Report #1 (W. Haeberli)

RC 1.1: General

With the extensive – even though somewhat selective – response to the comments by three reviewers and the revision of the originally submitted manuscript, the contribution has made an important step forward towards better equilibrated assessments and discussions. The adjusted title and the now more modest formulation concerning the possibilities and limitations of the workshop report increase the credibility of the product.

AR 1.1: We thank the reviewer for the positive appreciation of our efforts.

RC 1.2: The response to the reviewer comments mentions "lead authors". It would be good to know who they are and what the concrete function of the many co-authors has been.

AR 1.2: By "lead authors" we meant the first three persons listed in the authors' list. These persons led and coordinated the review-writing process. As far as we know, Copernicus journals do not foresee an "authors contributions" section or statement. In this respect, we are on a line with the reviewer, and would equally appreciate the possibility of providing that information.

RC 1.3: Some aspects can still be improved (see below and the annotated file). The reference list, for instance, does still not contain all papers cited in the text but duplicates others, uses variable formats and must be adjusted concerning the (alphabetical, etc.) sequence of cited reports.

AR 1.3: We do apologize for the incompleteness and heterogeneity in our last version's reference list. This issue has now been fixed by using the Journal's "bibliography style file".

RC 1.4: The most astonishing point is still that neither the abstract nor the conclusions contain any concrete statement about the "current state and trend" concerning snow and ice in Europe. The quite dramatic fact that Europe is essentially loosing its glaciers within decades, for instance, appears not important enough to be mentioned. At least for the fast readers who do not want to go through all the detailed discussions in the text, the impression may remain that no essential take-home messages can be made. At least for them, the comment by reviewer 2: What can the reader learn from the paper as it stands now?" "What is the benefit of the paper in comparison to the list of individual papers summarized/extracted there"? "My expectation is that from summarizing the previous studies/papers new insight/findings should result." hardly receives a convincing answer in the abstract and in the conclusions. Rather, data and communication issues seem to be the main concern of the authors. Such data and communication issues are indeed important but not specific for the European cryosphere for which the density and availability of quantitative information is probably the best worldwide.

AR 1.4: In hindsight, we can understand the reviewer's discontent. With the new submission, we performed a major effort to address this question. In particular, we significantly revised our Section 3, in which we formulate our "take home messages" and "lesson learned". This section has been decisively streamlined by removing individual parts, extending others, and integrating some of the elements in the preceding Sections. The Section is now subdivided into 4 Subsections addressing modelling issues (Sec. 3.1), cascading processes and process chains (Sec. 3.2), uncertainties in measuring and estimating high-altitude precipitation (Sec. 3.3), and other issues related to observational data (Sec. 3.4). Through the new structure and the revised elements, we gained much substance for the conclusions as well. This is not only reflected in that section, but also in the revised abstract.

RC 1.5: Data and communication issues also concern the cumulative glacier mass balances compiled in Figure 2. The review comments concerning this presentation are quite basic and should not be ignored: The mass balance graph mixes together things of different type and quality level: Storglaciären is the longest and probably best glacier mass balance program while Clariden is a largely uncalibrated model calculation from isolated point observations with estimates of calving activity using climate data, etc. On page 28, lines 16/17 the revised text treats the need for " … adequately evaluating and communicating … uncertainties" Figure 2 should follow this principle and discriminate in a transparent way excellent and carefully calibrated field measurements (Storglaciären) from numbers involving calculations using a degree-day model, i.e. climate data (mass balances from Switzerland), and especially from shaky low-quality reconstructions based on uncalibrated point observations and crude estimates of calving fluxes (Clariden). Uncalibrated measurements/estimates can contain systematic errors, which sum up in calculations of cumulative values over time, biasing long-term trends. The fact that the reconstructed cumulative Clariden mass balances are the most positive/least negative in the graph concerning the Alps could well have been caused by a systematic underestimation of the (unmeasured) calving fluxes in the past. Eliminating the – at best controversial – reconstruction of glacier mass balances for Clariden would improve the information provided in Figure 2.

AR 1.5: Although we do not agree with all of the reviewer's opinions, we have removed the curve referring to Clariden from Figure 2.By doing so, we are confident to have addressed the reviewer's major concern.

RC 1.6: Another aspect related to data needs and communication concerns the different purposes of modeling/analysis. Flux-driven approaches for modeling glacier thicknesses, for instance, are scientifically interesting but rather intransparent, require large amounts of input information, must be heavily tuned and are an unnecessary "overkill" in the case of practical applications, where much simpler, transparent, robust and rapid approaches using easily available input information and needing no tuning provide equally good results. More complicated approaches are not in all cases better approaches.

AR 1.6: Here, we completely agree with the reviewer's comment. In fact, the comment is very much in line with the findings of the main work addressing this topic (doi:10.5194/tc-11-949-2017), which is a work that we adequately cite.

RC 1.7: Specific remarks. A few additional specific remarks and suggestions can be found in the annotated file. The reference list needs careful and systematic editing.

AR 1.7: We thank the reviewer for the many detailed comments provided within the manuscript. We directly implemented these suggestions wherever we could. As mentioned above already, the reference list was completely reworked.

Report #2 (Anonymous)

RC 2.1: This is improved and offers a logical, reasonably thorough summary of the state of knowledge of European cryosphere-climate research, along with challenges and gaps in understanding. Most of the remaining edits that are needed are editorial in nature.

AR 2.1: We thank the reviewer for this positive comment.

RC 2.2: I do think that some of the essential weaknesses still remain - there is a lack of novelty and insightful analysis, and for my part, I did not learn much in working carefully through this manuscript. This works passably as a review paper, but it covers well-understood and thoroughly documented ground, e.g., without much that is new relative to the IPCC (2013) cryosphere chapter. That said, there are some newer references pointing the field forward, e.g., with some new ideas in distributed permafrost and glacier thickness modelling. With these ideas and with the logical, strong presentation of material, this article may serve well as an introduction to the European cryosphere for those that are new to the field.

AR 2.2: We tried to address this “essential weaknesses” through the substantial re-work that we performed for both Section 3 and the “conclusions” section (cf.AR 1.4). In particular, we also better highlighted the positive parts that the reviewer mentioned in the context of permafrost modelling. We are convinced that this helped to strengthen the manuscript as a whole, and hope that this will make it of interest to both, researchers that are new to the field, and researchers that are familiar with it.

Report #3 (Anonymous)

RC 3.1: Based on the reviewer’s comments the paper was clearly improved. However, I am still struggling with my decision for this paper, by hesitating between reject and possibly accept after revisions. The paper is still a weak summary report on the status of European mountain cryosphere, unfortunately, without showing significant new results and without deriving any clear conclusion (which is my main concern). Additionally, I also do not see a strong review work of the status of research on European mountain cryosphere. I really wonder if such paper is needed to support cryospheric sciences and the research community. Maybe there is some value of the paper as a result of the Riederalp workshop mentioned in the acknowledgements. But, why is it not possible to make something more significant out from this workshop material?

According to my understanding a review article should do a critical, constructive analysis of the existing literature by summarizing, classifying, analyzing and comparing. This needs real work to be done and, to some degree, this is what I miss in the Beniston et al. paper.

AR 3.1: We do understand the reviewer's comment and do agree with that. In the resubmitted version, we have reworked the paper structure (see also next answer) and have put much effort in condensing our messages. With this, we hope to have achieved to provide the "critical and constructive analysis that the reviewer was anticipating.

RC 3.2: The title of the paper was slightly changed. The title of the paper is now "The European mountain cryosphere: A review of its current state, trends and future challenges". This is also reflected by the general structuring schema of the paper, which seems logical. However, the structure is filled up with too weak content. Even with good will, I hardly can derive any useful take home message after reading the paper. Additionally, the paper follows a concept of rather subjective examples selected (e.g. for cryosphere impacts), which is hard to understand.

AR 3.2: The structure of the paper was revised (cf. AR 1.4): Besides the introduction (Sec. 1) and conclusions (Sec. 4) we now have a section dedicated to the current state and future trends in the European mountain cryosphere (Sec. 2) and one dedicated to the challenges in cryospheric research (Sec. 3). Together with the significant work promoted to condensate our main messages and to remove the pars of "weak content", we are convinced that this has resulted in a much more solid and understandable manuscript.

RC 3.3: As the aim of the paper is a review of European mountain cryosphere, I would like to see the introduction to be more informative on this topic. Is this the first review of European mountain cryosphere? Probably it is the first one covering all cryosphere components, but there are several reviews for single cryosphere components (e.g. snow cover or glaciers).

AR 3.3: Indeed, there are other papers covering cryospheric issues, including for example in the latest IPCC report (2013). However these other papers are slowly becoming outdated, and we believe that there are new findings and a grouping of issues in a single paper that may be one of its "added-values".

RC 3.4: Though the topic is on European mountains, there is no clear definition which mountain regions are included and how "mountain regions" are defined for this study. Obviously, Svalbard is included (and is not defined as Arctic cryosphere). What about other mountain regions in Europe e.g. of the Russian territory? Shouldn't they be part of a review on European mountain cryosphere?

AR 3.4: We now include a definition for the addressed regions in the introduction, that reads "We focus on mainland Europe, in particular the European Alps and Scandinavia, but also include – where possible – the Pyrenees and other mid-latitude European mountains". Accordingly, Svalbard is no longer included in our review

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RC 3.5: Given the new title of the paper, it would be good to define at the beginning of the paper how you quantify both the "current state" and "trends" of the cryosphere components. Ideally, it should be done by some comparable statistical measures, but clearly practice could be different. I wonder how you define the "status" of a cryo component. For glaciers you provide data on area and volume. For permafrost you only show borehole temperatures (as it is the standardized GTN-P variable). Would be good to show the areal extent of permafrost from empirical modelling efforts, though there is significant uncertainty on the data. Otherwise, what is the current status of permafrost (a ground temperature)? Additionally, you have borehole data from Switzerland and France but not from Germany, Italy or Austria? Are there no useful data from there? Are your borehole temperature data representative for the entire Alps then?

AR 3.5: Unfortunately we are not aware of any "comparable statistical measures" that would allow for a direct comparison between individual cryospheric components. Whenever possible, we do include basic data about area extend and total volume (such as for glacier area and volume, or maximal snow cover extent), but such information is difficult to obtain for permafrost. For what the last part of the comment is concerned, we were indeed unable to retrieve data from other countries. The difficulty in obtaining such data is one of the main points that we highlight in out "Challenges" section (Sec. 3).

RC 3.6: For some of the cryosphere components your review of the status and changes of the European mountain cryosphere is based on snapshots only. SWE (as the example for snow shown in Figure 1) excludes e.g. Scandinavian and Carpathian Mountains or the Pyrenees. Why not use an example where you have all regions covered by you snow example.

AR 3.6: A similar comment as above applies: With the present data-management policies, it is a literally prohibitive effort trying to obtain such data at the spatial scale suggested by the reviewer. We hope our contribution and the call we make in it to be a starting point for making this situation change in the near future.

RC 3.7: My main concern, however, is related to the conclusions of the paper. Currently, the paper concludes that: (i) Mountain cryosphere research urgently needs data of high quality; (ii) access to state of the art models with high spatial and temporal resolution are needed for better understanding of feedbacks and future behavior; (iii) communicating research results is a challenge and needs careful consideration; (iv) from the focus of impacts cryosphere is key element of environmental changes in high mountain regions. These four items from above are nothing relevant and there is no real conclusion related to the presented material of the paper. In particular, there is no conclusion related to the topic of the paper: the current status, trends and future challenges of mountain cryosphere (maybe the presented conclusion could be somehow related to future challenges, but the drawn conclusions are nothing new). Such results (type of conclusions) could be useful as a workshop report but not for a scientific review paper.

AR 3.7: With the major rework that we performed in response to the comments of the three reviewers, we also increased the substance of our conclusions. In particular, we now (1) highlight that the changes in the European mountain cryosphere are large, and that they will require some adaptation strategies in the future, and (2) summarize the challenges for cryosphere research that we identified in the re-structured Section 3.

RC 3.8: The authors also state that in their paper much attention has been devoted to data issues. Data issues are clearly an important task of cryosphere sciences. However, the discussion on data issues remains rather general/superficial and on topics which are quite well known. Important topics such as gaps in observations, standardization of measurements, best practices for observations, data quality control and data homogenization are not really captured in-depth. Again, I can't see much value in a paper which remains that generally and which excludes the relevant challenges of science.

AR 3.8: We substantially reduced this part, particularly removing those addressing topics that the reviewer identified as to be "well known". We now focus on aspects of future data policies, that we indeed see as one of the most important points when aiming at further progress in the domain of high-alpine research.

RC 3.9: Uncertainty: The paper explains the difference between uncertainty and error as well as the different meaning of forecast and scenario. However, nothing, with respect to uncertainty, is related to the cryosphere data itself. This is not useful. The different meaning of uncertainty vs error and forecast vs scenario can be found in many textbooks of climatology, no need to explain it here. However, it would be good to get some information on uncertainty of presented data of glacier/permafrost/snow status and changes. I also still see no much value in Figure 9 (difference between gridded data of precipitation from different sources). Without going into more details of gridding procedure and underlying observational networks this Figure is hard to understand.

AR 3.9: Also in this case, we considerably shortened the part mentioned by the reviewer, and condensed our thoughts to a minimum. In particular, we now specifically address modelling uncertainties (Sec. 3.1.4), which we see as the main issue.

RC 3.10: Page 14/10: The comment of increased severe flooding in the Alps for the future is on weak basis and is not appropriate. There are large number of papers on this topic for the Alpine region showing that the general statement covering the entire Alps is not useful, consequently a regionalized focus on floods is needed (e.g. Blöschl et al., 2015). Gobiet et al. (2014), so generally an important contribution, is not a good reference for floods in the Alpine region. The same is for droughts. Your reference to Gobiet et al. (2014) is fuzzy if you argue an increase of occurrence and severity. Do you speak about future scenarios? There is no increased trend of droughts observed for the Alpine region (as described in Gobiet et al., 2014).

AR 3.10: We removed the reference to the work by Gobiet et al. (2014) at the place indicated by the reviewer. Similarly, we removed the erroneous claim that a trend in drought frequency is observable in the Alps. We kept, however, the reference to works indicating a future increase in drought conditions.

RC 3.11: Page14/25: You mention in the introduction of your paper that you do not capture lake ice. However it is mentioned here under the heading of "changes in meltwater hydrology". This is rather unmotivated and I suggest to cover the topic of lake ice right from the beginning or to omit it entirely.

AR 3.11: We followed the reviewer's suggestion and removed the reference to lake ice in the section addressing meltwater hydrology.

RC 3.12: I am not convinced by your example of alpine ibex for impacts of cryosphere on ecosystem functioning, as this species is particularly vulnerable not only to impacts from climate and cryosphere change but also from disease (e.g. scabies). I guess there are other more robust examples like plant species.

AR 3.12: We significantly reduced the prominence by which the alpine ibex and rock ptarmigan examples are presented. In the revised manuscript, in fact, both examples are directly included in the section discussing changes in snow cover (Sec. 2.1.2). By doing so, we hope to have adequately clarified that the two case-studies were meant as examples only, and that we did not want to attribute them any general character.

RC 3.13: Figure 1: I the light of paper title would be very good/needed to cover also other regions of the European mountains for showing snow (SWE) trends

RC 3.14: Figure 2: Why not include glaciers from Russian mountain regions? Or make clear why they are excluded!

