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Which glaciers are the largest in the world?

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Abstract

Glacier monitoring has been internationally coordinated for more than 125 years. Despite this long history, there is no authoritative answer to the popular question: 'Which glaciers are the largest in the world?' Here, we present the first systematic assessment of this question and identify the largest glaciers in the world – distinct from the two ice sheets in Greenland and Antarctica but including the glaciers on the Antarctic Peninsula. We identify the largest glaciers in two domains: on each of the seven geographical continents and in the 19 first-order glacier regions defined by the Global Terrestrial Network for Glaciers. Ranking glaciers by area is non-trivial. It depends on how a glacier is defined and mapped and also requires differentiating between a glacier and a glacier complex, i.e. glaciers that meet at ice divides such as ice caps and icefields. It also depends on the availability of a homogenized global glacier inventory. Using separate rankings for glaciers and glacier complexes, we find that the largest glacier complexes have areas on the order of tens of thousands of square kilometers whereas the largest glaciers are several thousands of square kilometers. The world's largest glaciers and glacier complexes are located in the Antarctic, Arctic and Patagonia.

1. Introduction

Ice sheets and glaciers currently cover 12.5% of Earth's land surface (Bamber and others, 2018). At present, ice masses consist of the continental ice sheets in Antarctica and Greenland and more than 200 000 glaciers distinct from the ice sheets (Pfeffer and others, 2014), representing potential sea-level rise of 57.9 ± 0.9 m (Morlighem and others, 2020), 7.4 ± 0.05 m (Morlighem and others, 2017) and <0.5 m (Farinotti and others, 2019), respectively. Together, these ice bodies store 69% of the world's fresh water (Gleick, 1996).

Glaciers form where snow accumulation exceeds the annual melt over decades to centuries. As glaciers form where climatic conditions permit (i.e. cold regions with sufficient precipitation), they often straddle complex mountainous terrain where different sections of the ice surface drain into different valleys. In addition, depending on the topographic as well as present and past climatic setting, glacier complexes can build ice caps or icefields that drain ice from common accumulation zones via outlet glaciers to different watersheds (Table 1). Traditionally, and for hydrological reasons, glacier complexes have been divided into glaciers, often with distinct names, based on their drainage basins.

As a consequence, the size of an ice body (and total number of glaciers) will depend on whether or not a glacier complex (e.g. ice caps and icefields) is considered as one single entity or subdivided into glaciers based on drainage divides. These can be calculated from a digital elevation model (DEM) representing the glacier surface and watershed algorithms that analyze the direction of surface flow with respect to a pour point outside the glacier extent (e.g. Bolch and others, 2010). While the division is often straightforward in regions where glaciers are surrounded by steep topography (Fig. 1a), it is much more difficult for glacier complexes that cover much or all of the underlying topography, and hence make identifying individual flow basins less obvious. This is especially true of ice caps with their radial flow, as they may initially be classified as one entity rather than a collection of glaciers having formed an ice cap (Fig. 1b). For icefields, it is challenging to define the correct position of ice divides as their outlet glaciers originate in relatively flat surface topography (Figs 1c, d). When a DEM of limited quality is used to derive the ice divides, the somehow arbitrary glacier separations visible in Fig. 1c can result. Separating glacier complexes into glaciers is further challenged by climate-change-driven shifts in ice divides and separation of glacier tongues and, in practice, by the lack of high-quality, contemporaneous, high-resolution elevation data.

The appropriate choice of glacier versus glacier complex varies with the purpose of the study and the perspective of the user. For example, considering glacier complexes as a whole might be sufficient to map glaciers for land-cover classifications or for projects where ice bodies represent a natural barrier for land-based infrastructure. Conversely, dividing a glacier complex into glaciers is important to properly evaluate the meltwater input to an individual hydrological drainage basin or to determine the mass flux to marine-terminating glacier fronts or ice shelves. Further, whether to divide a glacier complex for modeling purposes depends on the model type. While some models rely on a glacier inventory that includes

Table 1. Terminology related to glaciers and glacier complexes according to Cogley and others (2011)

Term	Definition
Ice body	Any continuous mass of ice, possibly including snow and firn, at or beneath the Earth's surface.
Glacier	A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow.
Glacier complex	A number of contiguous glaciers; a generic term for all collections of glaciers that meet at [ice] divides.[a]
Ice cap	A dome-shaped ice body with radial flow, largely obscuring the subsurface topography and generally defined as covering less than 50 000 km^2.
Icefield	A large ice body that covers mountainous terrain but is not thick enough to obscure all of the subsurface topography, its flow therefore not being predominantly radial as is that of an ice cap.
Ice sheet	An ice body that covers an area of continental size, generally defined as covering 50 000 km^2 or more.
Outlet glacier	A glacier, usually of valley-glacier form, that drains an ice sheet, icefield or ice cap.

