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Initial validation of Randolph Glacier Inventory: Version 5.0 data over Canada using 250 m MODIS-derived Annual Minimum Snow/Ice extent

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Abstract

This report describes the background, methodology and results of using annual Minimum Snow and Ice (MSI) extent derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m data to validate glacier outline data from the Randolph Glacier Inventory: Version 5.0 (RGI 5.0). This work was a four part collaborative effort conducted by 1) a team from the Canada Centre for Remote Sensing (CCRS) who produced the MODIS MSI raster data and worked with the Atlas of Canada Data (Atlas Data) team to facilitate the use of the raster imagery, 2) the CCRS GeoAnalytics team who evaluated sources of glacier data, 3) the Atlas Data team who carried out the classification and vectorization of the MODIS raster imagery and the validation of the RGI 5.0 glaciers and 4) the Geological Survey of Canada (GSC) who advised on the interpretation of Google Earth and LANDSAT 8 OLI_TIRS image products that were used as references. In particular, it was observed that seventeen glaciers with an area greater than 2.0 km^2 are suspected of having either fully or significantly melted. They are distributed across northern Canada, with four located in the Yukon, seven located in Arctic Canada South region and six located in Arctic Canada North region. The validated glacier data will be generalized to the 1:1,000,000 scale and used as a national scale dataset for Canadian glaciers.

1. Background

The **Atlas of Canada's National Scale 1:1,000,000** datasets are a collection of integrated geospatial datasets at the medium to small scale. They include boundary, coast, island, place name, railway, river, road, road ferry and waterbody features that have been derived from a variety of sources and integrated so that the data's relative positions are correct. The datasets were compiled to be used for atlas scale mapping (1:1,000,000 to 1:3,000,000) that reflects the accuracy and details appropriate to a national scale view. The glaciers are one of the defining features of the Canadian Arctic and Western mountains essential for a national scale view of the Canadian landmass. So far, only one published national scale data set containing glacier data exists in the Atlas of Canada data collections. This dataset is the **North American Atlas - Glaciers** at the 1:10,000,000 scale and it was derived from the 1:7,500,000 Atlas of Canada Reference Map, **The National Atlas of Canada, 5th edition: Canada Glaciers** published in 1985, http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3d72522b-6b33-56f4-9cca-6b0a4816978c.html. This North American Atlas dataset is not only out of date but also at too coarse a scale for integration with the 1:1,000,000 data.

Accurate, up-to-date, spatial and temporally consistent information from reliable sources is, therefore, required to improve the accuracy of the glacier layer in the Atlas of Canada data collections. The goal for the Atlas Data team was to locate such an up-to-date authoritative source for glaciers covering the Canadian landmass, that could be generalized and integrated with the existing 1:1,000,000 Atlas of Canada Data to produce a new glacier layer for Canada.

After analysis of available data, it was decided to use the latest Randolph Glacier Inventory (RGI version 5.0), a global inventory of glacier outlines as a source for our updated glacier layer (Arendt et al., 2015). The RGI's design was a good fit for our requirements as it provides representation for regional and global scales with a standardized set of attributes, and freely available at the Global Land Ice Measurements from Space initiative (GLIMS) website[1]. Being

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[1] Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 5.0 (2015, July 20)

probably the world's most complete glacier inventory, the RGI dataset is not protected from possible inaccuracies: inconsistencies between glacier delineation techniques used by different glacier compilation teams, large temporal span of data, uncaptured trends and dynamics of the glaciers fluctuations due to insufficient sampling as stated in the technical report released by the RGI team (Arendt et al., 2015).