RC 3.15: Figure 3: see my previous comment (borehole temperatures from Germany, Austria, Italy).

RC 3.16: Figures 4 and 5: these Figures are rather site specific in terms of a review of all mountain regions in Europe (would like to see more on cryosphere changes in mountain region in Europe in general)

RC 3.17: Figure 6: Again this Figure is rather site specific. Why not aggregate it into one Figure with the useful results from various simulations done by Huss et al., for Switzerland or similar simulations for all other mountain regions in Europe?

AR 3.13-3.17: In all the mentioned cases, we re-present already-published results. Since we have no access to the original data (a general problem that we very much stress in our Section 3.4), we have no means of extending the figures as proposed by the reviewer without investing a major effort into data retrieval. We acknowledge this not to be a particularly satisfactory answer, but this is exactly the point that we raise in one of our main conclusions!

RC 3.18: Figure 7: See my previous comment (I think this example is too speculative and there are other, more powerful, examples for impacts of snow on ecosystem functioning)

AR 3.18: We integrated this example in Section 2.1.2 and removed the figure. For details, see answer to RC 3.12.

RC 3.19: Figure 9: See my previous comment. Additionally, if you use this Figure you have to explain all acronyms.

AR 3.19: Here, we are not entirely sure to what the instruction "see previous comment" refers to: The previous comments all highlight the site-specificity of the examples, whilst here we show a map for the whole of Europe. Our understanding is, that this is in line with the reviewer's suggestion. The acronyms are now all explained in the figure caption.

RC 3.20: Figure 10: Motivation to show this Figure appears rather weak to me. In particular if you set the number of Figure with marginal information on status/change of European cryosphere (5 figures) against the number of figures providing information on the key topic of the paper (5 figures from which 2 are with site specific information for Switzerland only)

AR 3.20: The figure was removed following the reviewer's suggestion.

The European mountain cryosphere: A review of its current state, trends and future challenges

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Abstract. The mountain cryosphere of mainland Europe is recognized to have important impacts on a range of environmental processes. In this paper, we provide an overview on t~~T~~h~~is pap~~e~~r reviews~~ current knowledge on snow, glacier, and permafrost processes, as well as their past, current and future evolution~~ in mountain regions in mainland Europe~~. In addition, w~~W~~e provide a comprehensive assessment of the current state of cryosphere research in Europe and point to the different domains requiring further research to improve our understanding of climate-cryosphere interactions, cryosphere controls on physical and biological mountain systems, as well as related impacts. Most likely, by the end of the century, the components of the mountain cryosphere will have changed to an extent that will significantly impact the landscape, hydrological regimes, water resources, built infrastructure in mountain areas and even downstream in the lowlands, entailing a wide range of so~~i~~cio-economical consequences. European mountains will have a completely different visual appearance, at low and mid-range altitues most glaciers will have disappeared~~ at low and mid-range altitues~~, and the (currently still relatively large) valley glaciers will be characterized by significant retreat and mass loss. Seasonal snow lines will be found at much higher altitudes, and the snow season will be much shorter than today, with a related shift from solid to liquid precipitation in all seasons due to increased air temperatures. These changes in snow and icemelt will cause a shift in the timing of discharge maxima and a transition from glacial towards nival, and from nival towards pluvial regimes, with drastic impacts on the seasonality of water availability from high altitude regions and consequences for water storage and management in reservoirs for drinking water, irrigation and hydropower production. Whereas an upward shift of the treeline and expansion of vegetation can be expected into current periglacial areas, the disappearance of permafrost at lower altitudes and its warming at higher elevations will likely result in mass movements and process chains beyond historical experience. Future cryospheric research has the responsibility to ~~be~~foster awareness of these expected drastic changes and develop targeted strategies to precisely quantify the ~~occurring changes~~magnitude of the occurences as well as their rate, and develop approaches capable to ~~address~~adapt to these changes and mitigate their consequences~~ changes.~~. Major joint efforts are required both in the measurement and monitoring as well as in the numerical modelling domain, as well as in the research in precipitation and cascading mass movement processes and process chains, but also in terms of data quality and common availability~~ and quality~~.

~~We highlight advances in the modelling of the cryosphere, and identify inherent uncertainties in our capability of projecting changes in the context of a warming global climate.~~

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1 Introduction

Ongoing climate change and the importance of its anthropogenic component have gained wide recognition (IPCC, 2013). Some regions thereby are likely to be more vulnerable to a changing climate than others ~~to~~ in both the expected physical changes and the consequences for ways of life. Mountains are particularly subject to rapid and sustained environmental changes (Gobiet et al., 2014), and the cryosphere is the physical compartment that exhibits the most prominent and visible changes. Changes in mountain snow, glaciers, and permafrost~~, moreover,~~ have resulted in significant downstream impacts in terms of the quantity, seasonality, and quality of water (Beniston et al., 2011). This is particularly true for areas where snow- and ice~~-~~melt represent a large fraction of streamflow. Countless studies have reported glacier retreat, permafrost warming, and snowfall decrease across mountain regions in Europe~~ and elsewhere~~, with implications for streamflow regimes, water availability, ~~or~~ and natural hazards. These can in turn negatively impact hydropower ~~produc~~generation, agriculture, forestry, tourism, ~~or~~ and aquatic ecosystems. C~~As a c~~onsequen~~ce~~tly, downstream communities will also be under pressure, and mountain forelands are densely populated areas and thus highly affected (Kaser et al. 2010, Huss et al.). Both political and scientific programs are calling for better preparedness, and for the development of strategies aimed at averting conflicts of interest that can arise, ~~for example~~e.g., between economic goals and environmental protection (Beniston et al., 2014).

In the following, we provide an overview of the current knowledge on European mountain permafrost, ice, and snow, and the observed changes in these elements of the cryosphere. We focus on mainland Europe, in particular the European Alps and Scandinavia, but also ~~address~~include – where possible – the Pyrenees and other mid-latitude European mountains undergoing large and rapid change. An assessment of the challenges that need to be addressed in cryosphere research is provided, and we identify areas where further progress is required to improve our understanding of climate-cryosphere interactions. We argue that such improved understanding is the key for better predicting changes and impacts of a cryosphere responding to rapidly changing climatic conditions, and for appropriate adaptation measures to be developed. The discussions that will follow reflect the current opinions of a body of scientists that focused on a number of issues at a conference held in Switzerland in 2016. We do not claim that all aspects of cryosphere sciences are exhaustively covered, nor that are all the possible elements of the cryosphere discussed (e.g., lake ice, river ice,~~;~~ ice in caves, etc.). However, we do believe that the elements that appear in the following text do represent much of current scientific ~~preoccupations~~ research work on this major component of mountain environments.

2. Current state and future trends in European mountain cryosphere and their impacts

2.1 Changes in snow

The snow cover is the most important interface between the atmosphere and the ground, strongly influencing the surface energy balance and thus also the other components of the cryosphere. Snow ~~is an important component of hydrology, but~~ affects ~~also largely other cryospheric components, i.e.,~~ glaciers ~~(~~through albedo and the mass balance~~ and the albedo)~~ and permafrost ~~(~~through its thermal insulation properties and melt water input~~)~~. ~~It also plays a key role for sustaining ecological and socio-economic systems in European mountains and also, quite often, in downstream lowland regions.~~ Moreover,~~ the snow cover is the most important interface between the atmosphere and the ground, also strongly influencing the surface energy balance and thus also other components of the cryosphere~~. ~~The~~ Iits extreme spatiotemporal variability remains one of the key factors of uncertainty concerning the impacts of climate change on the cryosphere. ~~Ongoing climatic change is significantly affecting the snow cover through different processes.~~ Snow also plays a key role for sustaining ecological and socio-economic systems in the mountain regions and also in the downstream lowland regions. Ongoing climatic change is

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Commented [HH2]: We should give an indication of which periods are considered when we say "observed changes" and "future changes", e.g. post-industrialization period and end of the century?

significantly affecting the snow cover through different processes. Snow observations canare therefore a prerequisite forcontribute to the are thus important for understanding of these processes, and for providing more reliable assessments of future changes.

2.1.1 Observed changes in of the snow cover

Most studies show negative trends in snow depth and snow duration over the past decades (Table 1). These negative trends are well documented in the Alps owing to the abundance of long-term observations. The changes are typically elevation dependent, with more (less) pronounced changes at low (high) elevations (Marty, 2008; Durand et al., 2009; Terzago et al., 2013). As Figure.. 1 demonstratesillustrates, the decrease in spring snow water equivalent (SWE) is clearly decreasing in the Alps (Bocchiola and Diolaiuti, 2010; Marty et al., 2017) as well as at low elevations in Norway at low elevations (Skaugen et al., 2012). Only in the higher and colder regions of the Fenno-Scandinavian mountains exhibit positive trends of do maximum snow depth and maximum SWE exhibit positive trends. However, in more recent decades, trends have become mostly negative in these regions too (Johansson et al., 2011; Skaugen et al., 2012; Dyrrdal et al., 2013; Kivinen and Rasmus, 2015). In the Pyrenees, a significant reduction of the snowpack is reported since the 1950s (Pons et al., 2009). In other European mountains, observations are less abundant, but several studies report declininges in snowpacks for the mountains in Romania (Birsan and Dumitrescu, 2014; Micu, 2009), Bulgaria (Brown and Petkova, 2007), Poland (Falarz, 2008), and Croatia (Gajić-Čapka, 2011) are reported.

The observed changes in snow depth and snow duration are mainly caused by a shift from solid to liquid precipitation (Serquet et al., 2011; Nikolova et al., 2013) and by more frequent and more intense melt conditions (Klein et al., 2016), resulting from both higher winter and spring air temperatures during winter and spring. In addition to a general warming trend, large-scale atmospheric circulation patterns such as the North Atlantic Oscillation (NAO) have been shown to influence the snow cover in Europe (Henderson and Leathers, 2010; Bednorz, 2011; Skaugen et al., 2012; Birsan and Dumitrescu, 2014; Buisan et al., 2015). For the Alps, 50% of the snow-pack variability seems to be related to the establishment of atmospheric blocking patterns over Europe, although in this case the correlation between the annual snow pack variability and the NAO is small, and limited to low elevations (Scherrer and Appenzeller, 2006; Durand et al., 2009). The NAO influence can be detected at higher elevations through a ‘cascade’ of processes that include the NAO influence on pressure fields, and the influence of pressure fields on precipitation. Together with the effect of air temperature, this determines the amount of snowfall. In recent decades, this cascade has led to an increased number of warm and dry winter days with warm and dry conditions, which obviously is unfavorable for snow accumulation (Beniston et al., 2011b). Moreover, the Atlantic Multi-decadal Oscillation (AMO), which is a natural periodic fluctuation of Northern Atlantic sea surface temperature, affects the low-frequency variability of Alpine alpine spring snowfall (Zampieri et al. 2013) and therefore also contributes to the described decline in snow cover duration.

	Time	Snow variable	Trend at low / high elevation		Source
Alps			**below 2000 m**	**above 2000 m**	
Switzerland	1958-1999	DJF snow cover duration	majority negative	no clear trend	Scherrer at al., 2004
Italy	1950-2009	DJFMA snow cover duration	majority negative	no clear trend	Valt & Cianfarra, 2010
France	1959-2005	Annual snow cover duration	majority negative	many negative	Durand et al., 2009
Scandinavia			**below 1000 m**	**above 1000 m**	
Norway	1961-2010	Maximum snow depth	majority negative	some positive	Dyrdall et al. 2013
Finnland	1978-2012	Annual snow cover duration	majority negative	-	Kivinen & Rasmus, 2014
Carpathians			**below 1000 m**	**above 1000 m**	
Bulgaria	1931-2000	Annual snow cover duration	no clear trend	no clear trend	Brown & Petkova, 2007
Poland	1954-2001	Maximum snow depth	no clear trend	no clear trend	Falarz, 2008
Romania	1961-2003	Annual snow cover duration	no clear trend	no clear trend	Micu, 2009
Pyrenees			**below 1000 m**	**above 1000 m**	
Spain	1975-2002	Annual snow cover duration	majority negative	majority negative	Pons et al., 2009

Table 1: *R~~Most r~~ecent studies of current snow cover trends in the major European mountain regions - only significant trends are listed: A direct comparison of sites is difficult because the considered time period and snow ~~snow~~ variable ~~is~~ differ between ~~ent for each~~ studies~~y~~. ~~Nevertheless, negative trends are clearly dominating.~~*

The observed changes in snow amounts are often abrupt in time, as a result of the interplay between ~~cold~~ low air temperatures and precipitation, both influenced by large-scale weather patterns. Several studies have reported a step-like change for snow depth occurring in the late 1980s ~~for snow depth~~ (Marty, 2008; Durand et al., 2009; Valt and Cianfarra, 2010) and for snow-covered areas of the Northern Hemisphere (Choi et al., 2010~~),). but also for other biophysical systems (Reid et al., 2016).~~ This step-like development, also observed for other biophysical systems (Reid et al., 2016), is mostly the result of stagnant winter temperatures ~~that have not risen further~~, ~~neither~~ both in large areas ~~in~~ of the Northern Hemisphere (Mori et. al. 2014) ~~nor~~ and in the Swiss Alps (Scherrer et al., 2013). Atmospheric internal variability (Li et al., 2015), as well as shrinking sea-ice extent~~ds~~ (Mori et. al. 2014) have been invoked as possible explanations. ~~-~~As a result, the monthly mean ~~(Dec-Apr)~~ snow covered area (SCA) in the Alps (for the months comprised between December and ~~-~~ April) has not decreased significantly since the late 1980~~'~~s (Hüsler et al., 2014).

Studies analyzing high-magnitude snowfall and maximal winter snow depth~~s~~ are rare, but indicate that extreme snow depths have decreased in Europe (Blanchet et al., 2009; Kunkel et al., 2016), with the exception of higher and colder sites in Norway (Dyrrdal et al., 2013). The decrease in~~g pattern for~~ extreme snow~~ ~~fall rates is less clear than for extreme snow depth, except for low elevations where the influence of increasing air temperature~~s~~ is predominant (Marty and Blanchet, 2012). ~~In addition~~Also, ~~there exist few~~ studies related to past changes in snow avalanche activity are scarce. However, ~~Over the last decades,~~ observations indicate that over the last decades (a) the number of days with prerequisites for avalanches in forests

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[Commented [MS5]: Skip unless used elsewhere] decreased (Teich et al., 2012), (b) the proportion of wet snow avalanches increased (Pielmeier et al., 2013), and (c) the runout altitude of large avalanches retreated upslope (Eckert et al., 2010, 2013; Corona et al., 2013) as a direct consequence of changes in snow cover characteristics (Castebrunet et al., 2012).

2.1.2 Future changes ~~in~~ of the snow cover

The projected increase in air temperature for coming decades is accompanied by ~~high~~ large uncertainties in changes of winter precipitation~~ changes~~. Ensemble means show no clear precipitation change until about the 2050s, but slightly increasing winter precipitation thereafter. Projected changes in snow cover are thus highly dependent on the ~~considered~~ applied greenhouse gas emission scenario and the ~~addressed~~ considered period, and regional patterns are variable (e.g., Marke et al.). ~~Under a~~For the SRES A2 scenario, regional climate model simulations show a dramatic decrease ~~in~~ both in ~~the~~ snow cover duration and SWE for Europe by the end of the 21st century (Jylhä et al., 2008).

