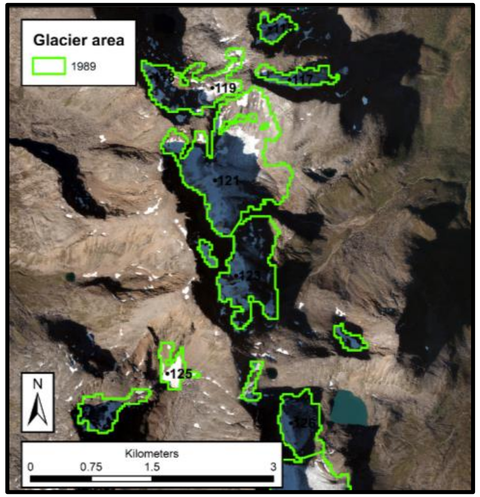
Identifying and mapping very small mountain glaciers on coarse to high-resolution imagery



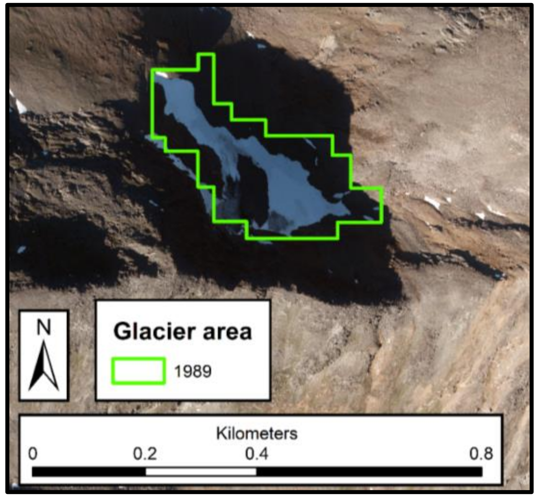
Joshua R. Leigh[1]

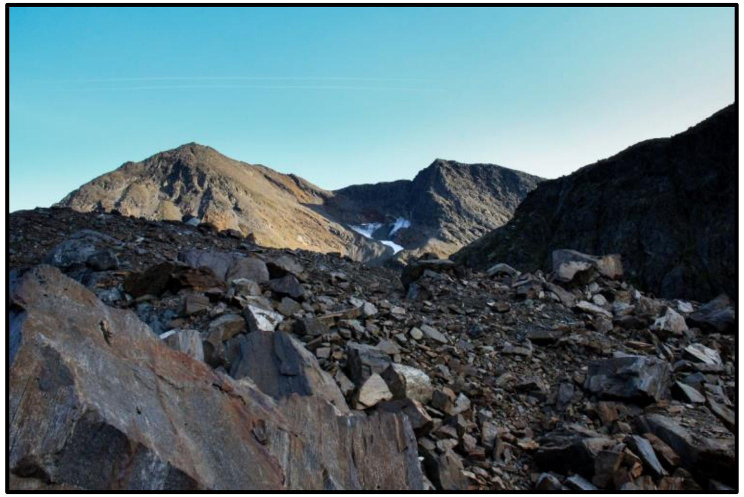
@J0sh_L

joshua.r.leigh@durham.ac.uk

and

C.R. Stokes[1], R.J. Carr[2], I.S. Evans[1], L.M. Andreassen[3] and D.J. Evans[1]





[1]Department of Geography, Durham University, Durham, UK
[2]School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK
[3]Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway

Durham University

Newcastle University

Norwegian Water Resources and Energy Directorate
NVE

IAPETUS
Doctoral Training Partnership

This presentation is based on our recently published paper:

Journal of Glaciology

IGS

Paper

Identifying and mapping very small (<0.5 km^2) mountain glaciers on coarse to high-resolution imagery

J. R. Leigh[1], C. R. Stokes[1], R. J. Carr[2], I. S. Evans[1], L. M. Andreassen[3] and D. J. A. Evans[1]

[1]Department of Geography, Durham University, Durham, UK; [2]School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK and [3]Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway

Cite this article: Leigh JR, Stokes CR, Carr RJ, Evans IS, Andreassen LM, Evans DJA (2019). Identifying and mapping very small (<0.5 km^2) mountain glaciers on coarse to high-resolution imagery. *Journal of Glaciology* **65**(254), 873–888. https://doi.org/10.1017/jog.2019.50

Received: 2 April 2019
Revised: 8 July 2019
Accepted: 9 July 2019
First published online: 27 September 2019

Keywords:
Glacier fluctuations; glacier mapping; mountain glaciers; remote sensing

