The Glaciers of the Dolomites: last 40 years of melting - Securo et al., 2024

The authors present a comprehensive overview of the state of glaciers in the Dolomites including detailed assessments of glacier volume and mass change for the main remaining glaciers in the region. They provide an informative discussion of the observed glaciological changes in the context of local climate and topography and contrast the evolution of glaciers in the Dolomites with glaciers in other European regions. As the authors point out, glacier change data from the Dolomites is sparse (by Alps standards) and this work is a valuable contribution towards a quantitative understanding of glacier change in this region over the last ~40 years. The authors highlight the importance of local, mostly topographic factors for the evolution of very small glaciers and the need for continued monitoring to better understand the possible future trajectories of these features. I agree with this. The 3D visuals are very cool and will be valuable assets in outreach activities.

I have some questions and comments which I hope can be addressed to improve the overall clarity of the paper. My impression is that the authors probably have everything needed to do this and it is a matter of providing additional explanations or changing the way some things are presented, rather than adding to or changing the analyses. My main points are below, the following brief notes are mostly just small quibbles I had while reading. I feel like some editing for more concise language would be beneficial but this is of course somewhat subjective.

Main questions/comments:

Surface change computation and treatment of errors

The section in the methods dealing with this is a bit fuzzy and I find it hard to follow at times. The error in surface elevation change is stated to depend on lidar accuracy, alignment between the point clouds, and a distance uncertainty. The lidar accuracy is “not considered” (L163) because ”relative distances” are used. I am unsure what the reasoning for this is. If I understood this section correctly the authors are comparing all other data to the 2010 lidar (L158), but this does not appear to explain why the vertical accuracy of the lidar is not a relevant factor (?) Are you only looking at the horizontal accuracy? If so, why?

I would also like more explanation of the process mentioned in L158: *“Every comparison included 2010 LiDAR data and has never been done using two historical SfM-point clouds at a time, to reduce possible sources of error.”* The results show surface elevation change values for various time steps before and after 2010. How were these generated if everything is compared to 2010? I do not see how comparing everything to 2010 first and then computing differences for other periods would cancel out the errors in the historical point clouds. I may have misunderstood what you did here but either way I think it requires some more explanation. Perhaps some sort of diagram showing the processing steps to arrive at surface elevation change for different time periods would help, or just a more structured explanation.

In the results (L206) it is stated that “*Higher accuracy and precision (E_AL 0.1-0.3 m) were obtained*” for the more recent years. Since the alignment error is considered the main source of uncertainty (this is my understanding based on the methods section) it would be interesting to

see these values for the historical data as well and to include some more information on how this error was determined. Can you quantify the total error of the volume change data for the different time steps?

Glacier area
The authors repeatedly refer to “common area” vs. “total area”. It is not entirely clear to me what they mean by common area and how it differs from total area, nor did it become clear to me which year (or average) they used for computations of volume and mass change. It would be beneficial to have a clear explanation especially of “common area” early on in the manuscript (methods section). A bias related to usage of different areas is discussed later on and it is apparent that the authors are aware of the influence of glacier area on further computations, so I think i is again just a matter of improving the clarity of how this is presented.
This publication may be of interest:
Florentine C, Sass L, McNeil C, Baker E, O’Neel S. How to handle glacier area change in geodetic mass balance. Journal of Glaciology. Published online 2023:1-7. doi:10.1017/jog.2023.86

Note that the glacier area is also related to overall uncertainties. The uncertainty in volume change is a function of the uncertainty in surface elevation change and uncertainty in the area. Neither of these factors seem to be included in the uncertainty estimate for the mass change given in the results, which appears to be based only on the uncertainty of the density conversion. I understand that it may not be possible to fully quantify the uncertainty but it would be good to at least mention this and explain that challenges related to exact area delineation (which you mention) also affect volume and mass change estimates. Note the large impact of area on uncertainties shown e.g. in Hugonnet et al 2021 (extended data Fig 5, https://www.nature.com/articles/s41586-021-03436-z).