To provide the quality assurance for Atlas of Canada' glacier layer derived from RGI 5.0 a new raster product "Minimum Snow and Ice" generated from MODIS 250 m imagery by CCRS was employed (Trishchenko et al., 2016) for validation. The 250 m imagery available from MODIS can be considered as a good basis for a joint snow/ice mapping over land. In terms of spectral signatures snow and ice have a certain degree of similarity; as such the glaciers were not mapped as a separate class, but combined together with a snow class. In addition, glaciers and ice caps may be covered with snow for the entire annual cycle or for the major part of the year. The specialized MODIS processing system was developed at CCRS to fully utilize the high quality of MODIS level 1 (L1) swath imagery over the northern latitudes (Khlopenkov and Trishchenko, 2008; Luio et al., 2008; Trishchenko et al., 2009). This system was employed to generate long-term time series of MSI using multi-temporal analysis within each annual melting season since 2000. (Trishchenko et al., 2016). The availability of two independent datasets: RGI inventory and CCRS MODIS MSI multi-year time series, enables comparing the RGI glacier data to the 2014 MODIS "Snow and Ice" data to confirm the glacier information and to ensure the high quality of the Atlas of Canada glacier layer and identification of possible inconsistencies in the RGI database.

2. Methodology

MODIS MSI data layer was utilized for the validation of RGI version 5.0 glacier data for our regions of interest. An updated RGI dataset will be used to generalize a glacier layer for the Atlas of Canada National Scale Data 1:1,000,000 collection and by the GeoAnalytics team to produce the revised 1:9,000,000 North Circumpolar Region map.

2.1 Minimum Snow and Ice (MSI) Layer Creation

Each pixel in the MODIS-derived MSI layer contains the probability of snow/ice presence computed from temporal analysis of 17 scene identifications – one for each 10-day interval starting on April 1 and ending on September 20. The 100% probability corresponds to all 17 values indicating the presence of snow or ice. Further details can be found in Trishchenko et al. (2016). The probability equal to 94% (i.e. 16 or 17 snow/ice points) was initially selected as the threshold value for 'permanent' snow/ice cover in Trishchenko et al. (2016). For convenience reasons, the probability in the MSI layer was coded by adding an offset 100, i.e. 94% would be coded as value 194. A vector MSI layer from the raster image was developed using the GIS and Mapping software ArcMap. A three step process was tested and used to create a vector polygon shapefile for MSI extent for the years 2000, 2012 and 2014. The results are outlined below using 2014 data as an example.

Years 2000 and 2014 correspond to the beginning and end of the time interval. Year 2012 was selected as representative of the smallest MSI extent for the Canadian Arctic, as discovered by Trishchenko et al. (2016).

MODIS raster imagery was reclassified using the "Reclassify" tool in ArcMap 10.1. Values in the range 100-194 were set to '0' and values in the range 195-200 set to '1'. This procedure was done for the 2014, 2012 and 2000 MSI images. The original image and the reclassified image are shown in Figure 1 for the year 2014.
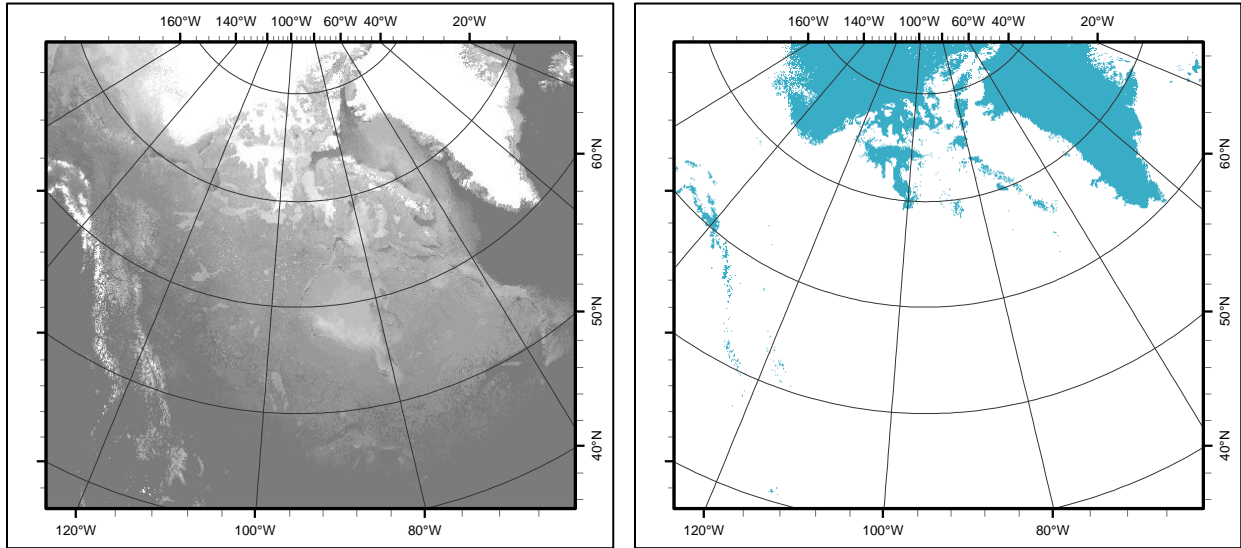

