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Optymalizacja przetwarzania zdjęć z bezzałogowych statków powietrznych na potrzeby analizy dynamiki rzeźby terenu w badaniach z zakresu geomorfologii glacjalnej

Optimization of the processing of images from unmanned aerial vehicles for the analysis of land surface dynamics in glacial geomorphology

Rozprawa doktorska napisana pod kierunkiem:
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Spis treści

Podziękowania

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Streszczenie

Niniejsza rozprawa doktorska łączy tematykę wykorzystania bezzałogowych statków powietrznych w badaniach z zakresu geomorfologii glacjalnej z problematyką efektywnego przetwarzania wysokorozdzielczych obrazów w oprogramowaniu fotogrametrycznym. Przeprowadzona kwerenda literatury wskazała istotne luki dotyczące opisu metodologii przetwarzania zdjęć w wielu publikacjach naukowych dotyczących zastosowania cyfrowych modeli wysokościowych i ortomozaik w geomorfologii glacjalnej. Błędy bądź niewiedza na tym etapie mogą mieć duże znaczenie dla dokładności produktów fotogrametrycznych, a w konsekwencji dla wyników dalszych analiz i interpretacji geomorfologicznych. Aby uzupełnić wskazaną lukę, w ramach pracy doktorskiej, przeprowadzono eksperymenty z wykorzystaniem oprogramowania Agisoft Metashape, mające na celu opracowaniu optymalnych schematów postępowania i doboru ustawień zależnie od oczekiwanych efektów: skrócenia czasu obliczeń lub uzyskania możliwie najmniejszych błędów cyfrowych modeli wysokościowych. Efektem prac były trzy skrypty w języku Python, które w znaczący sposób ułatwiają pracę w oprogramowaniu, jak i wspomagają efektywne zarządzanie wieloma projektami jednocześnie, np. przy użyciu wielowątkowego klastra obliczeniowego. Ostatnią częścią rozprawy było wykorzystanie wiedzy z przeglądu literatury wraz z opracowanymi skryptami do analizy dynamiki rzeźby terenu przedpola lodowca Kvíár na Islandii. Kwantyfikacji zmian form terenu dokonano na podstawie zdjęć pozyskanych z bezzałogowych statków powietrznych w latach 2014–2022. Zrealizowane badania potwierdziły użyteczność opracowanych skryptów do pracy z rozbudowanym zbiorem danych, udokumentowały wysoką dynamikę form na przedpolu lodowca związaną przede wszystkim z wytapianiem trzonów lodowych oraz wskazały pewne ograniczenia metody Structure-from-Motion. Całość pracy stanowi ważny wkład w rozwój metodologii przetwarzania obrazów z bezzałogowych statków powietrznych w badaniach z zakresu geomorfologii glacjalnej, a opracowane skrypty mogą być przydatne dla innych naukowców pracujących z podobnymi danymi.

Słowa kluczowe: Structure-from-Motion, bezzałogowy statek powietrzny, geomorfologia glacjalna, detekcja zmian, fotogrametria, Agisoft Metashape

Abstract

This doctoral dissertation integrates the application of unmanned aerial vehicles in glacial geomorphology with the challenges of efficient processing of high-resolution images in photogrammetric software. The literature review revealed significant gaps in describing image processing methodologies in numerous scientific publications related to the application of digital elevation models and orthomosaics in glacial geomorphology. Errors or lack of knowledge at this stage can have a considerable impact on the accuracy of photogrammetric products and, consequently, on the results of further geomorphological analyses and interpretations. As part of the doctoral research, to address this identified gap, experiments were conducted using Agisoft Metashape software. The aim was to develop optimal procedures and settings depending on the desired outcomes: either reducing computation time or achieving minimal errors in digital elevation models. The outcome of these efforts resulted in three Python scripts, significantly facilitating work within the software, and supporting effective management of multiple projects simultaneously, for example, through using of multi-threaded computing clusters. The final part of the dissertation involved applying the knowledge from the literature review along with the developed scripts to analyze the dynamics of the terrain in front of the Kvíár glacier in Iceland. Quantification of changes in landforms was carried out based on images acquired from unmanned aerial vehicles between 2014 and 2022. The conducted research confirmed the usefulness of the developed scripts for working with extensive datasets, documented high dynamics of landforms in front of the glacier primarily associated with the degradation of ice cores, and indicated certain limitations of the Structure-from-Motion method. The entire work constitutes a significant contribution to the development of image processing methodologies in glacial geomorphology research, and the developed scripts may be valuable for other researchers working with similar data.

Keywords: Structure-from-Motion, unmanned aerial vehicle, glacial geomorphology, change detection, photogrammetry, Agisoft Metashape

Publikacje wchodzące w skład rozprawy doktorskiej

Rozprawa doktorska składa się z trzech artykułów naukowych stanowiących spójny tematycznie zbiór publikacji, które w tekście oznaczono cyframi rzymskimi. Wskaźniki bibliometryczne oraz liczba cytowań była aktualna na dzień 8 lutego 2024 r.

I. Śledź, S., Ewertowski, M. W., & Piekarczyk, J. (2021). Applications of unmanned aerial vehicle (UAV) surveys and Structure from Motion photogrammetry in glacial and periglacial geomorphology. *Geomorphology*, *378*. https://doi.org/10.1016/j.geomorph.2021.107620

Q2 Web of Science; 93 percentyl Scopus (2021); IF2021 = 4.139; MEiN$_{2021}$ = 100 pkt

Liczba cytowań: Google Scholar: 75; Scopus: 56; Web of Science: 50

II. Śledź, S., & Ewertowski, M. W. (2022). Evaluation of the Influence of Processing Parameters in Structure-from-Motion Software on the Quality of Digital Elevation Models and Orthomosaics in the Context of Studies on Earth Surface Dynamics. *Remote Sensing*, *14*(6). https://doi.org/10.3390/rs14061312

Q1 Web of Science; 90 percentyl Scopus (2022); IF2022 = 5.349; MEiN$_{2022}$ = 100 pkt

Liczba cytowań: Google Scholar: 10; Scopus: 9; Web of Science: 7

III. Śledź, S., Ewertowski, M. W., & Evans, D. J. A. (2023). Quantification of short-term transformations of proglacial landforms in a temperate, debris-charged glacial landsystem, Kvíárjökull, Iceland. *Land Degradation & Development*, *34*(17), 5566-5590. https://doi.org/10.1002/ldr.4865

Q2 Web of Science; 91 percentyl Scopus (2022); IF2022 = 4.377; MEiN$_{2023}$ = 200 pkt

Liczba cytowań: Google Scholar: 0; Scopus: 0; Web of Science: 0

1. Wstęp

Bezzałogowy statek powietrzy (BSP), w literaturze definiowany jako ang. *Unmanned Aerial Systems* (UAS), *Unmanned/Uncrewed/Unoccupied Aerial Vehicle* (UAV), *aerial robot* lub popularnie *drone* (Colomina i Molina, 2014), jest przykładem narzędzia, które jako platforma do montażu wybranego sensora, umożliwia operatorowi zdalne zbieranie danych o punktowych lub obszarowych obiektach badawczych bez bezpośredniego kontaktu z nimi. Dzięki możliwości konfiguracji i wysokiej mobilności, znajduje on obecnie szerokie zastosowanie w różnych dziedzinach badań środowiskowych, w tym w geomorfologii (Westoby i in., 2012), hydrologii (Carrivick i Smith, 2019), glacjologii (Bhardwaj i in., 2016) czy rolnictwie precyzyjnym (Anderson i Gaston, 2013). Zdjęcia wykonywane z pułapu BSP są konkurencyjną alternatywą, zarówno dla wysokorozdzielczych zobrazowań satelitarnych, jak i tradycyjnych lotniczych nalotów fotogrametrycznych (Manfreda i in., 2018). Zastosowanie BSP oferuje lepszą elastyczność czasową oraz wyższą rozdzielczość przestrzenną zdjęć (nawet rzędu kilku milimetrów) przy niskim koszcie nabycia (poniżej 10 000,00 PLN), do którego jednak należy doliczyć koszty szkolenia operatora oraz jego pobytu w terenie.

Zdjęcia pozyskane przy pomocy BSP przetwarzane są najczęściej w oprogramowaniu fotogrametrycznym, gdzie wykorzystuje się metodę Structure-from-Motion (SfM) do łączenia zdjęć wykonanych pod różnym kątem i z różnej odległości (Westoby i in., 2012). Algorytm SfM łączy je ze sobą na podstawie punktów charakterystycznych, wyznaczonych przynajmniej na dwóch zdjęciach. W efekcie otrzymuje się najpierw rzadką chmurę punktów (ang. *sparse point cloud*), a w kolejnym kroku gęstą chmurę punktów (ang. *dense point cloud*), która jest podstawą do wygenerowania końcowych opracowań fotogrametrycznych: ortomozaiki oraz cyfrowego modelu wysokościowego (DEM – ang. *Digital Elevation Model*), będącego trójwymiarowym odwzorowaniem powierzchni badanego obszaru (Agisoft, 2022). Wymienione opracowania są powszechnie stosowane do kartowania geomorfologicznego (Allaart i in., 2018; Dąbski i in., 2020; Ewertowski i Tomczyk, 2020; Storrar i in., 2019), analizy zmian objętości form glacjalnych (Chandler i in., 2020a; Fugazza i in., 2018; Tomczyk i in., 2020; Whitehead i in., 2013), badania procesów morfogenetycznych (Chandler i in., 2020b) czy badań sedymentologicznych (Kociuba, 2017; Westoby i in., 2015). Kosztowniejszą alternatywą dla metody SfM jest LIDAR (ang. *Light Detection and Ranging*), gdzie wynikiem pomiaru laserowego jest chmura punktów, którą również wykorzystuje się do opracowania cyfrowego modelu wysokościowego (Mosbrucker i in., 2017).

W badaniach z zakresu geomorfologii glacjalnej cyfrowy model wysokościowy oraz ortomozaika stanowią bardzo dobre uzupełnienie tradycyjnych pomiarów terenowych (Śledź i in., 2023). BSP i metoda SfM są szczególnie użyteczne w badaniach dynamiki rzeźby terenu, w których kładzie się nacisk na regularne pomiary w celu ilościowego ujęcia zachodzących zmian (Chandler i in., 2020a; Westoby i in., 2020). Od 2014 roku można zaobserwować zauważalny wzrost liczby publikacji z wykorzystaniem BSP i metody SfM w badaniach geomorfologicznych (Bhardwaj i in., 2016; Gaffey i Bhardwaj, 2020; Śledź i in., 2021), jednak wcześniej nie podjęto próby ich usystematyzowania pod kątem użytego sprzętu, technologii i techniki wykonywania zdjęć. Metodyka badań w terenie, jak i wytyczne dla prezentacji wyników są dobrze poznane i opisane w literaturze (Carbonneau i Dietrich, 2017; Ewertowski i in., 2019; James i in., 2019), jednak brakuje publikacji szczegółowo i krytycznie opisujących poszczególne etapy przetwarzania zdjęć w oprogramowaniu fotogrametrycznym wykorzystującym metodę SfM (de Haas i in., 2021; Hendrickx i in., 2018; Nota i in., 2022; Śledź i Ewertowski, 2022). Brakuje ponadto artykułów prezentujących narzędzia usprawniające pracę z dużymi zbiorami danych (np. zdjęć pochodzących z cyklicznych pomiarów tego samego obiektu badań) i ułatwiających wybór optymalnych procedur (Śledź i Ewertowski, 2022), co w połączeniu z rosnącą szczegółowością i ilością danych obrazowych pozyskiwanych z BSP staje się coraz bardziej istotnym zagadnieniem metodycznym.

W niniejszej pracy skoncentrowano się na określeniu optymalnych warunków wykorzystania metody SfM do przetwarzania zdjęć pozyskiwanych z niskiego pułapu lotniczego na potrzeby analiz geomorfologicznych. Celem rozprawy doktorskiej było:

1) rozpoznanie luk w aktualnym stanie wiedzy dotyczących wykorzystania BSP w badaniach geomorfologicznych i przetwarzania zdjęć w oprogramowaniu fotogrametrycznym metodą SfM;

2) przetestowanie wpływu parametrów przetwarzania zdjęć metodą SfM na dokładność uzyskiwanych opracowań fotogrametrycznych;

3) zaproponowanie możliwości optymalizacji przetwarzania zdjęć z BSP metodą SfM dzięki automatyzacji opartej na skryptach;

4) przetestowanie zaproponowanych rozwiązań na przykładzie analizy dynamiki rzeźby terenu na przedpolu lodowca Kvíár na Islandii.

W rozprawie doktorskiej autor prezentuje wyniki przeprowadzonej kwerendy literatury i wykonanych badań, które mają na celu uzupełnienie wymienionych luk w dotychczasowym stanie wiedzy. W kolejnych rozdziałach przedstawiono zarys treści publikacji wchodzących

w skład rozprawy, syntetycznie opisując ich problematykę, użyte metody badawcze oraz otrzymane wyniki. W podsumowaniu przedstawiono wkład rozprawy w aktualny stan wiedzy oraz wskazano nowe problemy naukowe wymagające dalszych badań. Na koniec, wraz z publikacjami i załącznikami, dołączono oświadczenia wszystkich autorów o swoim wkładzie w ich powstanie.

2. Zarys treści publikacji

2.1. Publikacja nr I

Celem artykułu nr I był przegląd dotychczasowych badań, w których BSP i metodę SfM wykorzystano w geomorfologii glacjalnej. W pierwszym kroku, zebraną literaturę uporządkowano pod kątem zastosowania danych obrazowych z BSP, wyznaczając cztery typy badań: kartowanie geomorfologiczne (ang. *geomorphological mapping*), analiza dynamiki rzeźby terenu (ang. *change detection*), badania nad procesami morfogenetycznymi (ang. *process-form studies*) oraz badania osadów powierzchniowych (ang. *assessment of surficial geology*). Przeanalizowano również sposób pozyskiwania danych, wykorzystany sprzęt oraz obszary badawcze. Dodatkowo, wskazano potencjalne przyszłe kierunki badań, dzięki którym możliwe będzie np. jeszcze lepsze zrozumienie zmian zachodzących na przedpolach lodowców w reakcji na globalne ocieplenie.

Przeanalizowano łącznie 62 publikacje z lat 2013–2020, opublikowane w czasopismach indeksowanych w JRC (ang. *Jurnal Citations Reports*). Pierwszym wynikiem przeprowadzonej kwerendy literatury była informacja o lokalizacji badań – przeważały prace przedstawiające wyniki badań prowadzonych w Arktyce (30 artykułów), w szczególności na Spitsbergenie (13 artykułów), Grenlandii (7 artykułów) oraz Islandii (6 artykułów). Drugim często badanym regionem były Alpy (15 artykułów, z których 3 dotyczyły lodowca Forni). Szczegóły, w tym graficzna prezentacja regionów badań, zostały przedstawione na rycinie nr 1 oraz w tabeli nr 1 (publikacja nr I). Drugim zagadnieniem poruszonym w artykule był udział poszczególnych typów badań. Zestawienie zdominowały publikacje, w liczbie 60, dotyczące kartowania geomorfologicznego oraz analizy dynamiki rzeźby terenu. Uzupełnienie stanowiły pojedyncze artykuły z zakresu badań nad procesami morfogenetycznymi oraz badań osadów powierzchniowych (publikacja nr I, Fig. 2). Warto zwrócić uwagę na rosnącą liczbę publikacji w kolejnych latach, z wyjątkiem lat 2017 i 2019. Ze względu na fakt, iż większość prac dotyczyła kartowania pojedynczych form polodowcwcych lub zmian ich powierzchni, obszar badań rzadko przekraczał 1 km^2. Z metodycznego punktu widzenia istotne były informacje dotyczące wykorzystanego typu BSP: wielowirnikowca (ang. *multirotor*) lub płatowca

(ang. *wing*). Charakterystyczne dla ogólnych tendencji było częstsze użycie płatowców w początkowym okresie analizy (lata 2013–2015), co w kolejnych latach zmieniło się na rzecz wielowirnikowców. Odnotowano również zastosowanie w badaniach platform hybrydowych, konstrukcyjnie łączących oba wcześniej wspomniane typy BSP. W 51 publikacjach autorzy zadeklarowali wykorzystanie oprogramowania firmy Agisoft LLC. W kolejnych podpunktach artykułu opisano zastosowane sensory, otrzymaną rozdzielczość przestrzenną produktów fotogrametrycznych, charakterystykę i ustawienia dotyczące nalotów oraz napotykane problemy techniczne związane z odbywaniem misji. Szczegóły dotyczące badań opisanych we wszystkich analizowanych publikacjach zebrano w formie bazy danych jako suplement do artykułu (publikacja nr I, Appendix A.) w formacie Excel, oraz dodatkowo w formatach kml i shp w celu ułatwienia przetwarzania zbioru w oprogramowaniu GIS.

Dodatkowo, wskazano proponowane przez różnych badaczy schematy postępowania związanego z przetwarzaniem zdjęć metodą SfM oraz poruszono problematykę organizacji nalotów fotogrametrycznych, fotopunktów czy rekomendacji dot. publikowania wyników badań z użyciem BSP i metody SfM. Z kolei w ostatniej części publikacji zasygnalizowano potencjalną problematykę przyszłych badań: studia związane z procesami geomorfologicznymi, łączenie fotogrametrii lotniczej z naziemną czy użycie metody SfM do przetwarzania archiwalnych zdjęć lotniczych. Publikacja nr I to pierwszy tak kompleksowy artykuł przeglądowy dla zastosowań BSP w geomorfologii glacjalnej.

2.2.   Publikacja nr II

Wyniki przeprowadzonej kwerendy literatury zwróciły uwagę autorów na znikomą liczbę publikacji opisujących poszczególne etapy przetwarzania zdjęć w oprogramowaniu fotogrametrycznym. Wcześniejsze doświadczenia autorów sugerowały jednak, że ustawienia poszczególnych parametrów przetwarzania i właściwe zarządzanie pozyskanymi danymi mają istotne znaczenie dla dokładności modeli wysokościowych i ortomozaik, a co za tym idzie wiarygodności późniejszych pomiarów. W związku z tym, w kolejnym artykule opublikowanym w otwartym dostępie postawiono za cel poznanie wpływu poszczególnych parametrów obliczeniowych w oprogramowaniu Agisoft Metashape na dokładność dwóch produktów fotogrametrycznych: cyfrowego modelu wysokościowego oraz ortomozaiki. W pierwszej kolejności sformułowano 375 różnych schematów postępowania w oprogramowaniu, które następnie sprawdzono przy przetwarzaniu tego samego zbioru zdjęć przedstawiającego przykładowy obszar proglacjalny. Dodatkowo, praktycznym celem badań było wytypowanie trzech schematów postępowania: (a) o najkrótszym czasie obliczeń;

(b) optymalnego, będącego kompromisem między dokładnością a czasem obliczeń; (c) możliwie najdokładniejszego, bez względu na czas obliczeń. Wybór oprogramowania Agisoft Metashape do przeprowadzenia analiz związany jest z jego wysoką popularnością, która została udokumentowana w wynikach publikacji nr I.

W eksperymencie przetwarzano zbiór 82 zdjęć przedstawiających zróżnicowaną rzeźbę terenu obszaru proglacjalnego lodowca Breiðamerkur, Islandia (publikacja nr II, Fig. 1). Naloty przeprowadzono we wrześniu 2021 roku w trybie autonomicznym przy użyciu BSP marki DJI Phatnom 4 Pro. Dla zapewnienia poprawnej georeferencji modelu, założono i wykorzystano w modelowaniu 40 fotopunktów (GCPs – ang. *Ground Control Points*), ustawionych w 4 rzędach po 10 punktów, oddalonych względem siebie o 15 metrów pod kątem 90º. Dodatkowo, w celu sprawdzenia dokładności cyfrowych modeli wysokościowych, założono losowo zlokalizowanych 30 punktów kontrolnych (CPs – ang. *Control Points*), których nie wykorzystano w georeferencji (publikacja nr II, Fig. 4). Pomiaru współrzędnych oraz tyczenia punktów dokonano przy pomocy odbiornika GNSS. Przetwarzanie fotogrametryczne zdjęć przeprowadzono przy użyciu stacji roboczej, której podczas obliczeń nie przydzielano innych zadań, by zachować jednakową moc obliczeniową dla wszystkich projektów.

Przyjęto, że ocenie wpływu na końcową dokładność produktów fotogrametrycznych i czas obliczeń zostaną poddane następujące etapy przetwarzania: (a) szczegółowość procesu łączenia zdjęć; (b) limit punktów charakterystycznych (*key points*) oraz punktów wiążących (*tie points*); (c) szczegółowość procesu generowania gęstej chmury punktów; (d) dobór parametrów optymalizacyjnych. Ostatnim etapem badań było sprawdzenie każdego cyfrowego modelu wysokościowego pod kątem dokładności wysokości, wykorzystując narzędzie Extract Values to Points i współrzędne punktów kontrolnych, by następnie obliczyć odchylenie standardowe (SD – ang. *Standard deviation*) i średnią kwadratową błędu (RMSE – ang. *Root Mean Square Error*). Wyniki eksperymentu dla każdego przyjętego schematu postępowania zamieszczono w suplemencie do artykułu w formie tabeli Excel (publikacja nr II, Appendix S1) i histogramów z rozkładem różnic wysokości między punktami kontrolnymi a cyfrowym modelem wysokościowym (publikacja nr II, Appendix S2).

Spośród 375 testowych schematów postepowania, w 195 nie udało się wygenerować produktów fotogrametrycznych. W 75 nieudanych przypadkach, przy niskiej dokładności generowania punktów wiążących, rzadka chmura punktów okazała się zbyt mało liczna do wygenerowania gęstej chmury punktów. To sugeruje, iż najniższy poziom dokładności generowania rzadkiej chmury punktów jest niewystarczający do obliczenia cyfrowych modeli wysokościowych oraz ortomozaik. Z kolei pozostałe 120 nieudane schematy nie zostały

zoptymalizowane przed wygenerowaniem gęstej chmury punktów parametrami optymalizacyjnymi k1 oraz k2, korygującymi dystorsję radialną zdjęć. Zdaniem autorów, taki stan rzeczy jest spowodowany wysoką dystorsją radialną obiektywu sensora DJI FC6310, z którego zdjęcia należy każdorazowo pod tym kątem korygować. Otrzymane wyniki użyto do krytycznej oceny każdego z badanych etapów przetwarzania w kontekście dokładności otrzymywanych cyfrowych modeli wysokościowych, jak i czasu obliczeń.

Wynikiem przeprowadzonych prac są trzy schematy postępowania: „najszybsze" (*The fastest*); „optymalne" (*Optimal*); „z najwyższą dokładnością" (*Best quality*). Ustawienia w wymienionych schematach wykorzystano do napisania trzech skryptów w języku Python do oprogramowania Agisoft Metashape, które w znaczący sposób ułatwiają pracę i automatyzują wiele procesów. „Najszybszy" skrypt (publikacja nr II, Appendix S3) może być użyty jeszcze w terenie, po odbytym nalocie i eksporcie zdjęć z BSP do mobilnej stacji roboczej, np. w celu obliczenia rzadkiej chmury punktów i sprawdzenia jej jednorodności, rozkładu punktów i stopnia pokrycia badanego obszaru. Skrypty „optymalny" i „najwyższa jakość" (publikacja nr II, Appendix S4 i S5) mają za zadanie ułatwić przetwarzanie zdjęć po zakończonej pracy terenowej, zależnie od preferencji użytkownika: otrzymanie najniższych możliwych wartości RMSE i SD (skrypt „najwyższa jakość") lub osiągnięcie kompromisu między dokładnością cyfrowego modelu wysokościowego a czasem obliczeń (skrypt „optymalny").

2.3. Publikacja nr III

Do sprawdzenia użyteczności i powtarzalności opracowanych skryptów, wykorzystano jeden z nich do badań z zakresu analizy dynamiki rzeźby terenu (*change detection*). Celem tego artykułu opublikowanego w otwartym dostępie było zilustrowanie i kwantyfikacja krótkookresowej ewolucji form polodowcowych na przedpolu lodowca Kvíár, Islandia, w oparciu o zbiory zdjęć z BSP z lat 2014, 2016, 2021 i 2022 (publikacja nr III, Fig. 1, 3). Teren ten został wybrany do badań, ponieważ jest bardzo interesującym przykładem krajobrazu utworzonego na skutek kilkukrotnego nasuwania się i stagnacji jęzora lodowcowego bogatego w materiał mineralny (ang. *incremental stagnation*) (Bennett i Evans, 2012; Bennett i in., 2010). Badane przedpole składa się z kompleksów moren, teras kemowych i sandrów, zarówno stabilnych, jak i takich, które są intensywnie przekształcane przez degradację trzonów lodowych i działalność wód roztopowych. Ilościowy model rozwoju takiego krajobrazu nie został wcześniej przedstawiony w literaturze, a jest ważny w kontekście interpretacji paleoglacjologicznych.

Naloty wykonywano dwoma typami BSP: płatowcem (producent SmartPlane) oraz wielowirnikowcami kilku generacji z serii Phantom (producent DJI) (publikacja nr III, Tabela nr 1). Podczas nalotów w 2022 roku, realizowanych przy pomocy wielowirnikowca DJI Phantom 4 RTK, założono lokalną stację referencyjną GNSS w celu zwiększenia dokładności pomiaru współrzędnych środka rzutów zdjęć przy pomocy precyzyjnej techniki pomiaru RTK (ang. *Real Time Kinematic*). Do korekty współrzędnych i zastosowania poprawek PPP (ang. *Precise Point Positioning*) dla zdjęć i fotopunktów użyto oprogramowania Topcon Link oraz RTKLIB, wraz z oszacowaniem wpływu pływów morskich na pomiar. Cyfrowe modele wysokościowe i ortomozaiki opracowano w oprogramowaniu Agisoft Metashape. Ze względu na fakt, iż w 2022 roku dysponowano BSP z odbiornikiem RTK, skorzystano z jednego ze schematów przetwarzania zbiorów zdjęć zaproponowanych przez Nota i in. (2022) – dopasowano jednocześnie zbiory zdjęć z wszystkich lat (ang. *co-alignment*). Fotopunkty nałożono wyłącznie na zdjęcia z roku 2022. Nie korzystano ze współrzędnych środka rzutów zdjęć z pozostałych zbiorów (2014, 2016 i 2021) jako referencji. Wynikiem takiego postępowania była jedna, wspólna rzadka chmura punktów, która następnie została podzielona na cztery chmury w osobnych projektach według lat 2014, 2016, 2021 i 2022, w których pozostawiono jedynie zdjęcia właściwe dla danego roku. Przetwarzanie zbioru przeprowadzono według parametrów schematu postępowania ze skryptu „optymalnego" (publikacja nr II, Appendix S4). Jedyną modyfikacją w skrypcie była wyższa dokładność generowania rzadkiej chmury punktów ze względu na częściowe wykorzystanie zdjęć w formacie JPG i niezadowalające wyniki na niskim poziomie. Efektem prac były cztery cyfrowe modele wysokościowe, których rozmiar komórki mieścił się w granicach od 0,05 do 0,08 m. Dodatkowo, wyeksportowano cztery wysokorozdzielcze ortomozaiki o rozmiarze komórki wynoszącej średnio 0,03 m.

Na podstawie opracowanych cyfrowych modeli wysokościowych oraz ortomozaik zdefiniowano cztery obszary zainteresowania na przedpolu lodowca (publikacja nr III, Fig. 2). Obszary te różnią się typem osadów, ukształtowaniem oraz dynamiką i skalą zmian powierzchni terenu. Na podstawie kartowania geomorfologicznego zidentyfikowano cztery zespoły form: terasy kemowej (ang. *kame terrace staircase*; *case study 1*), sandru (ang. *outwash plain*; *case study 2*), kompleks pagórków lodowo-morenowych (ang. *ice-cored hummocky moraine complex*; *case study 3*) oraz pokryty lodem, pagórkowaty teren z nieciągłymi, krętymi grzbietami (ang. *ice-cored hummocky terrain*; *case study 4*) (publikacja nr III, Fig. 3).

Do oszacowania zmian powierzchni badanych form konieczne było porównanie otrzymanych cyfrowych modeli wysokościowych z różnych terminów. W tym celu,

do obliczenia plików wynikowych, tzn. cyfrowych modeli różnic wysokości (DoDs – ang. *DEMs of Difference*) oraz zmian objętości, wykorzystano oprogramowanie ArcMap i przeznaczoną dla tego oprogramowania wtyczkę do detekcji zmian Geomorphic Change Detection (GCD) (źródło: http://gcd.riverscapes.xyz) (Wheaton i in., 2010). Przed importem cyfrowych modeli wysokościowych do wtyczki dokonano ich przepróbkowania do rozmiaru komórki 0,06 m. Kartowanie badanego obszaru wykonano na podstawie ortomozaik, bezpośrednich badań terenowych i dokumentacji fotograficznej. Dodatkowo, aby sprawdzić, jaki był wpływ dynamiki lodowca na przekształcenia form, wyznaczono położenie czoła lodowca na podstawie serii czasowej (2011–2022) zobrazowań satelitarnych PlanetScope (rozmiar komórki 3,00 m) oraz opracowanych ortomozaik.

Wynikiem badań była dokumentacja zmian czoła lodowca: w latach 2011–2022 zaobserwowano zarówno nasunięcie jak i wycofanie krawędzi lodowca, a jednocześnie zachodziły duże różnice pomiędzy dynamiką północnej i południowej części jęzora lodowcowego (publikacja nr III, Fig. 5). Różnice te interpretowane są odmiennym tempem ablacji (ze względu na zróżnicowanie rozmieszczenia osadów supraglacjalnych) oraz inne źródła zasilania obu części lodowca. Warto również odnotować znaczący rozwój jeziora proglacjalnego od początku okresu obserwacji i jego powiększającą się powierzchnię. Jednak głównym wynikiem badań jest pomiar zmian powierzchniowych i objętościowych zespołów form (*case study 1–4*) przeprowadzony na podstawie DoDs. Ze względu na różnice w zasięgu przeprowadzanych nalotów BSP, pierwszym rokiem analizy był rok 2014 lub 2016. Do DoDs dołączono profile ilustrujące zmiany dla najbardziej charakterystycznych lokalizacji (publikacja nr III, Fig. 6, 7, 8, 10), a średnie zmiany powierzchniowe, objętościowe i pionowe przedstawiono w tabeli nr 2 (publikacja nr III, Tabela nr 2).

Terasy kemowe i sandr (*case study 1 i 2*) okazały się bardzo stabilne na większości swojej powierzchni. Obszarem o największych zmianach i najwyższej aktywności był kompleks pagórków lodowo-morenowych (*case study 3*). Porównując rok 2014 z 2022, różnice odnotowano na 87% powierzchni badanego obszaru (publikacja nr III, Tabela nr 2). Zmiany wysokości tej formy w ciągu niepełna 8 lat osiągnęły nawet 20 m, co można odczytać z profilu K–L (publikacja nr III, Fig. 8). Co istotne, dynamika była wysoka nawet w jednym roku (DoD 2021–2022), gdy wysokość zmieniła się punktowo aż o 5 m. Ostatni analizowany zespół form (*case study 4*) również okazał się aktywny w badanym okresie. Przekształcenia dotyczyły 76% jego powierzchni (DoD 2016–2022), a profile M–N i O–P wykonano w centralnej, najaktywniejszej części moreny, gdzie widać wyraźnie, że różnice w ukształtowaniu oraz

objętości koncentrują się w pobliżu jeziora (publikacja nr III, Fig. 10). W odległości powyżej 130 m od brzegu jeziora rzeźba terenu była stabilna.

W dalszej części artykułu nr III szerzej opisano uzyskane wyniki, wskazując na prawdopodobne procesy odpowiedzialne za ewolucję rzeźby terenu. Przedstawione zostały wyniki obliczeń średnich rocznych zmian objętości (ang. *average annual volume change*) oraz średnie roczne maksymalne miąższości zmian (ang. *average annual maximum thickness change*) (publikacja nr III, Tabela nr 3 i 5, Fig. 11). Ilościowe rezultaty zostały zestawione z danymi z literatury i przeprowadzonych wcześniej badań w celu porównania otrzymanych wyników z krótkookresową i długookresową dynamiką rzeźby terenu na przedpolach kilkunastu innych lodowców. Szczególną uwagę w dyskusji poświęcono kompleksowi pagórków lodowo-morenowych (*case study 3*) oraz przedstawiono historyczną rekonstrukcję zmian lodowca i przekształceń rzeźby terenu na jego przedpolu (publikacja nr III, Fig. 12). Na koniec odnotowano zauważone ograniczenia metody SfM, opisując komplikacje związane z modelowaniem terenu ze zbiornikami wodnymi (publikacja nr III, Fig. 14).

3.   Dyskusja

Z wyników badań wyłania się kilka kluczowych wniosków w kontekście wykorzystania BSP w geomorfologii glacjalnej. Pierwszym z nich jest widoczny wzrost powszechności stosowania BSP. Przegląd literatury wykazał, że jest on mobilnym i elastycznym narzędziem, który stanowi realną, tanią alternatywę dla platform lotniczych i satelitarnych. W niskobudżetowych projektach, polegających na cyklicznych obserwacjach z powietrza stosunkowo niewielkich obszarów (<1 km^2), BSP są trudne do zastąpienia. Producenci BSP oferują coraz to bardziej specjalistyczne konstrukcje stworzone pod konkretne zadania, stąd należy uznać, że obecnie BSP stały się na tyle popularnym narzędziem, iż jego stosowanie w badaniach staje się normą. Ponadto, nowoczesne BSP zostają wyposażone w moduł GNSS RTK, który w połączeniu ze stacją referencyjną pozwala dostarczać zdjęcia z kilkucentymetrowym błędem położenia środka rzutów. Dzięki temu możliwe jest pominięcie procesu zakładania i pomiaru fotopunktów, co zdecydowanie obniża koszty misji i jej czasochłonność. Należy jednak podkreślić, że istotnym ograniczeniem BSP jest jego zasilanie (krótki efektywny czas lotu), jak i podatność na warunki atmosferyczne, co przy wielkoobszarowych obiektach badawczych czy trudnych warunkach meteorologicznych może dyskwalifikować go jako efektywne narzędzie do obrazowania. Dlatego, w niektórych przypadkach tanią alternatywą dla zdjęć z BSP mogą być nawet zdjęcia wykonane z telefonów komórkowych (smartfonów), wyposażonych w nowoczesne kamery, które pozwalają

na dostarczenie wysokorozdzielczych zdjęć wybranych obiektów badawczych (zwłaszcza stromo nachylonych, np. klifów czy wąwozów), zdatnych do szczegółowego modelowania (Fugazza i in., 2018; Tavani i in., 2020). W ocenie autora, w przyszłych badaniach z wykorzystaniem BSP w geomorfologii glacjalnej należy szukać możliwości łączenia danych pozyskanych z BSP z archiwalnymi zdjęciami lotniczymi lub satelitarnymi. Może to zdecydowanie wydłużyć okres obserwacji o kolejne lata wstecz, dzięki czemu w badaniach dotyczących np. procesów geomorfologicznych (Chandler i in., 2020b) będzie można przeprowadzić rekonstrukcje powstawania wybranej formy z większą pewnością.

Wraz ze wzrostem powszechności użycia BSP w badaniach geomorfologicznych rośnie liczba użytkowników oprogramowania fotogrametrycznego, którzy otrzymane zdjęcia przetwarzają w celu opracowania cyfrowego modelu wysokościowego oraz ortomozaiki. Odbywanie nalotu fotogrametrycznego najczęściej poprzedza szkolenie teoretyczne i praktyczne operatora, wraz z egzaminem weryfikacyjnym sprawdzającym jego wiedzę oraz umiejętności. To pozwala mieć pewność, że operator jest merytorycznie przygotowany do planowania i odbywania misji – dostępna literatura szczegółowo opisuje ten etap prac. Wspomniane we wstępie rozprawy braki w wiedzy związane z etapem przetwarzania zdjęć w oprogramowaniu fotogrametrycznym, zidentyfikowane w 2019 roku podczas planowania badań do niniejszej rozprawy, na przestrzeni ostatnich trzech lat są w ocenie autora sukcesywnie uzupełniane (de Haas i in., 2021; Nota i in., 2022; Śledź i Ewertowski, 2022; Wang i in., 2021). Wkładem publikacji nr II w uzupełnienie wiedzy o przetwarzaniu są wyniki dotyczące parametrów optymalizacyjnych i zaproponowane skrypty do efektywniejszej pracy ze zbiorami zdjęć. Zastosowanie skryptów, zamiast ręcznego wybierania właściwych ustawień, będzie szczególnie pomocne podczas jednoczesnego przetwarzania wielu projektów w klastrze obliczeniowym, wpływając pozytywnie na efektywność jego wykorzystania. Ta użyteczność będzie kluczowa dla wieloletnich, cyklicznych analiz tych samych obszarów badawczych (np. przedpoli lodowców), gdyż zapewnia stały i porównywalny schemat postępowania, skróci czas przeznaczany na obliczenia i przygotowywania projektów oraz uwiarygodni porównywanie modeli między sobą, np. w badaniach geomorfologicznych z zakresu analizy zmian objętości. Warto w tym miejscu zwrócić uwagę na czas obliczeń w relacji do wielkości błędów, gdyż zmiana parametrów obliczeniowych w celu opracowania dokładniejszego cyfrowego modelu wysokościowego może okazać się niewspółmierna do czasu obliczeń, a co za tym idzie ponoszonych kosztów pracy stacji roboczej. Skrypty są dostępne za darmo dla każdego zainteresowanego na stronie czasopisma. Obserwując obecne trendy można wnioskować, że w przyszłości badania skoncentrują się na optymalizacji przetwarzania danych

z BSP z wykorzystaniem algorytmów sztucznej inteligencji. W najnowszej literaturze można znaleźć przykłady ich stosowania do generowania chmury punktów i cyfrowego modelu wysokościowego oraz klasyfikacji punktów (Feng i in., 2023; Maiwald i in., 2023).

W publikacji nr III skorzystano z powodzeniem ze skryptu (publikacja II, Appendix S4) do przetwarzania zbioru zdjęć z czterech lat obserwacji (rok 2014, 2016, 2021 i 2022). Skrypt pozwolił na zautomatyzowanie prawie wszystkich etapów obliczeń, pozostawiając użytkownikowi jedynie manualny import zdjęć do oprogramowania i zaznaczenie fotopunktów na zdjęciach. Do tego zwiększył wykorzystanie klastra obliczeniowego, który przy manualnym zarządzaniu po każdym zakończonym etapie obliczeń pozostałby bezczynny do momentu ręcznego uruchomienia kolejnego etapu. Z użyciem skryptu obliczenia wykonują się automatycznie i zgodnie z harmonogramem, wraz z eksportem cyfrowego modelu wysokościowego i ortomozaiki do wybranego formatu, co pozwala użytkownikowi zaoszczędzić czas i daje możliwość przeznaczyć go na inne czynności badawcze. Propozycja Nota i in. (2022) dotycząca schematu przetwarzania danych ze zbiorem zdjęć pozyskanym przy pomocy odbiornika RTK okazała się skuteczna i dała zadowalające wyniki, w efekcie dostarczając właściwie obliczone DoDs. Realizując cele publikacji autorzy zwrócili uwagę na problemy związane z modelowaniem powierzchni wody – jest ona szczególnie ważna na dynamicznie zmieniających się przedpolach lodowców, zawierających znaczne ilości szybko wytapiającego się martwego lodu. W literaturze znane są przykłady udanego modelowania terenów podwodnych na podstawie wyznaczonych punktów znajdujących się pod wodą w płytkich, przezroczystych zbiornikach (Carrivick i Smith, 2019), jednak algorytm i metoda SfM jest nieskuteczna w przypadku zmętnionej wody bądź występowania w niej zawiesiny (Tomczyk i Ewertowski, 2021). Przypadek ten dotyczył jeziora proglacjalnego na analizowanym obszarze, którego powierzchnia wody została początkowo błędnie zrekonstruowana w modelu. Aby ograniczyć wpływ tych artefaktów na dalsze obliczenia, zreklasyfikowano i usunięto mało wiarygodne punkty charakterystyczne występujące w granicach zbiornika. Dodatkowo, granice obszarów zainteresowania (*case study 1–4*) wytyczono w taki sposób, by nie zawierały terenów pokrytych przez wodę (publikacja nr III, Fig. 14a). Interesującym przykładem wskazującym na konieczność terenowej walidacji danych teledetekcjach i ciągłego weryfikowania wyników analiz jest modelowanie przez algorytm mniejszych, przeźroczystych zbiorników, które nie w każdym przypadku zostały w odpowiedni sposób zrekonstruowane (publikacja nr III, Fig. 14b). Przykładowo, w *case study 2* (sandr) w latach 2021–2022 zanotowano wzrost objętości tej formy o 192 m^3, jednak analiza

ortomozaiki wykazała, że wzrost wysokości nie był związany ze zmianą ukształtowania terenu, ale z wodą, która z biegiem czasu wypełniła zagłębienie (publikacja nr III, Fig. 14c).

4. Podsumowanie

Przeprowadzona kwerenda literatury pozwala stwierdzić, że wykorzystanie BSP w badaniach glacjalnych stało się rzeczą powszechną, normą. Naukowcy wybierają różnego typu platformy do pozyskania wysokorozdzielczych zdjęć, które następnie są przetwarzane w oprogramowaniu fotogrametrycznym przy pomocy metody Structure-from-Motion do opracowania cyfrowego modelu wysokościowego oraz ortomozaiki. Wymienione produkty fotogrametryczne są szeroko stosowane w badaniach geomorfologicznych, szczególnie w badaniach dotyczących dynamiki wybranych form polodowcowych czy kartowania przedpoli lodowców. Występująca luka badawcza w postaci niedostatecznej wiedzy o wpływie parametrów obliczeniowych w oprogramowaniu fotogrametrycznym na dokładność cyfrowych modeli wysokościowych i ortomozaik została przez autora uzupełniona w postaci wyników przeprowadzonego eksperymentu. Na ich podstawie wyznaczono trzy schematy postępowania w zależności od żądanych efektów, które opublikowano w formie skryptów w języku Python w otwartym dostępie. Użyteczność skryptów potwierdzono analizując serię czasową zdjęć dla przedpola jednego z lodowców na Islandii, znacząco przyspieszając cały proces obliczeń oraz zwiększając efektywność wykorzystania wielowątkowego klastra obliczeniowego.