Abstract
L 8, L 50 and elsewhere in the manuscript: unmanned aerial vehicle
Please consider using the neutral term “uncrewed aerial vehicle”

L 10: from 1980s to 2023
The 1980s and 1990s are frequently referred to as time periods throughout the text. I feel like more specific phrasing would be helpful for the reader. In the abstract and as you explain your workflow it would be good to know that, e.g. “1980s” refers to data from 1980 or 1982 as per table 2.

L10: …33% of which between 2010-2023…
Missing word? → of which occurred (?) between 2010-2023

L11 negative with a smaller amplitude
Consider changing to “less negative” for clarity

Introduction

29: valley bottoms

I think “valley floors” is the more common term for this

L62: providing a description of the glaciers in the Dolomites that are still active,

How do you define “active” glaciers?

Previous studies

L69 No glacier in the area has mid or long-term mass balance dataset available

Missing “a”? (has a mid or long-term mass balance dataset…)

L88 Results show an area variation of approximately -50% from 1910 to 2009.

Consider rephrasing for clarity: “...show an area loss of …”

L91 and following

Consider restructuring for clarity. You could move the sentence starting with “also of great significance” to the end of the paragraph so that the sentence citing Serrano et al (2021) appears directly after the first use of the term ice patch.

Why is the debris cover of great significance? You might state that it is abundant without using the word significance, which is often associated with statistical parameters.

L106 Other Dolomites massifs that still host minor ice deposits devoid of any evidence of dynamics are not included in this work

What do you consider evidence of dynamics and how did you determine that none is present at these features compared to the nine you study?

Table 1: state in the caption or in the table for which year the area value is valid. Same year as the cited publication?

Caption: Smiraglia and DIolaiuti → typo

Data and methods

Table 2: *2010 and 2012 photos have been used only for visual reference and not for mass balance reconstructions*

Would this be an opportunity to compare results using the 2010 photo vs. the 2010 lidar and assess the difference in elevation change between the different methods/data sources?

L157: *…using common area with regards to different years.*

Unsure how to interpret this - does this mean you used the same area value for all computations of geodetic mass balance? Which area value (from which year) did you use?

L157: *Every comparison included 2010 LiDAR data and has never been done using two historical SfM-point clouds at a time, to reduce possible sources of error. .. Every comparison included 2010 LiDAR data and has never been done using two historical SfM-point clouds at a time, to reduce possible sources of error.*

Does this mean you compared every other year to 2010? See general comment above.

L163 ±*0.12m* I am assuming this refers to vertical accuracy? Consider clarifying
In this study, our comparisons were done using relative distances; therefore, it may not be considered
I don't understand what you mean here. Are you saying uncertainties in the lidar measurements are not considered? Please clarify why not.

EM3C2 was available as a direct output of the algorithm (i.e., distance uncertainty), and considering our dataset was negligible compared to the EAL.
So E_al was the main error source? Can you quantify the relative contribution of the different errors?

L170 *imageries* → imagery

Weather station network

L180
Additionally, years with missing data exceeding 5% of the accumulation (November to April) or ablation (June to August) season
Unusual definition of accumulation and ablation season, please explain the reasoning behind this. What happens in the missing months? (May, September, October)

L182 *This was implemented at the level of individual AWSs, ensuring the availability of data for each year after averaging across all stations*
Why average over all of them? If the goal is to get one T&P time series for the region, consider leading with that.

L183 *All the time series begin between 1985 and 2001 and end between 2020 and 2022*
Does this mean that none of the time series extend beyond 2022?

L189 *where xa is either the total precipitation during the accumulation season (for the precipitation SAI, Pr SAI), and the mean…*
Should this be "or the mean" ?

L191: *The accumulation and ablation seasons were defined according to local climatology*
Please specify what this means.

