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Glacier area and length changes in Norway from repeat inventories

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Final Response to Referee Comments (Interactive Discussion)

This is a response to the three referee comments published at TCD, and describes how we will revise our manuscript. In this letter, we reply to the referee comments of the two first anonymous referees and the third referee Holger Frey point by point.

We want to thank the two anonymous referees and Holger Frey for their valuable and constructive and detailed comments. The comments will improve the manuscript and are greatly acknowledged.

Comments by Anonymous Referee #1:

(1) *In addition to this characterization, the authors discuss the impact of the North Atlantic Oscillation (NAO) on the observed retreat in area and length of glaciers by building on the assessed impact of NAO on Norwegian climate as documented in the literature. This latter aspect is however in my view the weakest part of an otherwise great, well written, exhaustive, sound, and exceptionally documented inventory. While I would support the publication of this work in The Cryopshere, I would however recommend that the consideration of the influence of NAO be better supported than merely in regards to previous and rather dated work and indirect interpretations. The richness of the inventory presented in this paper, as well as is exhaustiveness could very much justify that the expected influence of NOA, hereby discussed, be revisited on the basis of a sound methodology and analysis. In fact my recommendation in this regard would even be that the indirect but somewhat still speculative discussion about the influence of NOA on the glacier behavior in Norway be only prudently suggested in this paper and that more definitive results in this regards be the purpose of a subsequent analysis for which the motivation seems evident in view of the new data.*

We agree and have rewritten the section about NAO. We follow referee #1's advice to only prudently mention the influence of NAO on the glacier behavior in Norway. In the section "4.4.3 Climatic transects" we have therefore shortened the paragraph where we discuss NAOs influence on glaciers in Norway. We have edited the Abstract and Conclusion and do not mention NAO. As the referee #1 suggests, the connection between NAO and Norwegian glaciers need further analysis. Here is the rephrased paragraph:

"Our analysis shows that glacier area and length changes are most pronounced for the northernmost glaciers (Figs. 6 and 7 and Tables 3 and 4). This agrees with geodetic and direct mass balance observations over the last decades. For example, the ice cap Langfjordjøkelen, shows a stronger thinning and retreat than any other observed glacier in mainland Norway. Often the glacier has no accumulation area left at the end of the mass balance year (Andreassen et al., 2012a). The ice cap simply does not have enough area at high altitude for the present climate.

Much of the annual variation in Norwegian climate is influenced by the North Atlantic Oscillation (NAO) (Hurrell, 1995). Glaciers in Norway span over a transect of ~1500km from south to north. Previous studies have shown that NAO influences the winter and annual surface mass balance, but its effect is reduced towards more continental glaciers, as well as glaciers located at high latitudes (Nesje et al., 2000)."

(2) *Additional specific comments and comments*

3072. L20: "…why is such occupation of Norway in the geographical grid relevant?"

Norway includes Svalbard and Jan Mayen, which are not part of this analysis. By stating the geographic extent of the study area, we make this clear.

(3) Technical suggestions

We agree with all other suggestions and we will change the manuscript accordingly.

Comments by Anonymous Referee #2:

(1) The methodology is clearly described and the results very well illustrated in tables and figures – though the fine print in figures 5-10 test this reviewer's eyesight to its limits !

We agree that some of the figures are challenging to interpret on a printed copy. However, the figures will be larger in the final TC-version. The figures can use the entire text width over two columns with a width of 17 cm. This will improve the visibility of the figure details.

(2) Overall results are stated for 'the past 30 years' but it's not immediately clear at first reading which time range this refers to, unless the 'Gln50' is set to 1970 for the 1945-85 period.

This is indeed not clear. We will remove *'the past 30 years'*. See Holger Freys comment point (3).

(3) Table 1 gives the mean time span as 32 years, but then the 326 sq km change would correspond to 10 sq km per year, rather than 11. Perhaps I am missing something in interpreting the results ? Are they perhaps weighted for each glacier by the time span between mapping and Landsat imagery which can range from 14-54 years ?

