

Supplementary Information for

Volumetric Quantifications and Dynamics of

Areas Undergoing Retrogressive Thaw Slumping in the Northern Hemisphere

Chunli Dai¹, Melissa K. Ward Jones², Jurjen van der Sluijs³, Nina Nesterova^{4,10}, Ian M. Howat⁵, Anna K. Liljedahl⁶, Bretwood Higman⁷, Jeffrey T. Freymueller⁸, Steven V. Kokelj⁹, Sindhura Sriram¹

¹ School of Forest, Fisheries, and Geomatics Sciences (FFGS), University of Florida, Gainesville, FL, USA.

² Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA.

³ Northwest Territories Centre for Geomatics, Government of Northwest Territories, Yellowknife, NT, X1A 2L9, Canada.

⁴ Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany.

⁵ Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, USA.

⁶ Woodwell Climate Research Center, Falmouth, MA, USA.

⁷ Ground Truth Alaska, Seldovia, AK, USA.

⁸ Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA.

⁹ Northwest Territories Geological Survey, Department of Industry, Tourism and Investment, Government of Northwest Territories, Yellowknife, NWT, X1A 2L9, Canada

¹⁰ Institute of Geosciences, University of Potsdam, Potsdam, 14476, Germany

Correspondence to: Chunli Dai, chunlidai@ufl.edu

Contents of this file

Figures S1-S15

Tables S1-S4

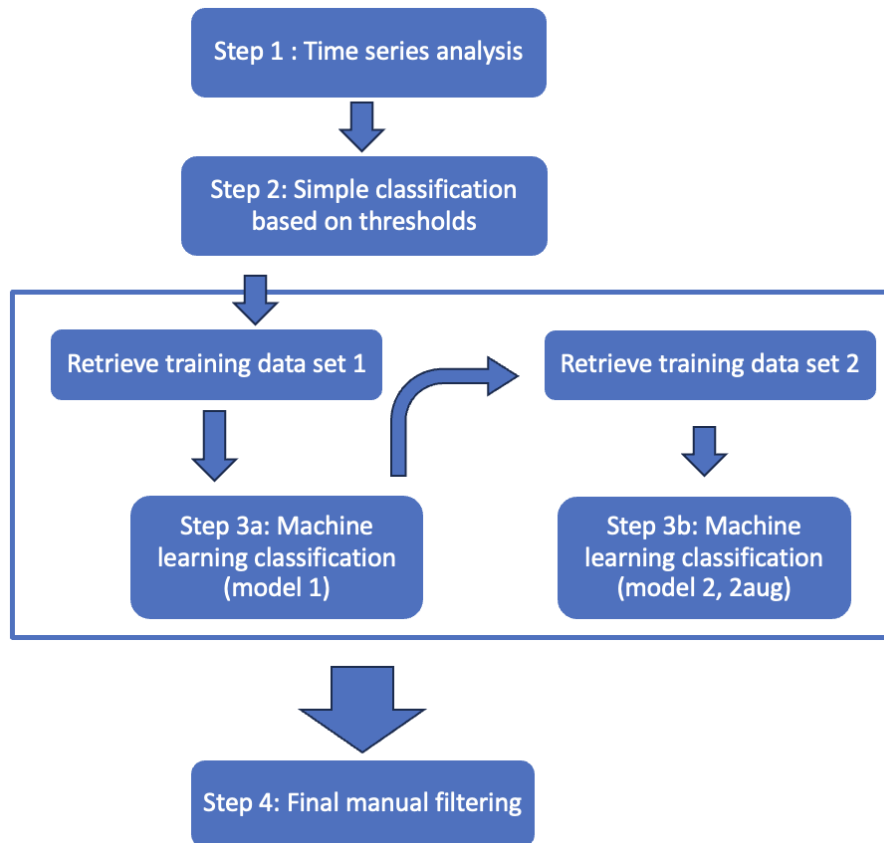


Fig. S1. Overview of workflow.

