Comparing simple albedo scaling methods for estimating Arctic glacier mass balance

Scott N. Williamson, Luke Copland, Laura Thomson, David Burgess

Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada
Department of Geography and Planning, Queen’s University, Kingston, Ontario K7L 3N6, Canada
Cryosphere Geoscience Section, Natural Resources Canada, Ottawa, Ontario K1A 0E8, Canada

ARTICLE INFO

Keywords:
Albedo
Glacier mass balance
MODIS
Canadian Arctic

ABSTRACT

Mass balance measurements in the Canadian Arctic are limited, particularly for smaller glaciers, which introduces significant uncertainties in regional mass balance assessment. Here we report on the correlations between Moderate Resolution Imaging Spectroradiometer (MODIS) Terra albedo measurements (Version 6) and net annual mass balance for five glaciers in the Canadian Arctic over the period 2002–2016. Three glacier albedo aggregation methods are tested for the melt season (June, July and August): minimum, raw average, and interpolated average. These are evaluated in terms of a 53–71% reduction in observations due to cloud cover in the raw albedo time series. For the minimum method, the whole glacier albedo is calculated from the average of the minimum melt season albedo of each grid cell, irrespective of the day on which they occurred, resulting in $R^2$ values between 0.20 and 0.87. In the raw average method, averaging all albedo values within a glacier outline over the melt season improves the correlation to mass balance to a range of 0.61–0.95. In the interpolated average method, linear interpolation of the raw average albedo values to fill cloud gaps, then averaging them, improves the raw average correlations for all ice masses by ~5% ($R^2$ range 0.68–0.97). Overall, the interpolated average albedo method performs substantially better for the smallest glacier than the minimum or the raw average methods. The most negative net mass balance occurs at Grise Fiord Glacier, which is the smallest (<4.0 km$^2$), but not the lowest elevation, glacier analysed. For this glacier, the interpolated average albedo improves the correlation to mass balance to an $R^2 = 0.68$ (p-value < .05), compared to an $R^2 = 0.17$ for the minimum albedo method (p-value > .05). When the five glaciers' interpolated average albedo is correlated to their ensemble mass balance, an $R^2 = 0.82$ is achieved. These results show that interpolated MODIS Terra melt season albedo measurements can realistically approximate net annual glacier mass balance for Arctic glaciers and ice caps, without additional information about precipitation or temperature, and in the absence of a melt model.

1. Introduction

The recent mass balance of Canadian Arctic glaciers is strongly negative (Koerner, 2005; Gardner et al., 2010; Harig and Simons, 2016; Noël et al., 2018) and melt rates have accelerated since 2005 (Sharp et al., 2011). Glaciers outside of the ice sheets total 3% of the Earth’s ice volume and contribute approximately 1/3 of contemporary sea level rise (Jacob et al., 2012; Church et al., 2013; Gardner et al., 2013), of which Canadian Arctic glaciers are the biggest contributor (Harig and Simons, 2016) and modelling suggests will provide a significant contribution through 2100 (Radić et al., 2014). The general patterns of glacier change in the Canadian Arctic (e.g., Box et al., 2018) are reasonably well understood from Gravity Recovery and Climate Experiment (GRACE) gravimetry (Harig and Simons, 2016) and regional climate model simulations (Noël et al., 2018). However, glacier-specific estimates of mass balance are limited (e.g., Koerner, 2005), especially for small and low-elevation ice caps and glaciers that contribute disproportionately to current sea-level rise. Small glaciers (i.e., ≤ 1 km$^2$) represent a large area and volume of ice when added together and could represent up to 10% error in global volume calculated from standard glacier inventories (Bahr and Radic, 2012). However, small ice masses are poorly monitored and have the potential to provide large contributions to sea level rise in the near future (Bahr and Radic, 2012). In addition, the mass balance of small glaciers is difficult to measure with coarse resolution observations, such as GRACE. Modelling of Arctic glacier mass balance is also difficult for small glaciers, where
models often don’t adequately capture the magnitude of melt (e.g., Noël et al., 2018).