Author for correspondence:
J. R. Leigh, E-mail:
joshua.r.leigh@durham.ac.uk

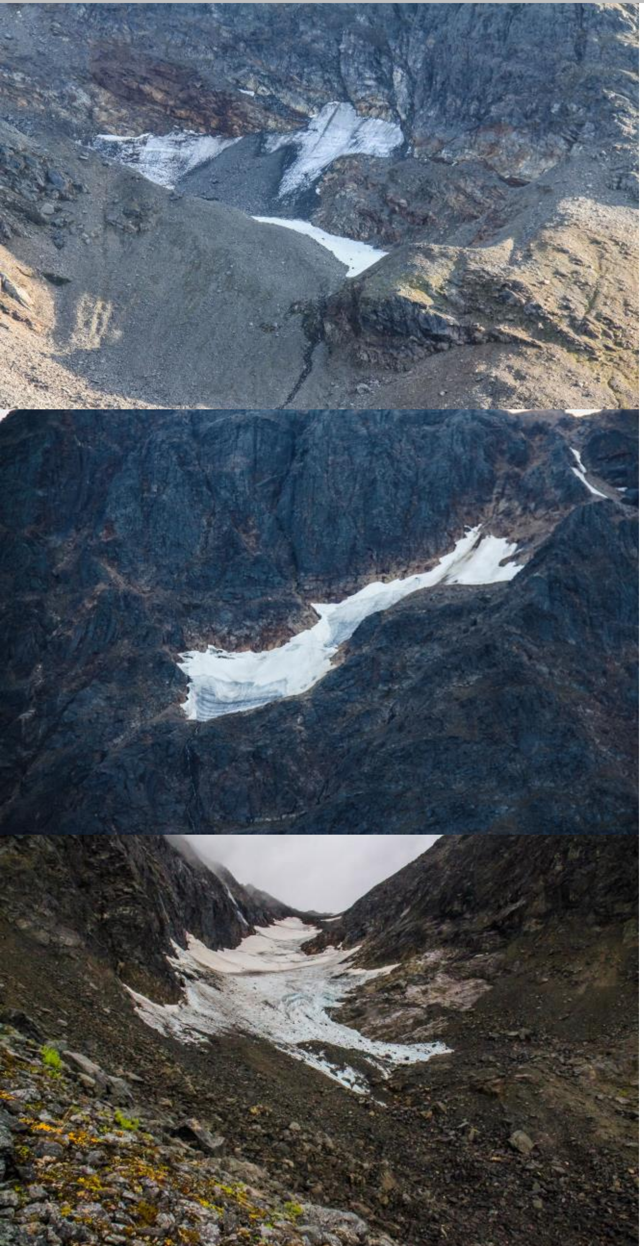
Abstract

Small mountain glaciers are an important part of the cryosphere and tend to respond rapidly to climate warming. Historically, mapping very small glaciers (generally considered to be <0.5 km^2) using satellite imagery has often been subjective due to the difficulty in differentiating them from perennial snowpatches. For this reason, most scientists implement minimum size-thresholds (typically 0.01–0.05 km^2). Here, we compare the ability of different remote-sensing approaches to identify and map very small glaciers on imagery of varying spatial resolutions (30–0.25 m) and investigate how operator subjectivity influences the results. Based on this analysis, we support the use of a minimum size-threshold of 0.01 km^2 for imagery with coarse to medium spatial resolution (30–10 m). However, when mapping on high-resolution imagery (<1 m) with minimal seasonal snow cover, glaciers <0.05 km^2 and even <0.01 km^2 are readily identifiable and using a minimum threshold may be inappropriate. For these cases, we develop a set of criteria to enable the identification of very small glaciers and classify them as *certain*, *probable* or *possible*. This should facilitate a more consistent approach to identifying and mapping very small glaciers on high-resolution imagery, helping to produce more comprehensive and accurate glacier inventories.

Leigh, J.R., Stokes, C.R., Carr, R.J., Evans, I.S., Andreassen, L.M. and Evans, D.J.A., 2019. Identifying and mapping very small (<0.5 km^2) mountain glaciers on coarse to high-resolution imagery. *Journal of Glaciology*, **65**(254), pp.873-888. DOI: https://doi.org/10.1017/jog.2019.50

Outline

Introduction



Small mountain glaciers are an important part of the cryosphere and tend to respond rapidly to climate warming.

The combined melt from mountain glaciers and ice caps between 2003 and 2009 accounted for 29 ± 13% of observed sea level rise (IPCC, 2013).

Recent work of Parkes and Marzeion (2018) has proposed that the combined melt from ‘uncharted glaciers’ (i.e. glaciers that are not currently included in global glacier inventories) may account for as much as 42.7 mm of sea level rise between 1901 and 2015.

Introduction

Threshold sizes used by different glacier mappers

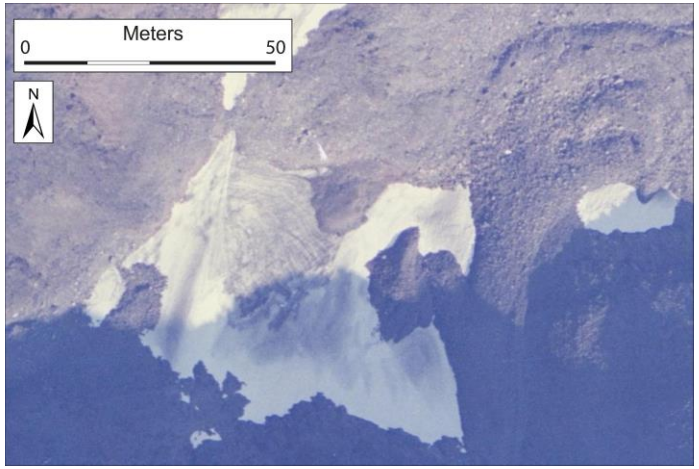
Authors	Study area	Image spatial resolution *m*	Minimum glacier size *km²*
Tielidze et al. (2020)	Caucasus Mountains	1.5–30	0.01
Barcaza et al. (2017)	Southern Andes	30	0.01
Ganyushkin et al. (2017)	Altai Mountains	0.5–30	0.01
Earl and Gardner (2016)	North Asia	30	0.02
Lynch et al. (2016)	Kamchatka Peninsula	15–30	0.02
Racoviteanu et al. (2015)	Eastern Himalaya	0.5–90	0.02
Burns and Nolin (2014)	Cordillera Blanca	3.2–79	0.01
Paul and Mölg (2014)	Northern Andes	<15–30	0.05
Pfeffer et al. (2014)	Global	≤30	0.01
Xiang et al. (2014)	Poiqu River basin	15–79	0.01
Bliss et al. (2013)	Antarctic periphery	15–200	0.01
Jiskoot et al. (2012)	East Greenland	14.5–15	2
Andreassen et al. (2012)	Norway	30	0.0081
Frey et al. (2012)	Western Himalayas	30	0.02
Rastner et al. (2012)	Greenland	15–2,000	0.05
Bajracharya et al. (2011)	Hindu Kush-Himalayan region	≤90	0.02
Bhambri et al. (2011)	Garhwal Himalayas	2.5–90	0.25
Kamp et al. (2011)	Himalaya Range of Zanskar	15–79	0.05
Paul et al. (2011)	European Alps	<30–90	0.01
Bolch et al. (2010)	Canadian Cordillera	≤30	0.05
Narama et al. (2010)	Tien Shan Mountains	1.8–30	0.01
DeBeer and Sharp (2009)	Monashee Mountains	4–30	0.01

Despite their importance and ubiquity, there is very little guidance on how to distinguish very small glaciers (<0.5 km^2) from perennial snowpatches when compiling remotely sensed glacier inventories or change assessments.