L191: *Finally, SAI values were spatially averaged, providing unique Pr and T SAI values for the entire region*
Does "spatially averaged" mean you produced some kind of gridded data set or is this simply one averaged time series over all the weather station data? Please clarify

L193: *The pre-processing applied to AWS data may result in an underestimation of total precipitation and therefore of the Pr SAI.*
Why? What part of the preprocessing leads to an underestimation?

L198 *collect a datum*
Consider rephrasing → record a value

L200: *Using this data, we reconstructed the October to June snow depth on the ground for the most relevant years of our study (1982, 1992, 2010, 2014, 2023).*
Reconstructed as in you averaged over October to June for the given years? Or does the reconstruction involve something more complex?

L202: *Additionally, we calculated the October to June snow depth on the ground averaged over the whole time frame for each station as well as the total annual snow accumulation.*
Could you explain your reasoning for using October to June average snow depth? Wouldn't the snow depth at the end of the accumulation season (late spring) be a more relevant metric?

Results
L206: *Higher accuracy and precision (EAL 0.1-0.3 m) were obtained…*
What does the EAL 0.1-0.3 m value represent? (accuracy or precision? Which years? What are the values in the years where lower accuracy(?) was obtained?)

L207 *Out of the 9 glaciers analysed, Sorapiss Occidentale, Antelao, Marmolada and Pale di San Martino areas were reconstructed starting from the 1980s while Popera and Cristallo reconstruction begins in the 1990s*
State the exact years, 1980s and 1990s is vague

L214:
In 1980s and 1990s the Dolomites glaciers were larger in number, with several of them that have now completely melted, turned into permanent ice patches without apparent ice dynamics and heavily buried by debris.
Consider rephrasing for clarity. Something like: In the 1980s and 1990s, there were more glaciers in the Dolomites, some of which have completely melted or turned into debris covered permanent ice patches without apparent ice dynamics.

L217 *Relative area reductions are not similar across all glaciers*
State min max range of area reduction to show variation?

L219: *topographic bounding*
Consider explaining this term

L226: *for common and total glacier area*
Please explain what you mean by common and total area. Is this stated somewhere?

L226:
Due to the impossibility of retrieving enough data for years 1999 and 2001, we considered the period from 1990s to 2010 as a unique time frame, instead of calculating the metrics at a decadal frequency. The average cumulative surface elevation change (Table 3) was calculated for three periods: 1980s with -5.21 m, 1990s-2010s with -14.09 m and 2010s with -9.31 m.

Does “unique time frame” just mean you used a longer time step? I think rephrasing would help clarify this, something like: *The average cumulative surface elevation change (Table 3) was calculated for three periods: 1980s with -5.21 m, 1990s-2010s with -14.09 m and 2010s with -9.31 m. Due to lack of data in 1999 and 2001 it was not possible to resolve the 1990s-2010 period at decadal frequency.*

L241 *The highest absolute losses, corresponding to almost 35 m, are reached in the area involved in the ice avalanche that happened in a detached part of Marmolada Principale, on 3rd July 2022, as shown by the Kernel Density plots of surface elevation loss (Fig. 5b)*
Can you mark this in the figure? I am unsure where I can see this in Fig 5b.

L243 *The Fradusta Inferiore Glacier was not included in the common area measurements as it had already disappeared before 2023 surveys took place.*
Again, what exactly is common area?

L246 *On that glacier a rise of more than 10 m has been observed close to a wide serac whose presence is possibly related to a small surge induced by a recent rockfall (Fig. 5a) in the accumulation area as well as by internal glacier dynamics*
Interesting! If possible consider marking this feature in the figure

L248 *This is well visible in Fig. 6a,*
Should this be Fig 5a?

L251 ff and Table 4: Do these uncertainties refer only to the uncertainty originating from the density conversion, or does this also include uncertainties in area and volume?