Figure 1. The image on the left is the original MODIS-based MSI image for 2014 used as the input for the "Reclassify" tool. The image on the right is the reclassified output where pixels with a value of '1' are displayed in blue and pixels with a value of '0' are displayed in white.

<u>Step 2</u>

The files created in Step 1 were processed using the "Set Null" tool to set all values other than '1' in the images to "Null". The resulting files contain values of '1' for all pixels in their respective original image that had values greater than 194. All other pixels have a 'NoData' value. The resulting image product for the year 2014 is shown in Figure 2.
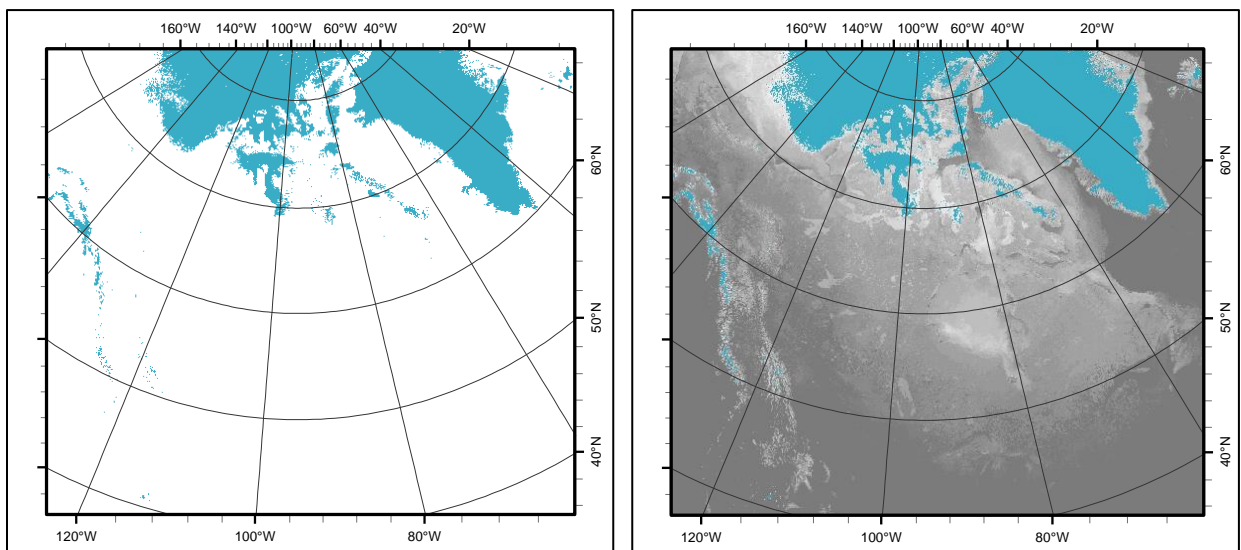

Figure 2. The image on the left is the output from the "Set Null" tool where pixels containing a value (in this case '1') are displayed in blue. The image on the right shows the "Set Null" output displayed over top of the original image.