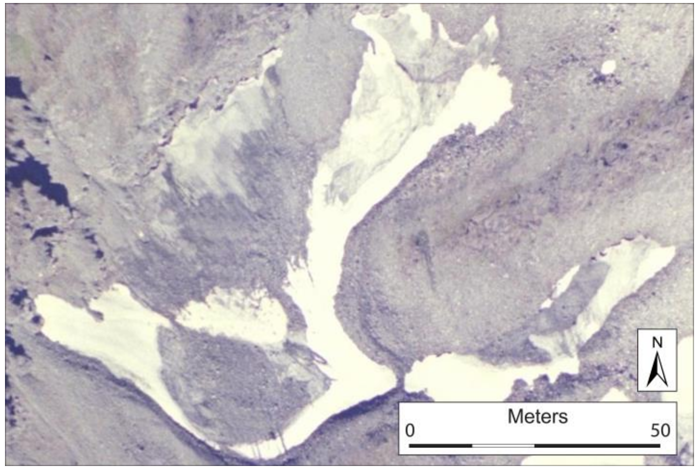
Aims

The aim of our research was to explore ways of improving the objectivity and consistency of mapping very small glaciers (<0.5 km^2 and especially those <0.05 km^2) on high-resolution satellite imagery and aerial photographs.

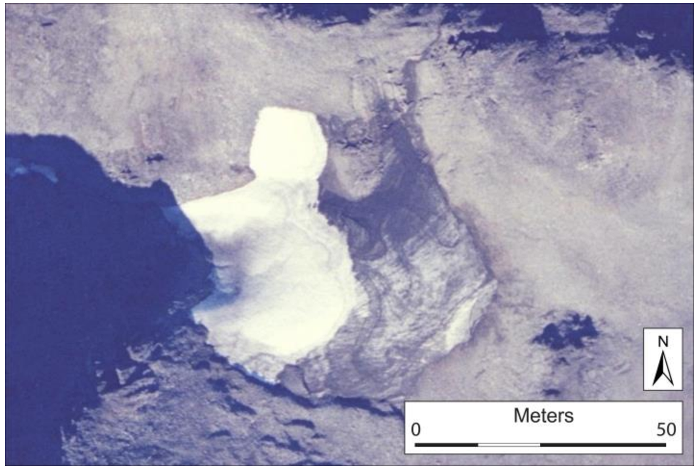
To achieve this aim we have developed new criteria to help the objective identification and mapping of very small glaciers using high-resolution imagery.



