DETERMINATION OF GEOSPATIAL CHANGES OF THE BARNES ICE CAP USING EO DATA

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ABSTRACT:

The determination of spatial changes in the arctic regions contributes to the understanding and quantification of spatio-temporal phenomena occurring in the polar environments and ecosystems. This paper presents the applicability of air and spaceborne earth observation data in the estimation of planimetric and elevation changes of the Barnes ice cap, located on Baffin Island, Nunavut in Northern Canada. Historic aerial photography, Landsat 7 imagery, NASA airborne LiDAR data and ICESat satellite LiDAR data were used to generate time series data consisting of orthoimages, DEM and terrain profiles. Indicative planimetric changes of the boundary edge of the ice cap were determined at sampled locations based on the available 1958 aerial ortho-images and the 2000-2002 Landsat 7 satellite ortho-image. These preliminary results indicate that the ice cap edge has retreated with an average rate of about 3-15m/yr during for the last 40 years. The elevation changes of the ice cap were estimated at the terrain profiles of the ICESat and NASA LiDAR elevation points, respectively using as reference 1958 photogrammetrically and contour generated DEMs. The comparison of the temporal terrain profiles indicates that the ice cap elevations have been lowered mostly at the sides of the ice cap and at the lower elevations, where the dropping average rate of the ice elevations is reaching approximately the 1m/yr during the last 40 years. The approaches for the determination of the planimetric and elevation changes are discussed and results are presented.

1. INTRODUCTION

Status and Change are two of the six scientific themes of the International Polar Year (IPY). Status aims to determine the present environmental state of the polar regions. Change aims to quantify and understand the various spatio-temporal phenomena in the polar regions and to improve future projections and modeling. Various observations and measurements indicate that the sensitive northern environments are experiencing significant changes (e.g., ERCC, 2008). These changes are occurring over a wide range of timescales and magnitudes and have environmental, social and economic impacts. The extent and remoteness of the Canadian north present a unique challenge for topographic mapping (state) and monitoring (change). Improved and new methods and tools need to be investigated, developed and implemented in support of the mapping and monitoring activities in Northern Canada. Aerial and satellite remote sensing sensors significantly contribute to the data acquisition by providing extended and frequent coverage.

Long-term multi-temporal records are required to study on-going landscape changes in the arctic regions. The existing remote sensing data do not go back in time enough to allow for significantly long time periods of observations. The historic aerial photographs of the National Air Photo Library of Canada, (NAPL, Natural Resources Canada (NRCan)), and the associated photogrammetric triangulated control point network –part of the Aerial Survey Database (ASDB, Natural Resources Canada)- are invaluable baseline datasets since they provide an almost complete aerial photographic coverage of Northern Canada dating back in the late 1950's. This legacy data integrated with current earth observation satellite data can provide time-series data over a time period of the last 40-50 years. While this period is insignificant in terms of geo-time scales, it represents a time cycle where spatial changes, such as those in ice caps, shorelines and water bodies can be detected. This can also provide indications about the patterns, magnitude and acceleration of changes during the last half a century.

Spatial change detection involves the comparison of two or more co-registered temporal datasets. Change detection determines the difference in the patterns (location, shape, orientation, attributes) of two or more data sets from different times t_1 and t_2 or derived by different methodology or using different sources. Quantification of spatial changes allows for the determination of the change parameters, such as magnitude, rate, direction, duration, and trend. Change detection usually consists of four processes, a) detection, that is the discovery of change, b) recognition, that is the thematic classification of the change, c) identification, that is the description of the feature of the thematic change and d) quantification, that is the measure of the magnitude of change. For the spatial data, the changes occur when the elements of location, shape, and attributes of various features are not similar between two datasets. Spatial changes can be distinguished into apparent changes and into actual changes. Examples of apparent changes are differences detected in temporal image data due to different accuracies, scales, atmospheric and illumination conditions or viewing geometries. Therefore, invariant to these conditions elements are to be selected (Habib et al., 2004). Actual changes are those that truly have changed either the location or the shape or the attributes of a feature.

Areal and elevation changes of ice caps and glaciers are important indicators for the assessment of climate change (Berthier et al., 2007; Hendriks and Pellikka, 2007; Savopol et al., 2007). Estimates of spatial changes can be translated into changes in mass balances or water fluxes with respect to water resources or sea level changes (Abdalati et al., 2004; Zwally et al., 2005; Hopkinson and Demuth, 2006;). The Barnes ice cap, located on Baffin Island, Nunavut (Lat: 70°00'00"N; Lon: 73°30'00"W), was the site of this study aiming at the estimation of changes of the ice cap planimetric coverage and of the ice cap elevations. The Barnes ice cap has maximum length and width of about 140km and 60km, respectively (Fig. 1). It has a maximum elevation of about 1100m and extends about 500m over the surrounding ground terrain.

