average increase of 223 %), while between the periods 2001-2004 to 2008-2009 and 2008-2009 to 2015-2017 the acceleration was significantly lower (average increase of 29%). Significant increase in displacement rates from the period 1948-1952 to 2001-2004 to the period 2001-2004 to 2008-2009 was observed for 97 rock glaciers, while only two landforms significantly decreased their displacement rates. From the period 2001-2004 to 2008-2009 to the period 2008-2009 to 2015-2017 an increase in displacement rates was observed for 40 landforms, while deceleration was observed in 18 landforms. The landform that presented the strongest deceleration (from 6.4 ± 0.1 m/y in period 2 to 2.8 ± 0.1 m/y in 2008-2009 to 2015-2017) is a destabilized rock glacier and presented in the site scale analysis (i.e. PP rock glacier).

Comparing the displacement rates with the destabilization ratings by Marcer et al (2019) indicates that landforms developing geomorphological evidences of destabilization show on average three to five times higher displacement rates than in landforms not developing such features (Figure 5, Table 1). Although this result indicates that rock glacier geomorphological characteristics are linked to dynamical behaviour, about 50% of the potentially destabilized rock glaciers (ratings 3b and 3a, according to geomorphological characteristics only) showed displacement rates below 2 m/y in the period 2008-2009 to 2015-2017 (Fig. 4 and 5). In total, 18 rock glaciers show both destabilization signs and high displacement rates (above 3 m/y) and are identified as destabilized. Their average displacement rates increased from 0.69 m/y in the period 1948-1952 to 2001-2004 to 4.55 m/y in the period 2008-2009 to 2015-2017.

Site scale analysis

Site scale analysis of displacement rates evolution is performed for all the destabilized landforms and three stable landforms for comparison. The reader is reminded that detailed site analysis is available in the annex document, while sites location can be found in figure 3. Displacement rates of stable landforms presented two phases: low displacement rates in the period 50s-90s followed by a second phase consisting of a gradual acceleration. Although they all follow a similar general trend, different sites have significant differences. For the Pb rock glacier, high displacement rates are observable also in the late 40s before the low velocity phase. Overall, the highest velocity was observed on the northern lobe of the Rib rock glacier (2.5 ± 0.2 m/y, period 2009 – 2013). The displacement rates for the Lau (Laurichard) rock glacier are used as reference for comparison between different landforms (Fig. 2, for the others sites see annex document “Destabilized rock glacier in the French Alps”), due to the outstanding long time series of geodetic measurements of surface targets since 1982 (Francou and Reynaud, 1992; Thibert et al, 2018).

Destabilized landforms also present as common pattern low displacement rates from the 1950s to 1990s and acceleration afterwards. In particular, no case of destabilization occurrence was observed during these four decades. Some destabilized landforms (PM and PB rock glaciers) showed onset of destabilization signs and higher displacement rates in the late 40s, reaching 3.8 ± 0.5 m/y in PB (period 1948 – 1952). The destabilization signs nevertheless little evolved between the late 50s until the 90s, consistently to the low displacement rates. After the 90s, destabilization onset can be observed in a few sites, and the 18 sites develop destabilization signs and acceleration across roughly two decades. Five rock glaciers entered the destabilization phase before 2000 (PB, RN, PC, PP, GB rock glaciers), ten between 2000 and 2010 (TL, PA, CA, CC1, CC2, PM, RD, PR1, PR2, PR3 rock glaciers) and only three after 2010 (OF, CL, AS rock glaciers). Deceleration (phase c, figure 1) can be observed in TL, PP, and RN rock glaciers only, indicating that most of the destabilized landforms in the region may have not peaked the destabilization process (phase c, Figure 1) in the years 2013 - 2018. The maximum displacement rate is measured between 2013 – 2015 on TL rock glacier, reaching 22.1 ± 0.3 m/y before a strong deceleration. Exceptionally high displacement rates are observed also on RD (15.2 ± 0.3 m/y in 2013 - 2016) and PC (9.7 ± 0.2 m/y in 2013 – 2016 m/y) rock glaciers, while the other landforms present maximum velocities commonly between 4 and 6 m/y.

The patterns of destabilization onset vary for the different sites. For most sites displacement rates increase gradually through the 90s and 2000s, concurrently with the development of increasingly severe destabilization signs. On the other hand, some sites exhibit an abrupt transition to the destabilization phase marked by sharp acceleration and sudden development of a severe destabilization sign. In AS rock glacier for example, velocity sharply increases from 1.3 ± 0.4 m/y in 2009 – 2013 to 6.5 ± 0.4 m/y in 2013 – 2016 in concomitance to the rapid development of a large crevasse sectioning the landform in its entire width. Similar phenomena are observed in TL, RD, OF, RN and PB rock glaciers. In PB rock glacier in particular, destabilization occurs as an abrupt increase in displacement rates from 1990 to 1995, concurrently to the development of three crevasses on the landform surface. However, in the following two decades no acceleration is observed, and it was only in 2013 – 2017 that the landform experienced a second destabilization phase concurrent to the development of a new series of crevasses and significant acceleration.

In general, we find that destabilization onset and the appearance of surface disturbances corresponds to a critical strain rate of roughly 10^{-2} y^{-1}, while the values for stable rock glaciers are one order of magnitude lower. The t-test shows no statistical difference between strain rates on stable rock glaciers and rock glaciers before the onset of destabilization (Figure 6). The critical strain rate for rock glacier destabilization and linked crevassing is consistent with the values for crevassing on alpine glaciers, which ranges from 10^{-2} to 10^{-1} for ice temperatures comprised between -10°C and 0°C (Vaughan, 1993). Most of the apparent variation in observed critical strain rates on alpine glaciers can be attributed to variations in the properties of ice, mostly due to ice temperature. For rock glaciers, variations in the volumetric ice content could be of equal importance. Even at given material properties, however, a given strain rate is not equivalent to a single unique combination of Cartesian stresses, which also depend on the geometry of the glacier (and of the rock glacier) (Colgan, 2016). In comparison to critical strain rates, critical stresses could provide a more robust criterion for fracture onset. However, neither ground temperature nor internal deformation profiles are known for the investigated set of rock glaciers and more specific studies are required to constrain the calculation of the stresses

Statistical analysis

The results demonstrate that rock glacier displacement rates are correlated with mean air temperature (MAT, Figure 7). The correlation is stronger for the logarithm of the displacement rate, indicating an exponential relation between air temperature and displacement rates. For all the active rock glaciers in the region, correlation coefficients range from R^2=0.21 for stable rock glaciers to R^2= 0.55 for destabilized landforms. The regression coefficients are always statistically significant (p-value < 0.01), rejecting the null hypothesis that the predictor variable (air temperature) has no effect on the response variable (rock glaciers displacement rates). Also at the sites scale, the correlation between MAT and displacement rates for destabilized (R^2 = 0.54, p-value<0.01) and stable rock glaciers (R^2=0.14, p-value <0.1) is statistically significant. Concerning the destabilization onset, air temperature anomaly is also found to be a "very good" (Area Under the Curve, AUC = 0.82, sensu Hosmer and Lemeshow, 2000) discriminator of the transition between the stable and destabilized phases of the local sites.

Discussion

Our results indicate a regional scale increase in rock glacier displacement rates in the past seven decades which has developed relatively synchronously, i.e. within two decades of the investigated period (1948 – 2018). Kääb et al (2020) reports analogous observations in the northern Tien Shan, central Asia. Overall, about 5% of the total active rock glaciers in the region shows destabilization, which developed since the late 1990s concomitant to the regional scale rock glacier acceleration. Destabilization affects about 40% of the ~~potentially destabilized rock glaciers~~ indicating that ~~destabilization~~ signs like cracks, crevasses and scarps may form in rock glaciers with low displacement rates and do not necessarily concur with strong acceleration typical of the destabilization process. Nevertheless, we also observed that the destabilization signs can prelude a future acceleration for the rock glaciers which have not experienced destabilization yet. This was observed for the cases of PB and PM rock glaciers, which show crevasses since the 1940s but entered the destabilization process only five decades later. In this sense, local geotechnical characteristics and landform structure are considered to be fundamental for destabilization onset and development (Marcer et al., 2019). While local topography creates extending flow patterns that increases the surface strain rates to a critical point, geotechnical characteristics in rock glaciers, determined by lithology, internal structure and ice/water contents, determine their resilience to temperature variations and mechanical stress and, ultimately, to the destabilization trigger (Yamamoto & Springman, 2017). Once the destabilization process is triggered, displacement rates display large variability from site to site. Highest displacement rates may depend upon geometrical characteristics of thickness and slope angle of the destabilized section as well as underground water circulation (Eriksen et al., 2018; Kenner et al., 2017). Temporal development of the "crisis" is also variable as some sites have already passed the acceleration phase and are now decreasing their velocity while others are still accelerating.

The evolution of the rock glacier displacement rates was found to be statistically correlated to air temperature, which is consistent with the fact that air warming trends cause a generalized rock glacier acceleration based on process understanding (Delaloye et al., 2008; Kellerer-Pirklbauer & Kaufmann, 2018). Two sites (PB and PM rock glaciers) showed evidence of an earlier destabilization phase in the period 40s to the 50s, while other five sites have significantly higher displacement rates in the period 1940 – 1970 than in the period 1980 – 1990 (RN, OF, CA, GB and PR1 rock glaciers). This phenomenon, also observed on other sites in Switzerland (Delaloye et al., 2013, Graben Gufer and Gugla rock glaciers) and Austria (Avian et al 2005, Hinteres Langtalkar rock glacier) roughly coincides with reported rock glacier acceleration linked to air temperature increase that took place during the late 40s (Nickus et al., 2013). This temporal pattern in rock glacier destabilization and displacement rates is also similar to the mass balance variability of the glaciers in the region, which, across the XXth century, was observed to be negative in the periods 40s to 50s and 80s to present (Vincent 2002; Huss et al, 2009, GLAMOS, 2018).

Overall, these observations suggest that air temperature warming is a necessary condition to destabilization onset. Increase in air temperature is known to be responsible for permafrost warming (Biskaborn et al., 2019), which can decrease the mechanical resistance of the material in the permafrost body of a rock glacier. This process can facilitate the development of surface openings in extending flow areas, which can increase the permeability of the rock glacier, engaging the positive feedback of permafrost degradation described by Ikeda and Matsuoka (2002) and Yamamoto et al (2017). Laboratory experiments for ice and ice-rich frozen soils have shown that the viscosity of the material depends exponentially on temperature (e.g. Mellor et al, 1969, Arenson et al 2005a). In this sense, the exponential correlation between displacement rates and air temperature anomaly at destabilized rock glacier sites suggests a process of permafrost degradation at the root of the rock glacier acceleration which, depending on local geotechnical conditions, may generate destabilization onset and development. Air temperature seems to lose the dominant control on destabilized rock glacier dynamics on longer time scales, as rock glaciers eventually encounter deceleration (phase d, Figure 1) despite further air temperature increase. Temperature increase can therefore be considered a necessary but not sufficient factor for destabilization onset at the regional scale, but losing its control on local scale dynamics after destabilization occurs and site local characteristics become dominant. Climate warming was already hypothesized as potential cause for rock glacier destabilization by a number of studies (Roer et al, 2008; Lambiel, 2011; Eriksen et al, 2018) and this work provides new evidence supporting this hypothesis, strongly suggesting that rock glacier destabilization should be investigated as a large scale phenomenon of climate-induced degradation of the cryosphere.

On larger time scales (e.g. century), it is widely accepted that increasing air temperatures cause permafrost loss that ultimately induces the inactivation of the creeping process (Scapozza et al., 2010). Older rock glacier generations that belonged to colder phases of the late Pleistocene and that inactivated during warm events are the proof of the fate of these landforms on the long term (Frauenfelder et al., 2001; Oliva et al., 2018). The decreasing number of accelerating landforms in the past two decades observed in this study may relate to the onset of a generalized inactivation process induced by present day climate change. Destabilization appears to be a critical step of this process, occurring on landforms whose stability is highly sensitive due to local characteristics. Nevertheless, since destabilized rock glaciers appear to be dynamically discontinuous landforms, areas upslope and downslope the discontinuity caused by the surface disturbances are likely to experience independent ~~fate,~~ The fast moving mass is expected to eventually inactivate when reaching gentler slopes or when a considerable amount of mass is wasted during its rapid advance (Delaloye et al., 2010; Kääb et al., 2007; Lambiel, 2011). The upslope areas may create a new front where the surface disturbances were located, replacing the destabilized, and ultimately removed, mass (Delaloye et al., 2013).

Methods

This study is based on the analysis of surface displacement rates, destabilization occurrences and their correlation with climate, evaluated using a statistical approach.

Statistical analysis

The correlation between mean air temperatures (predictor variable) and displacement rates during the same period (response variable) is estimated at first using a linear regression model, weighting each observation proportionally to the duration of the period covered. The performance of the regression model is evaluated using the correlation coefficient R^2 and the statistical significance of the correlation is evaluated using the p-value. In addition to linear regression, logistic regression is used to quantify the discriminative power of mean air temperature in destabilization occurrence. For each local site, displacement rates periods are classified into a binary response variable depending upon their belonging to either a stable phase (see phase a in Figure 1) or a destabilized phase (see phases b, c, and d in Figure 1). The transition from phase a to phase b is determined for each site when development of destabilization signs was first observable (Figure 5). Mean air temperatures for each period are computed and used as predictor variable for the rock glacier phase in logistic regression model. Model quality is evaluated using the Area Under the Curve (AUC), measuring the discriminatory ability of air temperature on the transition of the rock glaciers from stability to destabilization (Hosmer and Lemeshow, 2000).

Rock glacier displacement rates

The displacement rates are estimated by diachronic orthoimages comparison (Kääb & Vollmer, 2000) for both the local and the regional scale analysis. Two steps are performed for each available orthoimage pairs: (i) manual tracking of rock glacier surface features to compute displacement rates, and (ii) definition of stable areas for uncertainty assessment. The methodological difference between the local and regional scale assessments lays in the amount of moving targets and stable areas used in the analysis, which are higher in the local scale assessment. This was done aiming to work with a reasonable trade-off between effort and study goals, which aimed to obtain a general regional context of rock glacier displacement rates to contextualize more detailed results obtained by the local scale analysis. Four of the destabilized sites benefit of an additional analysis, consisting of (iii) automatic feature tracking of high-resolution orthoimages, allowing to calculate spatially distributed 2-dimensional displacement rate fields.

Manual feature tracking

Surface displacements were measured by tracking boulders clearly identifiable in all available frames. The displacement rates were then computed by dividing the distance covered by the boulders by the time elapsed between two frames. In the regional scale analysis, only one boulder, located in the area qualitatively showing largest displacements, was tracked and used to compute displacement rates. In the site scale analysis, are tracked at least two boulders located upslope and downslope the surface disturbances, in order to observe the displacement rates evolution of different landform areas. The fastest moving boulder is used in the statistical analysis.

Uncertainty assessment

Using orthoimages pairs to evaluate displacement rates involves a source of uncertainty belonging to the errors in the orthoimages used for the surface feature tracking process. The main source of uncertainty is due to orthoimages local distortions. In order to account this source of uncertainty, stable areas (e.g. bedrock, vegetated patterns) are identified in different orthoimages and their relative movements are then used to quantify the uncertainty in displacement rates assessment due to local distortions.

Uncertainty assessment in the regional scale analysis was performed by identifying only one stable area per investigated landform, providing the displacement rate uncertainty for each orthoimage pair. Rock glacier displacements that were lower than twice the apparent movement in the stable area were considered as not significant and discarded. In the local scale analysis, four to ten stable areas were identified, depending on the study site. The displacement rate uncertainty was then computed for each moving target by using a mean function linearly weighted on the distance between the moving target and the available stable areas apparent movements.

Spatial distribution of displacement rates

The spatial distribution of the displacement rates was computed using the IMCORR algorithm and orthoimages pairs that presented sufficiently high quality and comparable lighting conditions. The software output consisted of a point grid of estimated displacements and directions. After manual filtering of output errors (e.g. unrealistic displacements due to shading and/or snow), the point grid was interpolated using inverse distance weighted method to produce a displacement rates heatmap.

Surface strain rates

Surface strain rates was calculated for each rock glacier analysed at the local scale. The displacement rate difference between the two closest moving targets upslope and downlslope the crevassed area was divided by their distance projected on the flow axis. This operation results in a variation of displacement rates [m/y] over a metric distance [m], simplified to a unit of measure of [y^{-1}]. For ten of the destabilized landforms, upslope displacement rates were not available, and strain rates could not be calculated. For stable rock glaciers, the same operation was performed over several pairs of targets in order to obtain the highest surface strain rates occurring on the landform, which was then used on the analysis.

