Author comments

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General response

We thank T. Johannesson, the anonymous referee and M. Pelto for contributing to the open discussion on our paper. We also thank scientific editor Etienne Berthier for his feedback to our paper before submission to TCD and after the referee comments were posted. We have prepared an updated manuscript based on our author comments. The main changes to the manuscript are change of title to 'Reanalysis of long-term series of glaciological and geodetic mass balance for ten Norwegian glaciers', adding text by addressing comments by anonymous and M. Pelto including some more references, adding the reference suggested by T. Johannesson and English proof-reading. Figures 2 & 4 have been updated to increase readability. Figure 3 has also been modified and the area-altitude distribution has been added to the figure.

Below we respond specifically to the comments in the open discussion. The citations from the referees are marked with *"<italic> "*. Our response to the referees is marked with ->> and our proposed direct text changes in the manuscript marked with '<text>'.

1. Response to Referee comment by T. Johannesson

We thank T. Johannesson for his positive comments on our paper.

"I have only one minor comment other than the trivial suggestions for rewording and corrections of typos below. p. 6584, l. 20: Maybe Magnússon (2015) should also be referenced here regarding spatial statistics:"

->> We have added the reference to Magnússon et al. (2016*), (*now published in TC)

->> On rewording and corrections of typos: we have gone through all the technical corrections that were suggested and incorporated them in the manuscript, except for

"p. 6588, l. 27-28: "and inhomogeneity is smoothed out." –> "and on inhomogeneity is introduced"" as we did not understand this change.

2. Response to Referee comment by anonymous

We thank anonymous for sharing his view on our paper. Although anonymous find our re-analysis *"beautifully-done"*, and the writing *"well structured"*, the suggestion is that our paper *"should be significantly modified before acceptance into either journal. To be accepted into TC, the authors should go beyond the accepted benefits of a thorough re-analysis and interpret the newly produced records in terms of regional glacier change."* according to anonymous.

We would argue that our paper is of significant scientific value and suitable for TC, which is clearly supported by the other comments in the interactive discussion. The anonymous referee suggests major rewriting, and publication of all the data prior to publication. We argue that observations are an important part of science and a fundamental requirement for the reproducibility of research results, modelling and process understanding. According to the information on the Cryosphere webpages, research article in The Cryosphere, should **"***report substantial and original scientific results within the journal's scope. Generally, these are expected to be between 6 and 12 journal pages, have appropriate figures and/or tables, a maximum of 80 references, and an abstract of 100–200 words."*

Our paper is the first re-analysis of the long-term mass balance series in Norway. We usually publish our data in annual or biannual reports by NVE. In addition, to the annual data reports and to this research article, we publish three NVE data reports on the reanalysis process with further details on Engabreen, Nigardsbreen and Ålfotbreen/Hansebreen (Elvehøy, 2016; Kjøllmoen, 2016a; 2016b). We have chosen to present the results of the re-analysis from 10 glaciers in one article, avoiding so-called salami paper publishing. For the first time we quantify and highlight the importance of internal and basal ablation, which the surface mass balance measurements are not accounting for. The data are analyzed, presented and discussed, and error estimates given.

As stated in the paper, seven of our glaciers are used as reference glacier for the WGMS. Our mass balance data are widely used by scientists, students, and policy-makers, from local to global scales. The fact that the mass gain of maritime glaciers is smaller than previously found is an important outcome of the reanalysis that will be of interest to many. The information on the use of our data by researchers was not explicitly stated in the manuscript for TCD. We have added a section on the application of data in science in the introduction, including new studies whereof two of them are papers were submitted to the Cryosphere within the last year: 'The data are widely used, for modelling and statistical analyses and at local, national and global scales (e.g. Rasmussen, 2004; Nesje and Matthews, 2012; Engelhardt et al., 2013; Trachsel and Nesje, 2015; Zemp et al., 2015).'

On data availability: We emphasize that our original data are available from NVE and the World Glacier Monitoring Service (WGMS). We also wrote about how we will make the homogenized and calibrated data series available from the NVE website (www.nve.no/glacier), and that we will submit it to WGMS so it is available in new versions of their datasets. Furthermore, the annual and seasonal area-averaged values will be available for download for the 10 glaciers from the NVE web site. In the supplement, we presented the three series of Nigardsbreen (original, homogenized and calibrated) as an illustration. We did not make the new data available prior to the acceptance of this paper, as revision process could have altered the final values. Furthermore, it is difficult to keep the paper well-written and readable, if we were to include much more of the large volume of data included in the analysis. However, the three NVE data reports mentioned earlier will give further details on four of the glaciers.