The files created in Step 2 were processed using the "Raster to Polygon" tool in ArcMap 10.1. The resulting files are shapefiles containing vector polygon features covering the areas that exceeded the 194 threshold for permanent snow and ice in their respective original images (2014, 2012 and 2000). The vector product for the year 2014 is shown in Figure 3.
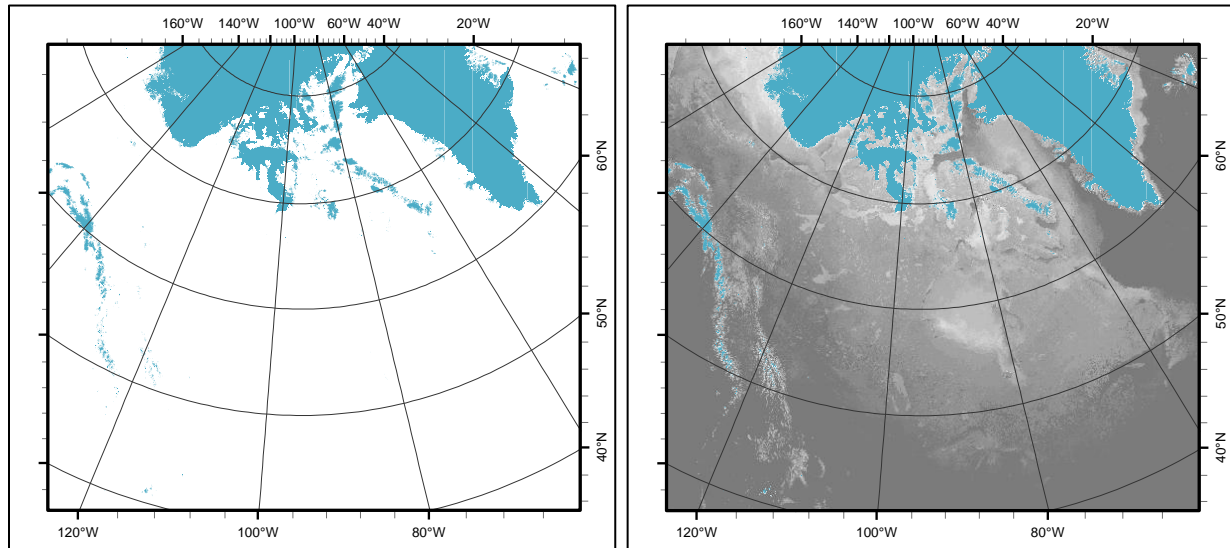

Figure 3. The image on the left is the vector MSI polygon output of the "Raster to Polygon" tool (the polygons are displayed with a solid blue fill). The image on the right shows the vector MSI layer displayed over top of the original raster image.

2.2 Initial Validation of RGI 5.0 Glaciers

The RGI glaciers are divided into nineteen first-order glacier regions (Arendt et al., 2015). The data is provided as one shapefile per region. Each shapefile contains the outlines of glaciers in geographic coordinates (longitude and latitude) which are referenced to the WGS84 datum. Out of nineteen first-order glacier regions there were four regions identified as being within our area of interest, the spatial extent of the Canadian landmass. These regions are:

01 Alaska *(includes the Yukon)*
02 Western Canada and USA
03 Arctic Canada (North)
04 Arctic Canada (South)

Upon inspecting the attributes of the shapefiles, it can be seen that many of the glacier polygons were digitized between 1999 and 2004. The question then arose as to whether some of this data was out-of-date. A process was developed to verify that these features are still present today (a decade or more from the time they were digitized). This validation process involved comparing the RGI glacier features to the newly created MSI vector layer to see where they overlap/intersect. This method assumes that a glacier is a feature that would present as 'permanent' snow and ice in the MODIS-based raster image (in addition to sea ice, frozen lakes, etc). If any of the RGI glacier polygons do not intersect with the MSI vector layer, they may either have melted completely or significantly enough that they cannot be distinguished accurately at the MODIS sensor spatial resolution. In order to isolate features from the RGI that may have a questionable existence in the present day, a "Selection by Location" operation was performed with the ArcMap 10.1 tools.