For the Alps and at an elevation of 1500 m a.s.l., recent simulations project a reduction in SWE of 80-90% by the end of the century (Rousselot et al., 2012; Steger et al., 2013; Schmucki et al., 2015). The snow season at that altitude is projected to start 2-4 weeks later and to end 5-10 weeks earlier than today (reference period 1992-2012), which is roughly equivalent to a~~n~~ shift in elevation ~~shift~~ of about 700 m (Marty et al., 2016). For elevations above 3000 m a.s.l., and despite assuming~~even~~ the largest projected precipitation increase, ~~results in~~ a decline in SWE of at least 10% is expected by the end of the century. Future climate will most probably not ~~see~~ allow for the existence of a permanent snow cover during summer even at the highest elevations in the Alps, with obvious implications for the remaining glaciers ~~evolution~~ (Magnusson et al., 2010; Bavay et al., 2013) and the thermal condition~~s~~ of the ground (e.g. Marmy et al. 2016; Draebing et al. 2017, Magnin et al. 2017~~, Draebing et al. 2017, Marmy et al. 2016~~; ~~(Draebing et al., 2017~~).

Projections for Scandinavia show clear decreases for snow amount and duration for all latitudes. E~~An e~~xceptions ~~is given by~~are the highest mountains in Northern Scandinavia~~the north~~, where strongly increasing amounts in precipitation ~~seems~~ could apparently~~to partly~~ compensate ~~for~~the temperature rise, and thus resulting in marginal changes only (Räisänen and Eklund, 2012). Simulations for the Pyrenees indicate a decline~~s~~ of the snow cover similar to ~~those~~ that found for the Alps (López-Moreno et al., 2009). Again, the dependency on future greenhouse gas emissions ~~has to be noted~~is significant: ~~Under~~ For a high emission scenario (RCP8.5), SWE decreases by 78% at the end of the 21st century at 1500 m a.s.l. elevation, whereas a lower emission scenario (RCP6.0) ~~still~~ shows a decline of 44%.

~~Mass movements involving snow often occur at very local scales, making them difficult to relate to climate model outputs, even with downscaling methods (Rousselot et al., 2012; Kotlarski et al., 2014).~~

Extreme values of s~~S~~now variables~~-related extremes~~ are often the result of a combination of processes (e.g., wind and snow for drifting snow), making predictions of their ~~future behavior~~expected frequency highly uncertain, not least because of the lack of related baseline data (IPCC, 2012; 2013). Model results suggest a smaller reduction in daily maximum snowfalls than in mean snowfalls over many regions of the Northern Hemisphere by the end of the 21st century (O'Gorman, 2014). An

Commented [HH6]: For central Europe? We should specify the region, and maybe give a reference for the models used

Commented [HH7]: Do we want to say latitude or altitude (or both)?

Commented [MS8]: Move to model part or remove investigation for the Pyrenees (López-Moreno et al., 2011), however, finds a marked decrease in the frequency and intensity of heavy snowfall events below 1000 m a.s.l., and no change in heavier snowfalls for higher elevations. Changes in extreme snowfall and snow depth~~s~~ are also likely to depend on compensation mechanisms between ~~warmer~~ higher temperatures (Nicolet et al., 2016), more intense precipitation, and increased climate variability, rendering any prediction of future snow storm regimes in terms of ~~number~~frequency, magnitude, and timing difficult. In addition, ~~nearly all~~most available studies either deal with marginal distributions or postulate stationarity (Blanchet and Davison, 2010; Gaume et al., 2013). Any change in moisture content or density of snow will affect infrastructure stability under extreme loading (Sadovský and Sykora, 2013; Favier et al., 2014). To date, the combined evolution of snow amount, type (dry, wet), and density in complex mountain topography remains virtually unknown.

Even ~~if~~ though empirical relations between snow avalanche activity and climate ~~do~~ exist (Mock and Birkeland, 2000), knowledge of long-term response~~s~~ of avalanche risk to climate change remains ~~largely~~ insufficient. With a few exceptions, existing studies focus on the very recent decades~~,~~ and ~~exist~~ only ~~for~~ on a very ~~restricted~~ limited number of regions (Stoffel et al., 2006; Corona et al., 2012, 2013; Schläppy et al., 2014, 2016). Direct effects of climate change on ~~the~~ avalanche frequency~~number~~~~events~~, timing, magnitude~~,~~ and type mainly exist in ~~the~~ form of changes in snow amounts, snowfall succession, density and stratigraphy as a function of elevation. ~~It can be assumed that the ongoing evolution~~The trend towards more wet than dry snow avalanches ~~will continue~~is expected to continue, although the overall avalanche activity will decrease, especially in spring and at low elevations (Martin et al., 2001; Castebrunet et al., 2014). In contrast, an increase in avalanche activity is expected ~~in winter~~ at high elevations in winter due to more favorable conditions for wet-snow avalanches earlier in the season (Castebrunet et al., 2014). Even if the expected rise of ~~the~~ tree line elevation~~s~~ may reduce both ~~the~~ avalanche frequency and magnitude, present knowledge on avalanche-forest interactions ~~remains quite lacunary~~is incomplete, even ~~under~~ for stationary conditions (Bebi et al., 2009).

Due to the highly non-linear nature of avalanche triggering response to snow and weather inputs (Schweizer et al., 2003)~~,~~ and to the complex relations between temperature, snow amounts, and avalanche dynamics (Bartelt et al., 2012; Naaim et al., 2013), it remains unclear whether warmer temperatures will indeed lead to fewer avalanches because of less snow. This is because of potentially higher instability levels in winter linked to larger climate variability (Beniston, 2005). The most destructive avalanches, moreover, mostly involve very cold and dry snow resulting from large snowfall, but may also result from wet snow events whose frequency has increased in the past (Sovilla et al., 2010; Castebrunet et al., 2014; Ancey, 2015). Finally, mass movements involving snow often occur at very local scales, making them difficult to relate to climate model outputs, even with downscaling methods (Rousselot et al., 2012; Kotlarski et al., 2014).

The reduction of the snow season ~~length~~ duration will have ~~large~~ severe consequences for winter tourism (Uhlmann et al., 2008; Steiger and Abegg, 2013; Schmuki et al., 2015b), water management (Laghari et al., 2012; Hill-Clarvis et al., 2014; Gaudard et al., 2014; Köplin et al., 2014) and ecology (Hu et al., 2010; Martz et al., 2016). However, d~~D~~ecreasing snow cover duration and ~~shrinking~~ snow depth~~s~~ are not the only changes with implications: especially in Fenno-Scandinavian mountains, the increasing number of hard (icy) snow layers due to higher temperatures (Johansson et al., 2011) can have a significant effect on the life of plants and animals. ~~In addition~~Moreover, earlier snowmelt is associated with an anticipation of ~~the blooming season of~~ plant phenology~~s~~ (Pettorelli et al., 2007) which can potentially induce a mismatch between plant blooming and herbivore activity, similar to ~~what is~~ observ~~ed~~ationsed in Arctic regions (Post et al. 2009). In the case of ~~Alpine~~ alpine ibex, ~~for instance~~as a prominent example, snow seems to have a dual effect: too much winter snow limits adult survival, whereas too little snow produces a mismatch between alpine grass blooming and herbivore needs (Mignatti et al 2012). Abundance of ~~Alpine~~ alpine rock ptarmigan populations, on the other hand, has been shown to depend on the onset of spring snowmelt, and the timing of autumn snow cover (Imperio et al., 2013).

2.2 Changes in glaciers

Mountain glaciers are recognized as a key indicator of rapid and global climate change. They are important for the supply with water resources in a catchment as they modulate the water cycle at different temporal and spatial scales, affecting irrigation, hydropower production, and tourism. Evaluating the retreat or complete disappearance of mountain glaciers in response to climate change is important to estimate impacts on water resources (e.g. Kaser et al., 2010; Pellicciotti et al., 2014), and to anticipate natural hazards related to glacier retreat, e.g., ice avalanches or the formation of new lakes (Frey et al., 2010; Gilbert et al., 2012; Faillettaz et al., 2015; Haeberli et al., 2016), with the latter also offering opportunities in terms of water storage.

2.2.1 Observed changes in glaciers

Glaciers in mainland Europe cover an area of nearly 5,000 km^2 (Table 2~~1~~) and have an estimated volume of almost 400 km^3 (Huss and Farinotti, 2012; Andreassen et al., 2015). ~~Based on~~From historical archives such as paintings and photography (Zumbühel et al., 2008), it ~~is seen~~can clearly be derived that glaciers have undergone substantial mass loss since the 19th century (Fig. 2) and the pace of mass loss has been increasing (Zemp et al., 2015). A loss of 49% in the ice volume was estimated for the European Alps for the period 1900-2011 (Huss, 2012).

Repeat~~ed~~ inventories have shown a reduction in glacier area of 11% in Norway between 1960 and the 2000s (-0.28%/yr) (Winsvold et al., 2014), and 28% in Switzerland between 1973 and 2010 (-0.76%/yr) (Fischer et al., 2014). Periods with positive surface mass balance have, however, occurred intermittently, notably from the 1960s to the mid-1980s in the Alps, and in the 1990s and 2000s for maritime glaciers in Norway (Zemp et al., 2015; Andreassen et al., 2016). Glacier area loss has led to the disintegration of many glaciers, which has also affected the observational network (e.g., Zemp et al., 2009; Carturan et al., 2016).

Country	Area (km²)	Volume (km³)	Year	Reference
Norway	2692	271	1999-2006	Andreassen et al., 2012b
Sweden	262	12	2002	Brown and Hansson, 2004
Switzerland	943	67	2008-2011	Fischer et al., 2014
Austria	415	17	2006	Abermann et al., 2009
Italy	370	18	2005-2011	Smiraglia and Diolaiuti, 2015
France (Alps)	275	13	2006-2009	Gardent et al., 2014
France-Spain Pyrenees	3	<1	2011	Marti et al., 2015
TOTAL	**4960**			

Table 2~~1~~: *Distribution of glacier surface area and estimated ice volume in continental Europe and mainland Scandinavia. Years of reference and respective publications are given for the glacier area. Ice volume estimates refer to 2003 (Huss and Farinotti, 2012) for continental Europe and Sweden, and to 1999-2006 for Norway (Andreassen et al., 2015). Uncertainties in ice volume are in the order of 10-20%.*

Glacier retreat during the 20th century has been attributed mainly to changes in atmospheric energy fluxes, which in turn non-linearly translate to air temperature ~~in a non-linear manner~~. However, good correlations between air temperature and melt exist, making long-term air temperature time series the favorite option to explain 20th century glacier retreat (Haeberli and Beniston, 1998). It has also been shown that changes in solar radiation could partly explain high melt rates in the 1940s (Huss et al., 2009). Several studies used calibrated temperature-index methods to simulate snow and ice melt responses to atmospheric forcing (Braithwaite and Olesen, 1989; Pellicciotti et al., 2005). However, the relevance of these approaches over multi-decadal time periods has been little assessed. This is due to both the lack of long-term in-situ meteorological measurements close to the study sites and the temporal evolution of melt sensitivity to temperature (Huss et al., 2009; Gabbi et al., 2014; Réveillet et al., 2017). Changes in climate variables affecting glacier behavior are driven by different factors, ranging from large-scale synoptic weather patterns to regional and local effects enhanced by topography. The latter influences, among others, the distribution of precipitation, solar radiation, and wind~~, among others~~. Several studies have shown for southwestern Norway that the glacier surface mass balance is particularly influenced by the NAO~~ influences glacier surface mass balance, in particular in southwestern Norway.~~; The glacier advances in Scandinavia during 1989-1995 are attributed to increased winter precipitation linked to the positive NAO phase during this period (Rasmussen and Conway, 2005). In contrast, in the European Alps, the relationship between the NAO and glacier surface mass balance is less pronounced (Marzeion and Nesje, 2012; Thibert et al., 2013).

The glacier evolution during the 20th century also highlights the importance of the surface albedo feedback, as albedo governs the shortwave radiation budget at the glacier surface, which is the dominant energy source for melting. Snow and ice ablation sensitivities to albedo have been generally assessed using physical energy-balance considerations (Six and Vincent, 2014) or degree-day approaches (e.g., Engelhardt et al., 2015). Oerlemans et al. (2009) and Gabbi et al. (2015) investigated the influence of accumulation of dust or black carbon on melt rates ~~on~~ for Swiss glaciers in the last decades, ~~which~~ reveal~~ed~~ing ~~increasing~~ annual melt rates increased by 15-19% compared to pure snow. Monitoring, reconstructing, or modelling the surface albedo of glaciers is challenging (Brock et al., 2000) as its spatial and temporal evolution is linked to changes in surface properties (~~e.g.,~~mainly snow grain size and grain shape) and to the deposition of impurities on the ice. Albedo changes are also determined by snow deposition (amount and spatial distribution), making the annual surface mass balance highly sensitive to snow accumulation (Réveillet et al., 2017). Properly quantifying the amount and distribution of accumulation over glaciers is therefore a key to better assess the glacier surface mass balance sensitivity to changes in climate, and to simulate its future evolution (Sold et al., 2013).

~~Due to a large ice mass loss during the 20th century, alpine glacier dynamics have been strongly affected, leading to a substantial decrease in ice flow velocities (e.g., Berthier and Vincent, 2012). However, g~~Glacier dynamics are influenced by numerous variables such as mass change and basal hydrology for temperate glaciers, and by ice temperature changes for cold glaciers. In temperate glaciers, ~~-~~ice dynamics is mainly driven by thickness changes and the basal hydrological system~~,~~ which in turn affects basal sliding. The large decrease in ice thicknesses over the last three decades has led to a strong reduction in ice flow velocities (Berthier and Vincent, 2012). Increased water pressure~~s~~, on the other hand, reduces the frictional drag and thus increases the sliding rate. Sliding velocities are low if the water under glaciers drains through channels at low pressure, and high if the water drains through interconnected cavities (Röthlisberger, 1972; Schoof, 2010). Although changes in seasonal ice flow velocities are driven by subglacial hydrology it seems that, at the annual to multi-annual time scales, the ice flow velocity changes do not depend on changes in subglacial runoff (Vincent and Moreau, 2016). A few temperate ~~alpine~~ alpine glaciers have shown large accelerations due to a change in subglacial hydrology, e.g., the Belvedere glacier in Italy (Haeberli et al., 2002), ~~even if~~whereby the mechanisms of this surge-type movement remain unclear. In some rare cases, the reduction of the efficiency of the drainage network followed by a pulse of subglacial water triggered a catastrophic break-off event as in the case of Allalingletscher in 1965 and 2000 (Faillettaz et al., 2015).

Several studies of cold glaciers in the ~~European Alps~~Monte Rosa and Mont Blanc area revealed that englacial temperatures have strongly increased over the last three decades due to rising air temperatures and latent heat released by surface meltwater refreezing within the glacier (Lüthi and Funk, 2000~~,~~; Hoelzle et al., 2011; Gilbert et al., 2014). A progressive warming of the ice is expected to occur and propagate downstream. As a result, changes of basal conditions could have large consequences on the stability of hanging glaciers (Gilbert et al., 2014). Such changes in basal conditions are understood to be responsible for, e.g., the complete break-off of Altelsgletscher in 1895~~, for example~~ (Faillettaz et al., 2015).