The Canadian Arctic typically has low annual snowfall, so annual glacier mass balance fluctuations are primarily a function of summer melt (Sharp et al., 2011), which is typically driven by the melting of snow and ice. Inter-annual variability of melt-period onset and duration in the Queen Elizabeth Islands (QEI) is primarily dependent on glacier surface elevation and distance from Baffin Bay (Wang et al., 2005). Melt onset typically occurs between late May and mid-July, with melt cessation occurring between mid-July and early September. Over the period 2000–2004, melt duration ranged from 100 days in areas facing Baffin Bay in the southeast QEI at low elevations, to one day at high elevations (Wang et al., 2005). Glacier surface elevation over the QEI ranges from sea level to 2616 m a.s.l. at the summit of Mt. Barbeau (81.927°N, 74.987°W) on northern Ellesmere Island. The average annual melt duration for the QEI was 37.7 ± 4.9 days between 1979 and 2011, with melt onset occurring ~2–3 days earlier at the end of this period than at the start (Wang et al., 2013). In addition to melt duration, the length of the snow free period in the Arctic has also increased by ~3–5 days decade⁻¹ over the last several decades (Bokhorst et al., 2016). Mortimer and Sharp (2018) used 16 day MODIS MCD43A3 shortwave broadband black sky albedo to identify Canadian High Arctic June, July and August glacier albedo changes between 2001 and 2016. Over this period the average summer albedo decreased by 0.029 ± 0.025 decade⁻¹, with most of the reductions recorded in July. The majority of the albedo decreases occurred between 2007 and 2012 at the margins of lower elevation ice masses.

Long-term field-based mass balance monitoring is limited to five locations in the Canadian Arctic (e.g., Koerner, 2005; Thomson et al., 2017; Burgess, 2017), which are insufficient to derive regional estimates of mass balance by extrapolation alone (Marzeion et al., 2017). This lack of detail in mass balance monitoring limits our understanding of melt patterns, and thus the ability to constrain predictions of future sea level rise. Studies suggest a strong climate-driven component in glacial mass losses (Gardner et al., 2011; Noël et al., 2018), but large scale, high resolution, measurements of energy balance in relation to melt are currently lacking, even though solar radiation provides the majority of energy required to melt glaciers (Van As, 2011). Longwave radiation has recently been shown to be important in glacier melt (Bennartz et al., 2013) and in limiting refreezing (Van Tricht et al., 2016). Thus, a complete energy balance, not just air temperature, is needed to explain the mass wasting of ice caps.

The processes that control a glacier’s surface mass balance (i.e., discounting substantial dynamic contributions) also dictate the seasonal variation of a glacier’s albedo, or the ratio of reflected to incident shortwave (solar) radiation. Glacier broadband albedo is on average ~0.85 across the whole of a snow covered glacier in the spring prior to the onset of melt (Cuffey and Paterson, 2010). Snow cover is typically retained at the highest elevations of a glacier throughout the summer melt period, in the accumulation zone, where weathering and snow grain metamorphosis decrease the accumulation area albedo to ~0.5 (Wiscombe and Warren, 1980). At a glacier’s lower elevations, in the ablation zone, bare clean glacier ice is typically present in the summer, which reduces the albedo to ~0.34–0.51 for areas of exposed ice (Paterson, 1994), although values between 0.5 and 0.6 have been reported for clean bare ice on the Greenland Ice Sheet (Beggild et al., 2010). Surface albedo values for bare ice can be much lower (as low as ~0.06) if dust, liquid water or rock debris accumulates in sufficient quantities on the surface (Cuffey and Paterson, 2010).

The Equilibrium Line Altitude (ELA) marks the boundary between the ablation and accumulation zones, and has been shown to scale effectively to annual glacier net mass balance (Braithwaite, 1984; Rabatel et al., 2005) for glaciers where the surface mass balance dominates (i.e., little or no dynamic discharge). Alternatively, the accumulation-area ratio (AAR) also scales to annual glacier net mass balance (Dyurgerov et al., 2009; Bahr et al., 2009) in a similar way to that of ELA. The AAR and ELA can be represented by albedo, providing that albedo values are measured in sufficient density across an entire glacier, meaning that a glacier’s mass balance can be estimated with satellite remote sensing. This technique integrates many aspects of glacier mass balance that are difficult to measure, such as summer snowfall events that restrict melt (Oerlemans and Klok, 2004). The use of albedo to determine glacier mass balance directly integrates shortwave solar radiation in a way that other measures of glacier mass balance do not. In general, satellite-measured albedo for an entire glacier is aggregated into a single value using one of two albedo aggregation methods: melt season minimum or melt season average, which are then correlated to net annual mass balance.

