Article

Applications of CryoSat to Measure the Surface Elevation and Mass Balance of Canadian Arctic Glaciers and Ice Caps

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The glaciers and ice caps of the Canadian Arctic cover an area of ~150,000 km^2, and comprise the largest area of land ice outside of the Greenland and Antarctic ice sheets. They have experienced strongly negative mass balance conditions over the past several decades, with a recent acceleration in mass losses as air temperatures have increased. Mean summer temperatures increased by an average of ~1°C across the Queen Elizabeth Islands between 2000 and 2015, with warming particularly concentrated at high elevations on the most northerly ice caps of Ellesmere and Axel Heiberg Islands (Mortimer et al., 2016). Terrestrial ice mass losses in the Canadian Arctic Archipelago averaged 60 Gt yr^{-1} over the period 2002-2014 (Harig and Simons, 2016), approximately 3 times greater than they were between 1995 and 2000 (Abdalati et al., 2004). This makes the Canadian Arctic the largest recent contributor to sea level rise outside of the ice sheets (Jacob et al., 2012). This aligns with observations from passive satellite microwave records that the average melt season on Barnes Ice Cap lengthened by ~33% between 1979–1987 and 2002–2010 (Dupont et al., 2012), and that near-surface firn temperatures have increased by ~10°C in the summit region of Penny Ice Cap since the mid-1990s (Zdanowicz et al., 2012). Losses have been particularly marked on small glaciers and ice caps, with independent ice masses <25 km^2 in size on Axel Heiberg Island retreating by ~50-80% between 1958-59 and 1999-2000 (Thomson et al., 2011).

Figure 1: Downloading an automated weather station near the summit of White Glacier, Axel Heiberg Island, Nunavut.

A significant challenge with measuring changes to the glaciers and ice caps in the Canadian Arctic is their remoteness and large spatial extent. The traditional method of glacier mass balance measurement uses the 'glaciological' method of measuring the annual change in height of a series of poles drilled into the surface along the centreline of a glacier. These measurements started in the late 1950s in the Canadian Arctic, and today the Geological Survey of Canada maintains long-term mass balance networks on Devon Ice Cap, Meighen Ice Cap and Melville South Ice Cap, while the University of Ottawa maintains the network on White Glacier, Axel Heiberg Island (Fig. 1). The data recorded by these mass balance networks is submitted annually to the World Glacier Monitoring Service in Zurich, Switzerland (http://wgms.ch/), and provides a valuable record of the long-term mass balance changes for these glaciers (Thomson et al., 2016). However, there are large regions of the Canadian Arctic where no *in situ* mass balance measurements exist, so airborne or remote sensing methods must be used to monitor the glaciers in these locations. To date, there are two primary methods that have been used to measure regional glacier changes in the Canadian Arctic:

(a) Measurements of changes in gravitational attraction, primarily measured by the Gravity Recovery and Climate Experiment (GRACE) satellite. Once corrections have been made for effects such as isostatic uplift, this method can provide detailed temporal information (~monthly) about mass balance changes since 2002, but at a low spatial resolution (~200 km) (Jacob et al., 2012; Harig and Simons, 2016).

(b) Measurements of changes in surface elevation, derived from repeat airborne altimetry measurements (Abdalati et al., 2004) or the construction of repeat digital elevation models (DEMs) of the glacier surface, typically derived from stereo aerial photography (Thomson et al., 2016) and/or stereo satellite imagery

(Gardner et al., 2012). This method can provide excellent spatial resolution (to a few centimetres), but typically poor temporal resolution (often at least 5 years between repeat measurements). The poor temporal resolution mainly relates to the high expense of conducting airborne surveys in the Canadian Arctic and the long periods of darkness and cloud cover that reduce the availability of optical satellite imagery for DEM production. In addition, spatial resolution is limited in areas of extensive snow cover, such as in the accumulation area of ice caps, where matching of surface features is problematic, particularly when relatively low resolution satellite imagery (e.g., ASTER, 15 m) must be relied upon.

From the above review, it is clear that we are currently lacking a method that can provide high spatial *and* temporal resolution records of glacier mass balance changes across the Canadian Arctic. Fortunately, there is a new source of data that can help to address this: the surface elevation information provided by the CryoSat-2 satellite. This satellite was launched by the European Space Agency in 2010 (after the failed launch of Cryo Sat-1 in 2005), and carries a radar altimeter, which means that it is able to make measurements during the polar night and in cloudy conditions. Previous high accuracy satellite altimetry measurements were undertaken by the laser-based ICESat satellite operated by NASA, which operated intermittently between 2003-2010, but suffered from premature failure of its lasers that limited the spatial coverage and temporal repeatability of its measurements.