2.2.2 F~~The f~~uture evolution of European glaciers

Estimates of future glacier changes in the European Alps and Scandinavia have both been motivated by purely scientific ~~questions~~ investigations ~~regarding~~ of the climate change sensitivity of glaciers, but also by applied ~~studies~~ research ~~related to~~of the consequences of declining ice volume for the availability of mountain ~~future~~ water resources in a warming future. Over the last two decades, various studies on potential future glacier ~~change~~ retreat in Europe have been published; ~~that~~

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These can be broadly classified into site-specific (e.g., Giesen and Oerlemans, 2010) and regional studies (e.g., Salzmann et al., 2012). Methods comprise

~~A large variety of approaches can be used for the projections of future glacier change, ranging from a~~ simple extrapolation of past surface or length changes to a ~~complete~~ complex modelling of glacier mass balance and ice flow dynamics. The applied models ~~vary in complexity and~~ range from simple degree-day models (e.g., Braithwaite and Zhang, 1999; Radic and Hock; 2006) to complete surface energy balance models (e.g., Gerbaux et al., 2005), and from simple parameterizations of glacier geometry change (Zemp et al., 2006; Huss et al., 2010; Linsbauer et al., 2013) ~~over~~ to flowline models (e.g., Oerlemans, 1997; Oerlemans et al., 1998) and to three-dimensional ice flow models solving the full~~-~~ Stokes equations (Le Meur et al., 2004; Jouvet et al., 2011; Zekollari et al., 2014). All models indicate a substantial reduction of glacier ice volume in the European Alps and Scandinavia by the end of the century. Small glaciers are likely to completely disappear ~~completely~~ (Linsbauer et al., 2013), and even large valley glaciers, such as Great Aletschgletscher, Rhonegletscher, Vadet da Morteratsch (Switzerland), or ice caps as Hardangerjøkulen and Spørteggbreen (Norway) are expected to lose up to 90% of their current volume by 2100 (Jouvet et al., 2009, 2011; Giesen and Oerlemans, 2010; Farinotti et al., 2012; Laumann and Nesje, 2014; Zekollari et al., 2014; Åkesson et al., 2017). Many glacier tongues will disappear, including for example the one from Briksdalsbreen, the famous outlet glacier of Jostedalsbreen, the largest ice cap in mainland Europe (Laumann and Nesje, 2009). At the scale of mountain ranges and for the 21st century, model studies relying on different approaches and medium-range emission scenarios consistently predict ~~, over the 21st century,~~ relative volume losses of 76-97% for the European Alps, and of 64-81% for Scandinavia (Marzeion et al., 2012; Radic et al., 2014; Huss and Hock, 2015). Such volume losses ~~of around 80% are~~must be expected ~~for the European Alps~~ even with strong efforts to reduce CO_2 emissions and to stabilize global warming at around +2°C as recommended by the Paris COP-21 climate accord (Huss, 2012; Salzmann et al., 2012), since the ~~.~~

~~Even with strong efforts to reduce CO_2 -emissions and to stabilize global warming at around +2°C as recommended by the Paris COP-21 climate accord, ice volume losses of around 80% are expected for the European Alps (Huss, 2012; Salzmann et al., 2012). Mo~~mountain~~s~~ glaciers in Europe are already ~~strongly~~ out-of-balance with the present climatic conditions, and substantial mass losses are already committed (e.g., Andreassen et al, 2012a; Mernild et al, 2013). Due to their high sensitivity to climate change and limited altitudinal extent, many ~~European~~ glaciers are unable to reach a new equilibrium with climate even if air temperatures are stabilized by the end of this century. Furthermore, the present-day ice caps in Norway~~,~~ that contribute to a large part of the total ice volume in Europe (Table 2~~1~~), are highly sensitive to mass balance–altitude feedback due to their hypsometry and large ice thicknesses. Model experiments suggest that Hardangerjøkulen will not regrow with its present mass balance regime once it has disappeared (Åkesson, 2017). However, uncertainties in projections of future glacier evolution are still considerable and improvements are required in both the quality of the input data and the physical basis upon which glaciological models are built (see Section 3.1~~2~~).

2.3 Changes in permafrost

Permafrost is defined as lithospheric material with temperatures continuously below 0°C, and covers approximately 20 million km^2 of the Earth surface, with a fourth of it being located in mountainous terrain (Gruber, 2012). Although the understanding of the thermal state of permafrost has increased significantly within the recent past, knowledge gaps still exist regarding the volume of ice stored in European permafrost, its potential impact on future water resources, and its effect on slope stability, including processes leading to permafrost degradation and talik formation (Harris et al., 2009; Etzelmüller, 2013; Haeberli, 2013).

2.3.1 Observed changes in permafrost and in rock glacier flow velocities and ice volume

Permafrost borehole temperatures are monitored in many European mountain ranges (GTN-P database, Biskaborn et al., 2015), several of the sites being accompanied by meteorological stations and ground surface temperature measurements (Gisnaas et al., 2014; Staub et al., 2016). However, as mountain permafrost is usually invisible from the surface, various indirect methods need to be employed to detect, characterize and monitor permafrost occurrences. These methods include surface-based geophysical measurements to determine the physical properties of the subsurface, including water and ice content distributions (Kneisel et al., 2008; Hauck, 2013), and geodetic and kinematic measurements to detect subsidence, creep and slope instabilities (Kääb, 2008; Lugon and Stoffel, 2010; Kaufmann, 2012; Kenner et al., 2014; Arenson et al. 2016).

The longest time series of borehole temperatures in Europe started in 1987 at the Murtèl-Corvatsch rock glacier in the Swiss Alps (Haeberli et al., 1998; Fig. 3), a period that is much shorter compared to the available ones for the other cryospheric components such as snow (cf. Section 2.1) or glaciers (cf. Section 2.2). The past evolution of permafrost at centennial timescales can to some extent be reconstructed from temperature profiles in deep permafrost boreholes (e.g., Isaksen et al. 2007), pointing at decadal warming rates at the permafrost table in the order of 0.04°–0.07°C for Northern Scandinavia and Svalbard. Permafrost has been warming globally since the beginning of the measurements (Romanovsky et al., 2010; Noetzli et al., 2016; Fig 3). This warming was accompanied by an increase of the thickness of the seasonal thaw layer (active layer thickness; Noetzli et al., 2016). The considerable year-to-year variability can be linked to variations in the snow cover, as a reduction in snow cover thickness reduces thermal insulation. Latent heat effects associated with thawing mask the recent warming trend for "warm" permafrost sites (temperatures close to the freezing point), which is otherwise clearly visible in cold permafrost (see Fig. 3).

The increasing trend in permafrost temperatures and especially the deepening of the active layer has been hypothesized to lead to an increased frequency of slope instabilities in mountain ranges, including debris flows and rockfalls (Gruber and Haeberli, 2009; Harris et al., 2009; Bommer et al., 2010; Stoffel, 2010; Fischer et al., 2012; Etzelmüller, 2013; Stoffel et al., 2014a, b). The disposition conditions and triggering mechanisms of slope instabilities can be diverse, and depend on subsurface material (e.g., unconsolidated sediments versus bedrock), its characteristics (fractures and fissures, ice and water content, slope angle, geological layering), and changes of these properties with time (Hasler et al., 2012; Krautblatter et al., 2012; Ravanel et al., 2013; Phillips et al., 2016). Water infiltration into newly thawed parts of permafrost is often mentioned as a possible triggering mechanism (Hasler et al., 2012), but to confirm this hypothesis only few observational data are available~~ to confirm this hypothesis~~. ~~Based on~~By means of tree-ring reconstructions (Stoffel et al., 2010; Stoffel and Corona, 2014), the temporal evolution of debris-flow frequencies has been addressed for a series of high-elevation catchments in the Swiss Alps. These studies point to increased debris-flow activity as a result of climate warming since the end of the Little Ice Age (Stoffel et al., 2008; Bollschweiler and Stoffel, 2010a,b; Schneuwly-Bollschweiler and Stoffel, 2012) and a dependence of debris-flow magnitudes due to instabilities in the permafrost bodies at the source areas of debris flows (Lugon and Stoffel, 2010; Stoffel, 2010).

Several studies have documented recent events of rock slope failures in the Alps (Ravanel et al., 2010; Ravanel and Deline, 2011; Huggel et al., 2012; Allen and Huggel, 2013). Some of these failures are clearly ~~seem~~ related to deglaciation processes (Fischer et al., 2010; Korup et al., 2012; Strozzi et al., 2010). Unusually high air ~~Extremely warm~~ temperatures have additionally been associated with these processes as the penetration of meltwater from snow and ice into cleft systems results in a reduction of shear strength and enhanced slope deformation (Hasler et al., 2012). Considering the multiple factors that affect rock slope stability, however, it is generally difficult to attribute individual events to one single factor (Huggel et al., 2013), and improved integrative assessments are necessary. Further evidence of climatic impacts on high-mountain rock slope stability comes from the analysis of historical events. For the Alps, inventories documenting events exist since 1990 ~~exist~~ (Ravanel and Deline, 2011; Huggel et al., 2012) and indicate a sharp increase in the number of events since 1990, such that the temporal distribution of rock slope failures resembles the evolution of mean annual temperatures. ~~Due to~~Given the fact that monitoring and documentation efforts for rock slope failures have been intensified during the past decades, it remains unclear to which degree this correlation is affected by varying temporal completeness of the underlying datasets.

Data on the ice volume stored in permafrost and rock glaciers are still~~remain, however,~~ scarce. To date, hydrologically oriented permafrost studies have been ~~based on~~utilizing remote sensing and meteorological data for larger areas, or have had a ~~locally~~ regionally constrained scope such as e.g. the Andes (Schrott, 1996; Brenning, 2005; Arenson and Jacob, 2010; Rangecroft et al., 2015), the Sierra Nevada (Millar et al., 2013) or Central Asia (Sorg et al., 2015; Gao et al., 2016). To our knowledge, until now no systematic studies exist on permafrost-hydrology interactions for the European mountain ranges ~~to date~~~~until now.~~.

In site-specific model studies, subsurface data are only available from borehole drillings and geophysical surveying. ~~High-resolution subsurface models can then be calibrated to the observed conditions, and used for subsequent climate impact studies, as long as the model calibration can be assumed to be constant in a future climate.~~ The ~~so~~ models used often have ~~often~~ originated from high-resolution hydrological models (e.g. GEOtop, Endrizzi et al. 2014), soil models (e.g. COUP model, Jansson 2012, Marmy et al. 2016) or snow models (such as Alpine3D/Snowpack, Lehning et al. 2006, Haberkorn et al. 2017) and have been successfully extended to simulate permafrost processes. Recently, ~~also~~ explicit permafrost models have been developed as well (e.g., Cryogrid 3, Westermann et al. 2016).

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~~2.3.3 Changes in rock glacier flow velocities and ice volume~~

Because of its complexity, permafrost evolution cannot be assessed by thermal monitoring alone. Kinematic and geophysical techniques are required for detailed process studies. Kinematic methods are used to monitor moving permafrost bodies (e.g., rock glaciers) and surface geometry changes. Hereby, methods based on remote sensing allow for kinematic analyses over large scales (Barboux et al., 2014, 2015; Necsoiu et al., 2016) and the compilation of rock glacier inventories (e.g., Schmid et al., 2015), whereas ground-based and airborne kinematic methods focus on localized regions and on the detection of permafrost degradation over longer time-scales (Kaufmann, 2012; Klug et al., 2012; Barboux et al., 2014; Müller et al., 2014, Kenner et al., 2014, 2016; Wirz et al., 2014, 2016). Long-term monitoring of creeping permafrost bodies ~~shows~~ exhibits an acceleration in recent years, possibly related to increasing ground temperatures and higher internal water content (Delaloye et al., 2008; Ikeda et al., 2008; Permos, 2016; Scotti et al. 2016; Hartl et al. 2016). The kinematic monitoring methods mentioned above, however, cannot~~, however,~~ be used for monitoring of permafrost bodies without movement or surface deformation (e.g., sediments with medium to low ice contents, rock plateaus, gentle rock slopes etc.). Remote sensing has so far not enabled thermal changes in permafrost to be assessed.

Geophysical methods can detect permafrost, and characterize its subsurface ice and water contents (Kneisel et al., 2008; Hauck, 2013). They also provide structural information such as active-layer and bedrock depths. In recent years, repeated geoelectrical surveys have been applied to determine ice and water content changes, thus complementing temperature monitoring in boreholes (Hilbich et al., 2008a; Pellet et al., 2016). Results from this Electrical Resistivity Tomography (ERT) monitoring show that permafrost thaw in mountainous terrain is often accompanied by a drying of the subsurface, as the water from the melted permafrost often leaves the system downslope, and is not always substituted in the following summer (Hilbich et al., 2008a; Isaksen et al., 2011). A 15-year ERT time series from Schilthorn, Swiss Alps, shows for example a clear decreasing trend of electrical resistivity, corresponding to ice melt, throughout the entire profile below the active layer (Fig. 4). The corresponding temperature at 10 m depth~~ (Figure 4a)~~ is at the freezing point, and shows no clear trend. ERT is increasingly used in operational permafrost monitoring networks to determine long-term changes in permafrost ice content (Hilbich et al., 2008b, 2011; Supper et al., 2014; Doetsch et al., 2015; Pogliotti et al., 2015).

2.3.2 Future evolution of European permafrost~~ evolution~~

Physically-based models of varying complexity are employed for process studies of permafrost (for a review see Riseborough et al., 2008; Etzelmüller, 2013) and specifically for the analysis of future permafrost evolution. These models should not be confused with permafrost distribution models (Boeckli et al., 2012, Gisnaas et al. 2016, Deluigi et al. 2017), which are statistical and often based on rock glacier inventories and/or topo-climatic variables such as potential incoming solar radiation and mean annual air temperature. Physically-based site-level models are used in combination with Regional Climate Models (RCM) for studies of long-term permafrost evolution (Farbrot et al., 2013; Scherler et al., 2013; Westermann et al., 2013; Marmy et al., 2016), similar to land-surface schemes used for hemispheric permafrost modelling (Ekici et al., 2015; Chadburn et al., 2015; Peng et al., 2016). Physically-based models are also used to explain the existence of low-altitude permafrost occurrences (Wicky and Hauck 2016) and to analyse the dominant processes for the future evolution of specific permafrost occurrences in the European mountains (Scherler et al., 2014; Fiddes et al., 2015; Zhou et al., 2015; Haberkorn et al., 2017; Lüthi et al. 2017). Simulations for different mountain ranges in Europe suggest an overall permafrost warming and a deepening of the active layer until the end of the century (see Fig. 5 for four examples from the Swiss Alps; similar simulations from Scandinavia are found in Hipp et al., 2012; Westermann et al., 2013, 2015; Farbrot et al., 2013).

The projected increase in permafrost temperatures is mainly due to the anticipated increase in air temperatures. The latter also causes the snow cover duration to decrease, thereby reducing the thermal insulation effect (Scherler et al. 2013, Marmy et al. 2016). However, in spite of similar trends in the above-mentioned RCM-driven permafrost studies, comprehensive regional scale maps or trend values for current and projected permafrost changes in Europe are not available to date. This is~~–~~ partly~~,~~ because ~~there is~~of ~~an~~ the insufficient ~~number of~~ borehole data ~~available~~, but mainly because of the large heterogeneity of the permafrost in European mountain ranges.~~,~~ ~~which~~ The latter strongly depends ~~strongly~~ on surface and subsurface characteristics (e.g., fractures/unfractured rock, fine/coarse-grained sediments, porosity, etc), microclimatic factors (snow cover, energy balance of the whole atmosphere/active layer system, convection in the active layer, etc.) in addition to classical topo-climatic factors (elevation, aspect, slope angle).