Glaciers were selected from the RGI database where they intersect the MSI vector layer (year 2014), and then the selection was reversed. For the purposes of this evaluation, the term "potentially melted" will refer to RGI 5.0 glacier polygons that do not intersect with the MSI polygons. MSI polygons for the years 2000 and 2012 were also used to track when glaciers may have potentially melted in relation to their date attribute.

This process was repeated again using a threshold value of 188, and then 176. It was finally decided that the threshold value of 176 would be used for the validation process based on a visual examination of the 2014 MODIS raster image (the most current available at the time of the validation work). Many of the RGI 5.0 polygons identified as potentially melted using 194 and 188 threshold values seemed to overlie groups of pixels with a value of 176 (meaning they were identified as having snow/ice cover for 13 out of 17 days or 76% of the time). This may also reflect the complexity of the optical reflectance dynamics during progression of the melting season for debris-covered glaciers. The resulting overlap of RGI 5.0 polygons with the 176 threshold MSI is shown in Figures 4 and 5. The lower values could be caused by firn, thin ice, cloud cover, debris cover or melted water accumulated on the surface of the glacier, i.e. surface features with a reduced reflectance that could be incorrectly classified as snow/ice free pixels (Fontana et al., 2010). For these reasons, The Atlas Data team has lowered the threshold for selecting potentially melted glaciers from the RGI to 176 (the threshold used to create future MSI vector data layers will remain at 194 for consistency with the raster product being produced by CCRS).
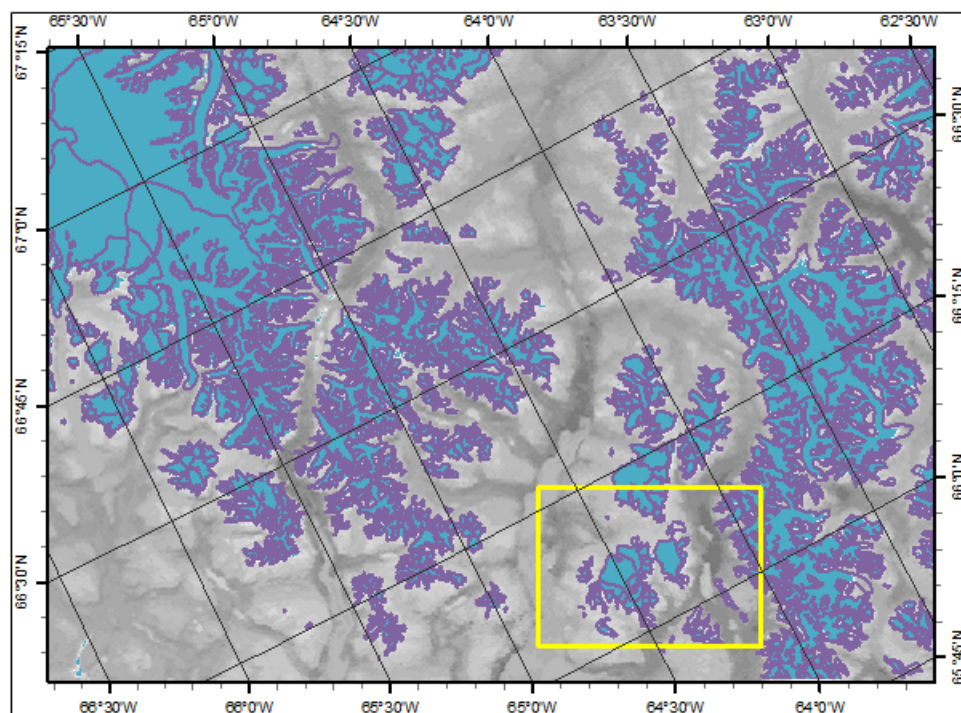