[a]Objects that may be divisible into more than one glacier (e.g. ice caps and icefields).

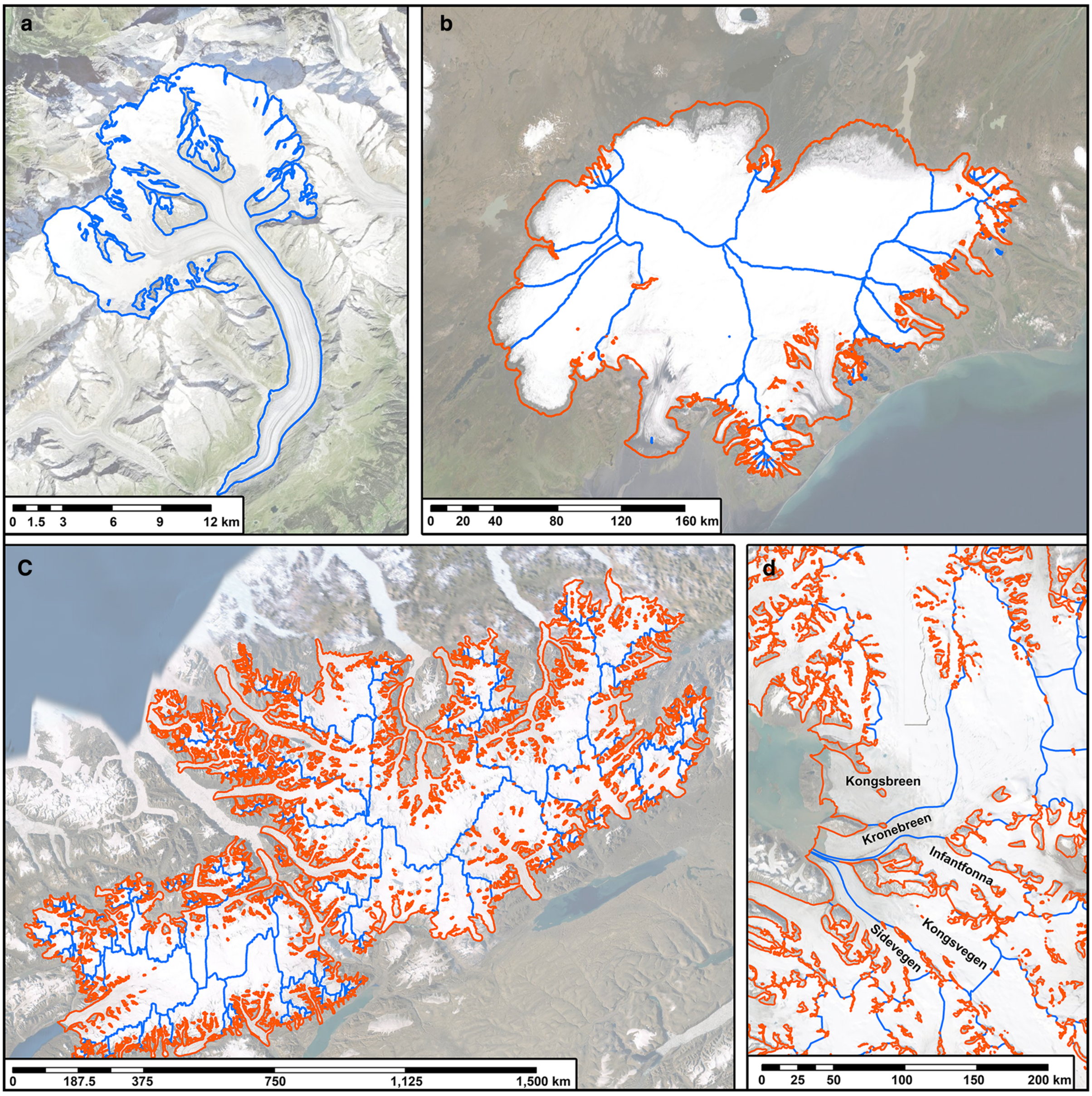

Fig. 1. Examples of glaciers and glacier complexes: (a) Aletsch Glacier in Switzerland, (b) Vatnajökull Ice Cap in Iceland and (c) Northern Ellesmere Icefield in the Canadian Arctic. Subplot (d) shows the Holtedalfonna-Isachsenfonna Icefields in Svalbard with a zoom to its contiguous outlet glaciers. Outlines of the glaciers and of glacier complexes are shown in blue and red, respectively; the background image is the ESRI World Imagery base map (ESRI, 2022).