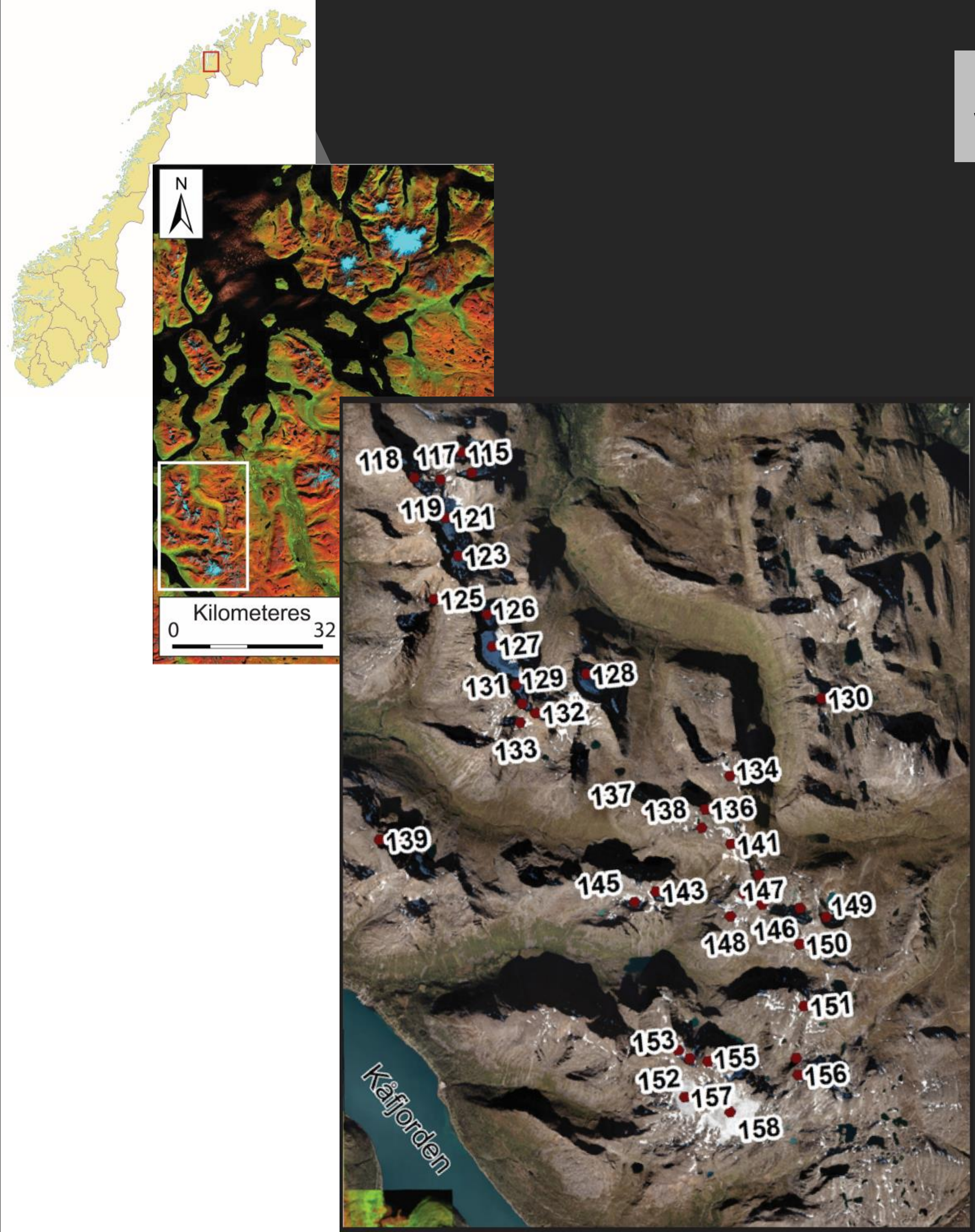
Unmapped glacier ~0.02 km^2



Unmapped glacier ~0.04 km^2



Mapped glacier (ID 130) ~0.02 km^2



Study area

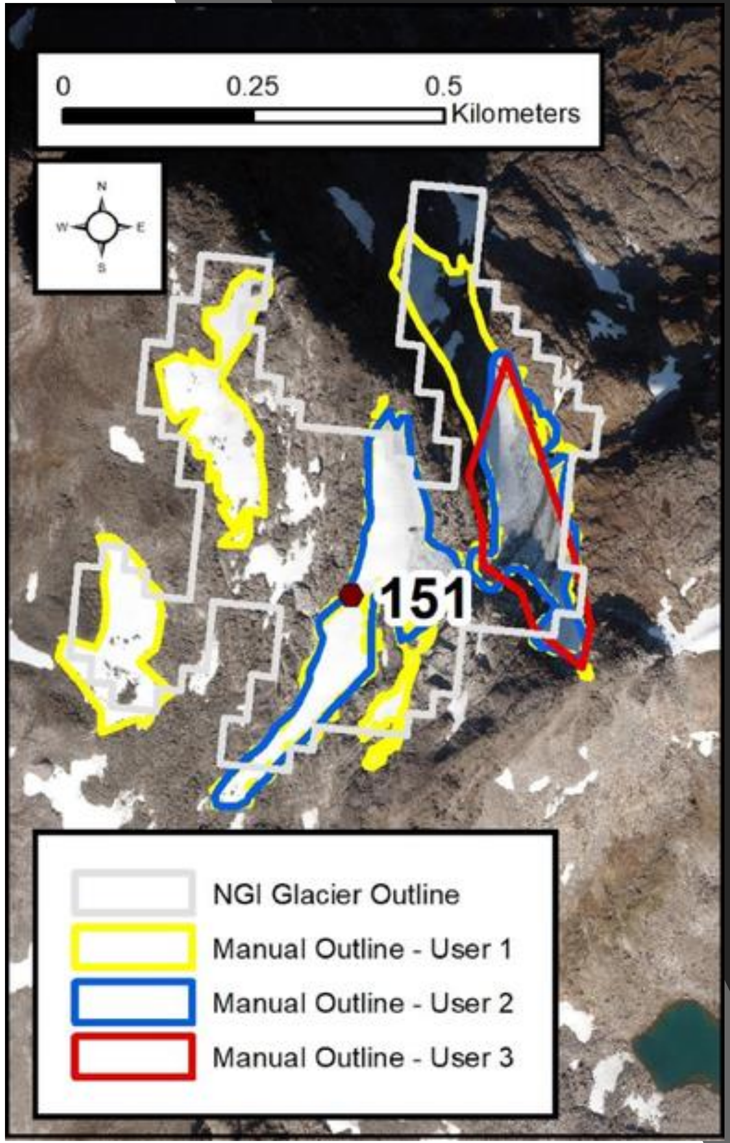
The study area lies within the Kåfjord/Nordreisa municipality, Troms county, northern Norway.

Dominated by valley and cirque-type glaciers.

Average monthly temperature typically varies from −10 to 15°C (station #91740: www.eKlima.no).

Within the study area the Inventory of Norwegian Glaciers (Andreassen et al., 2012) records 40 glaciers, with a total glacier extent of 12.09 km^2

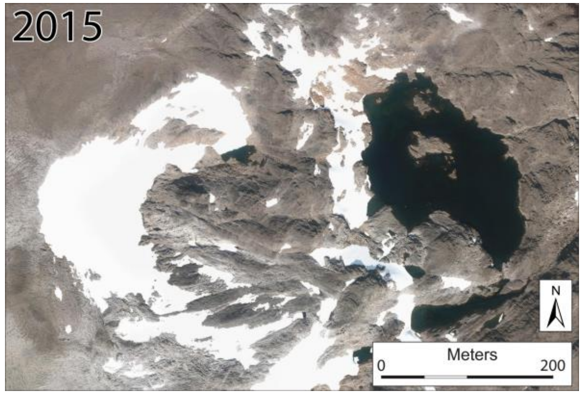
A new scoring system

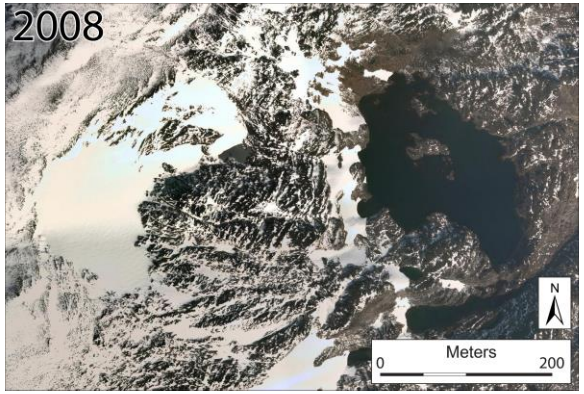


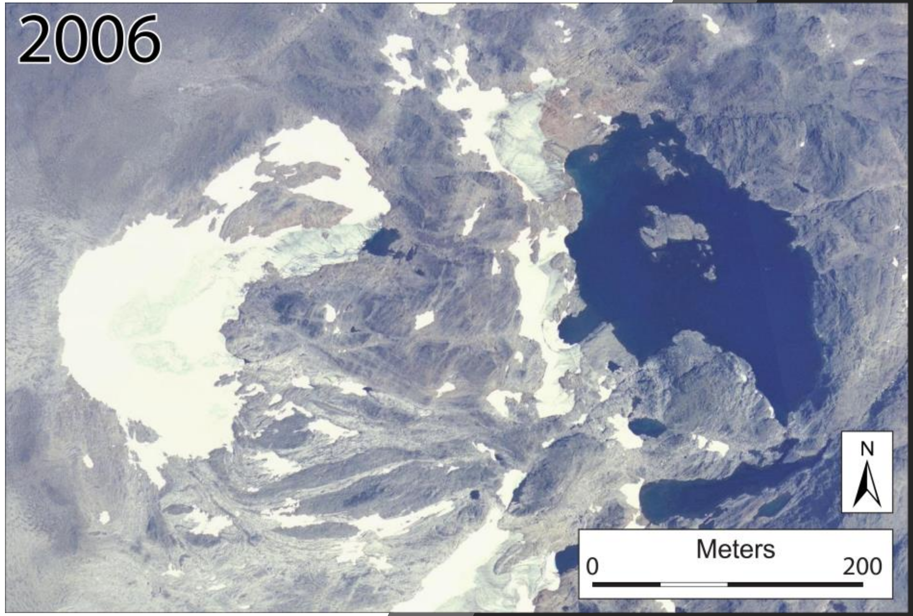
A lack of guidance on how to distinguish very small glaciers from snowpatches, when mapping from high-resolution remotely sensed imagery results in disparity between results from different mappers.

We have therefore, developed a new scoring system to increase objectivity when identifying very small glaciers on high-resolution imagery.

A new scoring system







Unmapped glacier ~0.09 km^2

The new scoring system is based upon the examination of each potential glacier unit for specific features.