Postępujący rozwój technologii związany z BSP już obecnie pozwala na rezygnację ze stosowania fotopunktów, co wraz ze spadkiem cen platform oferujących technikę RTK powinno stać się w kolejnych latach powszechnym schematem postępowania obniżającym koszty nalotów. W ocenie autora, przyszłym kierunkiem badań z zakresu optymalizacji przetwarzania zdjęć metodą SfM powinno być użycie algorytmów sztucznej inteligencji, które mogą jeszcze bardziej skrócić czas obliczeń, jak i zapewnić lepszą kontrolę nad coraz to dokładniejszymi i liczniejszymi zbiorami zdjęć z BSP. Najnowsze publikacje wskazują na użyteczność algorytmów sztucznej inteligencji w georeferencji archiwalnych zdjęć lotniczych na podstawie aktualnych danych z BSP, co wpisuje się w prognozę autorów publikacji nr I o tym kierunku badań jako przyszłościowym i wartym analiz.

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Publikacja nr I z załącznikiem

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Do publikacji dołączono załącznik (Appendix A.) – bazę danych dot. badań z zakresu geomorfologii glacjalnej z wykorzystaniem bezzałogowych statków powietrznych.
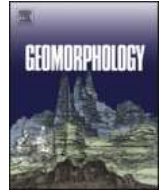
Applications of unmanned aerial vehicle (UAV) surveys and Structure from Motion photogrammetry in glacial and periglacial geomorphology

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ABSTRACT

Unmanned aerial vehicles (UAVs, UAS, drones) combined with Structure-from-Motion (SfM) photogrammetry have emerged over the last decade as the basis for a very efficient workflow in glacial and periglacial geomorphology by filling the spatial gap between traditional ground-based surveys and aerial or satellite remote sensing data. UAV-generated data offer flexible spatial and temporal resolution, thus enabling a shift from a pure description of geomorphological forms to a better understanding of process-form relationships, e.g., by quantification of short-term landscape changes in response to various drivers. In this contribution, we present an overview of current applications of UAV-SfM in studies of modern and past glacial environments that include mostly geomorphological mapping and change-detection analysis. We also indicate potential future applications, e.g., by combining UAV-data with historical archives, terrestrial SfM, and crowd-based image gathering to allow for a better understanding of landscape changes in response to present climate warming.

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Contents

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1. Introduction

Glacial geomorphology focuses on landforms developed as a result of processes related to glacier activity (Benn and Evans, 2010). Studying glacier-related landforms is important, as the areas affected by Quaternary glaciations encompass almost 1/3 of the Earth's surface, and various human activities (agriculture, construction, tourism) occur in terrains deglaciated after the end of the last glacial maximum, so a detailed knowledge of glacial sediments and landforms would be essential from an engineering standpoint (Evans, 2017). Moreover, sediments and landforms on deglaciated terrains can be used for reconstruction of the character of former glaciers and ice sheets, which is crucial to understanding their response to environmental changes. Studying glacial geomorphology concerning modern glaciers is also essential since proglacial landscapes are one of the most dynamic landscapes on Earth. Their transformations are important as they are a potential source of sediments and meltwater (from dead ice), which can affect sediment delivery to valleys and oceans and potentially be hazardous to life and infrastructure (e.g., by the initiation of such processes like debris flows or glacier lake outburst floods). Hazards are also associated with transformations of another element of the cryosphere – permafrost. High-dynamics of glacial and periglacial landscapes require the use of high-frequency monitoring tools. In the last decade, significant progress in mapping ability has been achieved, especially in the context of mapping and monitoring of relatively small areas characterized by high dynamics, due to the emergence of unmanned aerial vehicles (UAV) and Structure from Motion (SfM) technologies that make it possible to develop cm-scale orthomosaics and digital elevation models (DEMs), therefore offering an exceptional tool for detailed, on-demand mapping.

The unmanned aerial vehicle (UAV), also known as Unmanned Aerial System (UAS), Remotely Piloted Aerial System (RPAS), aerial robot or more popularly as "drone" (Colomina and Molina, 2014), is an example of a tool that, as a platform for mounting of a selected sensor (e.g. RGB, multispectral, or thermal imaging camera), enables the operator to execute the remote acquisition of data on a point or area without direct contact with it. The advent of UAV technology dates to the years of the Cold War when UAVs were designed for military purposes. In the late 1990s, the first UAVs were constructed for scientific purposes, where they were used to monitor, for instance, vegetation (Watts et al., 2012). The first publications describing the use of UAVs in scientific research highlighted their high efficiency in obtaining data, and Anderson and Gaston (2013) even heralded a revolution in environmental research thanks to the novel UAV technology. The great potential of UAVs in remote sensing research results from the flexible (and potentially very high) temporal resolution combined with a very high spatial resolution of the acquired imagery. An additional advantage of UAVs is the ability to choose surveys date and scope of research in accordance with the need of particular research group (e.g., allowing for on-demand surveys in case of occurrence of extreme events). Therefore, in the case of small study areas, UAV surveys are more economical and provide a more detailed alternative to high-resolution satellite imagery, which, despite the recent increase in spatial resolution and temporal coverage, is still not characterized by such high flexibility (Manfreda et al., 2018).

Glacial geomorphology has had a long tradition in the use of remote sensing data such as aerial photographs, satellite imagery and LIDAR (Light Detection And Ranging) surveys (cf., Benn and Evans, 2010; Mancini et al., 2013; Ely et al., 2017; Chandler et al., 2018), but these are much more expensive than UAV technology (Hackney and

Clayton, 2015; Wigmore and Mark, 2017). Aerial photographs, covering a larger area than those taken by UAVs, are useful for detailed analyses of large areas, but despite the possibility of being able to provide a high spatial resolution, they are not the optimal choice when a high temporal resolution is required (Hackney and Clayton, 2015). Satellite imagery offers high efficiency in imaging large territories and phenomena, but are characterized by a lower spatial resolution (down to 0.3 m) and susceptibility to weather conditions (cloud coverage) (Whitehead et al., 2013) which significantly affects the regularity and quality of the acquired data. Recently, PlanetScope satellite images (1-day revisit) started offering high time resolution data, providing images of the entire globe, but their spatial resolution (3 m) is still much worse than what could be achieved with UAVs. Before the emergence of small UAVs, an increase in the spatial and temporal resolution of remote surveys was attempted using small-format aerial photography obtained from cameras mounted on various platforms like kites, balloons, paragliders (see Aber and Gałązka, 2000; Boike and Yoshikawa, 2003; Aber et al., 2008, 2010).

UAV-generated images need to be processed to be useful for further analyses. The most common workflow utilizes Structure from Motion (SfM) photogrammetry with multi-view stereopsis (MVS) (Westoby et al., 2012; Smith et al., 2015). SfM-MVS combine images taken from different angles and distances to reconstruct the geometry of the scene based on characteristic points appearing in several images classified by the SIFT (Scale Invariant Feature Transform) algorithm (Westoby et al., 2012). As a result, the location of each image is solved, and a sparse point cloud is generated. Then, the dense point cloud is calculated. In the next step, Digital Elevation Model (DEM) and the orthomosaic are produced based on the dense point cloud. It is generally accepted that the SfM method is ideal for high-resolution collections of UAV images because, with its low financial expenditure, large datasets can be processed while the resulting high-resolution products (point cloud, DEM, orthomosaic) can easily be generated (Westoby et al., 2012), providing the basis for future geomorphological analysis.

In this study, we concentrated on the applications of UAVs in glacial and periglacial geomorphology, with particular focus on the description and recognition of landforms and landscapes resultant from the former activity of ice masses. Such studies provide knowledge on depositional and erosional processes and their interaction with ice and climate dynamics (Napieralski et al., 2007). So far, reviews of the use of UAVs in glaciology (Bhardwaj et al., 2016) and cryosphere studies in general (Gaffey and Bhardwaj, 2020) have been presented; however, no comprehensive evaluation of UAV applications in glacial geomorphology has been conducted. Such a review is crucial to providing a recap of current practices and ensuring meaningful compatibility of outputs from future works. The aim of this article is, therefore, to present recent applications of UAV and SfM in the field of glacial and periglacial geomorphology. In addition, potential directions of research development are also indicated (analysis of archival photo collections, integration of aerial and terrestrial photogrammetry, or the acquisition and analysis of image data from crowd-sourcing), by which it may be possible to understand better landscape changes taking place in response to global warming.

2. Review of previous studies

This paper reviewed the most relevant publications, which described UAVs' use in studies related to glacial, paraglacial or periglacial geomorphology. The publications were selected from the Web of

Table 1

List of selected publications in the field of glacial and periglacial geomorphology using UAV technology in the research. During the literature review, Internet bibliographical databases such as Google Scholar, Web of Science, and Scopus were used. The works included in the table were published before November 30, 2020.

Region	Authors	Type of study	Key points of the research and/or encountered problems
Antarctica			
Argentine Islands	Lamsters et al. (2020a)	Geomorphological mapping	Mapping of multiple islands in high resolution by using UAV surveys and GNSS measurements
Heritage Range	Westoby et al. (2015)	Assessment of surficial geology	The remote UAV-SfM method used for particle size analysis reduces the workload compared to traditional methods
Kings George Island	Dąbski et al. (2017)	Geomorphological mapping	A comprehensive inventory of periglacial forms in the area of 0.5 km^2; 19 types of forms were detected (824 polygons in total)
Kings George Island	Dabski et al. (2020)	Geomorphological mapping	Flights over the forelands of 3 glaciers at the same time; high altitude (500 m above sea level), DEM resolution of only 25 cm
Kings George Island	Pereira et al. (2020)	Geomorphological mapping	Three different computational methods were tested to detect patterned grounds and describe their characteristics
Arctic			
Alaska (USA)	Kienholz et al. (2020)	Change detection	Long-term observations of the glacier and the deglaciation process and the study of the impact of this process on floods
Bylot Island (Canada)	Bash and Moorman (2020)	Change detection	Observation of the rate of glacier melting
Bylot Island (Canada)	Whitehead et al. (2013)	Change detection	In addition to UAV images, images were also taken from a manned helicopter
Greenland	Chudley et al. (2019)	Geomorphological mapping	Research without establishing GCP
Greenland	Jouvet et al. (2016)	Change detection	Combination of UAV and Landsat satellite imagery to observe glacier melting and landscape transformation
Greenland	Jouvet et al. (2018)	Change detection	Application of the hybrid UAV construction: Firefly6 UAV
Greenland	Lamsters et al. (2020b)	Geomorphological mapping	Glacier foreground mapping with the use of GPR and UAV
Greenland	Ryan et al. (2015)	Change detection	An attempt to use UAV-data in geomorphic change detection; due to the problem with GNSS measurements, the altitude of the DEM turned out to be inaccurate
Greenland	Tomczyk and Ewertowski (2020)	Geomorphological mapping	Mapping of the geomorphological effects of glacial lake outburst flood in permafrost terrain, Zackenberg River, NE Greenland
Greenland	Tomczyk et al. (2020)	Change detection	Quantification of changes in response to glacial lake outburst flood, Zackenberg River. Observations were carried out the day before the flood, during the flood and after the water returned to the average level, and revealed the short-term response of permafrost in riverbanks
Iceland	Chandler et al. (2016)	Geomorphological mapping	Very accurate landform mapping based on UAV images – focus on small recessional moraines
Iceland	Chandler et al. (2020a)	Process-form studies	The first use of time-series of UAV data to analyse the processes of formation of glacial forms
Iceland	Chandler et al. (2020b)	Change detection	Comprehensive mapping of glacial landforms; time series of UAV data were used to detect recent changes in the proglacial landscape
Iceland	Evans et al. (2016)	Geomorphological mapping	The research developed a conceptual model of the spatial and temporal development of glacial formations in the foreland of the Fláajökull
Iceland	Hackney and Clayton (2015)	Geomorphological mapping	Mapping of glacial forelands using UAV wing construction in manual flight mode
Northwest Territories (Canada)	Van der Sluijs et al. (2018)	Change detection	The use of UAVs for the observation of permafrost and its impact on infrastructure
Svalbard	Allaart et al. (2018)	Geomorphological mapping	The first sedimentological studies of drumlins; apart from UAV images, aerial images were used
Svalbard	Bernard et al. (2017)	Change detection	Research on the dynamics of moraine formation; problems with weather conditions during flights; ground collapse after heavy rainfall detected by the model of differences
Svalbard	Bernard et al. (2018)	Change detection	The difference of DEMs between 2010 and 2016 showed noticeable morphological changes in the foreland, e.g., the appearance of new channels
Svalbard	Berthling et al. (2020)	Geomorphological mapping	Detailed analysis of slopes in two different locations allowed to estimate the erosion rates of the slopes; TLS data, aerial imagery, DSMs, DTMs and UAV data were used
Svalbard	Ewertowski and Tomczyk (2020)	Geomorphological mapping	Investigation of geomorphological agents responsible for the transformation of temporarily stabilised ice-cored moraines in high-Arctic settings
Svalbard	Ewertowski et al. (2016)	Geomorphological mapping	Mapping of two different parts of Nordenskiöldbreen foreland, UAV data used to map flutes in details
Svalbard	Ewertowski et al. (2019)	Geomorphological mapping	A detailed description of the workflow for using the UAV-SfM in glacial geomorphology; presented with the example of mapping the Hørbyebreen foreland
Svalbard	Lousada et al. (2018)	Geomorphological mapping	Images taken by UAV revealed 180 polygons out of 268 measured in the field (ice-wedge research)
Svalbard	Midgley et al. (2018)	Change detection	Quantification of deglaciation of the high-Arctic landscape (Midtre Lovénbreen) over eleven year period
Svalbard	Rippin et al. (2015)	Geomorphological mapping	A significant correlation between the roughness of the terrain and its reflection when examining snowmelt channels were demonstrated using UAV-generated data
Svalbard	Tomczyk et al. (2019)	Geomorphological mapping	The analysis of the morphology of the alluvial sediments shows that since 1960 the area of unstable (fresh) fluvial sediments has been systematically increasing
Svalbard	Tonkin et al. (2016)	Change detection	A conceptual model of moraine evolution was developed based on a combination of different data sources
Svalbard and Iceland	Storrar et al. (2020)	Geomorphological mapping	Details of the formation and evolution of two eskers complexes in Spitsbergen and Iceland
Other locations			
Alps (Austria)	Fey et al. (2017)	Change detection	Thanks to numerous data sources, the behaviour of a rockslide after the retreat of the glacier was reconstructed
Alps (Austria)	Kaufmann et al. (2018)	Change detection	Images were acquired from 5 different UAVs and combined with other archival data sources; presenting changes in the area from 1954 to 2017
Alps (Austria)	Seier et al. (2017)	Change detection	The ice block collapse was detected within two months, noting a height difference of 31 m between the models

Table 1 (continued)

Region	Authors	Type of study	Key points of the research and/or encountered problems
Alps (Italy)	Fey and Krainer (2020)	Change detection	Calculation of the velocities of the active rock glacier using UAV data and GNSS measurements
Alps (Italy)	Fugazza et al. (2015)	Change detection	Small-scale classification based on Landsat 8 satellite and UAV images showed a difference in area between the two sources by 1.5%
Alps (Italy)	Fugazza et al. (2018)	Geomorphological mapping	Combination of UAV images, ground-based images and TLS data were also used to analyse geo-hazards related to the transformation of glacial landsystem
Alps (Italy)	Scaioni et al. (2018)	Change detection	Identification of large displacement of earth masses over one year period
Alps (Italy)	Westoby et al. (2020)	Change detection	Evolution of a debris-covered glacier surface based on three years of UAV observations
Alps (Switzerland)	Buhler et al. (2016)	Change detection	In addition to RGB images, infrared images were also taken by removing the built-in filter from the APS-CMOS sensor
Alps (Switzerland)	Eichel et al. (2020)	Geomorphological mapping	Movements of small boulders by up to 16.5 cm were recorded Between 2014 and 2017
Alps (Switzerland)	Groos et al. (2019)	Change detection	Two last scheduled flights were unsuccessful due to technical problems; own UAV construction
Alps (Switzerland)	Hendrickx et al. (2020)	Change detection	Combination of UAV and TLS data demonstrated that debris flow, snow push phenomena, and rill erosion were the main geomorphological processes operating within high-alpine talus scope
Alps (Switzerland)	Rossini et al. (2018)	Change detection	The fastest melting of the glacier was recorded in the summer season
Alps (Switzerland)	Storni et al. (2020)	Change detection	Observation of rock glacier over a short period; visible displacement of the glacier due to landslide movement
Alps (Switzerland)	Vivero and Lambiel (2019)	Change detection	The destabilised part of the rock glacier mobilised around 27,000 m^3 of material
Altai (Russia)	Hedding et al. (2020)	Geomorphological mapping	Investigation of the dynamic retreat of the Aktru glacier and the succession of vegetation onto the glacial foreland
Andes (Chile)	Wilson et al. (2019)	Geomorphological mapping	Mapping of geomorphological effects of glacial lake outburst flood in Chileno Valley, Patagonia
Andes (Peru)	Wigmore and Mark (2017)	Change detection	Own UAV construction; due to the low air density, the power of the UAV was only enough for 12 min of flight at an altitude of 5000 m above sea level (25 min at sea level)
Dartmoor (SW England)	Mather et al. (2019)	Geomorphological mapping	Automated mapping of patterned ground using multiple types of data
Făgăraș Mountains (Romania)	Tîrlă et al. (2020)	Geomorphological mapping	Geomorphological mapping of glaciokarst
Henan Province (China)	Le Heron et al. (2019)	Geomorphological mapping	Study of a subglacial landscape carved beneath ice masses in the Shimengou area (Henan Province, China)
Himalaya (Nepal)	Van Woerkom et al. (2019)	Change detection	The reduction of the moraine area (31 cm per year) increases the thickness of the sediment in the study area (max. 8 cm per year)
Himalayas (India)	Ramsankaran et al. (2020)	Geomorphological mapping	Use of UAV-generated data to map glacial foreland in the Himalayas; lack of adequate satellite coverage, landing problems, and low air density were mentioned as the most significant problems
Himalayas (Nepal)	Immerzeel et al. (2014)	Change detection	The first use of UAVs on a debris-covered glacier in the Himalayas
Himalayas (Nepal)	Kraaijenbrink et al. (2016)	Change detection	The rate of rock mass movement turned out to be the highest in summer; the upper part of the glacial tongue shows the greatest movements, the lower part remains stable
Wales	Glasser et al. (2020)	Geomorphological mapping	Use of UAV data and numerical ice-sheet modelling for the investigation of glacial abrasion in bedrock surfaces
Wales	Tonkin et al. (2014)	Geomorphological mapping	One of the first publications where UAV-SfM approach was used in glacial geomorphological research

Sciences, Scopus and Google Scholar databases based on a combination of keywords such as drone, unmanned/uncrewed aerial vehicle/ system, UAV/UAS, remotely piloted aircraft system, RPAS, remotely operated aerial vehicle, ROAV, and glacial/periglacial/paraglacial geomorphology/geomorphological. Table 1 presents the list of key papers recorded in the Web of Sciences or Scopus before November 30, 2020, in which UAV component played a significant role and was used with a clear geomorphological context. Information about the research region and type of studies, together with a brief description of the most important findings or particular problems encountered while using UAV are also included (Table 1). In Section 2, we focus on a synthetic description of the analysed articles, while detailed information about each conducted study (including the type of research, coordinates, number of images, type of UAV and sensor, etc.) are presented in the supplementary material (Appendix A), together with a geodatabase to enable the reader to visualise the spatial distribution of the reviewed works.

2.1. Region of study

The literature review shows that in the years 2013–2020, there were a total of 62 publications in which the UAV-SfM method was instrumental in providing data related to glacial, paraglacial or periglacial geomorphology, of which 30 studies were carried out in the Arctic region (Fig. 1). Almost half of them were located on Svalbard (13 studies) (Fig. 1B), where the most popular sites were Nordenskiöldbreen, Austre and Midtre Lovénbreen, and Hørbyebreen. Studies from Greenland (7 publications, 2 of which about Store and Bowdoin glaciers), Iceland (6 articles, two about Fjallsjökull), Canada (2 publications

about the Fountain glacier on the Bylot Island) and Alaska were also represented.

The second most frequented region for glacial and periglacial geomorphological research using UAVs was the European Alps (15 publications) (Fig. 1C), where the Forni glacier turned out to be the most popular object of study (3 publications). Antarctica was the research site in five studies, three of which concerned King George Island. The areas of the Lirung glacier in the Himalayas were mapped twice (a total of four studies from Himalayas region). The remaining 8 publications concerned individual sites in various regions of the world, e.g., mapping the foreground of the Maliy Aktru glacier in the Altai Mountains (Hedding et al., 2020) or observations of the dynamics of the Llaca glacier foreland in the Cordillera Blanca mountain range (Wigmore and Mark, 2017).

2.2. Types of study

A systematic increase in the use of the UAV-SfM method in glacial geomorphological studies can be seen (Fig. 2). The most popular topic was one-time geomorphological mapping (30 papers in total): 21 papers, most of which concerned single landforms or landform assemblages, were related to the mapping of a glacial foreland, and 9 studies were related to mapping periglacial and paraglacial elements of the landscape, such as rock glaciers, alluvial fans, or talus slopes. The same number of publications (30) were related to geomorphic change detection, which was also the subject of one of the first published articles utilizing UAV-SfM technology in the field of glacial geomorphology (2013 and 2014). The use of UAVs for sedimentological studies and research focusing on processes shaping glacial landforms was much less widespread (one
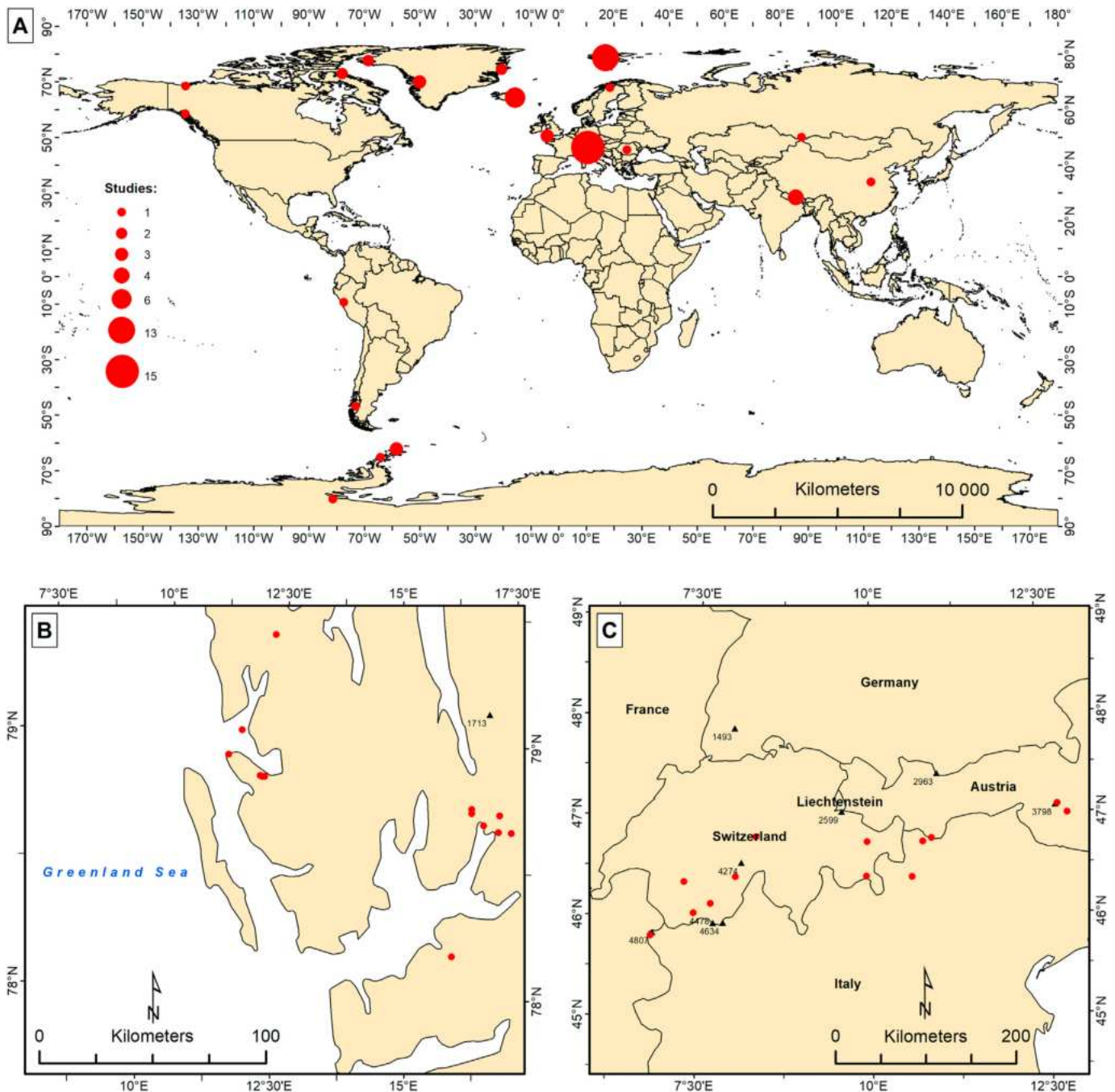
Fig. 1. The spatial distribution of publications in the field of glacial and periglacial geomorphology using UAV technology in the research. Part (A) contains a diagram of all research locations, while below are two maps with the location of the research carried out in Spitsbergen (B) and in the Alpine region (C). Locations are for works that were published before November 30, 2020, and listed in Web of Sciences or Scopus. Note, that in some cases, the concentration of publications in a particular region (e.g., Svalbard, Iceland) is associated with the same research group.

publication each). The high number of publications in 2020, which was 22 at the time the article was submitted, shows a significant increase in the popularity of UAVs in recent glacial geomorphological research. It might also reflect the global pandemic situation, which limited the opportunity to go into the field. Instead, many scientists focused on processing and publishing data collected in previous years.

2.3. Size of the studied area

The area surveyed by UAV in most publications did not exceed 1 km^2, because most of the research concerned individual landforms or landform assemblages. The main factors limiting the size of the surveyed areas were the unfavourable meteorological conditions

(wind and precipitation), a limited number of available power packs, the desired spatial resolution and flight altitude necessary to achieve it, high image overlap necessary for proper reconstruction of landform details, and the UAV's weight which impacted the ability to transport the UAV within the study area. Severe restrictions were also related to the limited processing capacity of large datasets, which require high-performance computer hardware. The studied area can be effectively increased, especially using a fixed-wing UAV, as proven, for example, by Dabski et al. (2020), who performed surveys of a total area of 16.8 km^2. Hence, small, lightweight multi-rotors represent a better solution to observe relatively small areas located far from roads where high mobility is essential, while for large areas, the wing-type construction will be a more effective solution.
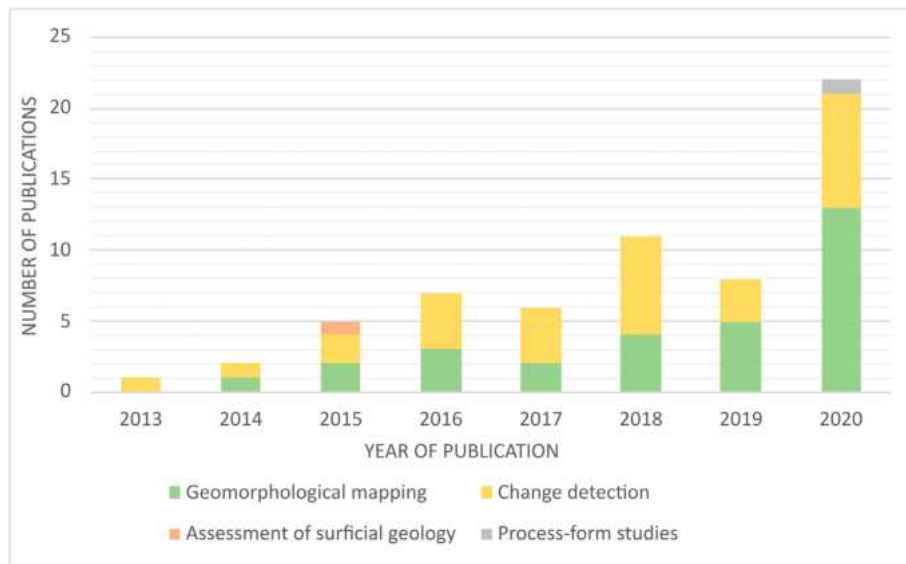
Fig. 2. Themes of works published in the years 2013–2020.

2.4. Type of UAV used

In the first publications from 2013 to 2015, UAVs with a wing design dominated, a multirotor was used only once (during the entire period under study, wing type was selected in 19 publications) (Fig. 3). This fact may be related to the lack of budget multi-rotors on the market, for it was only in 2013 that the Chinese company DJI presented its most popular family of vehicles, the "Phantom". Its second version, available at the end of 2013, was first used for fieldworks in 2014 (e.g., Evans et al., 2016; Ewertowski et al., 2016; Tomczyk et al., 2019; Ewertowski and Tomczyk, 2020), and since then the use of DJI products in glacial geomorphological research has become dominant (out of 38 publications that used multi-rotors, 32 were produced by DJI). From 2016, the share of multi-rotors in publications began to increase - thanks to their small size, low cost, and easy transport. They become the preferred type of construction, as was evident in their sizable representation in studies published in 2020 (mainly DJI Phantom versions 3 and 4). Among the fixed-wing constructions, the most frequently

chosen UAVs were SenseFly (a subsidiary of the French company Parrot SA) eBee, and SwingletCAM models. In 2016, Jouvet et al. (2018) were the first to use BirdsEyeView's Firefly6 hybrid construction, which despite the appearance of "wing" has four engines with double propellers, eliminating the disadvantages of the classic wing constructions such as the lack of vertical take-off and landing.

2.5. Type of sensor

RGB images from low altitude were used in all reviewed publications. Due to the type of gimbal used and the limited load capacity, budget multi-rotors limit sensor selection and modification. Therefore, in all publications that used the popular DJI Phantom models, images were taken with a built-in RGB sensor having a sensor of 12 to 20 MPx (depending on the specific UAV model). Larger constructions, such as the DJI S800 hexacopter or the Skywalker X8 wing, made it possible to mount a higher-class digital camera, which significantly improves the quality of images compared to built-in solutions. The most popular
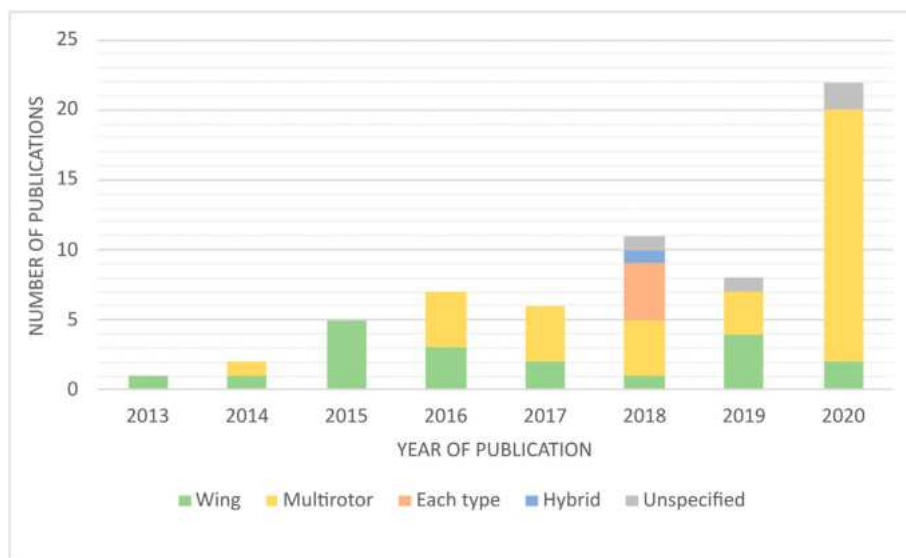
Fig. 3. Types of UAVs used in studies from the years 2013–2020.

cameras were Canon EOS-M, Sony α6000, and Panasonic Lumix. In some studies, UAV-generated RGB optical data were supplemented by multispectral data and point clouds from the terrestrial laser scanning (TLS), or from satellite or airborne altitude.

2.6. Spatial resolution

The most significant advantage of using UAV in glacial geomorphology studies is the ability to obtain very high resolution (cm-scale) orthomosaics and DEMs. In most studies (50), the ground sampling distance (GSD) varied from 0.02 m to 0.20 m (see Supplementary materials - Appendix A). Therefore, compared to satellite or aerial images, researchers were able to collect more accurate data with much less financial expenditure, which allowed them to conduct very detailed studies of small glacial landforms and processes (e.g., fluted moraines, small push moraines).

2.7. Mission design and performance

The advantage of the off-the-shelf UAVs, in addition to the relatively low purchase costs, is the optimized software for controlling the UAV and managing the mission, often available in the form of a mobile application (free or available to download for a small fee on Android or iOS devices). This software allowed operators to easily plan a flight directly in the application based on the selected research area. Autonomous flight programming was declared in 35 publications, in most cases based on linear flight and automatic taking of interval images from a pre-set altitude. To generate a more accurate model, in some publications, the image overlap was set to a value of even 90% (Ryan et al., 2015). In 14 other studies, UAVs were manually piloted, and all flight parameters were controlled directly by the UAV operator. In some works, in addition to vertical images, oblique images were also taken (e.g., Westoby et al., 2015; Chudley et al., 2019; Tomczyk et al., 2019; Tomczyk and Ewertowski, 2020), which during processing resulted in more accurate mapping of the vertical and near-vertical objects, e.g. large boulders, escarpments.

2.8. Problems encountered

The on-site meteorological conditions were the most common source of problems with UAV operations. Low cloud cover, fog, strong winds, and rainfall can effectively disrupt the work schedule and force operators to reschedule surveys. In addition, several other sources of problems were mentioned in the literature. Animals, especially birds, are a real threat to the success of a UAV flight; and in the Arctic, polar bears pose a potential danger to operators. Problems with GNSS cover and magnetometer readings can enforce a switch to manual flight instead of preplanned missions (Bernard et al., 2017). There were also problems with maintaining the desired image overlap during an autonomous flight (Fugazza et al., 2018), inaccurate GNSS measurements leading to low accuracy of the DEM (Ryan et al., 2015) or insufficient supply of power packets (which drains faster in a cold environment), causing the need to complete the surveys on another day (Lamsters et al., 2020b).

3. Overviews of current UAV applications in glacial and periglacial geomorphology

3.1. Geomorphological mapping

Detailed mapping is the primary application of UAV-generated data in studies related to glacial and periglacial geomorphology. Maps developed based on orthomosaics and DEMs, often combined with fieldwork ground-truthing, can be produced for regions of glacial forelands, usually focusing on a specific landform type or landform assemblage (Fig. 4), or, less often, for a whole glacial foreland. Such products provide

an inventory of various glacial landforms and constitute a basis for understanding the evolution and dynamics of glacial landsystems.

UAV data are often combined with other data sources, and a common practice involves a less detailed mapping of larger areas (e.g., whole glacial forelands) based on high-resolution satellite or aerial images, combined with a more detailed mapping of particular areas of glacial landsystems. Such an approach was used in the case of Fláajökull (Iceland) to produce a small scale map (1:6250 scale) of the whole glacial foreland complemented by a more detailed map (1:350 scale) of a sample area of a recently exposed landform assemblage that enabled a detailed analysis of this glacial landsystem (Evans et al., 2016). A similar approach was used in mapping Nordenskiöldbreen (Spitsbergen) by combining high-resolution satellite data (WordView-2) with historical aerial photographs to produce small-scale maps of the whole glacial foreland, and UAV data for a very detailed mapping that focused on the fluted surface to provide morphometrical details of flute assemblage (Ewertowski et al., 2016). The same glacial foreland was also mapped based on aerial images combined with offshore data to produce geomorphological maps comprising onshore and offshore areas (Allaart et al., 2018). In this case, UAV-generated data were used to provide an inventory of drumlins present in the Nordenskiöldbreen foreland and to provide contexts for the results of sedimentological studies of these landforms (Allaart et al., 2018). Storrar et al. (2020) conducted a study of the esker complexes on the foreland of the Hørbyebreen (Spitsbergen) and Breiðamerkurjökull (Iceland). To analyse the formation and evolution of these forms, they used very detailed maps of both esker complexes, which were based on the UAV-generated data. Ely et al. (2017) produced an orthophotomap and a DEM of the Isfallsglaciären foreland in Sweden, aiming to assess the morphological properties of fluted moraines and to demonstrate the usefulness of UAV technology for registering minor details of glacial landforms.

Mapping the entire glacial foreland with the sole use of UAV-generated data is much less common, as achieving such extensive coverage is time-consuming and, in most cases, requires flights beyond visual line of sight (BVLOS), which is complicated from an organizational and law regulation standpoint. One example was demonstrated by Dabski et al. (2020), who surveyed the forelands of three glaciers (Ecology, Sphinx, and Baranowski on King George Island in West Antarctica) to determine the area and spatial distribution of individual glacial landforms. They used a large fixed-wing UAV construction, which allowed for effective acquisition of images (only three flights were performed) over a reasonably large territory (the total linear distance covered by the UAV was 720 km in 7 h). The achieved GSD of 0.06 m for orthomosaic and 0.25 m for DEM was, however, slightly lower than in most other applications of UAV in glacial geomorphology.

Apart from mapping with a strict focus on glacial landforms, UAV-generated data have also been used in paraglacial and periglacial geomorphology. For example, Lousada et al. (2018), based on UAV images, aerial images and satellite imagery, mapped a valley fragment at Adventdalen (Spitsbergen) to critically evaluate these three sources of remote sensing data for the detection of ice wedges. The authors emphasized that only UAV data and aerial images allowed for effective mapping of these structures, offering a resolution that was better than 0.2 m. The WorldView-1 satellite imagery (0.5 m GSD) only allowed for detecting 1/3 of the polygons inventorized within the study area. Tomczyk et al. (2019) surveyed the Dynamisk Creek alluvial fan (Spitsbergen) using a low-cost UAV and produced a very detailed (1:850 scale) geomorphological map confirming the usefulness of UAV-SfM technology for mapping the surface morphology of fans which developed as the landscape responded to the retreat of glaciers. They also indicate the UAV's susceptibility to weather conditions, limited power efficiency, or uselessness during polar nights. In other publications, UAV technology was used to (i) map the immediate reaction of the periglacial landscape to a glacial lake outburst flood (Tomczyk and Ewertowski, 2020), (ii) produce an inventory and describe
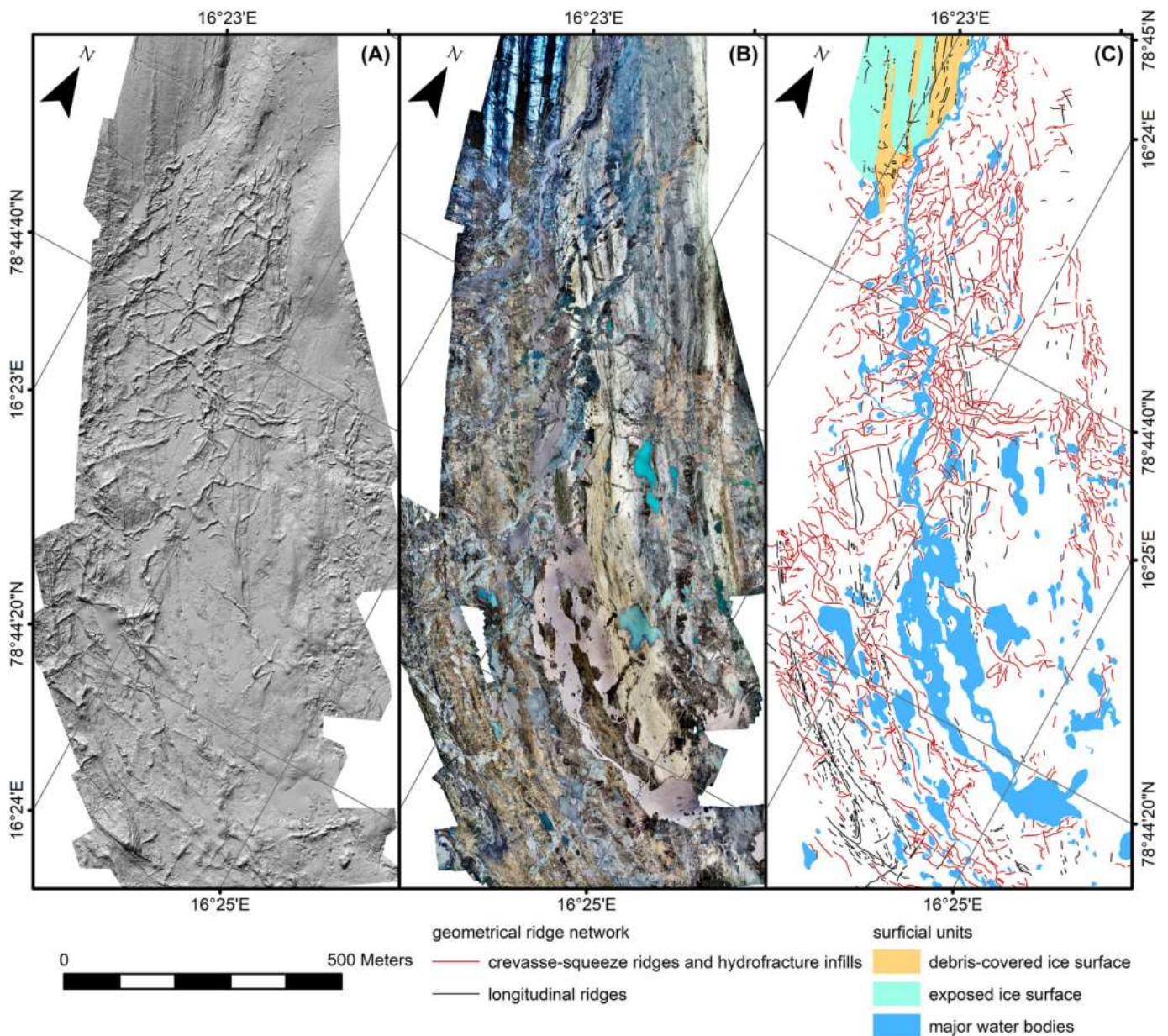
Fig. 4. An example of geomorphological mapping based on hillshade model and orthomosaic: a network of geometrical ridges in front of Hørbyebreen, Svalbard: (A) hillshade model; (B) orthomosaic; (C) geomorphological map showing complex pattern of cross-cutting ridges (Ewertowski et al., 2019).

the characteristics of stone circles (Pereira et al., 2020), (iii) observe the phenomenon of solifluction and its relationship with different factors, e.g., with the bedrock character (Eichel et al., 2020), or (iv) produce a general inventory of periglacial forms in the studied area (Dąbski et al., 2017).