Using the glacier minimum albedo and MODIS data, statistically significant correlations between mass balance and minimum albedo have been found for glaciers in the European Alps (Dumont et al., 2012; Davaze et al., 2018), New Zealand (Sirguey et al., 2016), Himalayas (Brun et al., 2015) and the Tibetan Plateau (Zhang et al., 2018). The minimum melt season albedo of a whole glacier as proposed by Dumont et al. (2012) describes the smallest whole glacier average albedo measured on a single day over the course of a melt season when there is no partial or total cloud obstruction (i.e., clear sky conditions). The most comprehensive analysis of whole glacier albedo correlation to mass balance was conducted for 30 mountain glaciers in the European Alps that had net annual mass balance records, of which 6 also had summer mass balance (Davaze et al., 2018). Near-daily MODIS white sky albedo data, produced at 250 m resolution using the MODImLab software following Sirguey et al. (2009, 2016), indicated large variability in correlation between minimum (spatially averaged) albedo and mass balance. The average melt season albedo correlated better with summer mass balance than did the minimum albedo with net annual mass balance, suggesting that glacier wide minimum albedo might not be the optimal aggregation method for glacier mass balance estimation. Inter-annual climate variability might, for example, produce the same annual minimum albedo, but change the shape of the seasonal albedo curve if a warm spring results in an earlier decline in albedo and associated increase in total summer melt. Furthermore, cloud cover might obscure the true minimum albedo value, which could be hidden within a cloud cover gap in the seasonal albedo curve.

Average albedo, measured with AVHRR (Advanced Very High Resolution Radiometer), has been correlated against the surface mass balance of six Svalbard glaciers (De Ryuter de Wildt et al., 2002; Calluay et al., 2005) with a large range of variances (R² = 0 to 0.87) for up to five years of mass balance records. The average albedo of various Greenland glaciers was correlated to surface mass balance using AVHRR by Greuell and Oerlemans (2004) for 13 years and with MODIS MOD10A1 by Colgan et al. (2014) for 10 years. The correlation coefficients for these studies were 0.84 and 0.90, respectively. MODIS Terra albedo modified to produce an average melt season total energy flux for two glaciers in Svalbard was found to be highly correlated to annual glacier net mass balance by Greuell et al. (2007) for six years of data.

In this study we first determine if glacier minimum average MODIS albedo for the melt season, calculated on a grid cell by grid cell basis, correlates to net annual mass balance for two valley glaciers and three small ice caps (hereafter, collectively referred to as glaciers) in the Canadian Arctic for which in situ mass balance measurements are available. We then assess if correlation to mass balance is improved by using glacier average albedo from the whole melt season (raw average). Lastly, we investigate if correlation between mass balance and albedo is further improved by using melt season glacier average albedo with gaps caused by cloud cover filled by linear interpolation (interpolated average). No such assessment between albedo and glacier mass balance has been previously made for the Canadian Arctic.
2. Study area

Five glaciers in the Canadian Arctic with net annual mass balance records between 2002 and 2016 are examined in this study: 1 - Melville South Ice Cap, located on Melville Island; 2 - Sverdrup Glacier Basin, an outlet of the northwest portion of Devon Island Ice Cap; 3 - Meighen Ice Cap, located on Meighen Island; 4 - White Glacier, located on western Axel Heiberg Island; 5 - Grise Fiord Glacier, located on southern Ellesmere Island. The 1999–2003 outlines for these ice masses were extracted from the most current Randolph Glacier Inventory version 6.0 (Pfeffer et al., 2014), retrieved from the Global Land Ice Measurements from Space database (https://www.glims.org/RGI/). Further descriptive information regarding these ice masses can be found in Table 1 and Fig. 1. The elevation values for glaciers is provided by the Canadian

Table 1
Glacier location, area and elevation information. Area information extracted from Randolph Glacier Inventory version 6.0, and originates from the 1999 to 2003 period.

<table>
<thead>
<tr>
<th>Glacier Location</th>
<th>Location</th>
<th>Latitude °N</th>
<th>Longitude °W</th>
<th>Area (km²)</th>
<th>Average elevation (m) ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Melville South Ice Cap</td>
<td>Melville Island</td>
<td>75.40</td>
<td>115.00</td>
<td>53.26</td>
<td>646.59 ± 42.25</td>
</tr>
<tr>
<td>2. Sverdrup Glacier Basin</td>
<td>Devon Island</td>
<td>75.42</td>
<td>83.25</td>
<td>746.94</td>
<td>1247.93 ± 385.93</td>
</tr>
<tr>
<td>3. Meighen Ice Cap</td>
<td>Meighen Island</td>
<td>79.95</td>
<td>99.13</td>
<td>92.93</td>
<td>144.67 ± 47.24</td>
</tr>
<tr>
<td>4. White Glacier</td>
<td>Axel Heiberg Island</td>
<td>79.45</td>
<td>90.70</td>
<td>38.54</td>
<td>1094.29 ± 325.07</td>
</tr>
<tr>
<td>5. Grise Fiord Glacier</td>
<td>Ellesmere Island</td>
<td>76.42</td>
<td>82.69</td>
<td>4.07</td>
<td>599.69 ± 19.06</td>
</tr>
</tbody>
</table>