Moreover, making all data available is not standard procedure according to the papers recently published in TC. Papers typically site the data sources used, but seldom offer modeling code or full sets of data or provide information about where data from the analyses have been submitted or are available. This is simply not common practice in the papers of the Cryosphere today. Our statement is based on the 15 papers available in Vol 1 of 2016 per 26 Jan 12 CET.

Regarding interpretation it in a regional view. *"What does it tell us about climate forcing and or the role of glacier geometry as a control on mass balance for the region?"* ->>We have analyzed long-term mass balance records, which represent 10 out of 3143 glaciers in Norway. The focus was on the series itself, but also to emphasize that the previously reported mass surpluses of maritime glaciers were overestimated and are now adjusted. We have geodetic surveys on many more glaciers without concurrent glaciological surveys. The plan is to publish these results in a separate paper on geodetic changes of glaciers in Norway and here the importance of glacier geometry and regional changes will be analyzed in more detail. ->> we added at the end of the discussion after 'Finally, the results call for continued geodetic surveys every 10 years to measure the overall changes and provide data for new reanalysis.': 'The resent geodetic surveys by airborne laser scanning conducted over the period 2008-2013 cover not only the 10 mass

balance glaciers presented here, but about 1/3 of the glacier area in Norway. The surveys provide an accurate baseline for future repeated mapping and glacier change detection. They will also be used for a regional overview of glacier changes from the 1960s to 2010s.'

"MINOR COMMENTS: "
"1. After so much rigor in homogenizing the records, the authors should refrain from hand-drawn fits to mass balance profiles." ->> As written in the TCD paper, p 6589, the sensitivity of the hand drawn method was tested by comparing three analyzers curves and gave very little difference. It was also tested to use automatic procedures to obtain the curves, but the data material are unfortunately not always suitable due to few points, and the manual drawn curves were considered the best method with the data material available. We added 'The profile method relies on the consistency of the annual mass balance gradient. Analyses of the mass balance gradients show vertical profiles of annual and seasonal mass balance are remarkably linear and vary little from year to year (Rasmussen, 2004; Rasmussen and Andreassen, 2005). Studies of Lemon Creek and Taku Glacier, Alaska, show also a consistency of the annual balance gradient (Pelto, et al., 2013). ' (also as response to one of Pelto's comments)

"2. Provide AADs in the Figure 3 example. "->> We assume that AAD is an acronym for Area-altitude distribution and have added it to figure 3.

"3. Figures 2 & 4 are hard to read" ->> Figures have been improved by increasing font etc. for better readability.

"4. A third panel in Figure 8 showing the difference between original and homogenized time series would be helpful in assessing the magnitude of the changes driven by the re-analysis. -> We show the original and homogenized/calibrated on this figure. ". ->>We have not added a third panel here, but the discrepancies are described in the paper.

"5. In section 3.1.1. how is density estimated for stake measurements in the accumulation area?"
->> added "using density estimates of remaining snow (usually 600 kg/m^3), melted firn (650-800 kg/m^3) and ice (900 kg/m^3) (e.g. Kjøllmoen et al., 2011)."

"6. Ending the paper with more research is needed is weak. Please end with something positive that this effort has contributed towards a better understanding of Norwegian glacier change."
->> Done. We have removed the last paragraph in the conclusion. The need for more research was also mentioned in the discussion and we rewrote this part. The conclusion now ends with 'The reanalysis effort has contributed towards a better understanding of Norwegian glacier change since the 1960s.'

3. Response to short comment by Mauri Pelto

We thank Mauri Pelto for his thoughtful comments on our paper and suggestions for clarifications. Below is a point-by-point response to his comments.
"6584-28: change "reference series of" to "reference glacier for"." ->> done
"6585-25: Does last century mean 1900-1999 or 1910-2010?" ->> We rewrote the sentences to: 'Norwegian glaciers have retreated throughout the twentieth century, although several periods of advance have also occurred. The most recent advance started in the late 1980s on many maritime

glaciers, but culminated around 2000 (Andreassen et al., 2012 b). Mass balance results show different behaviour of the ten study glaciers.'
"6586-1: "most so" to "greatest at"." ->> done
"6586-3: What about prior to the 1990's?" ->> added comma
"6587-1: Is the end of summer transient snowline used as a measurement?" -> Not systematically. Often snow is covering it so it is not always observed. No action