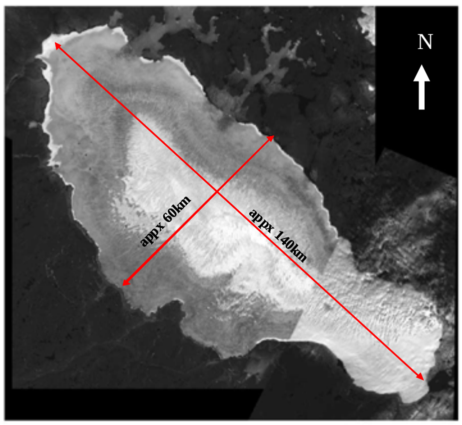


Figure 1. Barnes ice cap

The multi-temporal earth observation data sets used for this Barnes ice cap study were:

- 1958 digital ortho-images (1mx1m spatial resolution) generated photogrammerically from scanned aerial photographs from the ASDB/NAPL.
- 2000 and 2002 three panchromatic Landsat 7 ortho-images (27Jul2000 / 2Aug2002 / 12Sept2002). The images were mosaicked to provide a planimetric raster dataset for the ice cap (15mx15m spatial resolution).
- DEM 1958, photogrammetric DEMs (5mx5m grid) generated from the scanned aerial photographs from the ASDB/NAPL.
- CDED 1958, DEM generated from the merging of four 1:250 000 1983 CDED DEM files of the area (50mx50m grid). Note: The 1:250 000 40m contours were derived from the 1958 aerial photography.
- 1995, 2000, and 2005 elevation profiles from NASA airborne LiDAR altimetric surveys. The average distances between the elevation points are between 20m, 25m and 35m.
- 2003-2005 elevation profiles from the ICESat satellite GLAS altimeter. The along track distance of the elevation points is about 170m.

The horizontal reference system of all data is UTM NAD83, Zone 18. The vertical reference system of all data except the ICESat data is the Canadian Geodetic Vertical Datum 1928 (CGVD28). ICESat elevations are referred to Canadian Gravimetric Geoid 2005 (CGG05), which deviates in this area from the CGVD28 by about 1m.

2. PLANIMETRIC CHANGES

Planimetric changes of the boundary edge of the ice cap were determined based on the available 1958 aerial ortho-images and the 2000-2002 Landsat 7 satellite ortho-image. As complete 1958 aerial ortho-image coverage of the ice cap is not available, three test sites were selected based on the positional orientation of the ice cap. The selected sites are situated in the North, North-East and South-West boundaries of the ices cap. Figure 2 shows the N, NW and SW test areas respectively.

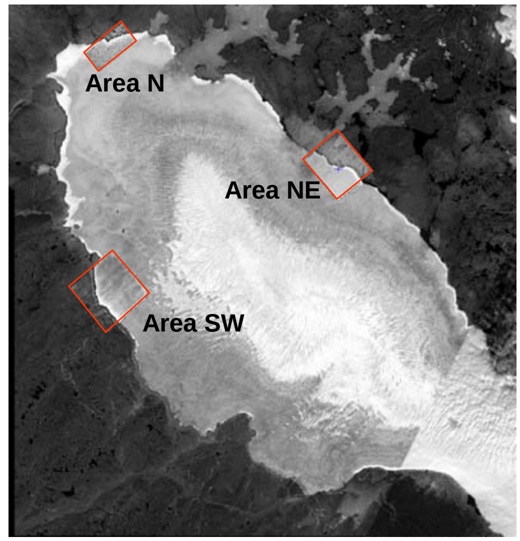


Figure 2. Test areas for the planimetric changes

Due to heterogeneity of the two temporal image data sets, a feature-based approach was selected for the estimation of spatial changes. The planimetric changes $\Delta x, \Delta y$ of a feature can be determined by comparing its planimetric position at two or more different time epochs, where $\{\Delta x(dt), \Delta y(dt)\} = \{(x(t2), y(t2)\} - \{(x(t1), y(t1)\}$. This feature-based approach involves the extraction of the boundary edge of the ice caps from the two ortho-image datasets, followed by comparison of the position of the two edge data sets. Through this approach problems related to the spatial, temporal and spectral variances of the characteristics of the two ortho-images are minimized. The accuracy of the detected changes is proportional to the accuracy of the image ortho-rectification and the extraction of the ice cap edge. The estimated planimetric accuracies at 90% confidence are 4-5m and 25-30m for the aerial and satellite ortho-images, respectively.