We agree that the method on how we extracted the annual glacier area change for the full epoch needs to be further explained. The reviewer's assumption is correct: the glacier change is calculated for each individual glacier and its respective unique year difference, before calculating the mean change. However, following Holger Frey's advice, we will take out the annual glacier area and length change numbers from the text and tables. See Holger Frey's point (4).

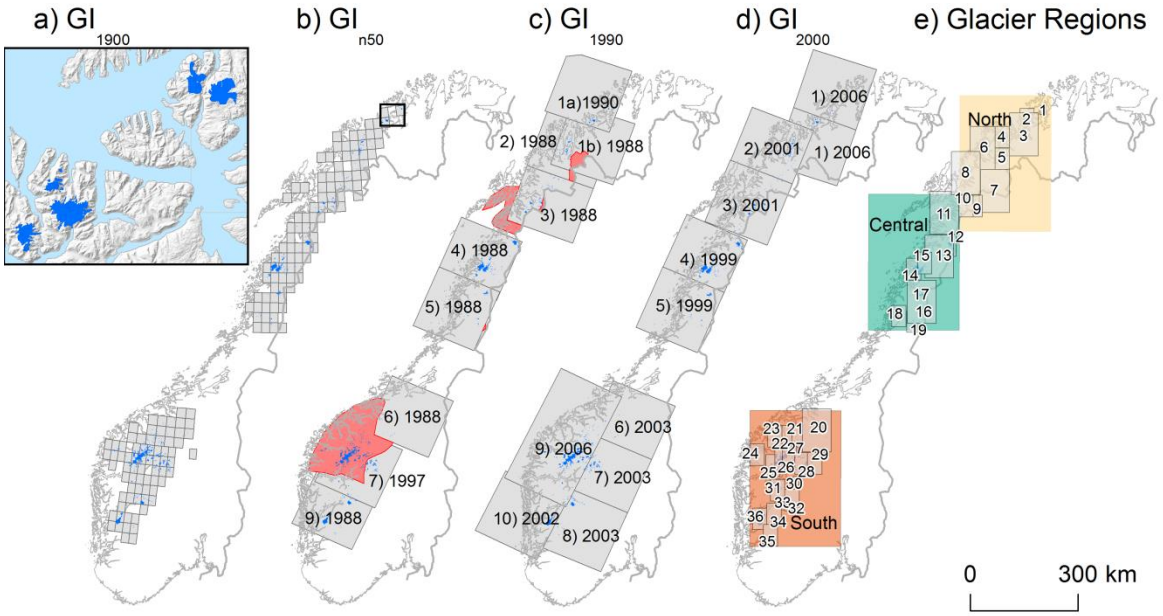
(4) Table 1 gives mean time spans of 17 and 12 years respectively for the two epochs (time intervals) studied, but Table 4 suggests that to calculate the change per year they used 14 and 11 years respectively (199/14 and 55/5). It's not clear to me then how these values were derived.

This issue is related to the previous comment.

Specific comments

(5) The numbering of figures and tables does not match their citation in the text: figures 6 and 7 are referenced before figures 3,4,and 5; tables 7 and 5 are referenced before tables 3,4 and 6.

We agree and include the map of Norway in figure 2 that illustrates the three parts of Norway and the glacier regions. This makes the citation to the figures a chronologically order.



(6) p3075, line 7: Landsat imagery is used rather than SPOT/ASTER due to larger swath width, but surely it is also due to availability, as SPOT/ASTER were not available for most of the time periods.

We have rephrased the sentence: "… the higher availability of Landsat images, as other optical satellites were not operational in most of the time periods"

(7) p3075, line 27: the authors used the TM 3/5 ratio (Red/MIR)... perhaps they might state why this is preferred over TM 4/5 or indicate a previous reference where this is stated.

We agree and added an explanation referring to Andreassen et al., 2008:
"We calculated the band ratios for the Landsat images by including the red band (TM3), and the short wave infrared band (TM5). We used TM3/TM5 rather than TM4/TM5 following Andreassen et al. (2008). Their results show that TM3/TM5 performed better for ice located in shadow and for debris covered ice compared to TM4/TM5"

(8) p3077, lines 14 and 17: the threshold values are given as 2.8 to 2.4 and then 2.0 to 2.4 - is there a reason why these are not consistent (smaller value first)

We have changed the order of the threshold values. This means 2.0 to 2.4 will be mentioned first, and then 2.4 to 2.8 after. See the changed section under the answer to Referee 3 Holger Frey

(9) In the references, page numbers are given where each reference occurs, but they partially conceal the date of the publication ... is this a new Cryosphere standard ? I don't see this in other discussion papers.