Fig. 1. Study area showing Canadian Arctic glaciers used in this study: 1. Melville South Ice Cap; 2. Sverdrup Glacier Basin; 3. Meighen Ice Cap; 4. White Glacier; 5. Grise Fiord Glacier. See Table 1 for location details. The blue areas indicate glacier ice extent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Digital Elevation Model (CDEM) produced at 3 arc sec (approximately 90 m) by Natural Resources Canada and acquired from https://open.canada.ca/data/en/dataset. These data were resampled to 500 m grids that correspond to the MODIS snow albedo grid.

3. Methods & data

3.1. Methods

We calculate the correlation between net annual mass balance and glacier averages of melt season (June, July, August) albedo, using the MOD10A1 MODIS/Terra Snow Cover Daily L3 Global 500 m SIN Grid, Version 6 albedo data downloaded from the National Snow and Ice Data Center (https://nsidc.org/data). These data were processed using the MODIS Reprojection Tool to produce daily albedo images in Lambert Conformal Conic projection with the WGS84 datum between June 1 and August 31 for the years 2002 to 2016. Large gaps in the albedo time series in 2000 and 2001 precluded their use.

Outlines for the five ice masses (Table 1) were used to subset the daily MOD10A1 albedo images. Many QEI glaciated regions are mountainous, with glaciers in deeply incised valleys, so shadowed areas were excluded to avoid the inclusion of unrealistically low albedo values. Furthermore, bright dry snow and cloud could have similar albedo but are notoriously difficult to distinguish in satellite reflectance (Stillinger et al., 2019). To reduce bias due to possible misclassified snow, we use expected ranges for glacier snow and ice albedo (Cuffey and Paterson, 2010) to filter the MODIS gridded daily albedo product. Albedo values > 0.99 were considered physically unrealistic for snow or glacier ice and were excluded; albedo values < 0.05 were considered to be influenced by shadow and were also excluded. In addition, data gaps of ~1 to 10 days due to cloud cover occur in the melt season daily albedo time series. These gaps do not present a strong seasonal pattern and can apply to some or all of a glacier’s extent.

Using these MODIS MOD10A1 daily snow albedo data, three different aggregation methods were used to determine a single average albedo value for each glacier and for each melt season:

1. Minimum: the minimum albedo value from June, July or August for each grid cell contained within each glacier outline was individually identified. This step produced a map of melt season minimum albedo for each glacier, which was averaged using equal weighting to produce a minimum average value for each of the five ice masses for each melt season between 2002 and 2016. This differs from the minimum method of Dumont et al. (2012), which uses the average minimum melt season albedo of an entire glacier on a single cloud-free day. This modification was necessary due to the prevalence of cloud cover over our Arctic study area, which severely limited the number of clear sky images of a glacier’s full extent over the course of a melt season.

2. Raw average: June, July and August average albedo was produced by averaging all available albedo values for each grid cell within a glacier outline (i.e., cells with cloud cover were excluded). This step produced a map of average melt season albedo for all cloud-free cells, which was then averaged into a single value for each glacier for each year using an equally weighted mean.

3. Interpolated average: the daily June, July and August albedo maps were gap-filled for periods when cloud cover was present by using linear interpolation of the daily time series for each grid cell. Spatial interpolation was not employed. For each grid cell, an equally weighted mean was used to produce maps of interpolated average melt season albedo, which were then averaged into a single albedo value for each glacier for each year using equal weighting.

The minimum, raw average and interpolated average glacier melt season albedo values were regressed against net annual mass balance using standard least-squares linear regression. Lastly, a representative
cloud cover value for each glacier was calculated as the proportion of grid cells in the raw images that were classified as cloud-covered by the MODIS algorithm, relative to the total number of grid cells. Cloud cover is also explored through its relation to glacier elevation.