The largest and most important impacts related to permafrost thawing have yet to occur. Along with changes in precipitation, permafrost thawing is projected to affect the frequency and magnitude of mass wasting processes in mountain environments in general (IPCC, 2012~~; Gobiet et al., 2014~~). This is especially true for processes driven by water, such as debris flows (Stoffel and Huggel, 2012; Borga et al., 2014). Based on statistically downscaled RCM data and an assessment of sediment availability, Stoffel et al. (2011, 2014a, b) concluded that the temporal frequency of debris flows is unlikely to change significantly by the mid-21st century, but is likely to decrease during the second part of the century, especially in summer. At the same time, ~~the authors concluded that~~ the magnitude of events~~, however,~~ might increase due to larger sediment availability. This is particularly true in summer and fall when the active layer of the permafrost bodies is largest ~~and~~ allowing~~s~~ for larger volumes of sediment to be mobilized (Lugon and Stoffel, 2010). Accelerations of rock-glacier bodies might play an additional role (Stoffel and Huggel, 2012). Providing projections for future sediment availability and release for areas that are experiencing permafrost degradation and glacier retreat ~~remains challenging, and significant efforts are required if the associated uncertainties are to be reduced. This~~ is particularly important in the European Alps, where the exposure of people and infrastructure to hazards related to mass movements is high (Haeberli, 2013).

Finally, it should be noted that in contrast to glacier melting, permafrost thawing is an extremely slow process (due to the slow downward propagation of a thermal signal to larger depths, and additional latent heat effects). As permafrost in European mountains is often as thick as 100 m, a complete degradation is therefore unlikely within ~~the next~~this century.

2.4 Changes in meltwater hydrology

In spring, summer, and autumn, the seasonal snow and glacier ice are released as meltwater into the headwaters of the alpine water systems. Because of the ~~seasonal~~ temporally shifted release of water previously stored ~~water~~ as snow and ice and the significant surplus of precipitation compared to the forelands, mountains have often been referred to as “water towers” (Mountain Agenda, 1998; Viviroli et al., 2007). The meltwater contribution to streamflow ~~often~~ is important for millions of people downstream (Kaser et al., 2010). The Alps, in particular, are the water source for important rivers that flow into the North Sea (Rhine), the Black Sea (Danube) and the Mediterranean Sea (Rhône and Po); a comprehensive overview of the major alpine water systems is given in EEA (2009).

The most important seasonal runoff signal in the Alps is the melt of snow (Beniston, 2012)~~. This is~~, because the precipitation distribution is fairly even throughout the year, and ~~because~~ the amount of water retained in and released from reservoirs and lakes is only a small fraction of the total water volume (Schaefli et al., 2007; López-Moreno et al., 2014). Temperature-induced changes in streamflow (rain-to-snow fraction, seasonal shift of snowmelt, glacier runoff contribution) are generally better understood than the ones caused by changing spatio-temporal precipitation patterns (Blaschke et al., 2011). Nevertheless, understanding long-term trends in runoff requires an accurate estimate of the amount and distribution of snow accumulation during winter (Magnusson et al., 2011; Huss et al., 2014). The response of snowmelt to changes in air temperature and precipitation is influenced by the complex interactions between climatic conditions, topography and wind redistribution of snow (López-Moreno et al., 2012; Lafaysse et al., 2014).

Several national assessments have addressed the hydrologic changes in alpine river water systems, highlighting important regional differences (FOEN, 2012; APCC, 2014); these reports contain a wealth of specific literature. Regional peculiarities are the result of spatial differences in temperature and precipitation changes, although other factors such as local land-use changes or river corrections may play a role as well (EEA, 2004).

Compared to snowmelt, the total ice-melt volume from glaciers in the Alps is minor. At sub-annual scales, however, contributions from glacierized surfaces can be significant not only for the headwater catchments close to the glaciers (Hanzer et al., 2016), but also for larger basins where glacierization is small (Huss, 2011). This is particularly true during summer when specific runoff yield from glacierized areas is much higher than from non-glacierized ones (Farinotti et al., 2016). In a warming climate with retreating glaciers this also holds for annual scales, as additional meltwater is released from ice storage that has accumulated over long time periods.

Scenarios of changing streamflow~~s~~ affected by retreating glaciers in a warming climate have recently been ~~presented~~ developed in various physically-based, distributed modelling experiments (Weber and Prasch, 2009; Prasch et al., 2011; Hanzer et al., 2017). ~~Figure~~ Fig. 6 illustrates future streamflow~~s~~ of a currently highly glacierized catchment (roughly 35% glacierization) in the Austrian Alps. Even for the moderate IPCC RCP2.6 scenario (IPCC, ~~year~~2013) which corresponds roughly to the COP-21 “2°C ~~Policy~~policy”, the glacier melt contribution to runoff becomes very small by the end of the century. In the second half of the century, summer runoff amounts decrease strongly with simultaneously increasing spring runoffs. While in the RCP2.6 scenario the month of peak runoff remains unchanged, RCP4.5 and RCP8.5 project the peak to gradually shift from July towards June. Alpine streamflow~~s~~ will hence undergo a regime shift from glacial/glacio-nival to

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nivo-glacial, i.e., the timing of maximum discharge will generally move from the summer months to spring (Beniston, 2003; Jansson et al., 2003; Collins, 2008; Farinotti et al., 2012; Prasch et al., 2011; Hanzer et al., 2017). For many streams utilized for hydropower generation, this phenomenon can be superimposed by the effects of discharge regulation. The regimes in Fig. 6 indicate that (a) the effect of warming increases after the mid of the century for all scenarios, (b) this effect is of the same order of magnitude as the one of the choice of climate model, and (c) the timing of the maximum contribution of ice melt to streamflow – referred to as "peak water" – has already passed, i.e., the effect of declining glacier area ~~has already become larger than~~overrides the increasing melt caused by the rising temperatures. This moment mainly depends on the size of the glaciers, and hence ~~does not necessarily hold true for other headwater catchments~~can occur at different times in adjacent glacierized catchments (Hanzer et al. 2017). Until the middle of the ~~21st~~ century and for large scales, such as the entire Austrian region, the amount of the decrease of annual streamflow is expected to be small.

By 2100, the glaciers in the Alps may have lost~~e~~ up to 90% of their current volume (Beniston, 2012; Pellicciotti et al., 2014; Hanzer et al., 2017), and peak discharge is likely to occur 1-2 months earlier in the year (Horton et al., 2006) ~~according to~~depending on the realized carbon-emission scenario~~s~~. In Switzerland, a new type of flow regime (called "*pluvial de transition"* i.e., transition to pluvial) was introduced to classify such newly emerging runoff patterns (SGHL/CHy, 2011; FOEN, 2012). Regime shifts have long been recognized and can be interpreted as the prolongation of observed time series, the longest one in the Alps being available since 1808 for the Rhine river. Some investigations, however, show that annual runoff totals may change only little, as the overall change resulting from reductions in snow and ice melt, changing precipitation, and increased evapotranspiration is unclear (SGHL/CHy, 2011; Prasch et al., 2011). Other studies, instead, highlight the significance of future regime shifts in headwater catchments (Pellicciotti et al. 2014). Obviously, the complex interplay of snow- and ice~~-~~melt contribution to discharge in a changing climate, combined with the other processes determining the streamflow regime, and their scale dependencies are not yet fully understood. There ~~exists a~~is general consensus~~, however,~~ that only a few high-altitude regions of the Alps will continue to have a glacial regime in the long term (FOEN, 2012).

During the past 30 years, the flood frequency has increased in 20~~ ~~% of the catchmens in Austria, mainly in small catchments North of the main Alpine ridge (Blöschl et al., 2013). For Switzerland, Allamano et al. (2009) found increasing flood peaks over the course of the last century, caused by increasing air temperature and precipitation. However, Schmocker-Fackel and Naef (2010) showed that this increase is comparable to ~~to~~ known past periods of increased flood frequency, and apparent changes in flood frequency can also be attributable to construction measures in the river reaches and the loss of regulation reservoirs.

~~Future trends are hard to predict.~~ Despite the general trend towards drier summers, signals have been found that severe flooding might become more frequent due to heavy or extended precipitation events in the future (Christensen and Christensen, 2003; Stoffel et al., 2016). Whereas in summer floods might occur less frequently,~~,~~ the magnitude and frequency of winter and spring floods might increase since more frequent rain-on-snow (ROS) events can add to liquid precipitation if atmospheric temperatures continue to rise (Würzer et al., 2016). However, a cutoff beyond which ROS events will decrease with increasing temperatures is expected when the amount of snow becomes significantly reduced in response to higher air temperatures (Beniston and Stoffel, 2016).

Concerning droughts in the ~~Alpine~~ alpine region, periods of persistent and exceptional dry conditions have been identified by means of a monthly index as the late 1850s to the 1870s and the 1940s to the early 1950s by van der Schrier et al. (2007). In the future, drought conditions in the ~~Alpine~~ alpine region are expected to increase due to ~~the~~ higher air temperatures, ~~higher~~ larger evapotranspiration with pronounced water use, and less precipitation (Calanca, 2007). The regions South of the Alps thereby ~~seems to be~~are particularly affected. An overview of related references is given in Gobiet et al. (2014).

~~Finally, climate change also effects the seasonal duration of lake ice and spring break-up dates (George, 2010), with an overall trend to earlier thawing of one week per century, approximately (Livingstone, 1997). The timing of the break-up is strongly correlated with local and regional surface temperatures, determined to a large extent by synoptic-scale meteorological processes. From a hydrological perspective, changes in lake ice thawing are important only at the local scale. However, in many regions such as St. Moritz/Engadin (Switzerland), the lake ice coverage during the winter months is an important landscape feature for tourism.~~

2.5 Impacts on downstream water management

Sectors that are directly dependent on alpine headwaters will need to adapt to the changes outlined above. Different scenarios therefore need to be considered, depending on how governance will cope with water-related conflicts that may arise from changes in water demand (Nelson et al., 2007; Beniston et al., 2011).

2.5.1 Agriculture

Shifts in agricultural production are expected with climate change (Jaggard et al., 2010; Gornall et al., 2010). Most studies conducted in the alpine regions project reduced soil water content as a result of increasing evaporation. This will lead to increased water demand for irrigation (Jasper et al., 2004; Schaldach et al. 2012; Riediger et al. 2014), and will add to the changes in water availability resulting from changing snow and glacier melt (Smith et al., 2014). The effects of more frequent droughts will affect both croplands and grasslands. In Switzerland, the latter cover around 75% of the agricultural land and sustain domestic meat and dairy production (Fuhrer et al., 2006). The majority of crops currently cultivated in the Alps have been shown to be very sensitive to precipitation deficits in the growing season (Fuhrer et al., 2006; Smith et al., 2014). High irrigation demands will thus likely put additional pressure on rivers, especially small ones as they suffer more from inter-annual variability (Smith et al., 2012). Together with generally decreasing summer discharge, this will ~~create~~ more frequently create low flow conditions which largely favour increasing water temperatures in streams with negative consequences for water quality and the aquatic fauna. Long-term water-management strategies will be important to face these challenges and to ensure that future agricultural water needs can be met (Riediger et al., 2014).

2.5.2 Hydropower

Climate change is a key driver in ~~power~~ electricity markets, as both electricity production and demand are linked to meteorological ~~variables~~ and, on the long term, on climate conditions (Apadula et al., 2012). As a consequence of earlier snowmelt and reduced water discharge from glaciers, hydropower production potential is expected to increase in winter and spring, and to decline in summer (Hauenstein, 2005; Kumar et al., 2011). Currently, energy demand is higher in winter than in summer, but this may change as rising summer temperatures increase energy requirements for the cooling of buildings (López-Moreno et al., 2008, 2011; Gaudard and Romerio, 2014). A study conducted for the Mattmark dam in the Swiss Alps and for the Val d´Aosta, Italy (Gaudard et al., 2014) revealed that peak hydropower production has so far not been affected by climate change. This is possibly the result of the large existing reservoir volumes~~,~~ which ~~are able~~enable to offset seasonal changes (Farinotti et al., 2016). Indeed, it has been suggested that no urgent adaptation of the hydropower infrastructure will be required in Switzerland within the next 25 to 30 years (Haunstein, 2005). Reservoir management, however, will become more challenging as a consequence of higher fluctuations in electricity demands linked to the intermittent production of new renewable energy sources such as photovoltaic~~,~~ and wind power, or biogas (Gaudard and Romerio, 2014). Furthermore, the inter-annual fluctuations in water availability are expected to increase (Gaudard et al., 2014). Run-of-river power plants are expected to be less vulnerable to climate change, as they are usually installed on streamflows with small hydrological fluctuations (Gaudard et al., 2014). Hydropower plants can also be effective in attenuating floods (Harrison and Whittington, 2001). Additional safety concerns include the melting of permafrost and the possibility of more frequent heavy rainfall, resulting in both more frequent slope instabilities and potential flood waves that may endanger power plants (Peizhen et al., 2001; Schwanghart et al., 2016). Increased sediment loads from deglacierized surfaces may additionally affect power generation, in particular by affecting the wear of infrastructure or the silting of storage volumes (Beniston, 2003).

2.5.3 Tourism

Increasing air temperatures are ~~anticipated~~ expected to result in shorter skiing seasons and a shift of the snow line to higher elevations (Abegg et al., 2007; Steiger, 2010). This will likely lead to smaller number of visitors and reduced revenues, and thus have important economic impacts on alpine winter tourism. Generation of artificial snow is designed to buffer the impact of inter-annual variability of snow conditions, and is increasingly considered as an adaptation measure in alpine ski resorts (Uhlmann et al., 2009; Steiger, 2010; Gilaberte et al., 2014; Spandre et al., 2016). In Switzerland, ski slope areas employing artificial snow-making equipment have tripled (from 10 to 33%) from 2000 to 2010 (Putz et al, 2011). In the French Alps, 32% of the ski slope area was equipped with snow-making facilities in 2014, and this proportion is likely to reach 43% by 2020 (Spandre et al., 2015). In Austria, this share is about 60%, mainly due to the lower average elevations of the Austrian ski areas, and in the Italian Alps, almost 100% of the ski areas are equipped (Rixen et al., 2011). Water consumption for tourism in some Swiss municipalities is high compared to other uses. A study focusing on three tourism destinations in Switzerland, for example, found this consumption to be equivalent to 36% of the drinking water consumption (Rixen et al., 2011). Water and energy demands of ski resorts will increase, which may in turn lead to higher prices for

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consumers (Gilaberte et al., 2014). Also, summer mountain resorts could be affected by water shortages in the future, thus calling for ~~improved~~ adapted water management (Roson and Sartori, 2012).

3 Challenges and issues for cryosphere research in European mountains

In the research on the phenomena, ~~occurence~~occurrence, and processes of the European mountain cryosphere, manyfold challenges remain for future work. In the~~is~~ following ~~part of the paper~~, we ~~want to select~~present four field~~key component~~s that we consider to be crucial for future research and major remaining ~~of the identifiedse~~ challenges ~~that we have identified~~: (i) the modelling of the cryosphere, (ii) cascading processes, (iii) the significant role of precipitation and its phase changes, and (iv) problems and issues related to existing or missing observational data. These four components are mutually connected in the research process. ~~Their improvement~~Appropriate answers and solutions to these challenges and issues will repr~~b~~esent a significant step towards improved understanding and predictability of the cryosphere in the future. ~~T~~In the following sections ~~also make~~ an attempt is made to outline some promising paths and approaches to address some of the identified issues.