This comment must the administration of The Cryosphere Discussion answer. We don't know why it is like this.

(10) Technical issues from reviewer #2:

We agreed with all of the technical issues and will change the manuscript accordingly:
p3070, line 10: changed to "total"
p3071,line 7: changed to "extensive"
p3072, line 20: changed to "Mainland Norway", line 23: changed to "number"
p3078, line 1: changed to "onscreen"
p3080, line 6: changed to "in the case of", line 7: changed to "are", line 12: changed to "each set of outlines", line 19: changed to "acquired".
p3082, line 2: changed to "because", line 25: changed to "into"

p3083, line 6: changed to “are”
p3085, line 26: changed to “of”
p3086, line 3: changed to “shows a mean”, line 4: changed to “in agreement”, line 6: changed to “for”, line 16: changed to “impact”, line 17: changed to “make”
p3087, line 10: changed to “In total”, line 10: changed to “decreased”.
p3091, line 13: changed to “termini”
p3092, line 1: changed to “the”, line 2: “very large” is removed, line 15: changed to “open”

Referee #3 Holger Frey:

(1) *Observed glacier changes are related to topographic and climatic characteristics of the study region. This is done only in a descriptive, qualitative way, i.e. in reference to other publications, although the data presented had the potential for quantitative analyses and testing of the supposed relations of glacier changes to theses region specific characteristics. However, this would probably go beyond the scope of this article.*

This is a good point, but a quantitative analysis on these data would be very time consuming and as Holger Frey implies already, it will go beyond the scope of this paper.

(2) *Explanations and calculations related to inventory dates and annual change require some more explanations and maybe some reconsiderations: The relatively large time ranges of the individual inventories are obvious and justified. However it is not exactly clear to me, how the numbers given in Table 1 are calculated. I assume they refer to glacier-specific time intervals. Nevertheless, it should be explained more clearly how the mean time span of 32 years for the full epoch is calculated. At first glance I thought this should be 36.5 a: 1966 (average of 1947 to 1985) to 2002/03 (average of 1999 to 2006).*

We agree and will expand the caption texts for the table 1. Referee #2 also commented on this (see point (3). We obtained the 32 years by taking the average of all glacier-specific time intervals included in the analysis.

“Table 1: The maximum, minimum and mean time span in years within each epoch. Note that the calculated glacier change is weighted by the time span between two data sets for each single glacier. The mean time span in this table is not weighted, but gives the mean of the time span for all glaciers included in each epoch.”

(3) *In addition, I suggest avoiding the expression ‘over the past 30 years’ when referring to the full epoch. In an article published in 2014, the ‘past 30 years’ are 1984 – 2014, not 1970 – 2000 (which is meant, I assume).*

Thanks, it is a good point! We have eliminated the “over the past 30 years” and only refer to the datasets instead.

(4) *“Related to the above point, I suggest avoiding average change rates (i.e. change per year), when referring to a baseline inventory that spans over 38 years, such annual change rates are not very significant and should only be applied to subsets of the analysis with consistent mapping dates. The number of ‘-11 km2 a-1’ should therefore be avoided in the abstract, text, and Tables 3 and 4. In Table 6 it is appropriate, because here the changes refer to equal time spans. The same applies to length change rates.”*

This is a good point, and to avoid confusion about this issue, we will take out the annual average change rates for both glacier area and length. We will remove this information from the text and table 3 and 4.

(5) *Sub-section 3.1.1 ‘Divisions of glacier’ should be moved to after the description of the different inventories (i.e. after 3.4), or better still after 3.5 ‘Digital Elevation Model (DEM)’. The first sentence of 3.1.1 (P3074, L17/18) in my view belongs to the study region section; the rest of*

3.1.1 is better placed after 3.5 (as section 3.6 or 3.5.1), since it uses the data described in these sub-sections.