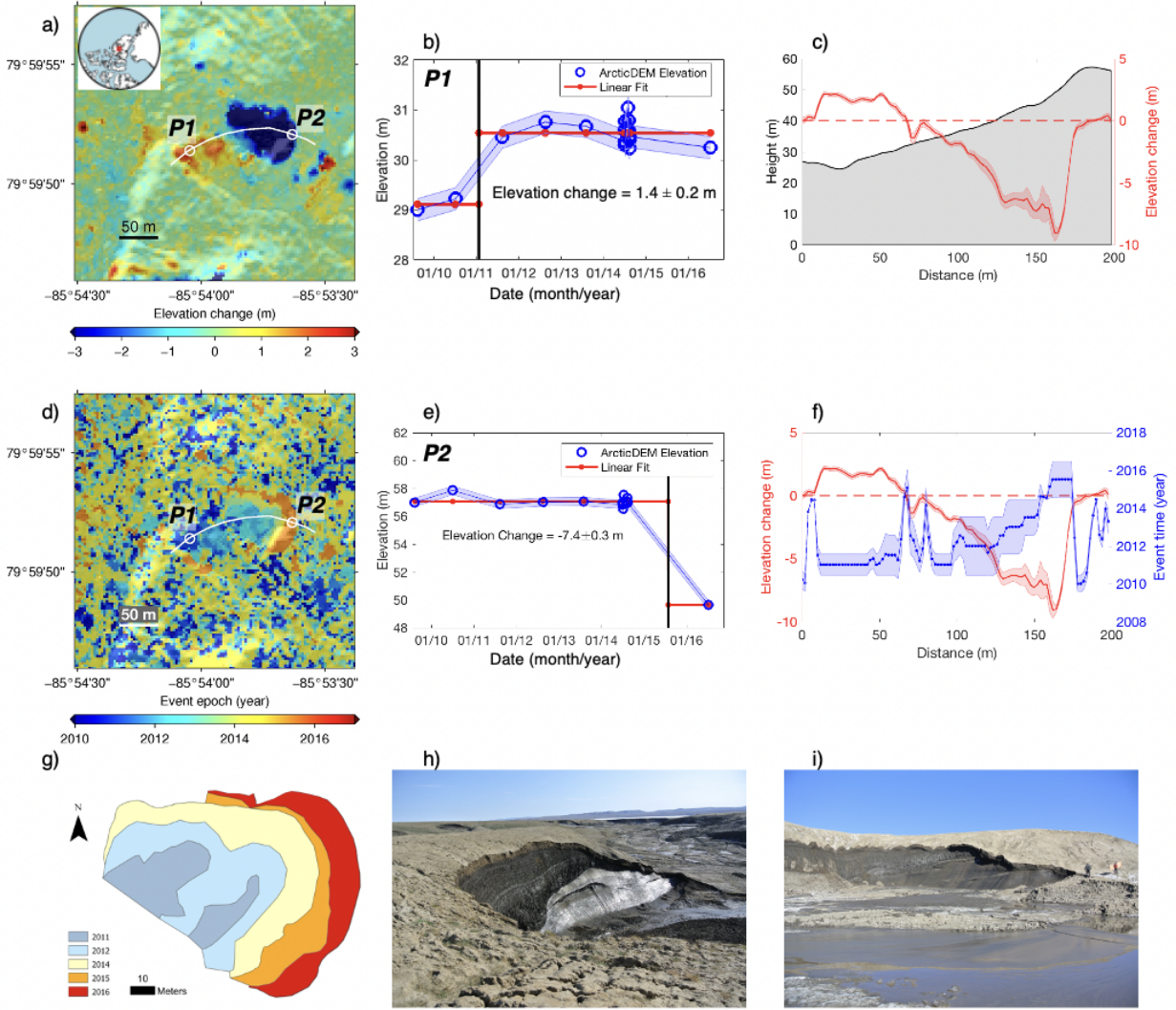


Fig. S2. Dynamics of an area undergoing RTS in Eureka, Canada⁵⁶. (a) Surface elevation change estimated from ArcticDEM time series. The background is the hillshade of the ArcticDEM mosaic. The inset shows the location of the site. (b) and (e) shows the elevation time series at points P1 and P2 (79°59'52.1"N, 85°53'38.0"W) in (a), where the x-axis is the date (month/year) and the y-axis is the surface elevation. The blue circles are the terrain elevations measurements, and the black vertical line shows the automatically detected time of elevation change. The deposition at this point (P1) appears to have occurred in 2011, while the deposition from later years may have flown and spread out downstream. The red line represents the linear model fit (equation 2) of the measurements. (c) Topography and elevation change across the manually drawn profile (the white line) in (a). The black line and gray shaded area (left y-axis) represent the earliest topography acquired on August 10, 2009, and the red line is the elevation change profile (right y-axis). (d) Estimated elevation change time in years. (f) the estimated elevation change time in years (right y axis). The estimated time identifies when the most substantial elevation change occurred within the time series. The red line and its shading are the estimated elevation change and uncertainty. DEM(s) created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery. (g) mapped headwalls from ⁵⁶ using either high resolution satellite imagery or field mapping with a dGPS. (h) Field image of this slump in July 2015 (i) Field image of this slump in July 2014, researchers provide scale.

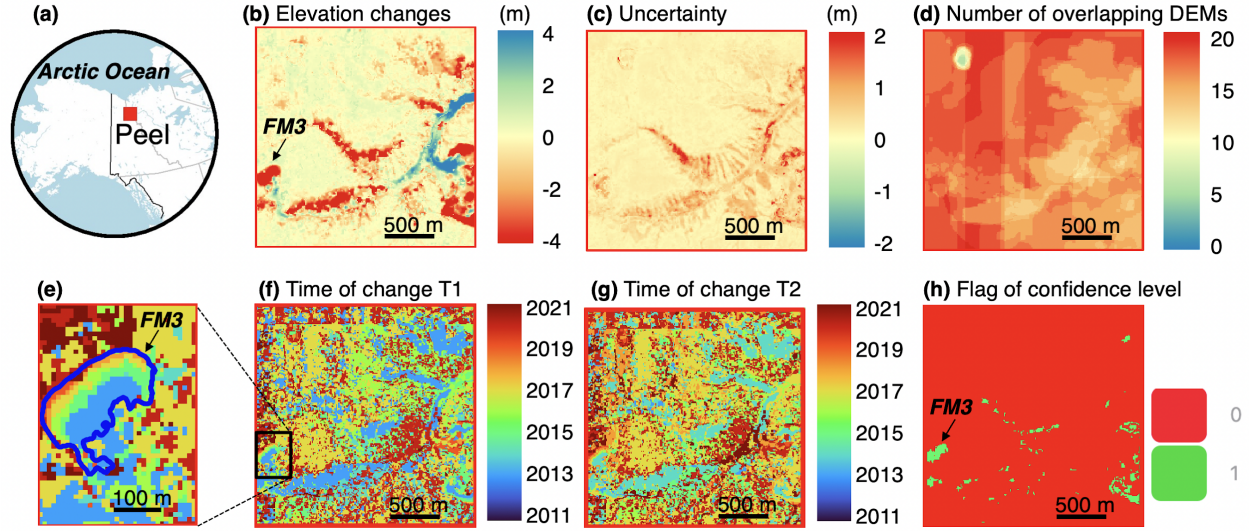


Fig. S3. Sample products in a 2 km by 2 km area in Peel Plateau, Canada. (a) The red square denotes the location of the study area. (b) The surface elevation change map near the slump FM3²⁷. The coordinate of FM3 is 135.274°W, 67.255°N. (c) The uncertainty of the surface elevation change. (d) The number of overlapping DEM strips. (e) A zoom-in view of slump FM3 for the estimated time of change. (f) Estimated time of change, T1. (g) Estimated time of change, T2. (h) Map of flags representing the confidence level of the estimated elevation changes. 1 means high confidence, and 0 means low confidence.