Data

Climatic data

Climate is described by the air temperature anomaly since the end of the pre-industrial (i.e. 1850) and it is evaluated at each rock glacier location using climate datasets for the French Alps. For the period 1958 – 2018 data are extracted from the SAFRAN reanalysis, which operate for 23 massifs in the French Alps, within which atmospheric conditions, in particular temperature, are assumed to be homogeneous and vary with elevation using 300 m elevation steps (Durand et al 2009). For earlier periods, the HISTALP gridded data (1 km cell) were used. They consist in an interpolation of weather station data in the

European Alps since 1780 (Auer et al, 2006). To combine these two different data sets, the overlapping period between SAFRAN and HISTALP data (1958 – 2014) was used to compute a linear model to extrapolate the SAFRAN data in the past from 1850 to 1957. The correlation coefficient between the two data sets (SAFRAN and HISTALP) varies from 0.4 to 0.9 depending on the rock glacier site.

Displacement rates

The displacement rate analysis is based on orthoimages that belong to three sources: (i) orthomosaics produced by the National Institute of Geography (IGN) for the entire French territory, (ii) local orthoimages produced using aerial images acquired by the IGN photogrammetric missions since the late 40s and (iii) local orthoimages produced using in-situ UAV photogrammetry, performed in 2017 and 2018. The regional scale analysis was based on the first source of data only, while the local scale analysis benefits from the second data source as well. UAV photogrammetry was conducted only on four destabilized rock glaciers (PB, RN, CL and TL). For a summary of available orthoimages and their characteristics using in the local scale assessment, see the supplementary materials.

Data source I: IGN Orthoimosaics

The orthoimosaics provided by the IGN consist of assembled orthoimages of each administrative department collected over a specific time period. Orthoimages in an orthomosaics can therefore be collected in different years. The supplementary materials provide a synthesis of orthoimage date per administrative department. The advantage of this data source consist in ready-to-use data at relatively high quality at the regional scale. This allows to focus on displacement rates data gathering rather than production of orthoimages at the regional scale. Each rock glacier in the region is observable in 4 orthomosaics from the years 1948-1952, 2001 – 2004, 2008 -2009 and 2015 - 2017. This allows to compute displacement rates over three periods referred here as: period 1 (second half of the 20th century), period 2 (first decade of the 21st century) and period 3 (Late 2000s to mid 2010s).

Data source II: Orthoimages from aerial photogrammetric surveys

Aerial images are acquired by the IGN regularly since the late 1940s, providing a valuable database for diachronic studies. This data source allows to increase the temporal resolution of the analysis significantly in the study sites. The aerial images are treated using the classic Structure from Motion (SfM) approach in Agisoft Photoscan (Smith et al., 2016). Ground control points (GCPs) coordinates to georeference the model were acquired from a master frame, i.e. the 2018 UAV orthoimage (described in the section below) or the 2015 - 2017 IGN Orthoimage when UAV data is unavailable. GCPs are collected around the perimeter of the rock glacier, in order to increase the accuracy of the resulting orthoimage within the landform area. GCPs number is at first kept at its minimum for the georeferencing and optimization process, i.e. three points, and increased if the resulting orthoimage did not present a suitable accuracy when compared to the master frame.

Data source III: Orthoimages from UAV in-situ photogrammetric surveys

As UAV photogrammetric missions are capable to provide high quality orthoimages and terrain models for rock glaciers (Dall'Asta et al., 2017; Vivero & Lambiel, 2019), two surveys took place in summer-fall 2017 and 2018 on the rock glaciers sites of PB, TL, RN and CL. Pictures were acquired using the commercial UAV Mavick Pro and the automatic flight planner Drone Map. Except for the mission at PB in 2017, where the flight planner failed, all the missions were conducted acquiring pictures with an overlap of 85 % at an altitude of at least 90m. For the 2018 a second flight level at 150 m altitude was added to the mission.

UAV pictures were treated using the classical SfM approach in Agisoft Photoscan. High precision GCPs were acquired only in 2018 using a Trimble GPS as rover and a Trimble as base. The method chosen was rapid-static and the raw data were post-processed in differential mode. This allowed to compute and georeference the DEMs and orthoimages for the 2018 survey, and use their fixed areas as GCPs to reference the models from the 2017 surveys. This method was not used for the Longet rock glacier as the GCPs survey did not take place in 2018. In this site, GCPs were measured from fixed areas in the available IGN orthoimage.

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Data availability

The authors declare that the main data supporting the findings of this study are available within the article and its Supplementary Information files. Extra data are available from the corresponding author upon request.

Code availability

The authors declare that the code used to obtain the main results of this study can be made available from the corresponding author upon request.

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Figures

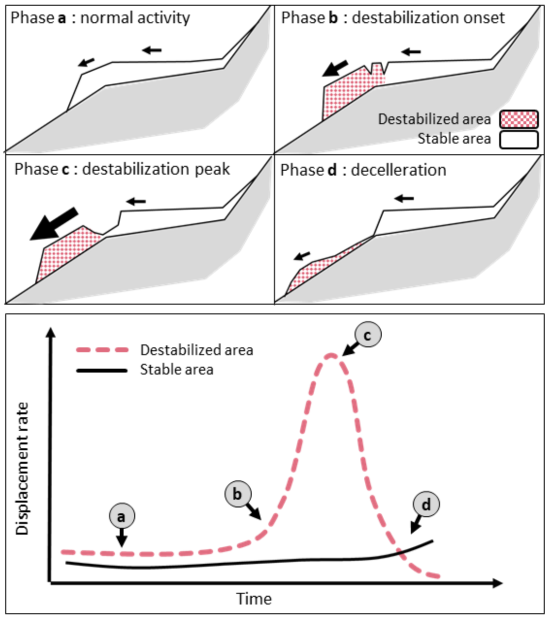

Figure 1: Conceptual representation of the destabilization process in terms of geomorphological (upper panel) and dynamical (bottom panel) evolution of the areas upslope (Stable area) and downslope (Destabilized area) the surface disturbances. A stable rock glacier is characterized by homogeneous displacement rates in both areas and there is no destabilized mass (phase a). The destabilization process can occur if the rock glacier presents topographical predisposition (e.g. topographical convexities). The destabilization onset is characterized by the development of surface disturbances (phase b), which accelerates the downslope area significantly, while the upslope area remains stable. The displacement rates of the downslope area reach their maximum (phase c) within few years/decades after the destabilization onset, creating a larger discontinuity between upslope and downslope velocities. After the peak phase (c), the destabilized area decelerates because of mass loss and/or flatter topography (phase d) and reaches inactivation.

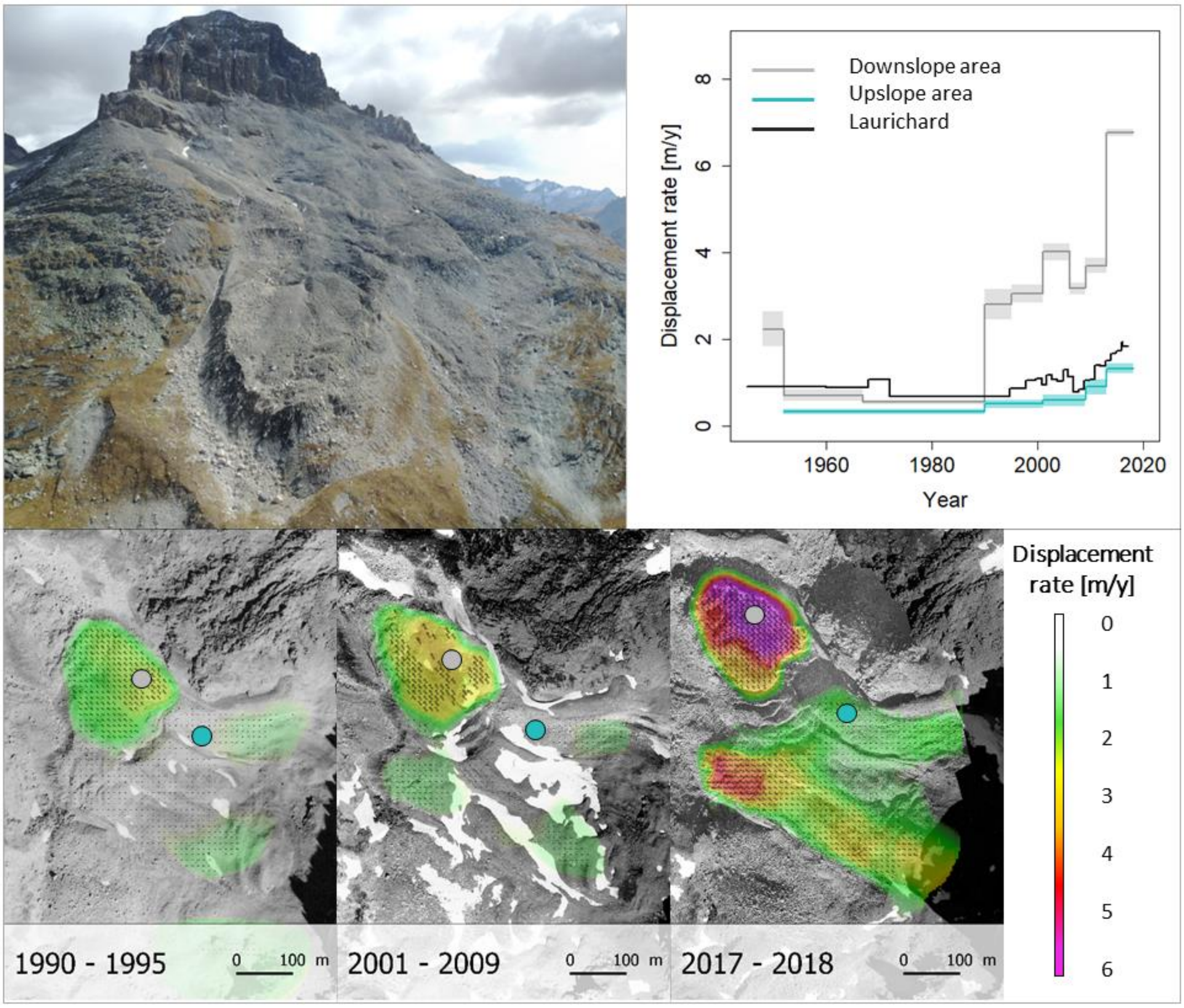

Figure 2- Destabilization example on the study site of Pierre Brune, a destabilized site approaching the peak phase (phase b to c in Figure 1). Similar results are produced for every site in this study, and available in the supplementary materials. Displacement rates are plotted altogether with the movements of the Laurichard rock glacier for comparison with a landform not showing destabilization. Destabilization onsets between 1990 and 1995 in relation to the fast development of crevasses. A crevasse is already visible in the area in 1990 and belongs to an earlier destabilization phase that occurred during the late 1940s. The destabilized mass starts moving faster than the upslope areas, creating a strongly discontinuous deformation pattern and the landform is dynamically disconnected in correspondence of the surface disturbances. While the upslope area presents a behaviour similar to the Laurichard rock glacier (not destabilized), the downslope mass is still accelerating reaching much higher displacement rates.

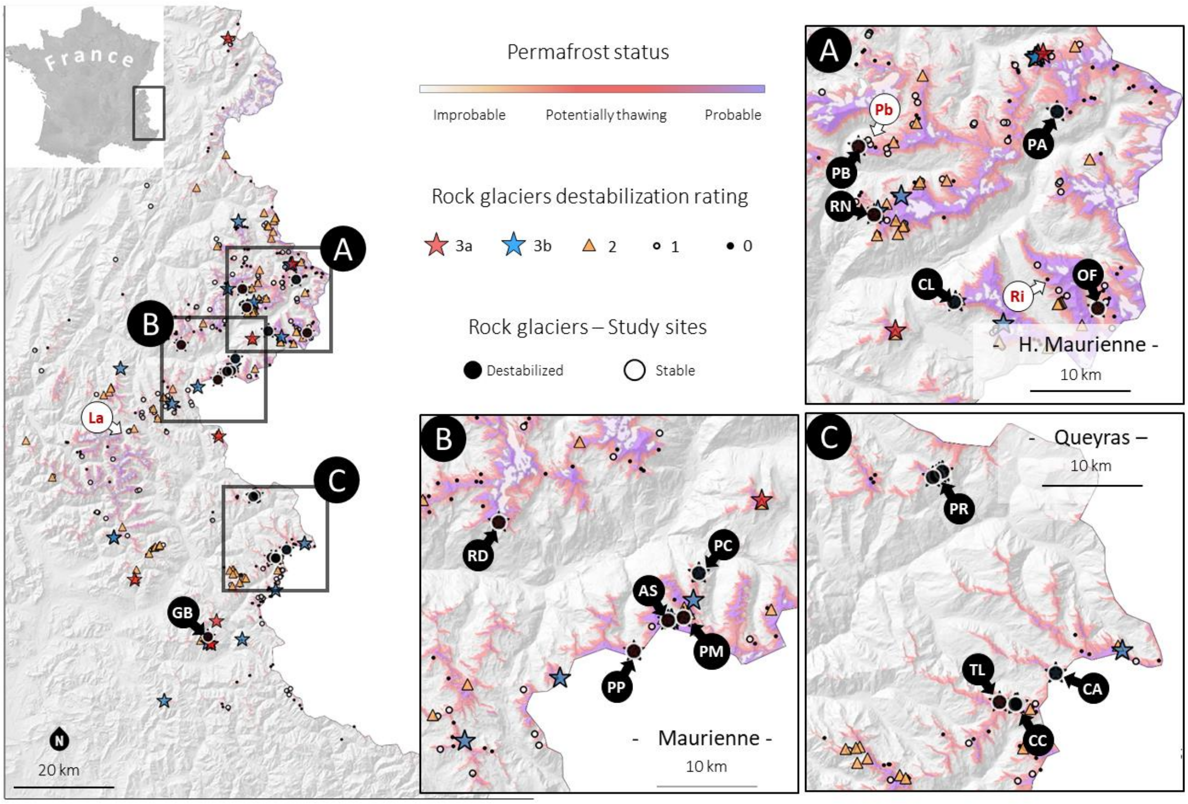

Figure 3 – French Alps: permafrost status and localization of active rock glaciers rated by geomorphological evidence of destabilization according to Marcer et al., (2019) and the present study. Destabilization ratings vary from 0 (no geomorphological evidence of destabilization) to 3 (evidence of developing surface disturbances and consequent dynamical discontinuity in the landform). In rate 3a the surface disturbances are characteristics of more severe destabilization, i.e. crevasses and scarps, while in rate 3b are observed only shallow cracks. Intermediary rates are 1 and 2, describing stable and developing surface disturbances respectively. Rock glaciers showing destabilization rating of 3 and found by this study to have displacement rates above 3 m/y are classified as destabilized and investigated in detail. The rock glaciers investigated by this study are referred by an acronym, the reader may refer to the annexes for a detailed description of each site.

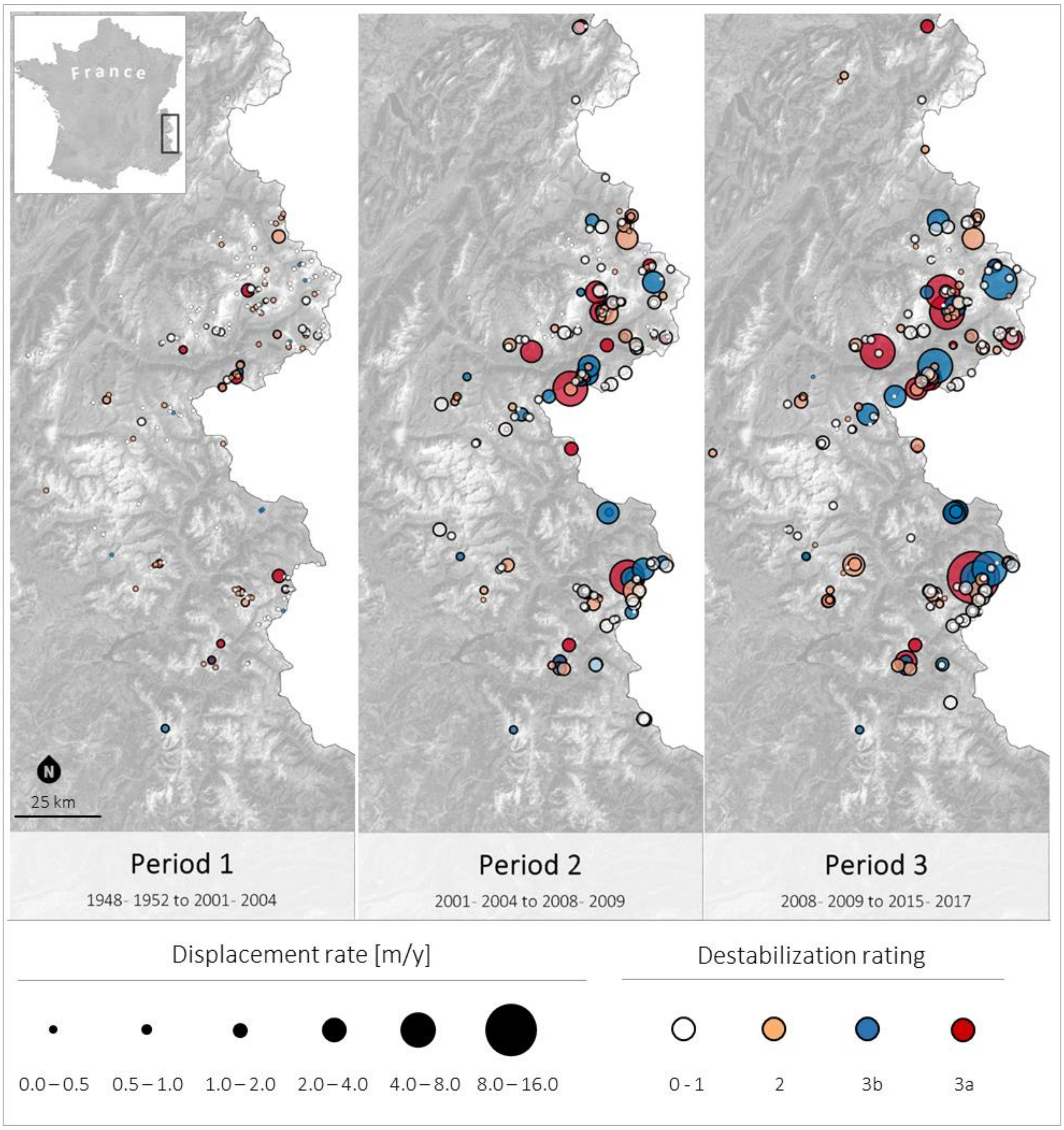

Figure 4 – Evolution of the rock glacier displacement rates in the French Alps in the three periods investigated. Symbol size is proportional to the measured displacement rate, while symbol colour is assigned accordingly to the destabilization rating (see Figure 3 for rating description).