Agreed and will be changed in the manuscript as section 3.6. And the first sentence in 3.1.1 is moved to the study area section.

(6) *On several occasions number of glacier or total glacier area is given without referring to a year or inventory (e.g. P3072, L21/22; P3073, L25; P3076, L25; P3082, L24). Please update.*

P3072, L21/2: Agreed, we will refer to the years or the Norwegian glacier inventory in the text.
P3073, L25: Here we explain what kind of data used for each GI. As we see it we refer to all glacier inventories. We will not change the text.
P3076, L25: As we see it we refer to both the Norwegian glacier inventory and GI2000. We will not change the text.
P3082, L24: Here we refer to the "full epoch" which is between GIn50 and GI2000. We will not change the text.

(7) *I suggest swapping Figures 5 and 6 as well as Tables 6 and 7: they are mentioned in reverse order in the text.*

Agreed. These figures and tables are swapped.

(8) *In general, when describing ranges, the smaller value should be mentioned before the larger value. E.g. related to inventories (P3075, L9/10) or the band-ratio thresholds (P3077).*

We agree and have rewritten the sentences mentioned.
P3075, L9/10 : "GI1990 and GI2000 span over a mapping period of 9 and 7 years respectively…"
P3077: see below for the rephrased paragraph.

(9) *"Please define the expression 'glacier unit'. In literature, often the terms 'individual glacier' and 'glacier complex' is used. From the context I assume glacier unit here refers to 'individual glacier', i.e. a glacier separated, but sharing common boundaries (drainage divides) with other individual glaciers. For instance, the two sentences on P3072, L21-23 are hardly understandable."*

We agree and wrote an explanation. The sentences will be changed to:
"In the most recent glacier inventory, glacier complexes are divided into individual glacier units. These glacier units share common divides if they are part of a glacier complex, otherwise they correspond to single glaciers without a drainage divide. The number of glacier units in the most recent glacier inventory is 3143."

(10) *P3071, L6: The free availability of georeferenced and orthorectified scenes is another reason for the popularity of Landsat data. Although an individual orthorectification was performed here, this could be mentioned in the general introduction.*

Agreed. We will mention this, and list all the advantages.

(11) *P3072, L21: The bracket '(0.7% of the area)' belongs to the next sentence and should be mentioned after the glaciers.*

Agreed. Will be done.

(12) *P3074, L13-15: A reference should be added.*

Agreed. Reference added.

(13) *P3075, L25: Reword 'an accuracy of less than : : :'. It sounds like a lower accuracy, but it actually denotes a higher accuracy.*

Agreed. We will write "…have an accuracy of ~30 m".

(14) Section 3.2: Is no filtering (i.e. a median filter to eliminate isolated pixels) applied? Is a minimum glacier area threshold applied? Please specify if yes. (I do not assume that every single pixel classified as glacier ice is considered in the inventory).

That is correct, a median filter is applied on the data set. We chose to not explain the derivation of glacier outlines from Landsat imagery in detail in this article, and chose instead to refer to the Inventory of Norwegian glaciers. In this book/pdf, the methods are described in detail. However, we will mention the median filter in the method: "**We applied a median filter on the glacier outlines to eliminate individual glacier pixels. Outlines were further** manually corrected in case of debris cover, glacier lake interfaces, clouds or cast shadow which hampered the automatic mapping " And further we will include: "The methods of **filtering,** human inspection and editing of the data sets are described in the glacier inventory by Andreassen et al (2012)."

(15) "P3077, L14-23: This section is hard to follow: I do not see why threshold changes from 2.8 to 2.4 (should be 2.4 to 2.8, see above) are treated separately from variations between 2.0 to 2.4, when the findings are the same for both ranges. What means 'mixed ice and terrain pixels' (P3077, L16)? Please reword."

