Charles Papasodoro
Sherbrooke University
2500 boul. de l'Université, Sherbrooke, Québec, Canada, J1K 2R1
Charles.papasodoro@usherbrooke.ca

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Dear reviewers and Editor,

We thank all of you for your constructive comments that undoubtedly improved the quality of our manuscript entitled: ‘Area, elevation and mass changes of the two southernmost ice caps of the Canadian Arctic Archipelago between 1952 and 2014’.

Please, find enclosed a point-by-point response to all reviewer comments. Upon request, we can provide a track-change version of the revised manuscript.

We hope that all of our corrections now bring our paper to the required level of quality for publication in The Cryosphere.

Sincerely,

Charles Papasodoro, Étienne Berthier, Alain Royer,
Christian Zdanowicz and Alexandre Langlois

Main changes made on the paper

1. Dedication to Dr. Gunnar Østrem

First of all, we decided to dedicate this paper to Dr. Gunnar Østrem, a pioneer of the study of Canadian Arctic glaciers, especially Grinnell Ice Cap. We thus added this sentence in the acknowledgements section:

'This paper is dedicated to Dr. Gunnar Østrem (Ph.D. Stockholm Univ., 1965) a tireless pioneer in the study of mountain and Arctic glaciers across Canada, who surveyed Grinnell Ice Cap in the early 1990s.'

In addition to that, a brief mention of his works was added in the introduction section (i.e in the previous works paragraph):

'Under the supervision of veteran Norwegian glaciologist Dr. Gunnar Østrem, other measurements were conducted on GRIC in the early 90s by a scientific team from Bates College (Maine, U.S.A.) and the Nunavut Arctic College.'

2. Figures

Following the comments from the different reviewers, we decided to incorporate the panel D of the previous figure 5 within figure 6 since the comparison between historical and recent trends on Terra Nivea Ice Cap (TNIC) is a good complement to the previous figure 6 single graph. The figure 5 thus now only contains three panels and furthermore, panels B and C were swapped. The new figure 6 now contains two different graphs of elevation change per hypsometry.

Figure 7 was merged from 2 different graphs to a single one in order to improve the comparison of both ice caps. New colors were also used.

We added a new figure (now figure 8) that compares a same geomorphological feature on bedrock by three different technologies. This allows seeing the advantage of the Pléiades products for feature identification and thus, for GCP collection that can then be used for photogrammetric process of archive photographs. We added this figure because we thought we didn't insist enough on the important advances provided by the GCP collection from Pléiades products.

The previous figure 8 is now the figure 9 in the new revised manuscript. Following reviewer 1 advice, we decided to invert the Y axis of the panel A. We also combined Panels B and C for a better comparison. We finally removed the previous panel D for many reasons. First, the area changes were already presented in another figure; second, the comparison of areal changes with Way (2015) is already described in the discussion section. Third, we found it more optimal to make this figure only 'climate-related'. Thus, the new figure 9 only has 2 panels.

Those are the main changes on the figures; see the following point-by-point comments for further minor changes.

3. Density factor

Following reviewer 2 advice, we instead chose a density constant of 900 ± 17 kg m-3 for the recent period of mass balance estimation on Terra Nivea Ice Cap. A brief look at images of 2007 and 2014 has shown no significant firn area so this new density constant is more appropriate for that type of ice. The previous density constant was kept for the historical estimation since the firn areas were likely more significant during the 60 years of study.

5. Changes in the climatic factors

Many things were changed in the climatic factors section, following some of the recommendations of the two reviewers. First, we removed every mention of Arctic amplification. We instead investigated the contribution of the longer sea ice retreat (i.e. later freeze-up in autumn) as an additional cause of stronger mass loss, after the main cause which is the rising summer temperatures. We also improved the analysis of temperatures and positive degree-days of this region by using the Adjusted and Homogenized Canadian Historical Climate Data, instead of the raw data.

See the revised manuscript for details.

6. Grammar

One of the main comments from reviewer 2 was to improve the grammar of the paper. For this new revised version, we put the emphasis on the review of the grammar which was conducted accordingly. Once again, upon request, we can send a track-change version of the revised manuscript.

7. Order in the data section

In the data section, the ASTER DEM section was placed after the ICESat section since the latter data are mentioned in the ASTER section. Moreover, the CDED section was moved at 3.2 before the historical aerial photo section that is now 3.3. We found it more obvious this way because in the process, the photos of 1952 were chosen because the CDED was not optimal over Grinnell Ice Cap.

8. Abstract

The abstract has been improved by adding remarks about the climatic factors and the use of Pléiades for exploiting aerial photograph archives.

1st reviewer: R. Way

General remarks: This is an interesting study investigating glacier change for two glaciers on the Meta Incognita Peninsula of southern Baffin Island. I believe it provides new insight and uses a wide swath of available data sources which present a consistent picture of the evolution of Grinnell and Terra Nivea ice caps over the past half-century. Although the paper is certainly not brief, I believe that the lack of existing literature for these particular ice caps warrants the fuller discussion provided by the authors in the introductory material. Overall the science is well-implemented and the results are consistent other recent studies examining the eastern Canadian Arctic. The additional information provided by in situ surveys along portions of Grinnell Glacier represent a very important contribution in that the results have been validated using both field and remote sensing-based methods. The use of a Pléiades-derived DEM for ground control on photogrammetry-based DEMs is also a novel methodological approach and hopefully its widespread application for other, more topographically complex environments is investigated in more detail in future works. Overall, this contribution warrants publication although I believe some of the Figures could be presented in a clearer fashion.

P1668L23-25 Two of the references for the currently observed Arctic warming section refer to paleoclimatic reconstructions, which although very interesting, may not be necessarily the best studies to cite with respect to the Arctic being currently warming rapidly. I would suggest Comiso and Hall (2014) or Cowtan and Way (2014) as perhaps being more appropriate in these cases, particularly in that they show the regional distributions of warming trends over the recent periods from satellite and surface temperature records.

Kaufman et al. (2009) has been deleted since it is not focusing on the very recent warming (post-2000). We disagree for deleting Tingley and Huybers (2013) because it uses both recent observations and paleo-data and have the merit of putting recent observations (post-2000) in a long-term perspective. Comiso and Hall (2014) was added as it supplements the referenced warming studies with the satellite components.

Study Area Section: P1670-1671 (1) Lenaerts et al (2013) modelled the surface mass balance for the ice caps to be strongly negative – this point might be useful to add to this section. **(2)** The authors note several of the major results suggested by previous work in the area but not the the recent results of the complimentary study by Way (2015) mentioned at the end of the introduction. Given the overlap in some aspects of the areal change analysis it may be worthwhile to note the major findings of that study in the same brief manner that it was done for the other studies in the Study Area section. Notably that areal decline has accelerated, that ice thinning appears to be occurring and that recent increases summer melt intensity were linked to this decline. In my view, this is a nice tie-in to the current study because Way (2015) qualitatively suggested that ice cap thinning was ongoing (Nunatak exposure) but did not present a quantitative assessment like this study does.

(1) We decided not to add any mention from the study of Lenaerts et al. (2013) because the resolution of this study is 11 km, which we considered too coarse to compare with our results. Our ice caps (TNIC and GRIC) are represented by ~1 single pixel in their modelling effort.

(2) A comparison to Way's results is already done in the discussion section and we find it unnecessary to repeat it in the study area section. The Way (2015) paper is also already mentioned in the introduction.

Data Section: P1672L2-5 Although it is true that in some late-summer images there appears to be very little winter snow accumulated (even at high elevations), there is a high degree of volatility in summer snow cover for these ice caps. A casual glance at Landsat imagery over the past two decades reveals both years where there is very little late-season snow cover and where it is more widespread therefore it may not be safe to assume that the absence of winter snow cover is an annual occurrence.

Reviewer advice is true and reviewer 2 made a similar suggestion. Thus these sentences were removed: '*This is particularly true for the present images, since the ice caps were nearly winter snow free. Thereby, this is a good qualitative primary concern about the ice caps' fate (Pelto, 2010).'*

P1672L10-20 (1) Using aerial photography in high snow accumulation environments can be very difficult, particularly when using 1950s-era black and white photography from the Canadian Arctic. The authors note that the photos are much higher quality than the photos used to derive the CDED data in terms of scale but how accurate was the delineation between snow cover and ice for these particular images. **(2)** The manuscript currently has a number of figures so I will leave it up to the editor and the authors to determine if they feel this is a worthwhile suggestion but given the exceptional nature of the photographs and the lack of field photographs of the region, would it perhaps be useful to have a two-panel figure which shows a portion of the ice cap in the aerial photography from 1952 and then again in 2014 in the satellite imagery so that readers can cross-compare and also evaluate the quality of each image source.

(1) The two sentences that cover lines 16 to 21 were replaced by those sentences: *'These photos, exceptional in their quality of detail and texture, were used for the extraction of historical elevations on GRIC and were preferred to the CDED for this ice cap. In fact, the CDED covering GRIC contained major artefacts (i.e. much larger than for TNIC) in the large snow-covered accumulation zone where the texture was particularly weak on the 1958 photos and thus, was not suitable for historical elevations of this ice cap.'*

(2) We decided not to add a figure to compare the look of the ice cap on both the photos and the Pléiades image. Instead, since we focus on the approach of GCP collection on Pléiades products, we added a figure about this approach. See comments below and new Figure 8.

P1673L1-4 Was this comparison done for the region and if so what was the average elevation difference in this area?

The raw CDED was in the CGVD1928 altimetric reference, while all our other data were in ellipsoid reference (WGS84 or GRS80). So a direct elevation difference calculation CDED vs ICESat would include a bias related to the different altimetric systems. Instead of including our own analysis that would contain this error, we rather added the results from an analysis that was already conducted. However, we removed statistics from Beaulieu and Clavet (2009), that are from different parts of the whole Canadian Arctic, and replaced it in the revised manuscript by the analysis done by Gardner et al. (2012) for the 340 CDED covering Baffin Island (including our area) to show the good accuracy of the CDED. Thus, we added this modified sentence:

'The average elevation differences and their standard deviation (SD) were previously calculated off glacier for 340 CDED maps tiles covering Baffin Island and ICESat laser altimetry points and were reported to be 1.1 m and 5.1 m, respectively (Gardner et al., 2012).'

P1673L20-23 Was the vertical precision spatially or more importantly altitudinally influenced?

We verified the vertical precision as a function of elevation for the 57 available points and we found nothing significant. Note that 57 points is a very little sample for this kind of analysis. In any case, we already considered the errors to be 100% correlated so it is not a problem here. Given all of this, we did not modify anything regarding this in the revised manuscript.

Meteorological data: Is this data from the Adjusted and Homogenized Canadian Historical Climate Data or just the raw measurement from the online database. The reason I ask is because eastern Canada was impacted by the time of observation bias when the climatological day was redefined in 1961 and this appears to have had an observed impact on minimum temperatures for Iqaluit's station based on Vincent et al's (2009) analysis.

To ensure that no such bias was included in our analysis, the adjusted and homogenized Data of Iqaluit weather station (Vincent et al. 2002) were analyzed for this revised study instead of the raw data. These data have been bias-corrected and homogenized, in particular for consistency of minimum air temperatures used in our PDD calculations. We also refer to the latest analysis of Vincent et al. (2015) for Arctic-wide climate trends in Canada. These details were added to the text of the section 3.8, the resulting new PDD data can be seen in figure 9 (formerly 9), panel A, and the brief analysis of the impact of the PDD was also changed in section 6.3.

Methods: P1680L13-19 although I believe that the approach used for calculating uncertainties in the respective DEMs is undoubtedly valid, I would suggest that an additional caveat be added to the discussion given that the uncertainty in DEMs derived from aerial photography and ASTER would possibly have larger errors at high elevations for the ice caps relative to at the same elevations for unglaciated terrain because of the difficulty in pixel matching. This point would be mitigated if each of the DEMs were collected in years without substantial high elevation snow cover (like the Pléiades DEM) but that is unlikely to be the case for all the imagery used.

This is a good point. This said, the difficulty in pixel matching for higher altitudes of the ice caps occurred only for the 1952 DEM and the CDED (not for the ASTER DEM, see the comments below). At page 1680 (lines 16-19) we already mentioned the possible occurrence of errors related to artefacts and low coverage at higher altitudes and we took account of it in the conservative uncertainty approach of our two historical calculations. Thus, we think that this technical point is already enough addressed in the methodology part and should not be explicitly mentioned again in the results or the discussion parts.

P1681L5-8 The 3% uncertainty seems to be appropriate for the most recent imagery where a detailed evaluation could be made but I believe this estimate may be a little optimistic for the earlier aerial photography where it can be more difficult to interpret between late-season snow and ice. This perhaps should be noted.

We agree with the reviewer. This uncertainty has been conservatively increased to 5% for both the old margins of the Grinnell Ice Cap (1952) and the Terra Nivea Ice Cap (1958/59) to account for the slightly more difficult distinction between late-season snow and ice. This had no impact on historical mass balance uncertainties but it changed a little the uncertainty of area changes.

Results: P1681L19-26 These results should be also in Table 2.

Area changes results were not added in the table 2 since they are already provided in figure 2. See below what was modified on figure 2.

Discussion: P1684 Section 6.1 The Pléiades DEM being used for photogrammetric ground control is interesting and is a very worthwhile contribution. The authors may note that multiple Pléiades acquisitions subsequent DEMs over the same area could be useful to increase the confidence in its use for ground control.

Good point, this certainly goes into future works but we don't think it is worthwhile to add in this paper. Further, we actually think that it would be a better use of fundings and satellite resources to target Pléiades acquisitions over other ice caps in the Canadian Arctic than repeating the acquisitions over Grinnell and Terra Nivea ice caps with a time span of only 1 or 2 years.

P1685 Section 6.2 Although the mass change results are placed in the context of the surrounding ice caps and glaciers the area change results are not. It may be worthwhile to add a few brief comments on this to the discussion, for example there were area changes noted on the small glaciers to the northeast on Baffin (Paul and Kaab, 2005/Paul and Svoboda, 2010/Svoboda and Paul, 2010), on northern Baffin (Anderson et al. 2008) and the south in the Torngats (Brown et al. 2012/Way et al. 2014), not to mention many of the other nearby ice caps.