3.1 Modelling of the cryosphere: spatial scales and physical processes in complex terrain

In historical mode, the models for the simulation of snow, glaciers and permafrost are using meteorological station observations or grids derived from such observations as forcing and input data. For future scenario simulations, ~~the~~ land surface models use the output of Regional Climate M~~m~~odels ~~which still are limited by the coarse representation of topography~~. However, there is a discrepancy in scale and a limitation in validity for RCM output and the level of model complexity that can be employed for the assessment of processes at the land surface. This implies, e.g., inaccurate representation of altitudinal temperature gradients and a crude separation of the precipitation phase, since convective processes are inaccurate~~dequate~~ly represented or oversimplified (Wilcox and Donner 2007, Chen and Knutson, 2008; Wehner et al., 2010, Sillmann et al., 2013). Future improvements in ~~the~~ climate simulations are required in the domains of increased horizontal resolution (Boyle and Klein, 2010), and in the refinement of the representation of vertical processes, including convection and cloud microphysics (Kang et al., 2015). Hence, RCM output not only has to be downscaled, but also bias corrected prior to ~~their~~ its use. These procedures still ~~produce a lot of~~introduce large uncertainty for ~~everything that follows~~subsequent steps in the modelling chain~~;~~ thus ~~there is hence still a lot to do in~~calling for substantial improvements~~ing~~ both in the process representation in ~~the Regional Climate Models~~RCMs, and in their appropriate spatial resolution for mountain regions. ~~Still, there is a discrepancy in scale and a limitation in validity between forthe RCM output and the level of model complexity which is possiblethat can be employed for the assessment of processes at the land surface.~~

The increasing abundance of field data helps refining our understanding through direct data-based inference (Diggle and Ribeiro, 2007) and assimilation techniques (Leisenring and Moradkhani, 2011). While such approaches are common to various fields of environmental sciences (e.g., Banerjee et al., 2003), the specificities of cryosphere data require adaptations of the general framework of statistical modelling. Cryosphere-specific difficulties include the existence of embedded spatial

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scales (Mott et al., 2011), strong vertical gradients (e.g., temperature, wind speed, phase of precipitation, etc.), and the non-linearity linked phase transitions (Morán-Tejeda et al., 2013). Taking maximum advantage of data sets of increasing size, variety and quantity also ~~involves proceeding in~~requires the parallel ~~with the~~ development of adapted and comprehensive statistical models (Gilks et al., 2001; Wikle, 2003; Cappé et al., 2005). The easiest way to address spatio-temporal data is to separate space and time effects (Cressie and Wickle, 2011). However, temporal evolutions at small spatial scales cannot be inferred ~~in~~ this ~~manner~~way. Regional climate change interacting with topography has, for example, resulted in different evolutions of avalanche activity over different parts of the French Alps (Lavigne et al., 2015). On this basis, other applications of non-separable spatio-temporal covariance models have great potential (Gneiting et al., 2007; Genton and Kleiber, 2015) ~~have great potential~~.

3.1.1 Snow modelling

Snow as a mostly non-permanent interface between the earth's surface and the atmosphere features a variety of ~~small- and large-scale~~ physical processes at all spatial scales, which significantly influence the mass and energy exchange at the surface. Small-scale processes include water transport in snow and firn (Würzer et al., 2016a, Wever et al., 2014; Wever et al., 2016), phase changes (i.e. melt, ~~refreeze~~refreezing, sublimation and condensation), drifting and blowing snow, as well as metamorphism (e.g., Aoki et al., 2011; Pinzer et al. 2012). While the mechanistic point-scale understanding of these processes is rapidly increasing (Wever et al., 2014), ~~the~~ a challenge arises from quantifying their effect at larger scales, i.e., ~~upscale~~ upscaling from the point-scale to the catchment or even continental scale. To date, such up-scaling techniques are missing to a large extent. Examples of ~~the~~ linking ~~between~~ large- and small-scale effects are the often significantly altered snow distribution after a storm (Lehning et al., 2008; Schirmer et al., 2009) or the change in snow albedo after a melt event. These effects (and many others) are insufficiently represented in large-scale hydrological, weather and/or climate models, yet most likely would lead to significant ~~changes~~ refinements in model predictions. The spatial distribution of small-scale snow properties is also essential for the correct interpretation of satellite remote sensing signals. For example, ice-lenses or the liquid water content in snow heavily influence the microwave backscatter (Marshall et al., 2007) ~~, which is~~being ~~the fundamental~~ ~~basis for many satellite remote sensing products~~.

For snow modelling at the point scale, ~~there are~~ two widely used, physically based models exist, namely ~~the French model~~ CROCUS (Vionnet et al., 2012) and ~~the Swiss model~~ SNOWPACK (Lehning et al., 1999). Nevertheless, many of the processes ~~used~~described in these models, such as ~~— including~~ metamorphism and mechanical properties for example ~~—~~still have a high degree of empirical parameterization (Lehning et al., 2002). The main challenge for snow model development at this smallest scale is the formulation of a consistent theory for snow microstructure (Krol and Lowe, 2016) and its metamorphism.

The catchment scale is mostly employed in hydrological applications (Kumar et al., 2013) ~~and~~. ~~snow~~ Snow models of ~~varying~~ different complexity levels are used for ~~that~~ this purpose (Essery, 2015; Magnusson et al., 2015). P~~A p~~rincipal challenges at this scale ~~is~~ are (a) to distinguish between uncertainties introduced by the model structure and uncertainties related to the input data (Schlögl et al., 2016), and (b) to develop ~~portable~~transferable, site-independent ~~models~~ model formulations ~~that can be used~~ without the need of calibration. The latter is particularly important for reliable predictions of climate change effects (Bavay et al., 2013) and for model applications to ungauged catchments (Parajka et al., 2013).

Large-scale models use relatively simple, parametric snow schemes, as these require only a small set of ~~few~~ input variables and are computationally inexpensive (Bokhorst et al., 2016). Current numerical weather prediction systems generally use oversimplified single-layer snow schemes (IFS documentation, 2016; GFS documentation, 2016). Only in some rare cases do these models explicitly represent the liquid water content within the snowpack, or incorporate a refined formulation for snow albedo variability (Dutra et al., 2010; Sultana et al., 2014). Climate models generally resolve the diurnal and seasonal variations of surface snow processes (i.e., surface temperature, heat fluxes) while they simplify the treatment of internal snow processes such as liquid water retention, percolation and refreezing within the snowpack (Armstrong and Brun, 2008; Steger et al., 2013) and the evolution of the microstructure due to snow metamorphism. Future research ~~will need to~~should clarify the degree of complexity required in snow schemes when ~~they are~~ integrated in large-scale climate models (van der Hurk et al., 2016).

3.1.2 Permafrost modelling

Similar challenges that need to be addressed in permafrost modelling include: (1) static large-scale permafrost distribution models, (2) high-resolution and site-specific permafrost evolution models and (3) transient hemispheric permafrost models or land-surface schemes of RCM/GCMs. Current state-of-the~~-~~-art permafrost distribution models (e.g., Gisnås et al. 2017) are ~~forced~~ not only forced by statistical and topo-climatic variables such as mean annual air temperature and potential incoming radiation, but also by operationally gridded data-sets of daily air temperature and snow cover. Statistical distributions of snow and other surface characteristics (soil type, roughness) allow for the representation of sub-grid variability of ground temperature (Gubler et al. 2011, Gisnås et al. 2014, 2016). However, the lack of spatial data on subsurface properties (thermal conductivity, porosity, ice content, etc.) prohibits a refined assessment of the permafrost distribution on catchment or local scales, at least for the discontinuous permafrost zone. Acquiring spatial data on subsurface properties as input and validation data is hereby one of the greatest current challenges in permafrost research (e.g., Hauck 2013, Etzelmüller 2013, Gubler et al. 2013).

Model inter-comparison studies ~~with~~ using uncalibrated model set-up~~s~~ show~~,~~ that due to the abundance of permafrost-relevant processes in the atmosphere~~,~~ and at the snow~~/~~ surface and subsurface, a detailed simulation of permafrost processes on local scales is impossible without the availability of surface and subsurface data (Ekici et al. 2015). This results from the difficulty of simulating phase changes in permafrost and corresponding latent heat transfer correctly~~,~~ which becomes more ~~important~~ relevant with increasing uncertainty regarding the initial ground ice content.

Challenges in regional or hemispheric permafrost modelling therefore include not only numerical aspects or process-oriented model improvements, but also data availability and up-scaling issues (Fiddes et al. 2015, Westermann et al. 2015). Most land surface schemes of current GCM's and RCM's now have soil freezing schemes included (e.g., McGuire et al. 2016), however, neither reliable ground ice content maps as input nor ground temperature maps for validation exist. Combined with the need of reliable snow, soil moisture and vegetation data, this lack of deeper subsurface information poses the largest uncertainties in current and future permafrost temperature and spatial distribution estimates.

3.1.3 Glacier modelling

To increase the accuracy of glacier mass balance and runoff estimates, the distribution of ice volume~~s~~ and ice thickness ~~distributions is~~ is of primary importance. Glacier overall volume and average thickness can be estimated from their surface area using scaling approaches (e.g. Bahr et al., 1997). However, such approaches do not provide the ice thickness distribution, which together with the surface mass balance controls the ice dynamics and therefore the response-time of the glaciers to ~~a~~ climate forcing. As it is currently impossible to measure ice thickness distributions of all glaciers individually, model applications are necessary. Several existing glacier models have been compared within the Ice Thickness Models Intercomparison eXperiment (Farinotti et al., 2017), revealing that results largely depend on the quality of the input data (glacier outline, surface elevation, mass balance or velocities). New high-resolution satellite images make such input data available, thus opening the way toward improved future global estimates of glacier thicknesses.

Another challenge in glacier modelling is the use of approaches that explicitly consider ice dynamics for glacier evolution. Jouvet et al. (2009) showed that 3D full-Stokes models representing ice flow without approximation can be applied if the required input data are available (e.g., glacier thickness, surface velocities), but such applications at the regional scale still require simplifications (Clarke et al., 2015). For estimating future glacier evolution, ice dynamics models need to be coupled to adequate representations of glacier surface mass balance. A key issue in this respect is the modelling of future surface mass balance at the mountain-range scale. The Glacier Model Intercomparison Project (Glacier-MIP, www.climate-cryosphere.org/activities/targeted/glaciermip) assesses the performance of regional to global-scale glacier models to foster the improvement of the individual approaches and to reduce uncertainties in future projections. There are uncertainties in future changes of meteorological variables and in their downscaling at a spatial scale compatible with glaciers. Some studies use degree-day approaches for long-term simulations of glacier-wide surface mass balance (Réveillet et al., 2017), or also account for potential radiation (Hock, 1999). However, with a ~~shift~~ change in timing and relative magnitude of energy fluxes at the glacier surface, calibrated degree-day factors ~~might~~ are likely to change too in the future. Application of process-based models ~~that are~~ able to resolve the full energy balance are thus required (Hanzer et al., 2016), but the accuracy and resolution of the input data needs to be improved. ~~A focus~~More emphasis on modelling winter mass balance and the spatial distribution of snow accumulation is also needed (Réveillet et al., 2017). Additional studies should assess the impact of supraglacial debris and related feedbacks on the surface energy balance (Reid and Brock, 2010). This is particularly important as many glacier tongues tend to become increasingly debris covered as they shrink. Feedback effects of black carbon and aerosols deposition on the glacier surface is also subject of study (Gabbi et al., 2015). Finally, more research on glacial sediment transport and erosion is needed as glacier retreat exposes large amounts of unconsolidated and erodible sediments that might – when entrained – represent a hazard downstream, or reduce the efficiency of hydropower plants (Lane et al., 2016).

3.1.4 Uncertainty in the modelling

~~As outlined throughout the manuscript, p~~Predicting the future evolution of cryospheric components is in many respects challenging. On the one hand, these challenges stem from the incomplete understanding of the physical processes leading to given changes, and from the lack of more comprehensive data sets~~,~~. ~~on~~ On the other hand, ~~future~~ predictions are intrinsically affected by a range of uncertainties. Adequately evaluating and communicating such uncertainties is all but a trivial task, ~~and this is~~ both because the interplay between individual systems can be complex, and because end-users of projections are typically uncertainty-adverse. Outside the scientific community, “uncertainty” and “error” are two concepts often not sufficiently distinguished. This can lead to important misunderstanding and misinterpretations. Improving the way uncertainties are communicated is especially important when presenting scientific results to policymakers or stakeholders, as this can significantly affect the level of trust assigned to a particular finding.

3.2 Cascading processes and process chains

The European mountains are ~~a~~ very dynamic systems and particularly sensitive to external changes (Bender et al., 2011), especially to climate warming and precipitation extremes (IPCC, 2013). An increase in air temperature ~~will likely~~ impliesy enhanced melting of snow and ice, which in turn can lead to glacier recession and glacier debuttressing, an acceleration of creep in perennially frozen talus with high ice contents and decreasing stability of steep, deeply frozen rock walls (Haeberli, 2013). Under certain conditions, new lakes will form in depressions left by receding glaciers (Haeberli and Linsbauer, 2013). The largest and most important impacts related to ongoing glacier wasting and permafrost thawing have yet to occur, with likely and potentially drastic impacts on the frequency and magnitude of mass wasting processes (such as rockfalls, rockslides, icefalls, debris flows) in mountain environments in general (IPCC, 2012). In high mountain environments, where relief energy is quite substantial, the occurrence of a single process can lead to a chain reaction or cascading process, thereby amplifying the magnitude and runout distance of the resulting process. In the case of new lakes ~~occurring~~ forming underneath hanging glaciers or at the foot of oversteepened and unstable rock slopes (Haeberli et al., 2010), for instance, mass movements into the lake could generate substantial flood waves (Worni et al., 2014). These waves could overtop the lake dam, form a breach (in the case of moraine or earth dams) and cause a downstream glacier lake outburst flood (GLOF) with discharges that ~~are~~ could potentially be much larger than ~~the usual~~ rainfall-induced floods.

An~~One~~ other example of a process chain is ~~related to~~ the ~~recent~~ 2017 rockfall at Piz Cengalo (Grisons, Switzerland), where its impact on a~~n assumed~~ debris-covered glacier has ~~produced~~ released sufficient liquid water to transform part of the rockfall mass into debris flows. The multiple debris flows, ~~formed out of~~resulting from the August 23, 2017 rockfall, have reached the village of Bondo where they caused substantial damage to an area that would have remained unaffected in the absence of an amplifying chain reaction. Other cascades include the assumed liquefaction of avalanche snow into debris flows in the Swiss Alps in October 2011 and during an intense rain-on-snow event (Moran-Tejeda et al., 2015), with massve

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The massive melting of glaciers and the increasing instability of permafrost bodies will possibly lead to the occurrence of mass movement events beyond historical experience, both in terms of frequency and magnitude (Stoffel and Huggel, 2012). If these processes occur as chain reactions, their negative consequences can become even much more severe devastating for the downstream localities and populations. For the time being, however, and as extreme events are scarce by definition, their description remains either theoretical or anectdotical (i.e. limited to the description of individual case studies) or theoretical. Modeling tools can be used to assess the hazard of potential process chains as observed in the case of GLOFs or in 2017 at Piz Cengalo, and process modeling can provide insights into such complex processes that remain difficult to observe in nature. Although a number of numerical models have been developed and applied to simulate different types of extreme flows, such modelling still faces challenges stemming from a lack of process understanding, difficulties in measuring extreme flows for calibration (Worni et al., 2014). In addition, individual models are better capable to represent single processes than process chains, and therefore the interactions and interdependencies between the individual processes involved still are under-represented in the modelling. not normally able to represent process chains, but single processes, and cannot therefore catch interactions and interdependencies between the individual processes involved. Much more and much larger efforts are still needed to improve our understanding of ongoing and future climate changes and related mass movements, and how these can evolve into cascading processes.

