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Radarsat Constellation Mission Derived Winter Glacier Velocities for the St. Elias Icefield, Yukon/Alaska: 2022 and 2023

Vitesses hivernales de glaciers dérivées de la Constellation Radarsat pour le champ de glace St. Elias, au Yukon et en Alaska: 2022 et 2023

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ABSTRACT

Here we use high resolution (5 m) Radarsat Constellation Mission (RCM) imagery acquired in winters 2022 and 2023 to determine motion across glaciers of the St. Elias Icefield in Yukon/Alaska. Our regional velocity mapping largely conforms with previous studies, with faster motion (>600 m/yr) for the glaciers originating in the Yukon that drain southward and westward to the coast of Alaska and relatively slower motion (100–400 m/yr) for the land terminating glaciers that drain eastward and northeastward and stay within the Yukon. We also identify two new glacier surges within the icefields: the surge of Nàłùdäy (Lowell) Glacier in Winter 2022, and Chitina Glacier in Winter 2023, and track the progression of each surge from January to March utilizing ∼4-day repeat RCM imagery. To evaluate the quality of RCM-derived velocities, we compare our results with 50 simultaneous measurements at three on-ice dGPS stations located on two Yukon glaciers and find the average absolute difference between measurements to be 6.6 m/yr. Our results demonstrate the utility of RCM data to determine glacier motion across large regions with complex topography, to support process-based studies of fast flowing and surge-type glaciers and continue the legacy of velocity products derived from the Radarsat-2 mission.

RÉSUMÉ

Des images haute résolution (5 m) de la Constellation Radarsat (RCM)) acquises au cours des hivers 2022 et 2023 ont été utilisées pour déterminer le mouvement les glaciers à travers du champ de glace St. Elias au Yukon/Alaska. Notre cartographie des vitesses régionales est largement conforme aux études précédentes, avec un mouvement plus rapide (>600 m/an) pour les glaciers provenant du Yukon qui s'écoulent vers le sud et l'ouest jusqu'à la côte de l'Alaska et un mouvement relativement plus lent (100 à 400 m/an) pour les glaciers terrestres qui s'écoulent vers l'est et le nord-est et restent au Yukon. Nous avons identifié deux nouvelles progressions glaciaires dans les champs de glace: l'avancement du glacier Nàłùdäy (Lowell) en hiver 2022 et celle du glacier Chitina en hiver 2023, et suivons leur progression de janvier à mars en utilisant des images RCM acquises aux ∼4 jours. Pour évaluer la qualité des vitesses dérivées de RCM, nous comparons nos résultats avec 50 mesures simultanées à trois stations dGPS situées sur deux glaciers du Yukon et constatons que la différence absolue moyenne entre les mesures est de 6,6 m/an. Nos résultats démontrent l'utilité des données RCM pour déterminer le mouvement des glaciers dans de vastes régions à topographie complexe, pour appuyer les études sur les glaciers ayant un écoulement rapide et une augmentation du volume et pour perpétuer l'héritage des produits de vitesse dérivés de la mission Radarsat-2.

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Introduction

Imagery from the Radarsat-1 and Radarsat-2 Synthetic Aperture RADAR (SAR) missions have played a critical role in monitoring the major elements of the Canadian cryosphere, including sea ice and snow cover. For glaciers specifically, data from the Radarsat-1 mission provided some of the first maps of glacier motion within the Canadian High Arctic and demonstrated the efficacy of Radarsat-1 data for this task (Short and Gray 2004, 2005). The launch of the Radarsat-2 mission in December 2007 allowed for the regular collection of SAR data in northern Canada, which enabled the determination of regional glacier velocities at annual time steps for the first time (Van Wychen et al. 2014; Waechter et al. 2015). These studies that relied on Radarsat-2 data are complimented by additional research that used imagery from other SAR and optical sensors to further quantify glacier motion within Canada (e.g., Burgess et al. 2013; Millan et al. 2017, 2022; Strozzi et al. 2017; Sánchez-Gámez and Navarro 2017). More recently, the open and continuous dissemination of glacier velocity products across Canada and elsewhere has been made possible through the use of Landsat imagery with the ITS_LIVE project (https://its-live.jpl.nasa.gov/; Gardner et al. 2018), and Sentinel-1 (S1) data with the FAU-Glacier Portal (https://retreat.geographie.uni-erlangen.de/; Friedl et al. 2021). Collectively, these studies and datasets provide a robust record of ice motion across northern Canada over the last two decades and have been critical for:

1. recognizing where, and over which time scales, glacier motion varies;
2. identifying and cataloguing the processes that control variations in ice motion;
3. determining where to initiate process-based and field studies to refine our understanding of the processes that control glacier motion, and;
4. quantifying dynamic discharge (i.e., iceberg production) to the ocean.