Figure 4. Selection by Location: RGI 5.0 polygons (purple outline) that do not intersect the MSI 2014 polygons (176 threshold; blue fill) are shown in this image. See Figure 5 for a detailed image of the data within the yellow box. The background image is the original MODIS – based MSI image.
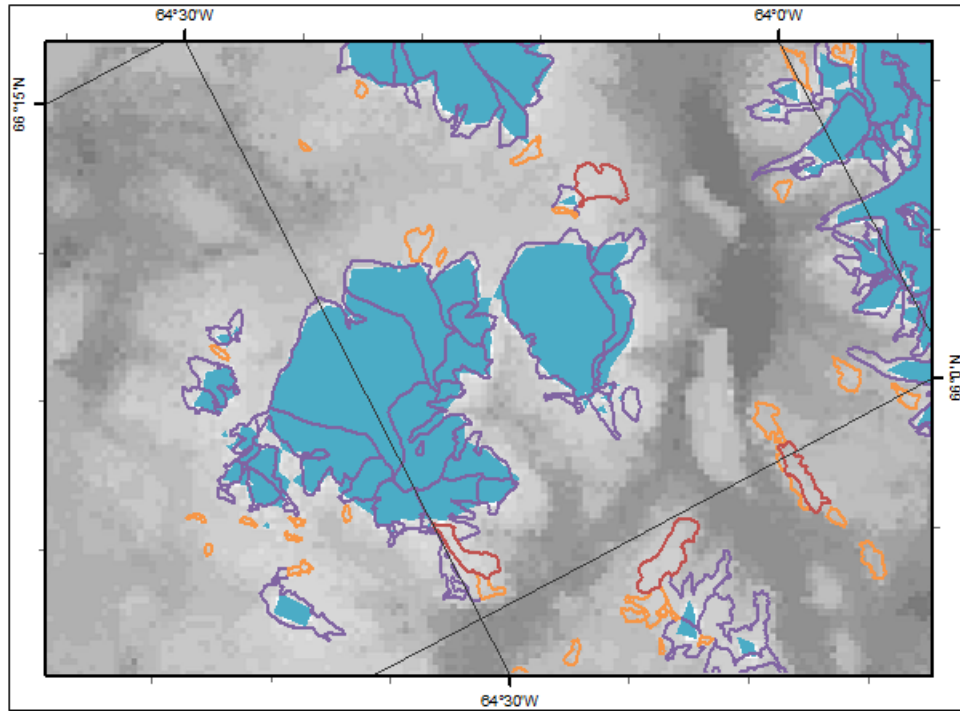
Figure 5. Examples of RGI 5.0 polygons (purple outline) that intersect with the 176 threshold MSI polygons (blue fill). The RGI 5.0 polygons that do not intersect the MSI layer and are smaller than 2 km^2 are displayed with an orange outline. The RGI 5.0 polygons that do not intersect the MSI layers and are 2 km^2 or larger are displayed with a red outline. The spatial extent covered in this image is approximately the area within the yellow box in Figure 4.