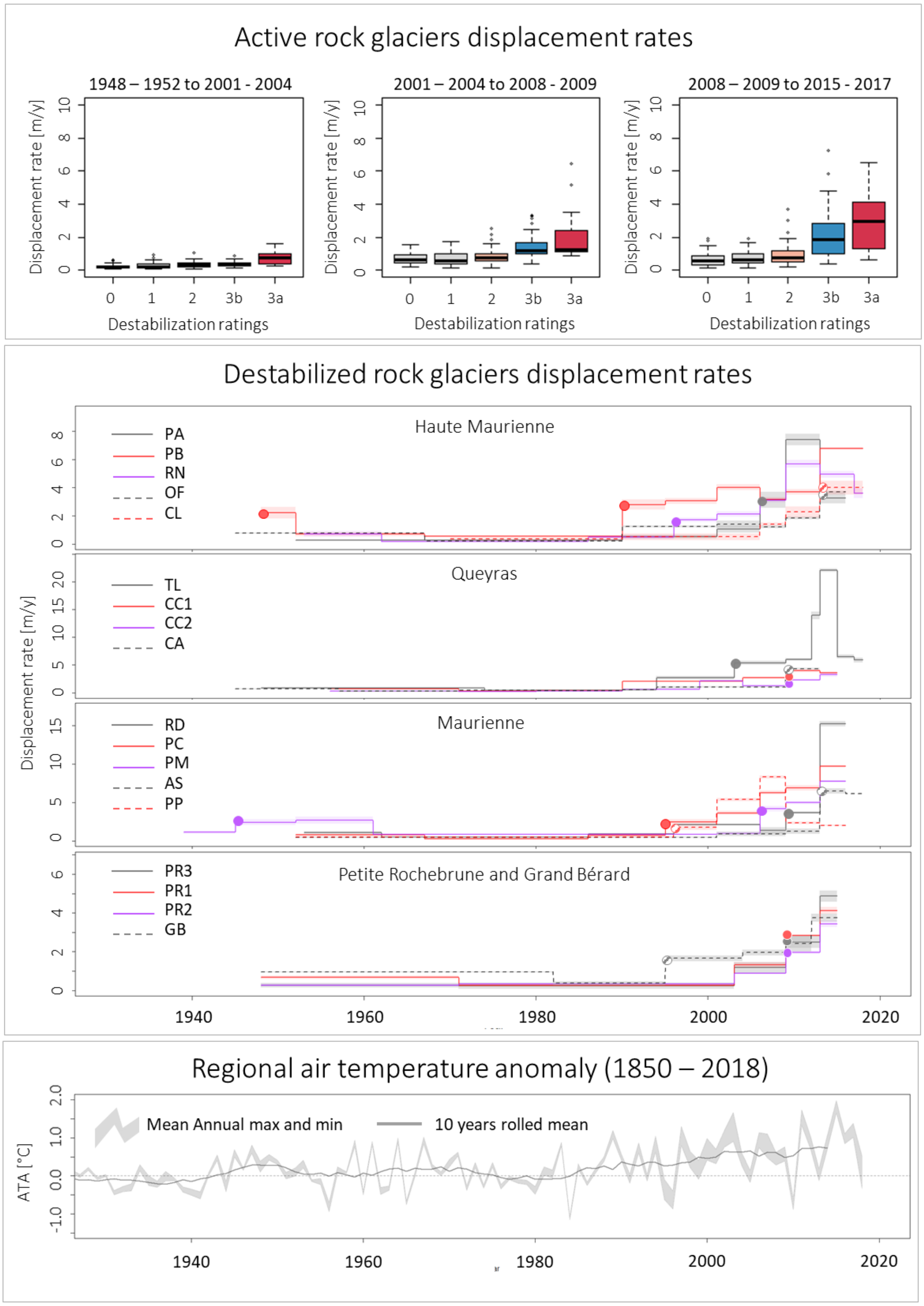

Figure 5 - Evolution in the past seven decades of regional scale rock glacier displacement rates (grouped by destabilization rate) and investigated destabilized rock glaciers displacement rates. Dots in destabilized rock glaciers graphs indicate the observed onset of the destabilized phase. On bottom, mean annual air temperature anomaly in the period 1850 - 2018.

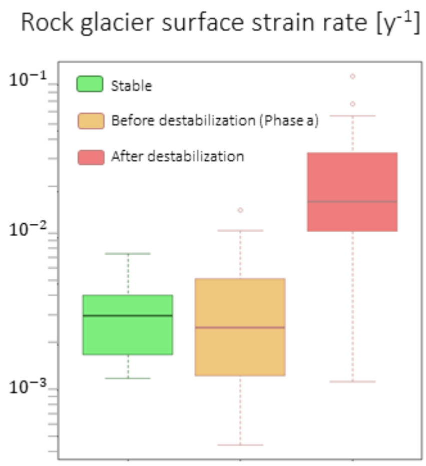

Figure 6 – Boxplots summarizing the surface strain rates measured at the local sites. Low values of strain rates in destabilized rock glaciers refer to the deceleration of the destabilized area (phase d – Figure 1).

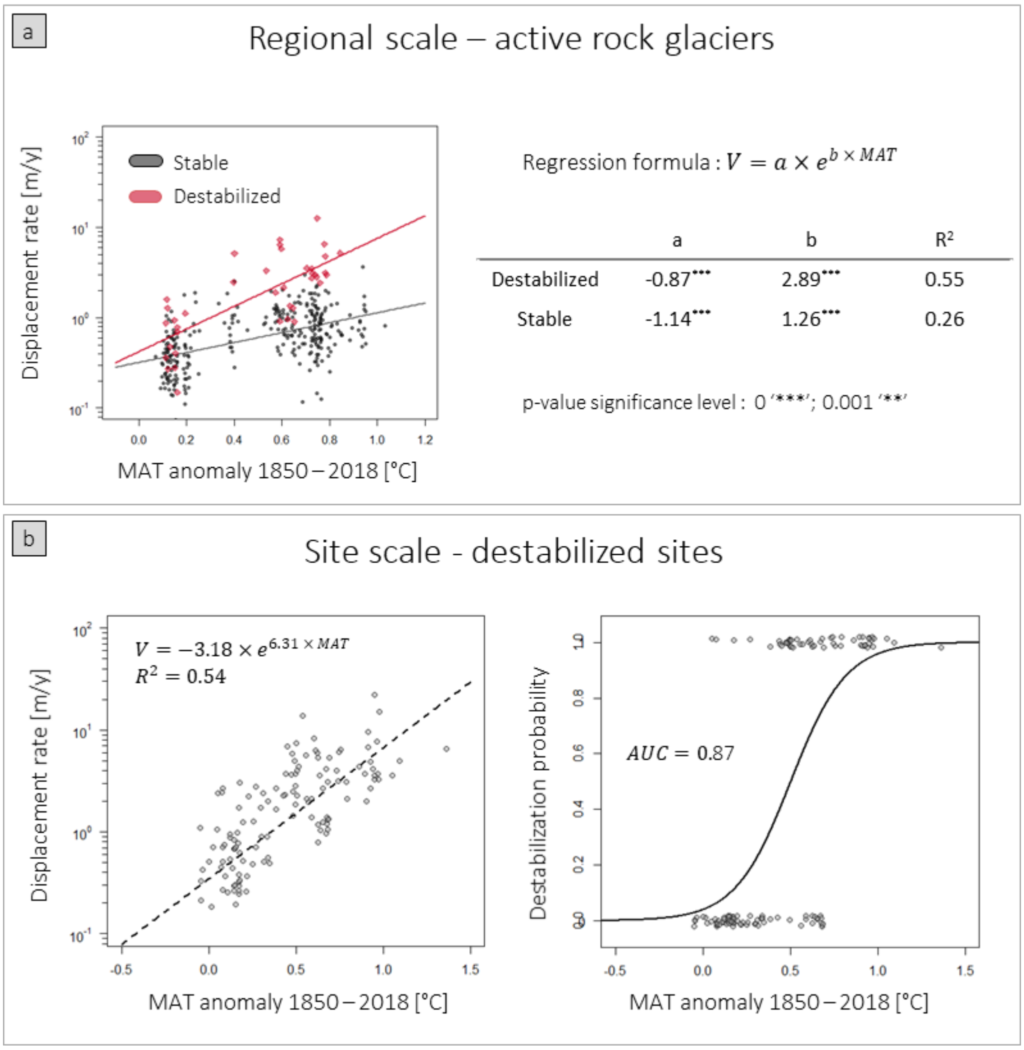

Figure 7 – Statistical analysis of the correlation between Mean Air Temperature (MAT) anomaly since the preindustrial and rock glacier displacement rates at the regional (a) and site (b) scales. For the regional scale analysis, the relation between MAT anomaly and displacement rates is modelled for both stable and destabilized rock glaciers and the regression coefficients are presented in the table. For the site scale analysis, linear and logistic regressions are evaluated on the aggregated measures for all sites.

Tables

Table 1: Regional scale displacement rates and relative increase in displacement rate (in %) by period and destabilization ratings. Period 1: from 1948-1952 to 2001-2004; Period 2: from 2001-2004 to 2008-2009; Period 3: from 2008-2009 to 2015-2017. Destabilization ratings (Marcer et al., 2019) characterize the landforms from their geomorphological evidences of destabilization. Rock glaciers with lower ratings do not show significant evidence of destabilization, while higher ratings are attributed to rock glaciers developing mild (rating 3b) or severe (3a) destabilization signs causing dynamical discontinuity in the landform.

	Mean displacement rate [m/y]			Relative increase in displacement rate [%]	
Dest. rating	Period 1	Period 2	Period 3	Period 1 to Period 2	Period 2 to Period 3
0	0.22	0.72	0.73	227	1
1	0.27	0.71	0.77	163	8
2	0.35	0.85	1.02	143	20
3b	0.39	1.46	2.36	274	62
3a	0.77	2.18	3.45	183	58
Mean	0.3	0.97	1.25	223	29

Regional scale investigation on rock glacier destabilization and links with climate change

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Abstract

Rock glaciers are ice-rich creeping landforms typical of permafrost mountain ranges that in particular topographic settings can develop an anomalous behaviour, called "destabilization". This phenomenon consists in a landslide-like behaviour of the rock glacier, which develops strain failures on its surface (e.g. cracks and crevasses) and an increase in the displacement rates by one to two orders of magnitude. Although several studies explored this event, investigations are conducted only on few landforms and, often, on limited time spans. Here, we investigate the evolution of rock glacier destabilization occurrence over the past seven decades for a large region, i.e. the entire French Alps, providing for the first time a regional-scale analysis of this phenomenon and covering the past seven decades. Our results show that rock glacier displacements are characterized by an acceleration since the 1990s, concurrent with the development of destabilization in 18 landforms (i.e. 5% of the 337 active rock glaciers in the region). We then perform a statistical analysis to evaluate the correlation between destabilization occurrence and air temperature variability, highlighting that the onset of this phenomenon is significantly correlated to the increase in regional air temperature and confirming the results of previous studies based on single-site analysis. Although sites characteristics play a critical role for the onset of destabilization, atmospheric warming is likely a necessary condition for the occurrence of this phenomenon. We therefore suggest that warming air temperatures are causing not only rock glacier acceleration at regional scale but also rock glacier destabilisation.

KEYWORDS: ROCK GLACIER, DESTABILIZATION, CLIMATE CHANGE, PERMAFROST

Introduction

Rock glaciers are debris landforms typical of the dry-cold mountain environment (Wahrhaftig & Cox, 1959) and are gaining interest in the contexts of water resources availability (Jones et al, 2017), paleoclimatology (e.g., Frauenfelder et al, 2001) and, due to their movement, potential natural hazards (e.g., Schoeneich et al, 2015). These landforms are generated when internal stresses, due to gravity, trigger a creeping mechanism in permafrost debris slopes that possess a sufficiently large ice content to allow for internal deformations (Haeberli, 1985). The creeping process confers to rock glaciers a typical cohesive flow morphology consisting of ridges and furrows created by compressive and extending stresses in the surface deformation patterns, which are clearly distinguishable in the landscape (Haeberli 1985, Frehner et al., 2015). The displacement rate of rock glaciers has been addressed in several studies describing the connection between climate and creep at different scales, ranging from seasonal (Wirz et al, 2016), decadal (Bodin et al, 2009), centennial (Shroder, 1976: Scapozza et al, 2010; Sorg et al, 2015), and millennial (Barsch, 1996: Kerschner et al, 1999). Rock glaciers were found to be climate sensitive as their displacement rates vary at the seasonal and decadal scales due to fluctuations in ground temperature and local hydrology characteristics (Buchli et al., 2018; Delaloye et al., 2010, Bodin et al., 2009, Cicoira et al, 2019a, Cicoira et al, 2019b).

Until few decades ago, rock glacier displacement rates were thought to be limited to a few decimetres per year, but recent studies have shown that acceleration can take place, bringing displacement rates of some landforms up to several meters per year (e.g. Delaloye et al, 2008, Kellerer-Pirklbauer et al, 2018). This acceleration pattern was described to be similar to the exponential relation between ice viscosity and temperature (Mellor et al, 1969), and a link between climate change and rock glacier displacement rates at the decade scale is, therefore, generally accepted by the scientific community (Arenson 2005a, Kääb et al 2007). In the European Alps it was observed that this climatic dependence process leads to a synchronous response of the landforms at the regional scale, from pluri-annual to pluri-decadal climatic trends, to the point that rock glacier dynamics have been suggested to be used as indicators of climate change impacts on the cryosphere (Delaloye et al, 2018).

However, in the past decades a growing number of studies reported anomalous rock glacier behaviour commonly addressed as “destabilization” (Avian et al., 2005; Bodin et al., 2016; Delaloye and Morand, 2011; Delaloye et al., 2013; Eriksen et al., 2018; Lambiel, 2011; Roer et al., 2008; Scotti, Crosta, & Villa, 2016; Vivero & Lambiel, 2019; Marcer et al, 2020). Though no widely accepted definition has yet emerged, rock glacier destabilization is mostly defined as a landslide-like behaviour of the landform, consisting of a sudden acceleration of part of the landform, where the displacement rates increase up to two orders of magnitude (see Figure 1). Such phase can last a few years up to several decades and generally resolves in a sudden deceleration or inactivation of the landform (Delaloye et al., 2013), although structural collapse of the landform may exceptionally occur (Bodin et al., 2016). Destabilization onset is also characterised by the development of tensile geomorphological features on the rock glacier surface (i.e. crevasses, cracks and scarps) called “destabilization signs”. These features most likely play a crucial role in the destabilisation process as they allow large infiltration from meteoric and melt water into the landform, as well as increased thermal exchange with warm summer air, reducing internal resistance and boosting the landslide-like behaviour. Thus, there is therefore a positive feedback process between acceleration and destabilisation signs development that once initiated rapidly compromise the rock glacier stability (Ikeda and Matsuoka, 2006). The destabilization signs mostly develop in steep and convex areas where extending flow occurs. Although this topographical predisposition is critical to the destabilization onset (Delaloye et al., 2013; Marcer et al., 2019), destabilization does not occur for all rock glaciers presenting high topographical predisposition (Marcer et al., 2019), suggesting that other geotechnical factors (e.g. rock glacier internal structure, temperature, hydrology, stress conditions related to overloading input of rock mass) also control the onset of the destabilization (Delaloye et al., 2013; Yamamoto and Springmann, 2017, Buchli et al., 2018). Once the process is triggered, the landform becomes dynamically discontinuous since the areas downslope from the destabilization signs develop a different dynamical behaviour than the areas upslope. In particular, the downslope areas generally experience a stronger acceleration, whereas upslope the behaviour of the rock glacier remains unchanged.