Launched in June 2019, and operational since November 2019, the Radarsat Constellation Mission (RCM) comprises the next iteration of the Radarsat program and represents one of the major sources of SAR data that can be used for measuring the velocities of Canadian glaciers. Whereas Radarsat-1 and Radarsat-2 were both single sensor C-band systems with an orbital repeat period of 24-days, the RCM is a three-sensor C-band mission with a 12-day orbital repeat period for each sensor and a 4-day orbital offset between sensors. From a glacier dynamics perspective, this setup is advantageous for three major reasons. First, the shorter temporal period between image acquisitions reduces the possibility of coherence loss due to significant surface changes on the glacier (e.g., snowfall or melt) that can result in poor performance of the tracking algorithms used to derive motion. Second, the shorter temporal period between image acquisitions allows for the motion of fast flowing glaciers, and glaciers that undergo short periods of fast flow (i.e., surge-type glaciers), which have surface features that can evolve significantly over time, to be more accurately and efficiently tracked. Third, the 4-day orbital repeat period allows for the investigation of variations in glacier motion, such as seasonality and surge progression, at a finer temporal resolution than was possible with either the Radarsat-1 or Radarsat-2 missions, which could only detect variations at 24-day intervals. Furthermore, data from the RCM is openly available to registered and vetted users (https://www.asc-csa.gc.ca/eng/satellites/radarsat/access-to-data/about.asp), via the Government of Canada's Earth Observation Data Management System (EODMS), which allows for easier access to imagery than has previously been the case for either Radarsat-1 or Radarsat-2.

Given that the RCM will be a critical source of SAR data within Canada, our goal here is to assess the usefulness of RCM High Resolution (5 m) mode data for regional glacier mapping activities. We use the St. Elias Icefield, and associated outlet glaciers, of Yukon/Alaska as our study region (Figure 1, inset). In addition, within the St. Elias Mountains, there are continuous records of glacier motion recorded at *in situ* dGPS stations that can be compared with the RCM derived results. This allows us to bound uncertainty margins for glacier velocity maps generated from RCM data and assess the capability of RCM for glacier monitoring activities. Thus, the specific objectives of this paper are to:

1. assess the quality of RCM derived glacier velocity products by comparing them with simultaneous dGPS records of ice motion;
2. use RCM data to derive glacier velocities for the St. Elias Icefield for winters 2022 and 2023, to update regional records presented by Van Wychen et al. (2018) and Waechter et al. (2015), which used ALOS PALSAR (L-band) and R2 data (C-band), respectively;
3. showcase the utility of RCM data, and the short 4-day repeat cycle that it offers, for monitoring