We haven't compared our area changes results to other ice caps located nearby, since it was already done in Way (2015). Nonetheless, we believe it is a good idea to mention that this comparison is already done in the paper of Way (2015). Here is the sentence that was added to the section 6.2:

'A comparison of the areal declines of GRIC and TNIC with those of other Baffin Island ice caps was already conducted in Way (2015) and is thus not presented here.'

P1687L13-20 (1) Although I can certainly see the importance of evaluating the sum of positive degree days there are limitations to its applicability in this case. A modest increase in the length of the melt season can be inferred from the results but its importance for the strongly negative elevation change rates is probably less than the importance of the melt season intensity. For instance, the meteorological analysis presented by Way (2015) suggests that although the melt season duration has modestly changed the melt intensity has substantially increased in the region. As a result, the ratio of warm season cumulative thawing degree days relative to cumulative freezing degree days has nearly doubled over the past decade (Way, 2015; Figure 5C). It would perhaps be more effective if the authors either referenced this finding or calculated melt-season thawing degree days which could be added to Figure 8 Panel A instead of the positive degree day sum. **(2)** I think it might also be worthwhile to mention that there is no particular trend in cold-season precipitation for the region (strengthening the result that mass changes are melt-driven).

(1) We believe that the Positive Degree-Days (PDD), which are widely and commonly used in glaciology, are appropriate as they encapsulate the cumulative effects of both the length and intensity (warmth) of the melt season. A difference between our PDD and the analysis of Way (2015) is the time interval: we used May-November whereas Way (2015) used April-Sept. Our May-November interval was chosen based on the fact that there are almost no PDD at all in April over the period of record, and (b) there are a few in November, particularly in recent years. According to all of this, we think it is out of scope to mention Way's results here.

(2) Different parts of the section 6.3 have been rewritten and we consider the mention of cold-season precipitation to be out of context of our analysis.

Conclusion: P1688L24-26 "…regional warming is linked to strong near-surface warming possibly caused by summer sea ice losses."

Following the rewritten section 6.3, this sentence was modified this way:
'…the ice cap wastage is linked to a strong near-surface regional warming and a lengthening of the melt season into the autumn that is possibly indirectly linked to the later freeze-up in Hudson Strait.'

Comments on Figures:
Figure 2: I believe that Panel C distracts from the focus of this figure, particularly given that there are so many outlines on the two images and also because it overlaps portions of both ice caps. A nearly duplicate figure to that of Panel C is also shown in Figure 8 Panel D. I would suggest that the areal changes provided in Figure 8 Panel D should remain (albeit in an altered form – see comments below) but that Figure 2 Panel C should be added to the Table 2 which could be slightly reconfigured to have both mass balance and area change.

We disagree with the reviewer on this. We believe that the complete figure 2 (with the three panels) makes it easier for readers to follow visually what happened on the maps as well as quantitatively on the graphs below. We however agree that the three different panels had to be slightly rearranged to enhance the readability of the figure. This was done.

Figure 4: The organization of the legend and line graph should be arranged in a more consistent manner as currently they appear to be disorganized.

The map legend and line graphs were rearranged.

Figure 5: (1) Captions b and c need to be rearranged. **(2)** From my perspective I do not believe that Figure 5 Panel A is needed or that it adds a particular amount of insight that could not be gleaned from Figure 5 Panel D currently. We can see from Figure 5B and Figure 5C that elevation changes have accelerated and Panel D emphasizes that**. (3)** Considering the uncertainties in ASTER DEMs I also find the area of elevation gain near the interior of the ice cap to be curious because upper elevations are more likely to be snow covered and therefore be more uncertain in the matching process of DEM generation. Do the icesat validation results for the ASTER DEM used by the authors suggest that accuracy is high at these upper elevations?

(1) Captions of maps B and C were slightly rearranged.

(2) We think that panel A is as valuable as panels B and C because it shows spatial variations of elevations changes for a different time interval. We believe that the three panels together well present historical and recent spatial trends. Following the comments from M. Pelto (see below), we instead decided to incorporate the panel D within the figure 6 because the comparison between historical and recent trends on TNIC is a good complement to the previous figure 6 single graph. The figure 5 thus now only contains three panels and furthermore, panels B and C were swapped.

(3) We understand that the elevation gain in the upper elevations mentioned by the reviewer is on the panel A, where we can see yellow (-0.25 to 0.25 m/yr) in the higher elevations. It might be curious but it is accurate. First, this class interval includes elevation gain and elevation lowering (i.e. -0.25 to 0.25 m/yr). After verification, this section of higher elevations on the ice cap is mainly characterised by little elevation lowering, rather than elevation gain (as we can also distinguished on the previous panel D that is now on figure 6).

Furthermore, looking to the 3B and 3N ASTER images that were used to automatically generate the DEM, the accumulation area is very weakly snow-covered. In fact, the images texture suggest a humid surface, rather than a snow surface, so the image matching was likely successful for the 2007 ASTER DEM (see the figures 1 and 2 below). We don't have any ICESat data from 2007 that covers the accumulation area to verify the accuracy of the DEM in those upper elevations. This said, patterns of d*H/dt* on panels B and C seems coherent and thus, suggest it is also the case for the panel A.

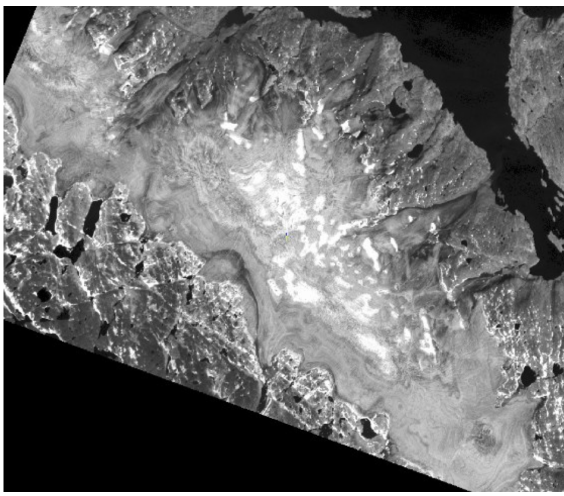

Figure 1. ASTER 3B

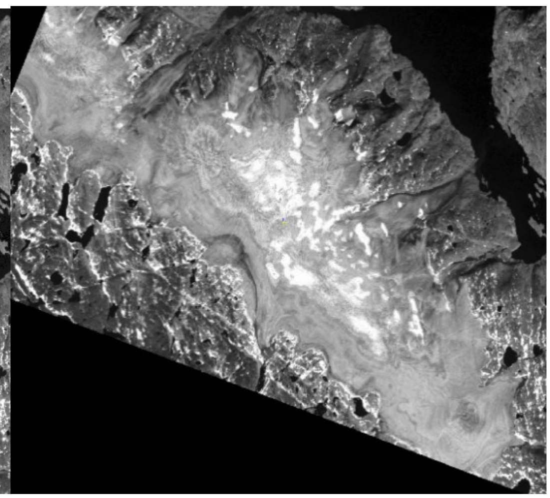

Figure 2. ASTER 3N

Figure 6: Top panel appears to have a portion of the graph cut off on the left.

Done. This figure now contains a second panel that was previously panel D of the figure 5.

Figure 8: I do not particularly like that Figure 8 Panel A has been inverted. I understand the point in that it is inverted to show a similar scale to the other three graphs but I believe that it is more intuitive to flip the scale to make sense (e.g. an increase in positive degree days).

We agree. The axis of this panel has been reversed back.

Figure 8 (1) Panels B and C show very similar results and perhaps should be combined – this would allow for panel A, B (combined) and C to be enlarged which is necessary for Panel D to be interpreted more easily**. (2)** As noted in the discussion of Figure 2, I believe that Panel D in Figure 8 duplicates the results to some degree from that earlier figure. I suggested that Figure 2 Panel C be removed and information be added to Table 2 but that Figure 8 D is retained. I do not necessarily believe that the dots from this study on Figure 8 D be connected by lines as that suggests that the results of this study and those of Way (2015) conflict whereas I believe they are very complimentary. These ice caps undoubtedly show large year to year variations in the amount of late-season snow cover which is why Way (2015) used multiple images for each average. Therefore it is not unexpected that deviations from the best fit lines would occur. The lines also suggest that substantial ice losses would have occurred between the 1950s and the mid-1970 results from Way (2015) whereas I believe that this is somewhat at odds with what is presented in that analysis. I suggest that the dots (all) are connected by a dotted line and that error bars are shown for the area estimates. The enlargement of the figure suggested above would facilitate this to be done and would enable a more useful figure.

(1) Done. Panels B and C were combined

(2) We finally decided to remove panel D of this figure for different reasons. First, it is true that this panel is very similar to the panel C from figure 2 so the added-value of this panel is weak. This is especially important for our paper since it already contains a great number of figures and that in response to the short comment by M. Pelto, another figure was added. Second, there are already many figures about glaciological changes and we find it reasonable that this figure could be only ‘climate-related’. Finally, the comparison of our results with other studies is also already done in the discussion section. Thus, the final figure 8 (newly figure 9) contains two panels: a first panel for Positive Degree-Days and second one for sea ice covered area in both Hudson and Davis Straits.

Short comment from M.S. Pelto

General comment

Papasodoro et al (2015) provide a valuable long term assessment of the changes over a 60 year period on the Grinnell Ice Cap and Terra Nivea Ice Cap. They utilize the recently launched Pleiades 1A and 1B satellites to supplement ICESat, ASTER and Historic aerial photograph based DEM's to assess changes in the glaciers. Two points that deserve more attention and would increase the value of the paper are: 1) Greater attention to the value that Pleiades imagery brought to the project. An additional figure may be needed of a small region to best illustrate this. The conclusion needs a mention of the added value. 2) The lack of a consistent accumulation zone without which a glacier cannot survive should be emphasized. Including reference to Landsat 8 imagery, even if not used in a figure. The thinning rate from 2004-2014 on the upper areas of both ice caps where the accumulation should be indicate that there is not an accumulation zone most years including superimposed ice.

Specific comment:

1670-22: Satellite images can show that this is true. Both 2012 and 2014 images (Fig. 1 and 2) illustrate the lack of retained snowcover. The imagery does not illustrate superimposed ice. However, superimposed ice cannot be retained if year after year there is now no snow or firn remaining. Further there can be no superimposed retained in an environment where ice thickness is being lost at more than a meter per year in the region where it would accumulate, and dynamic thinning is not capable of causing the change.

Visual observations at the summit of Grinnell Ice Cap in the early spring of 2003 and 2004 by one of the authors (CZ) showed that there was superimposed ice (SI) below the seasonal snow cover. It definitely was not firn, nor was it pure glacier ice. If SI was the main form of accumulation for an extended period of time (as probably was the case on this ice cap), it may take a while before it is entirely removed by successive high-melt years. In fact, there may not be any left at present. However, to avoid ambiguity, we decided to delete the sentence about superimposed ice from this paper.

On the following sentence, we added this:

'Hence the summit of the GRIC is probably close, or slightly below, the present-day equilibrium line altitude (ELA), making it highly susceptible to experience net mass losses (Pelto, 2010).'

1681-10: How much of the area change is due to expansion of nunatak/bedrock areas amidst the GIC? This is where the Pleiades imagery could be illustrated to best advantage. For a specific nunatak how accurately can the area be determined using Pleiades versus the Aug. 2014 Landsat 8 ore aerial photographs?

We agree that the use of Pléiades for GCP collecting is an important advance of our paper. We thus added a figure (figure 8) that compares the representation of the same geomorphological feature on ice-free terrain with different technologies, namely an aerial photography (August 1952), a Pléiades panchromatic band (3 August 2014) and a Landsat 8 panchromatic band (15 August 2014). Given our quite long paper, we decided not to insert any new figure or analysis of nunatak determination using Pléiades but only to focus on GCP collection. Also, Way (2015) already focused on nunataks of GRIC.

We added this sentence in the section 6.1 (discussion) for analyze of this figure:

‘Furthermore, the very fine resolution of Pléiades can help to improve the accuracy of nunataks and/or whole ice caps delimitation, especially when compared to the frequently used Landsat images (Fig. 8).’

1682-16: Elevation change rate sharply decreased should be rephrased. The rate elevation loss greatly increased.

Given the negative values, we believe that the correct formulation would be ‘decreased’. However, ‘increased’ is certainly more obvious for those kind of results. We thus used ‘increased’.

1682-23: The change of -1.7 m in elevation at the highest of the icefield indicates the lack of an accumulation zone. This change in elevation would be useful to show in Figure 6. It is more important to show the increase in rate of ice loss in recent years compared to 1952-2014 than simply showing the long term trend. This comparison is shown in the small insets in Figure 4 and 5, but either need their own figure or be shown in Figure 6. Further as Pelto (2010) notes this is a clear indication that neither ice cap can survive current climate, let alone further warming.

We agree with this comment. We thus merged the panel D of figure 5 to the previous figure 6. Those two graphs go well together to compare historical and recent trends.

1683-22: You can use AAR to estimate mass balance based on ELA identification from Satellite imagery. Not suggesting you need to do this, but it is not accurate to say mass balance cannot be estimated.

Reviewer is partially right here because the ELA is above the maximum elevation of Grinnell Ice Cap now so the AAR method could not work for this particular ice cap. However, to avoid ambiguity, we removed this sentence.

1688-7: A key aspect of the paper is utilizing the Pleiades data, can you elaborate here on the advantages that were realized from these DEM’s.

We added this sentence:

‘This approach takes fully advantage of the highly precise Pléiades products and represents an important advance for eventually unlocking the vast archives of historical aerial photographs.’

We also decided to add this sentence to the paper abstract:

‘On a methodological level, our study illustrates the strong potential of Pléiades satellite data to unlock the under-exploited archive of old aerial photographs.’

1684-13: The utility for Ground Control Point position determination is an important advance. At the same time that the nunatak expansion is illustrated, the GCP ability could be illustrated.

This was added, see the comments above.

1688-23: In the areas noted by the three references Kerguelen, Southeast Alaska and Patagonia there is considerable loss by tidewater glacier calving. Further all of these areas have substantial accumulation areas remaining. In the case of GIC and TNIC the snowline is rising above the glacier and there is no calving loss. The ice losses are not sustainable with current climate, since there is no accumulation zone. That is vastly different from the other regions in terms of impact and should be emphasized.