Ice Cap DEM Production from CryoSat Data

Our first work with CryoSat data (Gray et al., 2013) demonstrated that 'swath processing' of radar interferometric data recorded by the satellite can be used to produce high resolution DEMs of glacier surface topography. Our method enables the determination of surface topography in regions away from the 'point-of-closest-approach' (POCA) that is most typically mapped by the satellite. This relies on using the interferometric phase of the returns in the L1b CryoSat product to map the heights of footprints beyond the POCA. This method is limited to regions where average surface slopes in the cross-track direction lie between ~0.5° and 2.0°, but fortunately these conditions often exist across the accumulation area of Canadian Arctic ice caps. By combining data from repeat passes, a DEM can then be created across large regions. CryoSat records waveforms approximately every 300 m along the satellite flight path, with a ground range swath of up to 5 km, dependent on the cross-track slope, and resolution of ~100 m.

We used this method to create a DEM of the western slopes of Devon Ice Cap (Fig. 2), based on satellite passes that typically occur 2 or 3 times per month on both ascending and descending orbits. A comparison of the DEM with near-simultaneous airborne laser altimetry measurements indicated a mean difference of 0.49 m and standard deviation of 0.75 m (Gray et al., 2013). While this DEM was created under ideal conditions, this method provides promise for measuring inter-annual changes in surface elevation in the accumulation region of Arctic ice caps.

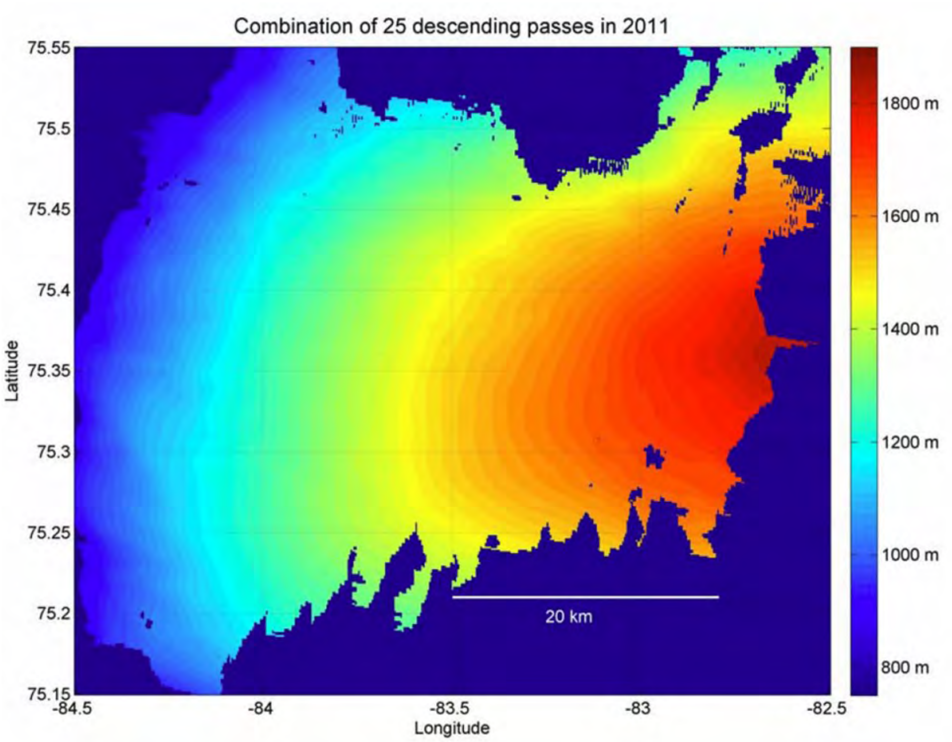

Figure 2: Digital elevation model of the western part of Devon Ice Cap produced from 25 descending CryoSat passes between February 2011 and January 2012. The rough north and south edges reflect locations where the surface slope is greater than ~2.0°, indicating locations where the interferometric processing produces a poor solution. From Gray et al. (2013).

Monthly Determination of Surface Elevation Changes from CryoSat Data

More recently we have extended our work to improve detection of the position of the POCA in CryoSat records, and from that the measurement of monthly changes in the height of ice caps in the Canadian and Norwegian Arctic (Gray et al., 2015). By developing a 'retracker' that estimates the POCA position in a CryoSat waveform from the maximum slope on the first significant leading edge of the return, we can measure individual point elevations on ice caps to an accuracy of ~1-1.5 m. However, by comparing spatial averages at different time periods, height change can be estimated with sub-meter accuracy. The repeat orbit period of CryoSat is 369 days, but it contains a 30-day orbit sub-cycle that enables approximately monthly measurements of the surface elevation of ice caps by averaging many thousands of individual returns. When applied to Barnes Ice Cap, Baffin Island, for example, this enables the nearly continuous monitoring of surface mass balance conditions (Fig. 3). An analysis of CryoSat records from the same period each year can then provide information on the annual mass balance. Comparisons between CryoSat-derived height changes on Devon Ice Cap and those recorded with an automated snow depth sounder show close correspondence, with the CryoSat measurements recording a mean height change of -0.72 ±0.5 m for 2011, compared to -0.64 ±0.03 m recorded by the in situ sensor (Gray et al., 2015).