data for each glacier draining a glacier complex (e.g. Huss and Hock, 2015; Maussion and others, 2019), other models treat the ice cover as a whole and do not require individual glacier inputs (e.g. Immerzeel and others, 2012; Seibert and others, 2018).

Despite more than 125 years of internationally coordinated glacier monitoring (Zemp and others, 2014; Allison and others, 2019) that have resulted in, among others, several glacier inventories (WGMS, 1989; Raup and others, 2007; Pfeffer and others, 2014), no official list has been compiled of the world's largest glaciers, although numerous inconsistent rankings exist in popular literature. This may in part be due to the aforementioned topographic complexity of glacier surfaces which complicates unambiguous drawing of glacier boundaries, further compounded by the fact that existing glacier inventories have not been designed for this purpose.

Here, we present the first systematic assessment of the largest glaciers in the world, based on area, over two domains: the seven geographical continents and the 19 first-order glacier regions as defined by the Global Terrestrial Network for Glaciers (GTN-G, 2017). Given the considerations above, we provide two rankings – one for glacier complexes and one for glaciers – using the Global Land Ice Measurements from Space (GLIMS) glacier data and the Randolph Glacier Inventory (RGI) 6.0. In addition, we discuss the main challenges for such rankings and provide an outlook on future work.

2. Glacier monitoring and inventories

Internationally coordinated glacier monitoring was initiated as early as 1894 (Forel, 1895; Allison and others, 2019), with a main focus on compiling standardized observations of changes in glacier length, and later, changes in glacier volume and mass (Haeberli, 2008). The need for a worldwide inventory of existing 'perennial ice and snow masses' was first considered during the International Hydrological Decade (IHD, 1965–74) and resulted in the World Glacier Inventory (WGMS, 1989) including statistical information, mainly based on aerial photographs and maps, of about one-third of the global glacier area. In 2005, the World Glacier Inventory was complemented, and later superseded, by the GLIMS glacier database, which was designed to store multi-temporal digital vector outlines of the world's glaciers and related topographic information primarily derived from optical satellite images (GLIMS Consortium, 2005; Paul and others, 2009). By 2013, GLIMS covered ~58% of global glacierized area including multi-temporal coverage for thousands of glaciers. The version of GLIMS used for this analysis contains ~383 000 glacier outlines including multiple outlines from different dates for many glaciers.

Stimulated by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) and an increasing need for complete global coverage for large-scale glaciological applications, a nearly complete global inventory with one vector outline for each glacier outside the ice sheets was produced. Named the Randolph Glacier Inventory (RGI), the first version (Pfeffer and others, 2014) complemented glacier outlines from GLIMS with new datasets from other sources originating mostly from the first decade of this century. The RGI has been updated several times since. The latest version (RGI 6.0; RGI Consortium, 2017) provides a snapshot for the beginning of the 21st century and includes ~215 000 glaciers covering an area of ~706 000 km^2. Note that RGI 6.0 does not contain the glaciers on the Antarctic Peninsula while GLIMS does include them.

As a result of the historic development and data provision by individual analysts, the RGI and GLIMS databases are not fully consistent due to differences in how analysts divide glacier complexes. Such divisions are in many cases difficult to apply, be it for technical reasons (low-quality DEM) or methodological ones (e.g. circular ice caps, ice aprons, glaciers with interrupted profiles). The available inventories thus present a mixture of divided and undivided glacier complexes as well as glacier extents following different definitions. Indeed, this results in problems when trying to answer the question about the largest glaciers in the world. This is discussed further in the discussion section on *Data consistency*.