We agree with the reviewer. Thereby, here is the new version of this comparison:

'The 2007-2014 mass balance on the TNIC is among the most negative multi-annual glacier-wide mass balances measured to date, comparable to other negative values observed in the southern mid-latitudes (e.g., Willis et al., 2012; Berthier et al., 2009) or in South-East Alaska (Trüssel et al., 2013). Given the absence of calving for TNIC, its high rate of mass loss can only be explained by negative surface mass balance due to an ELA that, for most years, is above the maximum ice cap altitude. Nonetheless, this similarity in rate of mass loss underlines the strong sensitivity of maritime low-elevation ice bodies to the currently observed climate change at mid-latitudes and in polar regions (Hock et al., 2009).'

Figure 7 Inset maps not needed if transects as on GIC are shown on previous diagram. Then the two glaciers can be combined in a single image for a more robust data set comparison.

We agree, the two glaciers were combined in a single graph with different colors, in order to better compare. We however decided to keep the two maps to help the reader. The final figure is more concise.

Figure 8 Panel D should show mass loss/ice thickness change as that is a more robust measure of the change. Panel A,B, and C show a transition to persistent negative values at the same time, does ice thickness rate show same?

For reasons mentioned above in the reviewer 1 advices and in the main comments, we decided to delete the panel D and to let the Figure 8 (newly figure 9) exclusively 'climate-related'.

2^{nd} reviewer – Alex S. Gardner

Overview and general comment

Papasodoro and coauthors present elevation and area changes for the two southern most ice caps on Baffin Island (Grinnell and Terra Nivea Ice Caps). They use exhaustive multitude of satellite and airborne datasets to reconstruct a sixty-two year record of glacier change. They show that both ice caps have experienced accelerated rates of elevation lowering and area loss in the most recent decades that they attribute to longer melt durations and loss of sea ice in Hudson Bay.

The authors have done a very good job reconstructing glacier changes for the Grinnell and Terra Nivea Ice Caps that confirms and compliments earlier works. Despite their small size, changes in these ice caps provide a good climate proxy for Southern Baffin Island. The authors also analyze elevations generated from Pleiades Satellite imagery and show that they provide good ground control for older imagery.

Overall the paper is in pretty good shape. My two main suggestions for improvement are for the authors to strengthen the attribution section and to carefully review grammar.

Major comments: 1. P1674L23 The RGI outlines for the Grinnell and Terra Nivea Ice Caps come from the CanVec dataset. . . check dates and source imagery provided in that dataset

Sentence was modified this way:

'For 1999, we used the ice cap contour from the Randolph Glacier Inventory (RGI 3.2; Pfeffer et al., 2014), which originates from the Canadian CanVec dataset for this region, itself derived from a September 1999 Landsat 7 image.'

2. P1680L7 I'm not sure that a density of 850 kg/m3 is appropriate for ice caps without significant firn area. I would recommend using a density closer to that of ice unless you can demonstrate that there are likely changes in the firn structure over the period of study.

This is a good point. Following the reviewer advice and after discussions with co-authors, we decided to keep the density constant of 850 ± 60 kg/m3 for the historical mass balance estimation on both ice caps, because we believe it is appropriate to assume that there has been significant firn on the ice caps during the last 60 years. However, we agree with the reviewer for the recent estimation since a brief look at both 2007 and 2014 images of TNIC (not shown here) is showing no significant firn area. Thereby, we instead chose the density constant of 900 ± 17 kg m-3 for this recent period. In the section 4.4.2 and 4.4.3 of the methodology, we modified the sentences this way in the revised manuscript:

'where ρ is the firn and/or ice density. For the historical mass balance of both ice caps, we used ρ = 850 kg m-3 (Huss, 2013), while we used ρ = 900 kg m-3 for the recent period on TNIC (2007-2014). The former value of ρ was chosen assuming that there was a firn zone on the ice cap during the last 6 decades, while a visual interpretation of our images (not shown here) suggests the absence of a significant firn zone after 2007. '

'Finally, an uncertainty of ± 60 kg m-3 (Huss, 2013) was assigned to the density factor when estimating the historical mass balance on both ice caps and of ± 17 kg m-3 (Gardner et al., 2012) for the recent estimation on TNIC.'

Furthermore, the new mass balance value was modified in all the paper.

3. P1686-1689 I would suggest removing any mention of Sea Ice and Arctic Amplification in the attribution section. The link between these two and rates of glacier change are complicated. Sea ice in Hudson Bay is likely responding to warmer spring temperatures but it is unclear how much changes in sea ice extent are in-turn modifying the summer temperatures over the ice caps. Glaciers are responding to warmer temperatures in summer, a period when we expect arctic amplification to be at a minimum. Gardner et al., 2007 and 2012 found that the vast majority of variance in the rate of glacier loss can be attributed to changes in lower-tropospheric temperature.

We consider that for glaciers of Meta Incognita Peninsula, which are located in such close proximity to Hudson Strait (unlike, for example Barnes or Penny Ice Caps), there are good grounds for considering a probable positive feedback associated with the accelerated retreat of sea ice cover, particularly in autumn. This is supported by PDD trends. The main forcing remains summer warming, of course. We have modified section 6 to be more explicit and specific about the possible indirect link to sea ice retreat.

Specific Comments: P1668 Remove acronyms from abstract

Done

P1668 recommend using a different acronym for the Grinnell Ice Cap as GIC is traditionally used for "Glaciers and Ice Caps".

Good point, we changed the GIC acronym to GRIC throughout the paper.

P1668L7 changes -> change Done

P1668L7 in-situ -> in situ Done

P1668L19 "the proximity" -> "the proximity to TNIC." Done

P1668 "In response to the currently observed warming in the Arctic" -> "In response to recent Arctic warming" Done

P1669L2 in 2009 -> during the 2007-2009 period Done

P1669 "An exception is a recent study (Way, 2015) which analyzed the changing rates of areal recession of both GIC and TNIC since the" -> "A recent study (Way, 2015) analyzed changing rates of glacier recession for the GIC and TNIC since the" Done

P1670L1 "data we used" -> "data used to determine glacier change." Done

P1670L2 delete "new" Done

P1670L5 delete "archive" Done

P1670L6 delete "possible" Done

P1670L7 delete "factors" Done

P1670L11 “rising at” -> rising Done

P1670L12 “extent near” -> extent to Done

P1670L15 “range to” -> “range as” Done

P1670L17 “cloudiness” -> “cloud” Done

P1670L20 “reached” -> “is” Done

P1670L22 “formed by in situ” -> “formed by” Done

P1670L23 “showed no firn”, “found no firn” Done

P1670L24 delete “net” Done

P1670L25 rate of surface lowering my melt -> amount of melt Done

P1670L26 very close -> close Done

P1671L13 DEM extraction on glacier -> glacier DEM extraction Done

P1671L20 especially accumulation area -> especially over the low contrast accumulation area Done

P1671L21 “and limit” -> and reduces the Done

P1672L2 delete “due to the more humid surface” Done

P1672L2 delete “This is particularly true for the present images, since the ice caps were nearly winter snow free. Thereby, this is a good qualitative primary concern about the ice caps’ fate (Pelto, 2010) Done

P1672L6 “These stereoscopic” -> Stereoscopic Done

P1672L7 “generation of recent DEMs -> DEM generation Done

P1672L8 “GIC.” -> GIC (Section 3.2). Done

P1672L9 “Archives aerial photos covering” -> “Historic aerial photos for” Done

P1672L11 delete “in this study,” Done

P1672L17 delete “mainly due to the late summer acquisition date.” Modified, see reviewer 1 comments

P1672L19 “elevation on the GIC and were thus -> GIC elevations and were” Idem

P1672L23 define “CDED” Done

P1673L3 An exhaustive validation of CDED for Baffin Island (340 map sheets) is provided in Gardner et al., 2012. They get a bias of +1.1 m and a std of 5.1m Added, see modifications from reviewer 1 suggestion.

P1673L7 “using the derived hillshade in order to exclude obvious false elevations” -> using a derived hillshade to exclude blunder in elevations This sentence was modified to :

Artefacts located in the accumulation areas of the TNIC CDED were manually identified and deleted using a shaded relief image derived from the DEM.

P1673L13 in order to calculate -> To calculate Done

P1673L16 “This DEM” -> “The DEM” Done

P1673L18 “with an horizontal” -> “with a” Done

P1673 did you do any filtering of the ICESat data for cloud returns? Did you apply the Gaussian

centroid bias? No filtering was conducted, only the obvious errors related to cloud were deleted. These error were easily to distinguish because they were of more than a few hundred meters.

P1673L6 were used for recent elevation change calculations -> used to estimate recent elevation changes Done

P1674L12 front of an outlet glacier -> front of one of the outlet glaciers Done

P1674L23 check original RGI source. . . CanVec Corrected, see in general comments

P1675L3 “we rather” -> we Done

P1675L9 August 2014 -> August of 2014 Done

P1675L10 is briefly -> is Done

P1675L12 “In order to” -> “To” Done

P1675L14 station for -> station for the period Done

P1675L24 but only allows reducing the vertical -> but can reduce the vertical Done

P1676L1 can be easily corrected on ice-free terrain with a good reference dataset -> can be corrected over ice-free terrain provided a good reference dataset is available Done

P1676L17 is thus expected -> is expected Done

P1676L24 The typical -> A typical Done

P1677L18 “Quantitatively, 66% of the GIC area was extracted with data gaps concentrated at the highest elevation in the texture-less accumulation areas” -> “66% of the GIC area was extracted with data gaps concentrated at the highest elevation in the texture-less accumulation areas” Done

P1677L22 DEM-based mass balance -> DEM based volume change Done

P1677L4 To evaluate the corrections constancy -> to evaluate the constancy of the corrections Done

P1677L5 DEMs -> DEM Done

P1677L10 delete “for such small zones.” Done

P1677L11 “Furthermore, the” -> “The” Done

P1677L11 DEM -> DEMs Done

P1677L12 subtracted -> differenced Done

P1677L14 These results prove -> these results confirm Done

P1679L1 delete “are useful to” Modified to ‘were used to’

P1679L4 delete “ using different DEMs in order” Done

P1679L5 “and mass balances” -> “from the DEMs” Done

P1679L7 delete “first” Done

P1679L7 delete “in order” Done

P1679L8 changes -> change Done

P1679L8 “, of elevation” -> “and elevation Done

P1679L9 “The no value pixels were assigned to the mean dH of the corresponding elevation band. Total volume change for an ice cap (dV) was then assessed by summing volume changes from all elevation bands (n) as follows:” -> “No value pixels were replaced with the mean dH of the corresponding elevation band. Total volume change for each ice cap (dV) was then determined by summing volume changes from all elevation bands (n) as follows:” Done in a slightly different way : *‘Pixels with missing data were replaced with the mean dH of the corresponding elevation band. Total volume change for each ice cap (dV) was then determined by summing volume changes from all elevation bands (n) as follows’*

P1679L18 “Sensibility” -> “Sensitivity” Done

P1680L7 a mean density of “850 kg/m3” is very low for an ice cap that has little to no firn area. I would recommend a value closer to that of pure ice. See our response to general comments

P1681L25 “has shrunk” = “shrank”, apply through entire document Done

P1682L6 delete “ “,a less pronounced rate when compared to” . . . start new Sentence Done

P1682L15 “(Fig. 5,uppser left map)” -> (Fig. 5a) Done

P1681L26 “with a reasonable” -> “with reasonable” Done

P1686/7 Lower tropospheric warming from advection of continual air masses in summer have been previously implicated in accelrated CAA glacier melt rates (Gardner et al, 2007 and Gardner et al., 2012) References added in the sentence.

P1686 Not sure if there is a clear link for changes in sea ice to be driving glacier melt rates. More thought need to given to link Arctic Amplification and Sea Ice to glacier changes. I would suggest that the authors revisit this section in its entirety.

This section was revisited and modified. All the mentions to arctic amplification were deleted. The sea ice impact explanation was limited to an additional contribution to stronger glacier melt, after the summer temperatures.

Figure 3 add “no data” to legend.

Adding no data colors to maps was too much altering the quality of maps. Instead, we add this mention in the description of the figure 3: *'For this figure as well as for the next ones, no color (i.e. hillshade is visible) represent no data'*

Area, elevation and mass changes of the two southernmost ice caps of the Canadian Arctic Archipelago between 1952 and 2014

C. Papasodoro[1], E. Berthier[2], A. Royer[1], C. Zdanowicz[3], A. Langlois[1]

[1] Centre d'Applications et de Recherches en Télédétection, Université de Sherbrooke, Sherbrooke, Québec, Canada. Centre d'Études Nordiques, Québec, Canada.

[2] Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique (LEGOS – CNRS, UMR5566), Université de Toulouse, 31400 Toulouse, France

[3] Department of Earth Sciences, Uppsala University, 75236 Uppsala, Sweden

Correspondence to Charles Papasodoro: charles.papasodoro@usherbrooke.ca

Abstract

Grinnell and Terra Nivea Ice Caps are located on southern Baffin Island, Nunavut, in the Canadian Arctic Archipelago. These relatively small ice caps have received little attention compared to the much larger ice masses further north. Their evolution can, however, give valuable information about the impact of the recent Arctic warming at lower latitudes (i.e. ~62.5° N). In this paper, we measure or estimate historical and recent changes of area, elevation and mass of both ice caps using in situ, airborne and spaceborne datasets, including imagery from the Pléiades satellites. The area of Terra Nivea Ice Cap has decreased by 34% since the late 1950s, while that of Grinnell Ice Cap has decreased by 20% since 1952. For both ice caps, the areal reduction accelerated at the beginning of the 21st century. The estimated glacier-wide mass balance was -0.37 ± 0.21 m a^{-1} water equivalent (w.e.) over Grinnell Ice Cap for the 1952-2014 period, and -0.47 ± 0.16 m a^{-1} w.e. over Terra Nivea Ice Cap for the 1958/59-2014 period. Terra Nivea Ice Cap has experienced an accelerated rate of mass loss of -1.77 ± 0.36 m a^{-1} w.e. between 2007 and 2014. This rate is 5.9 times as negative when compared to the 1958/59-2007 period (-0.30 ± 0.19 m a^{-1} w.e.) and 2 times as negative when compared to the mass balance of other glaciers in the southern parts of Baffin Island over the 2003-2009 period. A similar acceleration in mass loss is suspected for the Grinnell Ice Cap, given the calculated elevation changes and the proximity to Terra Nivea Ice Cap. The recent increase in mass loss rates for these two ice caps is consistent with trends across the Canadian Arctic Archipelago and is linked to a strong near-surface regional warming and a lengthening of the melt season into the autumn that may be indirectly strengthened by a later freezing of sea ice in the Hudson Strait sector. On a methodological level, our study illustrates the strong potential of Pléiades satellite data to unlock the under-exploited archive of old aerial photographs.