To reduce the laborious interactive heads-up digitization of the ice cap boundary edge from both the aerial and satellite ortho-images and to have a measure of subjective interpretation on where the edge is located, an edge detection spatial filter was used to extract the boundary of the ice cap. This was based on the apparent contrast between ice cap coverage and bare terrain. Due to the differences in spatial resolution of the two ortho-images a 25x25 kernel was applied on the aerial ortho-image and a 3x3 kernel on the satellite ortho-image, respectively. Some noise was removed from the extracted edge layers by applying a 7x7 kernel median filter.

The superimposition of the two edge data revealed an evident retreat of the ice cap boundary edge between 1958 and 2000-02 (~40 years period). Figure 3 shows the differences of the edge lines in the North facing test area N. The 1958 edge is shown in light blue and the 2000-02 edge in light red. Distance measurements along several transects across both edges indicate the following linear planimetric displacements:

- For Area N: edge retreat from 300 to 450 metres (7.5-11.25 m/yr)
- For Area NE: edge retreat from 120 to 220 metres (3-5.5 m/yr)
- For Area SW: edge retreat from 320 to 600 metres (8-15 m/yr)

The range of displacements exceeds by far the estimated range accuracy of about 31m at 90%. The SW area as exposed to the sun heat has the highest retreat rate, while the NE area has the lowest retreat rate indicating exposure to colder temperatures. Interestingly enough, the north facing area has edge displacements values closer to the ones of the SW area. However, the rate of retreat also depends on the local slope of the ice cap, the local thickness of ice, the local terrain topography and any local micro-climatic conditions.

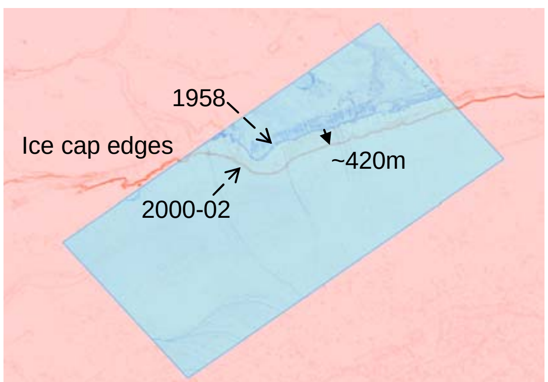


Figure 3. Planimetric changes in test Area N

3. VERTICAL CHANGES

Similarly, the vertical changes Δh of the ice elevations were determined by comparing the elevation component h at two or more different time periods. That is, $\Delta h(dt) = h(t2) - h(t1)$, where $\Delta h(dt)$ is estimated at terrain detail points. These points are either selected discrete -and sometimes marked- points or points used to describe the terrain surface as DTM (DEM, TIN, DSM), terrain profiles, or contour lines. Δh is determined by comparing the temporal elevations at the selected discrete points or comparing the corresponding temporal DTM, terrain profiles and contour lines.

In many cases, the comparison is based on heterogeneous elevation data types due to lack of similar data at the various times. Therefore, when comparing old DEM and new terrain profiles, the determination of the elevation of these "new" profile points in the "old" DEM can be accomplished by vertically extending the plumb line passing through the planimetric position of the "new" points until this vertical line intersects the "old" DEM terrain surfaces. The point of intersection on the DEM surface is set to be the "old" elevation of the profile. The "old" h value at the point of intersection was determined by interpolating the "old" DEM at the new X,Y location as $h_{X,Y} = f(DEM(X,Y,Z))$. Then the elevation change can now be determined at the terrain profile points. Figures 4 and 5 show an overview and a detail of these LiDAR terrain profiles.