It can be used with a single image but is best when used in conjunction with multiple images from differing years (if available), to confirm that features persist and to allow assessment under different snow cover conditions.

Each candidate glacier is scored based on the features visible on the imagery and the resultant total score is used to classify the feature as either a:

‘***certain***’, ‘***probable***’ or ‘***possible***’ glacier.

The “Glacier Identification Scoring System”

Our scoring system follows the basic outline as shown below

Feature	Score	Description	Example
The user looks for specific features visible on the ice surface and/or in the immediate glacier foreland.	A score from 1-5 is assigned to each specific feature and once all visible features are recorded their associated scores are added together for a total score of 20 ‘points’.	A description of each specific feature is provided.	An example of what this feature might look like is also provided.

Summing the feature scores provides degree of confidence in identification as a glacier:

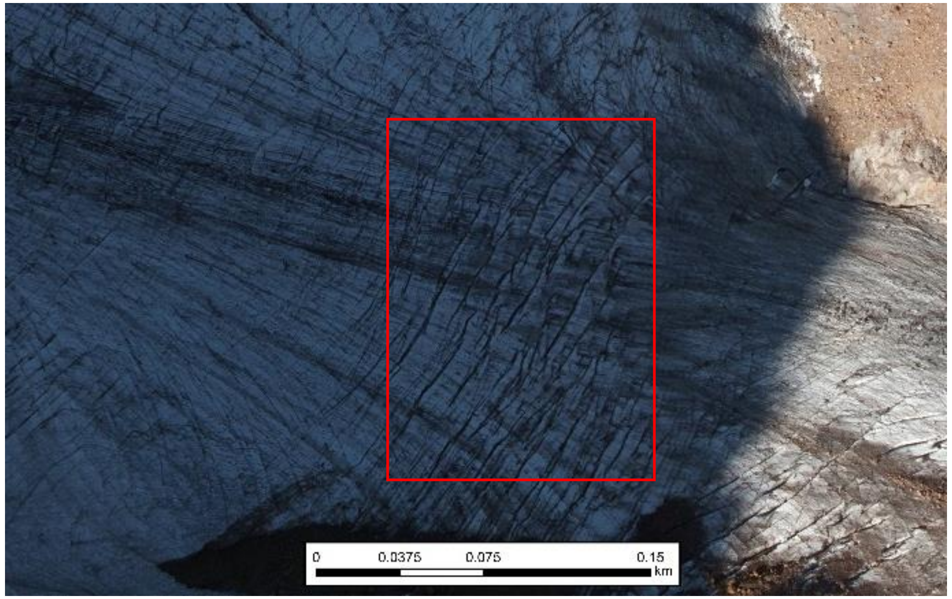
11–20 = certain

6–10 = probable

2–5 = possible

1 = perennial snow

The "Glacier Identification Scoring System"

Feature	Score	Description	Example
Crevasses	5	Cracks and/or fractures, of any depth, in the surface of a glacier.	

The clearest evidence of flowing ice is a set of crevasses, or deformation of banding lines and so each of these is awarded 5 points.

The “Glacier Identification Scoring System”

Feature	Score	Description	Example
Flow features and deformed stratification	5	Features such as the deformation of glacier banding, presence of foliation or distinct proglacial debris transport when comparing images from multiple time steps.	

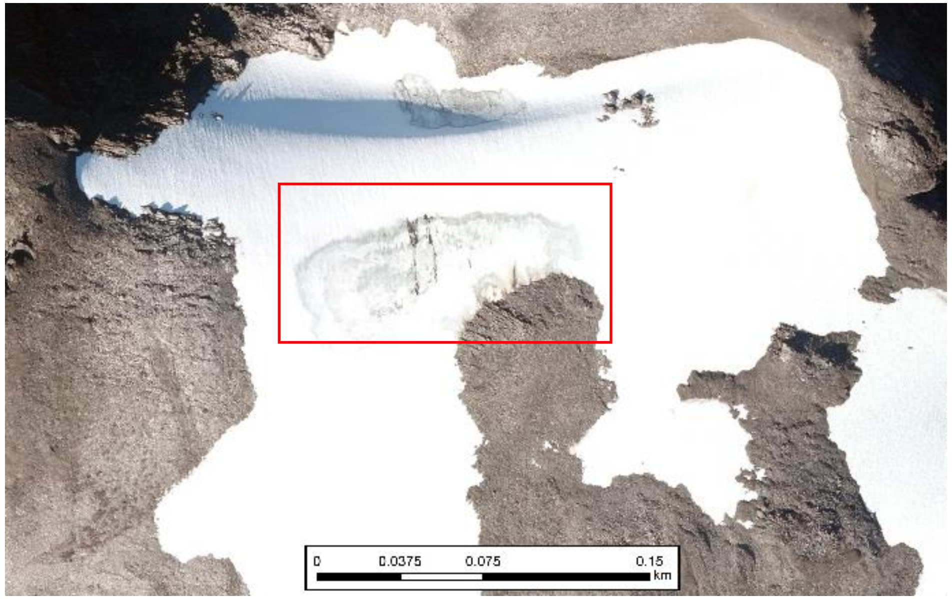
The clearest evidence of flowing ice is a set of crevasses, or deformation of banding lines and so each of these is awarded 5 points.

The “Glacier Identification Scoring System”

Feature	Score	Description	Example
Multiple debris bands in ice	3	Parallel stripes of alternating darker/lighter ice observed on the surface of small glaciers resulting from stratification of supraglacial debris in ice.	

Un-deformed parallel banding, from stratification of debris-rich versus debris-poor ice, indicates persistence and probably flow and receives 3 points, as does exposed uniform ice.

The “Glacier Identification Scoring System”

Feature	Score	Description	Example
Ice	3	Visible as areas of grey/blue compared to white for nearby snow.	

Un-deformed parallel banding, from stratification of debris-rich versus debris-poor ice, indicates persistence and probably flow and receives 3 points, as does exposed uniform ice.

