SAR RADARSAT-2 and optical Pléiades stereo imagery for monitoring the melt of Baffin Island ice caps (Nunavut, Canada)

PAPASODORO, C.1,2, ROYER, A.1,2, LANGLOIS, A.1,2 AND BERTHIER, E.3

ABSTRACT

Given the recent pronounced warming in the Canadian arctic and associated glacier melt, the development of new innovative monitoring tools has become essential to better understand their response to climate change. Here we exploit two recent satellite technologies, namely the radarsat-2 (R2) stereo radargrammetry (SRG) and the Pléiades stereo imagery, for monitoring historical and recent melt of Barnes ice cap, penny ice cap, Grinnell ice cap and Terra Nivea ice cap. Digital elevation models (DEMs) derived from R2 SRG show a vertical precision of better than ~7 m (standard deviation) on ice-free terrain without using any ground control point and with the advantage of being weather independent. Combined with different other datasets, we obtain a glacier-wide mass balance of \(-0.49 \pm 0.21\) m a\(^{-1}\) w.e. (water equivalent) for Barnes ice cap between 1960 and 2013, while it strongly decreases to \(-1.07 \pm 0.90\) m a\(^{-1}\) w.e. for the period 2005-2013, in agreement with other studies. Over Penny ice cap, we rather obtain a mean annual elevation change of \(-0.60\) m a\(^{-1}\) between 1960 and 2012, also in agreement with other studies. Over Grinnell ice cap, Pléiades derived DEMS combined with other datasets allow to estimate a historical mass loss rate of \(-0.37 \pm 0.21\) m a\(-1\) w.e between 1952 and 2014. The rate of mass loss on Terra Nivea ice cap was slightly stronger at \(-0.47 \pm 0.16\) m a\(-1\) w.e between 1958/59 and 2014, with a strong recent acceleration between 2007 and 2014: \(-1.68 \pm 0.36\) m a\(-1\) w.e.

Keywords: stereo radargrammetry, RADARSAT-2, Pléiades, Barnes Ice Cap, Penny Ice Cap, Grinnell Ice Cap, Terra Nivea Ice Cap, Baffin Island, mass balance, elevation change

INTRODUCTION

Glaciers and ice caps of the world are rapidly evolving, especially in the observed global warming context (Vaughan et al., 2013), and their monitoring is of primary importance to better understand and warn the impacts of these changes (e.g. sea-level rise, water resources, etc.). Perfect examples are the ice caps from the Canadian Arctic Archipelago (CAA) for which the rates of mass loss strongly accelerated in recent years. For the southern part 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 \(-92 \pm 12\) 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.

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The main goal of this project was to explore two recent remote sensing technologies, namely the RADARSAT-2 (R2) stereo radargrammetry (SRG) and the Pléiades stereo imagery, for monitoring historical and recent melt of four Baffin Island ice caps: Barnes Ice Cap (BIC), Penny Ice Cap (PIC), Grinnell Ice Cap (GIC) and Terra Nivea Ice Cap (TNIC). Used here over BIC and PIC and combined with different other datasets for assessing elevation and mass changes, our study represents to our knowledge the first glaciological use of R2 SRG. Despite the somewhat worse vertical precision of the SRG R2 compared to the interferometric approach, the SRG approach using R2 images is rather compensated by its weather independence and its higher operability and capability to quickly generate on-demand Digital Elevation Models (DEMs) with no ground control point (GCP), thanks to the Rational Polynomial Coefficients (RPCs), orbits information and accurate geometric models. This was also evidenced during the finalization of the Canadian Arctic 1:50k mapping, north of 81° N, in which R2 SRG has been a very efficient replacement of the typical cartography methods, such as photogrammetry and optical stereoscopic satellite (Clavet et al., 2011). As regards the Pléiades stereo imagery and their very precise derived DEMs (Berthier et al., 2014), they were compared to other datasets to analyze elevation and mass changes of GIC and TNIC over the 60 last years (Papasodoro et al., 2015).