3.2. Change detection

Change detection (volumetric and/or planimetric) is another popular application of UAV-generated data in geomorphological research. The UAV's high mobility and flexibility (e.g., in terms of sensor selection) allow for a much more flexible choice of the date of survey in comparison to regular aerial images or high-resolution satellite imagery. Multi-temporal surveys constitute a basis for the creation of time series of orthomosaics and DEMs. After subtracting the spatially overlapping cells of the two rasters, it is possible to obtain a DEM of Difference (DoD), illustrating the difference in height between the two models (e.g., Tonkin and Midgley, 2016; Chandler et al., 2020a)

(Fig. 5). The main motivations for conducting cyclical observations of landforms included understanding the evolution of the landscape (Tonkin et al., 2016; Seier et al., 2017; Kaufmann et al., 2018) or research into the influence of factors such as temperature and precipitation on landform transformation (Bernard et al., 2017).

Change detection can include one-period observations (e.g., month-to-month, year-to-year) to provide data on landscape change in this period, or can comprise a series of multiperiod observations to be able to judge not only the general direction of landscape transformation (i.e., erosion or deposition) but also trend in these changes (e.g., acceleration of erosion, seasonality). For example, Bernard et al. (2017) calculated a DoD of the Austre Lovénbreen (Spitsbergen) moraine during only a 7-day field visit (the first flight was made on 24 September 2015, and the second one on 1 October 2015). Even in such a short period, UAV-generated data enabled the detection of landform changes in the foreland caused by sudden flooding, which accounted for local terrain collapse to a depth of 3 m. Tonkin et al. (2016) also made a one-time change detection of the moraine relief
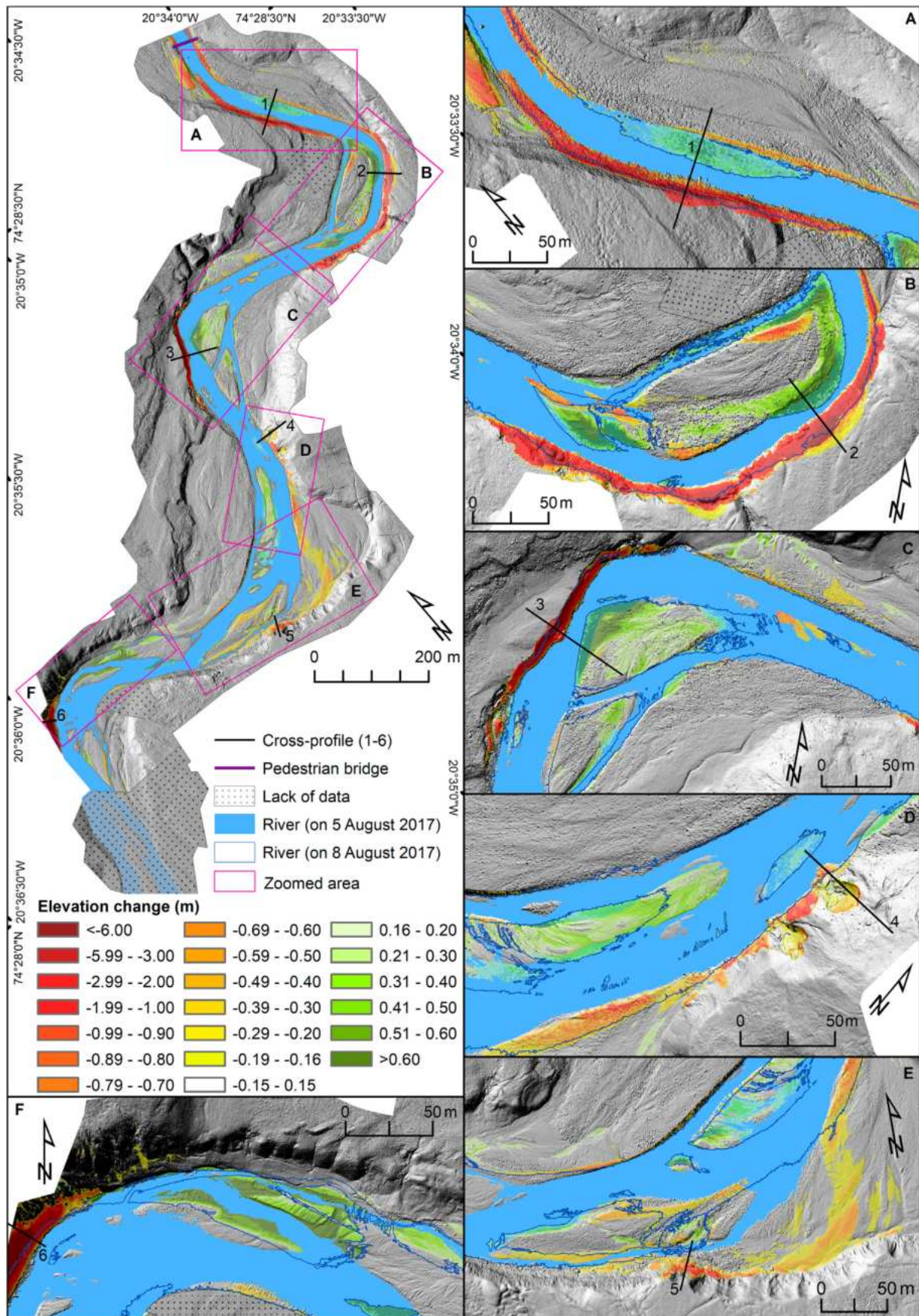
Fig. 5. An example of DEM of Differences used to study elevation changes in response to glacial lake outburst flood along the Zackenberg River, Greenland (Reprinted from Journal of Hydrology, Vol 591, Tomczyk et al., Geomorphological impacts of a glacier lake outburst flood in the high arctic Zackenberg River, NE Greenland, 125300, Copyright (2020), with permission from Elsevier.

on the same glacial foreland, but for a more extended period — they compared the images from 2003 (aerial photographs) and 2014 (UAV), quantifying the dynamics over this relatively long 11-year period. In publications that described a one-period change detection using UAV data, the most common interval between the two surveys varied from several dozen days to several years (e.g., Whitehead et al., 2013; Immerzeel et al., 2014; Ryan et al., 2015; Jouvet et al., 2016; Tonkin et al., 2016; Bernard et al., 2017; Seier et al., 2017; Wigmore and Mark, 2017; Jouvet et al., 2018; Rossini et al., 2018; Scaioni et al., 2018; Groos et al., 2019; Bash and Moorman, 2020).

Multiple-period analyses of surface changes are noticeably less common in the literature. This can be explained by the need to conduct regular observations of the same site, which is time-consuming and requires frequent field trips. In several studies that present the results of the multiperiod analysis, the difference between subsequent surveys was usually about one year (e.g., Kraaijenbrink et al., 2016; Fugazza et al., 2018; Kaufmann et al., 2018; Chandler et al., 2020b). In some cases, UAV-generated data were complemented with archival LIDAR data or aerial images (e.g., Fugazza et al., 2018; Chandler et al., 2020b). Repeated analyses of surface changes and regular observations of glacial and periglacial landscape transformation using UAVs can help to understand the dynamics of landforms better and enable the quantification of changes related to low-frequency and high-magnitude events such as intense melting, rainfall or glacier-lake outburst floods. For example, Tomczyk et al. (2020) provided an insight into the geomorphological response of high-arctic Zackenberg river to glacial lake outburst flood, by quantification and description of the spatial pattern of riverbank erosion and bars' modification (Fig. 5). Such results were possible thanks to UAV time-series' high temporal resolution - data were collected immediately before-, during-, and after- flood (5th, 6th, and 8th August 2017). It is probable that due to the growing popularity of UAVs in glacial studies, there will be an increase in studies that describe multiperiod observations.

3.3. Process-form studies

Another less popular application of UAV-generated data in glacial geomorphology is the study of processes forming and modifying glacial landforms. A time series of DEMs and orthomosaic enables monitoring changes in morphology and can therefore be used to observe or infer constructional and erosional processes and, as a consequence, to propose new models of landscape evolution. Chandler et al. (2020a) presented an example of such an approach, using a relatively long series of UAV observations (4 surveys between 2016 and 2019) of the foreland of Fjallsjökull (Iceland) to demonstrate the frequency of small push moraine formation. For the first time, UAV technology was able to provide clear evidence of the sub-annual moraine formation, which made it possible to develop a conceptual model of the formation of small recessional moraines in front of active temperate glaciers receding into overdeepenings.

3.4. Mapping of surficial geology

Sedimentological studies using UAV images and the SfM method in glacial and paraglacial areas are still rare. However, very-high-resolution images (better than 0.1 m) taken from a low altitude are a potentially excellent data source, e.g., to study grain size and distribution, thanks to the development of very accurate orthomosaics and DEMs which make it possible to identify sediment textures with high precision. Westoby et al. (2015) used UAV-SfM method, terrestrial SfM and terrestrial laser scanning (TLS) data to analyse the particle size distribution of the moraine complex at the Heritage Range (Antarctica) to determine if the SfM method could be used to interpret grain-size distribution in a site-scale, thereby replacing the traditional manual screening usually limited to patch-scale. Their research confirmed UAV-SfM workflow's usefulness, which enabled upscaling of

site-scale results to model median grain-size in a moraine-scale. Several other approaches which analysed orthomosaic texture, point cloud/DEM roughness or single image texture were used to quantify particle sizes from UAV data in fluvial geomorphology (cf., Carbonneau et al., 2018; Woodget et al., 2018), which can also be adapted to the glacial environment.

3.5. Existing workflows for UAV-SfM in glacial geomorphology

Several years of experience with the use of UAVs in geomorphological research mean that, in addition to publications presenting examples of applications of UAV technology, substantial methodological studies have also been published (e.g., Carbonneau and Dietrich, 2017; James et al., 2017, 2020). James et al. (2019) draw attention to the fact that due to reduction in the level of complexity with the use of computational methods (thanks mainly to the automated data processing software), many users are not sufficiently prepared in the theoretical aspects of numerical methods used in photogrammetric programs. This argument prompted them to provide a systematic guideline with details that should be presented in publications where UAV-SfM was used. The proposed guidelines include such aspects as the contribution of the publication to the progress of science, a detailed description of the sensors used, or the adopted calculation parameters in the software (James et al., 2019).

The methodology for using UAV-SfM in glacial and periglacial geomorphology is usually hierarchical, which is especially visible in publications where the authors first describe in detail the step-by-step workflows (e.g., Ely et al., 2017; Gindraux et al., 2017; Ewertowski et al., 2019), and later demonstrated its application on a real-world case study. The most common workflow is based on several key consecutive activities: (a) selection of the study area and appropriate equipment, (b) transport and preparatory field work (e.g., setting up Ground Control Points [GCPs]), (c) planning and execution of the UAV flight, (d) initial processing of the imagery in SfM software at a low level of details (i.e. on the lowest processing settings to enable rapid verification while still in the field) to ensure that the extent and quality of the data are satisfactory; (e) final processing and generation of orthomosaics and DEMs; and (f) geomorphological analysis (e.g., mapping, change detection). In the beginning, the set is preselected (blurred or overexposed images are rejected, etc.) and imported into a photogrammetric software (e.g., Agisoft Metashape) (e.g., Ewertowski et al., 2019). As the software processes the file using the SfM method, based on characteristic points appearing in several images, the number of characteristic points is crucial for the quality of the model. Hence, both the quality of the sensor and resolution of the images play a critical role (Westoby et al., 2012; Gindraux et al., 2017).

Depending on the field situation, available equipment, and the adopted research objectives, it is possible to omit the establishment of GCPs (Evans et al., 2016; Chudley et al., 2019) which will reduce the external accuracy of the model; however, data georeferenced based on an onboard GNSS will be of sufficient quality for a one-time mapping. If the external GCPs are surveyed, the most critical factor influencing the final accuracy is the optimal distribution, i.e. maintaining a maximum distance of 100 m between the GCPs (cf., Tonkin and Midgley, 2016). An alternative georeferencing solution, which can be used instead of surveying GCPs, is co-registration of the two surveys during the image alignment stage (Cook and Dietze, 2019).

4. Potential future applications

As presented in Section 2, the use of UAV-SfM technology in glacial and periglacial geomorphological research has increased recently, and more publications are expected to appear soon. The use of UAVs is quickly evolving as well, from the simple landform mapping in its earlier days to more advanced applications such as process-form studies. UAV-SfM technology has been successfully delivering high-resolution

spatial data over the past few years, which is ideal for change detection studies. In this section, we suggest some other potential future applications of UAV and SfM in glacial and periglacial geomorphology, which can be enhanced by combination with other data sources. The UAV optical imaging data can also be potentially combined with LIDAR laser measurements using a special scanner designed for UAVs (e.g., Livox Mid-40).

4.1. Investigation of geomorphological processes

Thanks to a flexible temporal resolution, a time series of UAV observations can be used to analyse processes involved in the development and modification of landforms in the glacier foreland, e.g., moraine formation processes (Chandler et al., 2020a). Researching this subject requires a long time series of data, which will make it possible to recognize the impact of individual processes. Such an approach should lead to a significant increase in knowledge of the process-form-sediment relationship, e.g., by studies focused on: (1) eskers systems emerging from the ice cover and their further modifications by slope processes and dead ice melting; (2) disintegration of ice-cored moraines by mass movement processes; (3) evolution of kame-and-kettle topography due to dead-ice melt out; (4) evolution of debris-covered glacial tongues and their transformation until full de-icing stage; (5) modelling of sediment storage and transport as an effect of paraglacial landscape modifications; (6) assessment of preservation potential of subtle glacial landforms and their potential fingertip in the geomorphological record. Similarly, UAV-generated data can be used to observe and quantify geomorphic outcomes of processes in a periglacial environment, such as ice-wedge polygon development or their degradation by thermo-erosion.

4.2. Combination of UAV and terrestrial photogrammetry

Another improvement in our understanding of glacial and periglacial landscapes may be related to the use of a combination of low-altitude (UAV-generated) and ground-based (terrestrial) images processed via the SfM workflow to obtain detailed models of steep surfaces like ice cliffs, gorges, and steep slopes. Such an approach was used by Fugazza et al. (2018), who, by comparing data from UAV, TLS and terrestrial photogrammetry, proved that the point density in the three obtained point clouds was the highest for images from terrestrial sensors. On this basis, it can be assumed that when examining vertical objects (e.g., steep gorges or cliffs), where there is a possibility of stable sensor positioning, ground photogrammetry will provide images of better quality than UAVs. Tavani et al. (2020) presented an effective modelling of the cliff using images taken by a budget smartphone, proving that even such a low-cost solution can be beneficial in geomorphological research. The advantage of terrestrial images of objects is undoubtedly the full freedom as to the choice of sensor, but with extensive, flat research objects, vertical and oblique images from UAVs would still be more favourable and more time-effective.

4.3. SfM processing of archival images

UAV images offer exceptional spatial and temporal resolution, but their temporal coverage is mostly restricted to the last decade. However, as demonstrated by several studies (e.g., Mertes et al., 2017; Midgley and Tonkin, 2017; Kaufmann et al., 2018; Sziło and Bialik, 2018; Holmlund, 2020; Kavan, 2020), the SfM workflow can be successfully used to process archival aerial photographs, providing an excellent baseline that can be subsequently updated with UAV surveys to provide a better picture of the evolution of glacial landsystems. For example, Mertes et al. (2017) and Midgley and Tonkin (2017) demonstrated that even oblique aerial photographs from the beginning of the 20th century could deliver valuable data about landscape changes. Similarly, a combination of historical ground-based photographs with archival

aerial photographs (both sets processed using SfM) enabled quantification of glacier changes (e.g., Mertes et al., 2017; Holmlund, 2020; Kavan, 2020). However, the relatively large values of uncertainties (of the magnitude up to several m) would have to be considered, limiting their usefulness in quantifying the evolution of smaller geomorphological features.

4.4. Use of crowd-sourced images

The spectacular increase in the popularity and ubiquity of social media in the last decade has significantly changed the way people share their data, e.g., images and videos, with others. Publishing images on a social network (e.g., Facebook, Twitter, and Instagram) with an added location and capture date may become valuable information for scientists, including geomorphologists. This source of data can be potentially useful in glacial and periglacial geomorphology, especially in areas commonly visited by tourists (e.g., Alps, SE Iceland). The growing number of high-resolution UAV-generated videos published on social media can be processed through SfM-MVS workflow, for example, frames from 4 K videos can be transformed into stills of about 12MP resolution and used to generate point clouds, DEMs and orthomosaics. Of course, such an approach would require the consent of the owners of images and/or videos. With a probable increase in the number of available movies, there is a potential to obtain high temporal coverage of data that can enormously enhance our ability to monitor and understand the processes of change and transformation concerning modern glacial and periglacial landscapes.

5. Conclusions

The UAV-collected images are the basis for the mapping of such forms as terminal moraines or alluvial cones, which are part of the current trend of developing thematic maps of selected landforms along with formulating detailed research questions for the studied phenomena (cf., Chandler et al., 2018). Recent works have focused on the mapping of individual landforms or their assemblages (e.g., Storrar et al., 2020), or mapping of the entire glacial foreground (e.g., Dabski et al., 2020). Repeated observations of landforms and regular acquisition of images make it possible to detect changes in their volume or area, which is necessary for understanding the dynamics, evolution, and response of glacial forelands to ongoing climate changes (e.g., Fugazza et al., 2015; Chandler et al., 2020b). The literature review revealed interesting information on the current use of the UAV-SfM method in glacial geomorphology:

1) Diverse research topics (mainly geomorphological mapping and geomorphological change detection analysis) and an increase in the number of publications in 2020 (22 papers, Fig. 2) prove the enormous usefulness of this method and its growing popularity.
2) Most of the studies were conducted in the Arctic and the Alps (Fig. 1), with a smaller number in Antarctica, Himalayas, Andes, and Alaska. The popularity of the Arctic (especially Svalbard and Iceland) and the Alps should come as no surprise. Climate changes, resulting in an increase in the average air temperature, tend to cause dynamic reactions in the glacial and periglacial landscape. The Arctic is also a natural "field-based laboratory" – the effects of climate change in the Arctic are much more intense than in other regions (see Moritz et al., 2002; Walsh et al., 2011; Duarte et al., 2012). Therefore, we can use Arctic-based observations to infer the future effects of climate warming in other areas, i.e. we may use the results of detailed quantification of processes in Arctic settings to speculate about the magnitude of future geomorphological changes in the lower latitudes.
3) In most cases, the study area did not exceed 1 km^2, but some observations were also made of the entire glacial foreland. Multi-rotors were the most popular type of UAV used. In nearly all publications,

RGB images were used to develop orthomosaics and DEMs with a spatial resolution from 0.02 m to 0.20 m. Most of the operators used an autonomous flight mode. The most encountered problems were unfavourable weather conditions and insufficient energy reserve.

The presented overview highlights the utility of UAVs for obtaining images, which can be used to develop high-resolution orthomosaics and DEMs, thereby enabling a detailed geomorphological mapping as well as a precise identification of their morphological characteristics - that would not be possible using other remote data sources. As to the multi-temporal surveys, increased research interest on the process-form relationship is expected, and a significant contribution to this type of research could be made through the more widespread use of a combination of UAV-based images with ground-based photogrammetry and archival aerial images. Time series of observations may be supplemented with images and videos from private (i.e., crowd-based) collections available through social media. We speculate than in the 2021–2030 decade the following can be expected:

1) Use of small UAVs will become a standard in glacial and periglacial geomorphology – especially in mapping exercises;
2) Lowering of the costs for RTK-GNSS will enable direct referencing with the accuracy of several cm, therefore removing the necessity of GCP collection;
3) More widespread use of sensors different than RGB cameras (e.g., LiDAR or ground penetrating radar [GPR]) mounted on UAV will increase the accuracy of terrain modelling (LiDAR) and enable to interpret at least some of the subsurface features (e.g., dead ice presence) within glacial foreland (GPR);
4) Increase in the availability of multi-temporal datasets will enable detailed quantification of geomorphological effects of different processes (e.g., debris flows, dead-ice melting, meltwater erosion) and development of worldwide databases containing rates of the intensity of geomorphological processes in different climatic and environmental settings;
5) Multi-temporal datasets will also enable quantifying post-glacial transformations of glacial landforms and assessing their preservation potential - thus improving the interpretation of Pleistocene glacial record.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.geomorph.2021.107620. These data include the Google map of the most important areas described in this article, and the full database (in Excel and shp formats), which can be used in GIS software.

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ID	Author	Year of publication	Region	Glacier/object	Latitude	Longitude	Date	Type of study	Forms	Size of studied area [km2]	Type of drone used	Name of drone used	Type of sensor	Name of sensor	Resolution of ortophotomap [cm]	Resolution of DEM [cm]	Total number of photos	Mission design and performance
1	Allaart et al. (2018)	2018	Svalbard	Nordenskiöldbreen	78.6719	16.9108	07.2017	Geomorphological mapping	drumlins	0.375	multirotor	DJI Phantom 4 Pro	RGB	build-in	N/A	11	671	Manually
2	Bash and Moorman (2020)	2020	Bylot Island (Canada)	Fountain glacier	72.9167	-78.6667	07.2016	Change detection	N/A	0.185	unknown	N/A	RGB	N/A	10	10	N/A	N/A
3	Bernard et al. (2017)	2017	Svalbard	Austre Lovénbreen	78.8867	12.1472	09.2015; 10.2015	Change detection	moraine	0.040	multirotor	DJI Phantom 3 Professional	RGB	build-in	N/A	N/A	N/A	Manually
4	Bernard et al. (2018)	2018	Svalbard	Austre Lovénbreen	79.4500	12.2500	2016	Change detection	N/A	N/A	multirotor	DJI Phantom 3 Advanced	RGB	build-in	10	10	1758	Autonomous
5_1	Berthling et al. (2020)	2020	Svalbard	Ny-Ålesund area	78.9667	11.3833	2016	Geomorphological mapping	various	N/A	unknown	N/A	RGB	N/A	20	20	N/A	N/A
5_2	Berthling et al. (2020)	2020	Svalbard	Blomstrandøya	79.0667	11.6333	2016	Geomorphological mapping	various	N/A	unknown	N/A	RGB	N/A	20	20	N/A	N/A
6	Buhler et al. (2016)	2016	Alps (Switzerland)	Flüela Valley	46.7503	9.9475	08.2015; 09.2015	Change detection	N/A	0,128; 0,363	multirotor	Falcon 8	RGB; NIR	Sony Nex-7	2.5	10	252; 359	Autonomous
7	Chandler et al. (2016)	2016	Iceland	Skálafellsjökull	64.3019	-15.7922	2013	Geomorphological mapping	moraine	2.000	wing	Quest UAV 200	RGB	Panasonic LUMIX DMC-LX5	N/A	9	1980	N/A
8	Chandler; et al. (2020a)	2020	Iceland	Fjallsjökull	64.0167	-16.4167	2016; 2017; 2018; 2019	Process-form studies	moraine	~0,500	multirotor	DJI Phantom 3 Advanced; DJI Phantom 3 Professional; DJI Phantom 4 Pro	RGB	build-in	~3	~6	515; 642; 706; 449	Autonomous; manually
9	Chandler; et al. (2020b)	2020	Iceland	Fjallsjökull	64.0167	-16.4167	2016; 2017; 2018; 2019	Change detection	foreland	~0,500	multirotor	DJI Phantom 3 Advanced; DJI Phantom 3 Professional; DJI Phantom 4 Pro	RGB	build-in	~5	~5	515; 642; 706; 449	Autonomous; manually
10	Chudley et al. (2019)	2019	Greenland	Store glacier	70.0667	-50.0833	08.2017	Geomorphological mapping	N/A	~5,000	wing	Skywalker X8	RGB	Sony α6000	15	20	~3000	Autonomous
11	Dąbski et al. (2017)	2017	Kings George Island (Antarctica)	Demay Point Peninsula	-62.2125	-58.4306	10.2015	Geomorphological mapping	various	0.500	wing	PW-ZOOM UAV	RGB	Canon 700D	5	20	766	Autonomous
12_1	Dąbski et al. (2020)	2020	Kings George Island (Antarctica)	Ecology glacier	-62.1833	-58.4667	11.2016	Geomorphological mapping	various	16.800	wing	PW-ZOOM UAV	RGB	Canon 700D	6	25	7678	Autonomous
12_2	Dąbski et al. (2020)	2020	Kings George Island (Antarctica)	Sfinks glacier	-62.1889	-58.4583	11.2016	Geomorphological mapping	various	16.800	wing	PW-ZOOM UAV	RGB	Canon 700D	6	25	7678	Autonomous
12_3	Dąbski et al. (2020)	2020	Kings George Island (Antarctica)	Baranowski glacier	-62.2000	-58.4500	11.2016	Geomorphological mapping	various	16.800	wing	PW-ZOOM UAV	RGB	Canon 700D	6	25	7678	Autonomous
13	Eichel et al. (2020)	2020	Alps (Switzerland)	Turtmann Valley	46.1333	7.6872	08.2014; 08.2017	Geomorphological mapping	moraine	0.0004	multirotor	OktoXL; DJI Phantom 4 Pro+	RGB	Panasonic Lumix GX1; build-in	0.2	0.2	416; 564	Manually
14	Ely et al. (2017)	2017	Lapland (Sweden)	Isfallsglaciären	67.9140	18.5720	08.2014	Geomorphological mapping	flutes	0.600	multirotor	DroidWorx Gexacopter	RGB	Nikon D5300	2	2	836	Autonomous
15	Evans et al. (2016)	2016	Iceland	Fláajökull	64.3653	-15.6522	09.2014	Geomorphological mapping	various	0.100	multirotor	N/A	RGB	N/A	2	3	175	Manually
16	Ewertowski et al. (2016)	2016	Svalbard	Nordenskiöldbreen	78.6667	17.1667	07.2014	Geomorphological mapping	various	0.500	multirotor	N/A	RGB	N/A	2	4	400	N/A
17	Ewertowski et al. (2019)	2019	Svalbard	Hørbyebreen	78.7667	16.3833	07.2016	Geomorphological mapping	various	~1,000	multirotor	DJI Phantom 3 Advanced	RGB	build-in	2	8	2614	Manually
18	Ewertowski and Tomczyk (2020)	2020	Svalbard	Ebbabreen, Ragnarbreen	78.7375	16.9496	2014	Geomorphological mapping	moraine	3.330	multirotor	DJI Phantom 3 Advanced	RGB	build-in	N/A	N/A	N/A	N/A
19	Fey and Krainer (2020)	2020	Alps (Italy)	rockglacier Lazaun	46.7469	10.7556	09.2016; 06.2017; 08.2017; 10.2017; 06.2018	Change detection	rock glacier	0.110	multirotor	Surveying Robot Mk.AD	RGB	Sony A6000	3	10	N/A	Autonomous
20	Fey et al. (2017)	2017	Alps (Austria)	Marzell rockslide	46.7800	10.8800	10.2012	Change detection	rockslide	N/A	multirotor	TWINS NRN	RGB	Ricoh GXR A12	5	N/A	N/A	N/A
21	Fugazza et al. (2015)	2015	Alps (Italy)	Forni glacier	46.3989	10.5903	08.2014	Change detection	various	0.960	wing	SwingletCam	RGB	Canon Ixus 127 Hs	12	60	N/A	Autonomous
22	Fugazza et al. (2018)	2018	Alps (Italy)	Forni glacier	46.3989	10.5903	2014; 2016	Geomorphological mapping	N/A	2.210	wing	SwingletCam	RGB	Canon Ixus 127 HS; Canon Powershot	15	60	N/A	Autonomous
23	Glasser et al. (2020)	2020	Wales	Moel Ysgyfarnogod	52.8872	-3.9961	N/A	Geomorphological mapping	bedrock surface	0.0004	multirotor	DJI Phantom 4	RGB	build-in	2.33	4.67	872	N/A
24	Groos et al. (2019)	2019	Alps (Switzerland)	Kanderfirn	46.8000	8.3333	09.2017; 06.2018; 08.2018; 09.2018	Change detection	N/A	3.400	wing	Own construction (Paparazii UAV project)	RGB	GoPro Gero 5 Black	5	25	314; 824; 850; 215	Autonomous
25	Hackney and Clayton (2015)	2015	Iceland	Skalafellsjökull; Heinbergjökull	64.3019	-15.7922	2013	Geomorphological mapping	foreland	15.000	wing	Quest UAV 200	RGB	Panasonic LUMIX DMC-LX5	5	10	1980	Manually
26	Hedding et al. (2020)	2020	Altai (Russia)	Maliy Aktru glacier	50.1008	87.6706	08.2018; 08.2019	Geomorphological mapping	moraine	1.700	multirotor	DJI Mavic Pro	RGB	build-in	5; 10; 5	17; 30; 10	787	N/A
27	Hendrickx et al. (2020)	2020	Alps (Switzerland)	Sanetsch Pass	46.3458	7.3042	2017; 2018; 2019	Change detection	talus slope	1,2; 1,3; 2,0	multirotor	DJI F550; DJI Phantom 4 Pro	RGB	Panasonic Lumix DMX-GM5; build in	10	10	1088; 2493; 3053	Autonomous
28	Immerzeel et al. (2014)	2014	Himalaya (Nepal)	Lirung glacier	28.4220	85.5170	05.2013; 10.2013	Change detection	N/A	1.600	wing	SwingletCam	RGB	Canon Ixus 125 Hs	10	20	776; 456	Autonomous
29	Jouvet et al. (2016)	2016	Greenland	Bowdoin glacier	77.6833	-68.5833	05.2015; 06.2015; 07.2015; 08.2015	Change detection	N/A	2.000	wing	Skywalker X8	RGB	Sony α6000	10	100	1000	Autonomous
30	Jouvet et al. (2018)	2018	Greenland	Bowdoin glacier	77.6833	-68.5833	07.07.2016 - 19.07.2016	Change detection	N/A	3.000	hybrid	Firefly6	RGB	Sony α6000	10	10	3900	Autonomous
31	Kaufmann et al. (2018)	2018	Alps (Austria)	Tschadinhorn rock glacier	46.9939	12.8631	07.2016; 08.2017	Change detection	rock glacier	0.053	each type	Hexacopter twinHex; QuestUAV; DJI Mavic Pro; Falcon 8; DJI Phantom 4	RGB	Ricoh GXR A12; Sony ILCE-6000; Sony NEX-5N; build-in	10; 5	2; 10	1636	N/A
32	Kienholz et al. (2020)	2020	Alaska (USA)	Mendenhall glacier	58.4958	-134.5322	2018; 2019	Change detection	N/A	N/A	multirotor	DJI Phantom 4 Pro	RGB	build-in	N/A	N/A	28900	N/A
33	Kraaijenbrink et al. (2016)	2016	Himalaya (Nepal)	Lirung glacier	28.1311	85.5242	05.2013; 10.2013; 05.2014	Change detection	N/A	~1,600	wing	SwingletCam	RGB	N/A	20	20	284; 307; 314	Autonomous
34	Lamsters et al. (2020)	2020	Greenland	Russell glacier	67.0958	-50.2167	07.2016	Geomorphological mapping	N/A	0.450	multirotor	DJI Phantom 3 Advanced	RGB	build-in	4	8	453	Autonomous
35	Lamsters et al. (2020)	2020	Antarctica	Argentine Islands	-65.2500	-64.2667	02.2018; 03.2018	Geomorphological mapping	N/A	4.480	multirotor	DJI Phantom 3 Advanced	RGB	build-in	3.4	6.8	9546	Autonomous

No	Reference	Year	Location	Site	Lat	Lon/Date	Purpose	Target	GSD	Platform	UAV	Sensor	Camera			Images	Flight mode
36	Le Heron et al. (2019)	2019	Henan Province (China)	Shimengou	33.9361	112.7139 N/A	Geomorphological mapping	various	N/A	multirotor	DJI Mavic Pro	RGB	build-in	N/A	N/A	~1000	N/A
37	Lousada et al. (2018)	2018	Svalbard	Advent Valley	78.1858	15.9239 07.2009	Geomorphological mapping	ice wedge	0.080	unknown	N/A	RGB	N/A	6	N/A	N/A	N/A
38	Mather et al. (2018)	2018	Dartmoor (SW England)	Leeden Tor	50.5273	-4.0292 08.2016; 09.2016	Geomorphological mapping	N/A	0,42; 0,12	each type	Sensefly eBee; DJI Phantom 3 Professional	RGB	build-in	3,6; 2,3	3,5; 2,6	219; 200	Autonomous
39	Midgley et al. (2018)	2018	Svalbard	Midtre Lovénbreen	78.8898	12.0563 07.2014	Change detection	moraine	N/A	multirotor	DJI S800	RGB	Canon EOS M	2	2	1042	N/A
40	Pereira et al. (2020)	2020	Kings George Island (Antarctica)	Barton Peninsula	-62.2333	-58.7667 02.2018	Geomorphological mapping	stone circles	0.013	multirotor	DJI Phantom 3	RGB	build-in	0.3	0.2	500	Manually
41_1	Ramsankaran et al. (2020)	2020	Himalaya (India)	East Rathong glacier	27.5667	88.1083 10.2017	Geomorphological mapping	N/A	1.070	wing	Sensefly eBee plus	RGB	Sony DSC-WX220; build in	10	10	135	Autonomous
41_2	Ramsankaran et al. (2020)	2020	Himalaya (India)	Hamath glacier	32.2667	77.3583 09.2018	Geomorphological mapping	N/A	0.750	wing	Sensefly eBee plus	RGB	Sony DSC-WX220; build in	10	10	107	Autonomous
41_3	Ramsankaran et al. (2020)	2020	Himalaya (India)	Panchinala-A glacier	32.7211	77.3044 06.2019	Geomorphological mapping	N/A	1.380	wing	Sensefly eBee plus	RGB	Sony DSC-WX220; build in	10	10	360	Autonomous
42	Rippin et al. (2015)	2015	Svalbard	Midtre Lovénbreen	78.8898	12.0563 08.2013; 09.2013	Geomorphological mapping	drainage pathways	~1,000	wing	Quest UAV 200	RGB	Panasonic LUMIX DMC-LX5	5	10	423	Autonomous
43	Rossini et al. (2018)	2018	Alps (Switzerland)	Morteratsch glacier	46.4094	9.9317 08.2016; 09.2016	Change detection	N/A	0,382; 0,634	multirotor	DJI Phantom 4	RGB	build-in	5	2	172; 368	Autonomous
44	Ryan et al. (2015)	2015	Greenland	Store glacier	70.4000	-50.6000 08.2013; 09.2013	Change detection	N/A	3,170; 4,950; 5,020	wing	Skywalker X8	RGB	Panasonic LUMIX DMC-LX5	N/A	40; 38; 39	611; 1051; 567	Autonomous
45	Scaioni et al. (2018)	2018	Alps (Italy)	Forni glacier	46.3989	10.5903 08.2014; 09.2016	Change detection	N/A	N/A	each type	SwingletCam; Tarot quadrocopter	RGB	Canon Ixus 127 HS; Canon Powershot ELPH 320 HS	N/A	N/A	N/A	Autonomous
46	Seier et al. (2017)	2017	Alps (Austria)	Pasterze Glacier	47.0856	12.7233 09.2016; 11.2016	Change detection	glacier tongue	0.340	wing	Quest UAV	RGB	Sony α6000	15	15	100; 354	N/A
47	Storni et al. (2020)	2020	Alps (Switzerland)	Moosfluh landslide	46.4000	8.0417 08.2018	Change detection	rockslide	N/A	multirotor	DJI Phantom 4 Pro+	RGB	build-in	3	N/A	~3000	Autonomous
48_1	Storrar et al. (2020)	2020	Svalbard	Hørbyebreen	78.7500	16.3833 08.2017	Geomorphological mapping	eskers	N/A	multirotor	DJI Phantom 3 Advanced; DJI Mavic Pro	RGB	build-in	5	16	N/A	N/A
48_2	Storrar et al. (2020)	2020	Iceland	Breiðamerkurjökull	64.0583	-16.3000 05.2017	Geomorphological mapping	eskers	N/A	multirotor	DJI Phantom 3 Advanced; DJI Mavic Pro	RGB	build-in	3	60	N/A	N/A
49	Tirla et al. (2020)	2020	Făgăraș Mountains (Romania)	Mușeteica glacial cirque	45.5754	24.6494 N/A	Geomorphological mapping	marble karst; caves	1.000	multirotor	DJI Phantom 4	RGB	build-in	10	50	1314	Autonomous
50	Tomczyk et al. (2019)	2019	Svalbard	Dynamisk creek fan	78.7000	16.6167 08.2014	Geomorphological mapping	alluvial fans	0.800	multirotor	DJI Phantonm 2 Vision	RGB	build-in	2	4	880	Manually
51	Tomczyk and Ewertowski (2020)	2020	Greenland	Zackenberg river	74.5000	-20.5000 08.2017	Geomorphological mapping	river	N/A	multirotor	DJI Phantom 4 Pro	RGB	build-in	N/A	N/A	~5000	Manually
52	Tomczyk et al. (2020)	2020	Greenland	Zackenberg river	74.5000	-20.5000 08.2017	Change detection	river	0.150	multirotor	DJI Phantom 4 Pro	RGB	build-in	1.8-2.8	3.6-5.6	~5000	Manually
53	Tonkin et al. (2014)	2014	Wales	Cwm Idwal moraine–mound complex	53.1139	-4.0272 N/A	Geomorphological mapping	moraine	0.211	multirotor	DJI S800	RGB	Canon EOS-M	2.2	8.8	543	Autonomous
54	Tonkin et al. (2016)	2016	Svalbard	Austre Lovénbreen	78.8867	12.0972 08.2014	Change detection	moraine	0.676	multirotor	DJI S800	RGB	Canon EOS-M	N/A	50	1856	Autonomous
55	Van der Sluijs et al. (2018)	2018	Northwest Territories (Canada)	Mackenzie River	68.5000	-134.5000 2015; 2016; 2017	Change detection	permafrost terrain	14.270	each type	Spyder PX8 Plus; RX4-S Surveyor; DJI Inspire 1 Pro; eBee Plus; Phantom 4 Pro	RGB	Sony a6000; Sony RX100 III; Zenmuse X5; build in	2.8	50	20461	Autonomous
56	Van Woerkom et al. (2019)	2019	Himalaya (Nepal)	Lirung Glacier	28.3833	85.9333 05.2013; 10.2013; 10.2015; 04.2016; 04.2017; 10.2017; 04.2018	Change detection	rock glacier; moraine	1.500	unknown	N/A	RGB	N/A	10	20	N/A	N/A
57	Vivero and Lambiel (2019)	2019	Alps (Switzerland)	La Roussette rock glacier	46.0368	7.4468 2016; 2017	Change detection	rock glacier	0.020	wing	eBee RTK	RGB	SONY WX; S.O.D.A.	~7	~7	63; 61; 57; 142; 150	Autonomous
58	Westoby et al. (2015)	2015	Antarctica	Heritage Range	-80.3000	-81.3442 N/A	Assessment of surficial geology	moraine	0.300	wing	N/A	RGB	Nikon D7000; Panasonic Lumix DMC-LX5	N/A	N/A	153	Autonomous; manually
59	Westoby et al. (2020)	2020	Alps (Italy)	Miage glacier	45.8042	6.8406 06.2015; 07.2016; 07.2017; 07.2018	Change detection	rock glacier	0.150	multirotor	DJI Phantom 3 Professional	RGB	build-in	N/A	100	1052; 718; 1623; 1569	Manually
60	Whitehead et al. (2013)	2013	Bylot Island (Canada)	Fountain glacier	73.0000	-78.5000 2010; 2011	Change detection	N/A	N/A	wing	Outlander UAV	RGB	Panasonic Lumix DMC-LX3	10	50	148	Autonomous
61	Wigmore and Mark (2017)	2017	Ands (Peru)	Llaca glacier	-9.4375	-77.4417 07.2014; 07.2015	Change detection	N/A	~0,500	multirotor	Own construction	RGB	Canon S110 Powershot	5	10	323; 826	Autonomous
62	Wilson at al. (2019)	2019	Ands (Chile)	Chileno Valley	-46.8667	-73.2000 02.2017	Geomorphological mapping	glacial lake	0.750	wing	Skywalker X8	RGB	Sony NEX-5 N	50	50	N/A	Autonomous

Publikacja nr II z załącznikami

Śledź, S., & Ewertowski, M. W. (2022). Evaluation of the Influence of Processing Parameters in Structure-from-Motion Software on the Quality of Digital Elevation Models and Orthomosaics in the Context of Studies on Earth Surface Dynamics. *Remote Sensing*, *14*(6). https://doi.org/10.3390/rs14061312

Do publikacji dołączono poniższe załączniki:

1) Appendix S1: Tabelę z wynikami eksperymentu dla każdego schematu postępowania w oprogramowaniu Agisoft Metashape;

2) Appendix S2: Histogramy rozkładu różnic wysokości, obliczonych na podstawie CPs dla każdego modelu otrzymanego w eksperymencie;

3) Appendix S3: Skrypt w języku Python do oprogramowania Agisoft Metashape. Wersja „The fastest";

4) Appendix S4: Skrypt w języku Python do oprogramowania Agisoft Metashape. Wersja „Optimal";

5) Appendix S5: Skrypt w języku Python do oprogramowania Agisoft Metashape. Wersja „Best quality".

Article

Evaluation of the Influence of Processing Parameters in Structure-from-Motion Software on the Quality of Digital Elevation Models and Orthomosaics in the Context of Studies on Earth Surface Dynamics

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Abstract: The fully automated Structure-from-Motion approach for developing digital elevation models and orthomosaics has been known and used in photogrammetry for at least 15 years. Years of practice and experience have allowed researchers to provide a solid description of the applicability and limitations of this method. That being said, the impact of input processing parameters in software on the quality of photogrammetric products has yet to be fully ascertained empirically. This study is aimed at identifying the most advantageous processing workflow to fill this research gap by testing 375 different setup variations in the Agisoft Metashape software for the same set of images acquired using an unmanned aerial vehicle in a proglacial area. The purpose of the experiment was to determine three workflows: (1) the fastest, which has the shortest calculation time; (2) the best quality, which is as accurate as possible, regardless of the time taken for the calculations; and (3) the optimal, which is a compromise between accuracy and calculation time. Each of the 375 processing setup variations was assessed based on final product accuracy, i.e., orthomosaics and digital elevation models. The three workflows were selected based on calculating the height differences between the digital elevation models and the control points that did not participate in their georeferencing. The analyses of the root mean square errors (RMSE) and standard deviations indicate that excluding some of the optimization parameters during the camera optimization stage results in high RMSE and an increase in the values of standard deviation errors. Furthermore, it was shown that increasing the detail of individual processing steps in software does not always positively affect the accuracy of the resulting models. The experiment resulted in the development of three different workflows in the form of Python scripts for Agisoft Metashape software, which will help users to process image sets efficiently in the context of earth surface dynamics studies.