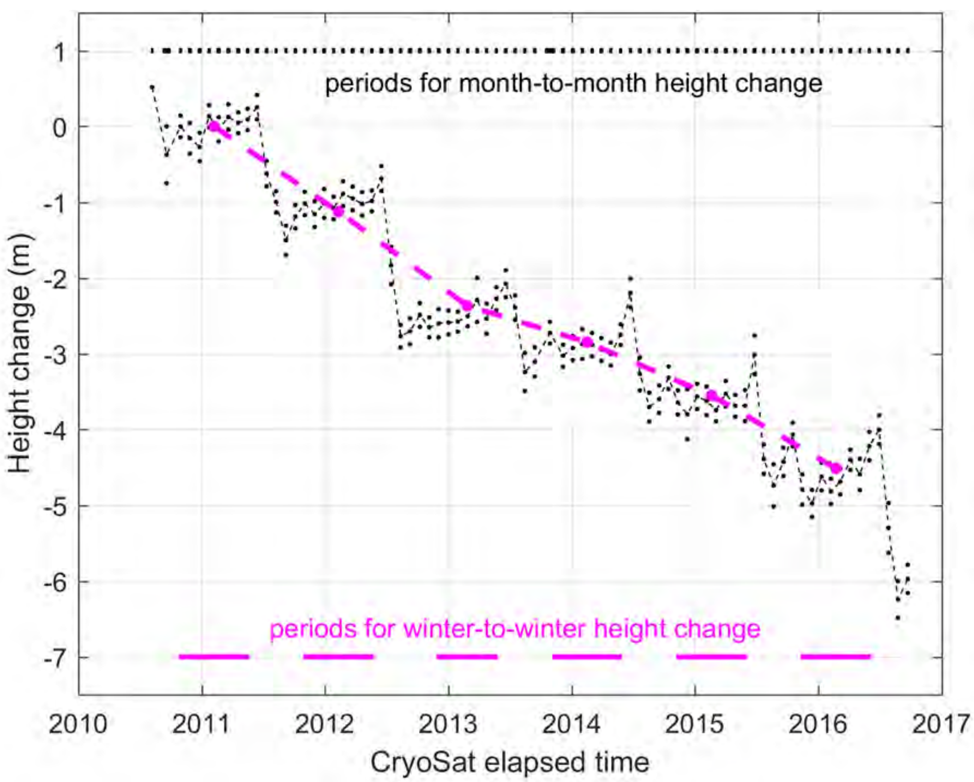

Figure 3: Evolution in surface height of Barnes Ice Cap between 2010-2016 based on the average of >65,000 waveforms recorded on >400 CryoSat passes. Data is grouped into approximately monthly periods, which are indicated by short dashed lines in the upper part of the figure. Purple dots and dotted purple line indicates the winter-to-winter height change calculated from the periods indicated by the solid purple lines.

These results do not come without limitations, however. One of the most significant issues is that CryoSat waveforms will penetrate a snow surface when it is dry, but reflect from the top of the snow surface when it is wet. This results in an apparent seasonal variability in the surface height of Arctic ice caps that isn't real, but instead reflects differential penetration of the radar wave. This is evident in Figure 3, where an apparent increase in surface height of >0.2 m occurs every May/June as melt starts on the ice cap surface. This means that only CryoSat data from the same period each year should be used to derive annual mass balances. However, this effect can also be useful by providing a method to detect timing of the onset of summer melt. A further limitation of CryoSat data is that it can only be used to measure surface slopes less than ~2.0°. This precludes the use of it to measure surface elevation changes on most outlet glaciers and the lower ablation regions of many ice caps.

Despite these limitations, CryoSat data can still provide valuable information concerning changes in the surface height, and therefore mass balance, of Arctic glaciers and ice caps at a higher spatial and temporal resolution than is possible with almost any other current remote sensing method. Ongoing work is focused on reducing errors in the CryoSat processing method and implementing CryoSat data for the operational monitoring of ice caps in the Canadian Arctic.

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About Luke

Luke Copland is a Professor in the Department of Geography, Environment and Geomatics at the University of Ottawa, and holds a University Research Chair in Glaciology.

His research program is focused on understanding the dynamics and recent changes of glaciers, ice caps and ice shelves across northern Canada, including in the St. Elias Mountains, Yukon, and the Queen Elizabeth Islands, Nunavut. This includes maintenance of the mass balance monitoring program at White Glacier, Axel Heiberg Island, which was established in 1959 and is the longest running in the Canadian Arctic.