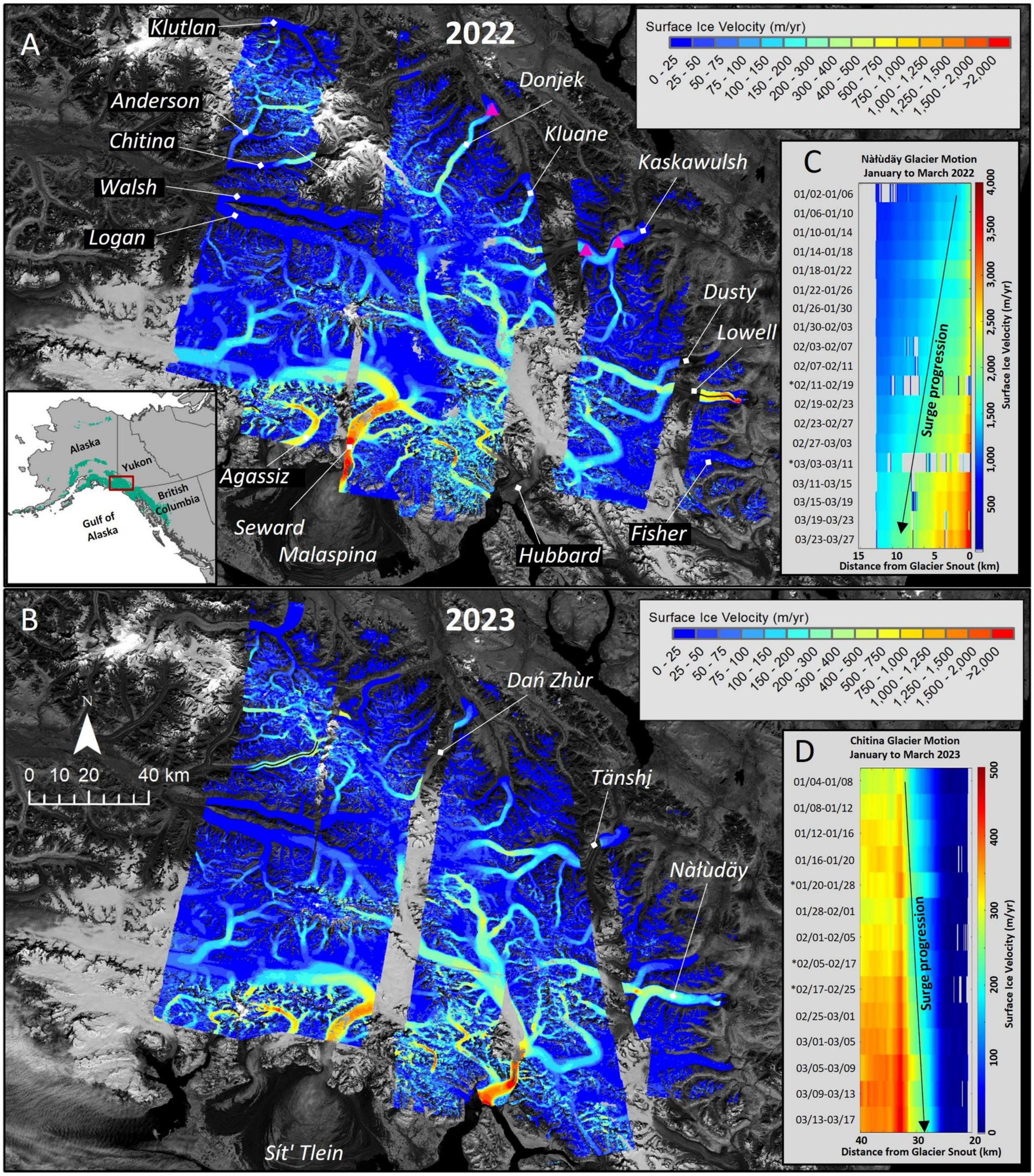

Figure 1. (a) Surface ice motion of the St. Elias Icefields derived from RCM imagery collected in January 2022, magenta triangles on Tänshį (Kaskawulsh) and Dań Zhùr (Donjek) glaciers indicate the location of *in situ* dGPS stations; (b) Surface ice motion of the St. Elias Icefields derived from RCM imagery collected in January 2023; (c) Extracted surface ice velocities depicting the surge progression in the lower terminus region of Nàłùdäy (Lowell) Glacier from RCM imagery collected from January to March 2022; (d) Extracted surface ice velocities depicting the surge progression in the middle section of Chitina Glacier from RCM imagery collected from January to March 2023. Centerline used for velocity extraction in (c and d) are shown in (a and b), respectively, and '*' provided on (c and d) denote velocity maps derived from imagery acquired greater than 4-days apart. RADARSAT Constellation Mission Imagery © Government of Canada (2022 and 2023), RADARSAT is an official mark of the Canadian Space Agency. Background image is a mosaic of Landsat-8 imagery.

the surge progression of Nàłùdäy and Chitina glaciers in the winters of 2022 and 2023, respectively.

Throughout this paper we use traditional glacier names when they are known, following the recommendation of Wong et al. (2020) (Figure 1b).

Datasets and methods

RCM data processing

The RCM provides a variety of SAR imaging modes, but of particular interest for glacier velocity mapping applications are the High Resolution (5×5 m pixel resolution) mode with a nominal swath width of 30 km, and the Very High Resolution (3×3 m pixel resolution) mode with a nominal swath width of 20 km. Both the High Resolution and Very High Resolution mode data can be obtained as single polarization (HH, VV, HV, VH), dual polarization (VV + HV, HH + HV, HH + VV) and compact polarization (CP). All data collection for RCM are arranged via a standard coverage plan (maps of standard coverages are openly available from the Canadian Space Agency at: https://www.asc-csa.gc.ca/eng/satellites/radarsat/access-to-data/standard-coverage-maps.asp). Standard coverage plans are developed by the Government of Canada to effectively manage and balance the acquisition of RCM data to support the needs of various operational programs, research programs and users, who are largely within Canadian federal departments (Dabboor et al. 2022). Ad hoc acquisitions of RCM data are possible, but only from Government of Canada users (Dabboor et al. 2022) and as such, we had no control over the beam mode or polarization collected over the St. Elias Mountains. We downloaded available High Resolution Mode data acquired over the study region via the EODMS data portal (https://www.eodms-sgdot.nrcan-rncan.gc.ca/). This enabled us to create regional mosaics of surface ice motion across the St. Elias Icefield in January 2022 and January 2023. Further, from January to March 2022, we downloaded RCM imagery collected over the location of three on-ice in situ GPS stations to validate RCM-derived velocities. For glaciers which showed surge activity in the regional mosaics, we collected the available RCM data acquired over Nàłùdäy Glacier from January to March 2022, and Chitina Glacier from January to March 2023. In most cases, this allowed us to generate glacier velocity maps from data separated by 4 days, although there are some instances when we used 8 and 12 day separated image pairs to derive velocity products. All data utilized in this study are summarized in Tables 1 and 2.