3. Methods

Glacier area (in km^2) is used as an obvious measure of glacier size that can be extracted as attributes from both the GLIMS and RGI databases. It is the primary variable associated with glacier vector outlines, which can serve as a baseline input for ranking according to secondary variables such as glacier length, volume or mass. However, a system for ranking glaciers by size cannot be directly derived as noted in Section 2. In addition, some RGI outlines are older than GLIMS outlines. Therefore, we used both the GLIMS glacier database (version 20190304; GLIMS Consortium, 2005) and the RGI inventory (version 6.0; RGI Consortium, 2017) to compile one recent outline for each glacier in the world. Further, how an analyst defines a glacier and a glacier complex is important to the outcome of the analysis. Depending on the research question, these can be defined in different ways, which could lead to different results. Here, we use the definitions from Cogley and others (2011) as listed in Table 1 when referring to glaciers, glacier complexes, ice caps or icefields.

Note that we do not consider the Greenland and Antarctic ice sheets in this analysis. However, we do include all glaciers peripheral to the Greenland Ice Sheet with connectivity levels 0 and 1 in RGI 6.0 (Rastner and others, 2012), which represent that the glacier is not connected to (i.e. physically separate from) the ice sheet or weakly connected (i.e. only touching the ice sheet at a distinct ice divide in the accumulation region, and not connected or only in contact in the ablation region), respectively. We also include all glaciers in the Antarctic periphery, which in RGI 6.0 consists of the glaciers on the Antarctic and Subantarctic Islands but lacks those on the Antarctic mainland.

We subdivided region 19 into the Antarctic mainland (second-order region 19-31 in GTN-G, 2017) and the Antarctic and Subantarctic Islands (second-order regions 19-01 to 19-24 in GTN-G, 2017). In addition, using GLIMS, we incorporate the ice body on the Antarctic Peninsula (north of 70° South) even though it is connected to the West Antarctic Ice Sheet and is, therefore, often considered part of the Antarctic Ice Sheet (Fretwell and others, 2013; IMBIE Team, 2018; Seroussi and others, 2020). Note that while other entities in Antarctica are also named glaciers (e.g. Thwaites and Pine Island), they are outlet glaciers of the Antarctic Ice Sheet (Fretwell and others, 2013). As such, we have excluded them from this analysis.

We query both databases and extract the glacier area attribute from them for each of the seven geographical continents and the 19 first-order glacier regions (GTN-G, 2017) (Fig. 2) – excluding ice shelves and the two ice sheets as described above – and use the extracted quantities as the de facto value for glacier area. The results from these queries were reviewed, and the three largest glaciers per region were obtained. In cases where a glacier's size differed between GLIMS and RGI, we compared the dates of the measurements and chose the one with the more recent date. If the measurement dates matched (same year), the areas were averaged.

To determine the size of glacier complexes, they had to be identified first. Glaciers that shared common boundaries with one or more neighboring glaciers were merged at their common ice divides to create a glacier complex outline. Even when glaciers were only connected by a small glacier confluence, we chose not to change the original data and, hence, merge these into one glacier complex (see the discussion on *Data consistency* for more information). The area of each glacier complex was then determined using a Python planar area function in an equal-area projection. The GLIMS glacier database alone was used for this part of the analysis with two exceptions: the Greenland Periphery (region 5) and the Antarctic and Subantarctic Islands (regions 19-01 to 19-24) where RGI had to be used.

Glacier names are those given in the GLIMS and RGI datasets, when available. For glaciers without names in these datasets, we