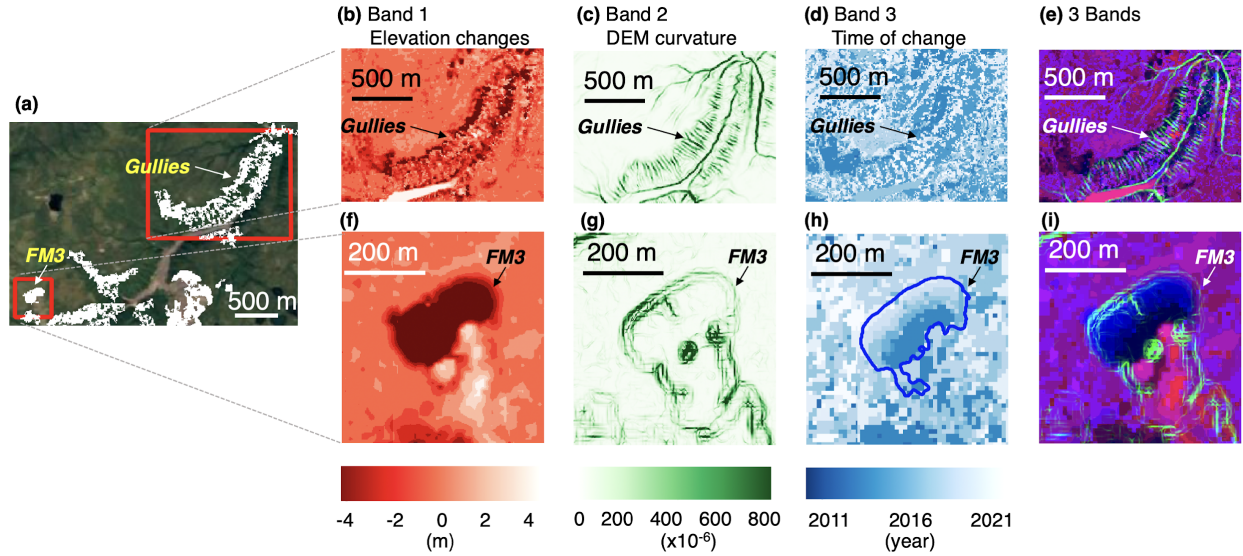


Fig. S4. Example of input images for deep learning. (a) Location of RTS candidates (135.274°W, 67.255°N) in Peel Plateau, Canada. The white pixels are highlighted RTS candidates from criteria 1-3. The domain of (a) is also marked as the white box in Fig. S5b. (b-e) Band 1, 2, and 3 of an image that includes the gullies feature. (f-i) Band 1, 2, and 3 of an image that includes the slump FM3.

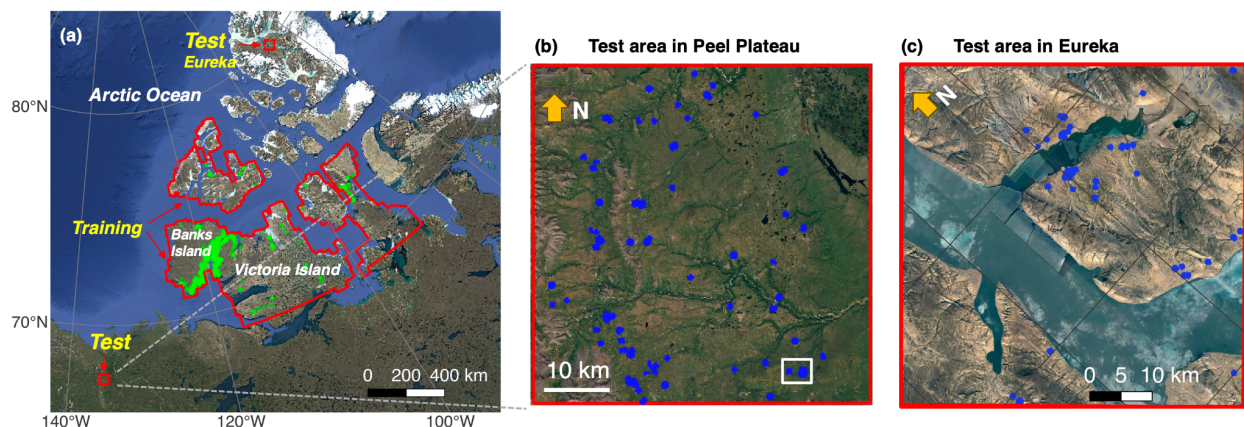


Fig. S5. Training and test data in northern Canada. (a) The red polygons represent the region of training/validation data sets, including a total of 1004 RTS (green dots). (b) a 50 by 50 km test area in Peel Plateau, including 83 RTS (blue dots). (c) a 50 km by 50 km test area in Eureka, Canada, including 45 RTS as ground truth (blue dots). The white box in (b) marks the location of Fig. S4(a). The background is the Google Earth image, shown in the UTM 8N projection.

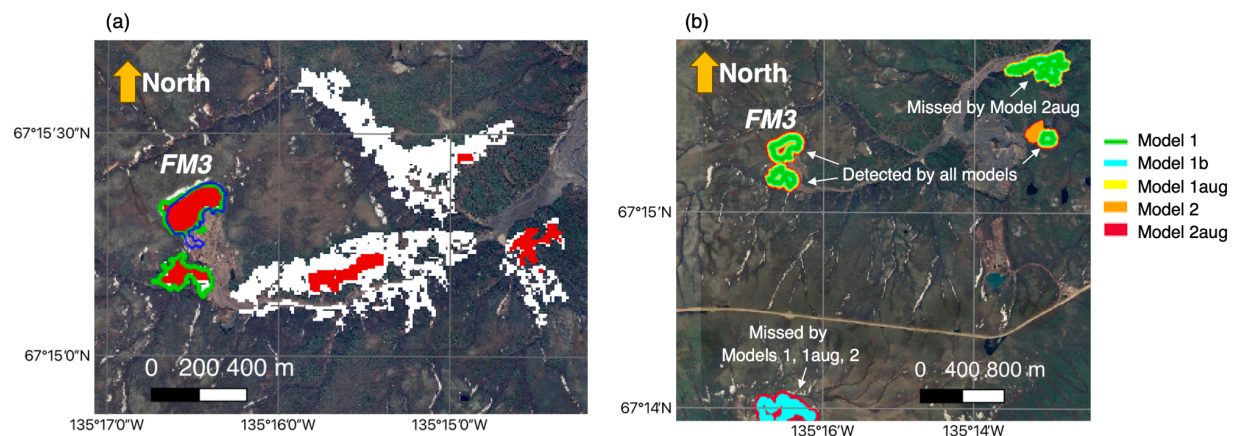


Fig. S6. Classification improvements in Peel Plateau, Canada. (a) Improvement from combining the simple thresholding method with deep learning in Peel Plateau, Canada. (a) White pixels are clusters from criteria 1-3, red are clusters from the deep learning approach (model 1 in Table S3), and blue is the ground truth outline of Slump FM3. Green outlines are slumps from the combined solution, and the rest (three clusters on the right) are rejected. The background is the Google Earth image, shown in the UTM 8N projection. (b) Improvement from the five-model ensembles (model details see Table S3). For the study area in this figure, only three clusters are commonly detected by all five models, while other clusters are missed by one or several models hence rejected from the ensemble solution.