All compact polarization (CH) RCM data were processed to derive glacier velocities using standard offset tracking procedures implemented in the commercial GAMMA software package (Strozzi et al. 2002). For each set of image pairs, the orbital information provided in the metadata was used to accurately co-register the images. As in Main et al. (2023), once the images are co-registered, a patch intensity cross-correlation is used to search for windows of matching pixels between the reference (first acquired) and secondary (second acquired) images. An initial filtering of the offsets is completed within the GAMMA software, which removes estimates which have a cross-correlation measurement below a user specified threshold. The calculated offset in both the azimuth and range directions between the matched windows between the reference and secondary image is then inferred to represent surface displacement. This approach has been effective for deriving glacier surface motion for Yukon/Alaska (Main et al. 2023) and elsewhere (Strozzi et al. 2017).

For processing, we used matching windows of 200 pixels in both azimuth and range directions, and offsets of 20 pixels in both azimuth and range, for all image pairs. We then utilized the Copernicus Digital Elevation Model (DEM) with 30 m resolution to geocode the results (this DEM is freely available to registered users through the PANDA catalogue: https://panda.copernicus.eu/web/cds-catalogue/panda under the product name 'COP-DEM_GLO-30-DGED'). For the geocoding, we again use the standard procedures within the GAMMA software, which uses resampling and interpolation using a geocoding look-up table to transfer corresponding coordinates from SAR range/doppler coordinates to map based projections (such as UTM) and vice versa.

All outputs were converted to GeoTIFF images (with the same 30 m resolution as the DEM) that could be imported into ArcMap 10.8, where the individual velocity maps were mosaicked to produce a single velocity map of the glaciers of the St. Elias Icefield. To be conservative, in areas of overlap between individual velocity maps we selected the minimum value between pixels in our mosaicked image. All displacements were normalized to, and are presented as m/yr, to allow for easier comparison with previously published work. A final check of the velocities was also completed, with areas of unrealistic results (e.g., flow speeds that are beyond what is

Table 1. Summary of Radarsat Constellation Mission data utilized to create glacier velocity mosaics for January 2022 and January 2023 and to track the surge progression of Nàłùdäy (Lowell) Glacier from January to March 2022 and Chitina Glacier from January to March 2023.

Imaging date 1	Imaging date 2	Beam mode	Polarization utilized	Incidence angle (°) Near range/Far range
	January 2022 mosaic			
2022-01-05	2022-01-09	MCP 1	CH	19.02/21.89
2022-01-15	2022-01-19	MCP 5	CH	26.28/28.89
2022-01-06	2022-01-10	MCP 8	CH	31.88/34.26
2022-01-05	2022-01-09	MCP 18	CH	46.98/48.65
2022-01-02	2022-01-06	MCP 20	CH	49.40/50.96
2022-01-20	2022-01-24	MCP 22	CH	51.67/53.12
2022-01-15	2022-01-19	MCP 23	CH	52.74/54.14
2022-01-04	2022-01-08	MCP 5	CH	26.28/28.89
	2022 Nàłùdäy (Lowell) Glacier data			
2022-01-02	2022-01-06	MCP 8	CH	31.88/34.26
2022-01-06	2022-01-10			
2022-01-10	2022-01-14			
2022-01-14	2022-01-18			
2022-01-18	2022-01-22			
2022-01-22	2022-01-26			
2022-01-26	2022-01-30			
2022-01-30	2022-02-03			
2022-02-07	2022-02-11			
2022-02-11	2022-02-19			
2022-02-19	2022-02-23			
2022-02-27	2022-03-03			
2022-03-03	2022-03-11			
2022-03-11	2022-03-15			
2022-03-15	2022-03-19			
2022-03-19	2022-03-23			
	January 2023 mosaic			
2023-01-02	2023-01-06	MCP 23	CH	52.74/54.14
2023-01-12	2023-01-16	MCP 20	CH	49.40/50.96
2023-01-04	2023-01-08	MCP 16	CH	44.37/46.17
2023-01-29	2023-02-02	MCP 12	CH	38.56/40.63
2023-01-07	2023-01-11	MCP 11	CH	36.97/39.12
2023-01-12	2023-01-16	MCP 10	CH	35.33/37.55
2023-01-14	2023-01-18	MCP 9	CH	33.63/35.93
2023-01-10	2023-01-14	MCP 6	CH	28.20/30.73
2023-01-27	2023-01-31	MCP 6	CH	28.20/30.73
2023-01-04	2023-01-08	MCP 2	CH	20.18/23.01
2023-01-09	2023-01-13	MCP 19	CH	48.21/49.83
	2023 Chitina Glacier data			
2023-01-04	2023-01-08	MCP 20	CH	49.40/50.96
2023-01-08	2023-01-12			
2023-01-12	2023-01-16			
2023-01-16	2023-01-20			
2023-01-20	2023-01-28			
2023-01-28	2023-02-01			
2023-02-01	2023-02-05			
2023-02-05	2023-02-17			
2023-02-17	2023-02-25			
2023-02-25	2023-03-01			
2023-03-01	2023-03-05			
2023-03-05	2023-03-09			
2023-03-09	2023-03-13			
2023-03-13	2023-03-17			