We agree and will rephrase the paragraph:
"Comparing the area derived from the thresholds TM3/TM5>=2.0 to 2.4, and TM1>= 35 with the reference value, a median area increase of 12% is encountered. This means a larger glacier area is mapped compared to using the reference values, also for glaciers in cast shadow, but it also implies that more noise was included in terms of mixed pixels containing snow/ice and rock/debris. Similarly, when comparing TM3/TM5>=2.4 to 2.8, and TM1>= 35 with the reference value, we find a median decrease in area of -11% (-3.1km2). Higher threshold values used for TM3/TM5 reduces noise, but includes less glacier area compared to lower threshold values, due to less mixed pixels including both ice and terrain features. The TM3/TM5 should be as low as possible to include the dirty ice around the glacier perimeter (Paul et al., 2013). If TM3/TM5 >=2.4 was used with TM1 >= 60 we find less variation when varying the threshold values compared to using the TM1 >= 35. This means a median area decrease of -4% (-1.2km2) using TM3/TM5 >= 2.4 to 2.8, and median area increase of 3% using TM3/TM5 >= 2.0 to 2.4."

(16) P3079, L18/19: It is not clear whether 4 transformations (spline, adjust, second order polynomial, and third order polynomial) or 3 methods (spline adjust, and second and third order polynomial transformations) were tested for the georeferencing.

We agree. We will rephrase the sentences: "For three composite glaciers in West-Finnmark (Langfjordjøkelen, Øksfjordjøkelen and Svartfjelljøkelen), we tested four transformation methods (spline, adjust, second order polynomial, and third order polynomial) for the georeferencing."

(17) P3080, L17-20: The last sentence of the DEM section should be moved upwards, to around P3080 L4: The acquisition date of the DEM should be mentioned already here because it is relevant for the content following from P3080 L5 onwards.

We agree. It will be moved.

(18) P3082, L21-23: The last sentence of this paragraph is not clear to me: Why are snow fields included in the analysis? Because they are assumed to be the remnants of glaciers included in the older inventories? Further explanations are needed.

We agree and will rephrase and further explain this paragraph. "For our analysis, we also included in total 400 snow- ice patches that could be remnants of glaciers into the GI2000 glacier areas, to make a more precise analysis of the area change. We assumed the snow fields were remnants of glaciers if they were located within previous glacier outlines older than GI2000".

(19) P3088, L18: ': : : because they [the ice caps in northern Norway] are located in a maritime climate : : :'. But on P3073, L3/4 it says that precipitation decreases from south to north. This is contradicting. The following discussion on differing sensitivities to ELA changes for steep and flat glaciers and ice caps is convincing, but I cannot follow the argument given in the sentence on P3088, L16-19.

We will rewrite and add some words to make it more clear: *P3073, L3-5* : "Norway has a latitudinal gradient in terms of mean temperature and precipitation, which both decrease from south to north. However, along the coast, there is no pronounced variation in climate because of the ice-free Norwegian Sea, although Norwegian glaciers span over ~1500 km from north to south"

P3088, L16-19: "Our results show that ice caps in northern Norway are particularly vulnerable to glacier area and length changes. Maritime glaciers are in general sensitive in Norway and retreat, but the glaciers in northern Norway retreat more because of less precipitation, warmer temperatures and for many glaciers a location at lower elevations."

The maritime climate along the whole coast is quite warm and wet because of the Gulf stream and the ice free Norwegian sea, also in northern Norway.