Keywords: unmanned aerial vehicle; Structure-from-Motion; photogrammetry; Agisoft Metashape

1. Introduction

The relief of the Earth's surface is constantly modified by natural processes (e.g., erosion, weathering) and direct human activity. These dynamics are important to studies of the landscape evolution as well as studies of processes which may pose threats to human life and infrastructure. Therefore, landscape dynamics have been studied in a number of contexts that include the following: (a) the possibility of the occurrence of landslides and areas susceptible to their formation [1–3]; (b) to observe areas at risk of snow avalanches [4]; (c) to monitor land surface changes due to mining activities [5,6]; and (d) to assess the dynamics of aeolian processes [7] or changes to riverscapes [8–12]. One example of areas characterized by particularly high dynamics of the surface is proglacial areas [13–17]. Ongoing climate warming [18–20], characterized by an increase in mean annual air temperatures

and changes in precipitation, causes the melting of glaciers [21] and reveals numerous geomorphological forms in their forelands, previously hidden under the glacier ice [20,22–24]. Moreover, proglacial areas are an important storage of water (in the form of dead-ice) and sediments, which can be relatively easy to mobilize [20,25,26]. For example, meltwaters often have a significant erosive potential and can cause large transformations both in the immediate foreland of the glaciers and in the areas further away, through glacier lake outburst floods or debris flows [11,27–31]. For this reason, proglacial areas are currently the subject of research by many scientists who use modern research techniques to monitor and collect data on land surface characteristics and landform dynamics in front of retreating glaciers worldwide [17].

Unmanned aerial vehicles (UAV, drone), equipped with a sensor in the form of an RGB camera, have recently become a popular platform for observing various objects or areas from above [32–34]. The undoubted advantage of UAVs in environmental research is low price, mobility and high configuration options, depending on the model and manufacturer. Anderson and Gaston rightly noticed in 2013 [35] that UAVs will revolutionize spatial ecology—UAVs can now be found in more and more applications related to scientific and commercial activities. Thanks to the UAV, the operator can take images of the selected research objects from a low altitude while performing a manual or autonomous flight. A dedicated UAV application allows for setting up parameters such as flight altitude, flight speed, forward and side overlap of images, or marking the area of interest and designing the mission path. The current mobile applications significantly support the operator during a mission, e.g., automatically interrupting it when the battery is low and warning against bad weather conditions such as strong gusts of wind. In glacial geomorphology, UAVs have been widely used since 2010, and different studies utilized various UAV construction types, sensors, and flight parameters, depending on the shape of the studied area, meteorological conditions, research objectives and the expected accuracy of photogrammetric products [12,36,37]. It should be emphasized that in addition to aerial images obtained from UAVs, images collected from terrestrial photogrammetry (robotic or stationary) are becoming more and more popular (e.g., [38]).

The end result of the survey mission is a collection of images, which is a record of the current state of the studied area. The images can be used as photographic documentation, but primarily as data for the development of a digital elevation model (DEM) and orthomosaic as the end products of processing in Structure-from-Motion (SfM) software [39]. Thanks to the external Ground Control Points (GCPs), measured with the differential Global Navigation Satellite Systems (dGNSS) receiver (external georeferencing) or the lo-cations embedded in the images from the on-board GNSS receiver (direct georeferencing, which can also be replaced by corrected camera positions as a text file imported to the software), the SfM software combines the images with each other based on characteristic points, marked on at least two images. As a result, first a sparse, and then a dense point cloud is obtained, which is the basis for generating the final photogrammetric products. A DEM, which is a three-dimensional model of the studied area's surface and orthomosaic, is commonly used for analyses related to geomorphological mapping (e.g., [22,28,40–42]), change detection (e.g., [38,43–45]), process-form studies [46] or mapping of surficial geology [47]. Evidence of the common use of UAV and the SfM method in geomorphology consists of publications in which the authors present the appropriate workflow of conduct during field research and in the further preparation of publications and presentation of results (e.g., [48–50]). Thus far, however, it has not been tested in detail how individual processing parameters in the SfM software affect the accuracy of the final result. Selection of the appropriate parameters is important because this stage has a crucial impact on the accuracy of the models obtained, which, if performed incorrectly, may lead to wrong results and thus incorrect conclusions from the conducted research.

Thus far, only limited publications have attempted to explain the influence of different calculation methods on the accuracy of photogrammetric products and possible ways to accelerate the processing of UAV-generated images into DEMs and orthomosaics.

For example, some attention was directed to the impact of mission design (e.g., [51–53]) or number and location of GCPs (e.g., [54–57]) on the accuracy of photogrammetric products. Another example is a work illustrating the processing of photo sets with no GCPs, but using co-registrations of the models (e.g., [58]). The authors proved that in this type of research, such as change detection, satisfactory results can be achieved even without GCPs, which is particularly important in the case of objects that are difficult to access. Similar conclusions were suggested by de Haas et al. [59], who presented evidence for the limited impact of GCPs on the increase in accuracy of models compared to projects where the co-alignment of multiple surveys is used. In addition, researchers also checked if the choice of software matters for the quality of DSM (e.g., [60]) and application of oblique photos (e.g., [61]), and critically assessed the use of RTK technology in UAVs compared to the traditional GCP scheme with UAVs without this technology [62]. The aim of this study was to investigate the influence of particular calculation parameters in the Agisoft Metashape software on the accuracy of photogrammetric products: DEMs and orthomosaics. Another objective was to find the most efficient workflows that can be used in the processing of large images sets of different research objects. For this purpose, 375 different workflows were formulated in the software, which were then checked while processing the same set of images representative of the proglacial area. Additionally, we aimed to select three workflows: (1) the fastest, which has the shortest calculation time; (2) the best quality, which is as accurate as possible, regardless of the time taken for calculations; and (3) the optimal, which is a compromise between accuracy and calculation time. These workflows are included in this article as Supplementary Materials in the form of Python scripts for processing a set of images in Agisoft Metashape. Thus far, there is no publication of such multi-threaded research in that form that can be easily implemented by other researchers in their work. The correct selection of the script and processing efficiency depend on the size of the image set, the expected accuracy, or the available computing power.

2. Materials and Methods

2.1. Study Area and Technical Information

The experiment used a set of UAV-collected images showing a sample area (~50,000 m^2) of diverse terrain within the foreland of the Breiðamerkurjökull, Iceland (Figure 1). The flight took place on 5 September 2021 using the Map Pilot Pro mobile application in autonomous mode. To acquire the images, we used a multirotor DJI Phantom 4 Pro UAV equipped with a DJI FC6310 camera at a resolution of 20 MP and a focal length of 8.8 mm (24 mm equivalent for 35 mm format). In total, 82 vertical RAW images with a resolution of 5464 × 3640 pixels were taken and saved in the DNG format. The forward and side overlap were programmed at 80%, while the flight altitude was set at 70 m, rate of the image capture: ~5 s. The photographic exposure was set at 1/160 s (19 images) and 1/120 s (63 images). The GSD (Ground Sample Distance) of the images was ~1.92 cm/pix. The intention of the authors was to carefully reproduce the typical settings for missions performed for similar purposes [37]. During the flight, no strong gusts of wind or rainfall were noticed, even though the sky was fully cloudy. The quality of the images was checked in the Agisoft Metashape software before processing using a dedicated tool "Estimate image quality"—each image taken for calculations had a value above 0.80. DNG images were directly imported into Agisoft Metashape and were not subjected to exposure nor color modifications.
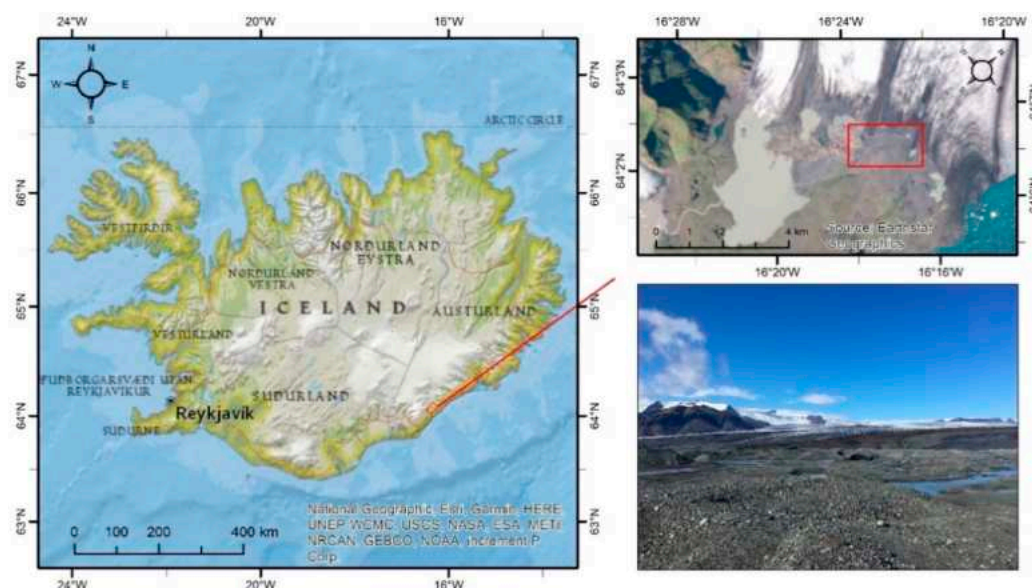
Figure 1. Location of the study area and a photo from the study area where the flight took place. The study areas represent a typical proglacial landscape, built from sands and gravel.

We used 40 GCPs, arranged in 4 rows of 10 points and 15 m apart at an angle of 90°, to georeference the model. Additionally, in order to check the accuracy of DEMs, 31 control points (CPs) not involved in georeferencing during SfM processing were randomly located in the study area. Each of the GCPs and CPs were constructed in the form of a circle of stones, in which the location of the middle stone was measured by the differential GNSS Topcon Hiper II receiver (Figure 2), using RTK survey technique and local base station (vector < 200 m). Survey uncertainties were between 0.008 and 0.015 m. The Agisoft Metashape Professional software (version 1.7.1 build 11,797) was used to process the set of images, model and generate DEMs and orthomosaics. The computing platform was a desktop computer with Windows 10 64 bit, a 6-core (12 thread) Intel Xeon E5-2440 processor with a base frequency of 2.40 GHz (2.90 GHz in Turbo mode), a GeForce GTX 1060 6 GB graphics card, and 79.97 GB DDR3 RAM. The computer was not used for other purposes during calculations to ensure the same computing power for all models.

(**a**)   (**b**)
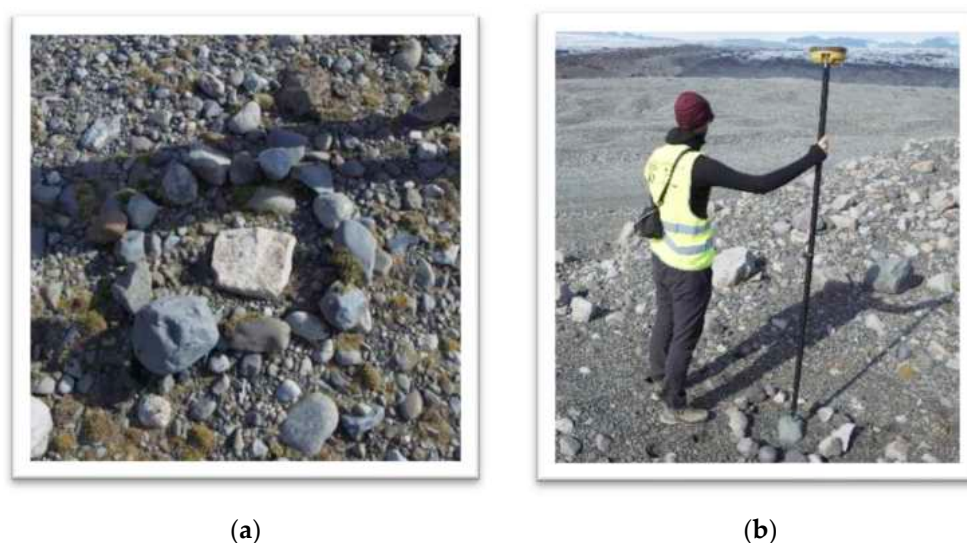
Figure 2. (**a**) Example of an established GCP; (**b**) method of measuring points with the GNSS receiver. GNSS measurement was carried out on the middle stone in the circle, which differed from the others by its size and shape.

2.2. Guidelines of the Experiment

Before starting the calculations, the planned variants of input processing parameters were formulated in the software, while naming of the projects followed a logical, structured and individual code (Figure 3). We investigated how the following parameters and their values would impact the final accuracy of the photogrammetric products (measured by errors on CPs) and calculation time:

- Alignment accuracy—five levels of accuracy: lowest, low, medium, high, and highest.
- The number of key points and tie—three sets were adopted:
    1. Set "A"—limit 10,000 key points and 1000 tie points.
    2. Set "B"—limit 100,000 key points and 10,000 tie points.
    3. Set "C"—no limit.
- Dense point cloud generation quality—five levels of quality: lowest, low, medium, high, and ultra-high.
- Optimization parameters—five sets were adopted:
    1. Set "A"—parameters: f.
    2. Set "B"—parameters: f, cx, cy.
    3. Set "C"—parameters: f, cx, cy, k1, k2.
    4. Set "D"—parameters: f, cx, cy, k1, k2, b1, b2.
    5. Set "E"—parameters: f, cx, cy, k1, k2, k3, k4, p1, p2, b1, b2.
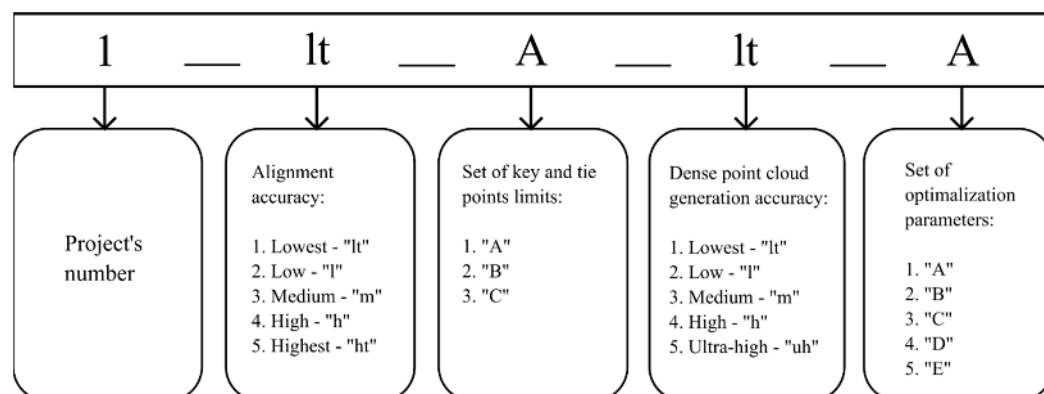
Figure 3. Scheme of project's code naming.

The levels of accuracy mentioned above determine the sampling rates at which the software processes the data. When the calculation accuracy is set to high at the image alignment stage, the software works on images with their original resolution. On the other hand, when the medium accuracy is set, the original image is reduced four times, in the low setting 16 times and in the lowest setting 64 times. For detailed photos, the highest level can be used, where the original resolution of the image is upscaled by a factor of 4 to find more key points. The meaning of these levels of settings is the same for the dense point cloud generation. In addition, during the image alignment step, the software calculates the optimization parameters that can be used to optimize the sparse point cloud. The f parameter is the focal length; cx and cy are intercepting axis of the lens optical with sensor plane; b1 and b2 are coefficients of affinity transformation and skew; coefficients k1, k2, k3 and k4 relate to radial distortion, and coefficients p1 and p2 to tangential distortion [63]. A detailed description of the processing steps, including the characteristics of the accuracy and quality settings, and a description of the optimization parameters process, can be found in the Agisoft Metashape software manual, available on the manufacturer's website (https://www.agisoft.com/downloads/user-manuals/ accessed on 3 March 2022).

Taking into account all possible values of the above-mentioned parameters, 375 (5 × 3 × 5 × 5 = 375) different workflows were formulated and processed. In the first stage, an "initial" project was created in Agisoft Metashape to which the images and

GCPs were imported in the UTM zone 28N coordinate system (EPSG: 25828). DNG photos were not modified or converted in any way before importing them into the software. Subsequently, GCPs were marked into all images. Prepared in this way, the project was duplicated 375 times in order to start processing in the next step in accordance with the adopted workflow for a given project. As part of the calculations, each sparse point cloud was filtered with the Gradual Selection tool, using the same parameters for all models (reprojection error = 0.5, reconstruction uncertainty = 10, image count = 2, projection accuracy = 20). The end result of the processing was a report, a DEM, and an orthomosaic (Figure 4).
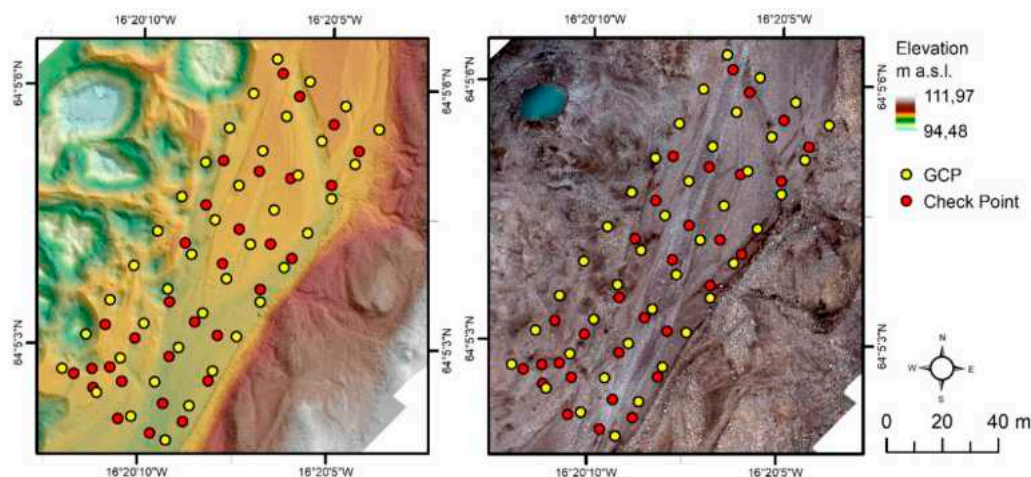
Figure 4. Example of end results of the processing: a DEM and an orthomosaic, with locations of GCPs and CPs.

In the next stage, DEMs were checked for height accuracy in the ArcMap software, using 30 CPs not participating in georeferencing. By selecting the Extract Values to Points tool, the differences in height between the CPs and the DEMs were obtained, and then the standard deviation and the root mean square error (RMSE) were calculated for the CPs of each model. We tested the accuracy of DEMs, not raw point clouds, as in most previous geomorphological works, DEMs were the most commonly used as final products for landform interpretation, mapping and change detection analysis [37]. In addition, we also visually checked raw point clouds in CloudCompare. For projects where RMSE values were low, the locations of control points were near to point cloud. For projects where RMSE values were high, control points were noticeably above or under the cloud. Additionally, based on the data from the report, the calculation time for each processing step was checked and the total calculation time for each project was summarized. Detailed information on each workflow is included in the Supplementary Materials (S1).

3. Results

Out of 375 projects, 195 did not generate a dense point cloud nor produced a DEM and orthomosaic. The step of aligning images at the lowest accuracy is responsible for the first 75 unsuccessful projects—the number of points remaining after filtration of sparse point clouds at this level (~600 points for all 75 chunks) was insufficient. Hence, the first result of the analysis is the statement that the level of accuracy of alignment set to lowest and subsequently filtered is insufficient to generate photogrammetric products. The sets of the "A" and "B" optimization parameters and alignment of images at low, medium, high, and highest accuracy are responsible for the remaining 120 projects, for which it was not possible to generate dense clouds. In these workflows, the sparse point clouds were not optimized with the k1 and k2 parameters, which were characterized by a high RMSE for GCPs of ~48.23 cm and a high reprojection error in the range of 2.74–5.80 pixels. Parameters k1 and k2 are responsible for the optimization of the sparse point cloud in terms of the

radial distortion of the lens—the conclusion is that images from the DJI FC6310 camera are burdened with high radial distortion. Due to the absence of dense point clouds and DEMs in these projects, they were not included in any further work, and so only reports were generated.

In the remaining 180 projects, DEMs, orthomosaics and calculation reports were generated, in line with the planned workflows. The spatial resolution of the photogrammetric products depended on the level of accuracy set for dense point cloud generation—at the lowest level the resolution was ~28 cm, at the low level ~14 cm, at the medium level ~7 cm, at the high level ~3.5 cm, and at the ultra-high level ~1.75 cm. The spatial resolution of all orthomosaics was the same: 1.75 cm. RMSE and standard deviation based on CPs were calculated. From the obtained results, it can be concluded that when the accuracy of alignment of images was set to the high or highest level and then combined with the exclusion of k3, k4, p1, and p2 optimization parameters, the results were characterized by an increase in the RMSE value and standard deviation based on CPs. RMSE/SD for the high level reached the values of 14–15 cm, and for highest level 43–44 cm. The increase in the RMSE value and standard deviation based on CPs occurs with an increase in the number of points in the sparse cloud. Only when the optimization of the sparse point cloud was conducted using the set "E" (optimization of the parameters f, cx, cy, k1, k2, k3, k4, p1, p2, b1, b2) were the high values of RMSE and standard deviations based on CPs reduced to values <2.5 cm. Figure 5 shows histograms for the 12 selected models, demonstrating the effect of parameters k3, k4, p1, and p2 on the height difference distribution based on CPs. Histograms of the height difference distribution, calculated based on CPs for each model, are included in S2 as Supplementary Materials. Moreover, a noticeable effect on the RMSE and standard deviation value was noted for the step of dense point cloud generation—with the increase in its quality and optimization of all parameters (set "E"), the values decrease.
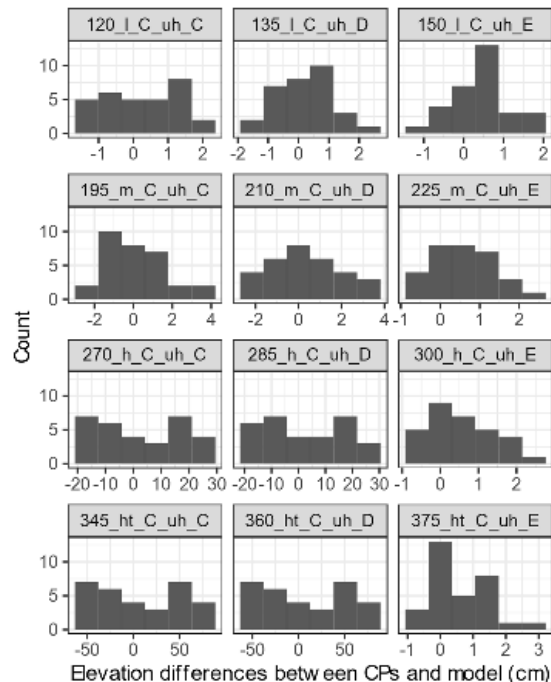
Figure 5. Distribution of the difference in elevation between 30 CPs and DEMs for the 12 selected workflows. The histograms are arranged according to the sets of optimization parameters and the level of accuracy of image alignment: in the first column there are four histograms for projects with the "C" set, in the second with the "D" set, and in the third with the "E" set. The level of accuracy for generating the sparse point cloud in the column is set from low (first row) to highest (fourth row).

All histograms are for projects where the quality of dense point cloud generation has been set to ultra-high. The following regularities can be seen: (1) increasing the quality of generating a sparse point cloud increases the differences in elevation for models with optimized parameter sets "C" and "D" (approximately from −2 to 2 cm for low, from −2 to 4 cm for medium, from −20 to 30 cm for high and from −50 to 50 cm for ultra-high quality); (2) optimization of the sparse point cloud with all parameters (set "E") significantly affects the accuracy of the models, resulting in the standard deviation of <2.5 cm.

In addition to analyzing the quality of the models, the calculation time for each step was checked, while calculation time for each project was summarized to compare the workflows in terms of calculation time and test if the increase in accuracy can be achieved with reasonable computing time. The step of generating a dense point cloud turned out to be crucial—the calculation time at the lowest level of accuracy may be shorter than ultra-high even six times, and between high and ultra-high three times (Table 1). The detailed results of the calculations, along with the quantitative and qualitative characteristics of the models, can be found in the Supplementary Materials (S1).

Table 1. An example of the calculation time data from Supplementary Materials (S1) for each processing step. The data concern 15 projects which include: accuracy of alignment of images at the medium level, three different sets of tie points and key point limits, accuracy of generating a dense cloud of points at five different levels, and a set "C" of optimization parameters. It is clearly visible that the step of generating a dense point cloud is the most time consuming. It is worth noting that the orthomosaic generation step can account for over 60% of the calculation time (e.g., project 181_m_A_lt_C).

Project's Code	Calculation Time (h)					
	Alignment of Images	**Optimization Parameters**	**Dense Point Cloud Generation**	**DEM Generation**	**Orthomosaic Generation**	**SUM**
181_m_A_lt_C	00:03:47	00:00:00	00:07:44	00:00:06	00:19:19	00:30:56
182_m_B_lt_C	00:04:30	00:00:05	00:07:09	00:00:05	00:20:28	00:32:17
183_m_C_lt_C	00:05:13	00:00:04	00:06:23	00:00:05	00:21:22	00:33:07
184_m_A_l_C	00:03:45	00:00:01	00:07:18	00:00:12	00:21:12	00:32:28
185_m_B_l_C	00:04:49	00:00:06	00:07:09	00:00:11	00:21:02	00:33:17
186_m_C_l_C	00:05:03	00:00:04	00:07:01	00:00:10	00:20:56	00:33:14
187_m_A_m_C	00:03:53	00:00:01	00:23:15	00:00:45	00:19:33	00:47:27
188_m_B_m_C	00:04:53	00:00:04	00:14:48	00:00:36	00:19:48	00:40:09
189_m_C_m_C	00:05:04	00:00:08	00:13:29	00:00:33	00:19:52	00:39:06
190_m_A_h_C	00:03:49	00:00:01	00:47:01	00:02:07	00:20:00	01:12:58
191_m_B_h_C	00:04:54	00:00:03	00:46:09	00:01:56	00:19:33	01:12:35
192_m_C_h_C	00:05:04	00:00:07	00:48:08	00:02:00	00:19:05	01:14:24
193_m_A_uh_C	00:03:50	00:00:01	02:51:00	00:06:33	00:25:20	03:26:44
194_m_B_uh_C	00:05:00	00:00:04	02:34:00	00:06:11	00:24:19	03:09:34
195_m_C_uh_C	00:04:38	00:00:06	02:44:00	00:07:04	00:23:00	03:18:48

4. Discussion

In the following subsections, we discuss the impact of subsequent processing steps in SfM software on the accuracy of DEMs and orthomosaics.

4.1. Influence of Processing Parameters

4.1.1. Alignment of Images

The level of accuracy in the alignment of images may affect the results of standard deviations and RMSE based on CPs; nevertheless, for each level of accuracy in this step, values below 1 cm are possible to achieve. However, higher values in the order of 9, 15 or 44 cm were recorded where the level of accuracy was set to high or highest, the sparse point cloud was not optimized with the k3, k4, p1, and p2 parameters ("E" optimization parameter set), and no point limits were introduced in the sparse cloud. Such high results

did not occur at the low and medium levels in projects with a similar number of points in a sparse cloud, hence the influence of the size of the sparse point cloud on this issue should be excluded. In addition, this step significantly influenced the calculation time—the use of high or highest level of accuracy, while not applying the key and tie points' limits, only increased the calculation time, but did not increase the accuracy of the photogrammetric products. At the low and medium level of accuracy, the difference in calculation time was visibly lower. It has to be noted that downsampling of the original images (i.e., levels lowest, low, and medium) can mix spectral values of pixels. Therefore, in the case of large spectral differences between control points and surroundings, this aspect can influence the accuracy assessment.

4.1.2. Key and Tie Points' Limits

The limit of key and tie points, with one exception, did not affect the accuracy of DEMs. In the group of projects with the set "A" (i.e., limit 10,000 key points and 1000 tie points), the lowest standard deviation based on CPs was 0.63 cm (which is the best result among all 180 projects). The most accurate project with the "B" set (i.e., limit 100,000 key points and 10,000 tie points) had a standard deviation of 0.65 cm, and with the "C" set (i.e., no limit on key or tie points) the standard deviation was 0.67 cm. Similar results of the sets "A", "B" and "C" were also recorded for the RMSE values (0.76, 0.76, and 0.80 cm, respectively). The exception here is the generation of a sparse point cloud at the high and highest level of accuracy, plus a lack of optimization with parameters k3, k4, p1, and p2, which significantly reduces the accuracy of the models (standard deviation and RMSE based on CPs in the range of 9–44 cm). Such large values for high and highest settings can be potentially related to the general roughness of the surface or false matches related to similar texture of the studied area.

Therefore, increasing the number of points in the sparse cloud by increasing the limit of key and tie points or removing them completely does not always improve the accuracy of the models, and may result in an extension of the calculation time during its generation and subsequent processing steps. This applies, for example, to the three projects with the longest calculation times, of which the longest was almost five hours.

4.1.3. Dense Point Cloud Generation

The process of generating a dense point cloud turned out to be a significant element in terms of the accuracy of the models. High and ultra-high quality in combination with optimization of the parameters from the "E" set produced the best results—the resultant DEMs were characterized by standard deviation and RMSE based on CPs ≤ 1 cm. That likely results from the texture of the surface (gravels)—in this case, more characteristic points can be identified in the images and used to construct point cloud. The increase of quality of the dense point cloud generation step, along with the use of the key and tie points' limits from the "A" set, result in a significant decrease in the value of the standard deviation and RMSE based on CPs. It should be underlined that calculating dense cloud with the highest possible quality resulted in the extension of the calculation time: in the case of the ultra-high quality, even several times. This is because the ultra-high settings oversample the original images and, therefore, quadruple memory consumption.

4.1.4. Optimization Alignment

The optimization of the sparse point cloud turned out to be the most important processing step in terms of the accuracy of DEMs. As mentioned in Section 3, projects with parameter sets "A" and "B" did not generate a dense point cloud. Only adding the parameters k1 and k2 to the sets "C", "D", and "E" resulted in the generation of a dense point cloud and photogrammetric products. These parameters relate to radial distortion [64], which characterizes the images from the DJI FC6310 camera [50], hence the lack of these parameters in the optimization could cause the problem with generation of a dense point cloud. The lowest RMSE and SD of CP errors were recorded in the

workflows with the "E" set, in which all possible optimization parameters were applied, i.e., responsible for radial and tangential distortion, affinity and orthogonality. Nearly all the most accurate models in the experiment have been optimized with these parameters, therefore we recommend their use. A comparison of DEM accuracy results in relation to the optimization sets is presented in Figure 6. However, the possibility of overparameterization should be taken into account [65], for it may result in a poorly modeled surface and that is not reflected in its actual shape. It should be emphasized that the option to skip this step completely or partially should be used only when the operator has more reliable calibration parameters than those estimated by the software (for example, when using cameras calibrated in laboratory conditions). The gain in time is negligible compared to the significant loss in accuracy. Before the use of DEMs for further analyses, we recommend checking them first with CPs.

(**a**) (**b**)
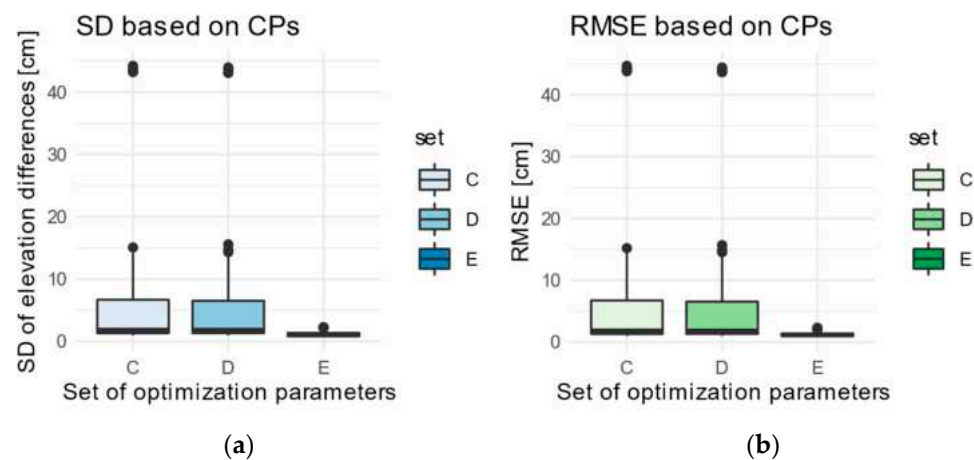
Figure 6. Distribution of standard deviation (**a**) and RMSE (**b**) values based on CPs. The figure suggests that use of the "E" set would result in lower error values. For the projects with the "E" set, no DEMs with very high errors of ~45 cm were found.

4.2. Best Workflows

Out of 180 completed projects, three workflows were selected, corresponding to the requirements formulated on account of the research aims. The main determinant was the low values of standard deviation and RMSE based on CPs in relation to the processing time of the set of images. On the other hand, when choosing the fastest procedure, it was assumed that the spatial resolution of the obtained DEM was better than 10 cm. The full characteristics of the workflows are presented in Table 2 based on the data contained in Supplementary Materials (S1).

4.3. Workflows in Python Scripts

In order to process many sets of images more efficiently or develop accurate DEMs and orthomosaics, workflows and their settings presented in the previous subsection were prepared in the form of Python scripts for Agisoft Metashape Professional (runs stable in version 1.7.1 build 11,797). The scripts are text files that run in the software with the Run script tool. They are written to make calculations on all chunks in an open project. The scripts should be used for projects with imported images, and to obtain a high-accuracy model, one should put GCPs on the images before running the scripts. Some of the previous studies have paid attention to the reproducibility of algorithms in Agisoft Metashape software, indicating that they may result in different outcomes (elevation variations ≥ 10 cm) even while using the same set of images and processed with exactly the same processing workflow [66]. For this reason, the scripts were checked on the same set of images used in the study, in which no significant differences were found based on reports and analysis of the results. Nevertheless, random differences in other larger sets of images cannot be excluded, such that the variance of the point cloud [50] or precision

map [67] should be investigated before proceeding with further analysis of the processed data. The scripts are provided as Supplementary Materials for this article.

Table 2. Detailed description of the three workflows that meet the requirements formulated in view of the research aims. The difference in the SD of CP errors between workflows I and II is 0.38 cm, and between II and III only 0.07 cm. However, the workflows differ from each other mainly in terms of the time of calculations, which in the I type was more than seven times faster than the III type. The conclusion is that setting higher levels of accuracy in the software is not always appropriate (remembering that the total calculation time depends mainly on the computing power).

Type of Workflow	Project's Code	Processing Parameters	DEM GSD (cm)	RMSE (cm)	SD of Elevation Differences (cm)	Calculation Time (h)
I. The fastest	128_l_B_m_D	1. Alignment accuracy: low. 2. Count of key and tie points: 100,000 (key points), 10,000 (tie points). 3. Dense point cloud generation quality: medium. 4. Optimization parameters: f, cx, cy, k1, k2, b1, b2.	7.01	1.03	1.01	00:35:08
II. Optimal	147_l_C_h_E	1. Alignment accuracy: low. 2. Count of key and tie points: no limits. 3. Dense point cloud generation quality: high. 4. Optimization parameters: f, cx, cy, k1, k2, k3, k4, p1, p2, b1, b2.	3.50	0.81	0.70	01:05:14
III. Best quality	223_m_A_uh_E	1. Alignment accuracy: medium 2. Count of key and tie points: 10,000 (key points), 1000 (tie points). 3. Dense point cloud generation quality: ultra-high. 4. Optimization parameters: f, cx, cy, k1, k2, k3, k4, p1, p2, b1, b2.	1.75	0.76	0.63	03:47:02

4.4. Potential Applications

The scripts can be used in the analysis of many research objects. The set of images analyzed in this study concerned proglacial areas with different terrain heights. Other potential applications may include, for instance, studies of alluvial fans [68], glacial landforms [40,69], glacier lake outburst floods [70,71] or aeolian landforms [72–74]. Furthermore, the scripts can be used for modelling various small objects, e.g., in archaeology [75] or geomorphology [76]. The presented scripts enabled a quick launch and systematic work, thereby making it possible to process more efficiently, e.g., several dozen large sets of images in agriculture [77], where each field can be used as a separate point of interest. The use of scripts, instead of selecting parameters manually, will be particularly helpful when processing many projects simultaneously in a computing cluster, positively influencing usage efficiency. This utility will be of most effective importance for multiannual, cyclical analyses of the same research areas (e.g., glaciers) [44,45], as it provides a constant, comparable workflow, reduces the time spent on calculations and project preparation, and will make comparisons between models more reliable, e.g., in research geomorphological fields such as change detection (e.g., [78]). In addition, field work may require a quick check on a

portable notebook to ensure that the selected flight parameters (altitude, forward and side overlap of images) are sufficient to generate an accurate model. Script #1, with the shortest calculation time, may well be the answer to such needs. To increase the chance of repeating our results, we emphasize the importance of the quality of the input data and recommend the use of RAW images.

5. Conclusions

In this study, we delivered the first empirical test of the impact of processing parameters in Agisoft Metashape on the accuracy of the results of SfM processing based on typical application in geomorphological research. To achieve accurate DEM, it is crucial to use correct settings, including parameters optimizing a sparse point cloud. Moreover, needlessly increasing the level of accuracy of calculations does not always result in an increase in the accuracy of photogrammetric products, but may only extend the calculation process and delay the obtainment of results. To address these problems, three different workflows in the form of Python scripts for Agisoft Metashape were prepared, which, depending on the needs and available computing power, allow for the development of accurate models. For many scientists dealing with surface dynamics, scripts in which automating calculation work is performed should be a noticeable facilitation and may turn out to be a new method of improving quality in their research work. Key calculation settings and parameters, applied in the form of editable scripts, will increase the efficiency in processing and comparing large datasets, in addition to significant time savings due to the use of a powerful computing cluster. The high usability of the scripts is seen in the long-term observations, for example, of many glaciers and their forelands, where the automated workflow allows for a better management of numerous projects, not to mention rendering the process of comparing models reliable. Moreover, the authors do not exclude that the developed scripts will find their use in creating other three-dimensional models of various objects, not necessarily those related to glaciers and their forelands. In addition, it is suggested to perform the same experiment in the future for sets of images from several different cameras, and also including ground-based and oblique images.