3.2. Data

3.2.1. MODIS Terra albedo MOD10A1 Version 6

The snow albedo data used in this study originated from the MODIS sensor on the Terra satellite platform. Terra is in a near-polar sun synchronous descending orbit and collects data with the MODIS sensor over a spectral range of 0.459 to 14.385 μm in 36 spectral bands. Daily MOD10A1 snow albedo is produced in 500 m grid cells for cloud-free conditions from the best single daily observation, which is determined by an algorithm that ingests illumination and satellite view angles, in addition to cloud mask and fractional snow cover (Hall et al., 2002). The glaciers in the high latitude study area are observed approximately 9 times each day because MODIS Terra is in a near-polar sun-synchronous orbit. As a result of the frequent MODIS Terra coverage, and to avoid any potential sensor calibration differences, data from MODIS Aqua was not used.

The MODIS Basic Quality Assessment (QA) for each albedo grid cell used in this study was analysed in relation to known issues with solar zenith angle (SZA). When SZA is greater than 70° the MODIS snow albedo product includes additional uncertainty (Stroeve et al., 2006). The possible QA values were defined as best quality, good quality, OK quality, night, ocean and no data. The night classification is for instances when the SZA is greater than 85°. When the range of SZA is 70° ≤ SZA ≤ 85° the QA is set to OK quality. The OK quality in these instances indicates an increased uncertainty in the albedo quality because of low illumination (National Snow and Ice Data Center (NSIDC), 2020).

The MODIS snow albedo data was not explicitly filtered for quality flags related to SZA for several reasons:

Fig. 2. Melville South Ice Cap: (a) minimum albedo, and (b) interpolated average albedo, for 2011. Contour lines with elevations in m a.s.l. are shown in black.
1. Analysis of the quality flag indicates that data that might suffer from poor illumination constitutes ~1–5% of the valid albedo data for the three southern glaciers (Sverdrup, Melville and Grise Fiord). This OK quality flag only occurred in 3 or 4 years of the 15 year time series, and when it did occur it was generally restricted to one to several days in the melt season. The two northern glaciers (White Glacier and Meighen) had the OK quality flag occur consistently for the last ~10 days of August, which comprised ~5–15% of the total melt season albedo data depending on the cloud-cover during this period. However, these low illumination conditions did not influence the timing of the minimum melt season albedo.

2. During high northern latitude summer the full inversion, and the poorer quality magnitude inversion, of the bidirectional reflectance distribution function for MODIS albedo products are typically similar (e.g., Schaaf et al., 2011; Williamson et al., 2016).

3. At high latitudes, the number of high quality albedo retrievals decreases considerably in the shoulder seasons compared to summer (Schaaf et al., 2011). In our analysis we use summer season only,

---

Fig. 3. Meighen Ice Cap: (a) minimum albedo, and (b) interpolated average albedo, for 2011. For White Glacier: (c) minimum albedo, and (d) interpolated average albedo, for 2011. Contour lines with elevations in m a.s.l. are shown in black.
thereby maximising the number of high quality albedo returns. The two highest latitude glaciers in the study likely violate this statement over the last \( \sim 10 \) days of August, but this data was retained for consistency between all glaciers in the study area and because melt could still be occurring during this period.

4. The base level input data to each method analysed here is identical, and the methods employed in our analyses are concerned with cloud cover data reduction, not data quality reduction. Therefore, in terms of model evaluation, the likelihood that some data are of poorer quality than others is not relevant to the comparison of models.

MODIS albedo data is recorded as unsigned 8-bit, with values from 0 to 255. Albedo values are recorded as 0–100, and ancillary data, such as cloud cover, assigned a static value between 101 and 254.

The MOD10A1 product (Hall et al., 2002) is suitable for investigating glacier-scale mass balance in the Canadian Arctic because of its high precision in ground positioning (\( \pm 50 \) m; Wolfe et al., 2002). The high spatial precision of MODIS is important because the albedo within a MODIS grid cell varies with land cover and snow properties. The accuracy of MOD10A1 Version 5 albedo in the glaciated St. Elias Mountains was found to be \( \pm 0.06 \) (Williamson et al., 2016) and \( \pm 0.07 \) on the Greenland Ice Sheet (Stroeve et al., 2006), both of which show that the product is reliable over glaciated terrain. Ryan et al. (2017) found that surface-based albedo measurements overestimate MOD10A1 (Version 6) albedo by up to 0.10 for bare ice surfaces on the Greenland Ice Sheet during the summer melt season because meteorological station footprints do not accurately represent within grid cell albedo variability, which is primarily related to the under-sampling of meltwater.