METHODS

For Barnes Ice Cap (BIC), ten R2 Wide Ultra-Fine images (pixel spacing of 1.6 m x 2.8 m (range x azimuth); swath coverage of 50 km x 50 km), forming five stereoscopic pairs, were acquired between September and November 2013. According to recent studies (Toutin et al., 2012, 2013), acquisitions made at the end of ablation season ensure a maximum degree of texture and decrease the depth penetration over ice caps (i.e. ice in ablation zone and soaked snow in accumulation area). DEMs were automatically extracted (i.e. correlation matching) from the five stereoscopic pairs using PCI Geomatica 2013 and were assessed by comparing to 2011 altimetric points (ATM Icebridge mission). They were then subtracted (1) to Canadian Digital Elevation Data (CDED) from ~1960 and (2) to 2005 ATM points in order to calculate historical and recent elevation and mass changes of BIC. For Penny Ice Cap (PIC), R2 images were provided by Pr. Luke Copeland (U. Ottawa) and were acquired between March and May 2012, making it difficult to extract elevations from the typical automatic correlation method because of the very low image texture of the ice cap at this time of year. Elevations were thus instead extracted by a 3D approach, essentially over the ablation area in lower elevations of the PIC. Elevations were at first assessed outside the ice cap and elevations over PIC were then subtracted to CDEDs in order to calculate historical elevation changes. Note that as a matter of limited space, no analysis of penetration depth is presented here.

Over Grinnell Ice Cap (GIC) and Terra Nivea Ice Cap (TNIC), we used an integrated approach based primarily on Pléiades DEMs of August 2014 that were compared (i.e. geodetic method) to many other datasets such as historical CDEDs, photogrammetric DEMs, ASTER DEMs and ICESat altimetric points (Papasodoro et al., 2015). This comparison allowed calculating elevation and mass changes over a period of 60 years. Furthermore, an innovative point of this paper was to use the Pléiades products (DEM and orthoimage) to collect numerous GCPs that were then used in the photogrammetric processing of archive aerial photos. More details on the methodology for those two ice caps can be found in Papasodoro et al. (2015).

RESULTS

Barnes and Penny ice caps

Before calculating mass changes, we assessed the SRG elevations to determine the limits of the technology. The vertical precision of the SRG DEMs (i.e. automatic extraction approach) measured on the ice-free surrounding low relief terrain of the BIC was ~7 m (Standard deviation). Those DEMs were extracted using the Rational Function geometric model which does not require any GCP. For elevations extracted by 3D vision approach over the ablation area of PIC, we rather
estimated a standard deviation of ~4 m. The 3D vision approach is however more laborious than the automatic approach.

Figure 1. (a) Annual elevation changes (dH/dt) measured on BIC over the period 1960-2013 between CDEDs and SRG DEMs. (b) dH/dt measured on BIC over the period 2005-2013 between 2005 ATM points and SRG DEMs.

Table 1. Mass balances estimated on Barnes Ice Cap, Grinnell Ice Cap and Terra Nivea Ice Cap for different time intervals

<table>
<thead>
<tr>
<th>Ice cap</th>
<th>Time interval</th>
<th>Dataset</th>
<th>Mass balance (m a(^{-1}) w.e.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnes</td>
<td>1960-2013</td>
<td>CDED and SRG DEMs</td>
<td>-0.48 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>2005-2013</td>
<td>ATM and SRG DEMs</td>
<td>-1.07 ± 0.90</td>
</tr>
<tr>
<td>Grinnell</td>
<td>1952 - 2014</td>
<td>Photogrammetric DEM and Pléiades DEM</td>
<td>-0.37 ± 0.21</td>
</tr>
<tr>
<td>Terra Nivea</td>
<td>1958/59 - 2007</td>
<td>CDED and ASTER DEM</td>
<td>-0.30 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>2007 - 2014</td>
<td>ASTER DEM and Pléiades DEM</td>
<td>-1.68 ± 0.36</td>
</tr>
</tbody>
</table>

Over BIC, the 2013 SRG DEMs subtracted to the 1960 CDED have shown historical elevation changes (dH) of -26.4 m to -40.4 m (i.e. dH/dt of -0.5 m a\(^{-1}\) to -0.76 m a\(^{-1}\)) (Figure 1). The majority of the area located below 600 m a.s.l. experienced thinning rates of -1 m a\(^{-1}\) whereas between 600 and 1000 m a.s.l., which composes ~70% of BIC area, this rate was about -0.5 m a\(^{-1}\). The comparison of SRG DEMs to 2005 ATM points has shown that over the period 2005-2013, the average rate of elevation changes decreased significantly to -1.2 m a\(^{-1}\) with a strong gradient of dH/dt per elevation. Between 400 and 1100 m a.s.l. elevation, which constitutes 97% of BIC area, thinning rates of -2.8 m a\(^{-1}\) to -0.7 m a\(^{-1}\) were measured. Additionally, annual thinning of up to -6 m a\(^{-1}\) were obtained between 350 and 400 m a.s.l.. Globally, those elevation changes are in agreement with Gardner et al. (2012) and thus reconfirm the clear recent acceleration of the thinning of the BIC. Using these elevation changes, we estimated glacier-wide mass balances of -0.48 ± 0.20 m a\(^{-1}\) w.e. (-2.8 Gt a\(^{-1}\)) for the period 1960-2013 and -1.07 ± 0.90 m a\(^{-1}\) w.e. (-6.2 Gt a\(^{-1}\)) for the period 2005-2013 (Table 1). Our glacier-wide mass balances are almost identical to the ones from Gardner et al. (2012) for analogous historical (1960-2010) and recent (2005-2011)
periods which, once again, reconfirms the strong recent mass loss of BIC. On a methodological level, although the error bars are high, our results reveal the potential of R2 SRG for relatively short time intervals when surface elevation changes are important.