"6589-20: The profile method relies on the consistency of the annual balance gradient. Pelto et al (2013) noted in Figure 4 and 6 the consistency of the balance gradient from year to year on Lemon Creek and Taku Glacier, Alaska that justifies its use. Rasmussen and Andreassen (2005) illustrate this for many of the glaciers in this study and Andreassen et al (2012) on Langfjordjokelen. This point should be more emphasized and its appropriateness quantified."
->> We added: 'The profile method relies on the consistency of the annual mass balance gradient. Analyses of the mass balance gradients show vertical profiles of annual and seasonal mass balance are remarkably linear and vary little from year to year (Rasmussen, 2004; Rasmussen and Andreassen, 2005). Studies of Lemon Creek and Taku Glacier, Alaska, show also a consistency of the annual balance gradient (Pelto, et al., 2013).' We also added in chapter 3.1.1. 'Furthermore, investigations showed that annual balance measured at stakes correlated well with glacier wide annual balance and that fieldwork could be simplified (Roald, 1973).'

"6587-2: What is the range of stake measurement density?" ->> We added 'Stake density is highest at the smallest glacier, 6/km^2 at Gråsubreen, and lowest at the largest glaciers, 0.2/km^2 at Nigardsbreen and Engabreen.'

6590-21: Please better quantify large surplus and small deficit. ->> We have added values.

"6590-25 or 6601-10: On Nigardsbreen there is a paucity of measurements from 600 to 1200 m, can you comment more directly on the role this has in potential geodetic/fieldmeasured mass balance, it is obliquely noted at 6604-3."
->> We added 'At Nigardsbreen, Engabreen and Rembesdalskåka only 1–2 stakes are available below the main plateau (see Fig. 3 for Nigardsbreen), However, this part cover less than 10 % of the total area, see also Kjøllmoen (2016a) and Elvehøy (2016) for further details.'

"6604-5 Any ability to discern if a changing flux through these steep fast flowing sections has caused some of the discrepancy?
->> Good point. This is a field for further study, but we have not looked at it in this study.

"6604-17: On Engabreen there is a lack of field mass balance data from 600 to 1000 m this could be specifically noted if as noted at 6604-3 this is the issue for accurate field mass balance data. On Alfotbreen there is a diverse mass balance pattern that the balance gradient poorly captures that is not necessarily well mapped by the stakes used according to the NVE annual reports, which are biased to the east side. Rasmussen and Andreassen (2005), note the highest standard deviations in gradient for this glacier. Is this the cause of the greater discrepancy? How is the lack of a representative balance gradient dealt with?" ->> On Engabreen, see response to 6589-20. On Ålfotbreen: As written in the paper, the stake network was reduced based on analyses. We have added in the paper in chapter 3.1.1.: 'Furthermore, investigations had showed that annual balance measured at stakes correlated well with glacier-wide annual balance and that the fieldwork could be simplified (Roald, 1973).' In the discussion we already wrote about the recommendation to increase the observational network once every decade in

order to reassess the spatial pattern of mass balance. We rewrote this part: 'The present results revealed here may call for a temporarily increased observational network on the glaciers with largest deficits differences between the methods (Engabreen, Nigardsbreen, Ålfotbreen, Hansebreen and Rembesdalskåka) to adjust the observational programmes in order to reduce uncertainty. It should be emphasized that it is far more challenging and expensive to maintain a stake network on a large glacier with high mass turnover like Nigardsbreen, where parts of the glacier must be visited by helicopter and stakes need maintenance several times a year, than the small Gråsubreen where stakes may survive many years and all parts are accessible by foot.'

"6606-10: Is the consistent finding that glaciological mass balances were too positive on each of these glaciers indicative of a specific field practice? Such as limited network of ablation stakes below the snowline or lack of end of summer snow depth soundings."
->> See response to 6590-25 or 6601-10.

"6608-27: Is there a relationship between mean density of annual measurements on a glacier and the magnitude of recalibration? This would be a key motivation for an increased observation network."

->> We wrote in the paper that an increased observation network should be considered. We modified it to 'The results revealed here may call for an increased observation network on the glaciers with largest differences between the methods (Engabreen, Nigardsbreen, Ålforbreen, Hansebreen and Rembesdalskåka) if resources are available.' See also comment to 6604-17, and our addition in the paper 'that is far more challenging and expensive to maintain a stake network on a large glacier with high mass turnover like Nigardsbreen …..'