Error in MODIS Terra albedo due to sensor degradation has been reported to reduce the absolute value of surface albedo measurements (Polashenski et al., 2015; Casey et al., 2017) and albedo trends of \( 0.01 \) decade\(^{-1} \) are near the limit of sensor calibration. The Version 6 correction applied to MODIS albedo largely compensates for sensor degradation found in the Version 5 data (Casey et al., 2017).

3.2.2. Field measurement of glacier mass balance

Glaciological (direct-method) mass balance observations in the QEI are conducted each spring in April–May and involve the measurement of snow accumulation and melt along stake networks installed along the centreline of five glaciers. The mass balance year spans September 1 to August 31 of the following year, comprising the accumulation season (generally fall and winter) and the melt season (generally summer). Ablation is dominated by surface melt (Noël et al., 2018) and is estimated from changes in glacier surface height relative to stakes drilled into the glacier surface. Mass loss can also occur by dynamic (i.e., iceberg) discharge for marine terminating glaciers, but Sverdrup is the only such glacier in this study and its dynamic discharge is negligible (~4%) in comparison to its surface mass balance (Van Wychen et al., 2017). Accumulation is determined from snow pit analysis at elevations above the historical ELA, where the previous summer surface at the snow pit base is commonly recognizable by the presence of a dense, sometimes dirty, layer overlain by depth hoar. A polynomial or linear fit through the point mass balance estimates versus elevation is used to estimate mass balance between stakes. The mass balance-elevation relationship is then extrapolated to unsampled glacier regions using known hypsometry and the profile method (Østrem and Brugman, 1991).

To correct for systematic errors due to change in glacier hypsometry over time, reanalysis of glaciological method mass balance estimates can be conducted using geodetic (volume-change derived) mass balance estimates. Reanalysis of White Glacier’s mass balance record revealed

---

**Fig. 4.** Sverdrup Glacier Basin: (a) minimum albedo, (b) interpolated average albedo, for 2011. Contour lines with elevations in m a.s.l. are shown in black.
no statistically significant difference between the average annual glaciological balance (−213 ± 28 mm w.e. a⁻¹) and geodetic balance (−178 ± 16 mm w.e. a⁻¹) over the 1960–2014 time period (Thomson et al., 2017). Random errors in the glaciological method are related to both field measurements and spatial interpolation and extrapolation across the glacier basin, and have been approximated to average ± 200 mm w.e. a⁻¹ (Cogley and Adams, 1998). This error is typically several times smaller than the annual mass balance for Arctic glaciers, especially in years of large mass loss. Furthermore, the error in the glaciological method has not acted as an impediment to other studies comparing albedo to mass balance (e.g., Dumont et al., 2012).

The World Glacier Monitoring Service (https://wgms.ch/) Fluctuations of Glaciers Database provides access to annual glaciological mass balance results in the form of a single, glacier-wide annual mass balance, as well as individual point mass balance values and the average mass balance conditions across elevation bands. In this study we use glaciological mass balance data (glacier-wide) from this database; geodetic mass balance data is not used.

4. Results

Net annual mass balance, together with melt season minimum albedo, raw average albedo and interpolated average albedo, are presented for each glacier in Table 2 for the period 2002 to 2016, together

![Fig. 5. Grise Fiord Glacier: (a) minimum albedo, and (b) interpolated average albedo, for 2011. Contour lines with elevations in m a.s.l. are shown in black.](image-url)
with average cloud cover. The annual mass balance was predominately negative during the study period, with only a few years of positive mass balance. Grise Fiord Glacier is the exception to this pattern, as its mass balance was consistently negative.

The albedo for the minimum albedo aggregation method is approximately 30% smaller than the albedo from the raw and interpolated averages, when averaged over the study period. The minimum method produced a range of albedo values of 0.22–0.42. The raw average method produced an albedo value range of 0.53–0.69 over the five glaciers, whereas the interpolated average method produced a similar range of 0.53–0.71. Figs. 2 through 5 illustrate the spatial distribution of minimum albedo and interpolated average albedo for 2011 over the five glaciers analysed in this study. The year 2011 was chosen because it was a particularly negative mass balance year, resulting in larger differences in albedo values between the methods and spatial location.

Figs. 2 to 5 reveal that the interpolated average method produces a stronger albedo – elevation gradient than the minimum method. The minimum method albedo maps often display a speckled surface which is consistent with the appearance of dirty ice, bedrock or melt ponds over the course of a melt season.