3.3 Estimating liquid/solid precipitation in complex terrain

Precipitation and its phase plays a key role in all cryospheric processes,: it determines the height level of the snowline, the amount of snow accumulation or the liquid water contribution to a snow-pack or a glacier, and it significantly determines the boundary conditions and energy transfer to or from a permafrost body beneath the land surface. At all scales, liquid rain instantaneously directly contributes to the storage or the direct runoff of water, whereas a fresh snowfall creates a temporary water storage and significantly reduces the energy input into the surface and as such immediately reduces anytherefore potential melting processes. The threshold effects connected withrelated to the phase transition of precipitation make its assessment and understanding indispensible for improved research on the mountain cryoshpere, though many uncertainties in its quantification, spatial and temporal distribution, and phase detection still exist.

At high elevations, large uncertainties affect the estimates of solid and liquid precipitation (Rasmussen et al., 2012). These uncertainties mainly arise from two facts: (a) The low density of precipitation gauges at high elevation (only 3% of homogenized stations worldwide are located above 2000 m a.s.l., and less than 1% above 3000 m a.s.l.; Pepin et al., 2015).; Wwhile areas >3000m comprise only a small fraction of the European landscape, it is exactly these regions where many cryospheric processes are located, e.g., permafrost or perennial snow cover. (b) The large biases in precipitation observations due to undercatch at high elevations is ion the order of 30% (Adams and Lettenmeier, 2003; Yang et al., 2005) and is

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particularly large for solid precipitation. This is because solid precipitationit is particularly influenced by wind, and perturbations due to icing and riming. Efforts are currently ongoing to address these problems (e.g., Solid Precipitation Intercomparison Experiment, WMO), but reliable references for ground truth measurements are still are not available.

While a precise quantification of precipitation and its spatial and temporal distribution are is crucial for cryospheric process research, large uncertainties also exist in the spatial and temporal distribution of precipitation from the point scale to larger areas due to its non-uniform nature, even if many observations exist. The spatial distribution of precipitation is not only is determined by synoptic systems but is also strongly affected by topography (Mott et al., 2010). For snow, post-depositional transport such as creep, saltation, suspension, and avalanching additionally influence the spatial distribution. How these processes may change as a response to future modifications in local and synoptic wind patterns is presently poorly understood. Remote sensing methods such as terrestrial and airborne laser scanning or radar have been successful in quantifying solid and liquid precipitation. Recent progress in measuring snow distribution in mountains (Grunewald et al., 2010; Kirchner et al., 2014) has allowed for a better understanding of typical distribution patterns of Alpine alpine water resources (Grunewald et al., 2014), as well as for making establishing a link toquantifying respective precipitation amounts (Scipion et al., 2013; Mott et al., 2014). The results have highlighted that even in highly instrumented mountain ranges such as the Alps, total precipitation yet is very poorly quantified. The combination of weather modelling with advanced data assimilation techniques, including precipitation radar data, new measurement options with more classical ones such as precipitation radar will lead to a more complete understanding of precipitation amounts in high mountains.

A requirement fFor future climate model scenario modelling are, continued efforts will have to be continuedin to increasing the modele resolution to a degree that allows for improved simulation of precipitation processes ("convection resolving", see 3.1). This will represent a first and very important step towards a complete picture of the changes in amount, distribution and phase of future patterns of precipitation.

3.4 Observational data: access, availability, quality, spatial and temporal distribution

Availability of observational data is a key for detecting, understanding, and projecting any environmental process (Lehning et al., 2016; Beniston et al., 2012; Quevauviller et al., 2012; Lehning et al., 2016). For cryospheric processes, at least two specific issues arise. First, several cryospheric processes – such as glacier retreat or permafrost thaw— are only noticeable over relatively long time scales (several years to decades), particularly which makesstressing the need for long-term data time series with homogeneous quality particularly strong. Only this way, in fact, can long-term trends be distinguished from inter-annual variability – a distinction that is crucial if reliable future porjections are to be made. However, only few long-term monitoring programs comprising meteorological, hydrological and/or glaciological data collection exist (Strasser et al. 2017). Second, ground-based observations of the crysosphhere are affected by the difficulties in accessing the regions of interest (Klemes 1990). Logistical challenages and related costs are about the main reasons introducing a bias in the availability of cryosphere -related observations. Even in European countries disposing of reasonable financial and the relatively wealthy and infrastructural resourcesly strong Countries affected by the European mountain cryosphere, in fact, have such observations have a bias towards low and mid elevations, as well as towards easily well accesible regions. This also is true for applies also to related environmental variables as well, including in particular meteorological variables in particular (Orlowsky and Seneviratne, 2014). Substantial efforts and new technical solutions are required to improve the spatial coverage and representativeness of the variables of interest at the high elevations of the European mountains.

The high logistical and monetary costs of acquiring data at high elevations also explains why many cryosphere related data across Europe still have restricted ownership. The consequences include lack of data, impossibility limitations toof accessing existing data, delays in obtaining them, and duplication of data-collection efforts. The current push for more open-data policies of major funding agencies (e.g., EC, ERC, NERC, ANR, DFG, SNF) has is therefore is to bevery welcomed. Some examples for successful data portals related to cryosphere are the Global Earth Observation System of Systems (GEOSS), a data catalogue of a partnership of more than 100 states and the European Commission, the National Snow and Ice Data Center (NSIDC), the World Glacier Monitoring Service (WGMS), the International Network for Alpine Research Catchment Hydrology (GEWEX-INARCH) and the Swiss Open Support Platform for Environmental Research (OSPER). The recent establishment of a Global Cryospheric Watch program at the World Meteorological Organization (WMO) facilitates the exchange of cryospheric data. To be successful, however, the definition of common standards for different data types is required, as well as adequate mechanisms for as is an adequate mechanisms for rewarding and acknowledging groups and agencies investing in field-data collection.

An effort towards rigorous open-data policies for the moutain cryosphere seems particularly promisingimportant, since. This is because mountain topography is often introduces used to define sharp administrative boundaries (such as cCountry borders), , and the latter because such boundaries can introduceoften impose artificial limitations in spatial coverage. As an exampleFor instance, large-scale studies on snow cover changes based on in-situ measurements barely exist, since such measurements are typically acquired from individual institutions or authorities, falling under separate jurisdictionssubject to different jurisdictions, competences, practices or priorities. The study by Marty et al. (2017b) is an exampleexception, covering large parts of the Alps regardless of administrative boundaries (see Fig. 1). Rather than adhering to administrative borders, however, environmental data should sample regions defined on the base of geomorphological, topographical, and climatologic considerations.

4 Conclusions

This review has summarized and highlighted prospects and challenges for research on the cryosphere as it responds to past, current, and future changes in climate in the fields of mountain snow, glacier ice and permafrost in European mountain regions. The paper has attempted to address the current state of knowledge in terms of the observed evolution of the European mountain cryosphere and associated impacts. By the end of the century, the components of the mountain cryosphere will have changed to an extent that will significantly impact the landscape, hydrological regimes, water resources, built infrastructure in mountain areas and even downstream in the lowlands, entailing a wide range of soico-economical consequences. – notably on water resources, ecosystems and the services provided by these resources.These impacts will have a bearing on ecosystems and the services provided by these resources, and on -a number of economic sectors, including hydropower, agriculture, tourism, management of natural hazards, and adaptation to climate change.

A catalog of challenges for future cryospheric research has been identified, focusing on as-yet unresolved issues of knowledge gaps, high-resolution modelling including understandable communication of uncertainty for scientists, politicians and stakeholders, cascading mass movement physical processes or process chains, quantification and spatio-temporal distribution of precipitation as key variable of the future climate, as well as the observational data availability and access, and quantification of associated risks and extreme events, and communication of uncertainty.. These issues have an obvious effects on our capability of projecting future shifts in the mountain cryosphere, and the impacts that these shifts are likely to generate. The latter will have a bearing on the viability of a number of economic sectors, including notably hydropower, agriculture, and tourism, management of natural hazards, and adaptaion to climate change.

The list enumeration of principal challenges within the cryosphere domains snow cover, glaciers and permafrost, presented in Section 3 includes both issues specific to a subdiscipline, as well as issues generally valid to the several of these components of the mountain cryosphere as well as specific to a subdiscipline. The biggest overall challenge, however, is however that the European mountain cryosphere is expected to undergo drastic changes in the next few decades as a result of anticipated climate change and its consequences. Most likely, by the end of the century, the components of the mountain cryosphere will have changed to an extent that will significantly impact, the landscape, hydrological regimes, water ressources, built infrastructure in mountain areas and even downstream in the lowlands, entailing a wide range of soico-economical consequences. European mountains will have a completely different appearance, most glaciers will have disappeared at low and mid-range altitues, and the (currently still relatively large) valley glaciers will be characterized by significant retreat and mass loss. Seasonal snow lines will be found at much higher altitudes, and the snow season will be much shorter than today, with a related shift from solid to liquid precipitation due to increased air temperatures. These changes in snow and icemelt will cause a shift in the timing of discharge maxima and a transition towards pluvial regimes, with drastic impacts on the seasonality of water availability from high altitude regions and consequences for water storage and management in reservoirs for drinking water and hydropower producgeneration. Whereas an upward shift of the treeline and expansion of vegetation can be expected into current periglacial areas, the disappearance of permafrost at lower altitudes and its warming at higher elevations will likely result in mass movements and process chains beyond historical experience.

- The most striking prominent features of the future European mountain cryosphere are namely: In addition, Significantly shorter snow season
- Shift of the seasonal snow line to higher altitudes, as a consequence of a
- Shift from solid to liquid precipitation due to increased air temperatures
- Shift in the timing of discharge maxima and transition towards other hydrological fluvial regimes
- Disappearance of most small glaciers at low and mid-range altitues
- Significant retreat and mass loss of the (currently still relatively large)larger valley glaciers
- Formation of new glacial lakes in the areas where of glaciers retreated

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- ~~Drastic impacts on the seasonality of water availability from high altitude regions and~~
- ~~Consequences for water storage and management in reservoirs for drinking water and hydropower production~~
- ~~Upward shift of the treeline and expansion of vegetation into current periglacial areas~~
- ~~Melt and disappearance of permafrost in many areas and in parallel to retreat to high altitues, resulting in~~
- ~~Slope instabilities, rockfalls, land slides and avalanches and other natural hazards~~

~~Despite being exhaustive, the above liste gives evidence that the expected changes are fundamental for high mountain areas as well as for large downstream areas with important consequences and implications resulting from these significant changes in the cryosphere components. Also, it seems to be clear that the Alpes and other European mountain regions will not be the same in the future as known and mananged at present.~~

For future cryospheric research ~~has to be~~the community of scientists can build upon the awareness of these expected changes and develop targeted strategies to precisely quantify the occurring changes as well as their rate, ~~and develop~~as well as approaches capable to address and mitigate these changes. Respective efforts are required ~~both~~ in the measurement and monitoring as well as in the numerical modelling domain. Current climate change scenarios relatively reliably predict ~~relatively reliably~~ the evolution of the components of the European cryosphere ~~roughly~~ until 2050. In the second half of the century, the further development will depend on potential measures to limit or to mitigate climate change. Precipitation thereby is a fundamental variable in future climate and in its prediction. Wh~~il~~ereas temperature predictions are rather clear and mainly depend on the employed emission scenario, there is much more uncertainty regardings the evolution of the quantity, timing and distribution of precipitation. ~~This is why this review has focused also particularly on this key input variable for most cryosphere components (Section 3.3).~~ In fact, driven by changes in air temperature, the phase (and the amount) of precipitation has a signigicant impact on the state of cryosphere components in the future.

Besides the emphasis on challenges in the modelling domain ~~(Section 3.1)~~ and ~~on~~ cascading mass movement ~~physical~~ processes and process chains~~(Section 3.2)~~, this paper has also devoted ~~much~~ attention to data issues ~~(Section 3.4)~~. Indeed, there are numerous limits to data availability, related to spatial and temporal sparseness, and restricted access. Financial and institutional barriers, as well as non-harmonized data policies add to the problem. Mountain cryosphere research urgently needs open access data of high quality for both understanding the functioning and evolution of the various elements in specific regions, and assess future changes in snow, glacier ice and permafrost ~~via~~ by means of modelling.

Access to physical models using high spatial and temporal resolution and capable to capture the changes of a cryosphere in transition as a function of greenhouse-gas emissions is essential to furthering our understanding of feedbacks between the atmosphere, the hydrosphere and the cryosphere. Global climate models have ~~seen~~ been increased in their resolution ~~increase~~ in recent decades, but much of the information still remains too coarse for most mountain cryosphere research. Physically-based, nested global-to-regional modelling techniques can provide adequate data for atmosphere-cryosphere studies, and much effort has been invested in increasing the spatial resolution and process representation in Regional Climate Models. However, ~~such~~ simulation results are highly-dependent on the initial and boundary conditions that drive the coupled models, and errors in these conditions obviously propagate into the model ~~solutions~~chain.

Finally, communicating research results on climate and cryospheric science is a challenge ~~that also needs careful consideration~~in itself. The ~~importance and~~ imminence of climatic change ~~is~~ generally is more convincing to a lay audience when changes become visible. A prominent example is the retreat of mountain glaciers, which can convincingly be brought to the public through photography portraying glacier evolution over time. In this sense, climate-induced changes in the cryosphere enable a unique and ~~convincing~~ effective form of communication to the public and to policymakers, and more effort should be dedicated to illustrate how these changes can ~~impact~~ affect ~~upon~~ water resources, mountain ecosystems, natural hazards, and thus a wide range of economic activities. Elevation-dependency and regional patterns of the phenomena related with a cryosphere adapting to rapidly changing climatic conditions is an important issue for future comparative research.

By highlighting the impacts of a changing cryosphere as climate evolves, this review has attempted to emphasize the central role of the cryosphere as a key element of environmental change in high mountains. ~~To respond to the changes in climate in coming decades, t~~There will ~~clearly~~ be an increasing need for robust knowledge on the cryosphere in Europe's mountainis to develop appropriate adaptation strategies ~~based on robust knowledge~~to respond to the changes in climate and its effects in the coming decades.