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Number	Code	Reprojection error [pix]	RMSE (GCP) [cm]	RMSE (CPs) [cm]	Standard seviation (CPs) [cm]	Point density [points/cm2]	Point cloud (after gradual selection) [points]	Dense point cloud [points]	Resolution [cm] DEM	Ortomosaic	Calculation time [h] Alignment	Optimization alignment	Dense point cloud generation	DEM	Ortomosaic	SUM
1	1_lt_A_lt_A	5.76	48.23				642				00:03:37	00:00:00				00:03:37
2	2_lt_B_lt_A	5.78	48.23				641				00:03:33	00:00:00				00:03:33
3	3_lt_C_lt_A	5.72	48.23				658				00:03:27	00:00:00				00:03:27
4	4_lt_A_l_A	5.78	48.23				655				00:03:28	00:00:00				00:03:28
5	5_lt_B_l_A	5.76	48.23				649				00:03:04	00:00:00				00:03:04
6	6_lt_C_l_A	5.76	48.23				636				00:03:23	00:00:00				00:03:23
7	7_lt_A_m_A	5.79	48.23				658				00:03:28	00:00:00				00:03:28
8	8_lt_B_m_A	5.75	48.23				650				00:03:11	00:00:00				00:03:11
9	9_lt_C_m_A	5.77	48.23				643				00:03:10	00:00:00				00:03:10
10	10_lt_A_h_A	5.76	48.23				648				00:03:34	00:00:00				00:03:34
11	11_lt_B_h_A	5.78	48.23				637				00:03:43	00:00:00				00:03:43
12	12_lt_C_h_A	5.80	48.23				632				00:03:30	00:00:00				00:03:30
13	13_lt_A_uh_A	5.79	48.23				646				00:03:09	00:00:00				00:03:09
14	14_lt_B_uh_A	5.76	48.23				656				00:03:01	00:00:00				00:03:01
15	15_lt_C_uh_A	5.76	48.23				642				00:03:06	00:00:00				00:03:06
16	16_lt_A_lt_B	5.60	48.23				638				00:03:23	00:00:00				00:03:23
17	17_lt_B_lt_B	5.56	48.23				643				00:03:32	00:00:00				00:03:32
18	18_lt_C_lt_B	5.57	48.23				665				00:03:40	00:00:00				00:03:40
19	19_lt_A_l_B	5.54	48.23				648				00:03:30	00:00:00				00:03:30
20	20_lt_B_l_B	5.60	48.23				644				00:03:30	00:00:00				00:03:30
21	21_lt_C_l_B	5.59	48.23				645				00:03:26	00:00:00				00:03:26
22	22_lt_A_m_B	5.62	48.23				646				00:03:26	00:00:00				00:03:26
23	23_lt_B_m_B	5.56	48.23				655				00:03:28	00:00:00				00:03:28
24	24_lt_C_m_B	5.58	48.23				658				00:03:28	00:00:00				00:03:28
25	25_lt_A_h_B	5.55	48.23				646				00:03:37	00:00:00				00:03:37
26	26_lt_B_h_B	5.57	48.23				643				00:03:29	00:00:00				00:03:29
27	27_lt_C_h_B	5.61	48.23				635				00:03:38	00:00:00				00:03:38
28	28_lt_A_uh_B	5.60	48.23				644				00:04:01	00:00:00				00:04:01
29	29_lt_B_uh_B	5.54	48.23				654				00:03:48	00:00:00				00:03:48
30	30_lt_C_uh_B	5.58	48.23				643				00:03:24	00:00:00				00:03:24
31	31_lt_A_lt_C	3.93	1.47				642				00:02:52	00:00:00				00:02:52
32	32_lt_B_lt_C	3.95	1.47				650				00:03:26	00:00:00				00:03:26
33	33_lt_C_lt_C	3.94	1.40				643				00:03:04	00:00:00				00:03:04
34	34_lt_A_l_C	3.93	1.47				643				00:03:32	00:00:00				00:03:32
35	35_lt_B_l_C	3.96	1.47				645				00:03:33	00:00:00				00:03:33
36	36_lt_C_l_C	3.97	1.47				631				00:03:34	00:00:00				00:03:34
37	37_lt_A_m_C	3.93	1.47				641				00:03:29	00:00:00				00:03:29
38	38_lt_B_m_C	3.94	1.47				644				00:03:28	00:00:00				00:03:28
39	39_lt_C_m_C	3.94	1.47				643				00:02:51	00:00:00				00:02:51
40	40_lt_A_h_C	3.94	1.47				643				00:02:50	00:00:00				00:02:50
41	41_lt_B_h_C	3.95	1.40				641				00:02:50	00:00:00				00:02:50
42	42_lt_C_h_C	3.94	1.40				643				00:02:49	00:00:00				00:02:49
43	43_lt_A_uh_C	3.97	1.47				653				00:02:55	00:00:00				00:02:55
44	44_lt_B_uh_C	3.94	1.47				643				00:02:52	00:00:00				00:02:52
45	45_lt_C_uh_C	3.96	1.47				639				00:03:30	00:00:00				00:03:30
46	46_lt_A_lt_D	3.99	1.44				642				00:03:38	00:00:00				00:03:38
47	47_lt_B_lt_D	3.96	1.44				651				00:03:46	00:00:00				00:03:46
48	48_lt_C_lt_D	3.98	1.44				651				00:04:07	00:00:00				00:04:07
49	49_lt_A_l_D	3.97	1.44				657				00:04:44	00:00:00				00:04:44
50	50_lt_B_l_D	3.96	1.44				634				00:04:57	00:00:00				00:04:57
51	51_lt_C_l_D	3.97	1.44				666				00:04:31	00:00:00				00:04:31
52	52_lt_A_m_D	3.97	1.44				654				00:03:54	00:00:00				00:03:54
53	53_lt_B_m_D	3.95	1.44				636				00:03:31	00:00:00				00:03:31
54	54_lt_C_m_D	3.97	1.44				654				00:03:27	00:00:00				00:03:27
55	55_lt_A_h_D	3.94	1.44				646				00:03:04	00:00:00				00:03:04
56	56_lt_B_h_D	3.94	1.44				643				00:02:46	00:00:00				00:02:46
57	57_lt_C_h_D	3.94	1.44				645				00:02:50	00:00:00				00:02:50
58	58_lt_A_uh_D	3.94	1.44				643				00:02:52	00:00:00				00:02:52

#	Name															
59	59_lt_B_uh_D	3.94	1.44				643				00:02:48	00:00:00				00:02:48
60	60_lt_C_uh_D	3.97	1.44				658				00:02:48	00:00:00				00:02:48
61	61_lt_A_lt_E	3.77	1.41				656				00:03:01	00:00:00				00:03:01
62	62_lt_B_lt_E	3.75	1.41				656				00:03:36	00:00:00				00:03:36
63	63_lt_C_lt_E	3.77	1.41				656				00:03:27	00:00:00				00:03:27
64	64_lt_A_l_E	3.74	1.41				645				00:02:49	00:00:00				00:02:49
65	65_lt_B_l_E	3.73	1.41				643				00:02:44	00:00:00				00:02:44
66	66_lt_C_l_E	3.73	1.41				643				00:02:48	00:00:00				00:02:48
67	67_lt_A_m_E	3.73	1.41				644				00:02:49	00:00:00				00:02:49
68	68_lt_B_m_E	3.73	1.41				639				00:02:48	00:00:00				00:02:48
69	69_lt_C_m_E	3.74	1.41				642				00:02:47	00:00:00				00:02:47
70	70_lt_A_h_E	3.73	1.41				643				00:02:49	00:00:00				00:02:49
71	71_lt_B_h_E	3.73	1.41				641				00:02:47	00:00:00				00:02:47
72	72_lt_C_h_E	3.73	1.41				647				00:02:51	00:00:00				00:02:51
73	73_lt_A_uh_E	3.75	1.41				646				00:02:48	00:00:00				00:02:48
74	74_lt_B_uh_E	3.73	1.41				633				00:02:48	00:00:00				00:02:48
75	75_lt_C_uh_E	3.72	1.41				641				00:02:47	00:00:00				00:02:47
76	76_l_A_lt_A	4.42	48.23				7325				00:03:35	00:00:00				00:03:35
77	77_l_B_lt_A	4.04	48.23				14869				00:03:05	00:00:01				00:03:06
78	78_l_C_lt_A	4.04	48.23				14830				00:03:05	00:00:02				00:03:07
79	79_l_A_l_A	4.42	48.23				7338				00:03:32	00:00:02				00:03:34
80	80_l_B_l_A	4.05	48.23				14852				00:03:46	00:00:02				00:03:48
81	81_l_C_l_A	4.05	48.23				14905				00:03:15	00:00:02				00:03:17
82	82_l_A_m_A	4.42	48.23				7312				00:02:55	00:00:01				00:02:56
83	83_l_B_m_A	4.05	48.23				14804				00:03:02	00:00:02				00:03:04
84	84_l_C_m_A	4.05	48.23				14885				00:04:04	00:00:02				00:04:06
85	85_l_A_h_A	4.42	48.23				7355				00:03:38	00:00:01				00:03:39
86	86_l_B_h_A	4.05	48.23				14846				00:04:04	00:00:02				00:04:06
87	87_l_C_h_A	4.05	48.23				14800				00:04:00	00:00:02				00:04:02
88	88_l_A_uh_A	4.42	48.23				7337				00:03:50	00:00:01				00:03:51
89	89_l_B_uh_A	4.05	48.23				14866				00:03:49	00:00:02				00:03:51
90	90_l_C_uh_A	4.04	48.23				14824				00:03:47	00:00:02				00:03:49
91	91_l_A_lt_B	4.20	48.23				7338				00:03:36	00:00:01				00:03:37
92	92_l_B_lt_B	3.84	48.23				14856				00:03:46	00:00:02				00:03:48
93	93_l_C_lt_B	3.84	48.23				14847				00:03:42	00:00:02				00:03:44
94	94_l_A_l_B	4.20	48.23				7335				00:03:41	00:00:01				00:03:42
95	95_l_B_l_B	3.84	48.23				14861				00:03:47	00:00:02				00:03:49
96	96_l_C_l_B	3.84	48.23				14823				00:03:48	00:00:02				00:03:50
97	97_l_A_m_B	4.20	48.23				7315				00:03:36	00:00:01				00:03:37
98	98_l_B_m_B	3.84	48.23				14815				00:03:44	00:00:02				00:03:46
99	99_l_C_m_B	3.84	48.23				14844				00:03:43	00:00:01				00:03:44
100	100_l_A_h_B	4.20	48.23				7343				00:03:41	00:00:02				00:03:43
101	101_l_B_h_B	3.84	48.23				14860				00:03:46	00:00:02				00:03:48
102	102_l_C_h_B	3.84	48.23				14842				00:03:45	00:00:02				00:03:47
103	103_l_A_uh_B	4.19	48.23				7333				00:03:40	00:00:01				00:03:41
104	104_l_B_uh_B	3.84	48.23				14829				00:03:47	00:00:02				00:03:49
105	105_l_C_uh_B	3.84	48.23				14872				00:03:47	00:00:02				00:03:49
106	106_l_A_lt_C	2.14	1.47	2.30	2.27	12.7	7345	595891	28.00	1.75	00:03:38	00:00:01	00:06:05	00:00:05	00:22:59	00:32:48
107	107_l_B_lt_C	2.04	1.47	1.97	1.88	12.7	14839	596488	28.00	1.75	00:03:26	00:00:01	00:05:28	00:00:05	00:23:00	00:32:00
108	108_l_C_lt_C	2.03	1.47	2.36	2.29	12.7	14881	596179	28.00	1.75	00:03:03	00:00:01	00:05:19	00:00:06	00:21:48	00:30:17
109	109_l_A_l_C	2.14	1.47	1.51	1.51	50.9	7336	2408238	14.00	1.75	00:02:55	00:00:01	00:06:28	00:00:11	00:20:30	00:30:05
110	110_l_B_l_C	2.03	1.47	1.37	1.37	50.9	14881	2407480	14.00	1.75	00:03:01	00:00:01	00:06:39	00:00:11	00:20:15	00:30:07
111	111_l_C_l_C	2.03	1.47	1.25	1.23	50.9	14851	2407602	14.00	1.75	00:03:05	00:00:01	00:06:38	00:00:10	00:19:38	00:29:32
112	112_l_A_m_C	2.14	1.47	1.10	1.08	203	7305	9653375	7.01	1.75	00:03:37	00:00:01	00:13:09	00:00:36	00:21:22	00:38:45
113	113_l_B_m_C	2.04	1.47	1.12	1.10	203	14886	9665509	7.01	1.75	00:03:41	00:00:01	00:13:35	00:00:31	00:19:30	00:37:18
114	114_l_C_m_C	2.03	1.47	1.02	1.01	203	14854	9652262	7.01	1.75	00:03:42	00:00:01	00:13:40	00:00:32	00:19:59	00:37:54
115	115_l_A_h_C	2.14	1.47	0.97	0.95	813	7315	39606670	3.51	1.75	00:03:23	00:00:01	00:41:29	00:01:57	00:20:32	01:07:22
116	116_l_B_h_C	2.04	1.47	1.09	1.09	813	14901	39487834	3.51	1.75	00:03:46	00:00:01	00:42:50	00:01:54	00:19:32	01:08:03
117	117_l_C_h_C	2.03	1.47	1.10	1.10	813	14854	39549825	3.51	1.75	00:03:47	00:00:01	00:41:43	00:01:56	00:19:18	01:06:45
118	118_l_A_uh_C	2.14	1.47	1.09	1.08	3250	7340	169961180	1.75	1.75	00:03:23	00:00:01	02:34:00	00:06:22	00:22:51	03:06:37
119	119_l_B_uh_C	2.04	1.47	1.01	0.98	3250	14836	168712490	1.75	1.75	00:03:04	00:00:01	02:35:00	00:06:10	00:22:05	03:06:20
120	120_l_C_uh_C	2.03	1.47	1.03	1.01	3250	14869	168000970	1.75	1.75	00:03:04	00:00:01	02:32:00	00:06:13	00:21:31	03:02:49
121	121_l_A_lt_D	2.14	1.44	2.22	2.05	12.7	7332	595995	28.00	1.75	00:03:32	00:00:02	00:05:24	00:00:06	00:22:38	00:31:41
122	122_l_B_lt_D	2.04	1.45	2.16	2.15	12.7	14894	596436	28.00	1.75	00:03:35	00:00:02	00:05:02	00:00:05	00:23:22	00:32:06
123	123_l_C_lt_D	2.04	1.45	2.33	2.30	12.7	14856	596416	28.00	1.75	00:03:14	00:00:01	00:05:10	00:00:05	00:21:49	00:30:19
124	124_l_A_l_D	2.13	1.44	1.45	1.45	50.9	7297	2409203	14.00	1.75	00:02:54	00:00:01	00:06:33	00:00:11	00:21:58	00:31:37

125	125_l_B_l_D	2.04	1.45	1.31	1.31	50.9	14878	2408165	14.00	1.75	00:03:02	00:00:01	00:06:40	00:00:10	00:23:39	00:33:32
126	126_l_C_l_D	2.03	1.45	1.27	1.27	50.9	14844	2409349	14.00	1.75	00:03:01	00:00:01	00:06:21	00:00:10	00:22:33	00:32:06
127	127_l_A_m_D	2.14	1.44	1.08	1.06	203	7360	9659089	7.01	1.75	00:02:57	00:00:01	00:13:13	00:00:37	00:20:19	00:37:07
128	128_l_B_m_D	2.03	1.45	1.03	1.01	203	14859	9654455	7.01	1.75	00:03:01	00:00:01	00:12:08	00:00:34	00:19:24	00:35:08
129	129_l_C_m_D	2.03	1.45	1.06	1.05	203	14838	9663972	7.01	1.75	00:03:24	00:00:01	00:12:55	00:00:34	00:20:03	00:36:57
130	130_l_A_h_D	2.14	1.44	1.22	1.21	813	7318	39631353	3.51	1.75	00:03:41	00:00:01	00:42:58	00:02:04	00:20:07	01:08:51
131	131_l_B_h_D	2.04	1.45	1.01	1.00	813	14870	39537312	3.51	1.75	00:03:38	00:00:01	00:41:44	00:01:57	00:19:16	01:06:36
132	132_l_C_h_D	2.04	1.45	1.07	1.05	813	14877	39572287	3.51	1.75	00:03:17	00:00:01	00:41:23	00:01:57	00:20:48	01:07:26
133	133_l_A_uh_D	2.14	1.44	0.98	0.95	3250	7345	169781610	1.75	1.75	00:02:54	00:00:01	02:35:00	00:06:09	00:23:18	03:07:22
134	134_l_B_uh_D	2.03	1.45	1.07	1.04	3250	14864	168190380	1.75	1.75	00:03:03	00:00:01	02:42:00	00:06:07	00:24:21	03:15:32
135	135_l_C_uh_D	2.03	1.45	1.02	1.01	3250	14877	168165260	1.75	1.75	00:03:01	00:00:02	02:22:00	00:06:05	00:23:14	02:54:22
136	136_l_A_lt_E	1.93	1.42	2.28	2.27	12.8	7312	598750	28.00	1.75	00:03:06	00:00:01	00:08:35	00:00:05	00:19:39	00:31:26
137	137_l_B_lt_E	1.86	1.43	2.05	2.01	12.8	14877	599275	28.00	1.75	00:03:33	00:00:02	00:07:21	00:00:05	00:19:35	00:30:36
138	138_l_C_lt_E	1.85	1.42	1.46	1.45	12.8	14849	598667	28.00	1.75	00:03:03	00:00:01	00:06:21	00:00:05	00:20:19	00:29:49
139	139_l_A_l_E	1.93	1.42	1.28	1.25	51.1	7394	2416529	14.00	1.75	00:03:23	00:00:01	00:06:35	00:00:10	00:20:15	00:30:24
140	140_l_B_l_E	1.86	1.43	1.23	1.20	51.1	14884	2415331	14.00	1.75	00:03:32	00:00:01	00:06:59	00:00:10	00:20:36	00:31:18
141	141_l_C_l_E	1.86	1.43	1.32	1.31	51.1	14846	2418264	14.00	1.75	00:03:38	00:00:01	00:06:56	00:00:11	00:19:38	00:30:24
142	142_l_A_m_E	1.93	1.42	1.03	0.94	204	7304	9695442	6.99	1.75	00:02:58	00:00:01	00:13:58	00:00:37	00:18:44	00:36:18
143	143_l_B_m_E	1.85	1.43	1.10	0.96	204	14845	9717000	6.99	1.75	00:03:02	00:00:01	00:13:40	00:00:31	00:19:12	00:36:26
144	144_l_C_m_E	1.86	1.43	1.05	0.95	204	14863	9699115	6.99	1.75	00:03:10	00:00:01	00:13:27	00:00:32	00:19:57	00:37:07
145	145_l_A_h_E	1.92	1.42	0.83	0.73	818	7285	39729463	3.50	1.75	00:02:54	00:00:01	00:40:29	00:01:56	00:20:31	01:05:51
146	146_l_B_h_E	1.86	1.43	0.85	0.76	818	14858	39762731	3.50	1.75	00:03:06	00:00:01	00:40:22	00:01:58	00:19:59	01:05:26
147	147_l_C_h_E	1.86	1.42	0.81	0.70	818	14837	39730386	3.50	1.75	00:03:29	00:00:01	00:39:38	00:01:51	00:20:15	01:05:14
148	148_l_A_uh_E	1.93	1.42	0.78	0.67	3270	7353	162745594	1.75	1.75	00:03:42	00:00:01	02:16:12	00:06:12	00:23:56	02:50:03
149	149_l_B_uh_E	1.86	1.43	0.76	0.65	3270	14870	162516495	1.75	1.75	00:03:40	00:00:01	02:12:22	00:06:13	00:24:10	02:46:26
150	150_l_C_uh_E	1.85	1.42	0.80	0.67	3270	14848	162829770	1.75	1.75	00:03:44	00:00:01	02:15:57	00:06:02	00:23:11	02:48:55
151	151_m_A_lt_A	4.18	48.24				6404				00:03:49	00:00:01				00:03:50
152	152_m_B_lt_A	3.57	48.32				82553				00:04:58	00:00:05				00:05:03
153	153_m_C_lt_A	3.44	48.33				103004				00:05:00	00:00:07				00:05:07
154	154_m_A_l_A	4.17	48.24				6406				00:03:49	00:00:01				00:03:50
155	155_m_B_l_A	3.57	48.32				82482				00:04:37	00:00:06				00:04:43
156	156_m_C_l_A	3.45	48.33				103039				00:05:13	00:00:07				00:05:20
157	157_m_A_m_A	4.18	48.24				6375				00:03:50	00:00:01				00:03:51
158	158_m_B_m_A	3.57	48.32				82467				00:04:51	00:00:06				00:04:57
159	159_m_C_m_A	3.44	48.33				103084				00:04:46	00:00:06				00:04:52
160	160_m_A_h_A	4.17	48.24				6415				00:03:44	00:00:01				00:03:45
161	161_m_B_h_A	3.57	48.32				82479				00:04:40	00:00:06				00:04:46
162	162_m_C_h_A	3.45	48.33				102942				00:05:09	00:00:06				00:05:15
163	163_m_A_uh_A	4.18	48.24				6416				00:03:48	00:00:01				00:03:49
164	164_m_B_uh_A	3.57	48.32				82506				00:04:46	00:00:06				00:04:52
165	165_m_C_uh_A	3.44	48.33				102973				00:06:00	00:00:06				00:06:06
166	166_m_A_lt_B	3.98	48.25				6405				00:03:46	00:00:01				00:03:47
167	167_m_B_lt_B	3.39	48.32				82548				00:04:58	00:00:05				00:05:03
168	168_m_C_lt_B	3.27	48.33				103009				00:05:06	00:00:07				00:05:13
169	169_m_A_l_B	3.98	48.25				6399				00:03:42	00:00:01				00:03:43
170	170_m_B_l_B	3.40	48.32				82467				00:05:08	00:00:06				00:05:14
171	171_m_C_l_B	3.27	48.33				103044				00:05:07	00:00:05				00:05:12
172	172_m_A_m_B	3.97	48.25				6402				00:03:46	00:00:01				00:03:47
173	173_m_B_m_B	3.40	48.32				82484				00:04:33	00:00:06				00:04:39
174	174_m_C_m_B	3.27	48.33				103028				00:06:01	00:00:06				00:06:07
175	175_m_A_h_B	3.97	48.25				6412				00:03:48	00:00:01				00:03:49
176	176_m_B_h_B	3.39	48.32				82480				00:04:56	00:00:07				00:05:03
177	177_m_C_h_B	3.27	48.33				103002				00:05:00	00:00:06				00:05:06
178	178_m_A_uh_B	3.98	48.25				6369				00:03:46	00:00:01				00:03:47
179	179_m_B_uh_B	3.40	48.32				82414				00:04:48	00:00:06				00:04:54
180	180_m_C_uh_B	3.27	48.33				103041				00:04:55	00:00:06				00:05:01
181	181_m_A_lt_C	1.13	1.49	2.59	2.58	12.7	6386	595068	28.00	1.75	00:03:47	00:00:00	00:07:44	00:00:06	00:19:19	00:30:56
182	182_m_B_lt_C	1.20	1.59	2.69	2.68	12.7	82454	595233	28.00	1.75	00:04:30	00:00:05	00:07:09	00:00:05	00:20:28	00:32:17
183	183_m_C_lt_C	1.17	1.59	2.65	2.65	12.7	103024	595591	28.00	1.75	00:05:13	00:00:04	00:06:23	00:00:05	00:21:22	00:33:07
184	184_m_A_l_C	1.13	1.49	1.31	1.30	50.7	6406	2400217	14.00	1.75	00:03:45	00:00:01	00:07:18	00:00:12	00:21:12	00:32:28
185	185_m_B_l_C	1.20	1.59	1.78	1.75	50.9	82518	2410243	14.00	1.75	00:04:49	00:00:06	00:07:09	00:00:11	00:21:02	00:33:17
186	186_m_C_l_C	1.17	1.59	1.81	1.79	50.9	102961	2405801	14.00	1.75	00:05:03	00:00:04	00:07:01	00:00:10	00:20:56	00:33:14
187	187_m_A_m_C	1.13	1.49	1.07	1.07	203	6386	9606136	7.01	1.75	00:03:53	00:00:01	00:23:15	00:00:45	00:19:33	00:47:27
188	188_m_B_m_C	1.20	1.59	1.54	1.53	203	82456	9713547	7.01	1.75	00:04:53	00:00:04	00:14:48	00:00:36	00:19:48	00:40:09
189	189_m_C_m_C	1.17	1.59	1.59	1.58	203	103017	9719720	7.01	1.75	00:05:04	00:00:08	00:13:29	00:00:33	00:19:52	00:39:06
190	190_m_A_h_C	1.13	1.49	1.21	1.17	813	6377	39546465	3.51	1.75	00:03:49	00:00:01	00:47:01	00:02:07	00:20:00	01:12:58

191	191_m_B_h_C	1.20	1.59	1.66	1.66	813	82550	39708195	3.51	1.75	00:04:54	00:00:03	00:46:09	00:01:56	00:19:33	01:12:35
192	192_m_C_h_C	1.17	1.59	1.48	1.48	813	103063	39648356	3.51	1.75	00:05:04	00:00:07	00:48:08	00:02:00	00:19:05	01:14:24
193	193_m_A_uh_C	1.13	1.49	1.13	1.11	3250	6407	170322326	1.75	1.75	00:03:50	00:00:01	02:51:00	00:06:33	00:25:20	03:26:44
194	194_m_B_uh_C	1.20	1.59	1.56	1.55	3250	82512	170998385	1.75	1.75	00:05:00	00:00:04	02:34:00	00:06:11	00:24:19	03:09:34
195	195_m_C_uh_C	1.17	1.59	1.58	1.57	3250	103067	170458614	1.75	1.75	00:04:38	00:00:06	02:44:00	00:07:04	00:23:00	03:18:48
196	196_m_A_lt_D	1.13	1.47	2.50	2.47	12.7	6382	594981	28.00	1.75	00:03:35	00:00:01	00:06:18	00:00:06	00:21:18	00:31:18
197	197_m_B_lt_D	1.20	1.57	2.51	2.51	12.7	82575	595910	28.00	1.75	00:05:02	00:00:03	00:05:24	00:00:05	00:20:36	00:31:10
198	198_m_C_lt_D	1.17	1.58	2.73	2.70	12.7	103121	595642	28.00	1.75	00:05:05	00:00:04	00:05:28	00:00:05	00:20:16	00:30:58
199	199_m_A_l_D	1.13	1.47	1.79	1.77	50.9	6387	2398428	14.00	1.75	00:03:13	00:00:01	00:07:04	00:00:12	00:20:02	00:30:32
200	200_m_B_l_D	1.20	1.57	1.82	1.81	50.9	82430	2406643	14.00	1.75	00:04:09	00:00:05	00:07:01	00:00:10	00:19:56	00:31:21
201	201_m_C_l_D	1.17	1.58	1.75	1.67	50.9	103034	2404470	14.00	1.75	00:05:17	00:00:06	00:07:10	00:00:10	00:21:40	00:34:23
202	202_m_A_m_D	1.13	1.47	1.19	1.18	203	6372	9688400	7.01	1.75	00:03:07	00:00:01	00:13:43	00:00:43	00:19:13	00:36:47
203	203_m_B_m_D	1.20	1.57	1.42	1.41	203	82478	9717756	7.01	1.75	00:04:23	00:00:06	00:13:54	00:00:35	00:18:04	00:37:02
204	204_m_C_m_D	1.17	1.58	1.52	1.49	203	103022	9713802	7.01	1.75	00:04:51	00:00:05	00:13:48	00:00:33	00:19:45	00:39:02
205	205_m_A_h_D	1.13	1.47	1.17	1.14	813	6396	39199156	3.51	1.75	00:03:45	00:00:01	00:47:22	00:02:03	00:20:18	01:13:29
206	206_m_B_h_D	1.20	1.57	1.44	1.44	813	82503	39701796	3.51	1.75	00:04:51	00:00:06	00:46:59	00:01:54	00:19:29	01:13:19
207	207_m_C_h_D	1.17	1.58	1.45	1.44	813	103020	39679297	3.51	1.75	00:04:56	00:00:04	00:47:01	00:01:57	00:19:45	01:13:43
208	208_m_A_uh_D	1.13	1.47	1.18	1.16	3250	6369	170577957	1.75	1.75	00:03:47	00:00:01	02:53:00	00:06:20	00:21:30	03:24:38
209	209_m_B_uh_D	1.20	1.57	1.33	1.33	3250	82443	170942828	1.75	1.75	00:04:53	00:00:04	02:46:00	00:06:03	00:20:43	03:17:43
210	210_m_C_uh_D	1.17	1.58	1.52	1.48	3250	103010	170301345	1.75	1.75	00:05:08	00:00:04	02:47:00	00:06:23	00:21:31	03:20:06
211	211_m_A_lt_E	0.52	1.45	1.78	1.78	12.8	6389	597651	28.00	1.75	00:03:56	00:00:01	00:05:57	00:00:06	00:19:52	00:29:52
212	212_m_B_lt_E	0.82	1.49	2.15	2.12	12.8	82427	598862	28.00	1.75	00:04:50	00:00:04	00:05:30	00:00:05	00:20:14	00:30:43
213	213_m_C_lt_E	0.81	1.49	1.98	1.98	12.8	102936	597737	28.00	1.75	00:05:02	00:00:04	00:05:43	00:00:05	00:20:08	00:31:02
214	214_m_A_l_E	0.52	1.45	1.34	1.27	51.1	6387	2414122	14.00	1.75	00:03:50	00:00:00	00:07:20	00:00:12	00:19:48	00:31:10
215	215_m_B_l_E	0.82	1.49	1.29	1.28	51.1	82482	2417684	14.00	1.75	00:04:53	00:00:03	00:07:18	00:00:11	00:19:10	00:31:35
216	216_m_C_l_E	0.81	1.49	1.19	1.17	51.1	103072	2416931	14.00	1.75	00:05:04	00:00:04	00:07:19	00:00:10	00:19:31	00:32:08
217	217_m_A_m_E	0.52	1.45	1.17	1.07	204	6385	9752426	6.99	1.75	00:03:51	00:00:01	00:14:10	00:00:46	00:19:02	00:37:50
218	218_m_B_m_E	0.82	1.49	1.10	0.99	204	82453	9780395	6.99	1.75	00:04:51	00:00:04	00:14:00	00:00:35	00:18:21	00:37:51
219	219_m_C_m_E	0.81	1.49	1.15	0.99	204	103012	9777214	6.99	1.75	00:05:03	00:00:03	00:12:28	00:00:33	00:19:07	00:37:14
220	220_m_A_h_E	0.52	1.45	0.92	0.79	818	6392	39430948	3.50	1.75	00:03:47	00:00:01	00:44:33	00:02:03	00:20:47	01:11:11
221	221_m_B_h_E	0.82	1.49	0.95	0.78	818	82492	40008382	3.50	1.75	00:04:50	00:00:03	00:43:36	00:01:54	00:20:53	01:11:16
222	222_m_C_h_E	0.81	1.49	0.92	0.78	818	103027	39996877	3.50	1.75	00:05:03	00:00:05	00:43:49	00:01:57	00:20:36	01:11:30
223	223_m_A_uh_E	0.52	1.45	0.76	0.63	3270	6412	162080776	1.75	1.75	00:03:51	00:00:01	03:16:00	00:06:17	00:20:53	03:47:02
224	224_m_B_uh_E	0.82	1.49	0.91	0.74	3270	82583	163876405	1.75	1.75	00:04:58	00:00:04	02:18:17	00:06:09	00:20:37	02:50:05
225	225_m_C_uh_E	0.81	1.49	0.94	0.75	3270	103108	163934110	1.75	1.75	00:05:07	00:00:04	02:14:31	00:06:59	00:21:02	02:47:43
226	226_h_A_lt_A	3.91	48.30				5932				00:04:06	00:00:01				00:04:07
227	227_h_B_lt_A	3.92	48.44				63743				00:07:26	00:00:11				00:07:37
228	228_h_C_lt_A	3.31	48.46				580883				00:13:47	00:00:34				00:14:21
229	229_h_A_l_A	3.91	48.30				5947				00:03:59	00:00:01				00:04:00
230	230_h_B_l_A	3.92	48.44				63419				00:07:10	00:00:06				00:07:16
231	231_h_C_l_A	3.31	48.45				580864				00:13:16	00:00:34				00:13:50
232	232_h_A_m_A	3.91	48.30				5919				00:04:02	00:00:01				00:04:03
233	233_h_B_m_A	3.91	48.44				63301				00:07:21	00:00:07				00:07:28
234	234_h_C_m_A	3.31	48.46				580662				00:13:47	00:00:35				00:14:22
235	235_h_A_h_A	3.91	48.30				5918				00:04:12	00:00:01				00:04:13
236	236_h_B_h_A	3.93	48.44				63859				00:07:30	00:00:08				00:07:38
237	237_h_C_h_A	3.31	48.46				581407				00:13:25	00:00:33				00:13:58
238	238_h_A_uh_A	3.92	48.30				5911				00:05:19	00:00:02				00:05:21
239	239_h_B_uh_A	3.92	48.44				63585				00:07:55	00:00:07				00:08:02
240	240_h_C_uh_A	3.31	48.45				580756				00:14:31	00:00:31				00:15:02
241	241_h_A_lt_B	3.72	48.30				5915				00:04:08	00:00:01				00:04:09
242	242_h_B_lt_B	3.74	48.43				63583				00:07:48	00:00:09				00:07:57
243	243_h_C_lt_B	3.14	48.44				580312				00:14:53	00:00:36				00:15:29
244	244_h_A_l_B	3.73	48.30				5915				00:04:09	00:00:01				00:04:10
245	245_h_B_l_B	3.74	48.43				63803				00:07:35	00:00:09				00:07:44
246	246_h_C_l_B	3.14	48.44				580606				00:14:11	00:00:30				00:14:41
247	247_h_A_m_B	3.72	48.30				5947				00:04:04	00:00:01				00:04:05
248	248_h_B_m_B	3.74	48.43				63618				00:07:34	00:00:07				00:07:41
249	249_h_C_m_B	3.14	48.44				580844				00:14:37	00:00:40				00:15:17
250	250_h_A_h_B	3.72	48.30				5924				00:03:58	00:00:01				00:03:59
251	251_h_B_h_B	3.74	48.43				64332				00:07:18	00:00:06				00:07:24
252	252_h_C_h_B	3.14	48.44				580428				00:13:55	00:00:39				00:14:34
253	253_h_A_uh_B	3.72	48.30				5924				00:04:00	00:00:01				00:04:01
254	254_h_B_uh_B	3.74	48.43				63725				00:07:17	00:00:06				00:07:23
255	255_h_C_uh_B	3.14	48.44				580831				00:13:41	00:00:28				00:14:09
256	256_h_A_lt_C	0.92	1.53	2.32	2.29	12.7	5929	596043	28.00	1.75	00:03:59	00:00:01	00:07:24	00:00:06	00:22:27	00:33:57

257	257_h_B_lt_C	1.01	3.02	5.91	5.85	12.7	63905	594387	28.00	1.75	00:07:28	00:00:07	00:07:08	00:00:06	00:22:05	00:36:54
258	258_h_C_lt_C	0.95	7.72	15.20	15.07	12.7	580774	592304	28.10	1.76	00:13:12	00:00:39	00:06:30	00:00:05	00:20:58	00:41:24
259	259_h_A_l_C	0.92	1.53	2.03	2.00	50.9	5962	2399747	14.00	1.75	00:04:01	00:00:00	00:08:08	00:00:12	00:21:18	00:33:39
260	260_h_B_l_C	1.01	3.01	5.14	5.00	50.8	63698	2400540	14.00	1.75	00:07:18	00:00:07	00:07:57	00:00:12	00:21:32	00:37:06
261	261_h_C_l_C	0.95	7.74	14.37	14.18	50.7	580219	2391459	14.00	1.76	00:13:02	00:00:29	00:08:15	00:00:11	00:22:17	00:44:14
262	262_h_A_m_C	0.92	1.53	1.41	1.41	203	5948	9604625	7.01	1.75	00:03:57	00:00:00	00:15:12	00:00:47	00:22:27	00:42:23
263	263_h_B_m_C	1.01	3.01	5.07	5.03	203	63494	9675219	7.02	1.75	00:07:58	00:00:07	00:15:21	00:00:48	00:21:10	00:45:24
264	264_h_C_m_C	0.95	7.72	14.42	14.20	203	580840	9627262	7.02	1.76	00:14:45	00:00:30	00:13:46	00:00:34	00:19:51	00:49:26
265	265_h_A_h_C	0.92	1.53	1.32	1.31	814	5952	39248014	3.51	1.75	00:04:08	00:00:01	00:47:40	00:02:16	00:21:57	01:16:02
266	266_h_B_h_C	1.01	3.01	4.80	4.78	813	63632	39541022	3.51	1.75	00:07:27	00:00:05	00:47:38	00:02:15	00:20:48	01:18:13
267	267_h_C_h_C	0.95	7.71	14.07	13.86	811	580557	39183942	3.51	1.76	00:14:16	00:00:24	00:41:57	00:02:04	00:20:13	01:18:54
268	268_h_A_uh_C	0.92	1.53	1.31	1.31	3250	5951	169642194	1.75	1.75	00:04:05	00:00:01	03:00:00	00:07:17	00:26:35	03:37:58
269	269_h_B_uh_C	1.01	3.02	5.01	4.94	3250	63840	173416704	1.75	1.75	00:07:27	00:00:08	02:55:00	00:07:12	00:26:14	03:36:01
270	270_h_C_uh_C	0.95	7.71	14.32	14.12	3250	580364	166535162	1.76	1.76	00:13:49	00:00:35	02:55:00	00:07:13	00:25:19	03:41:56
271	271_h_A_lt_D	0.91	1.51	2.43	2.43	12.7	5952	596121	28.00	1.75	00:04:00	00:00:01	00:06:06	00:00:06	00:24:26	00:34:39
272	272_h_B_lt_D	1.01	3.13	5.66	5.66	12.7	63510	593737	28.10	1.75	00:07:19	00:00:07	00:05:54	00:00:06	00:22:30	00:35:56
273	273_h_C_lt_D	0.95	8.05	15.69	15.57	12.7	581406	591904	28.10	1.76	00:13:35	00:00:26	00:06:08	00:00:06	00:21:31	00:41:46
274	274_h_A_l_D	0.92	1.51	1.55	1.54	50.9	5924	2401887	14.00	1.75	00:03:57	00:00:01	00:07:32	00:00:12	00:23:10	00:34:52
275	275_h_B_l_D	1.01	3.14	5.63	5.56	50.8	63621	2400931	14.00	1.75	00:07:17	00:00:07	00:07:34	00:00:12	00:22:15	00:37:25
276	276_h_C_l_D	0.95	8.03	14.89	14.66	50.7	580991	2389022	14.00	1.76	00:13:13	00:00:31	00:07:44	00:00:10	00:19:47	00:41:25
277	277_h_A_m_D	0.92	1.51	1.42	1.40	203	5947	9603489	7.01	1.75	00:04:18	00:00:00	00:14:31	00:00:46	00:20:45	00:40:20
278	278_h_B_m_D	1.01	3.14	5.30	5.22	203	63639	9680400	7.02	1.75	00:07:40	00:00:06	00:15:26	00:00:45	00:21:28	00:45:25
279	279_h_C_m_D	0.95	8.04	14.54	14.32	203	580773	9613025	7.02	1.76	00:14:28	00:00:37	00:14:28	00:00:34	00:20:25	00:50:32
280	280_h_A_h_D	0.91	1.51	1.43	1.43	814	5922	39236149	3.51	1.75	00:04:07	00:00:01	00:50:21	00:02:16	00:20:33	01:17:18
281	281_h_B_h_D	1.01	3.12	5.08	5.07	813	63310	39563293	3.51	1.75	00:07:27	00:00:05	00:48:43	00:02:14	00:21:38	01:20:07
282	282_h_C_h_D	0.95	8.04	14.28	14.08	812	581147	39160569	3.51	1.76	00:14:12	00:00:34	00:46:34	00:02:06	00:23:14	01:26:40
283	283_h_A_uh_D	0.92	1.51	1.29	1.28	3250	5919	169839566	1.75	1.75	00:04:04	00:00:01	02:53:00	00:07:19	00:27:02	03:31:26
284	284_h_B_uh_D	1.01	3.13	5.13	5.02	3250	63740	173378669	1.75	1.75	00:07:34	00:00:06	02:54:00	00:07:22	00:24:58	03:34:00
285	285_h_C_uh_D	0.95	8.03	14.12	13.93	3250	580628	166297589	1.76	1.76	00:13:27	00:00:35	02:50:00	00:07:05	00:24:36	03:35:43
286	286_h_A_lt_E	0.20	1.48	2.24	2.24	12.8	5925	598398	28.00	1.75	00:03:58	00:00:01	00:06:04	00:00:06	00:21:22	00:31:31
287	287_h_B_lt_E	0.34	1.53	2.10	2.10	12.8	63656	597983	28.00	1.75	00:07:11	00:00:06	00:06:09	00:00:06	00:21:29	00:35:01
288	288_h_C_lt_E	0.50	1.57	1.98	1.97	12.8	580727	597994	28.00	1.75	00:13:23	00:00:26	00:06:17	00:00:05	00:21:15	00:41:26
289	289_h_A_l_E	0.19	1.48	1.46	1.44	51.1	5934	2410324	14.00	1.75	00:03:59	00:00:00	00:08:09	00:00:12	00:21:21	00:33:41
290	290_h_B_l_E	0.34	1.53	1.39	1.33	51.1	63780	2416502	14.00	1.75	00:07:15	00:00:04	00:07:38	00:00:12	00:21:03	00:36:12
291	291_h_C_l_E	0.50	1.57	1.47	1.41	51.1	580896	2417227	14.00	1.75	00:14:29	00:00:28	00:07:34	00:00:11	00:21:26	00:44:08
292	292_h_A_m_E	0.20	1.48	1.14	1.02	204	5945	9655156	6.99	1.75	00:04:13	00:00:00	00:14:12	00:00:46	00:21:44	00:40:55
293	293_h_B_m_E	0.34	1.53	1.29	1.17	204	63854	9757132	6.99	1.75	00:07:32	00:00:06	00:14:14	00:00:45	00:20:58	00:43:35
294	294_h_C_m_E	0.50	1.57	1.29	1.12	205	580832	9729605	6.99	1.75	00:14:41	00:00:35	00:13:16	00:00:34	00:22:51	00:51:57
295	295_h_A_h_E	0.20	1.48	1.02	0.85	818	5923	39500229	3.50	1.75	00:04:09	00:00:01	00:44:06	00:02:12	00:21:38	01:12:06
296	296_h_B_h_E	0.34	1.53	1.09	0.92	818	63307	39890397	3.50	1.75	00:07:44	00:00:04	00:47:10	00:02:14	00:22:17	01:19:29
297	297_h_C_h_E	0.50	1.57	1.12	0.94	818	580902	39768495	3.50	1.75	00:14:23	00:00:26	00:43:08	00:02:06	00:23:03	01:23:06
298	298_h_A_uh_E	0.20	1.48	0.89	0.75	3270	5931	162977762	1.75	1.75	00:04:00	00:00:01	02:27:27	00:07:08	00:24:40	03:03:16
299	299_h_B_uh_E	0.34	1.53	0.98	0.82	3270	63555	163489114	1.75	1.75	00:07:21	00:00:04	02:25:16	00:07:29	00:25:34	03:05:44
300	300_h_C_uh_E	0.50	1.57	0.99	0.82	3270	580247	163100877	1.75	1.75	00:13:07	00:00:28	02:17:24	00:07:05	00:24:19	03:02:23
301	301_ht_A_lt_A	3.68	48.31				6718				00:05:48	00:00:01				00:05:49
302	302_ht_B_lt_A	3.61	48.42				71218				00:09:33	00:00:09				00:09:42
303	303_ht_C_lt_A	2.92	48.58				2427735				01:38:09	00:03:37				01:41:46
304	304_ht_A_l_A	3.68	48.31				6687				00:05:42	00:00:02				00:05:44
305	305_ht_B_l_A	3.60	48.42				71388				00:09:39	00:00:09				00:09:48
306	306_ht_C_l_A	2.94	48.64				2431645				01:27:26	00:03:28				01:30:54
307	307_ht_A_m_A	3.69	48.31				6705				00:05:58	00:00:01				00:05:59
308	308_ht_B_m_A	3.60	48.42				71477				00:09:16	00:00:07				00:09:23
309	309_ht_C_m_A	2.94	48.61				2440241				01:41:33	00:03:08				01:44:41
310	310_ht_A_h_A	3.69	48.31				6617				00:06:02	00:00:01				00:06:03
311	311_ht_B_h_A	3.60	48.42				71569				00:09:16	00:00:09				00:09:25
312	312_ht_C_h_A	2.94	48.62				2441951				01:41:45	00:03:16				01:45:01
313	313_ht_A_uh_A	3.69	48.31				6677				00:05:49	00:00:01				00:05:50
314	314_ht_B_uh_A	3.60	48.42				71494				00:09:22	00:00:07				00:09:29
315	315_ht_C_uh_A	2.93	48.62				2448781				01:42:01	00:03:29				01:45:30
316	316_ht_A_lt_B	3.50	48.31				6684				00:06:08	00:00:01				00:06:09
317	317_ht_B_lt_B	3.42	48.41				71264				00:09:29	00:00:08				00:09:37
318	318_ht_C_lt_B	2.78	48.65				2428111				01:35:17	00:04:53				01:40:10
319	319_ht_A_l_B	3.48	48.31				6735				00:05:32	00:00:01				00:05:33
320	320_ht_B_l_B	3.41	48.41				71384				00:09:23	00:00:08				00:09:31
321	321_ht_C_l_B	2.77	48.64				2444591				01:42:27	00:04:49				01:47:16
322	322_ht_A_m_B	3.49	48.31				6652				00:05:47	00:00:02				00:05:49