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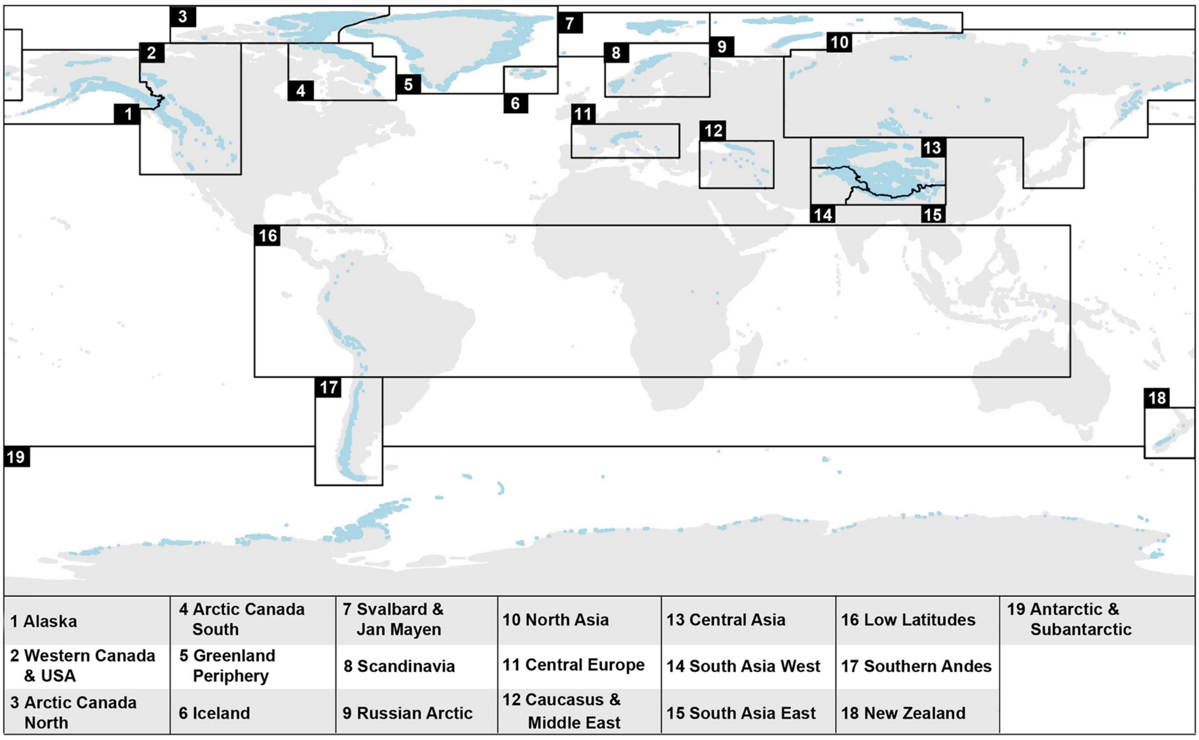

Fig. 2. Global overview of glacier area used in this analysis (blue) with the 19 first-order GTN-G glacier regions (GTN-G, 2017) (black outlines). Numbers refer to the GTN-G region numbers. Region 19 is subdivided into two regions (mainland and islands) but this subdivision is not shown on this map.

searched for a corresponding name in the Fluctuations of Glaciers database (WGMS, 2021), the World Glacier Inventory (WGMS and NSIDC, 2012), OpenStreetMap (2021) and in the scientific literature. If a name was still unknown, we named the glacier after a prominent geographic feature (e.g. Alexander Island Glacier No. 1). For glacier complexes, we used either an existing name (e.g. Southern Patagonian Icefield, Agassiz Ice Cap, Vatnajökull) – where available – or named the complex after its largest glacier(s) (e.g. Grosser Aletsch Glacier Complex, Gepatsch-Hintereis Glacier Complex), or a related prominent topographic feature (e.g. Vilcanota Glacier Complex, Western Kunlun Icefield). We recognize that some glaciers carried indigenous names before they were renamed by explorers. For example, Malaspina Glacier was Sít' Tlein (Thornton, 2012). For a list of the glaciers and glacier complexes for which we created the names, see Windnagel (2022).

4. Results

An overview of the ten largest glaciers and glacier complexes in the world is presented in Table 2, and the largest from each of the 19 GTN-G regions is shown in Figs 3 and 4. The three largest in the seven geographical continents are presented in Table 3. A complete list is given in Supplementary Table S1. The world's largest glacier complexes are located in the polar regions, and the ice body covering the Antarctic Peninsula (north of 70°S) is by far the largest, with an area of almost 81 000 km^2. It consists of ∼1500 ice bodies that are sometimes treated as glaciers (Huss and Farinotti, 2014; Huber and others, 2017) and by others as part of the Antarctic Ice Sheet (Fretwell and others, 2013). The second largest glacier complex covers an area of ∼47 000 km^2 and is located on Alexander Island in the Antarctic; this area excludes the ice shelves connected to the island. Third largest is the Malaspina-Seward Glacier Complex in Alaska covering 30 000 km^2, followed by the Severny Island Northern Ice Cap in the Russian Arctic at just over 20 000 km^2. Finally, in the Canadian Arctic, there is the Northern Ellesmere Icefield, the Prince of Wales Icefield and the Agassiz Ice Cap, with areas between 18 000 and 19 500 km^2. Outside the polar regions, the Southern Patagonian Icefield is the largest glacier complex with a size of ∼13 000 km^2.