Keywords: Canadian Arctic Archipelago, Grinnell Ice Cap, Terra Nivea Ice Cap, Baffin Island, mass balance, Pléiades satellites

1. Introduction

With a glacierized area of ~150 000 km², the Canadian Arctic Archipelago (CAA) is one of the major glacier regions in the world (Pfeffer et al., 2014). In response to recent Arctic warming (Tingley and Huybers, 2013; Vaughan et al., 2013; Comiso and Hall, 2014), glaciers in the CAA have experienced an acceleration in their mass loss. For the southern parts of the CAA, annual thinning of glaciers has doubled between the historical (1963-2006) and recent (2003-2011) periods (Gardner et al., 2012). Over the entire CAA, the rate of mass change has tripled between 2004 and 2009, reaching -92 ± 12 Gt a^{-1} during the period 2007-2009 (Gardner et al., 2011), making this region one of the main contributors to eustatic sea-level rise for this period, after Greenland and Antarctica (Gardner et al., 2013; Vaughan et al., 2013). Continued monitoring of CAA glaciers is thus critical.

Located in the southeastern part of the CAA, Baffin Island is the largest island of the archipelago (Andrews et al., 2002) and has a total ice-covered area of ~37 000 km². In addition to two major ice caps, Barnes (~5 900 km²) and Penny (~6 400 km²), Baffin Island is also covered by a number of isolated icefields and small ice caps, including Grinnell Ice Cap (GRIC) and Terra Nivea Ice Cap (TNIC) on Meta Incognita Peninsula, at the southernmost tip of the island (Fig. 1). Compared to Barnes and Penny Ice Caps, GRIC and TNIC have received little scientific attention so far (Andrews et al., 2002). Different in situ geophysical measurements were carried out in the 1950s (Blake, 1953; Mercer, 1956), and in the 1980s by teams from Cambridge University and the University of Colorado (Dowdeswell, 1982; 1984). Under the supervision of veteran Norwegian glaciologist Dr. Gunnar Østrem, other measurements were conducted on GRIC in the early 1990s by a scientific team from Bates College (Maine, U.S.A.) and Nunavut Arctic College. Later in 2003-04, glaciologists from the Geological Survey of Canada carried out in situ measurements on GRIC (Global Navigation Satellite System (GNSS) elevation measurements, automatic weather observations, snow depth and surface mass balance measurements) with the objective to establish a long-term observing site. However, consistent prohibitive weather conditions coupled with difficult access to the ice cap led to the cancellation of the project (Zdanowicz, 2007). A recent study (Way, 2015) analyzed changing rates of glacier recession for GRIC and TNIC since the 1950s using historical aerial photographs, satellite (Landsat) imagery and digital elevation models (DEM). In the present study, we supplement these results by presenting a comprehensive analysis of historical and recent fluctuations of area, surface elevation and mass for GRIC and TNIC over the period 1952-2014. This is done by combining data from spaceborne instruments (laser altimetry and optical stereo imagery), DEMs, airborne imagery (air photos) and in situ (differential GPS) surveys. Our analysis differs from that of Way (2015) in the choice of photos, DEMs, and spaceborne, remotely-sensed data used to determine glacier change. In particular, we explored the use of sub-meter resolution stereo pairs obtained from the Pléiades satellites to derive DEMs and to collect accurate, numerous and homogeneously distributed ground control points (GCPs) for the photogrammetric processing of aerial photos. We place our findings in the context of the observed pattern of regional glacier changes across the CAA, and discuss climatic forcing factors of particular relevance for the southernmost Baffin Island region.

2. Study area

GRIC and TNIC (Fig. 1) are located on Meta Incognita Peninsula, 200 km south of Iqaluit, Nunavut. GRIC (62.56° N, 66.79° W) covers an area of 107 km² (August 2014; this study) with the highest elevations rising 800 m above sea level (a.s.l.). On the northeast side, some outlet glaciers extend to Frobisher Bay, which opens into the Labrador Sea. TNIC (62.27° N, 66.51° W) is located ~17 km south of the GRIC. It covers an area of approximately 150 km² (August 2014; this study) with a similar elevation range as GRIC. Mercer (1954) suggested three factors supporting the continued presence of plateau ice caps on Meta Incognita Peninsula: (1) cool summers (2) frequent low-level cloud and (3) heavy snowfall. Data from the permanent weather station in Iqaluit (34 m a.s.l.) indicate that winter temperatures (DJF) in this region averaged -24°C over the past 60 years, while mean summer temperatures (JJA) averaged 6.5°C. Total annual precipitation is ~500 mm (snow: ~300 mm; rain: ~200 mm). Field observations in winter 2003-04 found no firn at the summit of GRIC, and the estimated winter snow accumulation there (~2-3 m snow; or ~0.65-0.75 m water equivalent) was approximately equal to the amount of melt in summer (Zdanowicz, 2007). Hence the summit of the GRIC is probably close, or slightly below, the present-day equilibrium line altitude (ELA), making it highly susceptible to experience net mass losses (Pelto, 2010).

Observations from various expeditions in the 1950s revealed that the western margin of GRIC was relatively stable, but that coastal outlet glaciers (eastern margin) were shrinking moderately when compared to photographs from 1897 (Mercer, 1954, 1956). Moraines studied near both ice caps in the early 1980s indicated that the most recent phase of recession dated from the last 100 years, and that both ice caps probably reached their largest areal extent during the Little Ice Age cold climate interval (Muller, 1980; Dowdeswell, 1982, 1984; Andrews, 2002). Dowdeswell (1982) estimated that the outlet glacier of GRIC that calves into Watts Bay extended much further out a few centuries earlier, but also reported that another outlet glacier to the south of the ice cap was advancing.

3. Data

3.1 Pléiades stereoscopic images

Launched respectively on December 17th, 2011 and December 2nd, 2012, the Pléiades 1A and 1B satellites have recently shown their high potential for glacier DEM extraction and thus, for mass balance estimations (Wagnon et al., 2013; Berthier et al. 2014; Marti et al., 2015). The two satellites follow the same near-polar sun-synchronous orbit and provide panchromatic and multispectral imagery at a very high ground spatial resolution, 0.7 m for panchromatic and 2.8 m for multispectral images, respectively (Astrium, 2012). Both satellites have independent stereoscopic capabilities. The fact that the panchromatic band images derived from Pléiades satellites are coded in 12 bits represents a clear advantage on a glacier surface (especially over the low contrast accumulation area), given the fact that a large radiometric range provides better contrast and reduces the risk of image saturation (Berthier et al., 2014).

Three stereoscopic pairs were acquired over our study area (Table 1): one for GRIC (August 3rd, 2014) and two for TNIC (August 14th, 2014 for the eastern part and August 26th, 2014 for the western part, with an overlapping area of 84 km²). The stereoscopic pair covering GRIC is cloud-free, while a few clouds (< 10% of the scene) were present over TNIC during scene acquisitions (Fig. 2). Acquisitions were made at the end of the ablation season to ensure a maximum degree of surface texture (Berthier and Toutin, 2008). Each image was provided with Rational Polynomial Coefficients (RPCs), which allows geometric modeling without GCP. Stereoscopic pairs were used (1) for DEM generation on both ice caps and (2) for GCP extraction for the photogrammetric processing of the historical aerial photos on GRIC (See Sect. 4.2).

3.2 Historic Canadian Digital Elevation Data

Historic Canadian Digital Elevation Data (CDED, Natural Resources Canada), provided at a scale of 1:50k, were acquired for the two ice caps. These elevations were derived by stereo-compilation of aerial photos acquired during summers 1958 and 1959. Raw elevations are orthometric and referenced to the Canadian Gravitational Vertical Model of 1928 (CGVD1928). The average elevation differences and their standard deviation (SD) between CDED and ICESat laser altimetry were previously calculated off glacier for 340 CDED maps tiles covering Baffin Island and were reported to be 1.1 m and 5.1 m, respectively (Gardner et al., 2012). Here, CDED were used (1) as historical elevations for TNIC and (2) elevations of the surrounding ice-free terrain were used for absolute coregistration for both ice caps (see Sect. 4.3). Artefacts (unrealistic elevations) located in the accumulation area of TNIC were manually identified and deleted using a shaded relief image derived from the DEM. These artefacts were likely due to the poor contrast and low texture of the 1958/59 aerial photos used to generate the CDED.

3.3 Historical aerial photos

Historic aerial photos covering GRIC were obtained through the Canadian National Air Photo Library (Natural Resources Canada). We used 24 photos acquired at the end of the ablation season, on August 21st and 22nd, 1952. A Williamson Eagle IX Cone 524 camera type with a focal length of 152.15 mm was used and the flight altitude was 16 000 ft (4879 m). The photos are distributed in 3 parallel flight lines with an overlapping coverage of ~30% between each line and ~60% between two photos of a same line. These photos, exceptional in their quality of detail and texture, were used for the extraction of historical elevations on GRIC and were preferred to the CDED for this ice cap. In fact, the CDED covering GRIC contained major artefacts (i.e. much larger than for TNIC) in the large snow-covered accumulation zone where the texture was particularly weak on the 1958 photos and thus, was not suitable for historical elevations of this ice cap.

3.4 ICESat altimetric points

Surface elevation profiles (GLA14, Release 634) collected by the Geoscience Laser Altimetry System (GLAS) onboard ICESat were acquired (Zwally et al., 2002). Each laser pulse-derived footprint corresponds to field-of-view with a diameter of ~65 m and a spacing of 172 m between each footprint (Schutz et al., 2005). ICESat elevations were converted from their original Topex Poseidon ellipsoid to the WGS84 ellipsoid using tools provided by the National Snow and Ice Data Center. The entire dataset (2003 to 2009) was used for absolute coregistration on ice-free terrain, while the data collected during a few selected dates (Table 1) were used to estimate recent elevation changes and to assess the precision of the ASTER August 2007 DEM (see below).

3.5 ASTER DEM

Products derived from the ASTER satellite mission have been widely used for glaciological studies (e.g., Kääb, 2008; Nuth and Kääb, 2011; Das et al., 2014). To estimate the recent mass balance for TNIC, we used a DEM (product AST14DMO) generated from an ASTER stereo pair acquired on August 3rd, 2007. The DEM was automatically derived from bands 3N (nadir-viewing) and 3B (backward-viewing) that have an intersection angle of 27.6°, which corresponds to a Base-to-Height ratio of 0.6 (Fujisada et al., 2005). The raw DEM was provided with a grid spacing of 30 m, and elevations are orthometric to the EGM96 geoid. Using 57 ICESat points from two different time periods, namely a few months before (April 2007) and after (November 2007) the ASTER acquisition, we assessed a vertical precision of 2.5 m (SD) on TNIC for this ASTER DEM. Due to cloud coverage, no suitable ASTER DEM was available for GRIC at the end of the ablation season.

3.6 In situ GPS measurements

In April 2004, a team from the Geological Survey of Canada measured three surface elevation profiles at 50-m horizontal intervals using a Trimble® high-precision Real-Time Kinematic (RTK) GPS system on the southeast, west and northwest sides of GRIC, and at the front of one of its outlet glaciers (Zdanowicz, 2007). Data acquisition was made using a fixed base station on a geodetic benchmark monument, and GPS positions were subsequently processed with the Canadian Center for Remote Sensing's Precise Point Positioning (PPP) System to obtain an accuracy of a few cm. For this paper, those transects were used for recent elevation change calculations. It is known that elevations calculated using a PPP System and referenced to the GRS80 ellipsoid can be assumed equal to the WGS84 ellipsoid (sub-mm differences).

3.7 Glacier outlines

Various datasets have been used to extract the areal extent of the two ice caps at the end of the ablation season (August/September). For GRIC, three datasets from different dates were used. The 1952 outline was derived manually from the orthorectified historical aerial photos. For 1999, we used the ice cap contour from the Randolph Glacier Inventory (RGI 3.2; Pfeffer et al., 2014), which originates from the Canadian CanVec dataset for this region, itself derived from a September 1999 Landsat 7 image. We manually digitized the 2014 margin from the orthorectified panchromatic Pléiades image. For TNIC, outlines were derived for four different dates. We used the raw vectors from the 1:250k Canadian National Topographic Data Base as the 1958/59 boundary. Anomalies were found in the delineation of the 1999 margin from the RGI 3.2 (i.e. off-glacier snow patches erroneously included). As an alternative, we manually digitized the ice cap margin using a 30-m resolution Landsat 5 image acquired on August 1998. The August 2007 limit was manually traced from an ASTER orthoimage (15 m resolution) provided with the on-demand AST14DMO product, while the 2014 margin was extracted from the orthorectified panchromatic Pléiades images (East and West). To decrease the effect of cloudiness on the Pléiades orthoimages (~20% of the ice cap outline obscured by clouds), we used a Landsat 8 panchromatic (15 m of resolution) image also acquired in August of 2014. The uncertainty assessment of the outlines is presented in section 4.4.3.

3.8 Meteorological and sea ice records

To quantify changes in the regional climate of the southern Baffin Island region over the period covered in our study, air temperature records were retrieved from the Adjusted and Homogenized Canadian Historical Climate Data of the Iqaluit weather station for the period 1950-2014 (Vincent et al., 2002). This is the permanent weather station in the eastern Canadian Arctic with the most continuous records, extending back to 1946. In addition, time series of sea ice cover area for Hudson Strait and Davis Strait were obtained from the Canadian Ice Service archives over the 1968-2014 period.

4. Methods

4.1 Pléiades DEM generation

The Pléiades DEMs were generated using the OrthoEngine module of Geomatica 2013. No GCP were available for the geometric correction so we relied on the RPCs provided with the images. Adding GCP does not improve the vertical precision of the Pléiades DEM, but can reduce the vertical bias (Berthier et al., 2014). The latter bias can be corrected over ice-free terrain when a good reference dataset, such as ICESat, is available (Nuth and Kääb, 2011).