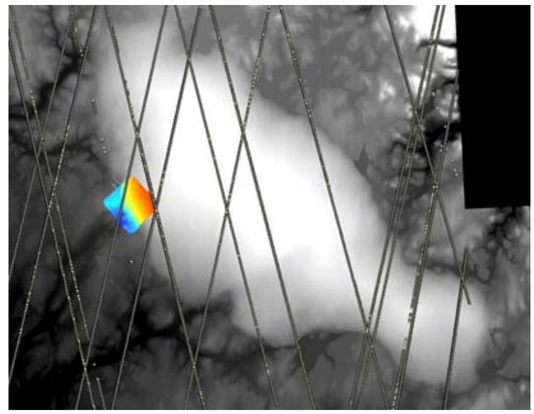


Figure 4. 2003-2005 ICESat profiles over CDED and high resolution photogrammetric DEMs

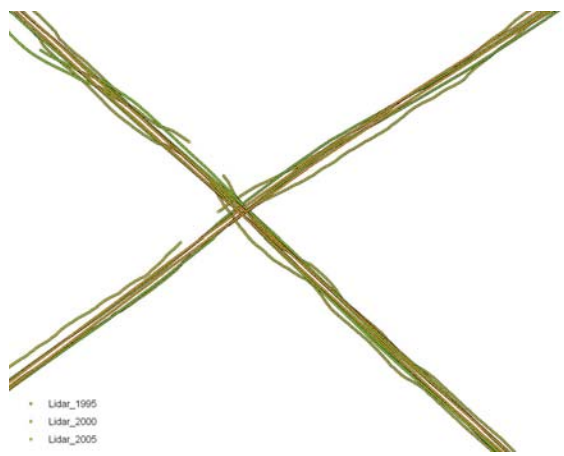


Figure 5. Detail of the 1995-2000-2005 NASA LiDAR tracks

The elevation changes in the ice cap were estimated at the profile points of the ICESat and NASA LiDAR elevation points, respectively. Both LiDAR data sets were compared to 1958 DEM and CDED elevation data to provide the following Δh elevation changes:

Δh = DEM1958 – NASALidar(1995/2000/2005)
Δh = DEM1958 – ICESat(2003-2005)
Δh = CDED1958 – NASALidar(1995/2000/2005)
Δh = CDED1958 – ICESat(2003-2005).

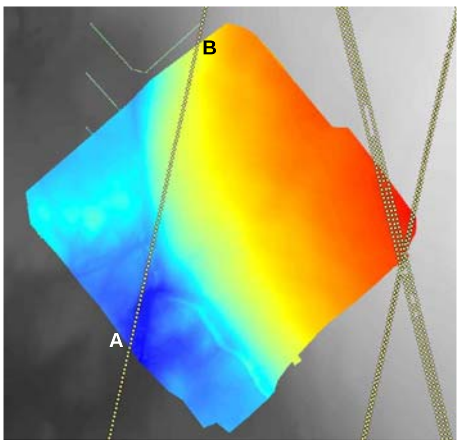
The elevation differences were determined in 32 profiles, distributed as follows:

DEM 1958 – NASALidar(1995/2000/2005): 4 profiles

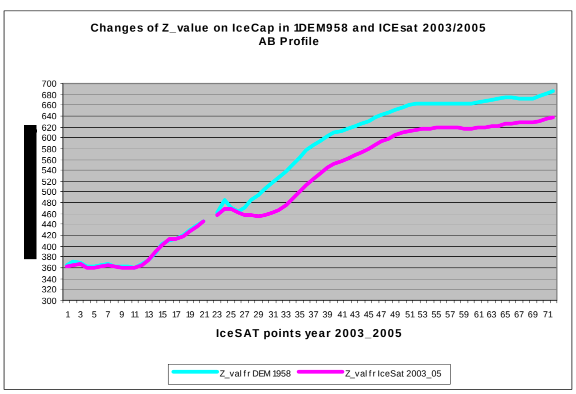
DEM 1958 – ICESat (2003-2005): 4 profiles
CDED1958 – ICESat(2003-2005): 6 profiles
CDED1958 – NASALidar(1995/2000/2005): 18 profiles.

This section presents the findings initially reported at the IPY GeoNorth 2007 International Conference (Armenakis et al., 2007). In any interpretation of the results the accuracy of the elevation data used should be considered. While the photogrammetric DEM has accuracy of about 6-7m at 90%, the CDED DEM was generated from the 40m contours and its estimated given accuracy is 50m at 90%.

In comparing the elevations between 1958 photogrammetric DEM and NASA LiDAR 1995, the results indicate that the ice heights along a given profile have been dropped by an average of about 20m over the 1958-1995 period (37 yrs), thus resulting in an average annual ice elevation change rate of about -0.50m/yr.