"6609-7: Rasmussen and Andreassen (2005) and Andreassen et al (2012) observe that the slope of balance gradients on Grasubreen, Hellstugubreen, Langfjordjokelen and Storbreen are quite uniform. Is this an important reason why there is good agreement with geodetic measurement?"

->> We have added text to address this: 'The glaciers that show good agreement between glaciological and geodetic measurements (Austdalsbreen, Storbreen, Hellstugubreen, Gråsubreen, Langfjordjøkelen) have several things in common. Their size is small to medium (2.2-10.6 km^2), and they have a higher stake density (1/km^2-6/km^2) than Nigardsbreen and Engabreen (0.2 km^2). Furthermore, most parts are accessible, providing a better stake coverage with altitude. Their altitudinal range is lower and their area-altitude distribution is uniform and not dominated by a flat upper part as in Nigardsbreen and Engabreen. Their glacier basins are also more defined. Furthermore, except for Austdalsbreen, the glaciers had a considerable mass loss and have more or less been constantly loosing mass throughout the observation record. Thus, smaller mountain glaciers with negative cumulative balances seems to be easier to measure correctly than the maritime outlet glaciers.'

"Table 4: I had trouble understanding column heading units." ->> In the table text it is stated that all mass balances and errors are in m w.e.a-1. We added reference to ch 3.4.1 for abreviations.

References

Elvehøy, H.: Reanalysing of a mass balance record. Engabreen 1970-2014. NVE Rapport X*, Norwegian Water Resources and Energy Directorate, 2016.

Engelhardt, M., Schuler, T. V., and Andreassen, L.M.: Glacier mass balance of Norway 1961–2010 calculated by a temperature-index model. Annals of Glaciology 54(63), doi:10.3189/2013AoG63A245, 2013.

Kjøllmoen, B.: Reanalysing a glacier mass balance measurement series – Nigardsbreen 1962-2013. NVE Rapport X*, Norwegian Water Resources and Energy Directorate, 2016a.

Kjøllmoen, B.: Reanalysing a glacier mass balance measurement series – Ålfotbreen (1963-2010) and Hansebreen (1986-2010). NVE Rapport X*, Norwegian Water Resources and Energy Directorate, 2016b.

Magnússon, E., Muñoz-Cobo Belart, J., Pálsson, F., Ágústsson, H., and Crochet, P.: Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data – Case study from Drangajökull ice cap, NW Iceland, The Cryosphere, 10, 159-177, doi:10.5194/tc-10-159-2016, 2016.

Nesje, A. and Matthews, J.A.: The Briksdalsbre Event: A winter precipitation-induced decadal-scale glacial advance in southern Norway in the AD 1990s and its implications. The Holocene. DOI: 10.1177/0959683611414938, 2012.

Pelto, M., Kavanaugh, J., and McNeil, C.: Juneau Icefield Mass Balance Program 1946–2011, Earth Syst. Sci. Data, 5, 319-330, doi:10.5194/essd-5-319-2013, 2013.

Rasmussen, L.A.: Altitude variation of glacier mass balance in Scandinavia. Geophys. Res. Lett., 31(13), L13401. (10.1029/2004GL020273.), 2004.

Rasmussen, L. A. and Andreassen, L.M.: Seasonal mass balance gradients in Norway. Journal of Glaciology. 51(175), 601-606, 2005.

Roald, L.: En undersøkelse over sambandet mellom nettobalansen malt på enkelte staker og breens totale nettobalanse. In Tvede, A. M. (ed.): Glasiologiske undersøkelser i Norge 1971. NVE rapport, 2, Norwegian Water Resources and Energy Directorate, 1973.

Trachsel, M. and Nesje, A.: Modelling annual mass balances of eight Scandinavian glaciers using statistical models, The Cryosphere, 9, 1401-1414, doi:10.5194/tc-9-1401-2015, 2015.

Zemp, M. Frey, H, Gärtner-Roer, I, Nussbaumer, S. U., Hoelzle, M.., Paul, F.., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, Guillermo., Dávila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O.., Holmlund, P., Karimi, N., Li, Zhongqin., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., Vincent, C.. Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61, 228, doi: 10.3189/2015JoG15J017, 2015.

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*: NVE data report in the ‘NVE Rapport’ series to be published. Will be available for download from www.nve.no