Concerning its onset, destabilization has been suggested to be the possible result of external mechanical loading (Delaloye et al, 2013; Scotti et al, 2016) or climatic forcing (Roer et al, 2008; Lambiel 2011; Eriksen et al, 2018). The first hypothesis addresses as triggering process those phenomena which force a variation in the rock glacier mass distribution in relation to the bedrock topography. These processes involve the passage of a thick area of the rock glacier over a steeper section or external loading caused by a rockfall on the landform surface. These processes induce internal stresses on the landform, that are suggested to compromise its creeping mechanism and lead to a strong acceleration. This hypothesis is supported by several studies that report destabilization onset after the occurrence of such phenomena (Delaloye et al., 2013; Scotti et al., 2016). The second hypothesis considers destabilization as a process induced or favoured by climate change. Increasing air temperatures are responsible for permafrost degradation (i.e., interstitial ice thaw and increase of water content), making the landforms velocity more sensitive to temperature (Mellor et al, 1969, Arenson 2005b, Kääb et al, 2007) and decrease in its internal stress resistance (Arenson 2005a, Yamamoto et al, 2017). Degrading permafrost is more prone to fracturing and to the development of openings (i.e. destabilisation signs) in the rock glacier surface (Arenson 2006, Yamamoto 2017). These openings enhance permafrost degradation by modifying local hydrology, establishing the positive feedback process that can compromise the landform stability (Ikeda et al., 2008; Yamamoto & Springman, 2017). Overall, both external mechanical loading and climatic forcing hypothesis are based on a limited number of case studies, and it is challenging to identify the main controlling factors in destabilization.

Although some studies have investigated regional scale evolution of rock glaciers displacements rates (Delaloye et al, 2008; Kellerer-Pirklbauer et al, 2018; Kääb et al, 2020), to date there are no similar investigations focusing on destabilization. In order to provide to the alpine permafrost community a valuable base to tackle these issues, this study aims to provide a regional scale systematic analysis of rock glacier displacement rates and destabilisation onset over the past seven decades (1948 – 2018). The region chosen for this study are the French Alps, i.e. the surface of the European Alps within the French national borders. These mountains are known to be rich in rock glaciers with a high number of potentially destabilized landforms (Marcer et al., 2017, 2019). For the same study region, Marcer et al. (2019) classified all the creeping rock glaciers in five classes of "destabilization rating" depending upon their geomorphological characteristics. The study indicated that 10% (i.e. 46) of the creeping rock glaciers in the French Alps show potential destabilization (Figure 3), giving therefore the opportunity to investigate the destabilization process on a larger scale than previous studies that typically focused on few sites.

The geomorphological observations provided by Marcer et al. (2019) are here combined with an analysis of the landforms horizontal displacement rates over the past seven decades, evaluated using manual feature tracking on aerial orthoimagery. This analysis is performed in three steps: regional scale assessment, site scale analysis and statistical analysis of the relationships with climatic conditions. At first, displacement rates of all active rock glaciers are estimated by manual feature tracking moving boulders on four orthomosaics provided by the French National Institute of Geography (IGN). The four orthomosaics are the result of the assemblage of orthoimages acquired during different periods: (i) 1948 to 1952, (ii) 2001 to 2004, (iii) 2008 to 2009 and (iv) 2015 to 2017, and allow to compute displacement rates over three time periods: period 1 from 1948-1952 to 2001-2004; period 2 from 2001-2004 to 2008-2009 and period 3 from 2008-2009 to 2015-2017. This analysis allows to obtain a rough estimation of the rock glacier dynamics in the region and its spatio-temporal evolution, and, most importantly, to identify the destabilized rock glaciers, i.e. presenting abnormally high displacement rates (> 3 m/y) and destabilization sings development (Study site localization in Figure 3; for a detailed site description of each landform see the annexed document "Destabilized rock glaciers in the French Alps"). The second step consists in a detailed analysis of displacement rates and geomorphological evolution of these destabilized landforms using a higher number of orthoimages. Additional to the destabilized landforms, three rock glaciers not presenting destabilization (from hereon referred as "stable") are also investigated, in order to provide displacement rates evolution to be compared to the destabilized landforms. Additional orthoimages are computed for each site using the Structure from Motion approach (Smith et al., 2016) from aerial imagery that was acquired by the IGN since the 40s at pluriannnial frequency (generally, five to fifteen years) and recent UAV surveys. The orthoimages are also used to explore the relationship between strain rates and crevasse formation at the local sites, which have been widely investigated in the field of glaciology (e.g. Holdsworth, 1969). For the destabilized rock glaciers, the strain rates are calculated between the stable and the destabilized area, while for stable rock glaciers strain rates are evaluated between upper and lower moving target available.

Finally, since the database provided by this study is unique and it allows new insights on rock glacier destabilization, we propose a basic analysis of the link between this phenomenon and climate changes aimed to explore the hypothesis of a statistically significant correlation between climate and destabilization development. In particular we evaluate correlation significance between the dynamical evolution of both and destabilized rock glaciers and the air temperature anomaly evolution, extracted for each rock glacier site using the SAFRAN meteorological reanalysis (Durand et al., 2009) and HISTALP database (Auer et al., 2006).

Results

Regional scale assessment

Significant displacement rates in at least one of the periods were evaluated for 337 rock glaciers, while significant movements in all three periods were obtained for 114 rock glaciers (Fig. 3). Incomplete displacement rate series were mostly due to insufficient image quality in one or more frames, sometimes causing movements to be below the detectability thresholds. Because these thresholds are inversely proportional to the duration of the time period, slow rock glaciers are more easily detectable over longer time periods. On average for our data set, only rock glaciers moving faster than 0.52 m/y could be detected in the period 2008-2009 to 2015-2017, while in the period 1948-1952 to 2001-2004 this threshold was 0.10 m/y.

Our results show an increase in rock glaciers displacement rates during the past seven decades (Figure 4, Table 1) for the French Alps. Mean displacement rates increased from 0.30 m/y (period 1948-1952 to 2001-2004) to 0.97 m/y (period 2001-2004 to 2008-2009) and finally to 1.25 m/y (period 2008-2009 to 2015-2017). On average for the whole region, displacement rate in 2008-2009 to 2015-2017 is six times higher than in 1948-1952 to 2001-2004. Most of the acceleration occurred between the periods 1948-1952 to 2001-2004 and 2001-2004 to 2008-2009 (average increase of 223 %), while between the periods 2001-2004 to 2008-2009 and 2008-2009 to 2015-2017 the acceleration was significantly lower (average increase of 29%). Significant increase in displacement rates from the period 1948-1952 to 2001-2004 to the period 2001-2004 to 2008-2009 was observed for 97 rock glaciers, while only two landforms significantly decreased their displacement rates. From the period 2001-2004 to 2008-2009 to the period 2008-2009 to 2015-2017 an increase in displacement rates was observed for 40 landforms, while deceleration was observed in 18 landforms. The landform that presented the strongest deceleration (from 6.4 ± 0.1 m/y in period 2 to 2.8 ± 0.1 m/y in 2008-2009 to 2015-2017) is a destabilized rock glacier and presented in the site scale analysis (i.e. PP rock glacier).

Comparing the displacement rates with the destabilization ratings by Marcer et al (2019) indicates that landforms developing geomorphological evidences of destabilization show on average three to five times higher displacement rates than in landforms not developing such features (Figure 5, Table 1). Although this result indicates that rock glacier geomorphological characteristics are linked to dynamical behaviour, about 50% of the potentially destabilized rock glaciers (ratings 3b and 3a, according to geomorphological characteristics only) showed displacement rates below 2 m/y in the period 2008-2009 to 2015-2017 (Fig. 4 and 5). In total, 18 rock glaciers show both destabilization signs and high displacement rates (above 3 m/y) and are identified as destabilized. Their average displacement rates increased from 0.69 m/y in the period 1948-1952 to 2001-2004 to 4.55 m/y in the period 2008-2009 to 2015-2017.

Site scale analysis

Site scale analysis of displacement rates evolution is performed for all the destabilized landforms and three stable landforms for comparison. The reader is reminded that detailed site analysis is available in the annex document, while sites location can be found in figure 3. Displacement rates of stable landforms presented two phases: low displacement rates in the period 50s-90s followed by a second phase consisting of a gradual acceleration. Although they all follow a similar general trend, different sites have significant differences. For the Pb rock glacier, high displacement rates are observable also in the late 40s before the low velocity phase. Overall, the highest velocity was observed on the northern lobe of the Rib rock glacier (2.5 ± 0.2 m/y, period 2009 – 2013). The displacement rates for the Lau (Laurichard) rock glacier are used as reference for comparison between different landforms (Fig. 2, for the others sites see annex document "Destabilized rock glacier in the French Alps"), due to the outstanding long time series of geodetic measurements of surface targets since 1982 (Francou and Reynaud, 1992; Thibert et al, 2018).

Destabilized landforms also present as common pattern low displacement rates from the 1950s to 1990s and acceleration afterwards. In particular, no case of destabilization occurrence was observed during these four decades. Some destabilized landforms (PM and PB rock glaciers) showed onset of destabilization signs and higher displacement rates in the late 40s, reaching 3.8 ± 0.5 m/y in PB (period 1948 – 1952). The destabilization signs nevertheless little evolved between the late 50s until the 90s, consistently to the low displacement rates. After the 90s, destabilization onset can be observed in a few sites, and ~~the~~ 18 sites develop destabilization signs and acceleration across roughly two decades. Five rock glaciers entered the destabilization phase before 2000 (PB, RN, PC, PP, GB rock glaciers), ten between 2000 and 2010 (TL, PA, CA, CC1, CC2, PM, RD, PR1, PR2, PR3 rock glaciers) and only three after 2010 (OF, CL, AS rock glaciers). Deceleration (phase c, figure 1) can be observed in TL, PP, and RN rock glaciers only, indicating that most of the destabilized landforms in the region may have not peaked the destabilization process (phase c, Figure 1) in the years 2013 - 2018. The maximum displacement rate is measured between 2013 – 2015 on TL rock glacier, reaching 22.1 ± 0.3 m/y before a strong deceleration. Exceptionally high displacement rates are observed also on RD (15.2 ± 0.3 m/y in 2013 - 2016) and PC (9.7 ± 0.2 m/y in 2013 – 2016 m/y) rock glaciers, while the other landforms present maximum velocities commonly between 4 and 6 m/y.

The patterns of destabilization onset vary for the different sites. For most sites displacement rates increase gradually through the 90s and 2000s, concurrently with the development of increasingly severe destabilization signs. On the other hand, some sites exhibit an abrupt transition to the destabilization phase marked by sharp acceleration and sudden development of a severe destabilization sign. In AS rock glacier for example, velocity sharply increases from 1.3 ± 0.4 m/y in 2009 – 2013 to 6.5 ± 0.4 m/y in 2013 – 2016 in concomitance to the rapid development of a large crevasse sectioning the landform in its entire width. Similar phenomena are observed in TL, RD, OF, RN and PB rock glaciers. In PB rock glacier in particular, destabilization occurs as an abrupt increase in displacement rates from 1990 to 1995, concurrently to the development of three crevasses on the landform surface. However, in the following two decades no acceleration is observed, and it was only in 2013 – 2017 that the landform experienced a second destabilization phase concurrent to the development of a new series of crevasses and significant acceleration.

In general, we find that destabilization onset and the appearance of surface disturbances corresponds to a critical strain rate of roughly 10^{-2} y^{-1}, while the values for stable rock glaciers are one order of magnitude lower. The t-test shows no statistical difference between strain rates on stable rock glaciers and rock glaciers before the onset of destabilization (Figure 6). The critical strain rate for rock glacier destabilization and linked crevassing is consistent with the values for crevassing on alpine glaciers, which ranges from 10^{-2} to 10^{-1} for ice temperatures comprised between -10°C and 0°C (Vaughan, 1993). Most of the apparent variation in observed critical strain rates on alpine glaciers can be attributed to variations in the properties of ice, mostly due to ice temperature. For rock glaciers, variations in the volumetric ice content could be of equal importance. Even at given material properties, however, a given strain rate is not equivalent to a single unique combination of Cartesian stresses, which also depend on the geometry of the glacier (and of the rock glacier) (Colgan, 2016). In comparison to critical strain rates, critical stresses could provide a more robust criterion for fracture onset. However, neither ground temperature nor internal deformation profiles are known for the investigated set of rock glaciers and more specific studies are required to constrain the calculation of the stresses

Statistical analysis

The results demonstrate that rock glacier displacement rates are correlated with mean air temperature (MAT, Figure 7). The correlation is stronger for the logarithm of the displacement rate, indicating an exponential relation between air temperature and displacement rates. For all the active rock glaciers in the region, correlation coefficients range from R^2=0.21 for stable rock glaciers to R^2= 0.55 for destabilized landforms. The regression coefficients are always statistically significant (p-value < 0.01), rejecting the null hypothesis that the predictor variable (air temperature) has no effect on the response variable (rock glaciers displacement rates). Also at the sites scale, the correlation between MAT and displacement rates for destabilized (R^2 = 0.54, p-value<0.01) and stable rock glaciers (R^2=0.14, p-value <0.1) is statistically significant. Concerning the destabilization onset, air temperature anomaly is also found to be a "very good" (Area Under the Curve, AUC = 0.82, sensu Hosmer and Lemeshow, 2000) discriminator of the transition between the stable and destabilized phases of the local sites.

Discussion

Our results indicate a regional scale increase in rock glacier displacement rates in the past seven decades which has developed relatively synchronously, i.e. within two decades of the investigated period (1948 – 2018). Kääb et al (2020) reports analogous observations in the northern Tien Shan, central Asia. Overall, about 5% of the total active rock glaciers in the region shows destabilization, which developed since the late 1990s concomitant to the regional scale rock glacier acceleration. Destabilization affects about 40% of the potentially destabilized rock glaciers indicating that destabilization signs like cracks, crevasses and scarps may form in rock glaciers with low displacement rates and do not necessarily concur with strong acceleration typical of the destabilization process. Nevertheless, we also observed that the destabilization signs can prelude a future acceleration for the rock glaciers which have not experienced destabilization yet. This was observed for the cases of PB and PM rock glaciers, which show crevasses since the 1940s but entered the destabilization process only five decades later. In this sense, local geotechnical characteristics and landform structure are considered to be fundamental for destabilization onset and development (Marcer et al., 2019). While local topography creates extending flow patterns that increases the surface strain rates to a critical point, geotechnical characteristics in rock glaciers, determined by lithology, internal structure and ice/water contents, determine their resilience to temperature variations and mechanical stress and, ultimately, to the destabilization trigger (Yamamoto & Springman, 2017). Once the destabilization process is triggered, displacement rates display large variability from site to site. Highest displacement rates may depend upon geometrical characteristics of thickness and slope angle of the destabilized section as well as underground water circulation (Eriksen et al., 2018; Kenner et al., 2017). Temporal development of the "crisis" is also variable as some sites have already passed the acceleration phase and are now decreasing their velocity while others are still accelerating.

The evolution of the rock glacier displacement rates was found to be statistically correlated to air temperature, which is consistent with the fact that air warming trends cause a generalized rock glacier acceleration based on process understanding (Delaloye et al., 2008; Kellerer-Pirklbauer & Kaufmann, 2018). Two sites (PB and PM rock glaciers) showed evidence of an earlier destabilization phase in the period 40s to the 50s, while other five sites have significantly higher displacement rates in the period 1940 – 1970 than in the period 1980 – 1990 (RN, OF, CA, GB and PR1 rock glaciers). This phenomenon, also observed on other sites in Switzerland (Delaloye et al., 2013, Graben Gufer and Gugla rock glaciers) and Austria (Avian et al 2005, Hinteres Langtalkar rock glacier) roughly coincides with reported rock glacier acceleration linked to air temperature increase that took place during the late 40s (Nickus et al., 2013). This temporal pattern in rock glacier destabilization and displacement rates is also similar to the mass balance variability of the glaciers in the region, which, across the XXth century, was observed to be negative in the periods 40s to 50s and 80s to present (Vincent 2002; Huss et al, 2009, GLAMOS, 2018).

Overall, these observations suggest that air temperature warming is a necessary condition to destabilization onset. Increase in air temperature is known to be responsible for permafrost warming (Biskaborn et al., 2019), which can decrease the mechanical resistance of the material in the permafrost body of a rock glacier. This process can facilitate the development of surface openings in extending flow areas, which can increase the permeability of the rock glacier, engaging the positive feedback of permafrost degradation described by Ikeda and Matsuoka (2002) and Yamamoto et al (2017). Laboratory experiments for ice and ice-rich frozen soils have shown that the viscosity of the material depends exponentially on temperature (e.g. Mellor et al, 1969, Arenson et al 2005a). In this sense, the exponential correlation between displacement rates and air temperature anomaly at destabilized rock glacier sites suggests a process of permafrost degradation at the root of the rock glacier acceleration which, depending on local geotechnical conditions, may generate destabilization onset and development. Air temperature seems to lose the dominant control on destabilized rock glacier dynamics on longer time scales, as rock glaciers eventually encounter deceleration (phase d, Figure 1) despite further air temperature increase. Temperature increase can therefore be considered a necessary but not sufficient factor for destabilization onset at the regional scale, but losing its control on local scale dynamics after destabilization occurs and site local characteristics become dominant. Climate warming was already hypothesized as potential cause for rock glacier destabilization by a number of studies (Roer et al, 2008; Lambiel, 2011; Eriksen et al, 2018) and this work provides new evidence supporting this hypothesis, strongly suggesting that rock glacier destabilization should be investigated as a large scale phenomenon of climate-induced degradation of the cryosphere.