(a)



(b)

Figure 6. Elevation changes between DED1958 DEM and ICESat 2003-2005

Comparing the elevations between 1958 photogrammetric DEM with the decimetre accurate ICESat 2003-2005, the results indicate that the ice heights along the A-B profile (Fig. 6) have been dropped at the lower side of the ice cap. At elevations between 460m and 680m, the ice heights along this profile have been lowered by an average of about 45m over the 1958-2005 period (47 yrs). This results in an average annual ice elevation change rate of about -1.0m/yr at the foot neighbourhood of the ice cap. They also indicate that there is a good agreement between the 1958 photogrammetric elevations and the ICESat 2003-2005 elevations over the bare terrain (Fig 6b).

The results from comparing several terrain profiles between CDED1958 and ICESat 2003-2005 indicate that during this 47 years period:

- at ice cap elevations of about 1100m at the top of the ice cap, the ice heights have been lowered by an average of about 5m, thus resulting in an average annual ice elevation change rate of about -0.11m/yr.
- at elevations of about 850m at the sides of ice cap the ice heights have been lowered by an average of about 20-25m, thus resulting in an average annual ice elevation change rate of about -0.42 to -0.53m/yr.
- at elevations of about 600m at the slopes of ice cap the ice heights have been lowered by an average of about 20-35m, thus resulting in an average annual ice elevation change rate of about -0.42 to -0.74m/yr.
- at the bottom of the ice cap, melting of ice has cause some rise of water level in lake bodies.
- old and new elevations describe common terrain morphology.
- over bare land both old and new elevations more or less match.

Table 1 summarizes the elevation changes between CDED1958 DEM and NASA LiDAR (1995 - 2000 - 2005) determined on a profile along the length of the Barnes ice cap.

Table 1: Changes between CDED1958 DEM and NASA LiDAR (1995 - 2000 - 2005)

Period	Elevation (m)	Δh (m)	Average Δh annual change (m/yr)	Filling up depressions at 850m (m)	Average Δh annual change at depression at 850m (m/yr)
1958-1995 37 years	> 1050 < 1050	-5 to +5 -15 to -35	-0.13 to +0.13 -0.40 to -0.95	+19	+0.51
1958-2000 42 years	> 1050 < 1050	-10 to +2.5 -20 to -45	-0.24 to +0.06 -0.48 to -1.07	+17.5	+0.42
1958-2005 47 years	> 1050 < 1050	-12 to 0.0 -23 to -55	-0.25 to 0.0 -0.49 to -1.17	+14	+0.30

The results in Table 1 indicate that:

- at elevations above 1050m at the top of the ice cap both positive and negative changes of the elevation have occurred, indicating both gain and loss of local ice mass.
- at elevations below 1050m and along the sides of the ice cap negative elevation changes have occurred, indicating local loss of ice mass.
- the trend of negative elevation changes is observed for all three periods of 37, 42 and 47 years respectively.

The positional tracks of the 1995, 2000 and 2005 NASA LiDAR profiles are within 250m corridors. This allows also for the determination of indicative (approximate) elevation changes amongst the NASA LiDAR elevation profiles for 1995, 2000 and 2005 in the vicinity of these profiles (Table 2). The results in Table 2 compared to those in Table 1 indicate that the average annual negative rate change in elevation is higher between 1995 and 2000 and has slowed down between 2000 and 2005. Overall the rate of negative elevation changes between 1995 and 2005 is higher than the previous periods from 1958 to 1995, 2000 and 2005, respectively.

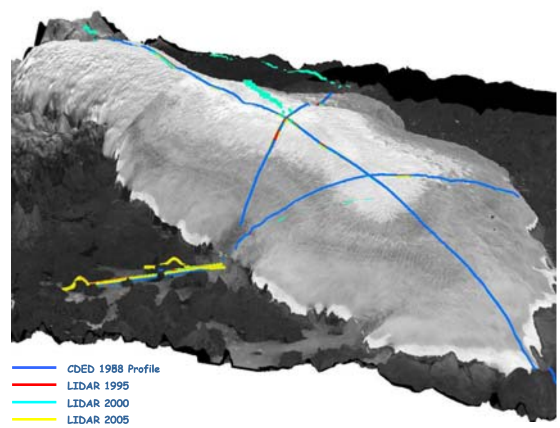
Table 2: Changes between NASA LiDAR (1995 - 2000 - 2005) data

Period	Elevation (m)	Δh (m)	Average Δh annual change (m/yr)	Filling up depressions at 850m (m)	Average Δh annual change at depression at 850m (m/yr)
1995-2000 5 years	> 1050 < 1050	-5 to -2.5 -5 to -10	-1.0 to -0.5 -1.25 to -2.9	-1.5	-0.3
2000-2005 5 years	> 1050 < 1050	-2 to -2.5 -3 to -10	-0.4 to -0.5 -0.6 to -2.0	-3.5	-0.2
1995-2005 10 years	> 1050 < 1050	-7 to -5 -8 to -20	-1.4 to -1.0 -1.6 to -4.0	-5	-1.0