The following steps of DEM extraction were repeated for the 3 Pléiades stereoscopic pairs. First, we collected 20 tie points (TPs) outside and 6 on the ice cap. Collecting well-distributed TPs was found to improve the relative orientation between the two images providing increased coverage (Berthier et al., 2014). For the DEM extraction, the following processing parameters were used in

OrthoEngine: the relief type was set to *Mountainous* and the DEM detail to *Low*. No interpolation was performed to fill data gaps. Finally, the DEMs were geocoded with a pixel size of 4 m.

Since the ice-free zones on our Pléiades DEM were not large enough to calculate an elevation accuracy with a sufficient number of ICESat points, we report here the vertical precisions obtained in recent glaciological studies. For example, Wagnon et al. (2013) measured a precision of 1 m (SD) on a glacier surface in Himalaya using Pléiades DEM. Berthier et al. (2014) also obtained a precision ranging between 0.5 and 1 m (SD), highlighting the consistent precision over glacier surfaces. This precision was shown to be mostly correlated with slope. For the small Ossoue Glacier (French Pyrénées), the precision was slightly lower at 1.8 m (Marti et al., 2015). A similar vertical precision is expected here.

4.2 Aerial photos DEM generation

Photogrammetry is widely used in glaciological studies for reconstructing glacier surface prior to the modern satellite era (Fox et Nuttall, 1997; Barrand et al., 2009). In this study, a 1952 DEM of GRIC was created from historical air photos using OrthoEngine. This software uses a mathematical model compensating for both terrain variation and inherent camera distortions (PCI Geomatics, 2013). A typical photogrammetric procedure was then followed to compute the model, solving the least-square bundle adjustment.

Collecting effective GCPs for photogrammetry in mountainous or polar regions remains one of the main difficulties, especially for archive photos (Barrand et al., 2009). To overcome this difficulty, Pléiades derived products (DEM and orthoimage) were used to collect GCPs. For each aerial stereoscopic model partially covering the surrounding ice-free terrain, 3 to 7 GCPs were collected outside the ice cap on topographic or geomorphologic structures visible on both the Pléiades orthoimage and the aerial photographs. In order to strengthen the mathematical model, every GCP was collected as stereo GCP (i.e. was identified in all possible aerial photographs). A total of 39 stereo GCPs were collected resulting in 106 GCPs. Also, 6 to 10 widely-dispersed TPs were collected for each aerial stereoscopic model. For the models situated in the middle of the photogrammetric block and covering only the ice cap (no ice-free terrain), only TPs were collected in order to connect them to the photogrammetric block. After the final bundle adjustment, the resulting residual averages of all the GCPs were 2.85 m in X, 2.74 m in Y and

2.68 m in Z. TPs residuals were 1.84 m in X and 2.15 m in Y. The generated global DEM was geocoded with a grid resolution of 10 m and no interpolation of data gaps was performed.

Validation of the resulting DEM (before coregistration) against 76 ICESat points on ice-free terrain showed a mean offset of -3.29 m (DEM above ICESat in elevations) and a SD of 4.96 m. Between the Pléiades DEM and the 1952 DEM (coregistered together, see section 4.3), the SD of the elevation difference on ice-free terrain was 13.8 m. In total, 66% of GRIC area was extracted, with data gaps concentrated at the highest elevations in the texture-less accumulation area.

4.3 DEM adjustments and coregistrations

DEM coregistration is of primary importance before performing any DEM based volume change calculations (Nuth and Kääb, 2011). This 3D coregistration method uses the relationship between aspect, slope and elevation differences over ice-free terrain (Nuth and Kääb, 2011). The Pléiades images only included a small corridor (~20 km²) of ice-free terrain near the ice caps (Fig. 2). This corridor coincides with limited number of cloud-free ICESat points (less than 100 points sparsely distributed around each ice cap) so that a direct coregistration between the Pléiades DEM and ICESat was not optimal. Instead, the CDED tile encompassing the two ice caps was first coregistered with approximately ~1000 ICESat points over ice-free zones. All other DEMs were then 3D coregistered to the corrected CDED, independently for each ice cap, and the corrected datasets were referenced to the WGS84 ellipsoid. To evaluate the consistency of the corrections, the offsets over ice-free terrain between each corrected DEM and the corresponding ICESat points were examined. The offset was below 1.5 m in each case, suggesting that the absolute coregistration was well conducted and that the effect of geoid variations (CGVD1928 and EGM96 vs WGS84) was negligible. However, one must interpret these results with caution given the sparsely distributed and limited number of ICESat points (less than 100) over moderate to hilly terrain.

The two independently coregistered Pléiades DEMs of TNIC (August 14th and 26th) were compared in their overlapping zone of 84 km^2 (Fig. 2). The offset measured over the ice-free terrain was -0.1 ± 2.1 (SD) m, while an average elevation difference of -0.64 ± 2.2 (SD) m was measured over the ice cap, probably due to the thinning between August 14th and 26th. These results confirm the robustness of the 3D coregistration using the corrected CDED DEM.

4.4 Elevation changes and mass balance calculations

4.4.1 Elevation changes along ICESat and GPS tracks

For both Grinnell and Terra Nivea Ice Caps, recent elevation changes were measured between 6 ICESat tracks from different laser overpass periods (autumn 2003 to winter 2007) and the 2014 Pléiades DEMs. For GRIC only, elevation changes were also calculated between the April 2004 in situ GPS transects and the 2014 Pléiades DEM. We did not attempt to compute glacier-wide volume or mass changes from those recent elevation changes measurements since (i) they are sparse and only cover a small fraction of the two ice caps and (ii) the GPS and some of the ICESat data were acquired at the end of winter, and limited data were available to apply a seasonal correction. Nevertheless, those recent elevation changes along selected tracks were used to complement the differential DEM analysis described below.

4.4.2 DEM derived elevation changes and mass balances

The geodetic method was applied in order to calculate glacier-wide elevation and mass balances from the DEMs. The following steps were performed for each calculation.

First, the coregistered DEMs were subtracted to obtain maps of elevation changes (*dH*) and change rates (*dH/dt*) after dividing by the interval time (*dt*). The *dH* values were binned into 50 m elevation bands and averaged after applying a three sigma filter to exclude outliers (Gardner et al., 2012; Gardelle et al., 2013). Pixels with missing data were replaced with the mean *dH* of the corresponding elevation band. Total volume change for each ice cap (*dV*) was then determined by summing volume changes from all elevation bands (*n*) as follows:

$$dV = \sum_i^n (\Delta H_i \cdot A_i), \qquad (1)$$

where i corresponds to an elevation band of 50 m, ΔH is the mean elevation change measured at elevation band i and A_i is the area of the elevation band. In this calculation, the ice cap hypsometry is based on the 1:250k CDED (1958/59), while the ice cap limit is conform to the year of the oldest DEM used in the calculation. Our own sensitivity tests have shown that the choice of the DEM used has a very low impact on the mass balance calculation (< 0.01 m a^{-1} w.e.), as was also demonstrated in Gardner et al. (2011).

The area-averaged change in elevation over the entire ice cap (glacier-wide), dH/dt_{avg}, was then calculated as follows:

$$dH/dt_{avg} = \frac{dV}{(\bar{A} \cdot \Delta t)}, \tag{2}$$

where $\bar{A}$ is the mean of the initial and final ice cap areas, and Δt is the time interval between the two DEMs. Note that *dH/dt* (elevation change rate from coregistered DEM subtraction) must be distinguished from dH/dt_{avg}.

Finally, the area-averaged specific geodetic mass balance rate (m a^{-1} w.e.), dM/dt, was calculated as follows:

$$dM/dt = dH/dt_{avg} \cdot \rho, \tag{3}$$

where ρ is the firn and/or ice density. For the historical mass balance of both ice caps, we used ρ = 850 kg m^{-3} (Huss, 2013), while we used ρ = 900 kg m^{-3} for the recent period on TNIC (2007-2014). The former value of ρ was chosen assuming that there was a firn zone on the ice cap during the last 6 decades, while a visual interpretation of our images (not shown here) suggests the absence of a significant firn zone after 2007. For the sake of readability, the area-averaged specific geodetic mass balance rate (Cogley et al., 2011) is hereafter simply referred as mass balance or glacier-wide mass balance.

4.4.3 Accuracy assessment

The main sources of uncertainty in our mass balance estimates are related to uncertainties in the elevation change measurements, the ice cap limits and the density used to convert volume to mass changes. For historical measurements, elevation change uncertainty was assumed equal to the standard deviation over stable terrain between the two coregistered DEMs (GRIC 1952-2014: 13.8 m; TNIC 1958-2007: 9.6 m; TNIC 1958-2014: 9 m), assuming that elevation errors were 100% correlated. This is a conservative approach that takes into account both the highly correlated CDED elevation errors (Gardner et al., 2012) and the possible errors associated to the aerial photos-derived DEM (i.e. artefacts and low coverage at higher altitudes).

Spatial autocorrelation between the ASTER 2007 and Pléiades 2014 DEMs was analyzed on ice-free terrain to better characterize the elevation change uncertainty in the recent mass balance estimation on TNIC. A low autocorrelation distance (< 100 m) was found between the two elevation products. Applying standard principles of error propagation (e.g., Zemp et al., 2013), we found a very low (± 0.1 m) uncertainty for the elevation change averaged over the entire ice cap. Because we consider this value to be likely underestimated, we conservatively assumed that the uncertainty for the elevation changes is equal to the quadratic sum of the two DEMs uncertainties (± 1 m for the Pléiades DEM from Berthier et al. (2014) and ± 2.5 m for the ASTER DEM from its comparison to ICESat nearly simultaneous on the ice cap), assuming that (i) the elevation errors are fully correlated within each DEM and that (ii) errors of the two DEMs are independent.

For ice caps outlines of 1998 and later, we estimated an error of 3%. This estimate includes possible image interpretation errors (< 2% of each ice cap extent) and the impact of the image resolution used for outline delimitation (< 1% of each ice cap extent). Since the ice caps were not covered by debris, interpretation errors were mainly related to the presence of snow-covered surfaces (i.e. snow patches) around each ice cap that may be misinterpreted as ice. The error attributed to the image resolution was established from a comparison analysis made between the Pléiades and Landsat 8 derived TNIC outlines, for which a small difference in extent was obtained (< 1%). The total uncertainty of 3% was used for mass balance estimation as well as for area change analysis. For the older (pre-1998) ice cap outlines, a more conservative error of 5% was applied to take into account the more difficult image interpretation between ice cap limits and snow patches. Those uncertainties are comparable to those reported in Paul et al. (2013) and Winsvold et al. (2014). Finally, an uncertainty of ± 60 kg m^{-3} (Huss, 2013) was assigned to the density factor when estimating the historical mass balance on both ice caps and of ± 17 kg m^{-3} (Gardner et al., 2012) for the recent estimation on TNIC.

5. Results

5.1 Area changes

Areal changes measured for Grinnell and Terra Nivea ice caps since the 1950s are shown in Fig. 2. GRIC experienced a mean rate of areal change of -0.10 ± 0.01 km^2 a^{-1} between 1952 and 1999, whereas a mean rate of -0.59 ± 0.03 km^2 a^{-1} is measured for TNIC between 1958/59 and 1998. These rates of area change have been significantly more negative since 1998/99 reaching -1.37 ± 0.04 km^2 a^{-1} for GRIC and -1.69 ± 0.05 km^2 a^{-1} for TNIC. For GRIC, the 2014 areal extent is about 20% smaller than in 1952, while TNIC area shrank by 34% between 1958/59 and 2014.

5.2 Elevation changes

Maps of historical and recent elevation change rates (*dH/dt*) for the two ice caps are presented in Figs. 3 to 5 (whole ice cap) and Figs. 4 and 6 (changes by elevation).

The glacier-wide rates of elevation change (dH/dt_{avg}) over the period 1952-2014 were -0.44 ± 0.25 m a^{-1} for GRIC and -0.56 ± 0.19 m a^{-1} for TNIC. Similar patterns of historical *dH/dt* are observed for both ice caps (Fig. 6 and *dH/dt* maps), revealing an average surface lowering reaching -1.1 ± 0.25 m a^{-1} for GRIC and -0.9 ± 0.19 m a^{-1} for TNIC in the lower altitudes (i.e. the outlet glaciers in the peripheries). Above 250 m a.s.l., the thinning rate was consistently 0.1 m a^{-1} more negative for TNIC than GRIC. The surface thinning was similar for all outlet glaciers of GRIC between 1952 and 2014 (Fig. 3), while on TNIC, a stronger lowering (< -1 m a^{-1}) was experienced on the northeast outlet glaciers between 1958/59-2007 (Fig. 5a).

Elevation change rates sharply increased in recent years for both ice caps. On TNIC, the recent (2007-2014) dH/dt_{avg} was -1.97 ± 0.40 m a^{-1}, a rate ~5.6 times as negative as the rate of -0.35 ± 0.22 m a^{-1} measured between 1958/59 and 2007. The acceleration of the thinning rate was particularly pronounced at lowermost elevations (-6.7 ± 0.40 m a^{-1} between 2007 and 2014 vs. -0.9 ± 0.22 m a^{-1} between 1958/59 and 2007), but was also unambiguously observed in the upper sections of the accumulation area (-1.7 ± 0.40 m a^{-1} between 2007 and 2014 vs. -0.3 ± 0.22 m a^{-1} between 1958/59 and 2007).

On GRIC, changes in *dH/dt* were evaluated over the periods 1952-2004 and 2004-2014 using overlapping areas of the 1952 DEM, in situ GPS measurements and ICESat transects (2004), and the Pléiades DEM (2014) (Fig. 4). Because of the lack of data about seasonal surface height fluctuations, no correction was applied to account for the different elevation acquisition periods of 1952 and 2014 (August) and 2004 (March/April). For the 203 points where elevation measurements are available for the three years (points superposed with black dots on Fig. 4), the *dH/dt* was up to 6 times more negative over the 2004-2014 period (-1.47 m a^{-1}) than over the 1952-2004 period (-0.25 m a^{-1}).

Additionally, elevation changes measured between ICESat repeat track transects and the Pléiades DEM over both GRIC and TNIC between 2003 and 2014 are shown in Fig. 7. This analysis reveals a similar range of variability of annual elevation changes between both ice caps during the 2003-2007 interval and a coherent pattern of seasonal to inter-annual fluctuations. The absolute difference in elevation change between 2003 and 2014 for the two ice caps (total thinning of ~11 m for GRIC vs ~16 m for TNIC) is likely at least partly explained by the fact that ICESat transects covering GRIC were located at higher altitudes (mean: ~65 m higher) than those over TNIC.