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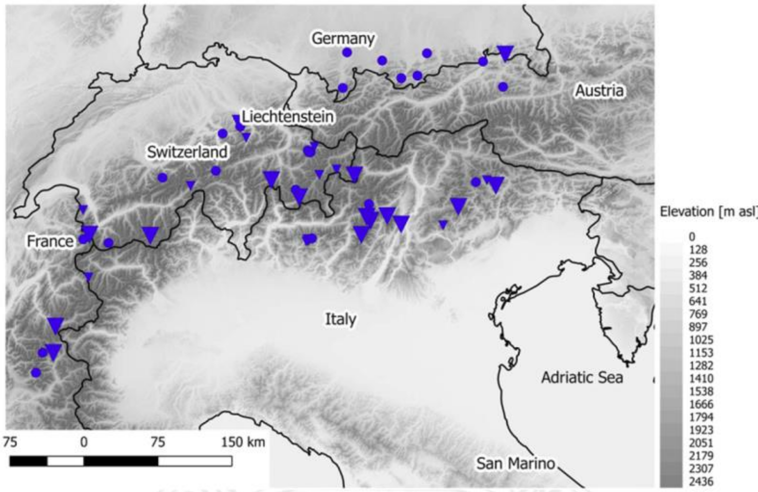

Figure 1: Geographical distribution of the 45 year trend (1968-2012) for April 1th SWE in the Alps. All stations show a negative trend. Large triangles indicate significant trends (p = 0.05) and small triangles indicate weakly significant trends (p = 0.2). Circles represent stations with no significant trend (p = 0.2). The elevation is given in gray. (Adapted from Marty et al. 2017b).

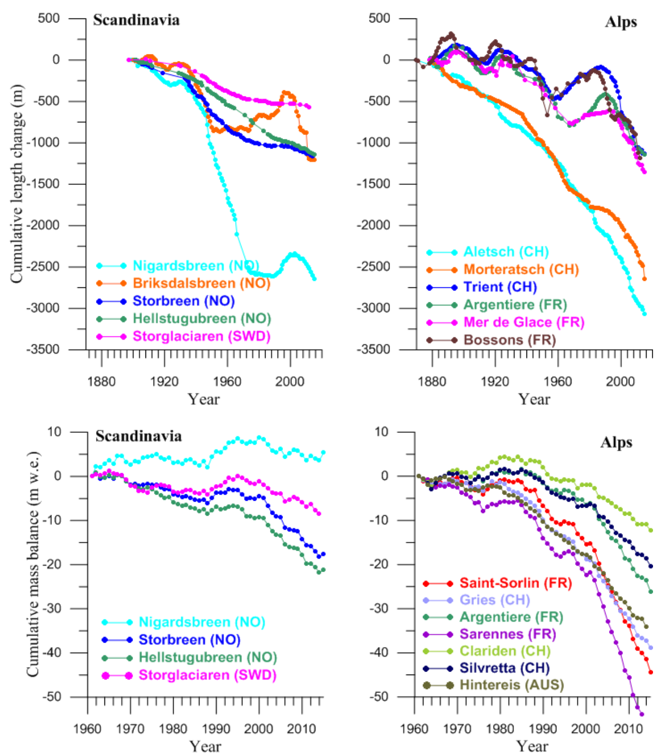

Figure 2: Length and surface mass balance changes documented with *in-situ* measurements for glaciers in Scandinavia and in the European Alps. Sources: WGMS (2015) and earlier issues with updates (Andreassen et al., 2016).

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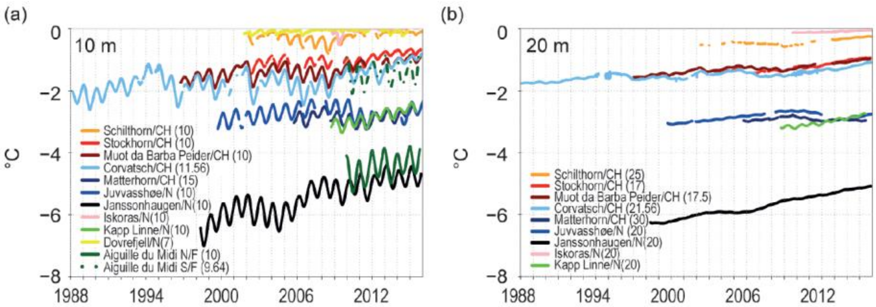

Figure 3: Temperature evolution of mountain permafrost in Norway (N), France (F), and Switzerland (CH) measured in boreholes at ~~(a)~~ 10m (a) and ~~(b)~~ 20m (b) depth (exact depth given in the ~~parenthesis~~parentheses). ~~Figure a~~Adapted from Noetzli et al. (2016).

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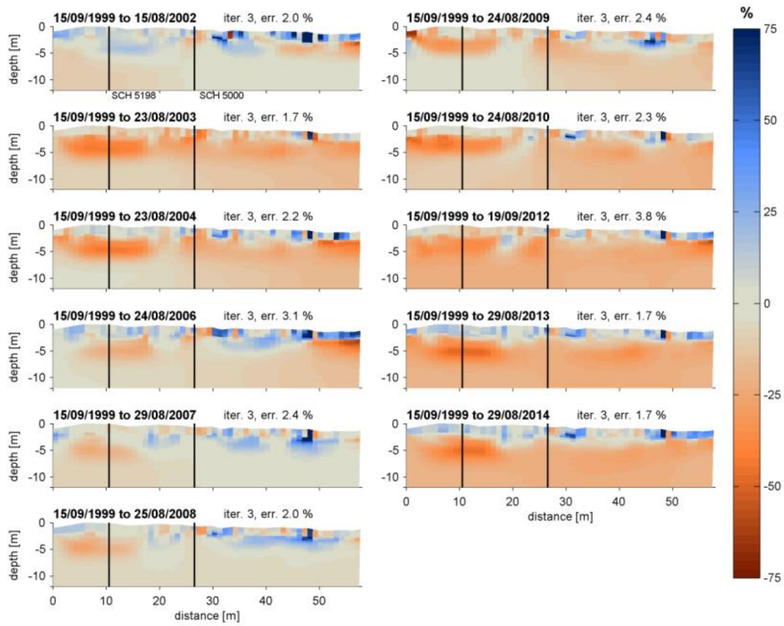

Figure 4: 15-year change in specific electrical resistivity (given as % specific resistivity change) along a 2-dimensional Electrical Resistivity Tomography (ERT) profile at Schilthorn, Swiss Alps (2900 m a.s.l.). Red colors denote a resistivity decrease corresponding to loss of ground ice with respect to the initial measurement in 1999 (see Hilbich et al. 2008a, 2011 for more details on ERT monitoring in permafrost). The black vertical lines denote borehole locations. (modified after Permos, 2016).

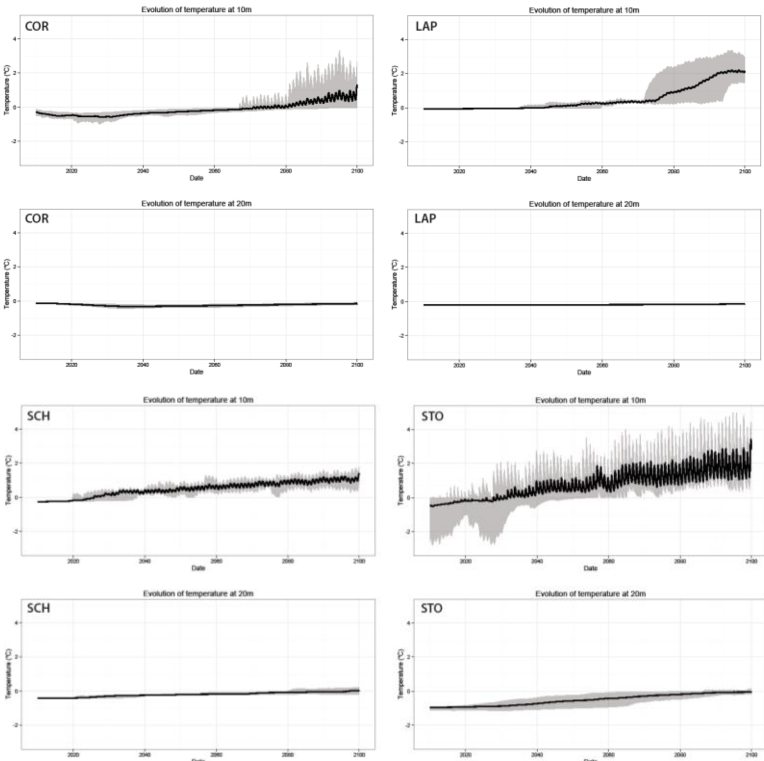

Figure 5: Modelled long-term evolution of ground temperatures at 10 m and 20 m at four different permafrost sites in the Swiss Alps (COR: Murtèl-Corvatsch, LAP: Lapires, SCH: Schilthorn, STO: Stockhorn), as simulated with the COUP model (Marmy et al., 2016). The black lines represent the median scenario and the grey zone the range of the 13 GCM/RCM chains which were used to drive the simulations. Modified after Marmy et al. (2016).

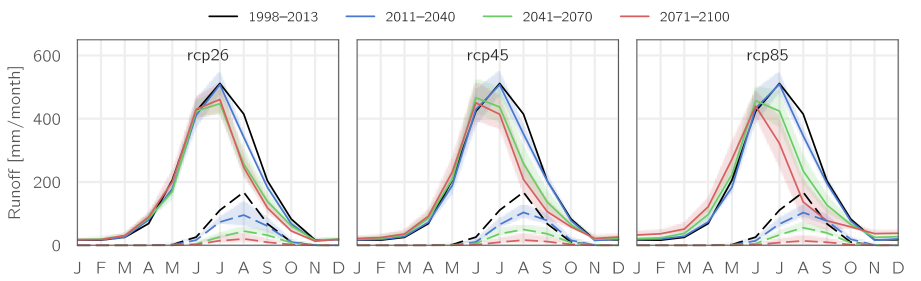

Figure 6: Shifts of streamflow regimes for the Rofenache catchment (Austrian Alps, 1891–3762 m a.s.l., 98 km², ~35 % glacierization as of 2006) as simulated with the AMUNDSEN model using downscaled EURO-CORDEX projections for the RCP2.6, RCP4.5 and RCP8.5 scenarios. Solid and dashed lines indicate the multi-model mean total and ice melt runoff, respectively, and shaded bands indicate the climate model uncertainty shown as ± 1 standard deviation. ~~Figure a~~Adapted from Hanzer et al. (2017).

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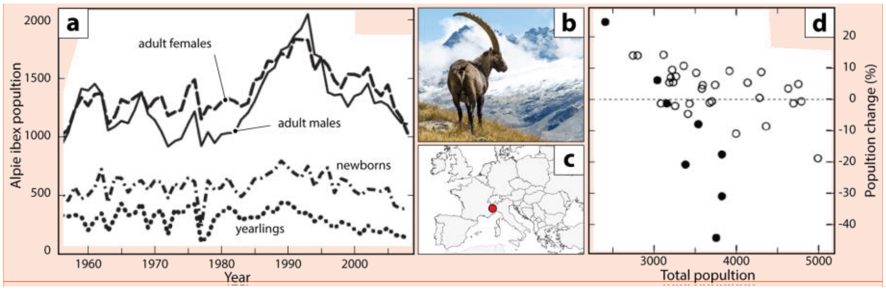

Figure 7: (a) Total number of adult Alpine ibex (b) counted at Gran Paradiso National Park, Italy (c). (d) Relative population change against population size. Solid circles indicate that the winter snow depth was more than half a standard deviation above the long-term average. Panels (a) and (b) are adapted from Jacobson et al. (2004).

Commented [US20]: In this figure are still two errors in the axes inscriptions, "Alpie" (left) and "Popultion" (right). I suggest to remove the old figs. 7 and 8, and already did so.

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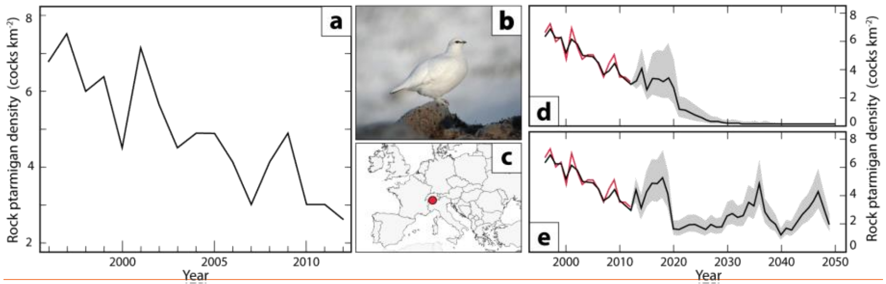

Figure 8: (a) Observed density of rock ptarmigan cocks (b) at the Veglia Devero protected area, Italy (c). (d+e) Reconstructed (red) and projected (black) rock ptarmigan density from two population dynamics models including (d) snow drivers only, and (e) snow and delayed density dependence. Panels (a), (d) and (c) are adapted from Imperio et al. (2013)

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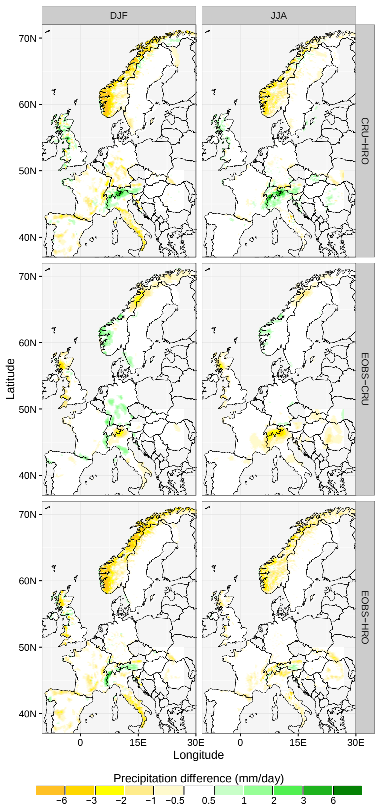

Figure 97: Seasonal average precipitation differences for December-January-February (DJF; left) and June-July-August (JJA; right) between CRU and HRO (first row), E-OBS and CRU (second row), and E-OBS and HRO (third row).

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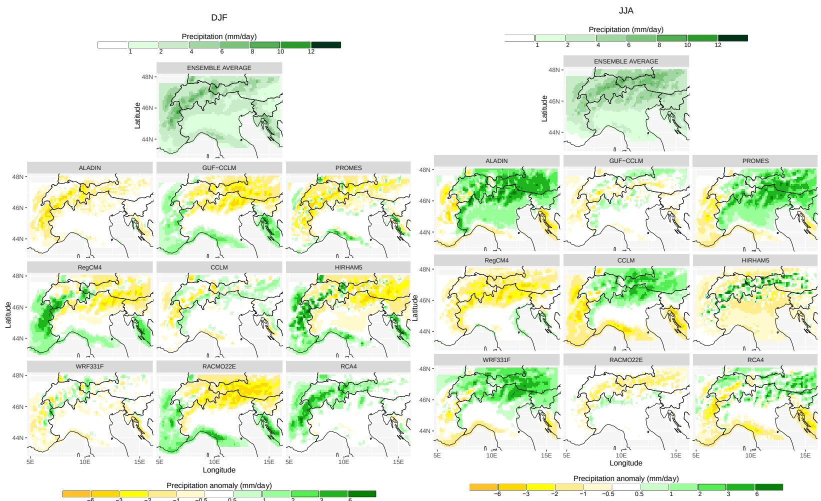

a b

Figure 108: DJF (aleft) and JJA (bright) precipitation as derived from 9 regional climate models. The average of the model ensemble is shown in the top center of the respective panel panelat the center.

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