Approximately 30% fewer features were identified as potentially melted using the 176 threshold versus 194 threshold value. Of these, only seventeen were greater than 2.0 km^2 in area (i.e. less than 4x8 MODIS pixels). These seventeen features (as well as a selection of smaller features) were more closely investigated using additional sources of high resolution imagery available from Google Earth (image acquisition: unknown date) and LANDSAT 8 OLI_TIRS images (acquisition: summer 2015) to determine the presence or absence of a glacier in that area. Nine of the seventeen features are suspected to have fully melted and eight other features are suspected of being significantly melted. The list of these glaciers with their RGI identification number and a description of the visual review report is provided in Appendix A, Table 1 - Potentially Melted RGI 5.0 Glaciers Greater Than 2 km². An example of this comparison is shown in Figure 6 for RGI 5.0 polygon RGI50-03.01877 in the Arctic Canada North region.
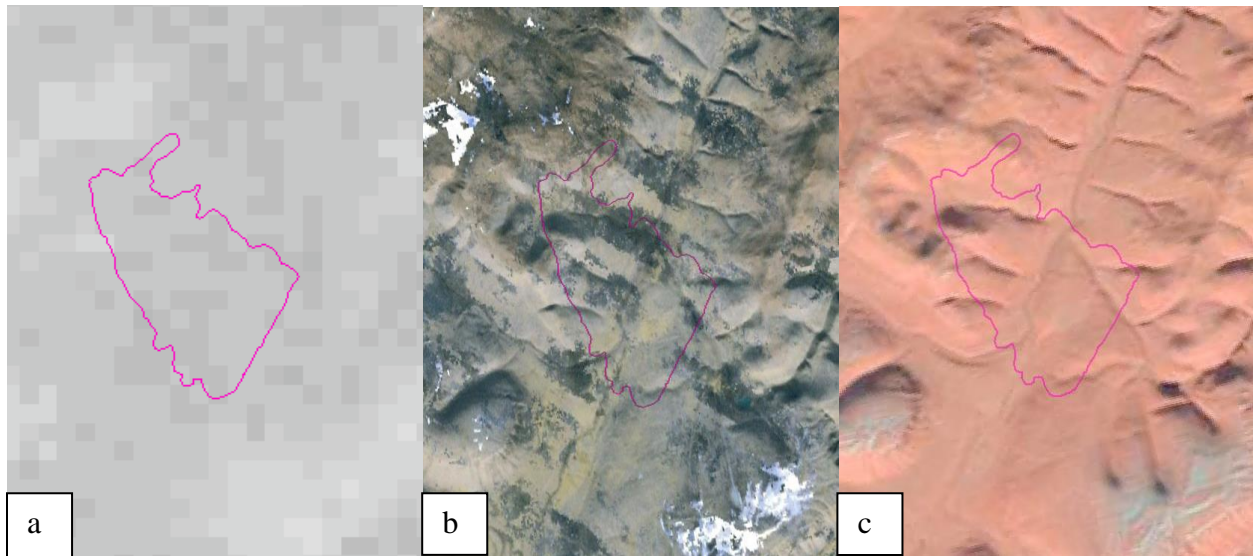
Figure 6. RGI 5.0 polygon RGI50-03.01877 (pink outline) overlaid on with a) original MSI 2014 image, b) Google Earth image, and c) LANDSAT 8 image (acquisition date 2015/08/14).

The supplementary analysis was conducted to identify any areas that exceeded the 194 MODIS MSI threshold and were not represented in the RGI (i.e. glaciers that have not been included or were omitted in error). To ensure that the selected features are glaciers and not frozen lakes or persistent snow cover, a new selection of features that intersect with 194 threshold MSI vector layer (year 2012) was created from the current set of selected features. Since 2012 was among the warmest years in Canadian Arctic since 2000, with the lowest minimum amount of snow and ice in the Arctic, if the selected features still appear in 2012 (i.e. the selected 2014 features overlap with the 2012 features) then they are more likely to be glaciers. The selection was further refined to include only the features that fall within the Canadian border to exclude features in Iceland, Greenland, and Alaska. Atlas Data coastline and island polygons were used as a reference for context and to ensure the features are on land and may represent glaciers not lake or sea ice. The final set of selected features was considered to contain possible glaciers that are missing from the RGI 5.0 and was exported to a separate shapefile. The features within this file were checked against Google Earth images to determine if they were actually glaciers. In many cases, they were determined to be snow packs (where there was no snow/ice observed on the Google Earth image), or areas where glaciers seem to have advanced compared to their boundaries in the RGI 5.0 polygons. This can be also explained by the presence of semi-permanent snow cover around the glacier perimeter and the difference in dates for RGI and MSI layers. As such, we concluded that there are no new features identified as glaciers that were not already included in the RGI 5.0.