(20) Typos and wording

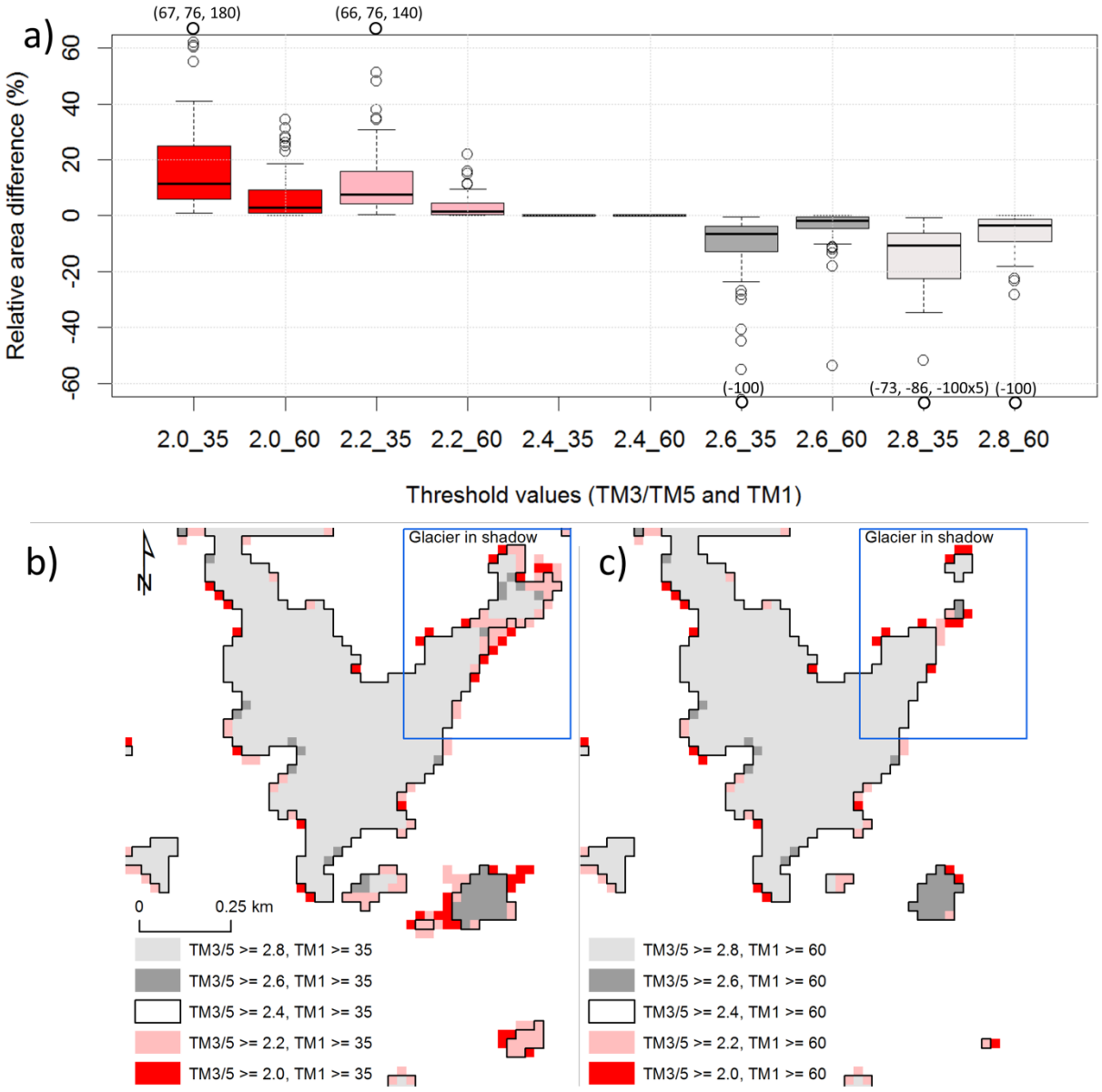
We agree with all other suggestions and we will change the manuscript accordingly.

(21) Tables

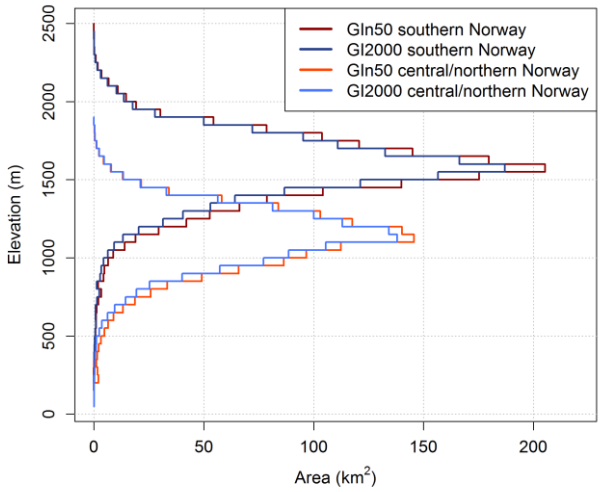
a. Table 1: See Anonymous Referee #2 point (3)
b. Table 2: Agreed, and corrections will be done in the table.
c. Table 3 and 4: We will remove the annual glacier change numbers in both tables.
d. Table 5: I can't find missing bracket.
e. Table 6: The numbers in Table 6 show the average decadal glacier change, calculated using the set of decadal change values for each glacier separately (relative to each glaciers time span). For this reason, and since we have a slightly different number of glaciers for each epoch, the averages cannot be summed together to get the total average.
    i. We will include a clarifying sentence in the caption: "The averages were calculated using the set of decadal change values in each epoch for each glacier separately."