Fig. S7. Training set 2. Green dots represent the training data set 2, with 1660 training and 189 validation images. The background is the Google Earth image, shown in polar stereographic projection.

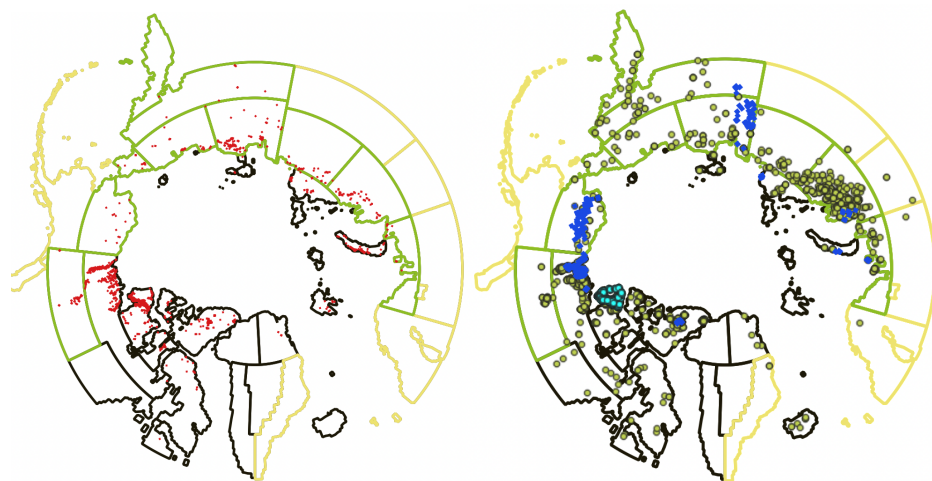


Fig. S8. Locations of RTS detected in this study (*left*) and in the literature (*right*). Black and green polygons show regions that have been visually inspected fully, and yellow polygons are the regions not checked. Red dots are RTS in this study, green dots are RTS by ⁴⁷, cyan dots are RTS by ³³, and blue points are others^{45,59,102,103,109–111}.

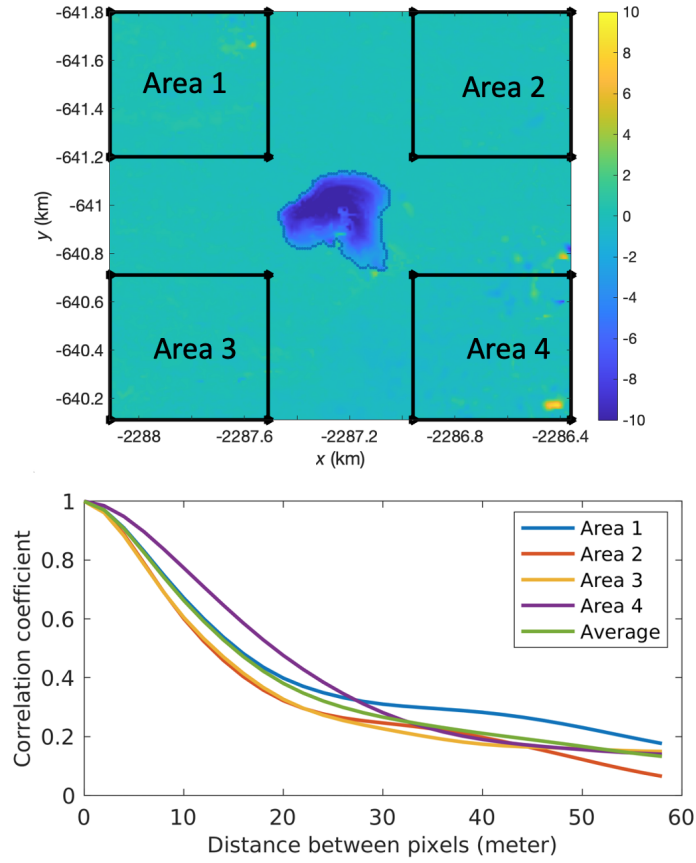


Fig. S9 The calculation of covariance between pixels for an RTS in Kitikmeot Region, Canada. (a) surface elevation changes in meters. Four boxes represent areas used for calculating covariances. x and y axes are polar stereographic coordinates. (b) the correlation coefficient between pixels using the periodogram method^{81,100} among the selected four areas. The green line is the average of the correlation coefficients of four areas. The volume of this slump (68.32449°N , $-119.3465^{\circ}\text{W}$) is estimated as $764,470 \text{ m}^3 \pm 12,525 \text{ m}^3$.