L256 *Our results show that the use of a fixed maximum glacier area in the geodetic mass balance leads to an underestimation of the m. w.e. loss when compared to common area calculations. In our case the bias introduced by total area is between -1% and -31% of the common area mass balance, depending on the site and considered period. There are some cases of decadal comparison (1980s-2010 in Cristallo, Antelao Inferiore and Marmolada) where total glacier area produced larger mass balance losses than calculations using common area*

I am still unsure about the differences between “fixed maximum glacier area” (this term is used for the first time here), common area, and total area.

Table 4: (a) *Sorapiss Occidentale values have been corrected removing the positive elevation gain portion for 2010-2023*

Why did this need to be corrected? Did you simply delete all positive values or was there some other correction? You measured the positive elevation change and suggested that this was due to a rockfall/surge process - what is the argument for removing the elevation gain when that is what your analysis shows?

Climate data

L266 . *Among the ten highest events, seven have occurred in the last 15 years (2007-2022).*
Consider rephrasing for clarity? highest → warmest

L269
The maximum Pr SAI has been calculated for 2014 with a value > 2, while 1996 is marked by the minimum value at -1.22.
Consider rephrasing for clarity, e.g.: Pr SAI was greatest in 2014 with 2.x and lowest in 1996 with -1.22.

L272 Temperatures have risen by 0.4-0.6 °C per decade since 1985, while precipitation showed an increase that lasted about 15 years from 1995, culminating in the extremely snowy year of 2014 (Fig. 6b). Fedaia station, the only one providing data since 1980, does not show any trend for the total snow accumulation (p-value = 0.61; Fig. 6c), however, increased extreme events can be observed in the last decade of its time frame. The other three snow monitoring stations exhibit slightly different patterns, demonstrating a higher frequency of snowy winters also in previous decades.

Did you also look at station variability for T and P? How do you identify extreme events in the snow time series?

Fig 6b: The dotted line is hard to see. I'm assuming the lines refer to hydrological year, i.e. 2023 refers to the 2022/23 winter season. Consider stating this in the caption or legend.

Discussion

L295 *In the Dolomites, a slight increase in winter snowfall has been observed at some high-altitude stations, such as Ra Vales site at 2620 m (Fig. 6)*
How do you determine this increase? It is not really obvious from Fig 6c and there is no mention of this in the results.

L296 *unfavourable years conditions for glaciation prevailed*
Extra word? Delete "years"

L302 *Within Alpine mass balance records, the ablation season of 2022 results unprecedented.*
Missing word? (...results were unprecedented…)

L305 *According to such climatic evolution, the Dolomites are rapidly turning from being mountains hosting sites favourable to local glaciation, to areas where peri-glacial processes will progressively gaining importance.*
→ gain importance

L317 *Dolomites glaciers mass balance rates are half of the average RGs rate during the last 13 years*
Interesting!

L334 *stabilise the dynamic of some glaciers of the Dolomites*
Do you actually mean dynamic as in movement or something else? Consider rephrasing

Fig 7: Cool figure! I'd be interested in seeing how the WGMS annual product compares to your values for the Dolomiti glaciers (just an idea, the figure is informative as is and this is not needed for the manuscript)
https://cds.climate.copernicus.eu/cdsapp#!/dataset/derived-gridded-glacier-mass-change?tab=overview

L360 *most representative*
If it is the largest it is not the most representative in terms of size. Consider removing this.

L374 *In this study we used the surface lowering observed during the last 13 years and direct observations on site to assess the glaciers end*
I would like to read this earlier, eg in the methods.

L397 *In the late 1950's the Dolomites were hosting 33 glaciers, of which only 9 are still active;*
Define somewhere what you mean by active

L402 *A few glacial bodies may eventually shift from glacial to periglacial, thus becoming more resilient in a warming climate.*
There seems to be an ongoing discussion about how and whether glacial features can turn into periglacial features (e.g. discussion comments here:
https://tc.copernicus.org/articles/18/1669/2024/tc-18-1669-2024-discussion.html)
Perhaps rephrase this sentence to avoid ambiguity. You could focus on the processes that would make the ice features more resilient without classifying them as glacial or periglacial.