(22) Figures

a. General comments: See Anonymous referee comment 2 point (1).
b. Figure 2: Agreed. The caption will be updated with: "The location of the subset is indicated by the black rectangle in 2b"
c. Figure 3: Agreed. We have zoomed in on a part of the same glacier. Additionally, we added a blue frame indicating glacier in cast shadow. We added text in the caption: "The blue frame indicates a glacier located in cast shadow".



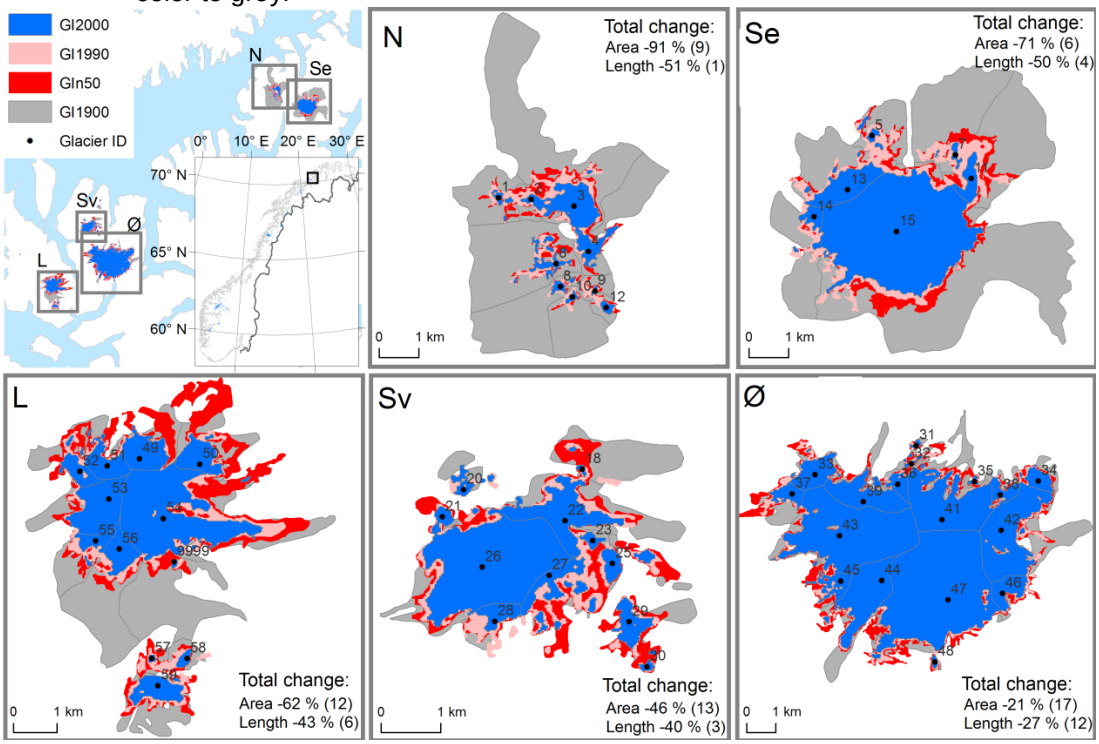
d. Figure 5: We agree and we have made the changes in the legend.



e. Figure 6: Agreed and will be moved.

f. Figure 6 and 7: Thanks! Good observation. The figures have been updated.

g. Figure 8: We agree and we have updated the figure changing GI1900 from dark red color to grey.



Additional changes to the manuscript (tc-2014-78)

The manuscript is changed according to the response letter published at TCD the 18th of August (the text above), except from some changes of technical nature that clarified the text and improved the language (e.g. correction of grammar), and some changed or added references. Additional changes are listed below. Note that the line numbers refer to manuscript submitted on 9.9.2014.