expected in the region) manually removed from the dataset. These areas are mainly located along the image boundaries and in areas of complex mountainous terrain, where the intensity cross-correlation algorithm has difficulty finding correct matches. Final velocity mosaics for both 2022 and 2023 were clipped to the glacier extents provided by version 6.0 of the Randolph Glacier Inventory (RGI; https://www.glims.org/RGI/).

To initially bound the uncertainty in our measurements, we extracted the apparent displacement over stationary bedrock areas adjacent to glaciers in our study area for both the January 2022 and January 2023 mosaic products. For the January 2022 mosaic we obtained a median displacement of ~8.1 m/yr from ~3 770 000 samples over bedrock, and for the January 2023 mosaic we obtained a median displacement of ~6.7 m/yr from ~4 200 000 samples over bedrock. These values align well with previous studies that have computed apparent displacements over stable ground from Radarsat-2 imagery (Waechter et al. 2015; Van Wychen et al. 2012).

Table 2. Summary of imagery used to evaluate in situ observations and Radarsat Constellation Mission derived displacements and their associated comparisons.

Imaging date 1	Imaging date 2	RCM beam mode	GPS location	GPS observed displacement (m/yr)	RCM derived displacement (m/yr)	Difference (m/yr)
2022-01-03	2022-01-07	MCP 5	Kaskawulsh Lower Station (60.77N, −138.76W)	106.7	120.4	13.7
2022-01-15	2022-01-19			111.1	108.6	−2.5
2022-01-19	2022-01-23			117.8	125.3	7.5
2022-01-23	2022-01-27			129.6	127.3	−2.3
2022-01-27	2022-01-31			135.5	131.9	−3.7
2022-01-31	2022-02-04			125.3	127.3	2.0
2022-02-12	2022-02-16			124.8	124.0	−0.8
2022-02-16	2022-02-20			125.6	122.8	−2.8
2022-02-20	2022-02-24			121.8	122.8	1.0
2022-02-24	2022-02-28			118.1	111.3	−6.8
2022-02-28	2022-03-04			115.8	113.4	−2.4
2022-03-16	2022-03-20			112.3	110.3	−2.0
2022-03-20	2022-03-24			114.5	106.1	−8.4
2022-01-02	2022-01-06	MCP 20	Kaskawulsh Lower Station (60.77N, −138.76W)	106.7	100.4	−6.2
2022-01-06	2022-01-10			106.7	114.0	7.3
2022-01-10	2022-01-14			107.0	143.1	36.1
2022-01-14	2022-01-18			110.0	101.8	−8.2
2022-01-18	2022-01-26			120.8	122.9	2.1
2022-01-26	2022-01-30			135.8	131.9	−4.0
2022-01-30	2022-02-03			128.6	128.9	0.3
2022-02-03	2022-02-07			122.0	110.4	−11.6
2022-02-11	2022-02-15			124.5	125.7	1.3
2022-02-15	2022-02-19			125.5	136.9	11.4
2022-02-19	2022-02-27			121.1	126.6	5.5
2022-02-27	2022-03-03			116.1	124.3	8.2
2022-03-03	2022-03-07			113.6	110.2	−3.5
2022-03-07	2022-03-11			111.5	119.8	8.3
2022-03-11	2022-03-15			111.0	116.1	5.1
2022-03-15	2022-03-19			112.4	106.7	−5.6
2022-03-19	2022-03-23			113.7	110.4	−3.3
2022-03-23	2022-03-27			116.7	91.5	−25.2
2022-01-02	2022-01-06	MCP 20	Kaskawulsh Middle Station (60.75N, −138.96W)	115.9	110.5	−5.4
2022-01-06	2022-01-10			120.4	116.9	−3.4
2022-01-10	2022-01-14			126.3	124.3	−2.0
2022-01-14	2022-01-18			132.8	125.9	−6.9
2022-01-18	2022-01-26			134.3	144.8	10.5
2022-01-26	2022-01-30			131.7	124.3	−7.4
2022-01-30	2022-02-03			131.4	129.2	−2.2
2022-02-03	2022-02-07			133.9	127.8	−6.0
2022-02-07	2022-02-11			137.2	139.1	1.9
2022-02-11	2022-02-15			137.9	130.1	−7.8
2022-02-15	2022-02-19			132.3	134.4	2.1
2022-01-07	2022-01-11	MCP 23	Lower Donjek (61.18N, −139.52W)	38.0	40.9	2.9
2022-01-11	2022-01-15			39.8	51.2	11.4
2022-01-15	2022-01-19			39.7	31.5	−8.2
2022-01-19	2022-01-23			40.2	51.0	10.9
2022-01-23	2022-01-27			40.2	48.6	8.4
2022-01-31	2022-02-04			40.3	33.6	−6.6
2022-02-28	2022-03-04			40.2	51.1	10.9
2022-03-16	2022-03-20			38.2	46.8	8.6
Average absolute difference						6.6
Root mean sum of squares error						8.9
Minimum absolute difference						0.3
Maximum absolute difference						36.1