The "Glacier Identification Scoring System"

Feature	Score	Description	Example
Bergschrund	2	A crevasse at the head of a glacier or snowpatch adjacent to a rock wall	

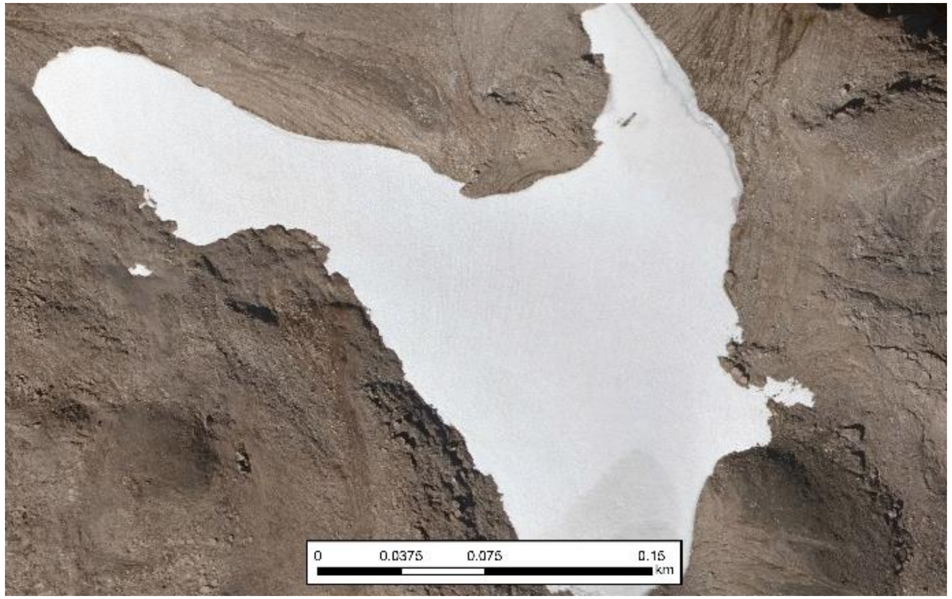
A bergschrund is a single crevasse indicating consolidation or movement away from a headwall, so it does not rate as highly as a set of crevasses and is given 2 points.

The "Glacier Identification Scoring System"

Feature	Score	Description	Example
Moraine/s	1	Moraines formed in front of potential glacier units and within the vegetation trimline	

A moraine indicates that a glacier has been present and may or may not have survived, so it is ancillary evidence and awarded only a single point.

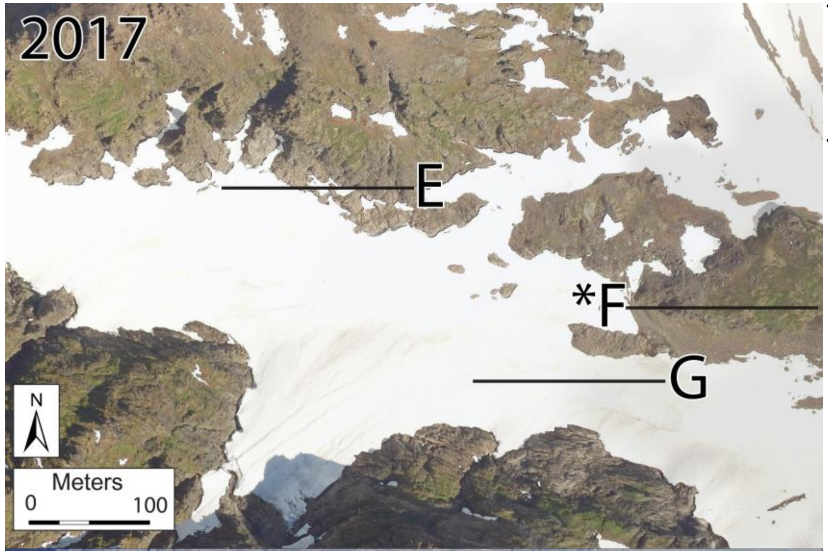
The “Glacier Identification Scoring System”

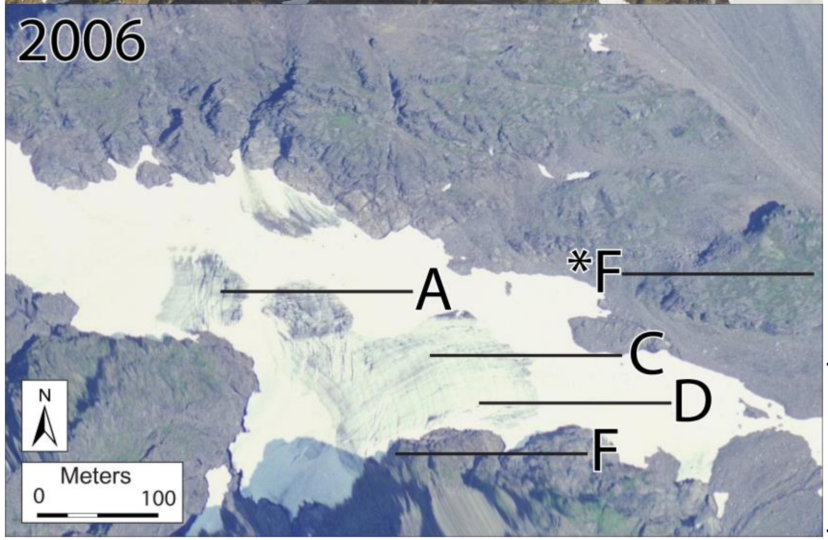
Feature	Score	Description	Example
Unbroken snow accumulation	1	Patches of unbroken white snow appearing convex and/or orientated downslope	

Late-summer snow is a normal companion of glacier presence, but this might also be a snowpatch without flowing glacier ice. Snow, therefore, is given a single point.

Implementing the "Scoring System"

A glacier not mapped in the Inventory of Norwegian Glaciers (Andreassen et al., 2012)