Text:

- Line 16: Removed “climatic aspects” to avoid confusion.

- Line 85-87: Moved a sentence from “4.4.2 Elevation“ to “2 Study region“ :
    - “Since the beginning of the 2000s, all glaciers monitored by NVE have been in a state of retreat (Andreassen et al., 2005, Winkler et al., 2009).”

- Line 111-114: To improve readability a list of the advantages of using Landsat images was added under section “3.2 GI2000 and GI1990 – Landsat satellite imagery”:
    - “The Landsat TM/ETM+ satellite images have multiple advantages compared to imagery from ASTER and SPOT due to: 1) the larger swath width of Landsat, 2) better availability of Landsat images, as other optical satellites were not operational during the time periods, and 3) Landsat has freely available georeferenced and orthorectified satellite scenes.”

- Line 150-155: Updated a sentence and reference under subsection “3.2.1 Band ratio accuracy and threshold sensitivity”:
    - Old: “Similar results were found on a test site in the Swiss Alps, where outlines derived from Landsat TM imagery were compared with a SPOT satellite scene, which revealed an area difference of 2.3 % (Paul et al., 2002)”
        - Changed to: “Fischer et al. (2014) show that Landsat derived outlines (year 2003; medium spatial resolution (30 m)) compared to orthophotos (year 2003; high spatial resolution (50 cm)) for eastern Switzerland show similar results meaning there is comparable accuracy between the medium-resolution and high-resolution source data for glaciers > 1 km2. On the other hand, they found that glaciers <1 km2 , the uncertainty of the outlines increased with decreasing glacier size.”

- Line 391-392: Corrected and updated sentence under subsection “4.2.1 Glacier length changes vs. in situ length changes”:
    - Old: “Nine of the glaciers show good agreement between the length change methods, corresponding to +-1 to 2 pixels.”
        - Changed to: “Eight of the glaciers show good agreement (of +- 1 to 2 pixels) between the length change methods.”

- Line 416-417: Due to an imprecise sentence and reference, we corrected and updated a paragraph under section “4.3 Glacier change since the beginning of 1900s”:
    - Old: “The glaciers response to the climate was not changes in the glacier dynamics, but rather by down-wasting (Paul et al., 2004).”
        - Changed to: “Strong thinning and retreat has been revealed for Langfjordjøkelen, one of the five ice caps, over the period 1966-2008 (Andreassen et al., 2012).

- Note! We took out the reference Paul et al., 2004, and refer now to Andreassen et al., 2012.

- Line 451-458: Clarified a paragraph in the section “4.4.2 Elevation”:
  - “These considerable changes are partly attributable to the glacier geometries: ice caps in Norway are relatively flat, and a high fraction of their surface remains close to the modern equilibrium line, which makes them highly sensitive to climatic change (e.g., Nesje et al., 2008), whereas the steep glaciers are less sensitive. If the equilibrium line rises on ice caps, large parts of the accumulation area is transferred to the ablation area, and the mass balance becomes strongly negative. For example the accumulation-area ratio (AAR) for Langfjordjøkelen, an ice cap in northernmost region, was 0% for many years during the 2000s, and the glacier is far from being adapted to the present climate conditions (Andreassen et al.,2012a).”

- Line 401-403: Clarified a sentence under “4.2.1 Glacier length changes vs. in situ length changes”:
  - Old: A limitation of using satellite images is the determination of glacier terminus in cast shadow, causing uncertainties in the derived length change (Paul et al., 2011).
    - Changed to: “The determination of glacier terminus in cast shadow is limited by the quality and resolution of the used satellite images, causing uncertainties in the derived length change (Paul et al., 2011).

Tables:

- Updated table 4:
  - Corrected the column “Start” with correct years. They were not updated in the previous version.
  - “Na”-values (Not available) was inserted for the glacier Midtdalsbreen(2964) under “Maps/satellite(m)” values “FE” and “E1”.
  - Line 304-305: Under the section “3.7 Deriving centerlines”, we have changed a sentence so it makes more sense when compared with the table:
    - “Some of the in situ measurements began before or after the GIn50 first mapping year, but series were included if the gap was no larger than 5 years”.