Dual-frequency global positioning system (dGPS) data

Three dGPS stations recorded in situ displacements of surface ice motion at the same time that our RCM images were acquired and overlap with the 30 m pixels in our RCM derived velocity products. The first station is in the lower ablation area of Tänshį (Kaskawulsh) Glacier, the second is in the middle of the ablation area of Tänshį Glacier, and the third is in the lower ablation area of Dań Zhùr (Donjek) Glacier (Figure 1a). Each station contains a Trimble NetR9 receiver connected to a Zephyr Geodetic antenna, mounted approximately 1.5 m above the glacier surface on a tripod that is frozen into place in the winter (see https://cryospheric.org/gallery/yukon-photos/img_2658/ for a photo of the middle Tänshį station). These units acquired data once every 15 seconds for 2 hours per day, which was processed using the online

Natural Resources Canada (NRCan) Precise Point Positioning (PPP) service (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en). This provides a horizontal positional accuracy of 1–2 cm (Waechter et al. 2015). We used the mean daily position at the start and end time of each GPS record, in Universal Transverse Mercator coordinates, to calculate the total in situ displacement of the station coincident with each RCM image acquisition period, and then standardize this to units of m/yr. In total, we compared in situ displacements with RCM displacements in 50 instances across 3 different RCM beam modes (MCP 5, MCP 20, MCP 23; Table 2).

Results and discussion

In situ GPS versus RCM derived displacements

Table 2 summarizes the *in situ* dGPS and RCM derived displacements, which show very good agreement between the two datasets. The mean absolute difference between these two datasets is 6.6 m/yr and the root mean sum of squares error is 8.9 m/yr. These values are similar to the displacements extracted over bedrock outcrops, while the minimum difference is 0.3 m/yr and maximum difference is 36.1 m/yr. Over a typical 4 day measurement period, this equates to a mean difference of 7.2 cm.

It is important to remember that we should not expect perfect agreement between the dGPS and RCM derived velocity datasets given that they are measurements of slightly different things. The on ice dGPS stations measure glacier displacement at a precise location, while the RCM-derived values measure the displacement of a group of pixels defined by the matching window sizes (i.e., 200 × 200 pixels) in our processing scheme. This means that, depending on the placement of the matching window on the glacier surface in relation to the dGPS station, and any velocity gradients across the matching window, there may be a discrepancy between these measurements.

Nevertheless, these results are similar to Waechter et al. (2015), who found a mean absolute difference of ∼5.2 m/yr based on 10 *in situ* dGPS derived displacements and velocity products determined from fine beam (8 m resolution) and ultrafine beam (3 m resolution) Radarsat-2 imagery. This suggests that the quality of the results generated from offset tracking algorithms applied to RCM and Radarsat-2 data are similar and thus provides continuity between longer term glacier velocity mapping projects that use imagery from both sensors (e.g., Main et al. 2023).