On larger time scales (e.g. century), it is widely accepted that increasing air temperatures cause permafrost loss that ultimately induces the inactivation of the creeping process (Scapozza et al., 2010). Older rock glacier generations that belonged to colder phases of the late Pleistocene and that inactivated during warm events are the proof of the fate of these landforms on the long term (Frauenfelder et al., 2001; Oliva et al., 2018). The decreasing number of accelerating landforms in the past two decades observed in this study may relate to the onset of a generalized inactivation process induced by present day climate change. Destabilization appears to be a critical step of this process, occurring on landforms whose stability is highly sensitive due to local characteristics. Nevertheless, since destabilized rock glaciers appear to be dynamically discontinuous landforms, areas upslope and downslope the discontinuity caused by the surface disturbances are likely to experience independent fate. The fast moving mass is expected to eventually inactivate when reaching gentler slopes or when a considerable amount of mass is wasted during its rapid advance (Delaloye et al., 2010; Kääb et al., 2007; Lambiel, 2011). The upslope areas may create a new front where the surface disturbances were located, replacing the destabilized, and ultimately removed, mass (Delaloye et al., 2013).

Methods

This study is based on the analysis of surface displacement rates, destabilization occurrences and their correlation with climate, evaluated using a statistical approach.

Statistical analysis

The correlation between mean air temperatures (predictor variable) and displacement rates during the same period (response variable) is estimated at first using a linear regression model, weighting each observation proportionally to the duration of the period covered. The performance of the regression model is evaluated using the correlation coefficient R^2 and the statistical significance of the correlation is evaluated using the p-value. In addition to linear regression, logistic regression is used to quantify the discriminative power of mean air temperature in destabilization occurrence. For each local site, displacement rates periods are classified into a binary response variable depending upon their belonging to either a stable phase (see phase a in Figure 1) or a destabilized phase (see phases b, c, and d in Figure 1). The transition from phase a to phase b is determined for each site when development of destabilization signs was first observable (Figure 5). Mean air temperatures for each period are computed and used as predictor variable for the rock glacier phase in logistic regression model. Model quality is evaluated using the Area Under the Curve (AUC), measuring the discriminatory ability of air temperature on the transition of the rock glaciers from stability to destabilization (Hosmer and Lemeshow, 2000).

Rock glacier displacement rates

The displacement rates are estimated by diachronic orthoimages comparison (Kääb & Vollmer, 2000) for both the local and the regional scale analysis. Two steps are performed for each available orthoimage pairs: (i) manual tracking of rock glacier surface features to compute displacement rates, and (ii) definition of stable areas for uncertainty assessment. The methodological difference between the local and regional scale assessments lays in the amount of moving targets and stable areas used in the analysis, which are higher in the local scale assessment. This was done aiming to work with a reasonable trade-off between effort and study goals, which aimed to obtain a general regional context of rock glacier displacement rates to contextualize more detailed results obtained by the local scale analysis. Four of the destabilized sites benefit of an additional analysis, consisting of (iii) automatic feature tracking of high-resolution orthoimages, allowing to calculate spatially distributed 2-dimensional displacement rate fields.

Manual feature tracking

Surface displacements were measured by tracking boulders clearly identifiable in all available frames. The displacement rates were then computed by dividing the distance covered by the boulders by the time elapsed between two frames. In the regional scale analysis, only one boulder, located in the area qualitatively showing largest displacements, was tracked and used to compute displacement rates. In the site scale analysis, are tracked at least two boulders located upslope and downslope the surface disturbances, in order to observe the displacement rates evolution of different landform areas. The fastest moving boulder is used in the statistical analysis.

Uncertainty assessment

Using orthoimages pairs to evaluate displacement rates involves a source of uncertainty belonging to the errors in the orthoimages used for the surface feature tracking process. The main source of uncertainty is due to orthoimages local distortions. In order to account this source of uncertainty, stable areas (e.g. bedrock, vegetated patterns) are identified in different orthoimages and their relative movements are then used to quantify the uncertainty in displacement rates assessment due to local distortions.

Uncertainty assessment in the regional scale analysis was performed by identifying only one stable area per investigated landform, providing the displacement rate uncertainty for each orthoimage pair. Rock glacier displacements that were lower than twice the apparent movement in the stable area were considered as not significant and discarded. In the local scale analysis, four to ten stable areas were identified, depending on the study site. The displacement rate uncertainty was then computed for each moving target by using a mean function linearly weighted on the distance between the moving target and the available stable areas apparent movements.

Spatial distribution of displacement rates

The spatial distribution of the displacement rates was computed using the IMCORR algorithm and orthoimages pairs that presented sufficiently high quality and comparable lighting conditions. The software output consisted of a point grid of estimated displacements and directions. After manual filtering of output errors (e.g. unrealistic displacements due to shading and/or snow), the point grid was interpolated using inverse distance weighted method to produce a displacement rates heatmap.

Surface strain rates

Surface strain rates was calculated for each rock glacier analysed at the local scale. The displacement rate difference between the two closest moving targets upslope and downlslope the crevassed area was divided by their distance projected on the flow axis. This operation results in a variation of displacement rates [m/y] over a metric distance [m], simplified to a unit of measure of [y^{-1}]. For ten of the destabilized landforms, upslope displacement rates were not available, and strain rates could not be calculated. For stable rock glaciers, the same operation was performed over several pairs of targets in order to obtain the highest surface strain rates occurring on the landform, which was then used on the analysis.

Data

Climatic data

Climate is described by the air temperature anomaly since the end of the pre-industrial (i.e. 1850) and it is evaluated at each rock glacier location using climate datasets for the French Alps. For the period 1958 – 2018 data are extracted from the SAFRAN reanalysis, which operate for 23 massifs in the French Alps, within which atmospheric conditions, in particular temperature, are assumed to be homogeneous and vary with elevation using 300 m elevation steps (Durand et al 2009). For earlier periods, the HISTALP gridded data (1 km cell) were used. They consist in an interpolation of weather station data in the

European Alps since 1780 (Auer et al, 2006). To combine these two different data sets, the overlapping period between SAFRAN and HISTALP data (1958 – 2014) was used to compute a linear model to extrapolate the SAFRAN data in the past from 1850 to 1957. The correlation coefficient between the two data sets (SAFRAN and HISTALP) varies from 0.4 to 0.9 depending on the rock glacier site.

Displacement rates

The displacement rate analysis is based on orthoimages that belong to three sources: (i) orthomosaics produced by the National Institute of Geography (IGN) for the entire French territory, (ii) local orthoimages produced using aerial images acquired by the IGN photogrammetric missions since the late 40s and (iii) local orthoimages produced using in-situ UAV photogrammetry, performed in 2017 and 2018. The regional scale analysis was based on the first source of data only, while the local scale analysis benefits from the second data source as well. UAV photogrammetry was conducted only on four destabilized rock glaciers (PB, RN, CL and TL). For a summary of available orthoimages and their characteristics using in the local scale assessment, see the supplementary materials.

Data source I: IGN Orthoimosaics

The orthoimosaics provided by the IGN consist of assembled orthoimages of each administrative department collected over a specific time period. Orthoimages in an orthomosaics can therefore be collected in different years. The supplementary materials provide a synthesis of orthoimage date per administrative department. The advantage of this data source consist in ready-to-use data at relatively high quality at the regional scale. This allows to focus on displacement rates data gathering rather than production of orthoimages at the regional scale. Each rock glacier in the region is observable in 4 orthomosaics from the years 1948-1952, 2001 – 2004, 2008 -2009 and 2015 - 2017. This allows to compute displacement rates over three periods referred here as: period 1 (second half of the 20th century), period 2 (first decade of the 21st century) and period 3 (Late 2000s to mid 2010s).

Data source II: Orthoimages from aerial photogrammetric surveys

Aerial images are acquired by the IGN regularly since the late 1940s, providing a valuable database for diachronic studies. This data source allows to increase the temporal resolution of the analysis significantly in the study sites. The aerial images are treated using the classic Structure from Motion (SfM) approach in Agisoft Photoscan (Smith et al., 2016). Ground control points (GCPs) coordinates to georeference the model were acquired from a master frame, i.e. the 2018 UAV orthoimage (described in the section below) or the 2015 - 2017 IGN Orthoimage when UAV data is unavailable. GCPs are collected around the perimeter of the rock glacier, in order to increase the accuracy of the resulting orthoimage within the landform area. GCPs number is at first kept at its minimum for the georeferencing and optimization process, i.e. three points, and increased if the resulting orthoimage did not present a suitable accuracy when compared to the master frame.

Data source III: Orthoimages from UAV in-situ photogrammetric surveys

As UAV photogrammetric missions are capable to provide high quality orthoimages and terrain models for rock glaciers (Dall'Asta et al., 2017; Vivero & Lambiel, 2019), two surveys took place in summer-fall 2017 and 2018 on the rock glaciers sites of PB, TL, RN and CL. Pictures were acquired using the commercial UAV Mavick Pro and the automatic flight planner Drone Map. Except for the mission at PB in 2017, where the flight planner failed, all the missions were conducted acquiring pictures with an overlap of 85 % at an altitude of at least 90m. For the 2018 a second flight level at 150 m altitude was added to the mission.

UAV pictures were treated using the classical SfM approach in Agisoft Photoscan. High precision GCPs were acquired only in 2018 using a Trimble GPS as rover and a Trimble as base. The method chosen was rapid-static and the raw data were post-processed in differential mode. This allowed to compute and georeference the DEMs and orthoimages for the 2018 survey, and use their fixed areas as GCPs to reference the models from the 2017 surveys. This method was not used for the Longet rock glacier as the GCPs survey did not take place in 2018. In this site, GCPs were measured from fixed areas in the available IGN orthoimage.

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Data availability

The authors declare that the main data supporting the findings of this study are available within the article and its Supplementary Information files. Extra data are available from the corresponding author upon request.

Code availability

The authors declare that the code used to obtain the main results of this study can be made available from the corresponding author upon request.

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Figures

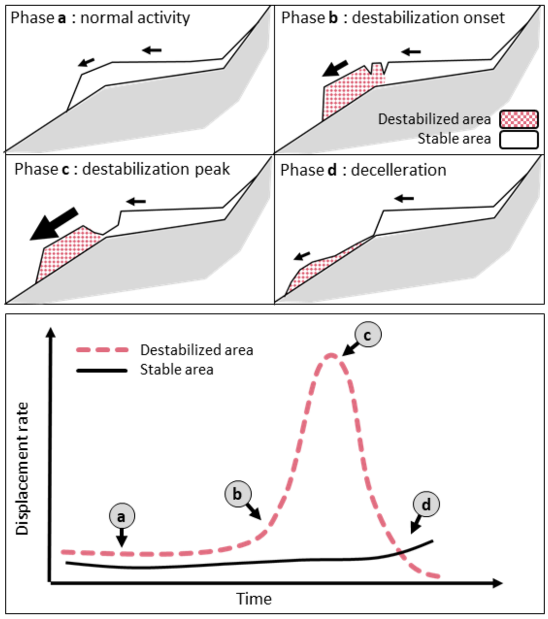

Figure 1: Conceptual representation of the destabilization process in terms of geomorphological (upper panel) and dynamical (bottom panel) evolution of the areas upslope (Stable area) and downslope (Destabilized area) the surface disturbances. A stable rock glacier is characterized by homogeneous displacement rates in both areas and there is no destabilized mass (phase a). The destabilization process can occur if the rock glacier presents topographical predisposition (e.g. topographical convexities). The destabilization onset is characterized by the development of surface disturbances (phase b), which accelerates the downslope area significantly, while the upslope area remains stable. The displacement rates of the downslope area reach their maximum (phase c) within few years/decades after the destabilization onset, creating a larger discontinuity between upslope and downslope velocities. After the peak phase (c), the destabilized area decelerates because of mass loss and/or flatter topography (phase d) and reaches inactivation.

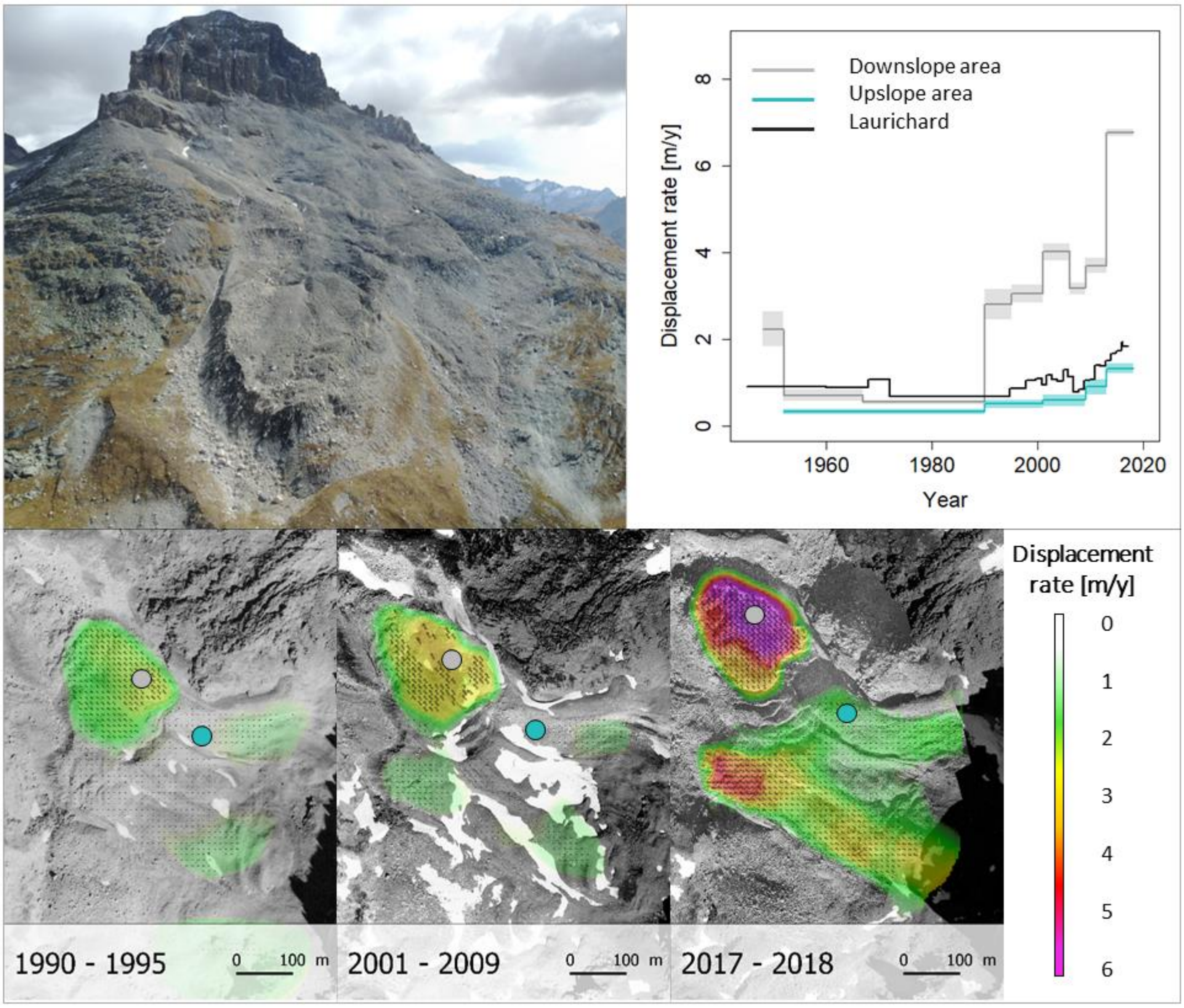

Figure 2- Destabilization example on the study site of Pierre Brune, a destabilized site approaching the peak phase (phase b to c in Figure 1). Similar results are produced for every site in this study, and available in the supplementary materials. Displacement rates are plotted altogether with the movements of the Laurichard rock glacier for comparison with a landform not showing destabilization. Destabilization onsets between 1990 and 1995 in relation to the fast development of crevasses. A crevasse is already visible in the area in 1990 and belongs to an earlier destabilization phase that occurred during the late 1940s. The destabilized mass starts moving faster than the upslope areas, creating a strongly discontinuous deformation pattern and the landform is dynamically disconnected in correspondence of the surface disturbances. While the upslope area presents a behaviour similar to the Laurichard rock glacier (not destabilized), the downslope mass is still accelerating reaching much higher displacement rates.