5.3 Mass balances

Mass balances for both ice caps are summarized in table 2. Between 1952 and 2014, a mass balance of -0.37 ± 0.21 m a^{-1} w.e. was estimated for GRIC. For TNIC, the historical mass balance (1958/59-2014) was more negative at -0.47 ± 0.16 m a^{-1} w.e.. The mass loss rate for the period 2007-2014 was 5.9 times greater (mass balance: -1.77 ± 0.36 m a^{-1} w.e.) than that for the period 1958/59-2007 (mass balance: -0.30 ± 0.19 m a^{-1} w.e.). As previously discussed (section 5.2), GRIC has likely experienced a similar acceleration of its mass loss since 2004.

6. Discussion

6.1 Pléiades as a tool for photogrammetric GCPs collection

In many regions of the world, vast archives of historical aerial photographs represent a potential gold mine for glaciologists in order to document multi-decadal volumetric change of glaciers and ice caps (e.g., Soruco et al., 2009; Zemp et al., 2010). DEMs generated from these aerial photographs allows to put the recent glacier variations (satellite era) in a longer-term perspective. However, these data remain difficult to exploit due to the logistical difficulties involved in the field collection of accurate and well-distributed GCPs in the remote high latitude or high altitude regions. Field GCPs were also lacking for the two ice caps studied here. Instead, we took advantage of the very high resolution of the Pléiades imagery (0.7 m) and the vertical precision of the derived DEMs (~ 1 m) to collect a sufficient number of GCPs for the adjustment of the stereo-model. GCPs were collected on well-defined features that were clearly identifiable on both the Pléiades imagery and the old aerial photos (Fig. 8, yellow arrow). GCP residuals of ~2-3 m in average were obtained after the block bundle adjustment, and a DEM vertical precision of ~5 m (SD) was measured with a few ICESat points available over ice-free terrain. This is a satisfactory result given that the aerial photos used here were affected by film distortions that could not be corrected. Our results demonstrate the usefulness of Pléiades stereo-images and DEMs to collect accurate GCPs for photogrammetric processing of old aerial photographs in remote environments. Furthermore, the very fine resolution of Pléiades can help to improve the accuracy of nunataks and/or whole ice caps delimitation, especially when compared to the frequently used Landsat images (Fig. 8).

6.2 Comparison to other studies

Our estimates of shrinkage for GRIC and TNIC can be compared with other studies from Baffin Island to verify the coherence of results and get a more complete picture of the pattern of glacier changes across this vast region.

Sharp et al. (2014) reported rates of areal change for TNIC of up to -0.66 km² a^{-1} (197 km² to 169 km²) between 1958 and 2000, while our own results give a nearly identical figure of -0.59 ± 0.03 km² a^{-1} (196.2 ± 9.9 km² to 173.2 ± 8.5 km²) over this similar period. For GRIC, however, the shrinkage rate of -0.36 km² a^{-1} (135 km² to 120 km²) reported by Sharp et al. (2014) over the period 1958-2000 is nearly 4 times more negative than our own figure of -0.10 ± 0.01 km² a^{-1} for 1952-1999 (131.8 ± 6.6 km² to 126.9 ± 6.3 km²). Way (2015) recently reported that between 1973-1975 and 2010-2013, the area of TNIC decreased by 22% (199.1 km² to 154.8 ± 7.5 km²), while that of GRIC reduced by 18% (134.3 km² to 110 ± 0.9 km²). Although results slightly differ between these studies, our results agree within reported errors (where given). We hypothesize that those small disparities could be explained by the errors of interpretation due to snow patches around the ice caps, and/or by the different spatial resolutions and acquisition dates of the data used in the different studies (Paul et al., 2013). A comparison of the areal declines of GRIC and TNIC with those of other Baffin Island ice caps was already conducted in Way (2015) and is thus not presented here.

Gardner et al. (2012) estimated that the average mass loss rate of all glaciers and ice caps on southern Baffin Island (South of 68.6° N, excluding Penny Ice Cap) increased from -0.20 ± 0.05 m a^{-1} w.e to -0.76 ± 0.12 m a^{-1} w.e (i.e. a factor of 4) between the periods 1957-2006 and 2003-2009. This acceleration is more than twice that estimated over similar periods for northern Baffin Island glaciers (North of 68.6° N, excluding Barnes Ice Cap). Barnes Ice Cap itself, located on central Baffin Island at elevations between 400 and 1100 m a.s.l., recently experienced a strong thinning acceleration (Sneed et al., 2008; Dupont et al., 2012), resulting in a mass loss rate of -1.08 ± 0.12 m a^{-1} w.e between 2005 and 2011 (Gardner et al., 2012). The estimated mass loss rate on Penny Ice Cap between 2003 and 2009 is lower, at -0.52 ± 0.12 m a^{-1} w.e., a difference which

Gardner et al. (2012) attribute to its much higher elevation range (up to ~2 000 m a.s.l). The comparatively large mass loss rates experienced by GRIC and TNIC in the past half-century can be ascribed to differences in size and to the hypsometry of the ice caps, but also possibly to local climatic factors, as described below.

6.3 Regional context and climatic factors

The accelerating recession of glaciers and ice caps across the CAA in recent decades, and the concurrent increase in surface melt over the Greenland Ice Sheet, have been ascribed to a sustained atmospheric pressure and circulation pattern that favours the advection of warm air from the northwest Atlantic into the eastern Arctic and over western Greenland (Sharp et al., 2011; Fettweis et al., 2013). This situation has led to warmer, longer summer melt periods on glaciers of the eastern CAA, and this largely accounts for their increasingly negative mass balance (Weaver, 1975; Hooke et al., 1987; Koerner, 2005; Sneed et al., 2008; Gardner and Sharp 2007; Gardner et al., 2012).

In the southern Baffin Island region, annual and seasonal mean air temperatures have generally increased since 1948 (except in the spring), but not monotonically (Vincent et al., 2015). At Iqaluit, seasonal trends from 1948 to ~1990 were non-significant or slightly negative (spring). Thereafter, temperatures rose, particularly in autumn (SON; +0.8 °C decade^{-1}) and winter (DJF; +2.9°C decade^{-1}), both of these trends being significant at the 95% level ($p < 0.05$), even when autocorrelation is accounted for (Ebisuzaki, 1997). Climate records from stations further south (e.g., Resolution Island, 61.5º N) are unfortunately too discontinuous to allow quantification of temperature trends on Meta Incognita Peninsula, but these are probably close to those observed in Iqaluit. Although GRIC and TNIC are only separated by 17 km, they did not experience the same historical and recent rates of shrinkage and mass loss (see the results section), and part of the difference is likely due to differences in hypsometry, which strongly influences the response of glaciers to a given climate forcing (Oerlemans et al., 1998; Davies et al., 2012; Hannesdóttir et al., 2015). GRIC lies at a slightly higher altitude than TNIC, with 77% of its area above 600 m a.s.l, compared to 68% for the TNIC, and is therefore expected to have a slightly less negative mass balance, as our observations confirm.

A factor that may have indirectly contributed to the accelerating rate of glacier recession on southernmost Baffin Island is the decline in summer sea ice cover in this region (Fig. 9b), one of the steepest observed across the entire CAA (up to -16 % decade^{-1} since 1968; Tivy et al., 2011). In the Hudson Bay - Hudson Strait - Foxe Basin region, up to 70-80 % of the sea ice decline since 1980 has been attributed to warmer spring and/or autumn surface air temperature, wind forcing accounting for the balance (Hocheim and Barber, 2014). The retreating sea ice cover in Hudson Strait, immediately south of Meta Incognita Peninsula, has been accompanied by a particularly large rise in surface air temperature during autumn months (SON) during or after the sea ice cover minimum, and the rate of autumn warming between 1980 and 2010 (0.15 ºC a^{-1}) is estimated to have been three times greater than the mean between 1950 and 2010 (0.05 ºC a^{-1}; Hocheim and Barber, 2014). A consequence of the sea ice retreat in this sector has been to increase the net solar flux absorbed annually at the sea surface at an estimated average rate of ≥ 0.8 W m^{-2} a^{-1} over the period 1984-2006, and probably faster after the mid-1990s when sea ice decline accelerated (Matsoukas et al. 2010; Hocheim and Barber, 2014). Meanwhile, the temperature record from Iqaluit (Fig. 9a) indicates that while the cumulative sum of positive degree-days (PDD) during the glacier ablation season (April-November) was relatively constant prior to 1990 (no significant trend), it increased at a rate of ~3.8 degree-day a^{-1} ($p < 0.05$) after 1990. The clearest increases in PDD occurred between summer and autumn (June to October: 0.24 to 1.46 degree-day a^{-1}; $p < 0.05$), while trends in spring months (April and May) were comparatively very slight or negligible. These observations suggest that while rising summertime temperature undoubtedly remain the main driver for the mass losses of GRIC and TNIC over recent decades (Gardner et al., 2012), the annual mass loss rate could be enhanced by a lengthening of the melt season into the autumn linked to the later freeze-up in Hudson Strait (Hocheim and Barber, 2014). The early autumn weeks, in particular, are a period during which ice-free, open waters surrounding Meta Incognita Peninsula are a large local source of heat to the lower troposphere, while the frequent low-level cloud cover in this season may contribute a further downwelling longwave radiation flux (Dunlap et al., 2007). In this respect, the situation for GRIC and TNIC could differ from that of Barnes Ice Cap (70°N) on central Baffin Island, where the lengthening of the melt season has been attributed to more frequent early spring thaw events (Dupont et al., 2012). Spaceborne monitoring of the melt duration over GRIC and TNIC by passive microwave sensing would help to verify if these two glacierized sectors of Baffin Island respond to regional warming in different ways.

7. Conclusions

This paper highlighted historical and recent trends in area, elevation and mass changes for the two southernmost ice caps of the Canadian Arctic Archipelago, Grinnell and Terra Nivea Ice Caps. Our analysis is based on multiple datasets and uses an original approach where ground control points for the photogrammetric processing of old aerial photographs are derived from sub-meter resolution Pléiades satellite stereo-images. This approach takes fully advantage of the highly precise Pléiades products and represents an important advance for eventually unlocking the vast archives of historical aerial photographs.

Results show that the areal extent of TNIC is 34% smaller in 2014 when compared to the end of the 1950s' extent, while GRIC shrank by nearly 20% between 1952 and 2014. Both ice caps also experienced an acceleration of their shrinkage rates since the beginning of the 21^{st} century.

The historical glacier-wide mass balance for GRIC was estimated to be -0.37 ± 0.21 m a^{-1} w.e. (1952-2014) and slightly more negative for TNIC at -0.47 ± 0.16 m a^{-1} w.e. (1958/59-2014). Between 2007 and 2014, the mass balance of TNIC was of -1.77 ± 0.36 m a^{-1} w.e., a rate 5.9 as negative as the mass balance of -0.30 ± 0.19 m a^{-1} w.e. measured between 1958/59 and 2007. This is also twice as negative as the average mass balance obtained between 2003 and 2009 for other larger ice caps in the southern part of Baffin Island (Gardner et al., 2012).

The 2007-2014 mass balance of TNIC is among the most negative multi-annual glacier-wide mass balances measured to date, comparable to other negative values observed in the southern mid-latitudes (e.g., Willis et al., 2012; Berthier et al., 2009) or in South-East Alaska (Trüssel et al., 2013). Given the absence of calving glaciers for TNIC, its high rate of mass loss can only be explained by negative surface mass balance due to an ELA that, for most years, is above the maximum ice cap altitude. Nonetheless, this similarity in rate of mass loss underlines the strong sensitivity of maritime low-elevation ice bodies to the currently observed climate change at mid-latitudes and in polar regions (Hock et al., 2009). The recent acceleration of ice cap wastage on Meta Incognita Peninsula is linked to a strong near-surface regional warming and a lengthening of the melt season into the autumn that may be reinforced by sea ice cover reduction and later freeze-up in Hudson Strait and nearby marine areas.

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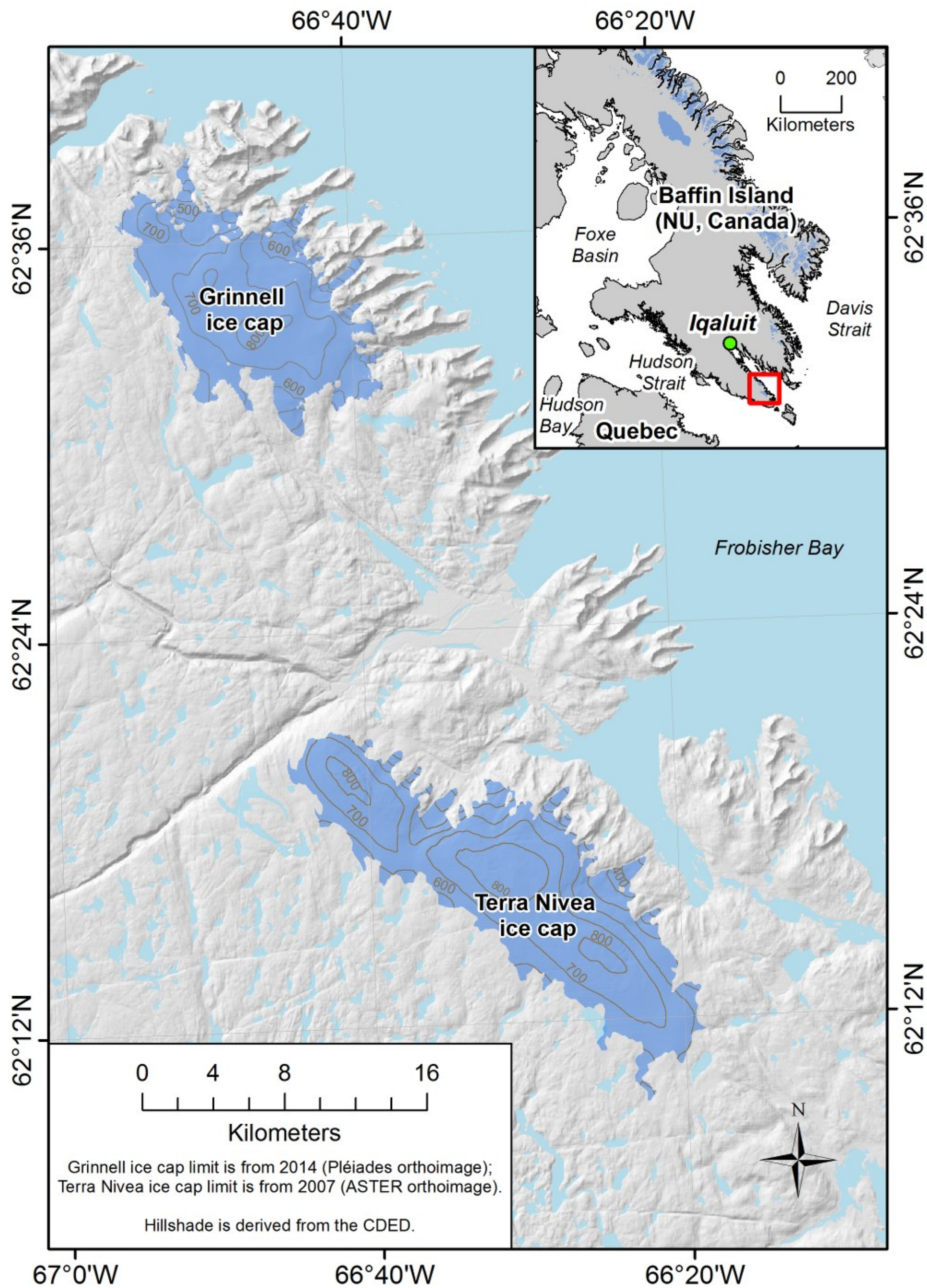

Fig. 1. Study area

Table 1. Elevation datasets used in this study with the acquisition date and the purpose of their use for each ice cap.