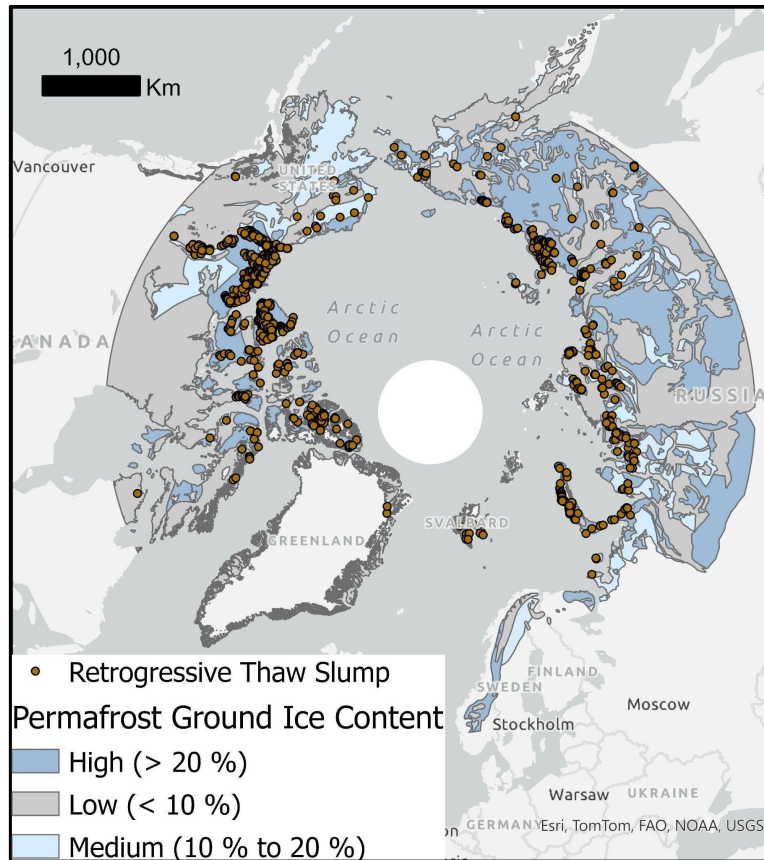


Fig. S10: The distribution of detected RTS with the ground ice map⁵⁴.

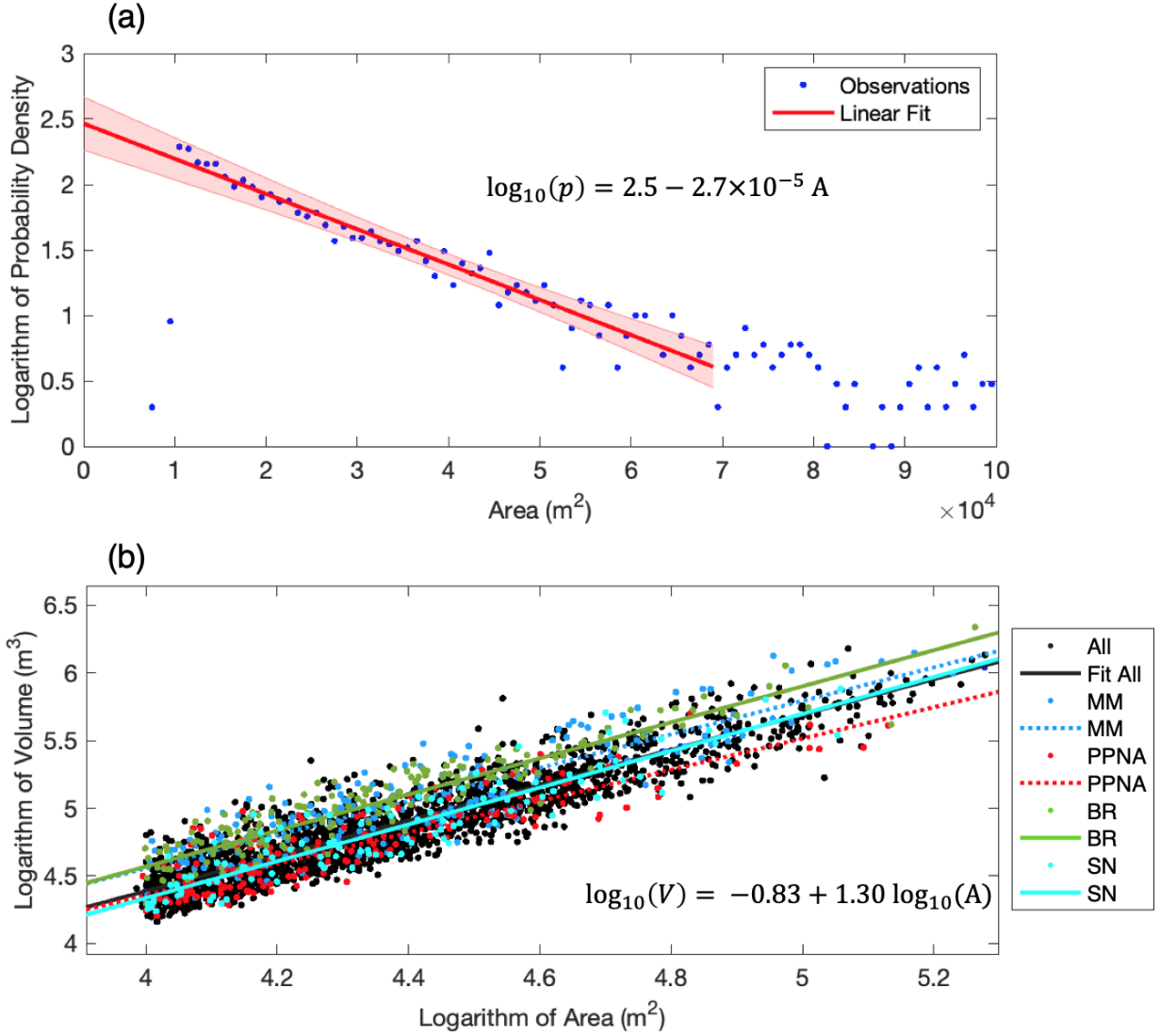


Fig. S11. Area-frequency and area-volume relationship. (a) Area-frequency distribution of 2,747 active RTS detected in this study. Blue dots are probability density of all RTS. Red line is the modeled fit (see Methods) of the area-frequency distribution, $\log_{10}(p) = \alpha - \beta A$, where A is RTS scar area (m^2) and p is the probability density. $p = c/(Nw)$, where c is the number of RTS within an area bin, w is the bin width ($1000 m^2$), N is the total number of RTS (2,747). Here, the model fit yields $\alpha = 2.5 \pm 0.2$, $\beta = (2.7 \pm 0.5) \times 10^{-5}$. In this figure, the shading area denotes the standard deviation multiplied by 5. (b) Area-volume relationship for all RTS, and four regions. Solid lines are the regions with high scaling exponents, South Nunavut (SN) and the Brooks Range (BR), and dot lines are regions with low scaling exponents, Plateaus and Plains of the Northern Asia (PPNA) and Mackenzie Mountains (MM). The black line is the relationship for all RTS.