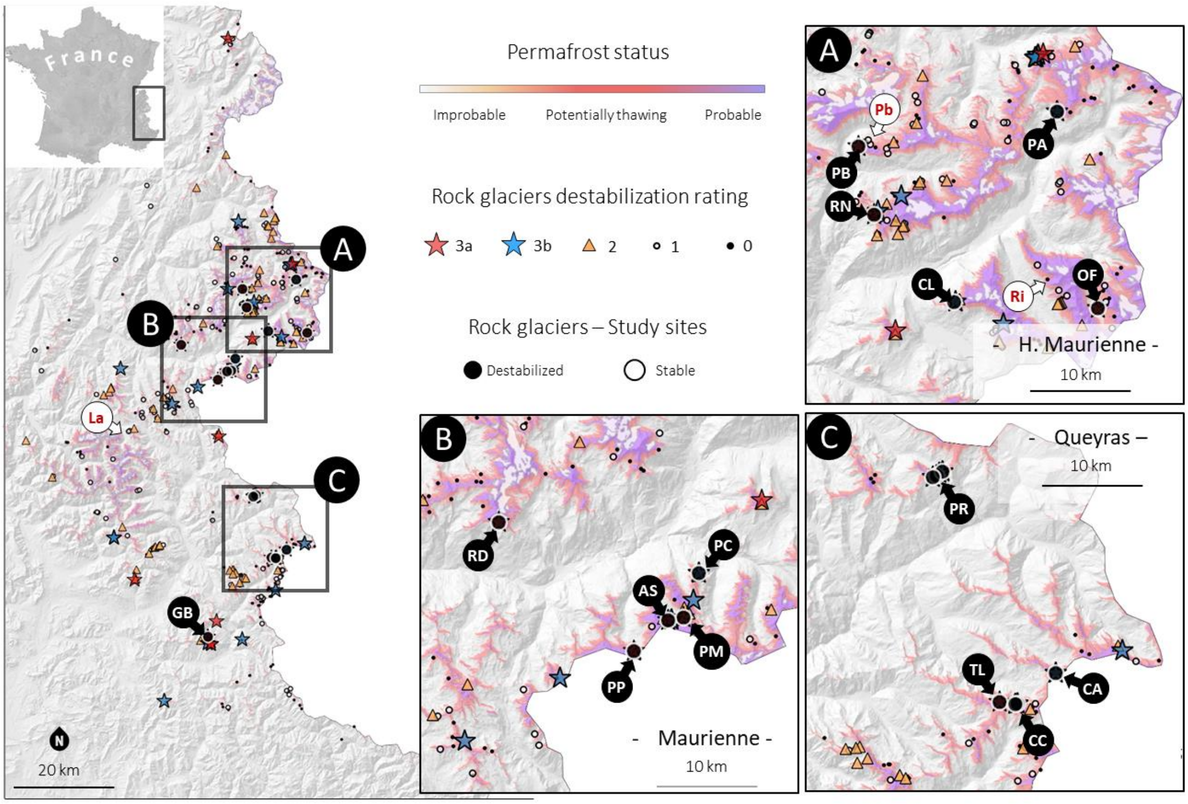

Figure 3 – French Alps: permafrost status and localization of active rock glaciers rated by geomorphological evidence of destabilization according to Marcer et al., (2019) and the present study. Destabilization ratings vary from 0 (no geomorphological evidence of destabilization) to 3 (evidence of developing surface disturbances and consequent dynamical discontinuity in the landform). In rate 3a the surface disturbances are characteristics of more severe destabilization, i.e. crevasses and scarps, while in rate 3b are observed only shallow cracks. Intermediary rates are 1 and 2, describing stable and developing surface disturbances respectively. Rock glaciers showing destabilization rating of 3 and found by this study to have displacement rates above 3 m/y are classified as destabilized and investigated in detail. The rock glaciers investigated by this study are referred by an acronym, the reader may refer to the annexes for a detailed description of each site.

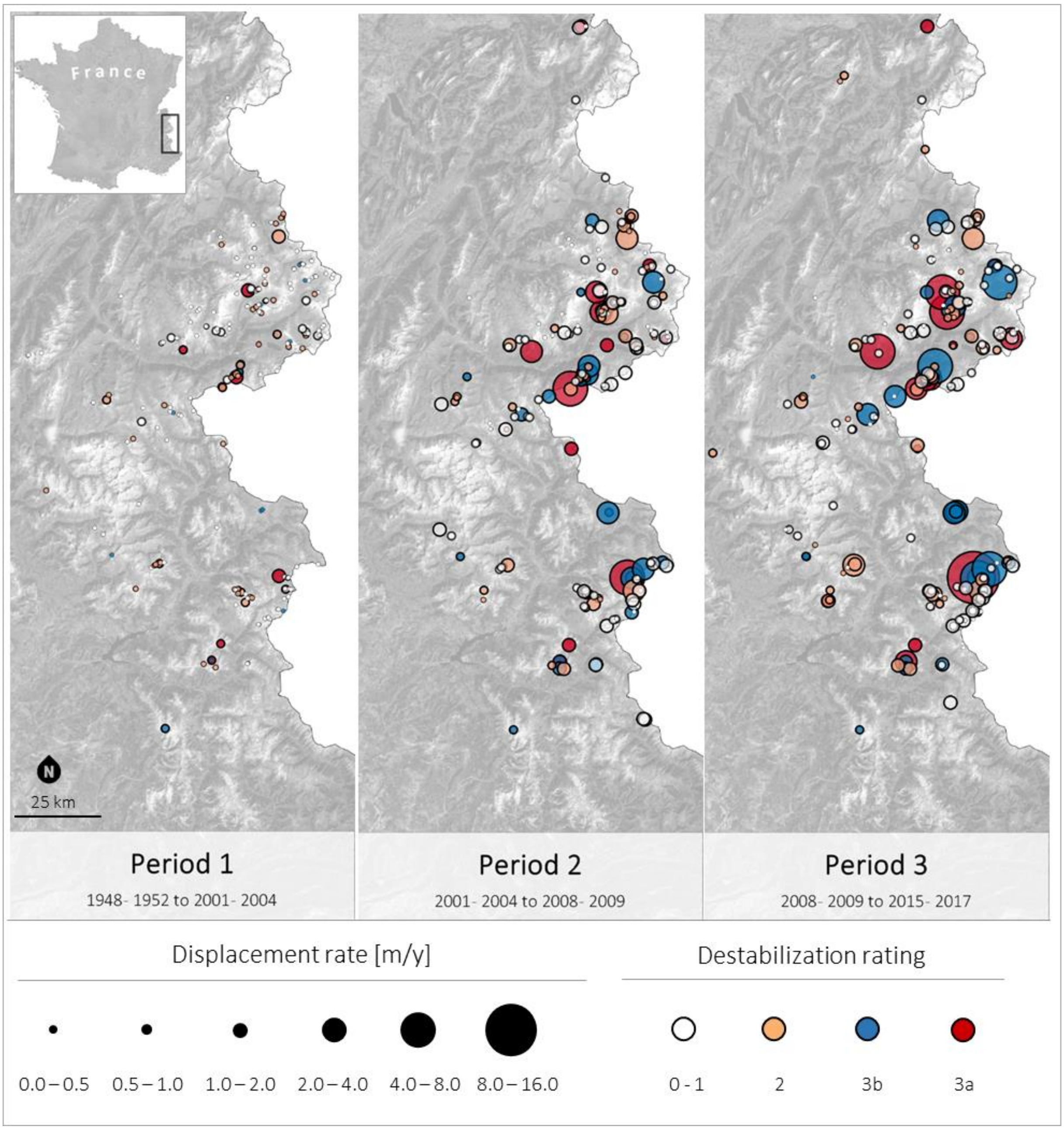

Figure 4 – Evolution of the rock glacier displacement rates in the French Alps in the three periods investigated. Symbol size is proportional to the measured displacement rate, while symbol colour is assigned accordingly to the destabilization rating (see Figure 3 for rating description).

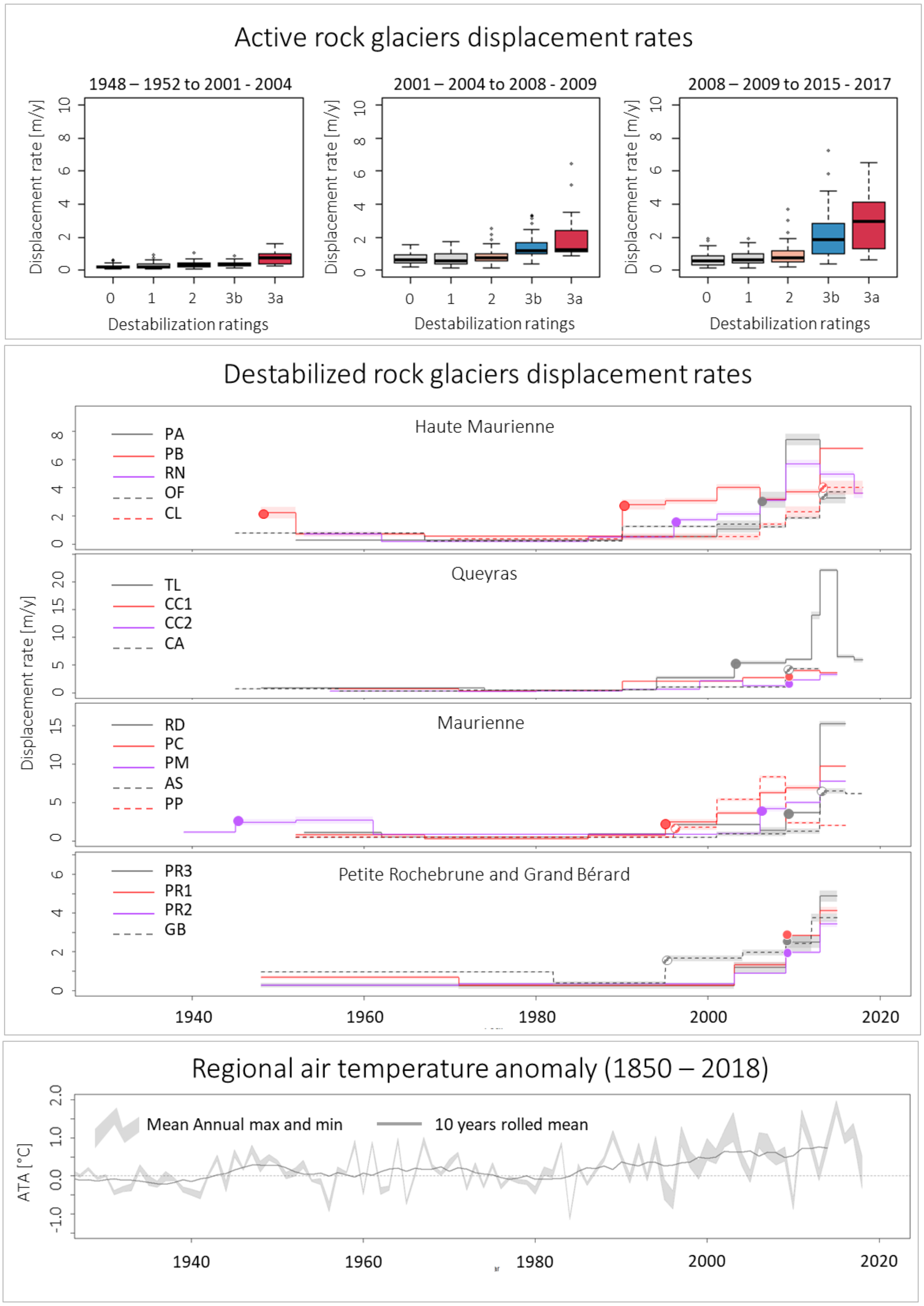

Figure 5 - Evolution in the past seven decades of regional scale rock glacier displacement rates (grouped by destabilization rate) and investigated destabilized rock glaciers displacement rates. Dots in destabilized rock glaciers graphs indicate the observed onset of the destabilized phase. On bottom, mean annual air temperature anomaly in the period 1850 - 2018.

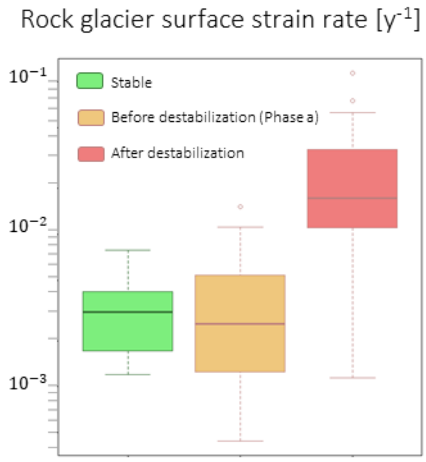

Figure 6 – Boxplots summarizing the surface strain rates measured at the local sites. Low values of strain rates in destabilized rock glaciers refer to the deceleration of the destabilized area (phase d – Figure 1).

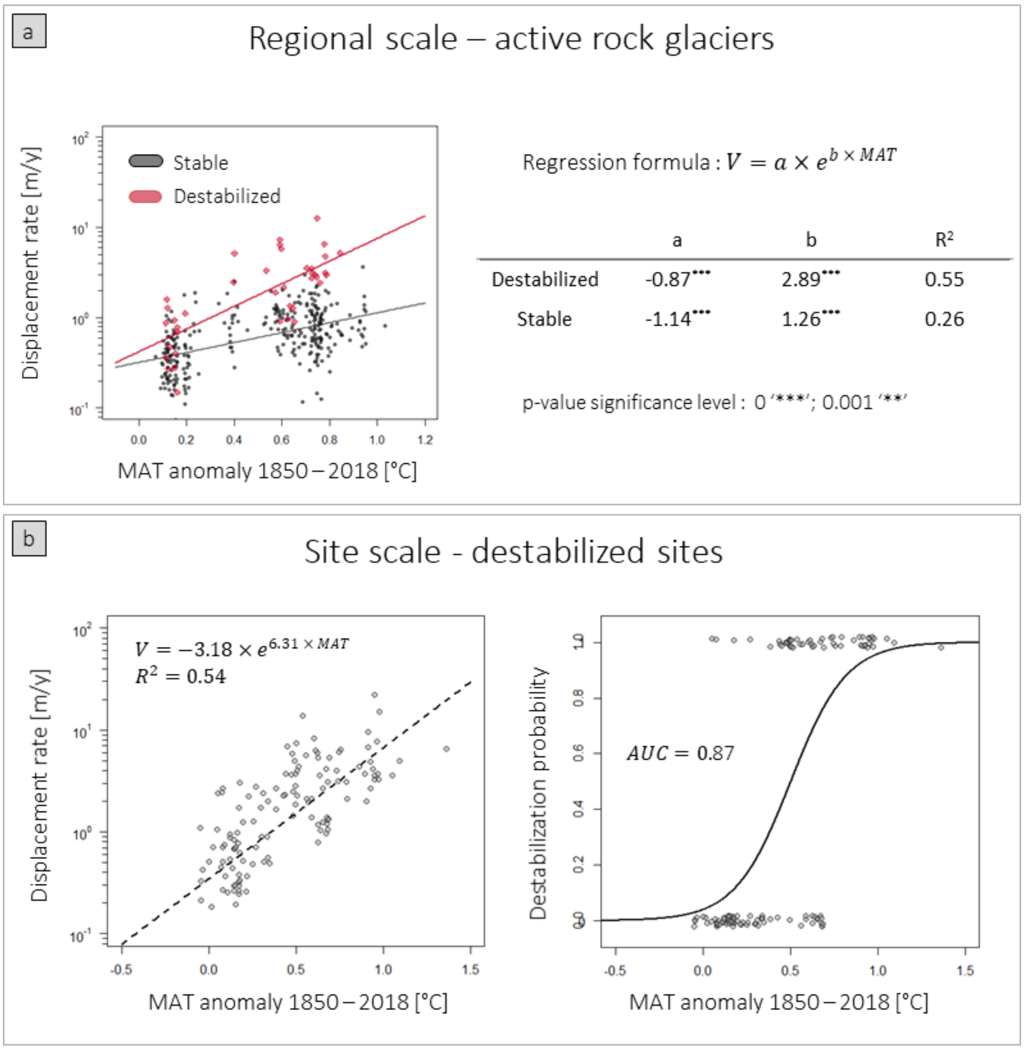

Figure 7 – Statistical analysis of the correlation between Mean Air Temperature (MAT) anomaly since the preindustrial and rock glacier displacement rates at the regional (a) and site (b) scales. For the regional scale analysis, the relation between MAT anomaly and displacement rates is modelled for both stable and destabilized rock glaciers and the regression coefficients are presented in the table. For the site scale analysis, linear and logistic regressions are evaluated on the aggregated measures for all sites.

Tables

Table 1: Regional scale displacement rates and relative increase in displacement rate (in %) by period and destabilization ratings. Period 1: from 1948-1952 to 2001-2004; Period 2: from 2001-2004 to 2008-2009; Period 3: from 2008-2009 to 2015-2017. Destabilization ratings (Marcer et al., 2019) characterize the landforms from their geomorphological evidences of destabilization. Rock glaciers with lower ratings do not show significant evidence of destabilization, while higher ratings are attributed to rock glaciers developing mild (rating 3b) or severe (3a) destabilization signs causing dynamical discontinuity in the landform.