Over the ablation area of PIC, the comparison of the 900 SRG elevation points of 2012 to the CDEDs of 1958 has shown a global dH/dt of 0.59 m a⁻¹ which is still in agreement with Gardner et al. (2012). The dH/dt varies from 0.4 m a⁻¹ at lower elevations to 1.2 m a⁻¹ at upper elevations of the ablation area (~1100 m). Since our elevations do not spread the entire ice cap, no mass balance could be estimated for PIC.

Grinnell and Terra Nivea ice caps

Grinnell Ice Cap (GIC) and Terra Nivea Ice Cap (TNIC) were already utterly analyzed in Papasodoro et al. (2015) so only the general results are presented here. On GIC, we measured an historical (1952-2014) averaged dH/dt of -0.44 ± 0.25 m a⁻¹ by comparing the 2014 Pléiades DEM to a 1952 photogrammetric DEM that was processed using GCPs derived from the Pléiades products. This historical rate represents a less pronounced rate when compared to TNIC for which an historical rate of -0.56 ± 0.19 m a⁻¹ was calculated between the 2014 Pléiades DEMs and the 1958/59 CDEDs. Similar patterns of historical dH/dt are observed for both ice caps, with surface lowering reaching -1.1 ± 0.25 m a⁻¹ for the GRIC and -0.9 ± 0.19 m a⁻¹ for the TNIC in the lower altitudes (i.e. the outlet glaciers) (Figure 2). In the same way than BIC, elevation change rates of GIC and TNIC strongly decreased in the recent years. For TNIC, the rate measured between 2007 and 2014 reached -1.97 ± 0.40 m a⁻¹, a rate 5.6 times as negative than the rate of -0.35 ± 0.22 m a⁻¹ measured between 1958/59 and 2007. Elevation change rates severely decreased in the recent years for both ice caps. At the lowermost altitudes of the ice cap, the thinning rate even reached -6.7 ± 0.40 m a⁻¹ during this time interval. On GIC, elevation changes measured between 2004 and 2014 (In situ GPS points vs Pléiades DEM) were up to 6 times more negatives (-1.47 m a⁻¹) when compared to the period 1952-2004 (-0.25 m a⁻¹). When converted in mass balances, we obtained a glacier-wide mass balance of -0.37 ± 0.21 m a⁻¹ w.e. for the period 1952-2014 on GIC. Over TNIC, the mass balance between 1958/59 and 2014 was -0.47 ± 0.16 m a⁻¹ w.e. but it strongly decreased to -1.68 ± 0.36 m a⁻¹ w.e. between 2007 and 2014. As previously discussed, the GIC has likely experienced a similar acceleration of its mass loss since 2004.

Figure 2. Annual elevation changes (dH/dt) measured on TNIC over the period 1958/2007 between CDEDs and an ASTER DEM (b) dH/dt measured on TNIC over the period 2007/2014 between an ASTER DEM and Pléiades DEMs.
CONCLUSION

Here we presented elevation and mass changes for four Canadian Arctic ice caps during the 4 to 6 last decades by emphasizing on recent satellite technologies, namely the RADARSAT-2 (R2) stereo radargrammetry (SRG) and the Pléiades stereo imagery. Used over Barnes Ice Cap and Penny Ice Cap, the R2 SRG has shown a decent potential for DEM extraction on glaciers with elevation vertical precision similar to the majority of other remote sensing DEMs (~7 m), without the need of GCPs and with the advantage of being weather independent. The elevation changes and mass balance obtained here are in well agreement with other recent studies. Our results thus suggest that the R2 SRG could be useful over glacial regions with frequent cloud conditions, such as Patagonia or Alaska. Tested on Grinnell Ice Cap and Terra Nivea Ice Cap, the Pléiades stereo imagery revealed a very strong potential for DEM extraction on glaciers, as also suggested in Berthier et al. (2014). Results presented here for those two ice caps are fully detailed in Papasodoro et al. (2015).

REFERENCES