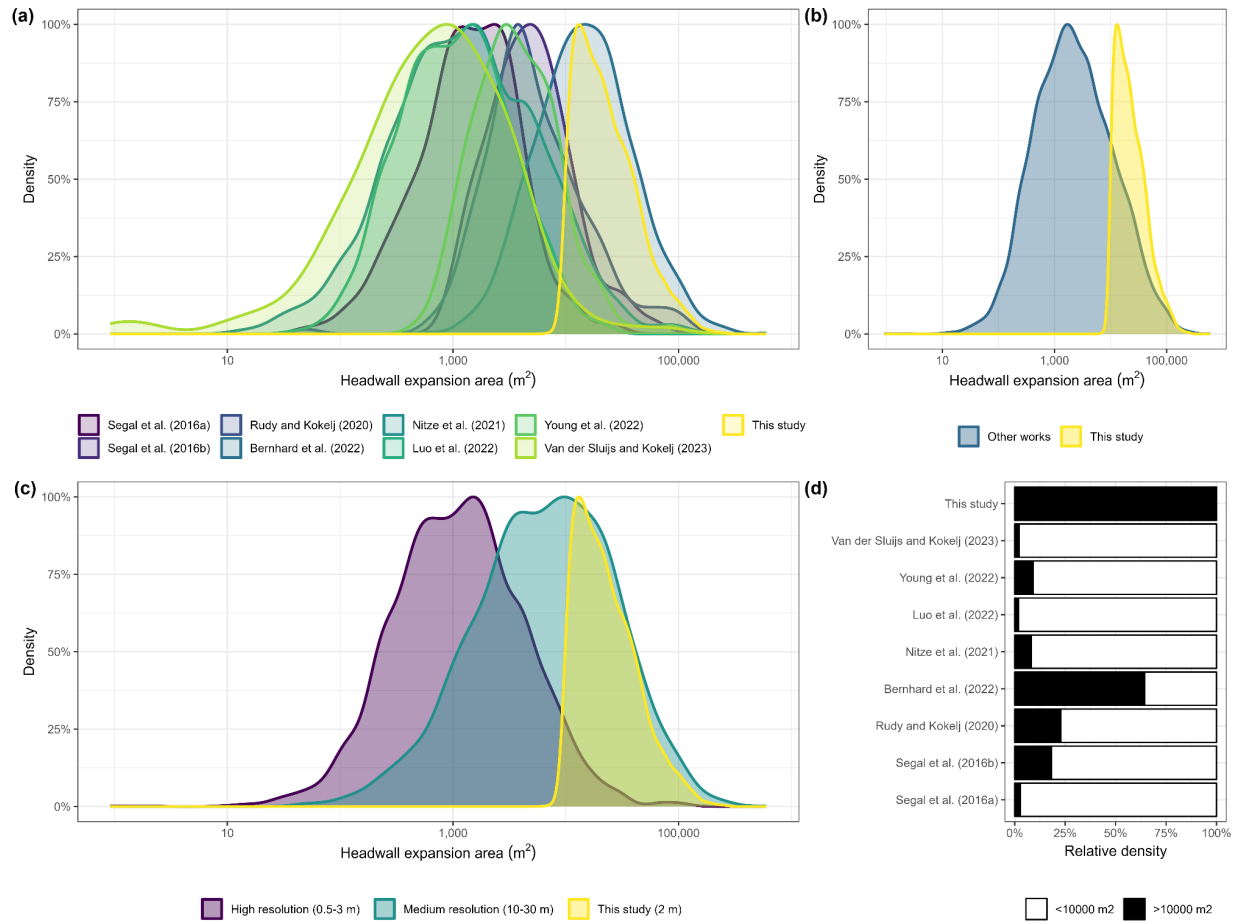


Fig. S12: Density distribution of several RTS inventories. (a) Distribution of headwall expansion area by individual RTS inventory and when harmonized to show the considerable number (82) of RTS smaller than this study's 10,000 m² minimum threshold (b). In (c) the same inventories were grouped by the resolution of source imagery, detailing how smaller headwall advances can be captured using higher resolution data. In (d) the binary distribution is shown per study, with 10,000 m² as threshold.

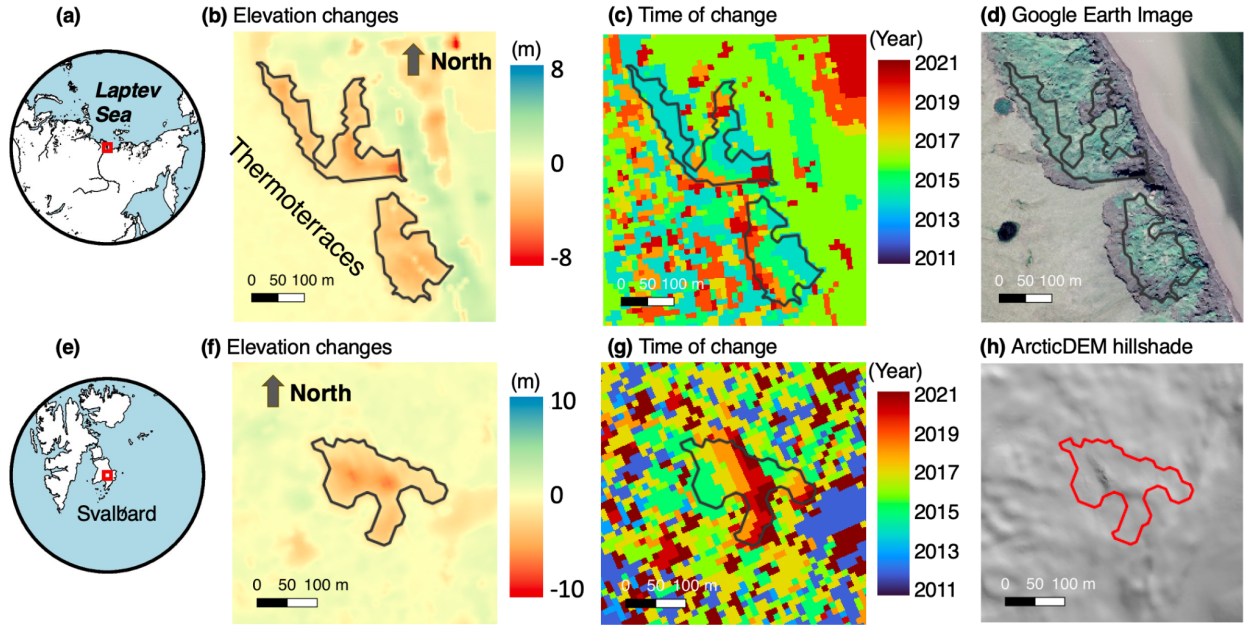


Fig. S13. Examples of thermoterraces (a-d) and glacier dead-ice back-slumping (e-h). (a-d) Two thermoterraces in Yakutia, Russia, at coordinate 129.353253°E, 71.851551°N. (e-h) a glacier dead-ice back-slumping in Svalbard located at 22.97598°E, 77.709341°N. Black lines denote RTS outlines identified in this study.