	Mean displacement rate [m/y]			Relative increase in displacement rate [%]	
Dest. rating	Period 1	Period 2	Period 3	Period 1 to Period 2	Period 2 to Period 3
0	0.22	0.72	0.73	227	1
1	0.27	0.71	0.77	163	8
2	0.35	0.85	1.02	143	20
3b	0.39	1.46	2.36	274	62
3a	0.77	2.18	3.45	183	58
Mean	**0.3**	**0.97**	**1.25**	**223**	**29**

Response to referees' comments

Title: Regional scale investigation on rock glacier destabilization and links with climate change

Authors: Marco Macer, Alessandro Cicoira, Diego Cusinqui, Xavier Bodin, Thomas Echelard, Renée Obregon, Philippe Schoeneich

Communications Earth & Environment (an open-access journal from Nature Research) Manuscript Number: COMMSENV-20-0319-T

Reviewer #1

Dear Authors, Dear Editor,

I am happy to see a study, which carries out an area covering analysis of collapsing rock glaciers and extraordinary accelerations of these landforms. This is an important field of permafrost research and has relevant socio-economic implications.

Dear Reviewer,
We are glad you enjoyed our study and we would like to thank you for taking the time to provide such a detailed revision, which certainly helped us to improve our manuscript. Please find below our comments to the revisions.

The basic approach chosen in this study is sound. However, there are still major changes necessary before the work can be published.

Major issues are:

1. The language and mode of expression. This should be checked by a native speaker.

Thank you for pointing this out, we agree that language can be improved. For the new version of the text, we had the article and annex corrected by a professional native speaker.

2. The precision and correctness of statements. The authors are much too often unclear, ambiguous or unprecise which sometimes results in simply false statements.

We agree that this is a significant issue, as some of your (and others reviewers) comments were caused by our lack of precision. We went through the text and made the necessary modifications to avoid further issues of this type.

3. The structure of the manuscript is currently a big mess. Information on methods, datasets or other specifications are distributed over all of the sections. They do not appear in a logical order, allowing the reader to follow the presented analysis. Why are methods written after results and discussion??

Unfortunately, we cannot agree on this point, although we are aware that this structure is not typically found in mountain permafrost related studies. The structure of the manuscript is currently consistent with common Nature Journal styles. You can find guidelines here:
https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf. This structure consists of:

1. Long introduction, should include the background and rationale for the work.
2. Results and Discussion
3. Detailed description of the methods

You can check this structure in others published articles in this and others Nature journals.

4. The methods are partly suboptimal or insufficient and the solidity of the results could be improved by adapting them. This aims especially on the little dataset on which deformation rates and accuracy analysis are based on (see detailed comments). If the authors stick to their methods, they must at least provide a sensitivity analysis how the low number of records effect their results.

We agree that in theory our methods could be better. However, methodological improvements that you suggests are very difficult to implement. You will find detailed comments on this subject on the line by line comments (In particular, see comment on line 350). Thank you for suggesting to assess the validity of our methods, this is a very good idea and we now provide such assessment in the methods section (See lines [369-374] and [390-396]).

5. The physical interpretation of the results is incomplete and partly misleading as well as based on outdated literature. There must be a better literature review considering the large number of publications on rock glacier dynamics of the last 10 years.

We agree that part of the interpretation is misleading, as written language was not enough specific and clear. As specified in point 2, we improved the text. We added new literature and included in our consideration recent works on rock glacier dynamics. Finally, we hope that having the text revised by professional English translator improved readability.

I made a lot of detailed comments in the attached PDF of the manuscript that will give clear evidence for the 5 points above.

I am looking forward for an improvement and successful publication of the work!

Thank you again for the detailed revision and support!

All the best

Robert Kenner

Line by line

16: After reading the abstract, I can allready say that language is a major problem. Both, English and the mode of expression require improvement. Try to be exact on what you want to say. I did some corrections for the Abstract but will not do it for the rest of the document. Perhaps you can ask a native speaker to improve it.

Yes agree, see point 1. A native speaker has been hired to improve language.

18: Research on this is quite young and I was wondering if we really want to keep this term? Your paper could be trend setting in this matter. "Destabilization" is actually not my favourit as active rock glaciers are never "stable". What about rock glacier collapse? Or crisis?

We agree that the term is controversial. We discussed about it with several colleagues without reaching any agreement. At the moment the IPA action group is working on this issue and they also seem to not manage to agree on a better term, and they want to keep “destabilization” as current term. We would prefer to not cause confusion and stick to IPA guidelines.

47: There is no climate at seasonal or decadal scales, there is only weather. Moreover if you want to summarize velocity patterns, there is systematical feedback of the rock glacier to external forcing at a day by day basis and at interanuual scales as well!

We added “weather” to our terminology. This point comes out several times during your revision, probably due to our bad terminology. We corrected when appropriate. We would like to point out that we work at the scale of five to seven decades, therefore we have to speak about climate and not weather.

56: I can really not understand why you write something like this and cite a paper from 1969 if your second author just finished his PHD concluding that this statement is simply wrong.

It is not clear in the text, but this is not the point of this section as we are here just reporting what was observed in previous studies. We updated the text to make it clearer. Also, notice Alessandro thesis focus on a different time scale than the one we are talking about here. For further comments concerning this issue, please notice that anything concerning Alessandro’s work was written and/or approved by Alessandro himself.

61: again, it is problematic to speak about climate if you are investigating pluriannual changes. Climate is >30 years

Yes, see comment on L47: we are investigating changes over 70 years.

69: really?

Yes, we have several cases in our annexes. In previous literature I have on top of my head the Plator from Scotti et al (2017).

71: meaning what?

The concept of “structural collapse” is described in the study cited. For info, this occurs when the rock glacier collapses with a rapid landslide, rapidly transitioning from rock glacier to landslide deposit.

72: I think I know what you mean but this is a strange expression

Ok, we just avoid “tensile”

74: :-D :-D

?

75: Very speculative, what about "cool winter air"?

In winter snow cover tends to insulate from air temperature. In any case we deleted this part of the sentence as it is quite a slippery slope as you point out.

123: From here on you describe methods. That is no more indroduction!

See comment on point 3. This is the description of the study rationale.

126: What about the accuracy of these Orthomosaics resp. of your displacement estimations??

This is not the place to discuss this. See comment on point 3

154 : Write a proper method section first! And describe clearly how exactely you calculated all the values that are given in the following.

See comment on point 3

155: give a reference, (one of the three periods given in xy....)

Agree

157: what happened to them? Did you throw them away?

Good observation. Now we specified that we don’t use them for evaluating average displacement rates over periods.

158: must be discussed somewhere

Yes, just next sentence. Also, see comment on point 3

159: this as well

See comment on point 3

163: Ok finally! but where do this values come from? Move this specification further up!

See comment on point 3

165: I guess have you excluded the incomplete displacement time series? If not that will systematically distort these values...

Good point, we corrected the values for rock glaciers only showing movements in all three periods.

Personally, i would prefer to see the relative changes here (analysed for every individual rock glacier and then averaged). At least as addition. I think this is more expressive.

Notice that the average is a linear function, the result will not change.

167: Do not get it. how does this fit together with the values above?

Good observation, thank you. This error was a leftover from previous revision. We just deleted the sentence as it belongs to discussion, and corrected it there.

168: becomes more and more susipcious. No idea how all these values fit together and how they were calculated!

6 times higer but 223% and 0.3 to 1.25m???

Good observation, thank you. This error was a leftover from previous revision. We just deleted the sentence as it belongs to discussion. We adjusted the values there.

172: perhaps it facilitates the reading if you substitute the years by period A,B,C... and add a little figure with a timeline or so where the periods are marked...

Good point, we changed to period 1, 2, 3

176: ok here you used period 2 (my favourite) but than again the year numbers... either or! Decide!

See above

189: Does this mean, the values given above are not based on time series of every individual site? Because simply comparing absolute values of different RG makes no sense..

The analysis on regional and local sites is explained in the study rationale in the introduction. It seems other reviewers did not have issues understanding this transition, therefore we believe that this misunderstanding is due to lack of clarity in the text. We hope that our revision and language check by professional will have improved the text enough to avoid further issue of this kind.

194: ???

Local analysis →individual rock glaciers. See study rationale in Introduction, also see comment on point 3 and on line 189

196: Make somewhere clear that these are names of individual rock glaciers. It is completely unclear why you choose these two rock glaciers here in this chapter and describe them here? Seems quite random and chaotic here...

Good point, we added this specification in the beginning of the section

196: ??? But this is less than your 3m threeshold for destabilized RG!? Do not get it...

See comment on point 189. We now made clearer that we also investigte about non-destabilized rock glaciers to provide a comparison with destabilized landforms.

197: which comparison?

See comments on line 189 and 196

206: terrible sentence, after the 90s? i.e. the 00ies? or the when? The 18? which two decades? Formulate more precisely!

Agree, we updated the text accordingly

207: Aha, here it is. So why this creepy sentence before?

See comment above

221: Well these are 7 years acceleration time. Is sharply the appropriate term for that? Perhaps use strong and less strong acceleration?

Agree – used strong acceleration

230: How did you define the strain rate?

See methods. Now we also added an early description in figure 1.

244: Mean annual air Temperature? (MAAT)

No, Mean Air Temperature, on the period studied

247: Not very impressive. No doubt, air temperature is the trigger but the correlation to velocity variation is so weak that I personally can not take much pleasure from these correlations which only have an indirect causal connection.

We agree that these correlations have indirect causal connection (see in discussion). Nevertheless, this is not meant to be impressive but descriptive, as we need it to talk about these indirect connections.

247: This shows the perverse consequence of the term "destabelized rock glacier". -> not destabelized rock glaciers are stable rock glaciers... stable rock glaciers!? Sounds like inaktive rock glaciers for me. I would reconsider these terminology see comment above.

Good point – we changed to “not destabilized”

252: Such an analysis makes much more sense to me as it highlights atmospheric warming as a trigger for the acceleration process, although it is not the physical driver of the process

Yes agree, that was our idea too in providing both analysis

281: Please cite your second author who just wrote a PHD Thesis which FINALLY substituted these old theories by fundamental physics!!! You may also find some explanations for correlating MAAT, Hydrology and rock glacier velocity in Kenner et al 2019 https://doi.org/10.1002/ppp.2023

See comment on line 56

297: I can not belive that you are writing something like this, if Alessandro just showed in his PHD that the temperature driven viscosity change of ice is not even close to explain the observed velocity changes. You have to rape the power law to explain velocity changes in the magnitude of meter. I know, some people did this in the past but this is shame for research. Rock glacier acceleration in those magnitudes your are talking about is always a result of friction loss in well defined shear layers and mainly controlled by water availability. Water availibility is in turn correlated to MAGTs.

See comment on line 56. We modified the text to make our point clearer

313: I doubt this strong connection of todays relict rock glaciers to colder phases. The evidences given by e.g. Frauenfelder are quite weak. What we realy know is, that many relict rock glaciers grew extraordinary fast during their active phase. This points toward a strong supply with debris and avalanche snow as main driver for their genesis. This debris supply was provided from freshly deglaciated headwalls during a phase of climate warming. Such a dynamic process can cause rock glacier formation in environments which are suboptimal for permafrost in the very long term. I.e. you can produce rock glaciers which are convicted to die in the long term without any change in climate but only as a result of decreasing erosion rates. Currently we observe the formation of a new rock glacier from the rock fall deposits at Flüela Wisshorn while older rock glaciers in the sourrouding melt slowely. See also references in https://doi.org/10.1002/ppp.1910

Interesting (and challenging) comment, as it argues against most of the available literature on this subject. We agree that local conditions can boost (or inhibit) rapid rock glacier development over short periods, but we would like to point that we are talking about regional scale trends, which were linked paleoclimatic evolution not only by Regula, but also many others (e.g. Oliva et al, 2018). Also, there is solid evidence of datation of relict rock glaciers, confirming this theory (e.g. Scapozza et al 2010, Amschwand et al, 2020). These are now cited in the text.

315: accelerating or "destabelising"?

315: in the? you mean "during the", i.e. the low number between 2010 and 2020?

Is this significant? I think it is dangerous to maks such statements based on a such small number of records.

Agree, sentence deleted

316: This is not a valid conclusion. In total rock glaciers are are still in a clear accelerating trend! A few less cases of rock glaciers crisis are no basement for such a statement.

Good point, sentence deleted

325: Why do methods come after the Discussion??

See comment on point 3

328: hard to follow, espacially the part of the logistic regression!

We believe that the issue here was language, which is now corrected by native speaker.

338: Where do they come from?

See data section

350: Why didn't you use an automatic correlation to match surface patterns between the images? You could have hunderts of records per site with less effort...

Yes that would be a beautiful thing to have, but unfortunately practically very difficult to achieve. We'll share our experience, in case you want to go through something like that. We spent some months to try it out, but the results were disappointing. We run the correlation algorithm on for each rock glacier in the inventory, but it produces results that need to be cleaned and validated. In fact, each rock glacier needs different settings, depending on displacement rates, image quality and surface texture. One snow spot, shadowed, different texture area can produce either produce high errors (easy to detect) as well as small ones (very difficult to detect and still significant). We ended up having to manually check each rock glacier, measuring by hand actual movement. This how we ended up starting the dataset we present here. The (many) rock glaciers that had errant displacement rates needed to be manually cleaned, have the algorithm re-run with different settings, etc. This is feasible for a small pool of rock glaciers, but we had more than 800 potentially creeping rock glaciers in our inventory.

352: Aha yes, thats what I am talking about. Why just for 4 sites?? Its no big deal to rush that through for dozens of images...

Se comment above. We decided to focus our efforts on the most interesting sites.

355: Hm using one or two boulders only is a rather weak and uncertain approach. You should at least carry out an honest sensitivity analysis to check how strong the results differ depending on which boulder you are choosing.

Good point, we now provide a methodological assessment. We did a comparison between this approach and the multiple boulder approach used for the local sites, showing that this is a good estimation of maximum velocity (see line [369-374].

359: ???

Out of several ways to define the most meaningful displacement rate value to characterize a rock glacier, we used the approach proposed by Kääb et al 2007, based on maximum velocity

363: The same issue as for the tracking method but even more critically here: one point or even a couple of points in stable areas do not give a valid picture of the distortions in the orthophoto. There is a strong spatial variability of these distortions that you can not assess with a few points. In particular the 1 point approach in the regional analysis is really a no-go. No sound method.

Actually it does give a good first order approximation of the distortions. We figured it out while doing the local scale analysis, as we could add as many stable areas as we wanted without having a significant change in the uncertainty. Of course, you need an aerial image with a consistent distortion pattern through your area of interest, but this is usually the case for rock glaciers (which are small with respect to the size of an aerial orhtoimage).

In any case, very good idea to quantify this. We now included in the text the results of a comparative analysis between the uncertainties obtained using this method and the multiple stable areas method used in the local analysis. We show that uncertainties in the regional scale tend to be over-estimated, probably because we selected intuitively areas with larger distortions. In addition, as specified in the text, we used the double of the computed uncertainty as detectability threshold, in order to make sure that we did not mislead apparent movements with actual displacements. This is now specified in [390-396]

375: ??What does this mean?

When you are studying a moving target, you have several ways of computing the uncertainty of your estimation. You can just make the average of all uncertainties from your stable areas, or you can give more weight to uncertainty estimations that are closer to your moving target. A weighted average based on distance does the second option (which we believe is more precise than the first option). We now clarified the text.

379: If the quality was high enough to orthorectify the images it is as well high enough to run a correlation algorithm. Both tasks rely on image correlation. Lighting conditions should not play a too critical role considering the strong movements, but you should check this out and quantify it

See comment on 350

383: the same here, why do you work on the scale of a few individual points? Using the imcorr output you could calculate strain rates between hundreds of points on a regular grid

See comment on 350

392: Temporal resolution?

SAFRAN is 1 hr temporal resolution, HISTALP 1 day

393: This is simply wrong. Climate exists much longer than 170 years and is discribed by several factors such as precipitation, MAAT, temperature variations at different temporal scales....

Be more thoroughly in what you are writing, this applies to many parts of the manuscript.

We now made more explicit that we are not trying to give a new definition of what climate is, but just describing our data.

395: What is that?

Acronym now specified

402: This is remarkably low for a relative comparison of temperature time series! For which time scale is that?

It is low yes, but notice that the data come form rather different sources. HISTALP is an interpolation of low elevation weather station data, while SAFRAN is a model dedicated to high mountain environments.

404: You wrote a couple of time about the accuracy analysis for these products but accuracy values are given nowhere!

It is given in the uncertainty analysis, described above.

Reviewer #2

The present review is based on a revised version of the original paper and on the comments of three anonymous reviewers.