The net annual mass balance time series and the time series for the three melt season albedo aggregation methods for the five glaciers are shown in Fig. 6. Grise Fiord Glacier, the smallest glacier studied, had the largest net mass loss. This glacier also showed the lowest values for albedo irrespective of albedo aggregation method. Sverdrup Glacier Basin, which is part of Devon Ice Cap, is the highest elevation and largest glacier considered in this study and showed the smallest net annual mass loss.

The proportion of grid cells that are masked as cloud-covered in the raw daily MODIS albedo images ranged between 53% and 71%.

Fig. 6. Net annual glacier mass balance (left axis), and whole glacier melt season (June to August) minimum albedo, raw average albedo and interpolated average albedo (right axis) for the five ice masses for the period 2002 to 2016.
Fig. 7. Relationship between elevation and average cloud covered days (2002–2016) for the five glaciers in the Canadian Arctic. Cloud cover is averaged over the course of the study period by grid cell. Trend lines are shown in red. Sverdrup, Meighen and White Glacier show statistically significant negative correlation between cloud covered days and elevation \((p < .05)\). Melville shows no statistically significant correlation and Grise Fiord Glacier shows a statistically significant positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

Our results show that MODIS Terra MOD10A1 snow albedo can be used to estimate the net annual mass balance of Canadian Arctic glaciers using a variety of aggregation methods. To start, the minimum albedo methodology was the least successful overall, providing a significant relationship with mass balance for four out of the five glaciers studied (Fig. 8) and an overall R\(^2\) of 0.62 (Fig. 9). Our minimum method incorporates more albedo data than is possible if the entire glacier is required to be cloud-free on a particular day as stipulated by Dumont et al. (2012). Our minimum method considers each grid cell independently, meaning that a grid cell can still be chosen even if surrounding cells are cloud-covered. This provides an improved opportunity to record cells when they reach their annual minimum albedo value in the Arctic. If no clouds occurred throughout the melt season the albedo values produced by our minimum method and Dumont et al.’s (2012) minimum method should be equivalent. Furthermore, the minimum albedo methods are likely insensitive to differences in annual net mass balance when a glacier no longer retains snow cover and the ELA has risen above its highest elevation.

Davaze et al. (2018) showed little correlation between glacier area and the statistical relationship between glacier daily minimum albedo (using the Dumont et al., 2012 method) versus net annual mass balance for 30 glaciers in the Alps. However, it’s difficult to compare minimum results calculated in different ways, and mid-latitude Alpine glaciers are generally much smaller than those in the Canadian Arctic, have higher surrounding mountains, and are subjected to more intense summer melting and more mixing of ice and rock within grid cells. Of the glaciers considered in this study, Grise Fiord Glacier compares most closely in physical dimensions with smaller alpine glaciers, but common cloud cover in the Arctic demands a different approach to minimum albedo aggregation.
The use of interpolated average albedo for the melt season produces a better correlation with net annual mass balance than the minimum or raw average albedo methods. This increase in correlation suggests that the averaging methods (raw and interpolated) better capture the total amount of absorbed solar radiation during the melt season than the minimum albedo method. Minimum albedo is indicative of the maximum solar radiation that a glacier absorbs over a short period of time, but does not capture the influence of cloud cover on the total solar radiation absorbed over an entire melt season. The use of average melt season albedo (both raw and interpolated) likely captures the effects of melt season snowfall events which can retard seasonal mass loss by raising the glacier albedo (Oerlemans and Klok, 2004).

The interpolated average albedo method connects observations made during cloud-free periods to gap-fill the intervening cloudy periods, and might underestimate albedo during the cloudy periods, particularly during summer snowfall events. The interpolated average albedo method likely scales better to mass balance than the minimum method explored here because it partially remediates observation bias caused by cloud cover. The interpolated average albedo likely produces a better correlation to mass balance than the raw average because spatially complete daily albedo values are obtained, rather than the albedo average values being skewed to cloud-free glacier areas and dates. This consistent albedo field weights the resulting melt season average equally.

A known bias in optical remote sensing of glaciers is the occurrence of persistent clouds and low level fog in the ablation area of Arctic glaciers near the ocean (Gilson et al., 2018), as found for three of the five glaciers analysed here (Fig. 7). This persistent cloud cover renders the application of the whole glacier minimum method proposed by Dumont et al. (2012) untenable because very few daily instances occur of a whole glacier being cloud free in the Canadian Arctic. The lack of inclusion of albedo data from these low elevation areas would skew the whole glacier raw average albedo to being higher than expected due to the dominance of high albedo accumulation area in the calculations. Support for this interpretation is found in Table 2, where the average albedo values for the interpolated average method are always less than, or the same as, the raw average method. Thus, the interpolated method weights each day equally, instead of skewing the average by using albedo data obtained exclusively under clear skies.