323	323_ht_B_m_B	3.41	48.41				71699				00:09:31	00:00:10				00:09:41
324	324_ht_C_m_B	2.74	48.62				2449862				01:44:56	00:03:26				01:48:22
325	325_ht_A_h_B	3.49	48.31				6705				00:05:33	00:00:01				00:05:34
326	326_ht_B_h_B	3.42	48.41				71422				00:09:28	00:00:09				00:09:37
327	327_ht_C_h_B	2.77	48.64				2445643				01:41:33	00:04:37				01:46:10
328	328_ht_A_uh_B	3.49	48.31				6676				00:05:52	00:00:02				00:05:54
329	329_ht_B_uh_B	3.41	48.41				71554				00:09:11	00:00:08				00:09:19
330	330_ht_C_uh_B	2.78	48.66				2434376				01:35:57	00:04:37				01:40:34
331	331_ht_A_lt_C	0.85	1.59	2.59	2.56	12.7	6702	595858	28.00	1.75	00:05:49	00:00:01	00:06:27	00:00:06	00:17:13	00:29:36
332	332_ht_B_lt_C	0.84	5.17	9.55	9.49	12.7	71630	592702	28.10	1.75	00:09:31	00:00:07	00:06:18	00:00:05	00:17:28	00:33:29
333	333_ht_C_lt_C	0.75	24.84	44.69	44.22	12.6	2447957	585739	28.20	1.76	01:47:56	00:02:21	00:02:21	00:00:05	00:17:24	02:10:07
334	334_ht_A_l_C	0.85	1.59	1.82	1.82	50.9	6672	2407560	14.00	1.75	00:05:59	00:00:01	00:08:00	00:00:09	00:17:58	00:32:09
335	335_ht_B_l_C	0.84	5.18	9.54	9.40	50.8	71399	2394527	14.00	1.75	00:09:41	00:00:09	00:08:03	00:00:11	00:18:01	00:36:05
336	336_ht_C_l_C	0.75	24.75	44.33	43.77	50.4	2433559	2355855	14.10	1.76	01:46:29	00:02:56	00:09:12	00:00:10	00:16:39	02:15:26
337	337_ht_A_m_C	0.85	1.59	1.72	1.69	203	6501	9660584	7.01	1.75	00:05:54	00:00:01	00:15:10	00:00:40	00:17:02	00:38:47
338	338_ht_B_m_C	0.84	5.17	9.44	9.30	203	71649	9633566	7.01	1.75	00:09:19	00:00:06	00:15:20	00:00:40	00:17:13	00:42:26
339	339_ht_C_m_C	0.75	24.69	43.92	43.35	202	2447359	9457077	7.04	1.76	01:52:18	00:02:41	00:14:43	00:00:29	00:17:13	02:27:24
340	340_ht_A_h_C	0.85	1.59	1.59	1.59	814	6687	39524879	3.51	1.75	00:05:54	00:00:01	00:57:10	00:02:03	00:17:50	01:22:58
341	341_ht_B_h_C	0.84	5.12	9.27	9.13	812	71283	39303915	3.51	1.75	00:10:03	00:00:08	00:54:09	00:02:04	00:17:02	01:23:26
342	342_ht_C_h_C	0.75	24.71	44.11	43.51	807	2435660	38903233	3.52	1.76	01:41:01	00:02:37	00:45:06	00:01:46	00:17:35	02:48:05
343	343_ht_A_uh_C	0.85	1.59	1.53	1.50	3250	6662	167306391	1.75	1.75	00:05:56	00:00:01	03:02:00	00:06:06	00:19:13	03:33:16
344	344_ht_B_uh_C	0.84	5.11	9.26	9.14	3250	71369	165685639	1.75	1.75	00:09:37	00:00:06	02:43:00	00:06:06	00:20:18	03:19:07
345	345_ht_C_uh_C	0.75	24.76	43.81	43.22	3230	2436167	161502084	1.76	1.76	01:42:12	00:02:24	02:36:00	00:05:40	00:20:10	04:46:26
346	346_ht_A_lt_D	0.85	1.58	2.40	2.37	12.7	6481	596272	28.00	1.75	00:06:04	00:00:01	00:06:44	00:00:06	00:17:10	00:30:05
347	347_ht_B_lt_D	0.84	5.43	9.90	9.82	12.7	71525	592185	28.10	1.75	00:09:46	00:00:07	00:05:56	00:00:06	00:16:27	00:32:22
348	348_ht_C_lt_D	0.75	25.29	44.41	43.96	12.6	2434356	584578	28.20	1.76	01:39:30	00:02:10	00:07:26	00:00:05	00:17:06	02:06:17
349	349_ht_A_l_D	0.85	1.58	2.08	2.03	50.9	6687	2409492	14.00	1.75	00:05:58	00:00:01	00:07:49	00:00:11	00:16:58	00:30:57
350	350_ht_B_l_D	0.84	5.42	9.60	9.45	50.8	71175	2391963	14.00	1.75	00:09:57	00:00:06	00:07:38	00:00:11	00:17:10	00:35:02
351	351_ht_C_l_D	0.75	25.45	44.19	43.62	50.4	2431625	2349263	14.10	1.76	01:39:02	00:02:02	00:08:53	00:00:09	00:17:11	02:07:17
352	352_ht_A_m_D	0.86	1.58	1.57	1.53	203	6624	9688326	7.01	1.75	00:06:04	00:00:01	00:15:14	00:00:41	00:17:48	00:39:48
353	353_ht_B_m_D	0.84	5.40	9.32	9.17	203	71174	9627276	7.02	1.75	00:09:49	00:00:06	00:15:11	00:00:43	00:16:24	00:42:13
354	354_ht_C_m_D	0.75	25.25	43.80	43.24	203	2442238	9514372	7.04	1.76	01:41:55	00:02:27	00:15:56	00:00:29	00:16:19	02:17:06
355	355_ht_A_h_D	0.85	1.58	1.79	1.79	814	6703	39520357	3.51	1.75	00:06:06	00:00:01	00:48:40	00:02:01	00:16:41	01:13:29
356	356_ht_B_h_D	0.84	5.37	9.18	9.07	812	71107	39279657	3.51	1.75	00:09:58	00:00:07	00:49:29	00:02:11	00:17:55	01:19:40
357	357_ht_C_h_D	0.75	25.26	43.72	43.13	806	2442980	38764070	3.52	1.76	01:37:30	00:02:19	00:43:38	00:02:05	00:17:22	02:42:54
358	358_ht_A_uh_D	0.85	1.58	1.52	1.52	3250	6714	166983664	1.75	1.75	00:06:00	00:00:01	02:57:00	00:06:23	00:18:36	03:28:00
359	359_ht_B_uh_D	0.84	5.38	9.24	9.10	3250	71125	165369819	1.75	1.75	00:10:02	00:00:08	02:56:00	00:06:23	00:18:53	03:31:26
360	360_ht_C_uh_D	0.75	25.26	43.66	43.07	3220	2444295	160928129	1.76	1.76	01:43:20	00:01:54	02:48:00	00:05:49	00:18:22	04:57:25
361	361_ht_A_lt_E	0.15	1.49	2.17	2.17	12.8	6674	599104	28.00	1.75	00:05:48	00:00:01	00:06:30	00:00:05	00:16:36	00:29:00
362	362_ht_B_lt_E	0.17	1.55	2.31	2.26	12.8	71402	598081	28.00	1.75	00:09:36	00:00:05	00:06:50	00:00:05	00:18:20	00:34:56
363	363_ht_C_lt_E	0.35	1.63	2.02	2.00	12.8	2429366	598026	28.00	1.75	01:38:36	00:01:04	00:16:26	00:00:06	00:17:31	02:13:43
364	364_ht_A_l_E	0.15	1.49	1.34	1.29	51.1	6614	2417643	14.00	1.75	00:05:54	00:00:01	00:07:17	00:00:12	00:17:28	00:30:52
365	365_ht_B_l_E	0.17	1.55	1.39	1.35	51.1	71267	2415869	14.00	1.75	00:10:07	00:00:05	00:07:29	00:00:11	00:16:54	00:34:46
366	366_ht_C_l_E	0.35	1.63	1.39	1.36	51.1	2447171	2411026	14.00	1.75	01:41:07	00:01:19	00:08:25	00:00:10	00:16:52	02:07:53
367	367_ht_A_m_E	0.15	1.49	1.18	1.07	204	6641	9799492	6.99	1.75	00:06:05	00:00:01	00:14:42	00:00:42	00:16:26	00:37:56
368	368_ht_B_m_E	0.17	1.55	1.30	1.13	204	71536	9740275	6.99	1.75	00:09:47	00:00:05	00:14:44	00:00:42	00:16:48	00:42:06
369	369_ht_C_m_E	0.35	1.63	1.29	1.15	204	2439110	9774112	6.99	1.75	01:39:12	00:01:12	00:15:25	00:00:31	00:18:28	02:14:48
370	370_ht_A_h_E	0.15	1.49	1.02	0.85	818	6701	39757616	3.50	1.75	00:05:52	00:00:01	00:48:16	00:02:06	00:17:08	01:13:23
371	371_ht_B_h_E	0.17	1.55	1.03	0.89	818	71679	39790733	3.50	1.75	00:09:30	00:00:05	00:47:11	00:02:05	00:16:39	01:15:30
372	372_ht_C_h_E	0.35	1.63	1.14	0.94	818	2446906	39704843	3.50	1.75	01:52:43	00:01:27	00:42:05	00:01:49	00:16:46	02:54:50
373	373_ht_A_uh_E	0.15	1.49	0.91	0.78	3270	6649	163060716	1.75	1.75	00:05:52	00:00:01	02:31:00	00:06:23	00:19:53	03:03:09
374	374_ht_B_uh_E	0.17	1.55	0.96	0.83	3270	71455	162982421	1.75	1.75	00:09:34	00:00:05	02:27:00	00:06:22	00:20:46	03:03:47
375	375_ht_C_uh_E	0.35	1.63	1.05	0.87	3270	2440847	162988611	1.75	1.75	01:42:36	00:01:24	02:20:00	00:06:08	00:21:07	04:31:15

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Elevation differences between check points and model

Appendix S3: Python Script #1 (the fastest).

```python
1    #First scheme: the fastest
2
3    import Metashape
4
5    doc = Metashape.app.document
6
7    for chunk in doc.chunks:
8
9    #alignment
10       chunk.matchPhotos(
11           downscale = 4,
12           keypoint_limit = 100000,
13           tiepoint_limit = 10000,
14           mask_tiepoints = False,
15           reset_matches = True,
16           generic_preselection = True,
17           reference_preselection = True)
18       chunk.alignCameras(reset_alignment = True)
19       doc.save()
20
21    #cloud filter
22       f = Metashape.PointCloud.Filter()
23
24       reprojection_error_threshold = 0.5
25       reconstruction_uncertainty_threshold = 10
26       image_count_threshold = 2
27       projection_accuracy_threshold = 20
28
29       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReprojectionError)
30       f.removePoints(reprojection_error_threshold)
31
32       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReconstructionUncertainty)
33       f.removePoints(reconstruction_uncertainty_threshold)
34
35       f.init(chunk, criterion = Metashape.PointCloud.Filter.ImageCount)
36       f.removePoints(image_count_threshold)
37
38       f.init(chunk, criterion = Metashape.PointCloud.Filter.ProjectionAccuracy)
39       f.removePoints(projection_accuracy_threshold)
40       doc.save()
41
42    #optimization of point cloud
43       chunk.optimizeCameras(
44           fit_f = True,
45           fit_cx = True,
46           fit_cy = True,
47           fit_b1 = True,
48           fit_b2 = True,
49           fit_k1 = True,
50           fit_k2 = True,
51           fit_k3 = False,
52           fit_k4 = False,
53           fit_p1 = False,
54           fit_p2 = False,
55           tiepoint_covariance = True)
56       doc.save()
57
58    #build dense cloud
59       chunk.buildDepthMaps(filter_mode = Metashape.AggressiveFiltering, reuse_depth = True)
60       chunk.buildDenseCloud(point_colors = True)
61       doc.save()
62
63    #build DEM
64       chunk.buildDem(source_data = Metashape.DenseCloudData)
65       doc.save()
66
67    #build orthomosaic
68       chunk.buildOrthomosaic(surface_data = Metashape.ElevationData)
69       doc.save()
70
71    #remove orthophotos
72       ortho = chunk.orthomosaic
73       ortho.removeOrthophotos()
74       doc.save()
75
76    Metashape.app.messageBox("Well done!")
77    #Metashape.app.quit()
```

Appendix S4: Python Script #2 (optimal).

```python
1    #Second scheme: optimal
2
3    import Metashape
4
5    doc = Metashape.app.document
6
7    for chunk in doc.chunks:
8
9    #alignment
10       chunk.matchPhotos(
11           downscale = 4,
12           keypoint_limit = 0,
13           tiepoint_limit = 0,
14           mask_tiepoints = False,
15           reset_matches = True,
16           generic_preselection = True,
17           reference_preselection = True)
18       chunk.alignCameras(reset_alignment = True)
19       doc.save()
20
21    #cloud filter
22       f = Metashape.PointCloud.Filter()
23
24       reprojection_error_threshold = 0.5
25       reconstruction_uncertainty_threshold = 10
26       image_count_threshold = 2
27       projection_accuracy_threshold = 20
28
29       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReprojectionError)
30       f.removePoints(reprojection_error_threshold)
31
32       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReconstructionUncertainty)
33       f.removePoints(reconstruction_uncertainty_threshold)
34
35       f.init(chunk, criterion = Metashape.PointCloud.Filter.ImageCount)
36       f.removePoints(image_count_threshold)
37
38       f.init(chunk, criterion = Metashape.PointCloud.Filter.ProjectionAccuracy)
39       f.removePoints(projection_accuracy_threshold)
40       doc.save()
41
42    #optimization of point cloud
43       chunk.optimizeCameras(
44           fit_f = True,
45           fit_cx = True,
46           fit_cy = True,
47           fit_b1 = True,
48           fit_b2 = True,
49           fit_k1 = True,
50           fit_k2 = True,
51           fit_k3 = True,
52           fit_k4 = True,
53           fit_p1 = True,
54           fit_p2 = True,
55       tiepoint_covariance = True)
56       doc.save()
57
58    #build dense cloud
59       chunk.buildDepthMaps(downscale = 2, filter_mode = Metashape.AggressiveFiltering,
60    reuse_depth = True)
61       chunk.buildDenseCloud(point_colors = True)
62       doc.save()
63
64    #build DEM
65       chunk.buildDem(source_data = Metashape.DenseCloudData)
66       doc.save()
67
68    #build orthomosaic
69       chunk.buildOrthomosaic(surface_data = Metashape.ElevationData)
70       doc.save()
71
72    #remove orthophotos
73       ortho = chunk.orthomosaic
74       ortho.removeOrthophotos()
75       doc.save()
76
77    Metashape.app.messageBox("Well done!")
78    #Metashape.app.quit()
```

Appendix S5: Python Script #3 (best quality).

```
1    #Third scheme: best quality
2
3    import Metashape
4
5    doc = Metashape.app.document
6
7    for chunk in doc.chunks:
8
9    #alignment
10       chunk.matchPhotos(
11           downscale = 2,
12           keypoint_limit = 10000,
13           tiepoint_limit = 1000,
14           mask_tiepoints = False,
15           reset_matches = True,
16           generic_preselection = True,
17           reference_preselection = True)
18       chunk.alignCameras(reset_alignment = True)
19       doc.save()
20
21   #cloud filter
22       f = Metashape.PointCloud.Filter()
23
24       reprojection_error_threshold = 0.5
25       reconstruction_uncertainty_threshold = 10
26       image_count_threshold = 2
27       projection_accuracy_threshold = 20
28
29       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReprojectionError)
30       f.removePoints(reprojection_error_threshold)
31
32       f.init(chunk, criterion = Metashape.PointCloud.Filter.ReconstructionUncertainty)
33       f.removePoints(reconstruction_uncertainty_threshold)
34
35       f.init(chunk, criterion = Metashape.PointCloud.Filter.ImageCount)
36       f.removePoints(image_count_threshold)
37
38       f.init(chunk, criterion = Metashape.PointCloud.Filter.ProjectionAccuracy)
39       f.removePoints(projection_accuracy_threshold)
40       doc.save()
41
42   #optimization of point cloud
43       chunk.optimizeCameras(
44           fit_f = True,
45           fit_cx = True,
46           fit_cy = True,
47           fit_b1 = True,
48           fit_b2 = True,
49           fit_k1 = True,
50           fit_k2 = True,
51           fit_k3 = True,
52           fit_k4 = True,
53           fit_p1 = True,
54           fit_p2 = True,
55           tiepoint_covariance = True)
56       doc.save()
57
58   #build dense cloud
59       chunk.buildDepthMaps(downscale = 1, filter_mode = Metashape.AggressiveFiltering,
60   reuse_depth = True)
61       chunk.buildDenseCloud(point_colors = True)
62       doc.save()
63
64   #build DEM
65       chunk.buildDem(source_data = Metashape.DenseCloudData)
66       doc.save()
67
68   #build orthomosaic
69       chunk.buildOrthomosaic(surface_data = Metashape.ElevationData)
70       doc.save()
71
72   #remove orthophotos
73       ortho = chunk.orthomosaic
74       ortho.removeOrthophotos()
75       doc.save()
76
77   Metashape.app.messageBox("Well done!")
78   #Metashape.app.quit()
```

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RESEARCH ARTICLE

WILEY

Quantification of short-term transformations of proglacial landforms in a temperate, debris-charged glacial landsystem, Kvíárjökull, Iceland

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Abstract

Proglacial areas are dynamic landscapes and important indicators of geomorphic changes related to climate warming. Systematic and repeat surveys of landforms presently evolving on glacier forelands facilitate the quantification of rates of change and an improved understanding of the processes generating those changes. We report short-term (2014–2022) transformations of the proglacial landscape in front of Kvíárjökull, SE Iceland, and place them in a longer-term context of glacial landsystem evolution using aerial image archives since 1945. Short-term quantification uses a time series of uncrewed aerial vehicle (UAV) surveys, processed utilizing a structure-from-motion (SfM) workflow, to produce digital elevation models (DEMs) and orthophoto mosaics. The land elements surveyed include a kame terrace staircase, an outwash plain, an ice-cored hummocky moraine complex and ice-cored hummocky terrain with discontinuous sinuous ridges, for which elevation and volumetric changes are quantified. The kame terraces between 2014 and 2022 and the outwash plain between 2016 and 2022 were mainly stable with, respectively, 87% and 85% of their surfaces showing no change. The ice-cored hummocky terrain with discontinuous sinuous ridges underwent a volume loss of 64,632 m^3 in 2016–2022, with a maximum surface lowering of ≤9 m. The most dynamic land element was the ice-cored hummocky moraine complex, with transformations recorded for more than 87% of its area in 2014–2022; the surface was lowered by ≤23 m in some places, with a total volume loss of 365,773 m^3. Our results confirm the ongoing degradation of ice-cored moraine and outwash complexes at variable rates related to buried ice volume and age of deglaciation. The evolution of chaotic hummocky terrain from debris-covered glacier ice, glacitectonic thrust masses, outwash fans/heads and complex englacial esker networks is an important modern analogue for informing palaeo-glaciological reconstructions.

KEYWORDS
change detection, debris-charged glacial landsystem, glacial geomorphology, proglacial landforms, UAV, uncrewed aerial vehicle

1 | INTRODUCTION

Global climate warming has contributed to landform transformation for decades (Song et al., 2018) and increasing average air temperatures have resulted in significant changes in regional climates and local ecosystems, thereby increasing the risks of fires, droughts, floods and landslides (Allen et al., 2010; Flannigan et al., 2009; Gariano & Guzzetti, 2016; Hirabayashi et al., 2013; Młynarczyk et al., 2022). In cold climate settings, the impact has been manifested as dynamic responses in glacial systems (Benn et al., 2012; Benn & Evans, 2010). The recent fluctuations in volume and extent of glaciers have been widely analysed (e.g., Bash et al., 2018; Bash & Moorman, 2020; Carrivick et al., 2019; Hugonnet et al., 2021; Jouvet et al., 2019; Kienholz et al., 2020; Małecki, 2016; Małecki, 2022; Rossini et al., 2018; Sziło & Bialik, 2018) but less attention has been paid to geomorphological transformations taking place in proglacial areas and their possible links to climate warming (Bennett et al., 2010; Bennett & Evans, 2012; Carrivick & Heckmann, 2017; Chandler, Chandler, et al., 2020; Evans et al., 2023; Ewertowski et al., 2019; Ewertowski & Tomczyk, 2020; Hedding et al., 2020; Schomacker, 2008; Seier et al., 2017; Staines et al., 2015; Strzelecki et al., 2018).

Observations on landscape change in proglacial areas are important because such terrains contain a large amount of often unstable, non-consolidated sediments as well as water stored in the form of lakes and ice-cored landforms. The combination of potentially large volumes of meltwater and highly mobile sediments means that rapid, climate-driven transformations in proglacial areas can release substantial, possibly catastrophic, floods and/or debris flows, which in turn can rapidly transform landscapes located downstream (Carrivick & Tweed, 2019; Knight & Harrison, 2012a, 2012b; Knight & Harrison, 2018; Tomczyk et al., 2020; Tonkin et al., 2016). In inhabited parts of mountain and polar regions, the dynamics and scale of landform transformations on glacial forelands may have serious implications for infrastructure and human populations located in the same catchment (Cook et al., 2016, 2018; Harrison et al., 2018). Therefore, there is a strong justification for the monitoring of proglacial areas in such settings in order to understand the temporal aspects of landscape change during deglaciation, especially the de-icing of buried glacier ice masses (Bennett & Evans, 2012; Blauvelt et al., 2020; Evans et al., 2023; Ewertowski & Tomczyk, 2015; Kjær & Krüger, 2001; Krüger & Kjær, 2000; Schomacker, 2008; Schomacker & Kjær, 2007, 2008), as they pertain to applied glacial and paraglacial geomorphology (Carrivick & Heckmann, 2017). Not unrelated to this is the need to better quantify glacial process–form regimes as they pertain to spatio-temporal change in modern glacial landsystems (e.g., Bennett et al., 2010; Bennett & Evans, 2012; Chandler, Chandler, et al., 2020; Evans et al., 2009, 2019, 2022; Evans & Twigg, 2002; Ewertowski et al., 2019; Eyles, 1983a, 1983b; Midgley et al., 2018; Price, 1980).

Most of the previous research on proglacial landscape transformations has focused on the analysis of changes in the glacier forelands on a decadal temporal scale (e.g., Bennett & Evans, 2012; Carrivick & Heckmann, 2017; Etzelmüller, 2000; Ewertowski, 2014,

2019; Staines & Carrivick, 2015). Recently, a number of studies have begun the quantification of changes that take place on shorter temporal scales, from years to days (e.g., Bernard et al., 2016; Bühler et al., 2016; Chandler, Evans, et al., 2020; Evans et al., 2023; Ewertowski & Tomczyk, 2015; 2020; Fey & Krainer, 2020; Groos et al., 2019; Jouvet et al., 2018; Kraaijenbrink et al., 2016; Rossini et al., 2018; Ryan et al., 2015; van der Sluijs et al., 2018; van Woerkom et al., 2019; Westoby et al., 2020), typically using mobile platforms and sensors to collect data (e.g., LIDAR or uncrewed aerial vehicle [UAV]; Śledź et al., 2021 for detailed review). Because of their more detailed temporal and spatial scale, these studies do not cover whole glacial forelands but instead only individual landforms or single landform assemblages.

The aim of this study is to illustrate and quantify the short-term evolution of several different glacial landform assemblages on the foreland of the temperate, debris-charged glacier Kvíárjökull in Iceland based on time series of UAV images. This foreland is an exceptional example of a landscape produced by the process of incremental stagnation (sensu Bennett & Evans, 2012; Eyles, 1979), whereby belts of debris-charged ice, representative of periodic influxes of debris to the glacier system, arrive occasionally at the receding glacier snout and give rise to the production of inset sequences of ice-cored hummocky moraine arcs over time. Each hummocky moraine arc therefore records the detachment of a debris-charged portion of the snout that is covered with supraglacial debris, retarding normal ablation rates. During progressive but slow de-icing, the hummocky moraine is subject to proglacial pushing or bulldozing by the actively receding glacier margin (Bennett et al., 2010; Bennett & Evans, 2012). Also important on the foreland of Kvíárjökull are landform assemblages representative of sedimentation and landform construction in a high debris turnover piedmont glacier terminating in an erosional overdeepening. This has given rise to the development of unusually large latero-frontal terminal moraines, inset with extensive ice-contact glacifluvial landform–sediment associations. These include kame terraces, englacial eskers and pitted outwash, all reflective of the large sediment loads of meltwater networks that have developed over the overdeepening and which have been confined proglacially by the enclosing latero-frontal moraine amphitheatre (Bennett et al., 2010; Bennett & Evans, 2012; Phillips et al., 2017; Spedding & Evans, 2002).

Previous quantification studies at Kvíárjökull by Bennett and Evans (2012) provided details on landform change relating to the melt-out of buried glacier ice and concomitant collapse of the ice-cored hummocky moraine arcs. They also documented the impact of the 1990s readvance (sensu Bradwell et al., 2006; Evans & Chandler, 2018; Evans & Hiemstra, 2005; Sigurðsson, 2005; Sigurðsson et al., 2007) of the glacier snout into the innermost moraine arc, which resulted in a phase of landform surface uplift by an average of 6.5 m following on from decades of collapse due to de-icing. This study aims to provide a continuation of the quantification of Bennett and Evans (2012) in order to evaluate the rate and extent of landscape degradation representative of modern-day glacierized settings characterized by debris-charged snouts with strong topographical constraints and subject to rapid melting in a warming

climate. An additional aim here is to facilitate the development of glacial process–form models constrained by real-time quantification, thereby strengthening, and indeed improving, those traditionally developed largely by ergodic principles (i.e., location for time reasoning, whereby a spatio-temporal continuum of landform genesis is reconstructed using examples of the landform at various stages of its development regardless of location; cf. Brunsden & Thornes, 1979; Evans, 2013; Evans & Twigg, 2002; Paine, 1985; Price, 1969).

2 | MATERIALS AND METHODS

This study is focussed on landform assemblages located on the northern part of the foreland of Kvíárjökull, a temperate, debris-charged outlet glacier of the Öræfajökull ice cap in SE Iceland (Figure 1a), and records their transformation based on time series of aerial photograph archives (Figure 1) and UAV data. Longer timescale change (decadal) was mapped using the digital scans of aerial photographs (0.5–0.9 m ground sampling distance [GSD], that is, ground distance between centres of two pixels) from National Land Survey of Iceland captured in 1945, 1964, 1980 and 1998 by Landmaelingar Islands and in 2003 by Loftmyndir ehf (see Bennett et al., 2010, for details) as well as pan-sharpened (0.5 m GSD) WorldView-2 satellite imagery from Maxar (formerly Digital Globe) for 2012 and 2014. For shorter timescales, we used the popular structure-from-motion (SfM) method (see Westoby et al., 2012) to produce digital elevation models (DEMs) and orthomosaics based on four sets of images obtained from different types of UAVs: fixed-winged (produced by SmartPlane) and several generations of Phantom series quadcopters (produced by DJI) (Table 1). Autonomous flights were carried out in 2021 (Phantom 4 Pro) and 2022 (Phantom 4 RTK), and partly in 2014 (Smartplane), while flights with Phantom 2 in 2014 and Phantom 3 in 2016 were conducted manually. PlanetScope satellite images (3 m GSD) (Planet, 2022), combined with our UAV orthomosaics, were used to map changes in the glacier front during our observation period of 2014–2022.

During the 2022 flying, the UAV was connected to a local GNSS base station in order to increase the accuracy of the coordinates of the images, facilitated by the use of a high-precision RTK survey. The Topcon Link and RTKLIB software were used for post-processing and the application of PPP corrections (Precise Point Positioning) for the 2022 set of images and Ground Control Points (GCPs), along with an estimation of the influence of ocean tides on the measurement (source: http://holt.oso.chalmers.se/loading/). The image sets were used to create DEMs and orthomosaics in the Agisoft Metashape 1.7.1 photogrammetry software. Due to the fact that the UAV was equipped with an RTK receiver in 2022, we used one of the image processing schemes proposed by Nota et al. (2022), whereby we co-aligned all sets of images with seven GCPs marked on the 2022 images. We did not use the coordinates of the images from the other sets (2014, 2016 and 2021) as references. The result of this procedure was one, co-aligned, large, sparse point cloud, which was then divided into four separate projects according to the year of survey (2014,

2016, 2021 and 2022), in which only the right images for a given year were processed further to generate dense point clouds. Then, we proceeded to the next steps of processing using the Metashape software, and their detailed description is contained in Śledź and Ewertowski (2022), from which we chose the settings and parameters according to the procedure in script no. 2 'Optimal'. The only modification in the script was the higher accuracy of generating a sparse point cloud (from low to high) due to the partial use of JPG images and unsatisfactory results at the low level. Śledź and Ewertowski (2022) also describe and illustrate the method for establishing GCPs in the field, in the form of stone circles and the technique for measuring them with a GNSS receiver, which was identical in this study. The results of the photogrammetric processing were four DEMs, with the GSD ranging from 5.35 to 7.36 cm. Additionally, four high-resolution orthomosaics with GSD of ∼3 cm were also exported.

Based on the DEMs and orthomosaics, we defined four case study areas on the glacier foreland which represent land elements (the fundamental level of the glacial landsystems hierarchy; sensu Eyles, 1983a, 2003; Fookes et al., 1978) within the debris-charged, active temperate glacial landsystem at Kvíárjökull (Bennett et al., 2010) (Figure 2). These areas differ from each other in terms of their genesis, material properties and morphology, as well as the rate and scale of surface changes. To estimate changes on the foreland in a quantitative way, we used DEMs of differences (DoDs; Wheaton et al., 2010), which are models showing elevation changes between two surveys. DoDs were calculated in ArcMap 10.8.1 using a Geomorphic Change Detection (GCD) add-in dedicated to this software (Source: http://gcd.riverscapes.xyz). Before importing the DEMs to the GCD, we resampled them down to 6 cm per pixel. We also performed an error analysis, whereby variations in elevation differences for the stable areas on each pair of DEMs were calculated to determine the minimum level of detection (minLoD) equalled to 0.2 m. The mapping of the studied area was based on orthomosaics, field surveys and photographic documentation.

3 | RESULTS

3.1 | Characteristics of land elements of the debris-charged, active temperate foreland at Kvíárjökull

Four land elements characteristic of the foreland were selected to investigate recent surface change or transformations (Figure 3), including case study areas: (1) a kame terrace staircase; (2) an outwash plain; (3) an ice-cored hummocky moraine complex and (4) ice-cored hummocky terrain with discontinuous sinuous ridges. These are representative of the broader proglacial area/foreland as previously mapped by Bennett et al. (2010) and are characterized by different topographies and buried glacier ice content, in addition to their distinctive genetic origins based on observations since the earliest aerial photographs captured in 1945 (Bennett et al., 2010; Bennett & Evans, 2012; Eyles, 1979, 1983b; Spedding & Evans, 2002).
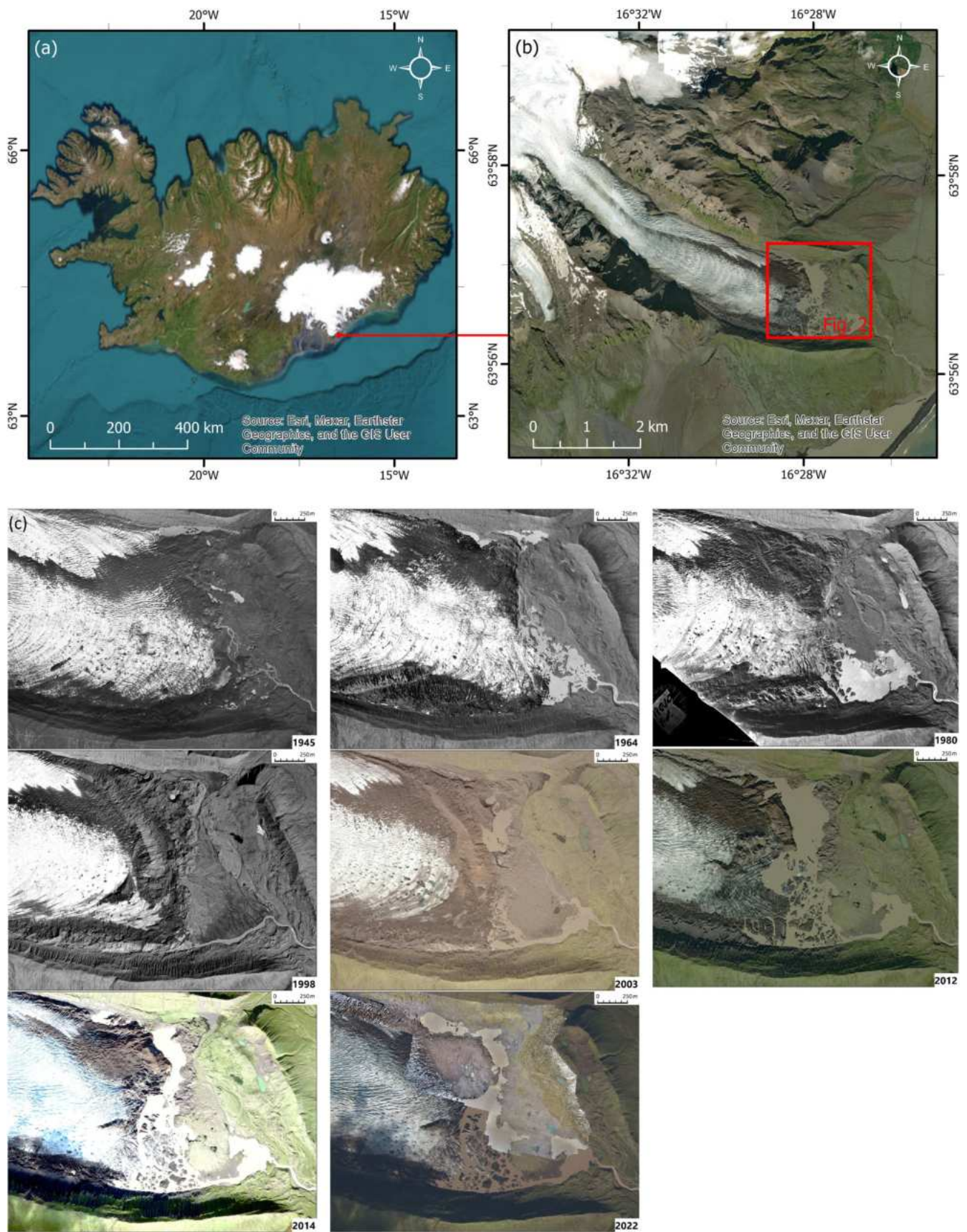
FIGURE 1 Kvíárjökull, SE Vatnajökull, Iceland: (a, b) location of the study area; (c) aerial photograph (1945–2003) and satellite image (2012–2022) extracts from various times since 1945, showing the changes to the glacier snout and foreland. *Source*: 1945–2003—aerial photographs, National Land Survey of Iceland; 2012 and 2014—WorldView-2 images, Maxar (formerly Digital Globe); 2022—PlanetScope, Planet (2022). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Platforms used for quantifying recent, short timescale landscape change and the characteristics of the images.

Date	Drone	Total number of images	Images format	Type of sensor
2014, September	DJI Phantom 2 Vision+	38	DNG	Build-in, RGB
	Smartplane	347	JPG	Canon PowerShot S100, RGB
2016, September	DJI Phantom 3 Advanced	488	DNG	Build-in, RGB
2021, September	DJI Phantom 4 Pro	717	DNG	Build-in, RGB
2022, May	DJI Phantom 4 RTK	880	JPG	Build-in, RGB

Note: In 2014, two types of UAVs were used: a multi-rotor (DJI) and a fixed wing (Smartplane). Images from the fixed-wing and the DJI Phantom 4 RTK were saved in JPG format because these models do not allow saving in RAW format.
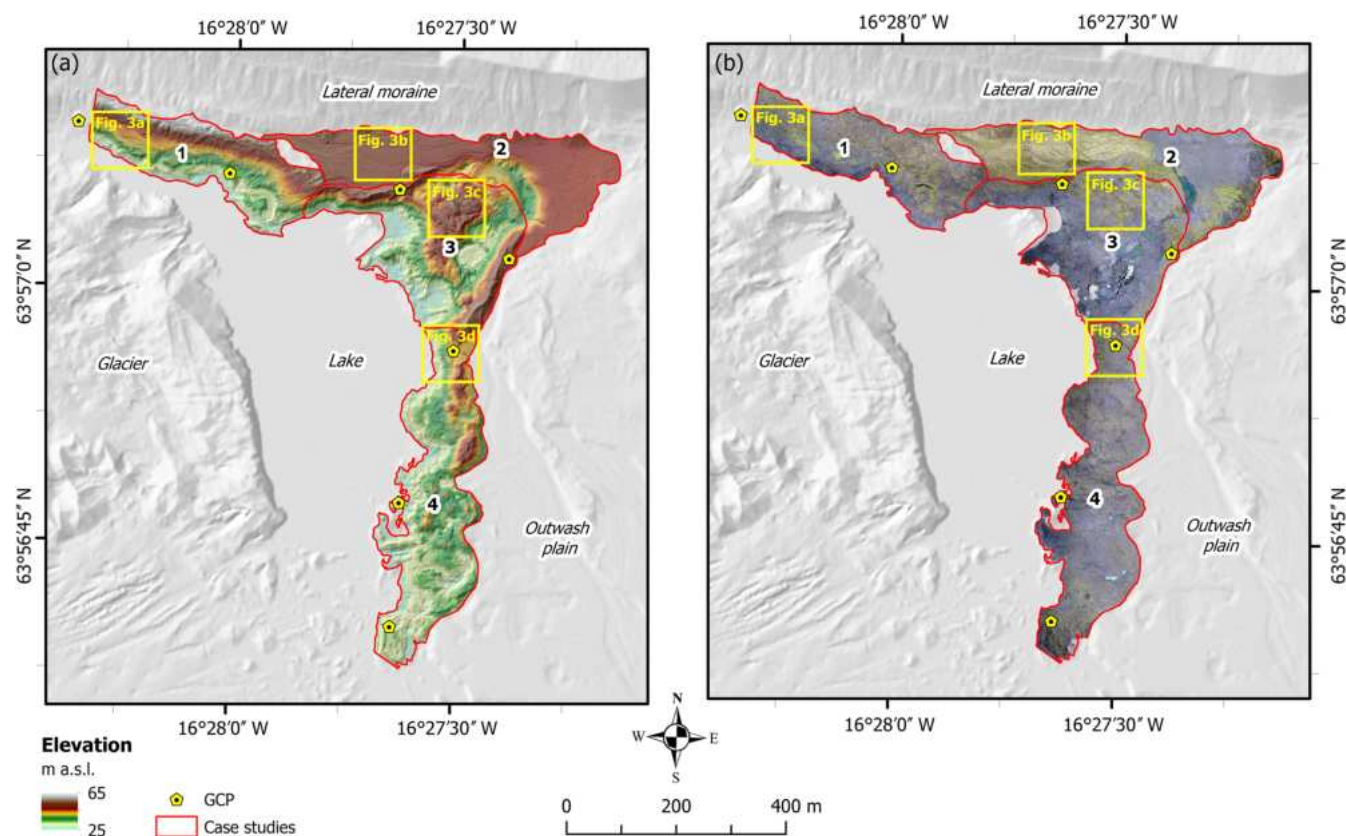
FIGURE 2 The extent of the four case study areas on the foreland of Kvíárjökull (1: a kame terrace staircase; 2: an outwash plain; 3: an ice-cored hummocky moraine complex; and 4: ice-cored hummocky terrain with discontinuous sinuous ridges), with locations of Ground Control Points (GCPs) marked on the digital elevation model with hillshade (a) and orthomosaic (b) from September 2021. The figure also shows the location of the examples of the land elements in Figure 3. Source of background: ÍslandsDEM v1.0. *Source*: https://www.lmi.is/. [Colour figure can be viewed at wileyonlinelibrary.com]