The paper deals with change detection of rock glacier kinematics in the French Alps and with an attempt to explain the observed changes (rock glacier speed-up and surface disintegration) with climate change, i.e. temperature increase. Similar studies (other regions, local sites, shorter observation periods) have been published focusing either on pure rock glacier flow measurements or on pure mathematical modelling of rock glacier flow/deformation. The present paper tries to link rock glacier flow velocity and observed strain rates with temperature (change). This analysis is complicated by the fact that the surface topography is very much influencing the flow behavior. Steeper terrain will cause an increase of flow velocity. If strain rates exceed a critical limit crevasses/cracks may occur. In case the rock glacier is moving in steeper terrain eventually landsliding will take place. This phenomenon is called “destabilization”, which means that the previously compact permafrost body gets disintegrated. The research question is whether acceleration of rock glaciers flow and observed rock glacier destabilization (in some cases) is a matter of climate change, i.e. atmospheric warming.

The three reviewers have thoroughly discussed the original manuscript and provided valuable comments for improving the paper. The reviewer expressed doubts about the novelty of the work presented, missing answers to possible research questions (What is triggering destabilization?), and some statistical issues.

The authors have addressed all remarks provided by the three reviewers and changed the original manuscript accordingly. The modifications refer to both text and figures.

The abstract is now fully concise and it provides the reader with all relevant details (definition, research question, possible answer). The speciality of the present paper is that the authors have investigated a large region, i.e. the entire French Alps, which is unique. Moreover, their analysis covers also a large time span, i.e. seven decades. Similar research is mostly on test sites comprising only one rock glacier or a group of rock glaciers, at most.

The reviewer thinks that the annex of the manuscript highlighting all 18 rock glaciers locations with “destabilization” characteristics is a great value not only to the very expert but also to the interested reader. The reviewer (belonging to the first group) liked to browse the annex.

The introduction provides an exhaustive review of the research question and its scientific background. They explain the terminology of “destabilization”. Maybe, this word is somehow misleading but it is used in the scientific community. The authors clearly state all possible causes (bedrock topography, climatic forcing, etc.) for the onset of “destabilization”. The authors once again highlight that they provide a regional scale systematic analysis of rock glacier displacement rates and destabilization onset over the past seven decades (1948-2018).

The authors put a lot of emphasis in gathering of the kinematic data needed for the analysis. They used all kinds of measurement techniques, from manual feature tracking, area-based orthophoto change detection using governmental data, re-evaluation of original aerial photographs applying modern structure-from-motion technology, and carrying out own UAV-based surveys. Such work is indeed laborious and time-consuming. Of course, in the long run we can think about high-precision orthophotos (10 cm resolution) and contemporaneous digital surface models (every orthophoto pixel gets a height) for high mountain regions to be provided by national mapping agencies, maybe for a three-years interval. Based on this data morphological changes of rock glaciers can be studied in full details, including 3D deformation analysis and analysis of mass balance (to answer the question of permafrost thawing/degradation due to atmospheric warming).

The results obtained are clearly stated. The statistical analysis is based on linear regression (correlation). Appropriate figures visualize the data used and the results obtained. The working hypothesis of the authors for the whole process of morphological change on the rock glaciers is summarized in Figure 1, which includes 4 phases, i.e. normal activity destabilization onset, destabilization peak and deceleration. This might be a nice takeaway for the interested reader.

The paper does not provide any information, but literature, on the mechanism of “destabilization”. High mountain environments are complex systems and thus difficult to understand. This paper is a good example to better understand rock glacier kinematics in the light of climate change based on excellent data (regional, accurate, long-term) and simple reasoning. The latter allows the inter-comparison of results obtained from other regions. The IPA (International Permafrost Association) Action Group “Rock glacier inventories and kinematics” supports this goal.

The paper is worthwhile to be published since it provides valuable new information/data on rock glacier kinematics and provides a working hypothesis about rock glacier surface disintegration as a function of flow velocity/strain rate and temperature over time.

We thank the reviewer for taking the time to provide us this detailed feedback. We also appreciate that the reviewer went through the previous version of the manuscript and evaluated our responses to the previous revision round. We are glad that the reviewer seems to fully understand our study aim and developments.

Comments

Introduction:

Line 48: 1976;

Corrected

Line 49: 1996;

Corrected

Line 61 and elsewhere: Please use “kinematics” instead of “dynamics” if appropriate.

Good point, we corrected here and elsewhere when appropriate

KAV/20

Reviewer #3

I have carefully read the manuscript of Marcer et al. “Regional scale investigation on rock glacier destabilization and links with climate change "and I found it interesting, well written and properly organized.
I also read the authors 'responses to the first three reviewers' comments.
The manuscript has substantially improved following the modifications made by the authors and now I believe that there are no significant obstacles in proceeding towards its publication

The main problem that was raised concerned the novelty of the article topic.
Reading the article, in light of the changes made by the authors, I don't think this drawback still exists. The aim of the work is clearly to provide readers with a vision of how the analysis of regional and local data underlines the (already known) effects of air temperature increase on the destabilization of rock glaciers. To my knowledge observations on such a regional scale are not available in the rest of the European Alps.
Moreover, also the quantification of the non-homogeneity of the responses of rock glaciers to the increase of air temperature (in terms of pre and post destabilization behaviour) is in my opinion an analysis not present on a regional scale.
Finally, the considerations on how the behaviour of rock glaciers is modulated also by the geotechnical characteristics give to the paper the right degree of completeness in the understanding of a complex phenomenon such as the mechanical behavior of a detrital body of variable thickness, partially frozen, placed on a bedrock with variable geometry and subject to a time-variant climatic stress.
In other words, I believe that the topic of the paper has been dealt with in depth, focusing of course on a specific topic but also considering other variables. I think that this type of vision is a merit that is not always detectable in papers that are addressed to a wide audience such as the one interested in climate change vs geomorphic response.

I think that in some places the text needs minor clarifications / changes (not substantial) (see annotated manuscript).
The illustrations are more than good, and part of the data/results is conveniently placed in the supplement material.
Hope this may help.
Best regards - Adriano Ribolini

Dear Reviewer,
We are glad you enjoyed our study and we would like to thank you for taking the time to provide such a detailed revision, which certainly helped us to improve our manuscript. We are also glad you took the time to go through the past revision round and give feedback on how we responded to the former reviewers. Please find below our comments to the revisions.

Line by line comments

L 40: I am not sure you can write "...are gaining interest..." and then report a citation of 20 years ago. I suggest adding also some more recent one (besides that of Regula)

True, we added a brand new study on this subject.

L 57 : For readers who are not permafrost expert, I suggest to clearly state already here which is the relation between climate change and displacement (i.e. increase in air/ground temperature and rock glacier displacement)

Good point, we modified the sentence accordingly

L 93 : please add a line to explain why an external loading may cause internal stress leading to destabilization. In case of an external loading over a steep bedrock section may seem the same aforementioned case

We now specify that external loading can cause a variation in the internal stress regimes

L94 : similarly to the landslide context, the climate change here seems to act both as a triggering (provoking) cause and a predisposing cause. Is this correct?

Our results show that climate change is a predisposing cause. We believe that the triggering causes are more complex and a combination of rock glacier structure, permafrost characteristics and ground water patterns.

L99 : now I found it, please consider to clarify this relation also before in the text (i.e. lines 57-59 pag. 2)

Yes, se comment on line 93.

L152: please put the acronym meaning in brackets (is it Système d’Analyse Fournissant des Renseignements Atmosphériques à la Neige?)

again: Historical Instrumental climatological Surface Time series of the greater Alpine region (right?)

Good point, both acronyms are now specified

L203: could you be more informative? Only two (PM and PB)?

Yes only 2, now specified (and later on the text for similar issues)

L206: are these 18 sites included in the "a few sites" mentioned in the line above?

We now specify the proper number of rock glacier per each observation

L242: this is interesting but please add somewhere a line to explain how this rock glacier-glacier analogy was derived (in terms of critical strain rate).

In other words how a rock glacier interior (debris-ice mixture) could be assumed to behave like a glacier interior (essentially ice) in terms of strain distribution.

We do not assume that they behave in the same way, we are just comparing the values we evaluated with the only other reference we have, which belong to white glaciers, discussing similarities and differences. We changed the text here to make it clearer.

L261 : please be more precise, seem to be the 5% of the total active rock glaciers

We now specified that we talk about the potentially destabilized rock glaciers, i.e. those that show destabilization signs but do not necessarily have high displacement rates

L277: It seems to me that the potential effect of external loading is not mentioned in the destabilization process

Corrected

L280: unclear to me. Necessary?

Not necessary, we deleted it

L300: please check

Corrected

21st Jan 21

Dear Dr Marcer,

Your manuscript titled "Regional-scale investigation of rock glacier destabilisation and links with climate change" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

See Attachment

Reviewer #3 (Remarks to the Author):

Dear Authors
many thanks for having taken into consideration my suggestions.
The paper was already fine before, and now it is even better (in my opinion of course).
I hope to see the paper published soon.
Congrats and best wishes

Adriano Ribolini

Dear Authors, Dear Editors.

I am pleased to say that the paper improved clearly. It is nice to read now and almost ready for publication and a valuable contribution to rock glacier research!

I have a few points left to adapt or to reconsider (much less than it seems by the length of the review, this is more a sign that these things are quite important to me!)

I am still confused by all the method description at the end of the introduction, however, if the editor is happy with this I will not complain about it. Sorry for my remarks about the order of the sections in the last review (Methods last). I was not aware of the journal style. I might be a bit old fashioned regarding this, it confuses me to read results if I do not know how they were achieved.

Here the detailed comments

Line 39: time scale

46….recent studies have shown that acceleration can take place, increasing the
47 displacement rates of some landforms to up to several metres per year (e.g., Delaloye et al., 2008,
48 Kellerer-Pirklbauer et al., 2018). This acceleration pattern has been explained by the exponential
49 relationship between ice viscosity and temperature (Mellor et al., 1969).

See my comment in the last review. Your answer on this point is not satisfying. An introduction has to present the **current** state of the art. Not just something that was said at one point in the past. In such a context (acceleration to several m/a) this statement is not correct!

Lets take Glens Law and have a look on figure 7 in his paper (Glen 1954) (Stress vs strain rate for different Temp.). For the deformation of pure ice in a 20° steep slope you would need a 26.3 m thick layer of ice to achieve the stress rates given in the very left of the diagram log (-0.1) Bar. If you warm this Layer from 1.5° to 0° (corresponds to 150 years climate warming) your strain rate increases from 0.01 to 0.08. I.e. the 26.3 m thick layer of pure ice accelerates from 26 cm per year to 210 cm per year. Rock glacier however do not consist of 26 m of pure ice but have generally clearly lower ice contents. Correspondingly, all available internal deformation measurements point to plastic deformation rates in rock glaciers very much closer to 26 cm than to 210 cm. Anyway, even with this very unrealistic extreme scenario above we achieve not even one full magnitude of acceleration. Rock glacier accelerations to 3, 4, 5 meter can not be explained by ice viscosity alone. In contrast, all evidences point towards shearing as main contributor!

Line 171 ff: See my last comment:

Personally, I would prefer to see the relative changes here (analysed for every individual rock glacier and then averaged). At least as addition. I think this is more expressive.

Notice that the average is a linear function, the result will not change.

Of course it will change. If a rock glacier accelerates from 10 to 20 cm and the other from 100 to 120, the mean relative acceleration is 60% (100% and 20%). The mean absolute acceleration is from 55 to 70 cm what is 27%.

Now I wonder how you calculated the relative values (159% and 32%) The first way or the other? Specify! This problem refers also to the comment on line 189 in my last review.

A suggestion regarding the Imcorr algorithm (For your next study). You can filter the vector fields automatically based on direction and magnitude to exclude erroneous vectors and to minimize manual editing.

And at last the long one on line 325/326. See my last remark:

313: I doubt this strong connection of todays relict rock glaciers to colder phases. The evidences given by e.g. Frauenfelder are quite weak. What we realy know is, that many relict rock glaciers grew extraordinary fast during their active phase. This points toward a strong supply with debris and avalanche snow as main driver for their genesis. This debris supply was provided from freshly deglaciated headwalls during a phase of climate warming. Such a dynamic process can cause rock glacier formation in environments which are suboptimal for permafrost in the very long term. I.e. you can produce rock glaciers which are convicted to die in the long term without any change in climate but only as a result of decreasing erosion rates. Currently we observe the formation of a new rock glacier from the rock fall deposits at Flüela Wisshorn while older rock glaciers in the sourrouding melt slowely. See also references in https://doi.org/10.1002/ppp.1910

Interesting (and challenging) comment, as it argues against most of the available literature on this subject. We agree that local conditions can boost (or inhibit) rapid rock glacier development over short periods, but we would like to point that we are talking about regional scale trends, which were linked paleoclimatic evolution not only by Regula, but also many others (e.g. Oliva et al, 2018). Also, there is solid evidence of datation of relict rock glaciers, confirming this theory (e.g. Scapozza et al 2010, Amschwand et al, 2020). These are now cited in the text.

I must disagree with your answer for several reasons:

1. During the late Pleistocene, your areas were covered under 1000m of ice!

Regardless of inconsistencies in these studies, pointed out below; do these studies really support your statement about relict rock glaciers which originate from colder climate? Take for example the paper of

Amschwand et al 2020. I read it and couldn't find a statement such as yours. The oldest sample that they found was about 8900y old and originates from a very warm period! Indeed the paper links the activity in the late Holocene to cooler climate. However, that is just half of the content and you can't pick out one part of the paper that by chance supports your statement. Amschwand et al. say in their very last conclusion:

Although the two rock-glacier generations originated in the same cirque, we find contrasting responses to external forcing by comparing typical advance rates and debris flux estimates for both rock glacier generations. This very different dynamic history of the two rock-glacier generations is expressed in the exposure age distributions of the different lobes.

"contrasting responses to external forcing" This is the very reverse of what you suggest here. This conclusion refers to the following statements in the paper:

"…the rapid advance of the debris-ice lobe was enabled and conditioned by debris supplied by the mobilisation of reworked Egesen cirque glacier-derived material (Frauenfelder et al., 2001, 2005) and the <u>warming-induced</u> rapid head wall weathering during the early Holocene (Kenner andMagnusson, 2017). We imagine the lower elevation part of Bleis Marscharock glacier as a <u>rapidly down-rushing, short-lived debris pulse</u> (cf. Kirkbride andBrazier, 1995).Our findings of a high rock glacier-headwall ratio (Kenner andMagnusson, 2017) despite relatively short activity phase of early-Holocene relict-inactive rock glaciers (Böhlert et al., 2011a)seems to be representative for the Julier-Albula region"

And

"The low-elevation older generation formed during the late Younger Dryas and persisted into the early Holocene in a short time frame of a favourable succession of climatic conditions: First, an aridification at still cold conditions during the late Younger Dryas, leading to glacier starvation, retreat, and permafrost growth, later followed by <u>significant warming at around 10ka</u>. "

Comment: The oldest exposure date they found was 8.9 ka, this was long after Younger Dryas in a distinct warm phase. I will come back on this.

Oliva is neither an appropriate reference here:

"Since the Last Glaciation there has been a long-term decrease in the area occupied by permafrost in the Mediterranean mountains. The existence of abundant inactive permafrost-derived <u>landforms</u> (rock glaciers, block streams, patterned ground features, ice wedges) <u>formed during the last Pleistocene glacial cycle</u> suggests…"

You are writing about the relatively moderate climate fluctuations during the Holocene in the Alps! During the Pleistocene, your area was covered under 1000m of ice. You cannot compare these things!

I give up on this point if you can find convincing answers to the following questions:

Amschwand suggests that the old inactive part of Bleis Marscha originates from a "*rapidly down-rushing, short-lived debris pulse … representative for the Julier-Albula region".* Today, in times of climate warming we talk about "rock glaciers on the run" and you are writing about extraordinary accelerations. Both sounds quite similar to me. Why are today's high rock glacier velocities explained by warm conditions and high rock glacier velocities in the early Holocene by cold conditions? (And which cold conditions?)

All the papers suggested, struggle to prove a clear temporal connection between phases of rock glacier activity and cool climate using independent climate data: The oldest sample Amschwand et al could found was 8.9 ka old. I.e. approximately 9000 Years ago, the rock fell of the rock wall. This was one of the warmest periods of the Holocene! However, why do Amschwand et al. date the formation time of this rock glacier to 11.5 and 9.0 ka?? Isn`t that a strange contradiction? I could not find a sound explanation…

Frauenfelder & Kääb 2000 (the paper on which Regulas GIS analysis is based on) estimate the difference of MAAT between today and the active phase of relict rock glaciers, based on rock glacier front elevations. The results differ drastically between neighboring regions (e.g. within Switzerland: Prealps (5.5°C) vs. Saas Valley (1°C)). Now, was climate warming during the Holocene more than 5 times stronger in the Prealps compared to Valais or is this analysis nonsense and rock glaciers lousy climate indicators?

I know the theory you state here is widespread also in the rock glacier action group. However, I want to encourage you to stay critical, research cannot always hide behind a political compromise. Give me enough rock and enough snow and I build you a rock glacier at the beach of Bali 😉

I whish you all the best!

Robert