Although the correlations between interpolated average albedo and net annual mass balance are highly significant (Fig. 8), there is a large difference between the four larger ice masses and the small Grise Fiord Glacier. In particular, mixed grid cells at the periphery of a glacier and around nunataks are a potential cause of error in the albedo signal, with smaller glaciers more susceptible to this error due to a larger proportion of MODIS grid cells on their periphery than larger glaciers. However, many small glaciers are too small to have perimeter grid cells buffered as a way to mitigate the mixed grid cell error. This coupled with the positional uncertainty (± 50 m) of gridded MODIS products suggests that the correlation between mass balance and minimum average albedo should be higher, and the overall uncertainty lower, for larger ice masses. The random errors in glacier mass balance determined by the glaciological method average ± 200 mm w.e. a⁻¹ (Cogley and Adams, 1998), but the consistently high correlation between mass balance and
melt season interpolated albedo for different glaciers, over multiple years, indicates that any error introduced by the glaciological method is small compared to the absolute mass balance.

Analysis of Fig. 9 shows that, when data from the five glaciers are combined, all three albedo methods produce statistically significant representations of net annual mass balance. However, the interpolated average albedo method represents the mass balance of the five glaciers with the highest degree of accuracy ($R^2 = 0.82$). In the interpolated average, Sverdrup Glacier Basin systematically underestimates mass balance in the ensemble model. The small Grise Fiord Glacier displays a larger amount of variation around the trend line than White, Melville or Meighen glaciers. However, for the most negative mass balance measurements Grise Fiord Glacier is close to the trend line, which indicates that the ensemble model is well suited for determining the mass balance of small glaciers in the Canadian Arctic.

6. Conclusions and further work

Interpolated average albedo over the melt season is highly correlated with net annual mass balance for Canadian Arctic glaciers where in situ mass balance has been measured. This provides a better correlation to glacier mass balance than the raw average method, and in turn both of these methods provide an improvement upon the minimum albedo method, particularly for the smallest glacier considered in this study. We found that glacier size, except for the smallest glacier (4 km$^2$), doesn’t produce a clear influence on the correlation between albedo and mass balance, indicating that the interpolated method scales well across different glacier and ice cap geometries and areas in the Canadian Arctic, but that there could be a lower limit to the efficacy of the method. The decrease in correlation coefficient and slope between mass balance and albedo for the small Grise Fiord Glacier compared to the larger glaciers indicates that when a glacier’s area is similar to the MODIS grid cell resolution a poorer correlation might be expected. The convergence of slopes between whole glacier interpolated average albedo and net annual mass balance suggests that this method could be used to model the mass balance for the entire Canadian high Arctic based exclusively on albedo. The whole glacier interpolated albedo method thus provides a potential technique for regional glacier mass balance assessment that is independent of glacier melt models.

Our results are based on in situ mass balance measurements on five Arctic glaciers between 2002 and 2016. An assessment of the use of interpolated average albedo to improve the mass balance to albedo relationship should be confirmed with measurements in other geographical areas and with other mass balance techniques. Image fusion with higher spatial resolution, but poorer temporal resolution, satellite data (e.g., Landsat, Sentinel 2) could be pursued to decrease the size of albedo grid cells. The high degree of correlation between albedo and glacier mass balance, at White Glacier in particular, suggests that
including a limited amount of data collected under low illumination conditions caused by high solar zenith angles, is not an impediment to reconstructing glacier mass balance. In light of the potential for MODIS sensor degradation and lifespan limitations, studies into albedo trend homogenisation for MODIS, and between MODIS and other satellite sensors, is required for the continuity of future albedo monitoring.

Acknowledgements

Financial and logistical support for this project was provided by the University of Ottawa, Polar Continental Shelf Program, ArcticNet and Natural Sciences and Engineering Research Council of Canada Discovery Grant. Natural Sciences and Engineering Research Council of Canada Northern Research Supplement Grant and the W. Garfield Weston Foundation provided postdoctoral fellowships to S. N. Williamson.

Credit author statement

SNW - Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing - original draft, Writing - review & editing. LT, LC and DB - Funding acquisition, Resources, Writing - review & editing.

References