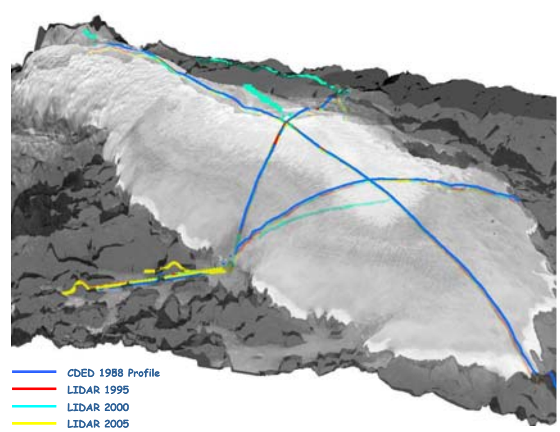
3.1 Visualization of vertical changes

Both the 1958 DEM and the newer terrain profiles were also explored using data visualization tools to have an overall understanding of the location of the new 3D data and the location of the elevation changes within the ice cap. Visualization tools, such as the ESRI ArcScene, support the manipulation of data in 3D space by rotating, translating and scaling the objects together with zoom-in/out, image draping functionality and a degree of transparency.

The latter provided a "see through" capability, thus making possible the viewing of any recent profile elevation with lower surface elevation and detecting areas of ice thinning. Some of these recent elevations tracks can be seen to disappear under the 1958 terrain surface as they trace the slopes and their lower elevations show that they are underneath the surface due to drop of the height of the ice. By rotating the surface these elevations can be clearly seen under the 1958 terrain surface. Figure 7 shows the NASA LiDAR data with image transparency off and on to show that several points of these profile tracks are displayed on the ice cap CDED1958 surface, indicating no drop on the ice elevations, and some tracks disappear and thus indicating a drop in ice elevations. Several of these 3D perspective views were generated showing for example an overview of coverage of the NASA LiDAR and ICESat data at CDED elevation and the ICESat 2003-05 profile elevations in relation to the 1958 high resolution photogrammetric DEM.



(a) transparency off



(b) transparency on

Figure 7. NASA LiDAR terrain profiles over the CDED1958

4. CONCLUDING REMARKS

The monitoring of the state of the arctic cryosphere provides important information on how this sensitive area is influenced by the changes in the climate. For recent changes within the last 40-50 years, historic aerial photographs and current earth observations have been used to determine planimetric and elevation changes of the Barnes ice cap, located at Baffin Island. Aerial photographs from the National Air Photo Library (NAPL, NRCan) and the Aerial Survey Database (ASDB, NRCan) are an excellent source of baseline data for Northern Canada dating back to 1950's and 60s. Historic 1958 aerial photographs were used to generate photogrammetric DEM and ortho-images at sampled locations of the Barnes ice cap. Recent EO datasets, extended from 1995 to 2005, consisted of Landsat 7 ortho-imagery and altimetric data from airborne NASA LiDAR data and satellite ICESat terrain elevation profile data.

The planimetric changes were determined at three sampled locations by estimating the linear displacements of the boundary edge of the ice cap between aerial and Landsat 7ortho-images. The boundary edge was extracted from both ortho-images using a spatial filter. Based on the sample locations, retreat ranges between 120-600m were measured.

The comparison of the temporal terrain profiles indicates that the ice cap elevations have been lowered mainly at the sides of the ice cap and at the lower elevations, where the average elevation dropping rate of the ice elevation is reaching approximately the 1m/yr during the last 40 years.

Ground validation of the results is necessary due to the magnitude of uncertainties in some of the data. Due to the remoteness of the area this might be somehow difficult. An indirect validation for estimating relative changes can be performed by extending the measurements over bare land areas and assume stability of these areas over time. Further, methods of comparing data of higher accuracy data, such as airborne and satellite LiDAR altimetric data have to be explored.

The results obtained are indicative of the spatio-temporal changes occurring in northern Canada and can contribute to the improvement of our understanding of the changes occurring in the polar environments and ecosystems, particularly if linked with atmospheric and environmental parameters. Airborne and satellite earth observations due to their extended and frequent coverage will continue to be the main tool for collecting geospatial data over the remote and vast areas of the arctic regions of Canada for mapping and detection of spatial changes.

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