2022 And 2023 St. Elias RCM derived velocity mosaics

Figure 1 provides the RCM derived velocity structure of the St. Elias Icefield and associated outlet glaciers based on the data outlined in Table 1, representing a snapshot of the flow speeds from January 2022 and January 2023. Higher velocities (i.e., greater than 500 m/yr) are found on the larger glaciers, which flow south from the icefield interior and into Alaska (e.g., Agassiz, Seward, and Hubbard glaciers), while the fastest flow (with speeds >3000 m/yr) is observed on Nàłùdäy Glacier in January 2022. Slower rates of motion (200–400 m/yr) are found on glaciers that drain the interior of the icefield and flow generally to the north and east and stay within the Yukon. These include Dań Zhùr, Tänshį, and Kluane glaciers. Others within the Yukon, such as Klutlan and Fisher glaciers, have rates of motion <50 m/yr in their lowermost terminus regions. Similarly, Logan and Walsh glaciers, which flow northwestward from the interior of the icefield, have velocities of <50 m/yr along most of their length. For the most part, glacier velocities can be determined across entire RCM scenes, with only some small gaps, likely due to a loss of coherence between scenes. For regions where there are large gaps, there was no suitable RCM data acquired for these areas. These areas of missing data represent a limitation of the current standard coverage plans for the region and indicate that these plans should evolve over time to provide full coverage of the entire icefields (Figure 1).

The general velocity structure of the St. Elias Icefields derived from RCM imagery in January 2022 and January 2023 (Figure 1) is consistent with the flow rates reported by earlier studies that have utilized SAR datasets to derive ice motion in this region (Van Wychen et al. 2018; Waechter et al. 2015; Abe and Furuya 2015; Burgess et al. 2013). One area of improvement offered by the use of 4-day repeat imagery in this study is the ability to resolve high velocities at the terminus of Hubbard Glacier (Figure 1b), where flow speeds of >2,500 m/yr have been difficult to track in an effective manner with previous sensors. For example, displacements across the lower part of Hubbard Glacier were so great during the 24-day Radarsat-2 orbital period that results could not be reliability obtained using a traditional single window and search size, which necessitated that Waechter et al. (2015) utilize a 'nested' approach of variable window and search sizes to determine motion in this region. Similarly, results for Hubbard Glacier are not provided by Abe and Furuya (2015) using

ALOS PALSAR data, which had a 46-day orbital repeat, due to the large displacement over this time interval. Although Van Wychen et al. (2018) were able to determine glacier flow for Hubbard Glacier using ALOS PALSAR data, a 'nested' approach similar to that of Waechter et al. (2015) was required, which significantly increases the processing time and complexity required to derive motion reliably. The 4-day repeat period offered by the RCM helps alleviate this issue and improves the ability to determine the motion of fast flowing glaciers within the study region (Figure 1).

Monitoring surge progressions

Our results indicate that Nàłùdäy Glacier was surging in the winter of 2022 (Figure 1a and 1c) and experienced similar flow speeds to those observed during its previous surge in the winter of 2009/10 (Van Wychen et al. 2018). Fortunately, from January to March 2022, RCM imagery was collected over Nàłùdäy Glacier nearly every fourth day (Table 1), providing an unprecedented opportunity to examine the progression of the surge (Figure 1c). These results show that the surge first starts in the lowermost portion of the glacier and then propagates upglacier over time. The surge also progresses rapidly: in early January 2022 flow speeds in the lower 15 km section are ∼1,500 m/yr or less, but by the end of January 2022 motion is ∼2,000 m/yr, and velocities of ∼1,500 m/yr had migrated ∼5 km upglacier from the terminus. This pattern of continued acceleration and upglacier migration of elevated flow speeds progresses through February and by the end of March 2022, flow speeds of >2,500 m/yr are observed in the lowermost 5 km section of the glacier (Figure 1c). Previous studies have been inconclusive in terms of determining where previous surges of Nàłùdäy Glacier initiate, and whether they propagate upglacier or downglacier (Bevington and Copland 2014). However, the results presented here clearly indicate that surge initiation occurs at the terminus and that the surge front propagates upglacier over time, a behavior that has been observed on other glaciers such as Sortebræ Glacier in East Greenland (Pritchard et al. 2005).

There were two instances when 4-day repeat imagery was not available, and therefore images separated by 8 days were used instead (February 11, 2022 and February 19, 2022; March 3, 2022 and March 11, 2022: Table 1). In each of these cases there were considerably more gaps in the extracted centerline velocities (Figure 1c), suggesting that the ice motion was sufficiently high at these times that it could not be reliably detected. Given that the last reported surge of Nàłùdäy Glacier ended in summer 2010 (Bevington and Copland 2014), and that the most recent surge had started by January 2022, our results indicate that there was a < 12-year quiescent period since the last surge, which is aligned with the observations of generally decreasing quiescent period lengths since the 1940s for Nàłùdäy Glacier by Bevington and Copland (2014). By January 2023, the flow speeds of Nàłùdäy Glacier had slowed considerably, indicating that the glacier was transitioning into its quiescent period.