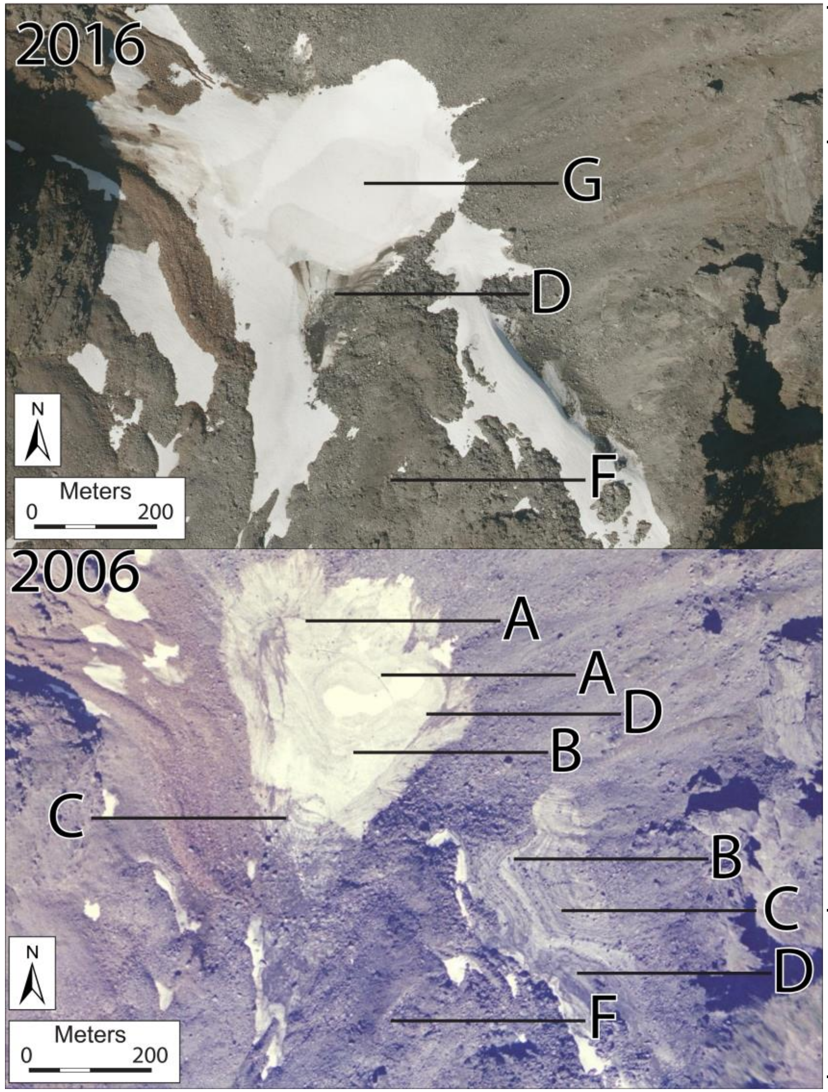


	Feature	Presence (Y or N; Image date)	Score
A	Crevasses	Y (2006)	5
B	Flow features and deformed stratification	N	0
C	Multiple debris bands in ice	Y (2006)	3
D	Ice	Y (2006)	3
E	Bergschrund	Y (2017)	2
*F	Moraine/s	Y (2016/17)	1
G	Unbroken snow accumulation	Y (2017)	1
	Total score / Classification		**15 / *Certain* glacier**
	Size in 2018 (Leigh et al., in press)		**0.03 km^2**

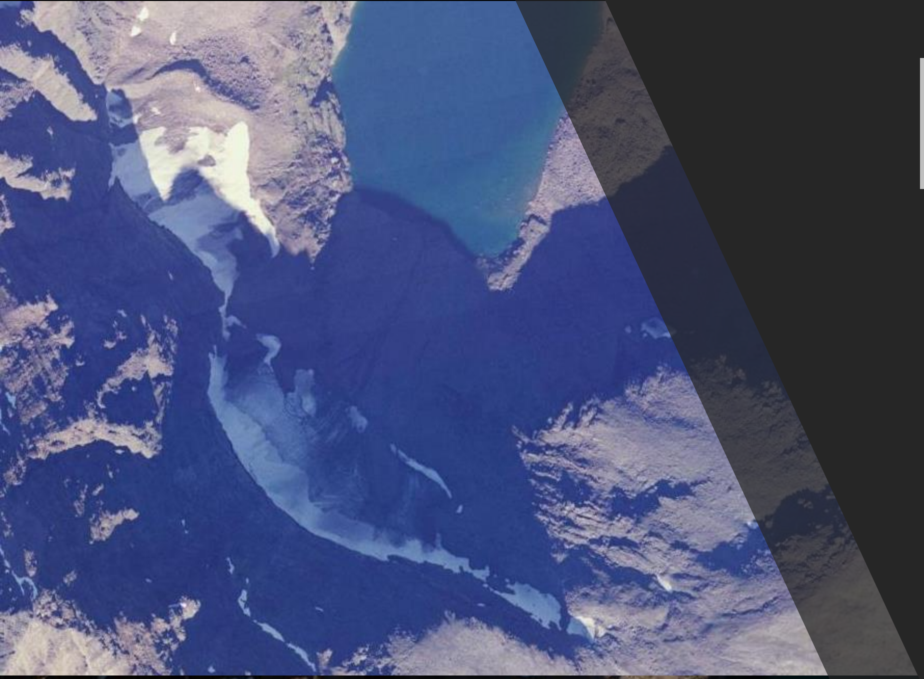
*moraine just out of frame

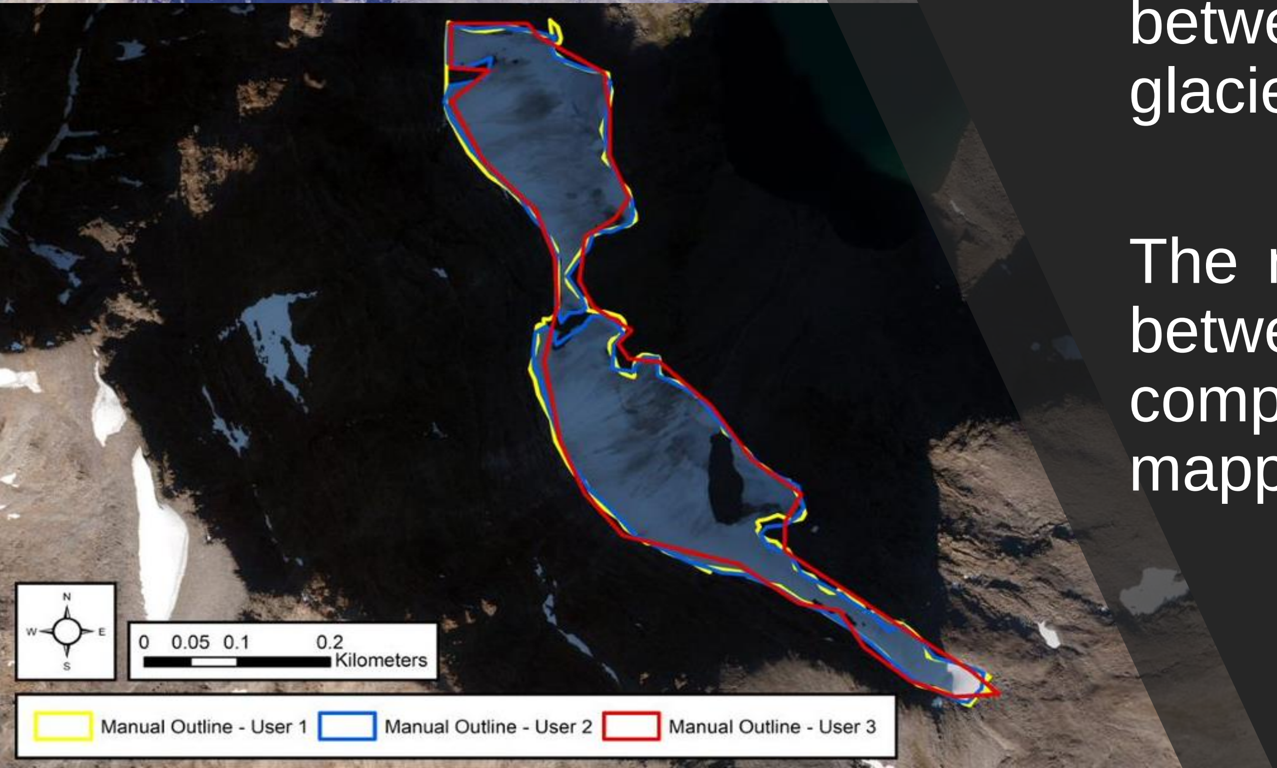
Implementing the "Scoring System"