Ice cap	Elevation data set	Acquisition date	Purpose
Grinnell	Photogrammetry derived DEM	August 21-22, 1952	*Historical mass balance and dH*
	CDED	September 6, 1958	*Absolute coregistration*
	ICESat points	All laser periods outside glacier	*Absolute coregistration*
		Nov 2003, Mar 2004, Mar 2005, Nov 2005, Mar 2006, Nov 2006 and Apr 2007 *(on glacier)*	*Recent dH*
	In-situ GPS points	April 2004	*Recent dH*
	Pléiades DEM	August 3, 2014	*Historical and recent mass balances and dH*
Terra Nivea	CDED	September 6, 1958 (West part) and August 4, 1959 (East part)	*Historical mass balance and dH, absolute coregistration*
	ICESat points	All laser periods outside glacier	*Absolute coregistration*
		Apr and Nov 2007 *(on glacier)*	*Evaluation of ASTER DEM*
	ASTER DEM	August 3, 2007	*Recent mass balance and dH*
	Pléiades DEM	August 14, 2014 (West part) and August 26, 2014 (East part)	*Historical and recent mass balances and dH*

Table 2. Historical and recent glacier-wide mass balances for both ice caps.

Ice cap	Time interval	Dataset	Data voids (%)	Mass balance (m a^{-1} w.e.)
Grinnell	1952 - 2014	Photogrammetric DEM and Pléiades DEM	34	-0.37 ± 0.21
Terra Nivea	1958/59 - 2014	CDED and Pléiades DEM	36	-0.48 ± 0.17
	1958/59 - 2007	CDED and ASTER DEM	21	-0.30 ± 0.19
	2007 - 2014	ASTER DEM and Pléiades DEM	29	-1.77 ± 0.36

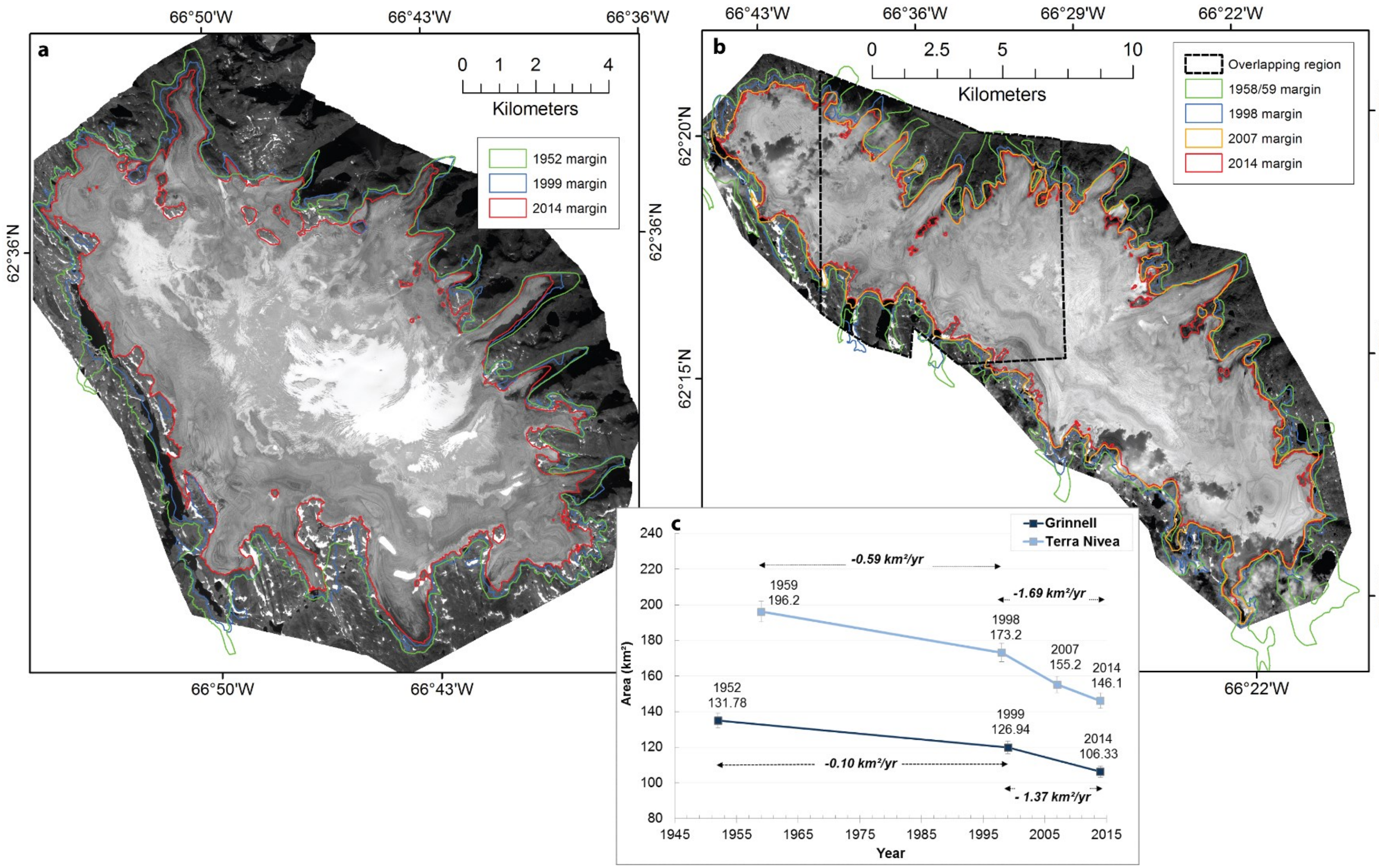

Fig. 2. (a) Pléiades orthoimage of Grinnell Ice Cap (August 3, 2014) superimposed with areal extents from 1952, 1999 and 2014 **(b)** Pléiades orthoimages of Terra Nivea Ice Cap (August 14, 2014 on the East side and August 26, 2014 on the West side) superimposed with areal extents from 1958/59, 1998, 2007 and 2014. The overlapping area between the two orthoimages is represented by the black dashed polygon **(c)** Historical and recent area changes for both ice caps. Error margins were estimated to 5% for historical areas and to 3% for 1998 and later outlines (section 4.4.3.)

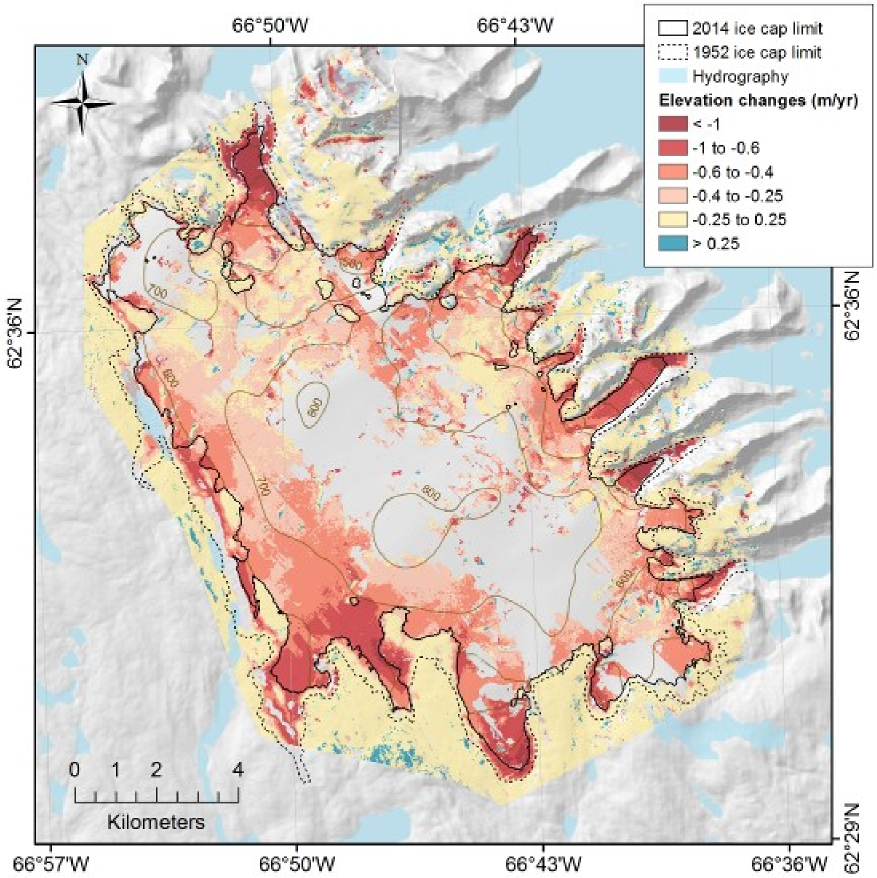

Fig. 3. Elevation change rates (m a^{-1}) on Grinnell Ice Cap between August 1952 (Aerial photo DEM) and August 2014 (Pléiades DEM). For this figure as well as for the next ones, no color (i.e. hillshade is visible) represent no data.

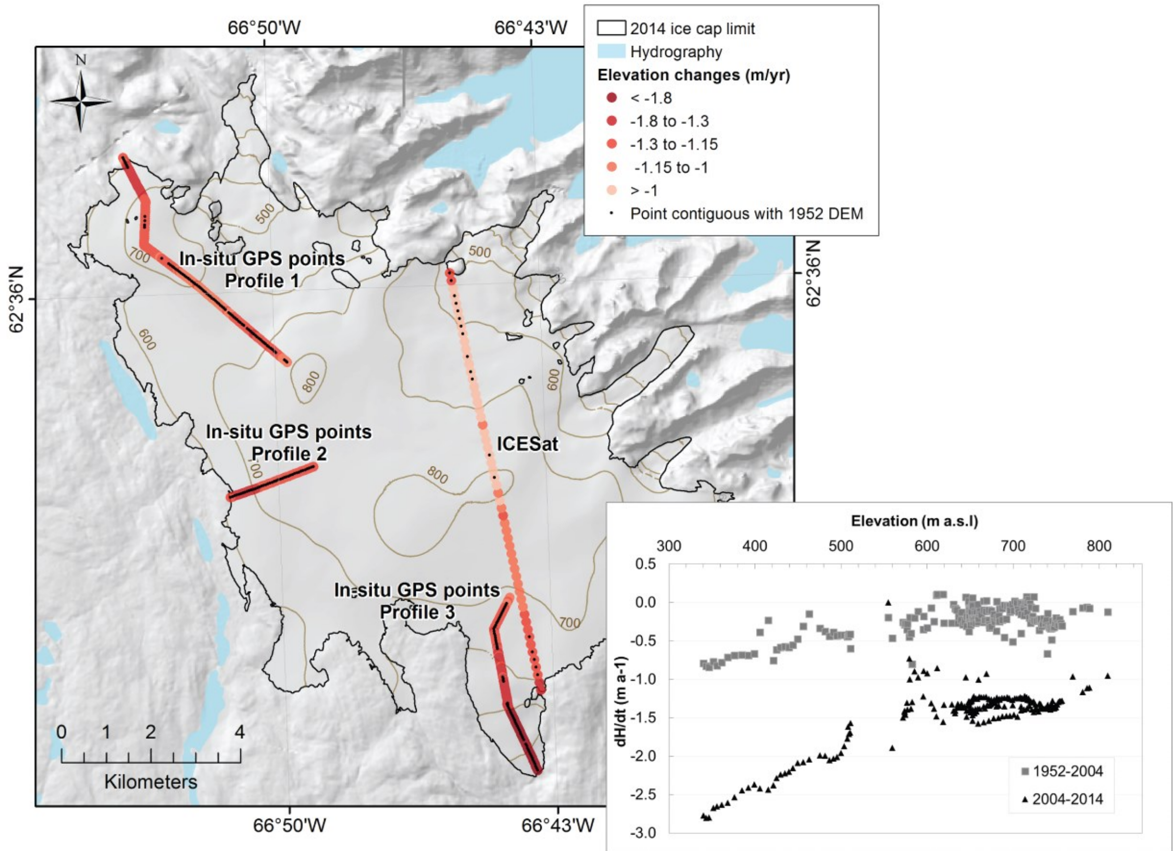

Fig. 4. Elevation change rates (m a^{-1}) on Grinnell Ice Cap between March/April 2004 (ICESat and in situ GPS points) and August 2014 (Pléiades DEM). Bottom right graph shows historical (1952-2004) and recent (2004-2014) rates of elevation changes along the 203 points contiguous with the 1952 DEM (represented as black dots on the map)