The kame terrace staircase (case study area 1; Figures 2 and 3a) was developed between the ice margin and the steep proximal slope of the 100-m-high left lateral moraine (Kumbsmýrarkambur) on the foreland. Five to six distinct terrace levels were visible and characterized by tread widths of 8–25 m and riser heights of 4–13 m, the latter likely representing different period lengths of ice surface stabilization. Kame terraces are formed by meltwater flowing between the ice margin and any constraining slope, in this case the Kumbsmýrarkambur lateral moraine, so that each tread represents a former river bed that became abandoned once the glacier margin receded from the ice-

contact slope/riser. Ground observations at the glacier margin since 1992 record the localized plunging of the meltwater streams beneath the glacier margin to form margin-parallel englacial tunnels whose glacifluvial infill are gradually buried by the aggradation of the terrace deposits (Figure 4); this results in the localized burying of remnant ice masses within the terraces (Bennett & Evans, 2012). The gradual melt-out of such buried ice masses gives rise to collapse pits, usually forming a hummocky/pitted appearance to the ice-contact slopes/ risers. Additionally, the edges of some of the terrace treads are characterized by the superimposition of small (1–2 m high) push moraines,
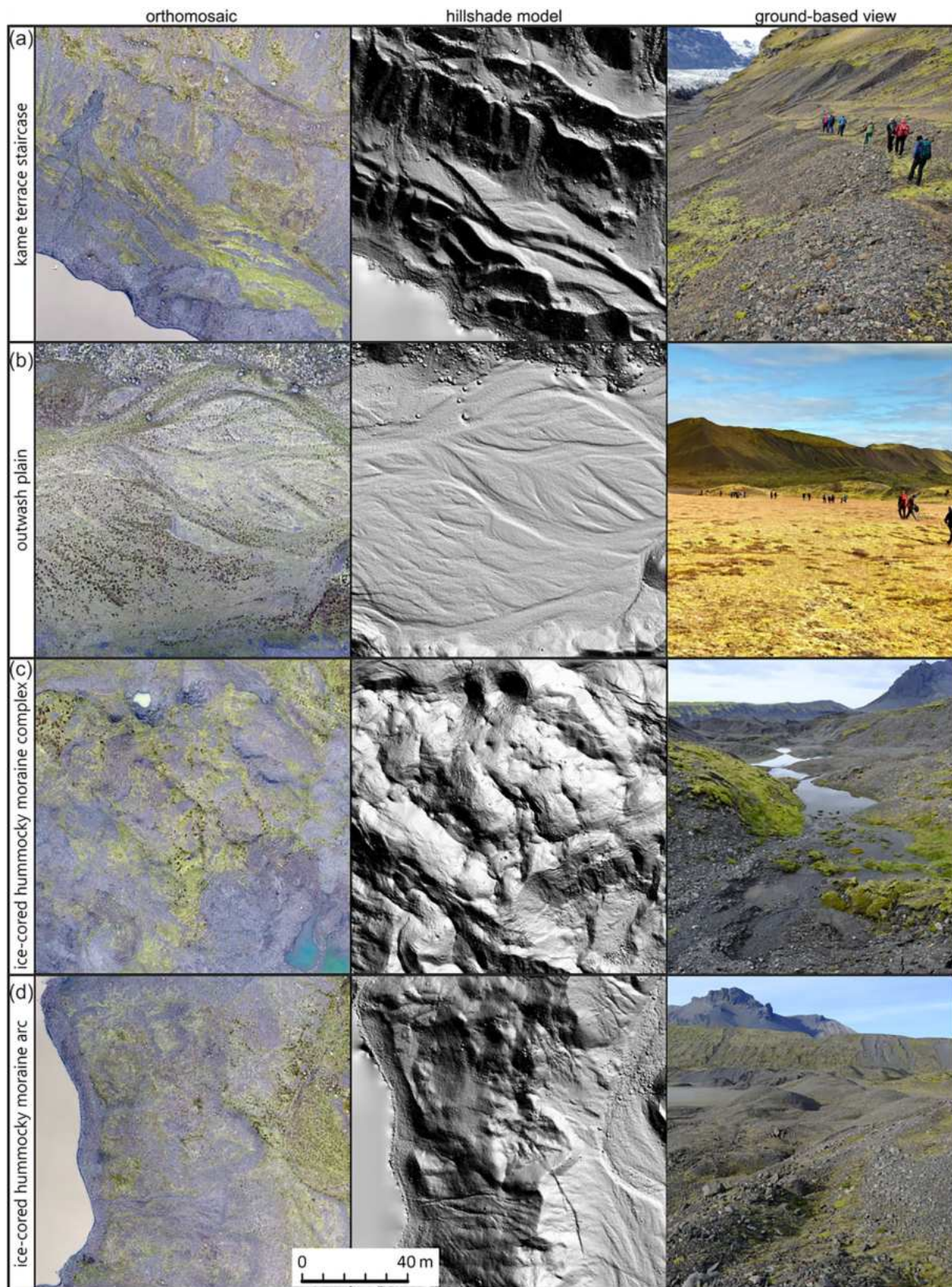
FIGURE 3 Examples of the landsystem elements on the foreland at Kvíárjökull viewed using remotely sensing data and ground photographs: (a) kame terrace staircase; (b) outwash plain; (c) ice-cored hummocky moraine complex and (d) ice-cored hummocky terrain with discontinuous sinuous ridges—see Figure 2 for location. Note that all images in the columns 'orthomosaic' and 'hillshade model' are presented at the same spatial scale. [Colour figure can be viewed at wileyonlinelibrary.com]
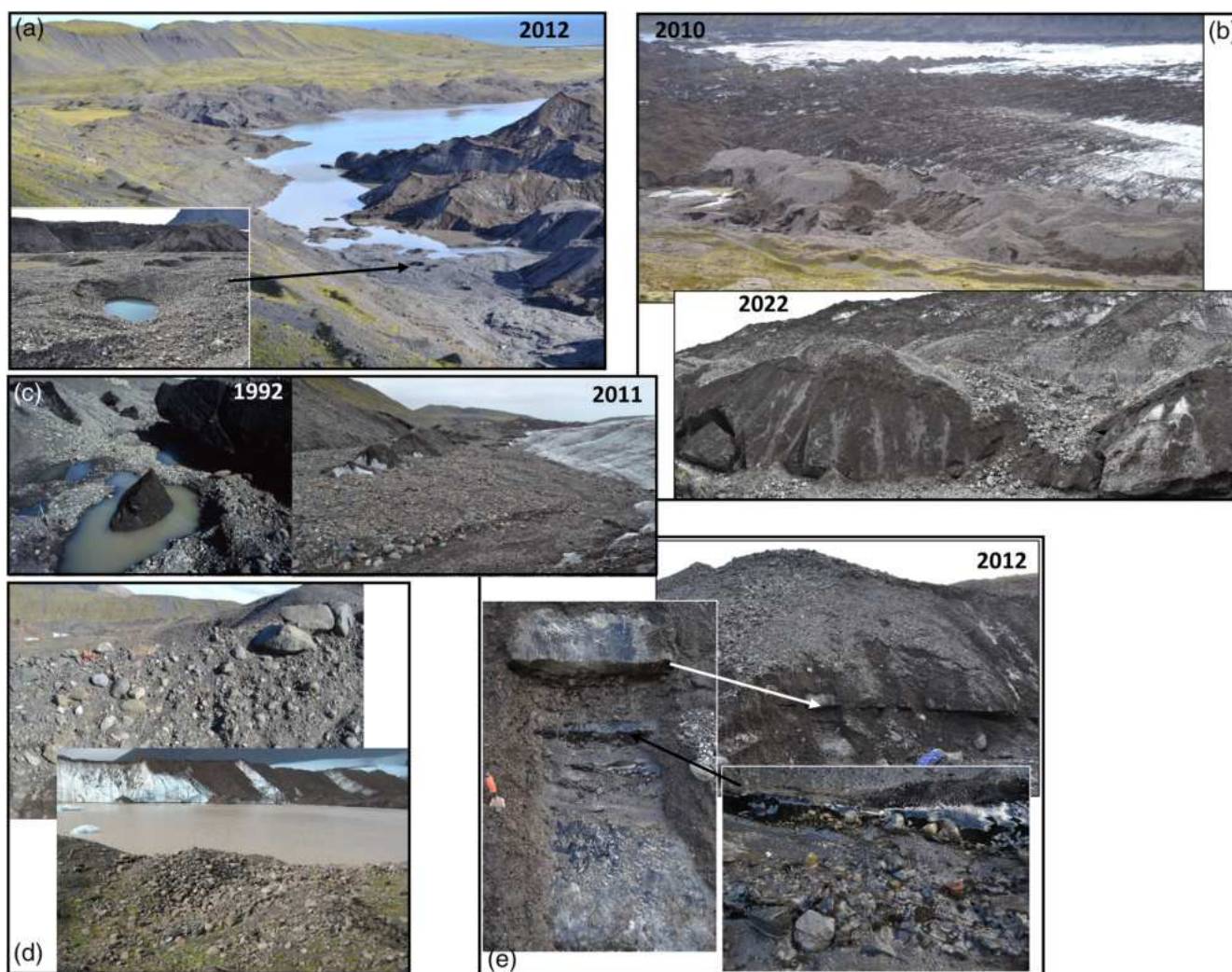
FIGURE 4 Field photographs of examples of the development of ice-marginal drainage and landform development along the northern margin of the snout captured at various times since 1992: (a) freshly abandoned pitted kame terrace in 2012, with active channel emerging from the ice below an englacial esker; (b) the englacial esker emerging in 2010 (grey-coloured gravel) and overlying ice with active tunnels, depicted in 2022 at a more advanced stage of collapse when the sub-marginal stream had abandoned the adjacent kame terrace; (c) remnant ice in the 1992 and 2011 kame terraces, emerging through marginal outwash gravel and representing collapsed and buried tunnels originally cut by sub-marginal streams; (d) mounds of water-worn gravels forming parts of the sinuous ridges emerging within the ice-cored hummocky moraine during downwasting due to melt-out in 2008 and (e) cross-sections through sub-marginal/englacial tunnel fills exposed after stream downcutting in 2012. [Colour figure can be viewed at wileyonlinelibrary.com]

some of which have been observed during formation (Phillips et al., 2017; Figure 3a). Continuous paraglacial reworking of the lateral moraine and the kame terraces has resulted in widespread dissection by debris flow and fluvial channels as well as the deposition of small debris flow-fed lobes and fans.

The outwash plain (case study area 2; Figures 2 and 3b) is a continuation of the highest of the kame terraces and forms a down-valley widening fan that was deposited around and over the outer downwasting glacier snout in the 1980s–1990s, infilling a proglacial/supraglacial lake that occupied the area in the 1960s–1980s (Bennett et al., 2010; Figure 1c). The meltwater deposited a large (~32,800 m²), flat area of glacifluvial sediments, overlying lake deposits and located between the ice-cored hummocky moraine complex and the former position of the 1990s ice margin to the south and

the Kumbsmýrarkambur lateral moraine to the north. The 1990s readvance moraine (sensu Bradwell et al., 2006; Evans & Chandler, 2018; Evans & Hiemstra, 2005; Sigurðsson, 2005; Sigurðsson et al., 2007) was constructed on the ice-contact face of the fan and now forms a prominent ridge along part of its southern edge. A network of braided stream channels is clearly visible on the outwash plain surface (Figure 3b) and small alluvial and debris flow-fed fans and isolated boulders have been deposited on its northern edge by paraglacial processes operating on the steep slopes of the Kumbsmýrarkambur lateral moraine.

The ice-cored hummocky moraine complex (case study area 3; Figures 2 and 3c) is a triangular-shaped area approximately 300 m long and up to 350 m wide, characterized by a chaotic hummocky topography with numerous, continuously expanding and contracting

areas of exposed glacier ice as a result of rapid and widespread topographic reversal (moraine belt A of Bennett & Evans, 2012). The outermost ridges of the complex are the product of pushing of the buried, stagnant ice mass into the outwash plain to the north and east as a result of the 1990s readvance, during which the surface of the ice-cored hummocky moraine belt increased in elevation by an average of 6.5 m (Bennett et al., 2010; Bennett & Evans, 2012). As a result, the easternmost edge of the moraine complex is very steep and separated from another, older hummocky moraine belt (hummocky moraine complex B of Bennett & Evans, 2012) by a narrow linear sandur that became constricted by the encroachment of the outer moraine edge and was then abandoned by meltwater drainage in the late 1990s (Figure 1c). These inset hummocky belts are the landform signature of incremental stagnation, with the overprinting of push ridges and/or development of glacitectonic structures that document readvance events such as the 1990s readvance (Bennett & Evans, 2012). Since around 2000, a proglacial and partially supraglacial lake (Figure 2) has developed at the western margin of the hummocky moraine complex as a result of more rapid ablation of the sparsely debris-covered glacier snout located up-ice. Lake development is a consequence of the gradual uncovering of the ≤100-m-deep overdeepening beneath the snout in this area (Spedding & Evans, 2002). In 2014, the highest hummocks reached 25 m above the water level, but as the degradation intensified, the maximum elevation above the lake was only 15 m in 2022. Sediments that have been visible in the outcrops created by topographic inversion over the last 20 years have ranged from poorly sorted boulder to cobble gravels, gravelly diamictons and localized pockets of well-sorted stratified gravels and sands, the latter representing the melt-out of englacial tunnels/eskers (Bennett et al., 2010; Bennett & Evans, 2012; Spedding & Evans, 2002). Numerous tension cracks, freshly developed collapse pits/sink holes, damp surface sediment and debris flows are visible on the hummocky moraine surface and indicate the presence and ongoing degradation of buried glacier ice (Figure 3c).

Case study area 4 (Figures 2 and 3d) is a 650-m-long arc of ice-cored hummocky terrain with discontinuous sinuous ridges that extends southwards from the ice-cored hummocky moraine of case study area 3. It forms the hummocky ice-proximal face of the large pitted outwash plain previously interpreted by Bennett and Evans (2012) as an emerging outwash head occupying the adverse slope of the underlying bedrock overdeepening. The width of the moraine belt varies from 70 to 200 m with elevations reaching 10–15 m above the proglacial/supraglacial lake level in 2016. Like the hummocky moraine to the north, the hummocks and ridges in case study area 4 comprise a range of poorly sorted boulder to cobble gravels, gravelly diamictons and well-sorted stratified gravels and sands, with the latter clearly relating to west–east trending sinuous ridges that have developed since the 1990s due to the melt-out of englacial eskers linked to the apex of the outwash head (Bennett et al., 2010; Bennett & Evans, 2012; Spedding & Evans, 2002). The outermost ridges of the ice-cored hummocky terrain are arcuate to slightly sinuous in plan form but orientated ice-margin parallel and are push moraines constructed in ice-proximal outwash during the 1990s readvance.

3.2 | Glacier snout changes

Between 2011 and 2022, the ice margin was highly dynamic and oscillatory and additionally there was a significant difference in the behaviour between the northern and southern parts of the snout (Figure 5). The margin in the southern part of the snout underwent an almost continuous and gradual retreat (except for 2018, when it advanced by ~120 m) as the glacier downwasted and disintegrated through the formation of widening crevasses and their flooding to produce tabular icebergs on the expanding proglacial/supraglacial lake. The northern part of the snout advanced by ~200 m in the period 2013–2018 and then remained stable from 2019 to 2022. Likely influential in this varied response is the fact that the southern and northern margins of the snout are fed by different ice-flow units, which flow down either side of a nunatak in the accumulation zone and are nourished in source basins of different sizes. Additionally, ablation rates and hence the extent of glacier surface downwasting will vary significantly between the two ice-flow units in the snout zone (Figure 1c). The southern part of the glacier is characterized by large areas of debris-poor ice and, with the exception of the supraglacial lateral moraines and arcuate debris bands on the extreme southern margin, lacks a supraglacial debris cover. In contrast, the northern part of the glacier has always been characterized by an extensive debris cover delivered to the snout by the pulsed delivery of englacial and supraglacial debris which results in the retardation of ablation (incremental stagnation; Bennett & Evans, 2012). Moreover, the two ice-flow units have different dynamics, whereby the north ice-flow unit has exhibited some significant readvances in addition to that of the 1990s (Phillips et al., 2017). Also, likely important is the apparent glacier karst network, manifested as numerous moulins, which has remained a stable characteristic of the southern ice-flow unit over time and indicates that a complex englacial-to-subglacial tunnel network exists and results in substantial ice surface collapse during downwasting. All of these characteristics are exacerbated by the continuously rapid growth of the proglacial/supraglacial lake since 2011.

3.3 | Recent transformations of the land elements

Using the DoDs, land surface and volume change are now presented for the four case study areas (land elements) over the last 8 years or less. Due to differences in the temporal coverage of aerial imagery, the first year of analysis is either 2014 or 2016. Areal, volumetric and vertical averages calculated from DoDs for each land element are summarized in Table 2.

3.3.1 | Case study area 1 (kame terraces)

Between 2014 and 2022, most of the kame terrace staircase was stable (Figure 6a) and detectable changes occurred in only 14% of the area, with a total net volume difference of -6402 ± 1118 m^3, reaching an average net thickness change of -0.99 ± 0.17 m (Table 2). A
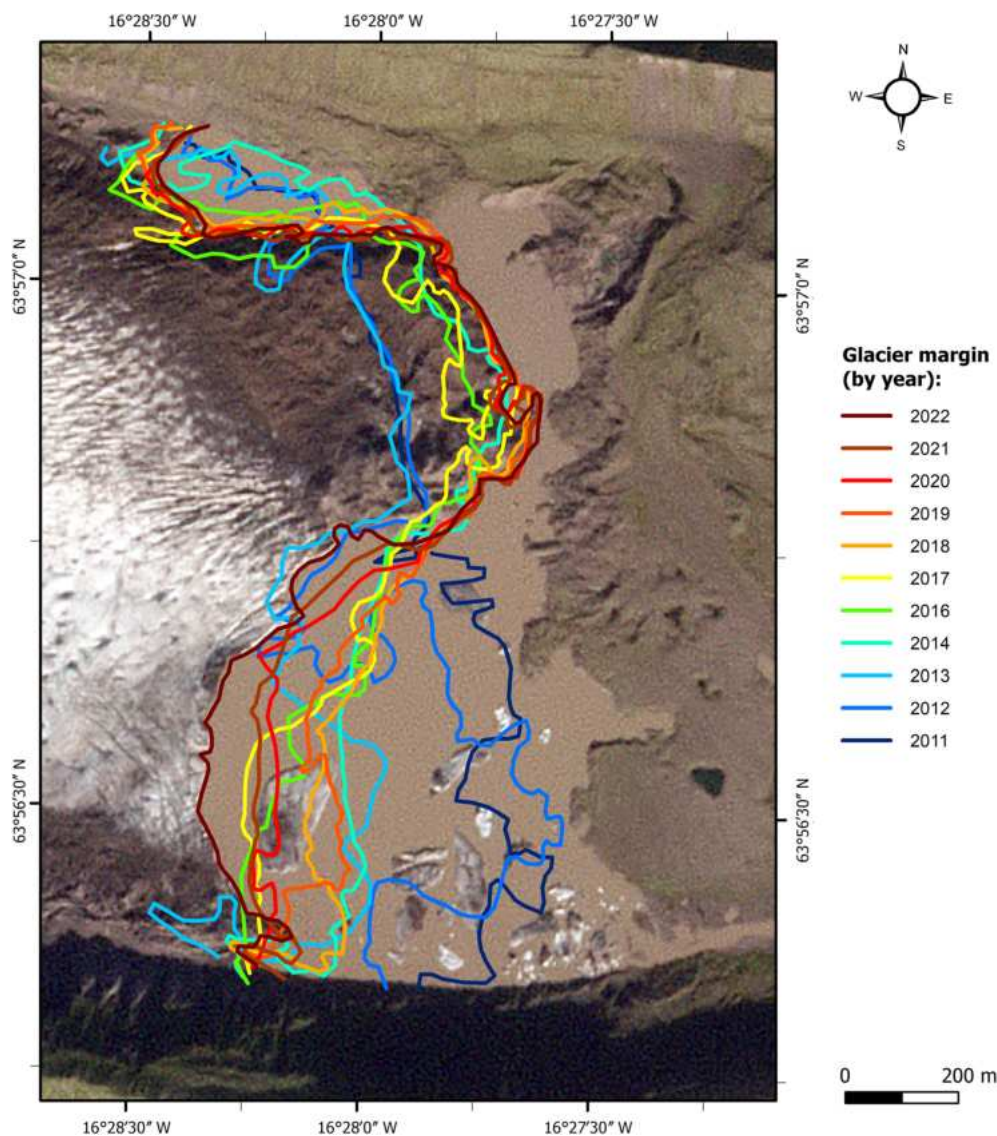
FIGURE 5 Changes in the margin of the glacier snout in the period 2011–2022 based on the PlanetScope satellite imagery (Planet, 2022). Note that in 2015, scenes from PlanetScope were not available for this location. Date of the background image is 2022. [Colour figure can be viewed at wileyonlinelibrary.com]

decrease in elevation of up to 10 m was recorded for the southern fringe (Figure 6a) or the most recent kame terraces, which was related to melting of the residual buried glacier ice that was created where marginal streams plunged into the lateral margin of the glacier and continued over short distances in englacial tunnels (Figure 4). An increase in elevation of up to 1 m was observed in the upper parts of the terrace sequence, which is likely associated with transfer of sediments from the adjacent lateral moraine slopes by mass movements. A further small area of positive change (≤3 m) occurred in the southeast tip of the most recent terraces and is associated with push moraine construction on their former ice-contact slopes during the 2014 snout readvance (Phillips et al., 2017).

3.3.2 | Case study area 2 (outwash plain)

Large areas of the outwash plain (Figures 2 and 7) also remained partly stable over the last 6 years. The changes in the period 2016–

2022 took place on only ~15% of the surface, with a total net volume difference of 15,440 ± 1764 m^3 (Figure 7c, Table 2). Two significantly active areas occur in the eastern half of the outwash plain. Firstly, an arcuate, lake-filled collapse pit occurs at the boundary of the ice-cored hummocky moraine complex (see case study area 3; Figure 7c), where the highest values of elevation loss of >3 m are recorded. The degradation of buried ice here started with the development of small, dry sink holes, which enlarged until the buried ice became visible and the expansion of sink holes led to the development of chains of depressions and, finally, to the formation of a single, large elongate depression. This depression has gradually extended northwards to the foot of the Kumbsmýrarkambur lateral moraine slope and is surrounded by arcuate concentric tension fault scarps. The western edge of the depression is dissected by a 25-m-long, ≤3-m-deep erosion gully (Figure 7e), which started developing after 2014. The increase in elevation between 2021 and 2022 (Figure 7b) is related to fluctuations in water level, which filled up the depression created between 2014 and 2021. Second, at the eastern, distal extremity of the

TABLE 2 Areal, volumetric and vertical change averages derived from DEMs of differences for each case study.

DoD	Total area of surface lowering (m²)	Total area of surface raising (m²)	Total area of detectable change (m²)	Pre cent of area of interest with detectable change (%)	Total volume of surface lowering (m³)	Total volume of surface raising (m³)	Total net volume change (m³)	Average depth of surface lowering (m)	Average depth of surface raising (m)	Average net thickness of difference (m) for area with detectable change
Case study 1 (kame terrace staircase)										
September 2014–September 2021	5676.20	1121.85	6798.05	14.15	7550.45 ± 1135.24	1019.99 ± 224.37	−6530.46 ± 1157.20	1.33 ± 0.20	0.91 ± 0.20	−0.96 ± 0.17
September 2021–May 2022	323.02	396.49	719.52	1.50	122.22 ± 64.61	92.58 ± 79.30	−29.64 ± 102.28	0.38 ± 0.20	0.23 ± 0.20	−0.04 ± 0.14
September 2014–May 2022	5502.00	982.57	6484.57	13.49	7344.58 ± 1100.40	942.95 ± 196.51	−6401.62 ± 1117.81	1.33 ± 0.20	0.96 ± 0.20	−0.99 ± 0.17
Case study 2 (outwash plain)										
September 2016–September 2021	9074.76	412.60	9487.36	15.36	15,792.40 ± 1814.95	141.78 ± 82.52	−15,650.61 ± 1816.83	1.74 ± 0.20	0.34 ± 0.20	−1.65 ± 0.19
September 2021–May 2022	210.33	865.61	1075.94	1.74	75.18 ± 42.07	267.95 ± 173.12	192.76 ± 178.16	0.36 ± 0.20	0.31 ± 0.20	0.18 ± 0.17
September 2016–May 2022	8811.90	409.10	9221.00	14.94	15,582.33 ± 1762.38	142.13 ± 81.82	−15,440.21 ± 1764.28	1.77 ± 0.20	0.35 ± 0.20	−1.67 ± 0.19
Case study 3 (ice-cored hummocky moraine complex)										
September 2014–September 2016	54,685.07	748.31	55,433.38	83.49	90,448.73 ± 10937.01	265.07 ± 149.66	−90,183.66 ± 10938.04	1.65 ± 0.20	0.35 ± 0.20	−1.63 ± 0.20
September 2016–September 2021	55,483.78	425.78	55,909.56	84.21	256,699.33 ± 11096.76	203.27 ± 85.16	−256,496.07 ± 11097.08	4.63 ± 0.20	0.48 ± 0.20	−4.59 ± 0.20
September 2021–May 2022	17,276.40	1440.67	18,717.06	28.20	17,720.79 ± 3455.28	513.23 ± 288.13	−17,207.55 ± 3467.27	1.03 ± 0.20	0.36 ± 0.20	−0.92 ± 0.19
September 2014–May 2022	57,304.12	753.32	58,057.43	87.41	366,080.27 ± 11460.82	307.27 ± 150.66	−365,773.00 ± 11461.81	6.39 ± 0.20	0.41 ± 0.20	−6.30 ± 0.20
Case study 4 (ice-cored hummocky terrain with discontinuous sinuous ridge)										
September 2016–September 2021	42,688.40	266.32	42,954.72	60.14	60,392.62 ± 8537.68	64.32 ± 53.26	−60,328.30 ± 8537.85	1.41 ± 0.20	0.24 ± 0.20	−1.40 ± 0.20
September 2021–May 2022	5828.46	170.91	5999.38	8.40	1908.44 ± 1165.69	56.66 ± 34.18	−1851.78 ± 1166.19	0.33 ± 0.20	0.33 ± 0.20	−0.31 ± 0.19
September 2016–May 2022	43,336.43	427.42	43,763.85	61.26	64,733.01 ± 8667.29	101.43 ± 85.48	−64,631.58 ± 8667.71	1.49 ± 0.20	0.24 ± 0.20	−1.48 ± 0.20
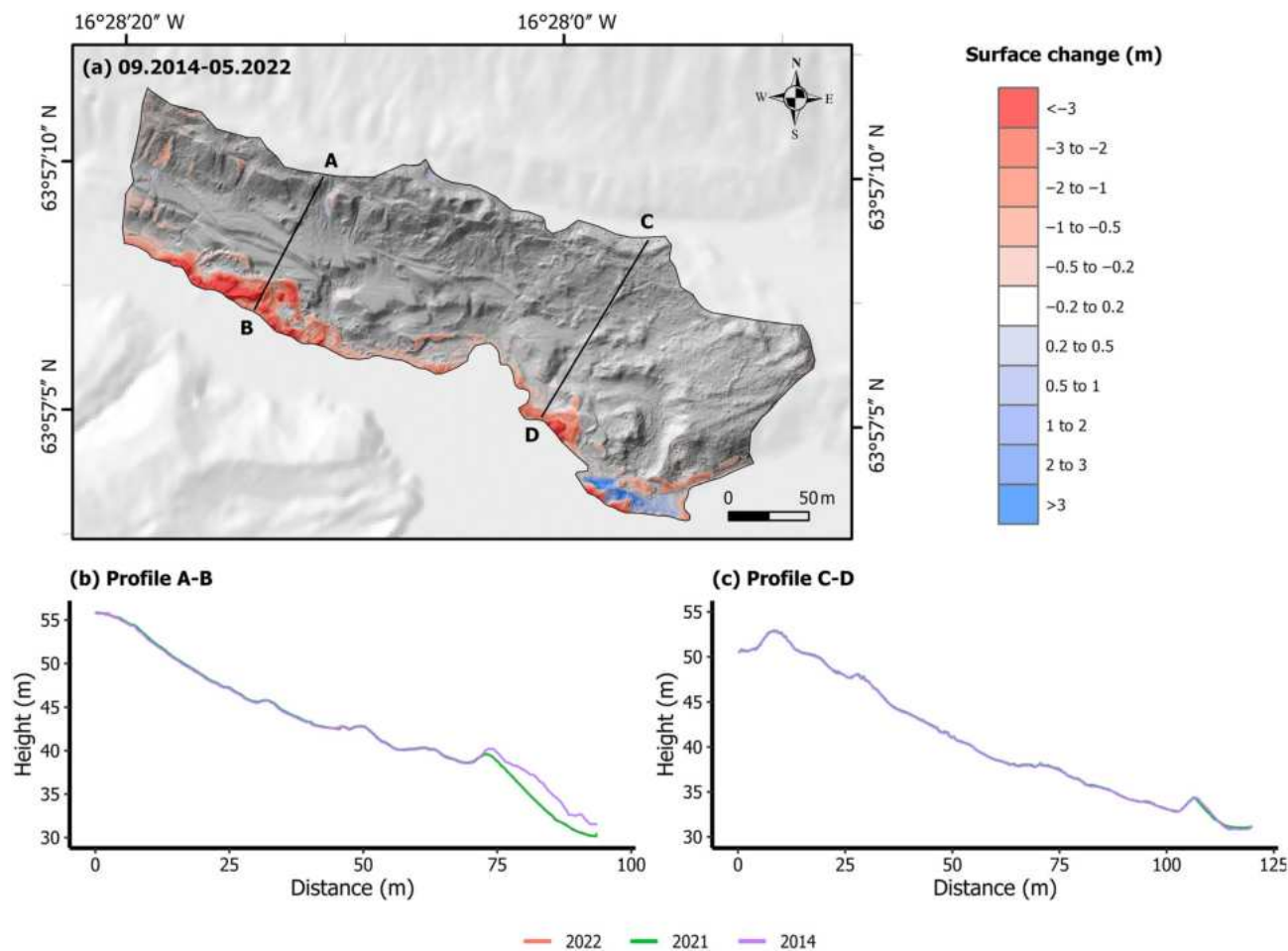
FIGURE 6 Elevation changes for the kame terrace staircase (case study area 1—see Figure 2 for location) between 2014 and 2022. The minLoD was set at 0.20 m. Source of background: ÍslandsDEM v1.0. [Colour figure can be viewed at wileyonlinelibrary.com]

outwash plain, a large, shallow collapse pit records the sinking of the outwash surface by up to 0.5 m. Other minor recorded changes include deposition in the north-eastern corner of the outwash plain where alluvial fans, debris flow-fed fans and boulders have accumulated as a result of paraglacial reworking of the steep slope of the Kumbsmýrarkambur lateral moraine.

3.3.3 | Case study area 3 (ice-cored hummocky moraine complex)

Case study area 3 is the area that underwent the most changes and maximum activity. Comparing 2014 with 2022 (Figure 8d), changes occurred in 87% of the case study area, reducing its volume by $-365,773 \pm 11,462$ m^3 (Table 2). Maximum elevation changes during this 8-year period reached >20 m (Figure 8f). Importantly, the ice-cored moraine complex also shows significant changes in surface morphology within 1 year (Figure 8c—DoD 2021–2022), where the maximum recorded decrease in elevation was 8 m. The average net thickness of difference for DoD 2014–2022 was -6.30 ± 0.20 m, which demonstrates the dynamism of the degrading ice-cored complex, suggesting that further degradation should be expected. This

high level of transformation was related to the melting and degradation of ice cores. The surface collapsed in several places, while indicators of downwasting, such as tension cracks and holes, are widespread. There is a fairly visible trend in the spatial distribution of highly active parts of the ice-cored moraine complex, with the highest rates of terrain collapse along the SW–NE axis, where a line of irregular, water-filled depressions was formed after 2016 (Figure 9). Another type of transformation was recorded along the lake shore, where the water edge enhanced debris sliding along the exposed ice cliffs, thereby facilitating ice melting. The inner part of the moraine complex was less dynamic, the transformations manifesting themselves through tension cracks and uneven lowering of different parts of the moraine.

3.3.4 | Case study area 4 (ice-cored hummocky terrain with discontinuous sinuous ridges)

The ice-cored hummocky terrain with discontinuous sinuous ridges also turned out to be active (Figure 10) as 61% of its area changed (Figure 10c—DoD 2016–2022) and its volume decreased by 64,632 $\pm$ 8668 m^3 (Table 2) over the course of 6 years. The average net
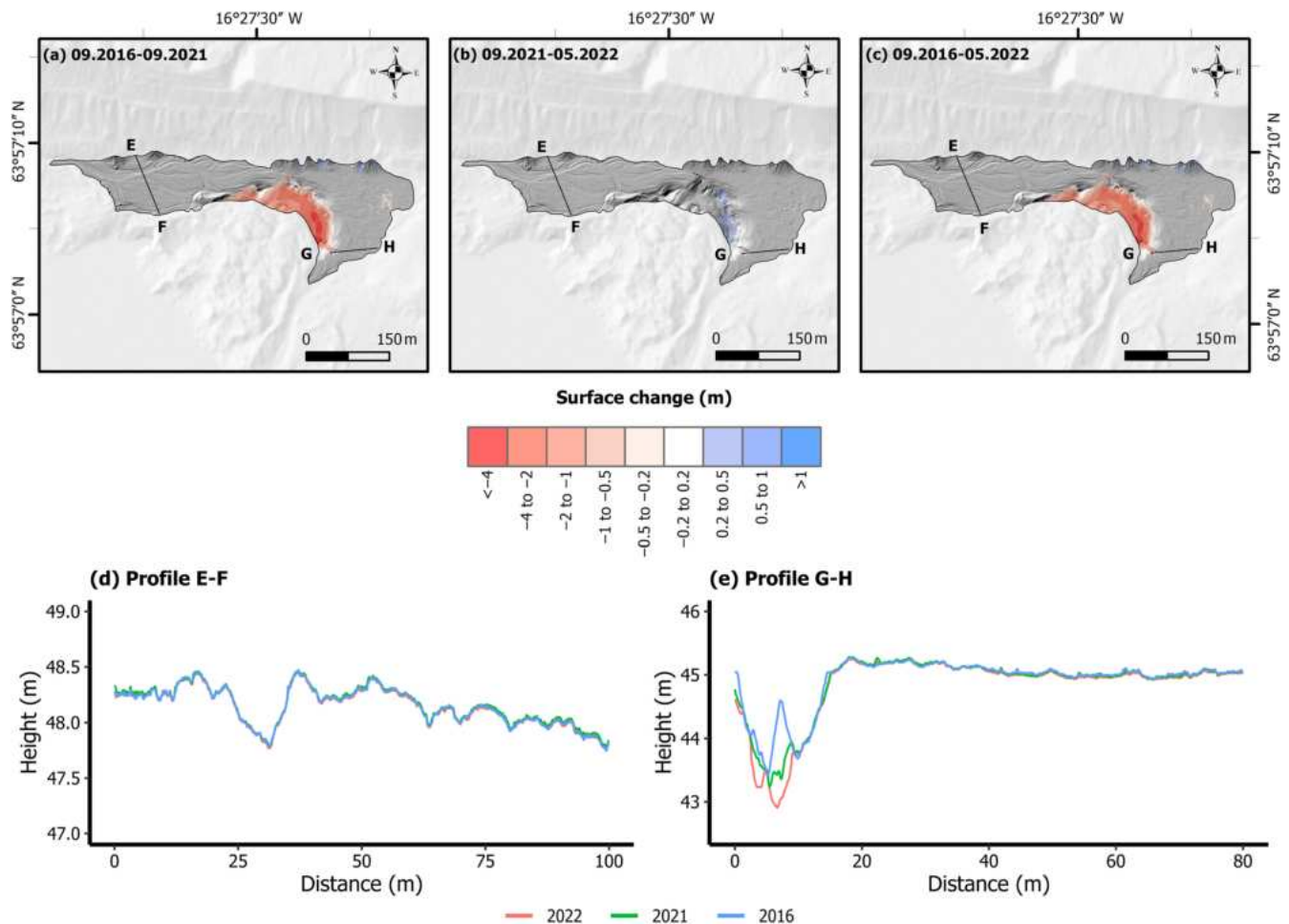
FIGURE 7 Elevation changes between 2016 and 2022 for the outwash plain (case study area 2—see Figure 2 for location). The minLoD was set at 0.20 m. Source of background: ÍslandsDEM v1.0. [Colour figure can be viewed at wileyonlinelibrary.com]

thickness of difference for the same DoD was −1.48 ± 0.20 m, but the highest decrease in elevation was >9 m. In the southern part of the area, minor surface accumulation was recorded, but no indicators of deposition were found during the field verification and so we treated this as an artefact due to an erroneous surface reconstruction for 2016. In the calculations for 2021–2022 (Figure 10b), a change in volume of −1852 ± 1166 m³ was noted. Reflecting this, the M-N and O-P cross profiles (Figure 10d,e) in the central, most active part of the moraine clearly show that the changes in morphology are concentrated near the lake and along the central axis of the ridge, whereas the rest of the area is more stable.

4 | DISCUSSION

4.1 | Spatial and temporal distribution of surface changes

During the observation period (2014–2022), the study areas underwent various scales of change (Figures 6–10). Very little activity took place in case study areas 1 and 2, the kame terraces and outwash plain, where ~85% of the total surface had not changed in the period 2014–2022. In contrast, case study areas 3 and 4 underwent more dynamic activity, especially the ice-cored moraine of case study area 3, where only 13% of the surface remained stable over the same period (Table 2). Such a diverse response is directly related to the presence of dead ice and its melting. The average annual rate of change for 2021–2022 in all case study areas was lower than in other periods, likely because the survey period comprised mostly the winter season (September 2021–May 2022), before the beginning of the summer ablation peak.

4.2 | Processes responsible for surface changes

The degradation of buried dead ice blocks and associated mass movements, including ground surface collapse and widespread debris flows, were the most critical processes responsible for transformation of the ice-cored moraine complexes of study areas 3 and 4 over the period 2014–2022. This was evidenced by the
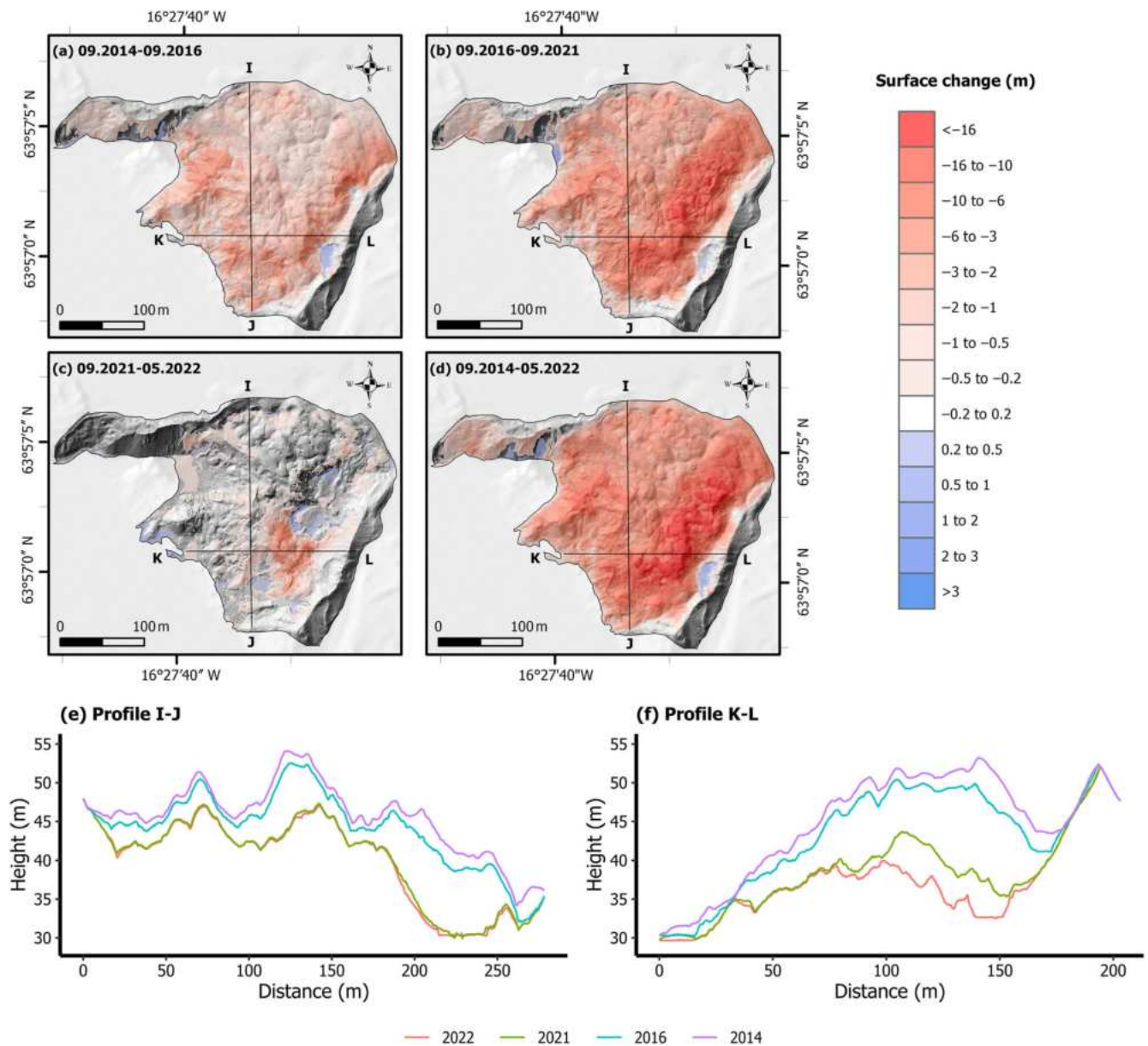
FIGURE 8 Elevation changes between 2014 and 2022 for the ice-cored hummocky moraine complex (case study 3—see Figure 2 for location). The minLoD was set at 0.20 m. Source of background: ÍslandsDEM v1.0. [Colour figure can be viewed at wileyonlinelibrary.com]

appearance and changing shape of numerous sinkholes and tension fractures on the moraine surfaces. Another process that impacted significantly on volume change was fluctuations in water levels and concomitant shore erosion around the margins of the proglacial/supraglacial lake and the ponds that developed in enlarging sink holes/kettles. Although surface collapse due to ice melt-out dominated as a process over the surveyed areas, some minor impacts and surface elevation increases were due to paraglacial activity in the historically developed and largely unstable lateral moraine topography, including the development of small debris flows, rockfalls, small rock avalanches and alluvial fans, which added debris to the tops of kame terraces and outwash margins.