3. Results

Based on our initial validation of the RGI 5.0 data using MODIS-based MSI product and the sources of high resolution satellite data such as Google Earth and LANDSAT 8 OLI_TIRS, it was determined that RGI 5.0 database can be considered as a generally accurate and reputable source over the Canada territory that can be used by the Atlas Data team to derive an updated glacier dataset to include in the 1:1,000,000 data collection. At the same time, multiple small features were found to be inconsistent between MODIS MSI and RGI 5.0. Of these, only seventeen were greater than 2.0 km^2 in area each and were further investigated. Due to the time constrains, consistency and traceability purpose, it has been decided that the features determined to be

potentially melted and listed in Appendix A, Table 1 – Potentially Melted RGI 5.0 Glaciers Greater Than 2 km², will not be removed from the generalized dataset at this time. Instead, a report on these potentially melted glaciers will be produced for further investigation and possible correction to the RGI source data. An analysis was also conducted for the MSI polygons with presence of snow/ice above the threshold level and where no RGI 5.0 glaciers were reported. It was concluded that over the Canadian landmass there were no glaciers missing in RGI 5.0, and the conflicting situations likely correspond to the presence of semi-permanent snow that was not melted during the summer season or possible deficiencies in the MODIS-based MSI algorithm.

Acknowledgements

Appendix A

We provide below the list of seventeen glaciers present in the RGI 5.0 dataset that we identified as potentially melted or significantly melted based on visual review of images available from the MODIS MSI 2014, Google Earth and LANDSAT 8 OLI_TIRS(summer 2015). Each of these seventeen RGI 5.0 glaciers has a total area greater than 2 km^2 and do not intersect with the MODIS MSI layer corresponding to threshold value 176.

Table 1 Potentially Melted RGI 5.0 Glaciers Greater Than 2 km²

	RGI 5.0 ID	RGI Region	Description
1	RGI50-03.02384	03 - Arctic Canada North	Appears to have perennial snow pack/late lying snow on Google Earth image and glacier melted with a small patch of ice remaining which may be lake ice on the LANDSAT 2015 image.
2	RGI50-03.01877	03 - Arctic Canada North	Appears to have completely melted.
3	RGI50-01.12824	01 - Alaska (Yukon)	Appears to have completely melted.
4	RGI50-03.02306	03 - Arctic Canada North	Appears to have perennial snow pack/late lying snow on Google Earth image and glacier partially melted with leftover snow and ice patches on the LANDSAT 2015 image.
5	RGI50-04.04217	04 - Arctic Canada South	Appears to have completely melted.
6	RGI50-04.04256	04 - Arctic Canada South	Appears to have melted with only a perennial snow pack along the south edge and a small ice patch or glacier remaining on the west side. Cloud shadow on part of the LANDSAT image.
7	RGI50-03.02017	03 - Arctic Canada North	Appears to have perennial snow pack/late lying snow on Google Earth image and glacier completely melted on the LANDSAT 2015 image.
8	RGI50-03.02996	03 - Arctic Canada North	Appears to have perennial snow pack/late lying snow and a small ice patch on Google Earth image and glacier completely melted on the LANDSAT 2015 image.
9	RGI50-01.11318	01 - Alaska (Yukon)	Appears to have significantly melted.
10	RGI50-03.02355	03 - Arctic Canada North	Appears to have perennial snow pack/late

			lying snow and glacier on Google Earth image and glacier partially melted on the LANDSAT 2015 image.
11	RGI50-04.04136	04 - Arctic Canada South	Appears to have significantly melted.
12	RGI50-01.16650	01 - Alaska (Yukon)	Appears to have significantly melted.
13	RGI50-04.04100	04 - Arctic Canada South	Appears to have perennial snow pack/late lying snow and two small ice patches on Google Earth image and glacier completely melted on the LANDSAT 2015 image.
14	RGI50-01.16683	01 - Alaska (Yukon)	Appears to have significantly melted.
15	RGI50-04.04263	04 - Arctic Canada South	Appears to have significantly melted.
16	RGI50-04.00188	04 - Arctic Canada South	Appears to have perennial snow pack/late lying snow and glaciers on Google Earth image and glacier partially melted on the LANDSAT 2015 image.
17	RGI50-04.04220	04 - Arctic Canada South	Appears to have completely melted.

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