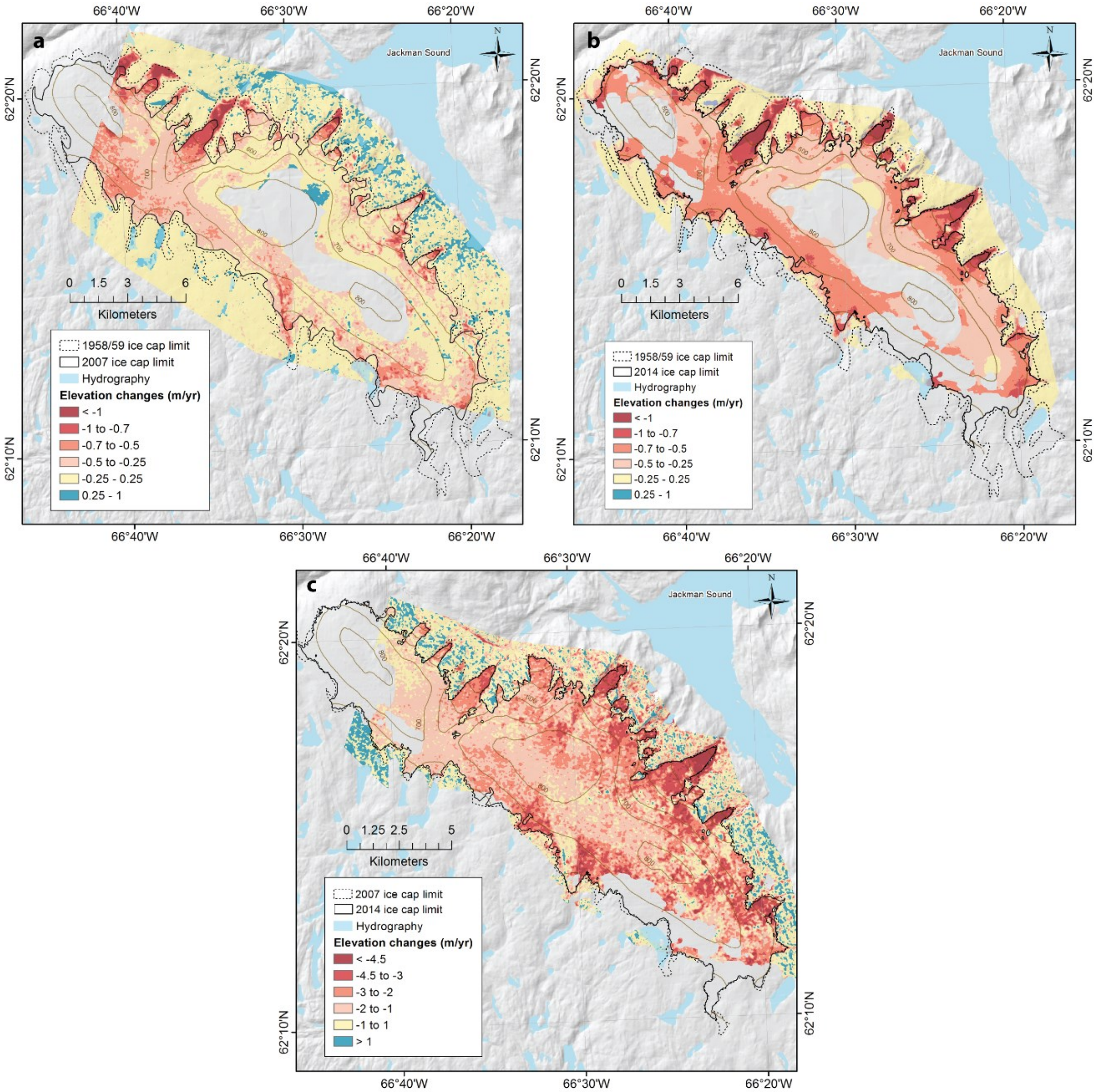

Fig. 5. (a) Elevation change rates (*dH/dt,* m a^{-1}) on Terra Nivea Ice Cap (TNIC) between 1958/59 (CDED) and 2007 (ASTER) **(b)** *dH/dt* on TNIC between 1958/59 (CDED) and 2014 (Pléiades DEM) **(c)** *dH/dt* on TNIC between 2007 (ASTER) and 2014 (Pléiades DEM). Note a different color scale for the lower panel (c).

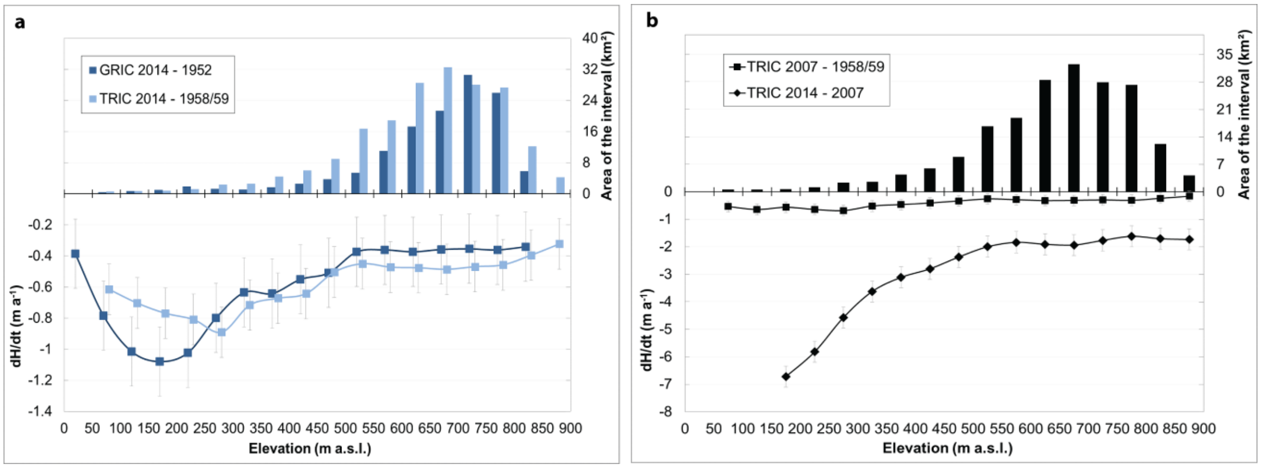

Fig. 6. (a) Historical averaged elevation change rates (*dH/dt*$_{avg}$) measured for GRIC (1952-2014) and TNIC (1958/59-2014) for each 50 m elevation band. **(b)** Historical (1959-2007) and recent (2007-2014) *dH/dt*$_{avg}$ for each 50 m elevation band on TNIC. The error margins are the elevation change measurement uncertainties determined in section 4.4.3.

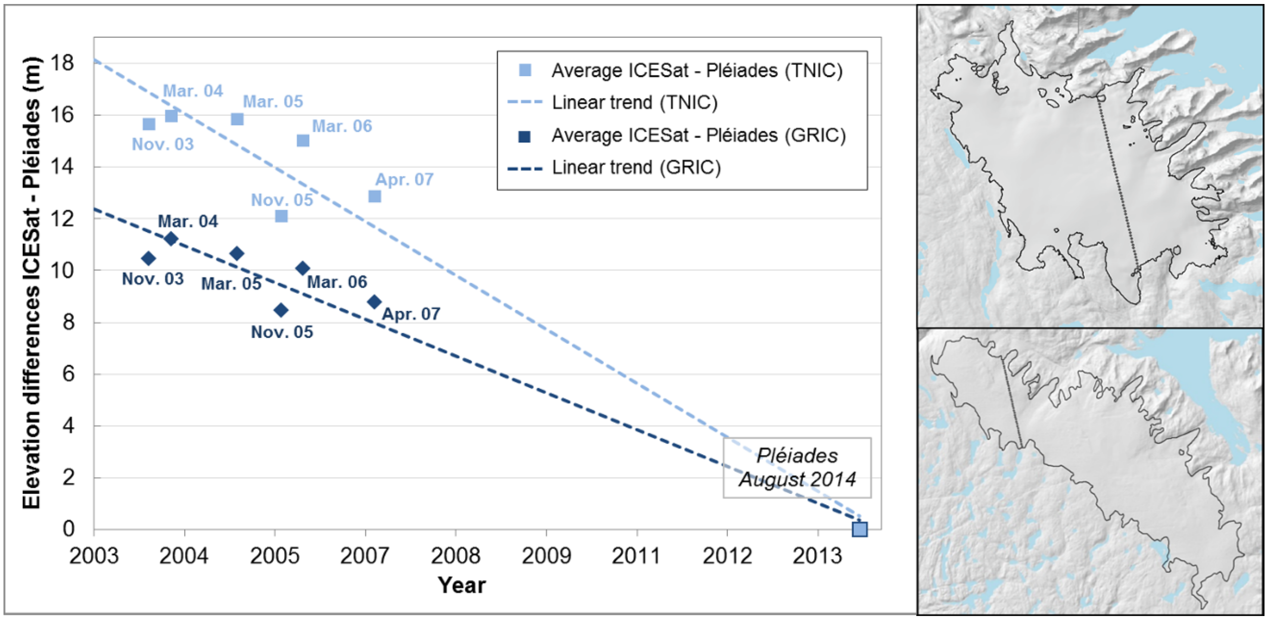

Fig. 7. Recent elevation differences on GRIC and TNIC measured between the Pléiades DEMs (2014) and ICESat altimetric points (2003 to 2007). Only the complete ICESat tracks available for both ice caps were used. The trend lines indicate the mean rate of elevation changes along these two ICESat reference tracks and are ~ -1.1 m a^{-1} for GRIC and ~ -1.6 m a^{-1} for TNIC. Transects location for each ice cap is shown on the inset maps (top for GRIC and bottom for TNIC).

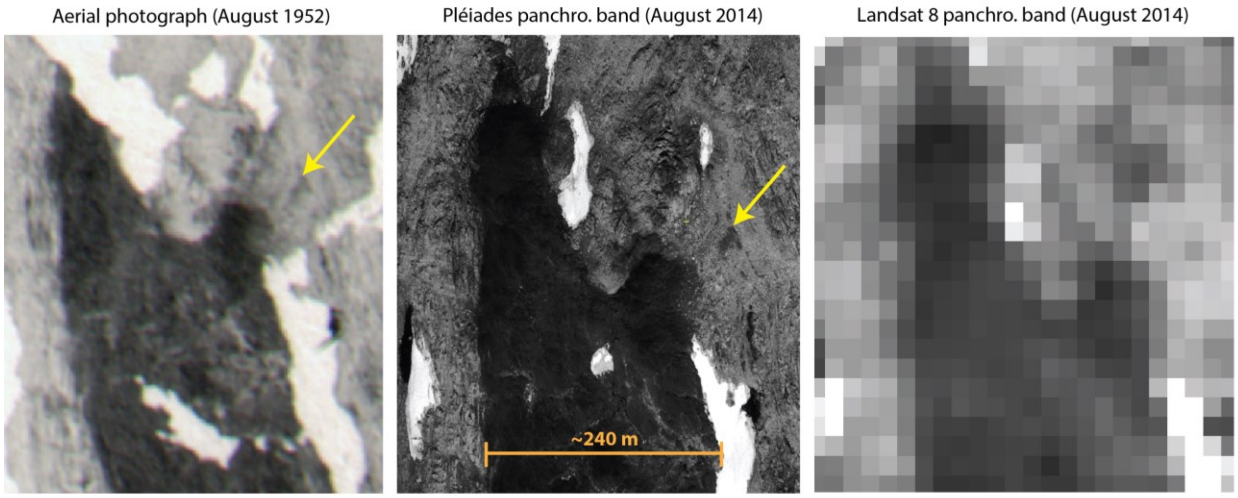

Fig. 8. Representation of the same geomorphological feature on ice-free terrain surrounding GRIC using three different technologies, namely an aerial photography (August 1952), a Pléiades panchromatic band (3 August 2014) and a Landsat 8 panchromatic band (15 August 2014). Note the very fine resolution of the Pléiades panchromatic band (70 cm), in comparison to the Landsat 8 panchromatic band (15 m), allowing to retrieve bedrocks and ice-free features on archives aerial photos and thus to collect GCPs (e.g. at the bedrock localised by the yellow arrow).

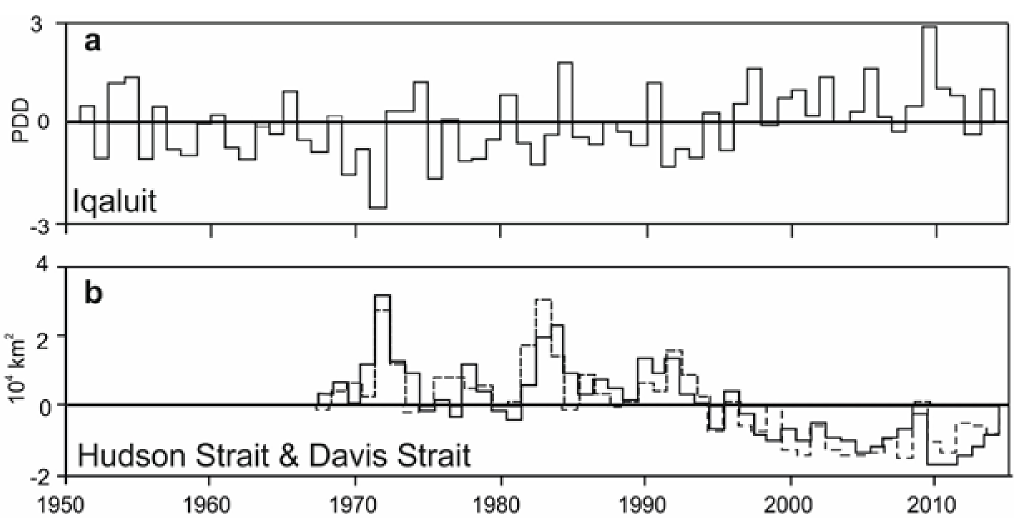

Fig. 9. (a) Annual anomalies in total positive degree-days (PDD) recorded from April to November at the Iqaluit weather station, 1952 to 2014, based on Homogenized Canadian Historical Climate Data (Vincent et al., 2015). **(b)** Anomalies in total sea-ice covered area during the summer and autumn (25 Jun-19 Nov) over Hudson Strait (full line) and Davis Strait (dashed line), 1968-2014. Data provided by the Canadian Ice Service. For region boundaries, see Tivy et al. (2011), their Fig. 4.