Our results also indicate that between January 2022 and January 2023, Chitina Glacier located in the northwestern portion of the St. Elias Icefield experienced an acceleration, with flow speeds increasing and propagating further downglacier by January 2023, indicating that a surge was underway. Figure 1d provides the centerline velocities extracted primarily from 4-day repeat imagery collected in January to March 2023 (Table 1) for the section of the glacier between 20 km and 40 km from the terminus. For Chitina Glacier, there were three periods when 4-day repeat imagery was not available, and 8-day repeat images (January 20, 2023 and January 28, 2023; February 17, 2023 and February 25, 2023) and 12-day repeat images (February 5, 2023 and February 17, 2023) were used to fill these data gaps. Although the speed-up is not as dramatic as Nàłùdäy Glacier, the middle section of Chitina Glacier clearly accelerates from maximum velocities of ∼250 m/yr in early January 2023 to >400 m/yr by mid-March 2023. Over this time, there is also a clear downglacier progression of the velocity peak, indicating that the surge initiates in the upper regions of the glacier and then propagates downglacier over time. Unlike the faster Nàłùdäy Glacier, where it is difficult to derive surge velocities with image pairs separated by more than 4-days, the slower surge speeds of Chitina Glacier allows for surge velocities to still be reliably determined from 8-day and 12-day separated image pairs (Figure 1c and 1d). Collectively, these results highlight the efficacy of utilizing 4-day RCM repeat imagery in fast flowing regions and indicate the high utility of these datasets for examining and investigating surge-glacier processes.

Conclusions and outlook

Our results demonstrate that 5 m High Resolution mode RCM imagery provides a useful dataset for determining glacier motion. Errors determined over off-glacier locations are similar to the uncertainty values provided by the processing of Radarsat-2 imagery to derive glacier velocities. Similarly, our results also show very good agreement with on ice displacements recorded by spatially and temporally coincident dGPS observations. Collectively, these results indicate that there can be long-term continuity between glacier velocity records derived from contemporary RCM products and those determined from the previous Radarsat-2 mission. However, although our results indicate that 5 m resolution RCM data provides an effective dataset for mapping ice motion at regional scales, there are a few drawbacks compared to Radarsat-2 imagery. First, the swath width of RCM High Resolution data is 30 km, compared to the 150 km swath width for Radarsat-2 Wide Fine (8 m resolution) products, which has been the primary dataset used for regional glacier velocity mapping activities within Canada (Van Wychen et al. 2016, 2020). This means that many more images need to be collected and processed to obtain the same spatial extent, and that data gaps are more likely when using RCM data. Second, at present, High Resolution RCM data is only being collected at a regional scale over the St. Elias Icefield, with no such imagery being collected systematically across other major glaciated regions in Canada such as the Canadian Arctic Archipelago (although targeted acquisitions over important glaciers are being collected, such as Trinity, Wykeham and Belcher). This is because of the priority of image collection in other areas in the standard coverage plan, which places an emphasis on activities other than glacier velocity measurements. As a result, it currently seems infeasible that regional mapping of glacier motion within Canada will be possible solely using RCM data as it was during the Radarsat-2 mission. Rather, it is more likely that a suite of SAR imagery (such as Sentinel-1, RCM, and TerraSAR-X), combined with motion determined from optical imagery, will be needed to map regional glacier motion across Canada at annual time scales.

Nevertheless, RCM data does provide some notable improvements from the previous Radarsat missions. First, the shorter temporal orbital repeat between sensors (as low as four days) means that there is less potential for a loss of coherence between images. Second, the shorter temporal period allows for the determination of glacier motion at time scales as low as every fourth day, greatly improving on the temporal resolution of other SAR data, such as Radarsat-2 (24 day), Sentinel-1 (6/12 day) and ALOS PALSAR (46 day), although this is dependent on imagery being collected with this temporal density. Already, our work has shown that from 4-day repeat collected imagery it easier to determine accurate flow rates on fast-moving (Hubbard) and surge-type (Nàłùdäy and Chitina) glaciers, which should further enable processed-based glacier studies.

Although in this study we have processed and presented our RCM data in a sequential manner to determine changes in ice motion, recent work has demonstrated the effectiveness of finding optimal temporal sampling to reduce data gaps and provide a more complete temporal coverage (Charrier et al. 2022). This is beyond the scope of the work presented here, which provides a first assessment of RCM derived displacements for glacier velocities, but it provides a framework for how RCM data might be processed in areas where the temporal coverage is irregular due to the standard coverage plan. Additionally, further work experimenting with differing window sizes used in the offset tracking procedure of fast flowing glaciers may be useful in terms of better resolving glacier velocities, which may be underestimated with the use of large window sizes. This will be especially useful in terms of finding optimal balance between using larger window sizes, which are more likely to have more unique and distinct patterns in the intensity matching windows, but at the expense of increased processing time. Overall, this study demonstrates the utility of RCM data to further monitor and investigate glacier processes within Canada and elsewhere.

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