A glacier not mapped in the Inventory of Norwegian Glaciers (Andreassen et al., 2012)



	Feature	Presence (Y or N; Image date)	Score
A	Crevasses	Y (2006)	5
B	Flow features and deformed stratification	Y (2006)	5
C	Multiple debris bands in ice	Y (2006)	3
D	Ice	Y (2006/16)	3
E	Bergschrund	N	0
F	Moraine/s	Y (2016/16)	1
G	Unbroken snow accumulation	Y (2016)	1
	Total score / Classification		**18 / *Certain* glacier**
	Size in 2018 (Leigh et al., in press)		**0.05km^2**





Summary

To test our scoring system, we conducted a mapping assessment following the criteria laid out in the previous slides.

Application of the scoring system reduced between-user differences in the total number of glaciers mapped by up to ~80%

The maximum difference in mean glacier size between users also decreased by ~45% compared to the difference when glaciers were mapped without guidance.

Conclusions

Our scoring system allows users to rank units according to specific features and classify glaciers with degrees of certainty, providing a more objective, repeatable and consistent approach to glacier mapping.

We, therefore, believe our scoring system provides a useful framework to reduce uncertainties in the next generation of glacier inventories using high-resolution imagery.

We do, however, note that due to issues regarding image resolution on imagery with 30-10 m pixel resolution a minimum size class threshold of 0.01 km^2 is still advisable.

References

Andreassen LM, Winsvold SH, Paul F and Hausberg JE (2012b) Inventory of Norwegian glaciers. In Andreassen LM and Winsvold SH ed. Inventory of Norwegian Glaciers. Norwegian Water Resources and Energy Directorate, Oslo, pp. 1–236.

Bajracharya SR, Maharjan SB, Shrestha F and Shrestha B (2011) Data col- lection and glacier mapping methodology. In Bajracharya SR and Shrestha BR (eds), The Status of Glaciers in the Hindu Kush-Himalayan Region. Kathmandu: International Centre for Integrated Mountain Development, pp. 7–13.

Barcaza G and 7 others (2017) Glacier inventory and recent glacier variations in the Andes of Chile, South America. *Annals of Glaciology* **58**(75), 1–15. doi: 10.1017/aog.2017.28.

Bhambri R, Bolch T and Chaujar RK (2011) Mapping of debris-covered gla- ciers in the Garhwal Himalayas using ASTER DEMs and thermal data. *International Journal of Remote Sensing* **32**(23), 8095–8119. doi: 10.1080/ 01431161.2010.532821.

Bolch T, Menounos B and Wheate R (2010) Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing of Environment* **114** (1), 127–137. doi: 10.1016/j.rse.2009.08.015.

DeBeer CM and Sharp MJ (2009) Topographic influences on recent changes of very small glaciers in the Monashee Mountains, British Columbia, Canada. *Journal of Glaciology* **55**(192), 691–700. doi: 10.3189/ 002214309789470851.

Frey H, Paul F and Strozzi T (2012) Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges, and results. *Remote Sensing of Environment* **124**, 832–843. doi: 10.1016/j.rse.2012.06. 020.

Ganyushkin DA and 5 others (2017) Present glaciers and their dynamics in the arid parts of the Altai Mountains. *Geosciences* **7**(4), 117. doi: 10.3390/ geosciences7040117.

IPCC (2013) Climate Change 2013, The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: WMO/UNEP, Cambridge University Press. doi: 10.1017/CBO9781107415324.

Kamp U, Byrne M and Bolch T (2011) Glacier fluctuations between 1975 and 2008 in the Greater Himalaya Range of Zanskar, southern Ladakh. *Journal of Mountain Science* **8**(3), 374–389. doi: 10.1007/s11629-011-2007-9.

Leigh JR., Stokes CR., Evans DJA., Carr JR., Andreassen LM. (in press) Timing of ‘Little Ice Age’ maxima and subsequent glacier retreat in northern Troms and western Finnmark, northern Norway, *Arctic Antarctic and Alpine Research*

Narama C, Kääb A, Duishonakunov M and Abdrakhmatov K (2010) Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (∼1970), Landsat (∼2000), and ALOS (∼2007) satellite data. *Global and Planetary Change* **71**(1–2), 42–54. doi: 10.1016/j.gloplacha.2009.08.002.

Paul F, Frey H and Bris RL (2011) A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results. *Annals of Glaciology* **52**(59), 144–152. doi: 10.3189/172756411799096295.

Parkes D and Marzeion B (2018) Twentieth-century contribution to sea-level rise from uncharted glaciers. *Nature* **563**(7732), 551–554. doi: 10.1038/s41586-018-0687-9.

Rastner P and 5 others (2012) The first complete inventory of the local glaciers and ice caps on Greenland. *Cryosphere* **6**(6), 1483–1495. doi: 10.5194/ tc-6-1483-2012.

Tielidze, L.G., Bolch, T., Wheate, R.D., Kutuzov, S.S., Lavrentiev, I.I. and Zemp, M., 2020. Supra-glacial debris cover changes in the Greater Caucasus from 1986 to 2014. *The Cryosphere **14**, 585–598. doi: 10.5194/tc-14-585-2020*