4.3 | Comparison with short-term rates of surface change at other locations

To compare the land surface dynamics between case studies of varying areal extent, we standardized the volumetric measurements by dividing them according to area and period of observation, thereby ensuring that the average change in annual volume was calculated (Figure 11). The results confirm the low volumetric change of case study area 1 (average elevation changes of -0.13 m a^{-1}), the intermediate volumetric change of case study areas 2 and 4 (-0.29 and -0.26 m a^{-1}, respectively, for the period 2016–2022) and the high-volume loss of case study area 3 (-0.82 m a^{-1} for the period 2014–2022). Additionally, Table 3 shows the maximum annual
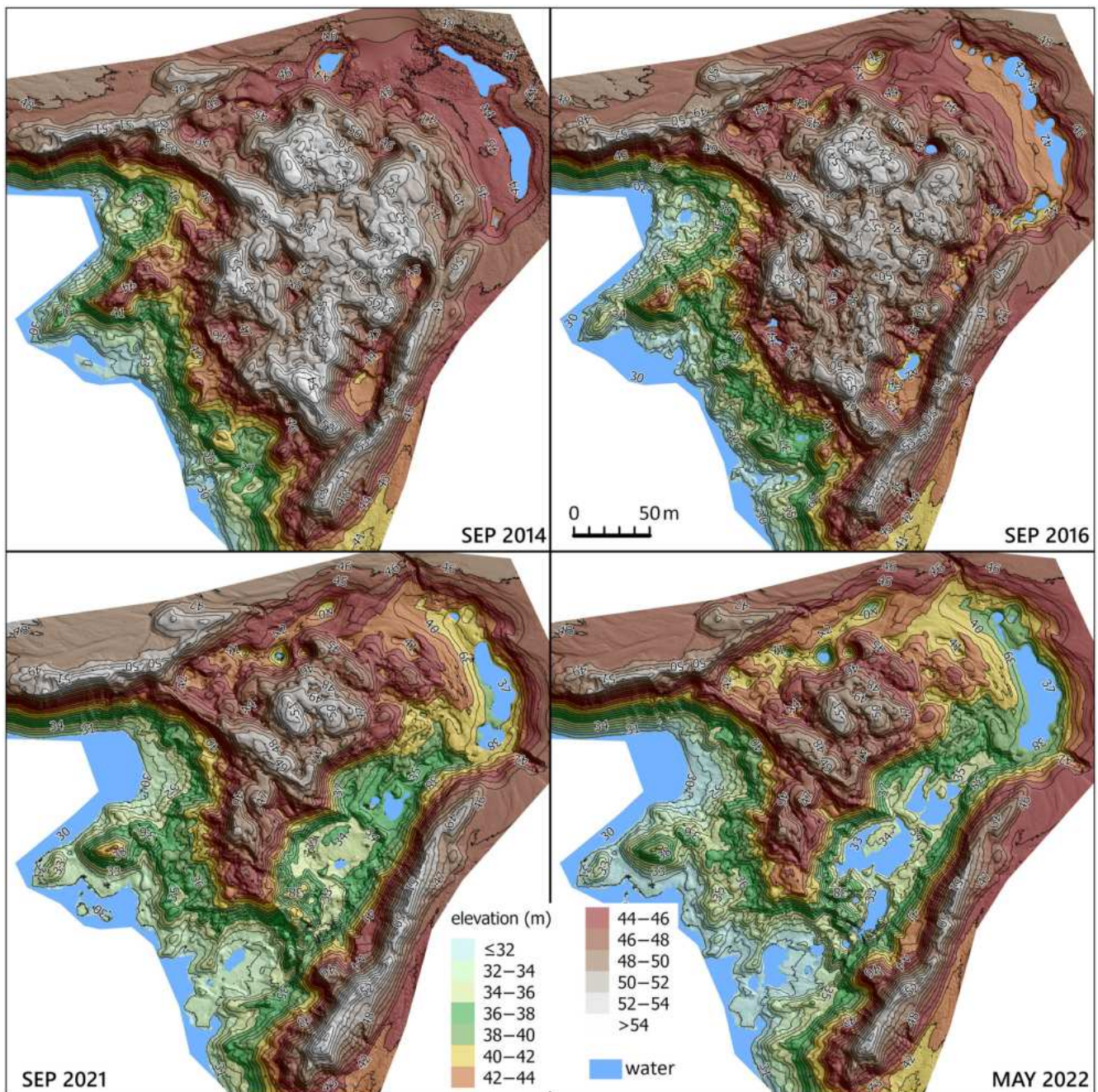
FIGURE 9 Evolution of ice-cored moraine complex at Kvíárjökull between 2014 and 2022—see Figure 2 for location. [Colour figure can be viewed at wileyonlinelibrary.com]

thickness difference for each DoD calculation, ranging from −2 to −3 m a^{-1} for case study areas 1, 2 and 4 up to −12.21 m a^{-1} and for case study area 3 for 2021–2022.

This range of values for volumetric change due to de-icing on the contemporary foreland of a rapidly receding glacier can be compared with those in other settings (Table 4). For example, on the forelands of Ebbabreen and Ragnarbreen, Svalbard, the average annual changes in thickness (i.e., sum of elevation changes divided by the area and period of observation) for an ice-cored moraine complex from 2012 to 2014 ranged from −0.14 to −1.83 m a^{-1} and the average annual

maximum thickness change (i.e., maximal values of elevation changes divided by the period of observations) ranged from −1.0 to −7.9 m a^{-1} (Ewertowski & Tomczyk, 2015). For the ice-cored moraine in the foreland of Midtre Lovénbreen, Svalbard, an average annual thickness change of −0.65 m a^{-1} was measured over the period 2003–2005 (Irvine-Fynn et al., 2011). For the same glacier, but a longer period (2003–2014), Midgley et al. (2018) reported changes ranged from −0.02 m a^{-1} for outwash plain (without buried ice) to −0.40 m a^{-1} for ice-cored medial moraine. In contrast, the ice-cored moraine on the neighbouring foreland of Austre Lovénbreen, Svalbard, displayed
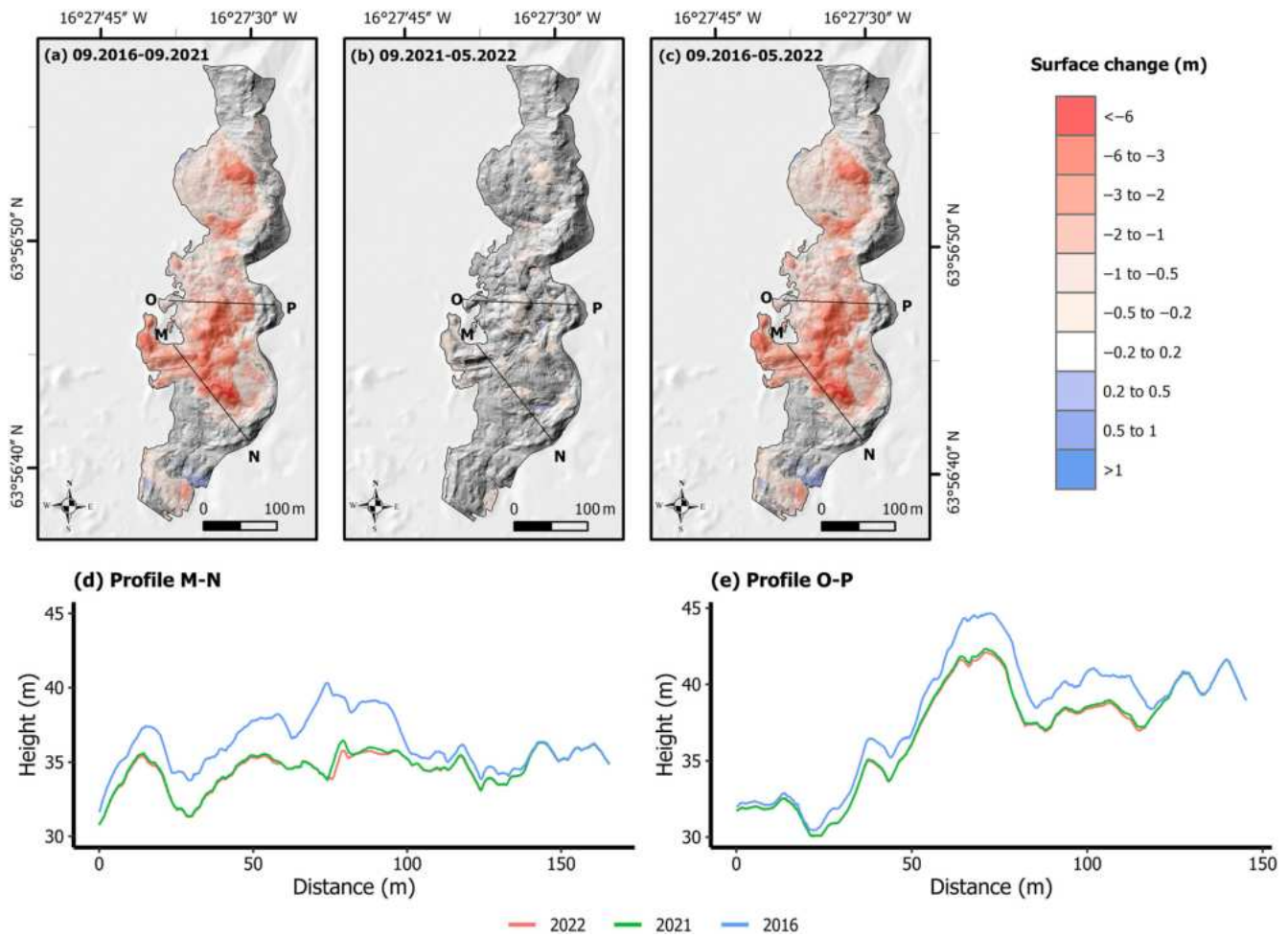
FIGURE 10 Elevation changes for the thrust ice-cored moraine arc (case study 4—see Figure 2 for location) for the years 2016–2022. The minLoD was set at 0.20 m. Source of background: ÍslandsDEM v1.0. [Colour figure can be viewed at wileyonlinelibrary.com]
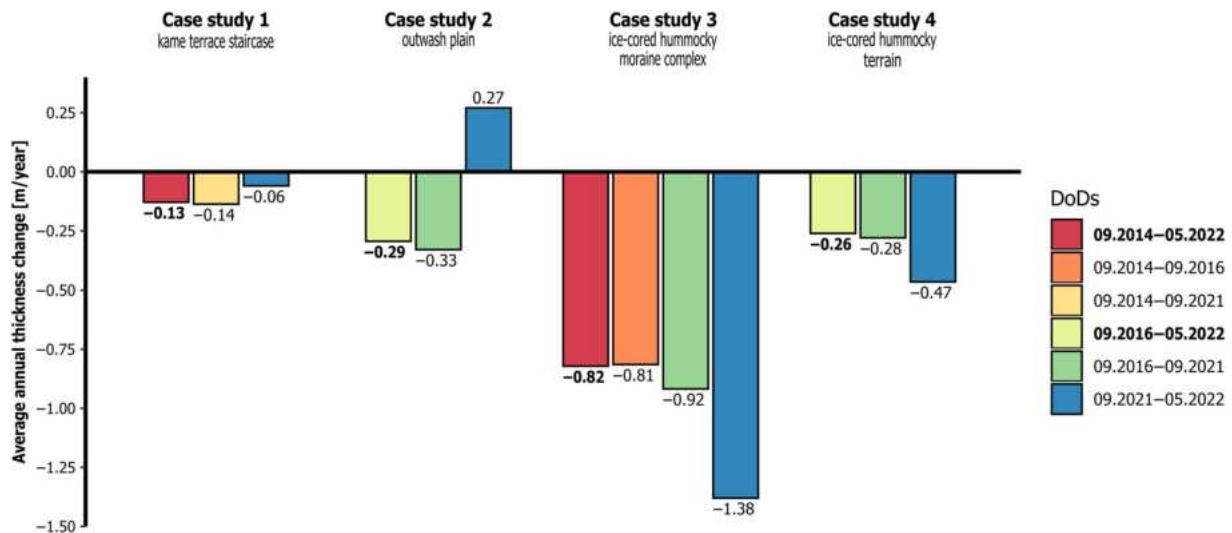
FIGURE 11 Average annual thickness change for different case study areas on the Kvíárjökull foreland. Changes calculated from the summary DoDs (i.e., differences between first and last surveys) for each case study area are indicated by bold fonts. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Average annual maximum thickness change for each case study area.

DoD	Average annual maximum thickness change (m)
Case study area 1	
September 2014–September 2021	−1.53
September 2021–May 2022	−2.70
September 2014–May 2022	−1.43
Case study area 2	
September 2016–September 2021	−1.26
September 2021–May 2022	−2.06
September 2016–May 2022	−1.02
Case study area 3	
September 2014–September 2016	−4.83
September 2016–September 2021	−3.81
September 2021–May 2022	−12.21
September 2014–May 2022	−2.96
Case study area 4	
September 2016–September 2021	−1.76
September 2021–May 2022	−2.69
September 2016–May 2022	−1.60

Note: Due to fact that the DoDs for September 2021–May 2022 are for a shorter period than 1 year, we calculate the mean with an accuracy of 1 month.

an average elevation change of only −1.42 m in the 11-year period 2003–2014 (∼0.13 m a^{-1}), with the maximum change exceeding −4 m (Tonkin et al., 2016). Much greater change has been observed on the foreland of Fjallsjökull, Iceland, where calculations have been made on an annual basis between 2016 and 2019; from 2016 to 2017 in particular, the highest rate of average maximum elevation change of −0.5 m per month (6 m a^{-1}) was recorded (Chandler, Evans, et al., 2020). Other land elements in the foreland of Fjallsjökull and Hrútárjökull (Iceland) were characterized by average annual elevation changes between −0.08 and −1.33 m a^{-1} (Table 4) (Evans et al., 2023).

4.4 | Short-term versus long-term changes in proglacial areas

Bennett and Evans (2012) assessed the dynamics of the Kvíárjökull foreland on a decadal temporal scale based on DEMs generated from aerial images taken in the period 1945–2003, generating four DoDs for the periods: 1945–1964, 1964–1980, 1980–1998 and 1998–2003. They identified the fact that elevation changes in the ice-cored moraine complex did not proceed at the same rate. Changes in the average annual thickness decreased during the first three periods (−0.8 m a^{-1} in 1945–1964, −0.3 m a^{-1} in 1964–1980 and 0.015 m a^{-1} in 1980–1998) and then started to slightly increase in the fourth period (0.044 m a^{-1} in 1998–2003). Positive values in the period

1980–1998 were a result of snout readvance into ice-cored terrain as a response to the 1990s readvance event in southern Iceland (sensu Evans & Hiemstra, 2005; Sigurðsson, 2005; Bradwell et al., 2006; Sigurðsson et al., 2007; Evans & Chandler, 2018). The results of our more recent, short-term calculations reveal that the trend of increasing rates of change for the period 1998–2003 have been sustained, with all the case study areas exceeding the average change in annual thickness of 0.044 m a^{-1} recorded by Bennett and Evans (2012) for the period 1998–2003 (Figure 11). These results are similar to those from other long-term analyses. For example, on the foreland of Ragnarbreen, Svalbard, the average annual change in elevation in the period 1961–2009 was −0.033 m a^{-1} (Ewertowski, 2014). Additionally, on the Hørbyebreen foreland, Svalbard, ground surface elevation changed annually on average by −0.15 m a^{-1} throughout the period 1960–2009, with an average maximum volume change of −1.3 m a^{-1} (Ewertowski et al., 2019). On the foreland of Brúarjökull, Iceland, there was an average ground surface change from −0.10 to −0.18 m a^{-1} over the period 1945–2005 (Schomacker & Kjaer, 2007) and on the Kötlujökull foreland, Iceland, ice-cored moraine surfaces dropped on average annually from −0.3 to −1.4 m a^{-1} in 1995–1998 (Krüger & Kjær, 2000). A similarly high level of activity has been reported for the ice-cored moraine on the foreland of Holmströmbreen, Svalbard, by Schomacker and Kjaer (2008), with a mean annual surface change of −0.9 m a^{-1} for the period 1984–2004 (similar to our case study area 3 at −0.82 m a^{-1} for the period 2014–2022).

4.5 | Degradation of an ice-cored moraine complex—implications for the interpretation of Pleistocene landforms and sediments

The four case study areas analysed here constitute land elements within the debris-charged, active temperate glacial landsystem at Kvíárjökull (Bennett et al., 2010), the evolution of which are presented in Figures 1c and 12. This provides an overview of landsystem development over the longer timescale of 1945–2014 (Figure 12), during which the kame terrace staircase (area 1), the outwash plain (area 2), the ice-cored hummocky moraine complex (area 3) and the ice-cored hummocky terrain with discontinuous sinuous ridges (area 4) have emerged and evolved on the northern half of the glacier foreland. In the wider context of the foreland, these land elements constitute the landform–sediment assemblages of an outwash head that has developed over the adverse slope of an overdeepening (Bennett & Evans, 2012; Spedding & Evans, 2002). This is a landsystem signature that is becoming more widely recognized on the rapidly evolving forelands of the southern Iceland temperate outlet glaciers, where high ice mass turnover and concomitant high meltwater discharges have given rise to substantial accumulations of glacifluvial sediments widely deposited over downwasting but active snouts (Bennett & Evans, 2012; Chandler, Evans, et al., 2020; Evans et al., 2018, 2019, 2023; Evans & Orton, 2015). Long-term meltwater drainage towards the outwash head can be reconstructed based on the repeat aerial imagery since 1945 and this has facilitated a much improved

TABLE 4 Comparison of glacial landform degradation rates in different sites in Iceland and Svalbard.

Location	Landform	Observation period	Annual average elevation change (m a^{-1})	Average maximum elevation change (m a^{-1})	Source
Short-term surveys (days to annual)					
Midtre Lovénbreen, Svalbard	Ice-cored moraine	2003–2005	−0.65	N/A	Irvine-Fynn et al. (2011)
Ragnarbreen, Svalbard	Ice-cored moraine	2012–2014	−0.14	−1.0	Ewertowski and Tomczyk (2015)
Ebbabreen, Svalbard	Ice-cored moraine	2012–2014	−1.83	−7.9	Ewertowski and Tomczyk (2015)
Fjallsjökull, Iceland	Ice-cored moraine	2016–2019	N/A	−6.0	Chandler, Evans, et al. (2020)
Fjallsjökull, Iceland	South overdeepening, including	2014–2022	−0.15	−1.94	Evans et al. (2023)
	(a) Large esker network	2014–2022	−0.08	−1.19	
	(b) Inner overdeepening (hummocky terrain)	2014–2022	−0.63	−1.94	
	(c) Adverse slope	2014–2022	−0.25	−1.13	
	(d) Outer overdeepening	2014–2022	0.00	N/A	
Hrútárjökull, Iceland	1990s thrust moraine	2014–2022	−0.96	−1.94	Evans et al. (2023)
Hrútárjökull, Iceland	Overdeepening	2014–2022	−0.79	−3.69	Evans et al. (2023)
Hrútárjökull, Iceland	Hummocky terrain/medial moraine	2014–2022	−0.51	N/A	Evans et al. (2023)
Hrútárjökull, Iceland	Collapsed sandur	2014–2022	−0.46	−1.87	Evans et al. (2023)
Hrútárjökull, Iceland	Debris-covered snout	2019–2022	−1.33	−8.5	Evans et al. (2023)
Kvíárjökull, Iceland	Kame terrace staircase	2014–2022	−0.13	−1.43	This study
Kvíárjökull, Iceland	Outwash plain	2016–2022	−0.29	−1.02	This study
Kvíárjökull, Iceland	Ice-cored hummocky moraine complex	2014–2022	−0.82	−2.96	This study
Kvíárjökull, Iceland	Ice-cored hummocky terrain	2016–2022	−0.26	−1.60	This study
Long-term surveys (decadal)					
Austre Lovénbreen, Svalbard	Ice-cored moraine	2003–2014	−0.13	−0.36	Tonkin et al. (2016)
Midtre Lovénbreen, Svalbard	Frontal moraine (limited buried ice content)	2003–2014	−0.09	N/A	Midgley et al. (2018)
Midtre Lovénbreen, Svalbard	Lateral moraine (ice-proximal slope)	2003–2014	−0.06	N/A	Midgley et al. (2018)
Midtre Lovénbreen, Svalbard	Medial moraine (ice-cored)	2003–2014	−0.40	N/A	Midgley et al. (2018)
Midtre Lovénbreen, Svalbard	Outwash plain	2003–2014	−0.02	N/A	Midgley et al. (2018)
Midtre Lovénbreen, Svalbard	Hummocky moraine	2003–2014	−0.03	N/A	Midgley et al. (2018)
Holmströmbreen, Svalbard	Ice-cored moraine	1984–2004	−0.9	N/A	Schomacker and Kjaer (2008)
Ragnarbreen, Svalbard	Ice-cored moraine	1961–2009	−0.033	−0.24	Ewertowski (2014)
Hørbyebreen, Svalbard	Ice-cored moraine	1960–2009	−0.15	−1.30	Ewertowski et al. (2019)
Brúarjökull, Iceland	Ice-cored moraine	1945–2005	−0.10 to −0.18	N/A	Schomacker and Kjaer (2007)
Kötlujökull, Iceland	Ice-cored moraine	1995–1998	−0.3 to −1.4	N/A	Krüger and Kjær (2000)
Kvíárjökull, Iceland	Ice-cored moraine complex	1945–1964	−0.8	N/A	Bennett and Evans (2012)
		1964–1980	−0.3	N/A	
		1980–1998	−0.015	N/A	
		1998–2003	−0.044	N/A	

understanding of englacial drainage pathways through snouts overlying overdeepenings (Figure 12).

Meltwater drainage towards the apex of the outwash head was clearly fed by a portal in the centre of the glacier snout but it was not obvious until the capture of 1964 imagery where the lake water centred over study area 2 in 1945 was draining away. This becomes apparent in the emergence of englacial eskers in the debris covered snout on the 1964 and 1980 imagery (Figure 12). An esker origin for these ridges is verified by their field characteristics of well-sorted stratified gravels and sands (Bennett & Evans, 2012; Spedding & Evans, 2002). After lake drainage, meltwater streams flowing over the kame terraces (area 1) to form the outwash plain (area 2) disappeared under the snout margin, emerging again on the northern part of the outwash head apex in 1964 (Figure 12). By 1980, this meltwater pathway through the snout becomes more obvious where an N-S trending stream draining through ice-cored terrain is clearly feeding the active apex of the outwash head at the centre of the snout. The emergence of englacial eskers is manifested in the imagery of the ice-cored moraine complex (area 3) by the appearance of sinuous ridges. These ridges document drainage through the ice in a NW-SE direction prior to 1980, constituting 'engorged eskers' (sensu Mannerfelt, 1945, 1949; Evans et al., 2018). However, later imagery from 2012 shows W-E–orientated ridges, likely documenting the drainage through the glacitectonic thrust mass constructed in the 1990s, towards the meltwater stream that was established around the front of the thrust mass at that time and visible on the 1998 imagery (Figure 12). By 2022, our UAV imagery reveals the emergence of a further set of englacial eskers in the lower part of the collapsing ice-cored moraine complex and aligned ENE-WSW (Figure 13). Drainage towards the higher topography in the ENE seems unlikely, especially as these eskers would have accumulated in tunnels cut through lower elevation ice after thrust mass construction. Consequently, we envisage their production by meltwater drainage away from the extensive collapsed terrain that has developed beneath the eastern end of the outwash plain and towards the contemporary proglacial lake. If correct, this interpretation highlights the development of 'engorged eskers', but of a type that is driven by a groundwater hydrology scenario in which water pressures are not glacier induced. Moreover, drainage directions are the reverse of those that would be reconstructed based solely on landform evidence in a fully deglaciated landscape. Additionally, eskers have developed at different levels within a downwasting glacier mass as a result of two entirely different 'engorged' drainage scenarios.

In addition to the unusually complex esker development, the ice-cored moraine complex (case study area 3) is an excellent example of a terrain produced by incremental stagnation of a debris-covered snout that was subsequently glacitectonically pushed by glacier readvance during the 1990s (Figures 1b, 12 and 13; Bennett and Evans (2012)). Arcuate ridges were constructed at the eastern end of the moraine complex, comprising compressed and thrust stacked ice-cored ridges and eskers, which were gradually emerging through the debris-covered snout prior to the readvance. This is an ice-cored version of a composite glacitectonic thrust moraine (sensu Aber

et al., 1989). The inclusion of buried glacier ice in the thrust mass has significant implications for glacial geomorphology in that de-icing will result in the gradual destruction of linearity and a final landform that resembles hummocky terrain rather than a recognizable glacitectonic thrust mass. In 2014 and 2016 imagery, the arcuate ridges diagnostic of thrust mass construction was still visible despite the significant mass lost through de-icing (Figure 13). Since 2014, however, downwasting due to de-icing has gradually fragmented the linearity and this has been replaced by increasing amounts of chaotic hummocky and pitted terrain as well as the ESE-WNW engorged eskers.

The historical development of the ice-cored hummocky terrain with discontinuous sinuous ridges (area 4) not only serves as an excellent genetic model for outwash heads but also provides insight into the operation of glacial meltwater pathways over overdeepenings. Like study area 3, this area appeared as ice-cored, pitted terrain at the elongate apex of the main proglacial outwash fan in 1980, but was glacitectonically compressed to form an ice-cored composite thrust mass fronted by push ridges in glacifluvial deposits during the 1990s readvance (Figures 1c and 12). As it then downwasted into hummocky terrain, it was also incised and reworked in several places by glacial meltwater streams existing from portals on the glacier snout. Associated with the portal positions have been sinuous ridges composed of well-sorted and stratified gravels and sands emerging from the downwasting ice-cored terrain over time. These ridges are interpreted as englacial eskers due to their continuation onto the glacier surface and their clear emergence from englacial positions (Bennett et al., 2010; Bennett & Evans, 2012; Spedding & Evans, 2002). The association of the eskers with an ice-cored proglacial outwash fan clearly demonstrates that the majority of the meltwater draining through the glacier snout has bypassed the floor of the overdeepening, explaining the very restricted occurrence of supercooled ice (Larson et al., 2010; Roberts et al., 2002; Spedding & Evans, 2002; Swift et al., 2006).

4.6 | Problems and limitations in using data collected with optical sensors on UAVs

While the use of UAVs in glacial geomorphology increased rapidly after 2015 (see Śledź et al., 2021), data processing results are not free of artefacts and can exhibit problems, which require careful investigations in order to avoid erroneous interpretation. The most common issues associated with SfM reconstruction are related to water surfaces, which are particularly important in rapidly changing glacier forelands prone to high levels of de-icing and concomitant pond and lake development, growth and decay. For example, SfM can reconstruct points located underwater in shallow, transparent ponds (Carrivick & Smith, 2019); however, the algorithm struggles in cases with high water turbidity or suspended sediments (see Tomczyk & Ewertowski, 2021). In our case studies, this was clearly the case in relation to the large proglacial/supraglacial lake, which was characterized by high suspended sediment concentrations combined with small wind-generated ripples, resulting in the erroneous reconstruction of the water surface. To avoid the impact of these errors on DoD
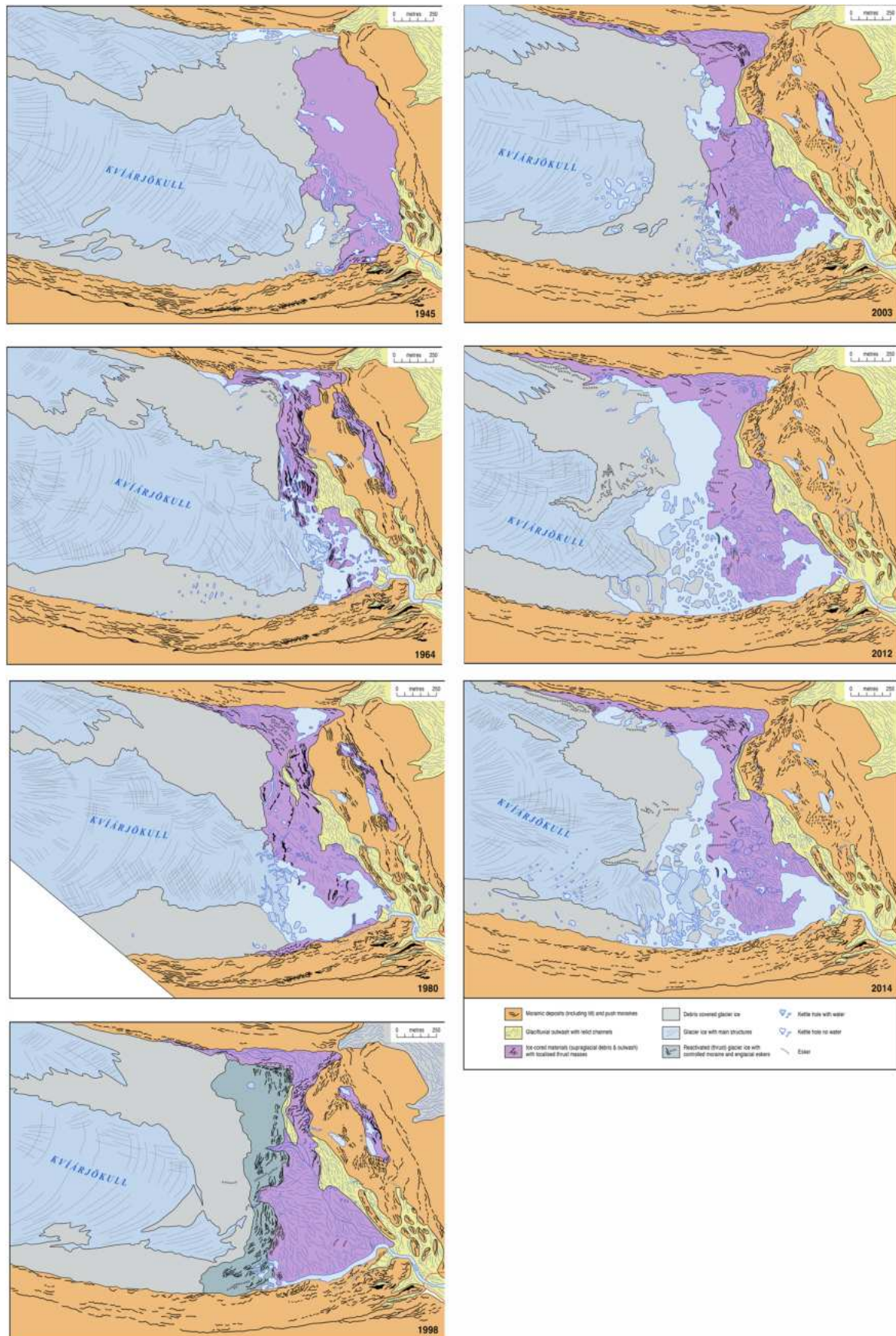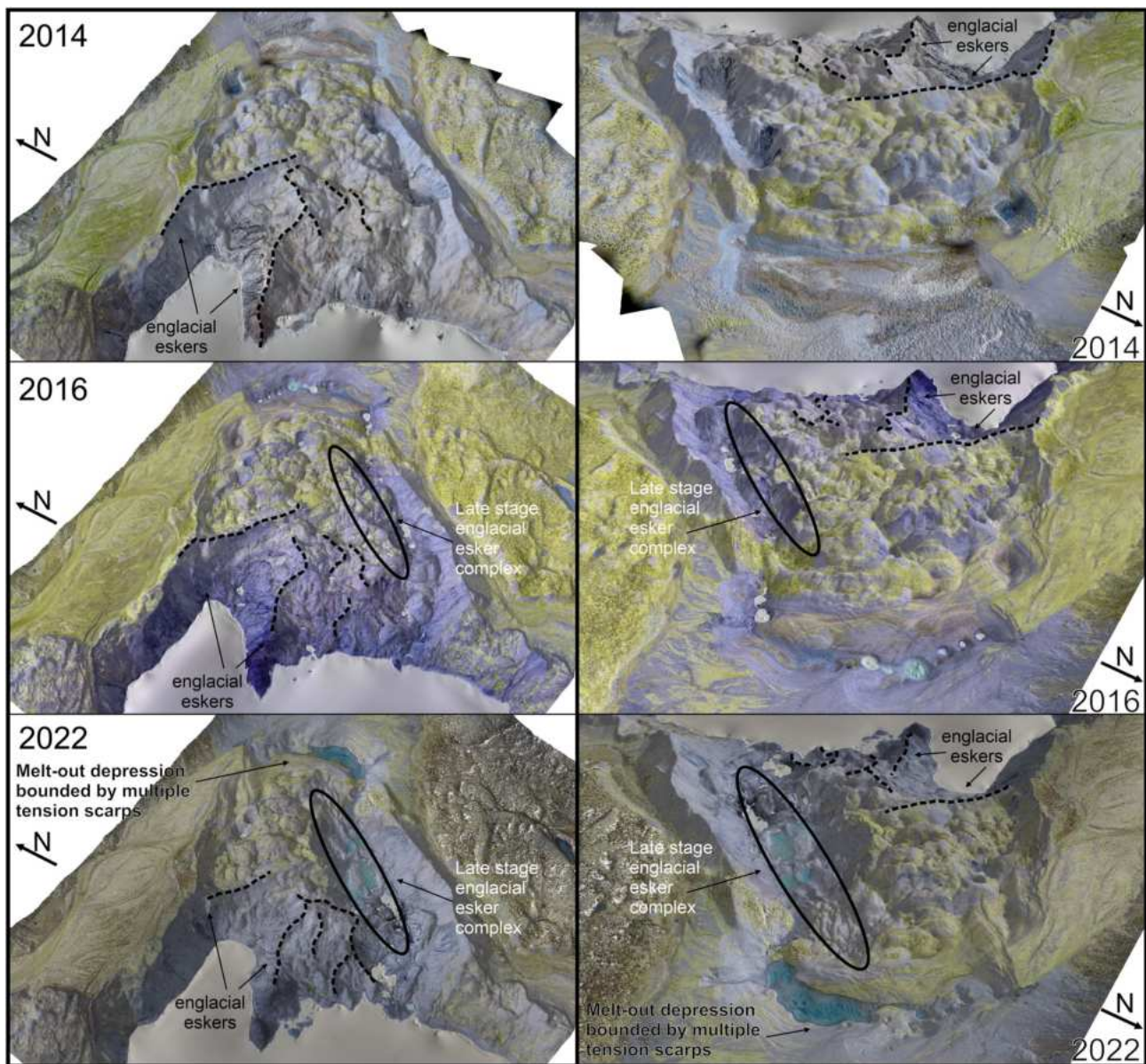
FIGURE 12 Legend on next page.

FIGURE 13 3D visualizations of the ice-cored moraine complex (see Figure 2 for location) between 2014 and 2022 illustrating different stages of degradation and the emergence of englacial eskers. [Colour figure can be viewed at wileyonlinelibrary.com]

calculations, points characterized by high uncertainty (e.g., located only on two images) were removed from the dense point cloud and a smooth water surface was thereby created (Figure 14a). Moreover, borders of case studies were delineated to avoid the lake area (Figure 2). In the case of minor, transparent waterbodies, depending on the water depth, underwater terrain was reconstructed to some extent, but in some cases erroneous points were generated and this impacted on elevation and shading models (Figure 14b). In such cases,

the careful examination of not only DEMs but also orthomosaics is required.

Indeed, the investigation of different products of SfM (point clouds, DEMs and orthomosaics), in combination with field verification, is crucial for accurate interpretations of geomorphological process–form regimes. For example, in our case study area 2 (outwash plain), a 192 m^3 increase in the volume was recorded for the 2021–2022 period (Figures 7b and 11, Tables 2, 4 and 5) but the analysis of

FIGURE 12 Palaeogeographic reconstructions of glacier change and landform development for the debris-charged, active temperate foreland at Kvíárjökull based on aerial imagery (1945–2003) and high-resolution satellite imagery (2012–2014). [Colour figure can be viewed at wileyonlinelibrary.com]
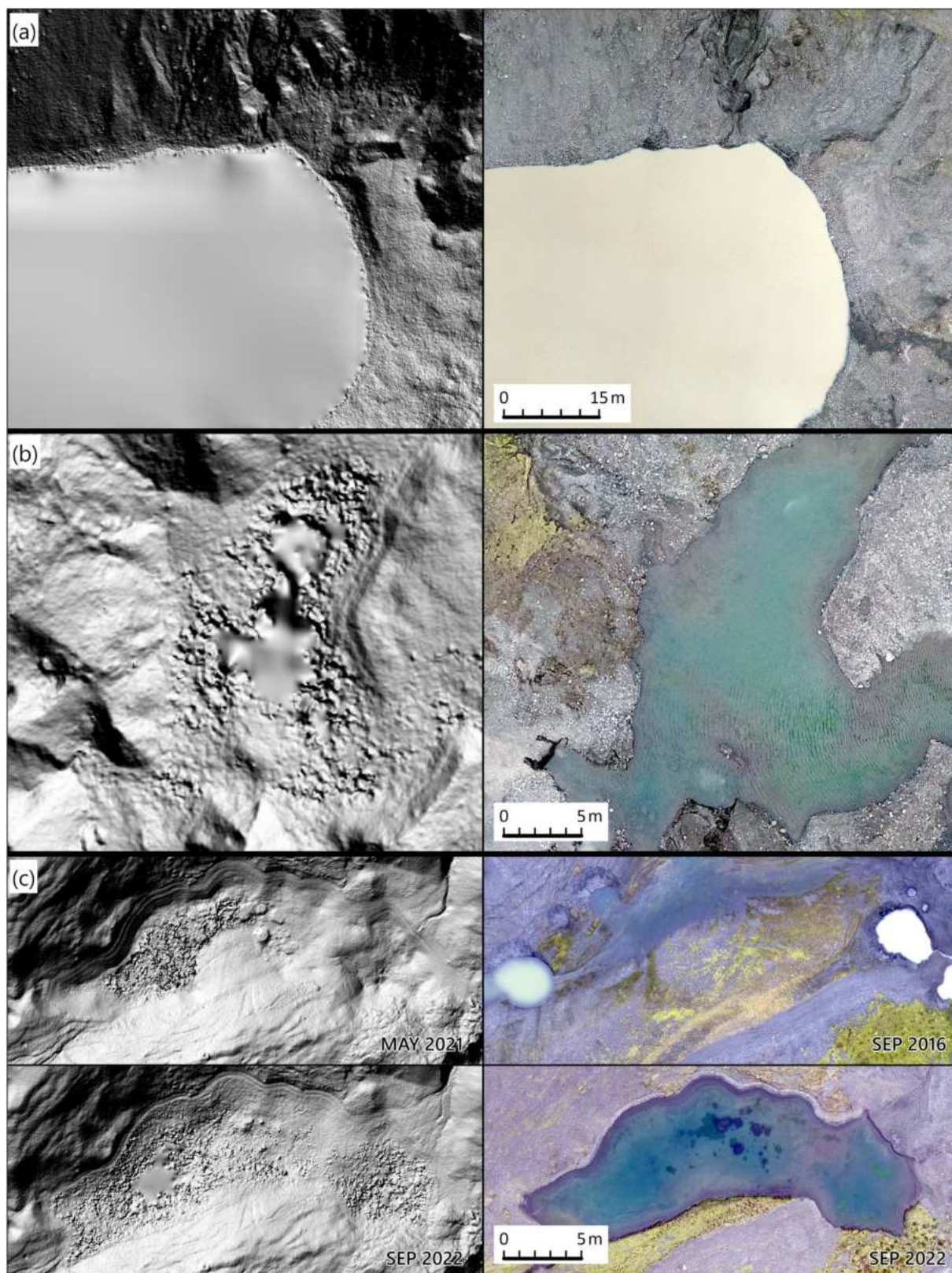
FIGURE 14 Examples of problems with data processing encountered in the study area: (a) lake with a high concentration of suspended sediments which required filtration of the point cloud; (b) small transparent waterbodies, which generated erroneous surfaces and (c) depression filled with water, which was responsible for an increase in volume recorded by DoD. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Average annual volume change for each case study.

DoD	Average annual volume change (m³)
Case study 1	
September 2014–September 2021	−932.92
September 2021–May 2022	−44.46
Total (September 2014–May 2022)	−834.99
Case study 2	
September 2016–September 2021	−3130.12
September 2021–May 2022	289.14
Total (September 2016–May 2022)	−2724.74
Case study 3	
September 2014–September 2016	−45,091.83
September 2016–September 2021	−51,299.21
September 2021–May 2022	−25,811.33
Total (September 2014–May 2022)	−47,709.52
Case study 4	
September 2016–September 2021	−12,065.66
September 2021–May 2022	−2777.67
Total (September 2016–May 2022)	−11,405.57

Note: DEMs of differencs (DoDs) for 09.2021–05.2022 mainly cover winter period, so average values are much lower than in other periods.

orthomosaics indicated that the elevation increase was not related to landform change, but instead to the water that filled the depression over time (Figure 14c).

5 | CONCLUSIONS

This study investigated landform transformation in relation to the development of the debris-charged temperate glacial landsystem on the foreland of Kvíárjökull, SE Iceland, for the period 1945–2022, with high-resolution quantification of surface change resulting from de-icing over the period 2014–2022. Observations were based on aerial photograph archives, high-resolution satellite imagery and a time series of UAV-gathered data. UAV images were processed using the SfM approach to generate DEMs, which were then used to develop the DoDs and perform the change detection. We selected four case study areas representative of specific landform elements, including a kame terrace staircase, an outwash plain, an ice-cored hummocky moraine complex and an ice-cored hummocky terrain with discontinuous sinuous ridges (englacial eskers). The recorded short-term dynamics of the landform changes at Kvíárjökull are consistent with those reported at other rapidly deglaciating forelands in the northern polar region. The average annual change in volume as derived from land surface lowering ranged from −0.06 m a⁻¹ in a relatively stable area of kame terrace staircase to −0.82 m a⁻¹ for the ice-cored hummocky moraine complex. Compared with long-term research in this foreland since 1945, our results confirm the

ongoing degradation of ice-cored moraine and outwash complexes, visible and quantifiable by using land surface collapse, at variable rates related to buried ice volume and age of deglaciation. The gradual evolution of largely chaotic hummocky terrain from not only debris-covered glacier ice but also from glacitectonic thrust masses, outwash fans/heads and complex englacial esker networks is an important modern landsystem analogue for informing palaeoglaciological reconstructions in areas characterized by hummocky 'moraine' and/or kame and kettle topography.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Oświadczenia autorów

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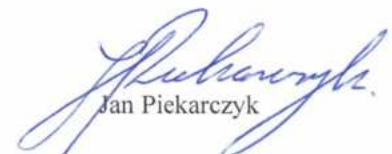| Afiliacja	Autor	Udział
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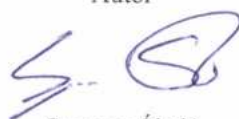Autor

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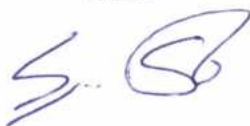
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DECLARATION
OF AUTHORS

The authors of the above publication declare their participation in its preparation as follows:

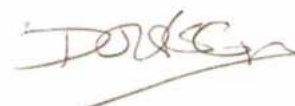| Affiliation	Author	Contribution
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	Marek W. Ewertowski	The author was responsible for the conceptualization of the research, development of the methodology, conducting part of the UAV surveys, processing of historical aerial photographs, data interpretation, preparation of figures 3,9,13,14, preparation of the manuscript, supervising the methodological correctness of the work, and preparation of the responses to the reviews.
Department of Geography, Durham University, Durham, UK	David J. A. Evans	The author was responsible for the conceptualization of the research, literature review, development of the methodology, conducting fieldwork, geomorphological mapping, data interpretation, preparation of figures 1c, 4, 12, preparation of the manuscript, supervising the methodological correctness of the work; preparation of the responses to the reviews.

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