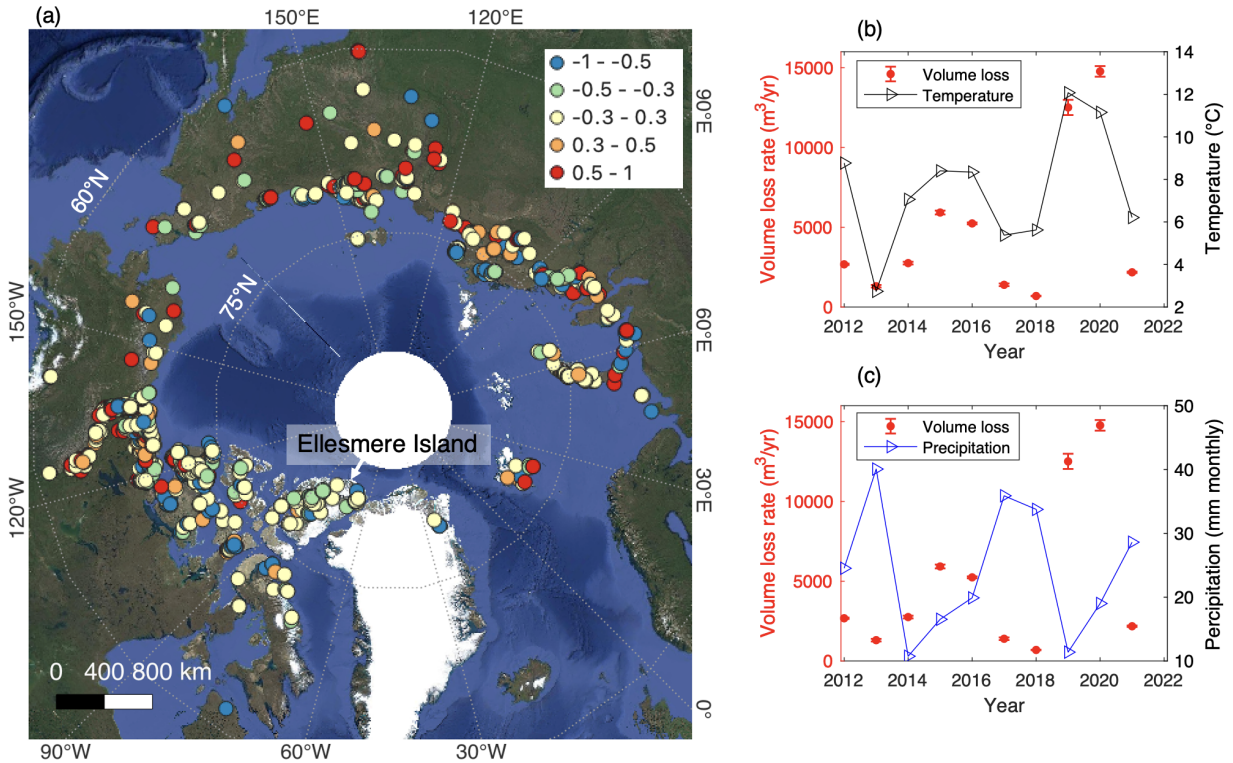


Fig. S14. The correlation of volume loss per year with mean summer (July-August) precipitation. The right panel shows the time series comparison between volume loss per year with temperature (b) and precipitation (c) at one RTS (79°47'52.4"N 84°38'50.6"W) in Ellesmere Island, Canada.

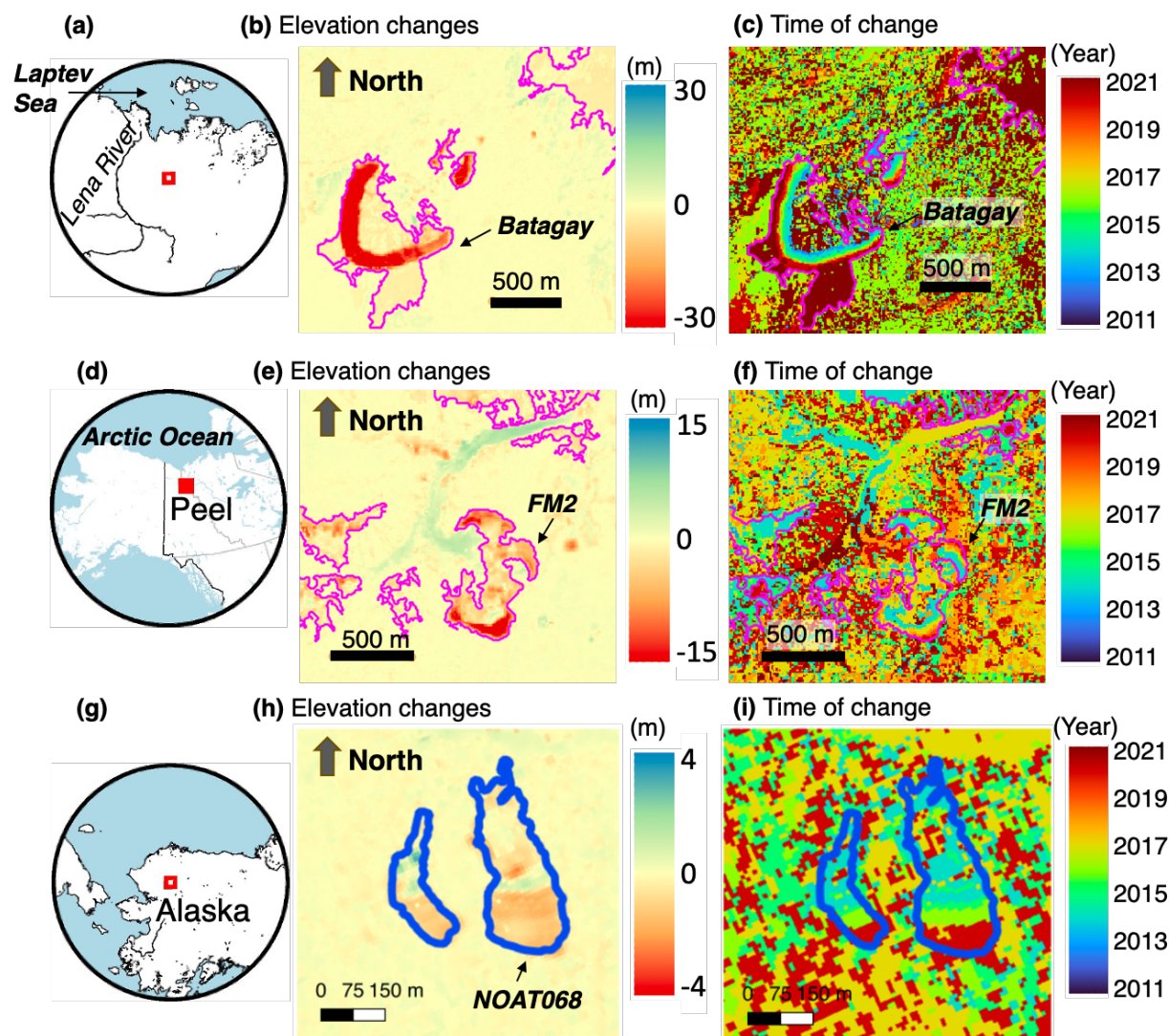


Fig. S15. Examples of RTS missed from our classification. Magenta polygons are classified RTS from Step 2. Two megaslumps^{22,68}, Batagay (b) and FM2 (e), are later filtered out in Step 3 due to the rainbow patterns (c,f) occupying only a limited portion of the polygons. (h) Slump NOAT068^{26,70} is filtered out in Step 2 since no pixels within the scarp area exhibited a significant elevation change exceeding 2 m, thereby failing to meet Criterion 2. Blue polygons are the slumps outlined by 70.

Table S1. The number of RTS candidates.

	Region 9 (369 tiles)	Peel Plateau (one 50 km by 50 km tile)
Criteria 1	936370	9498
Criteria 1-3	17184 (50 times less)	1238 (8 times less)

Table S2. Deep learning performance at Peel Plateau (one 50 km by 50 km tile).

	True Positive	False Positive	False Negative	Precision	Recall
Criteria 1	83	9415	0	1%	100%
Criteria 1-3	77	1161	5	7%	94%
Mask R-CNN (Model 1)	76	897	6	8%	93%
Combined	71	357	12	17%	86%

Note: the total number of ground truth 83.

Table S3. Deep learning improvement by merging several models.

Deep learning models	Peel Plateau					Eureka				
	True Positive	False Positive	False Negative	Precision	Recall	True Positive	False Positive	False Negative	Precision	Recall
DL (model 1)	71	357	12	17%	86%	34	31	10	52%	77%
DL (model 1b)	71	518	12	12%	86%	34	35	10	49%	77%
DL (model 1aug)	71	524	12	12%	86%	34	38	10	47%	77%
DL (model 2)	73	673	10	10%	88%	34	42	10	45%	77%
DL (model 2aug)	74	849	9	8%	89%	34	58	10	37%	77%
Merge above all	68	210	15	24%	82%	34	18	10	65%	77%

Note: the total number of true positives (ground truth) is 83 for the Peel Plateau and 45 for Eureka, Canada. The results here are all combined solutions with criteria 1-3. The configuration of training parameters for all rows is the same except for the model 1b, which has the maximum iteration as 2000 (cfg.SOLVER.MAX_ITER). Model name with 'aug' denotes a model with data augmentation. Models 1, 1b, and 1aug are trained using training data set 1, and models 2 and 2aug are established using training data set 2.

Table S4. The number of candidates from different steps.

ArcticDEM Region Name	ArcticDEM Region ID	Step 2 (Criteria 1-3)	Step 3	Step 4 (Manual selection from step 3)
Iceland	1	18,720	2,450	0
Southwest Greenland	3	69,110	7,309	0
Northeast Greenland	5	32,005	6,339	7
Northwest Greenland	6	21,114	2,796	0
Ellesmere, Canada	7	48,366	8,128	189
Baffin, Canada	8	37,414	5,688	15
Victoria, Canada	9	6,674	2,253	1,286
North Mainland, Canada	10	66,888	9,636	564
North Hudson, Canada	11	22,773	5,986	1
Svalbard	14	19,241	2,533	11
Novaya Zemlya, Russia	15	15,297	1,859	162
Franz Josef, Russia	29	4,615	365	0
Northern Taymyr, New Siberian Islands, Severnaya Zemlya Islands, Wrangel Island, Russia	30	9,067	1,633	102
South Canada	12	304,146	50,277	93
East Yakutia and Chukotka, Russia	18	85,754	11,269	51
Magadan, Russia	19	323,314	26,626	13
Kamchatka, Russia	20	195,611	17,763	1
East Yakutia, Russia	21	214,518	22,321	116
West Yakutia, Russia	23	194,989	29,008	45
West Siberian Arctic, Russia	25	83,792	16,843	61
European Arctic, Russia	27	95,370	19,547	17
North Alaska	34	145,953	19,154	13
Southeast Greenland	2	172,331	79,258	N/A
Southern Central Siberia, Russia	22	796,816	95,662	N/A
Southern West Siberia, Russia	24	245,028	51,924	N/A
European central Russia	26	482,507	96,575	N/A
Scandinavia	28	559,753	114,719	N/A
South Alaska	31	368,949	21,287	N/A
Total		4,640,115	729,208	2,747

Note: Yellow rows were the regions not checked, since they have too many candidates for visual inspection and have no known evidence of RTS activities. Green rows are the regions that are checked within the vicinity (~10 km) of RTS activity reported in previously published literature. White rows are checked for the entire domains. This table only includes medium- to large RTS with areas larger than 10,000 m² exhibiting a minimum elevation change of -2 m.