The world's largest (individual) glaciers are found in the Antarctic, led by Seller Glacier (7018 km^2) on the Antarctic Peninsula, and then Thurston Island Glacier No. 1 (5261 km^2) and Alexander Island Glacier No. 1 (4766 km^2), both located on Antarctic islands. Outside the Antarctic, the largest glaciers (∼3000 km^2) are Malaspina-Seward Glacier in Alaska followed by Wykeham Glacier South in the Canadian Arctic and Bering Glacier in Alaska.

For context, the sum of the total area of the ten largest glaciers is ∼5% of the total area of all the glaciers in the world, which is ∼786 800 km^2, arrived at by summing the total area from RGI with the total area of the glaciers on the Antarctic Peninsula. The total area of the ten largest glacier complexes is just over 34% of the total glacier area on Earth.

Note that the uncertainty in the outlines in these databases is an important point to consider when assessing the results from this analysis. GLIMS provides uncertainties for individual outlines (for some glaciers), but RGI does not. Hence, we can only discuss the potential influence of these uncertainties on glacier area and ranking but not provide quantitative error estimates for each of the largest glaciers (see the discussion on *Data quality* for further information).

5. Discussion

5.1 The largest glaciers and their geographical occurrence

Our study shows that the question of which glaciers are largest depends on whether, and how, glacier complexes are distinguished from individual glaciers. We find that the largest glacier complexes cover areas larger than 10 000 km^2, whereas the largest glaciers cover up to 10 000 km^2 (Table 2). For comparison, the largest glacier complexes cover areas similar to smaller countries (e.g. Bhutan or Austria), smaller US states (e.g. New Jersey or South

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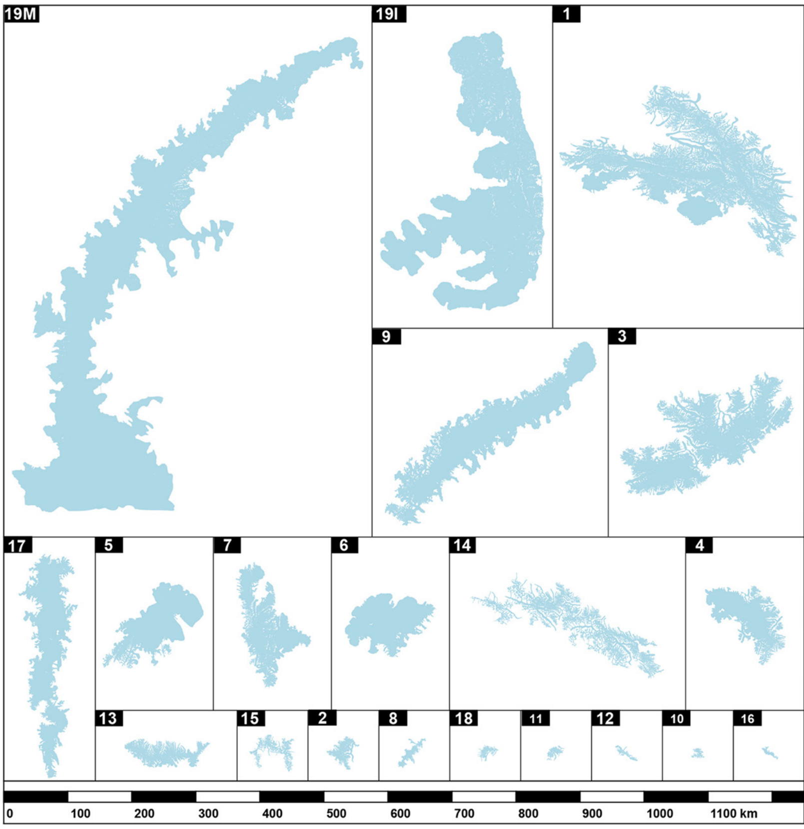
Table 2. The world's ten largest glacier complexes and glaciers, excluding the ice sheets but including glaciers in their periphery as well as the ice body on the Antarctic Peninsula

Ranking	Name	Region name (region No.)	Area (km^2)	Year
Glacier complexes				
1	Antarctic Peninsula Ice Body[a]	Antarctic Mainland (19)	80 852	2002
2	Alexander Island Glacier Complex	Antarctic and Subantarctic Islands (19)	47 486	1979–2001
3	Malaspina-Seward Glacier Complex	Alaska (1)	30 195	1999–2010
4	Severny Island Northern Ice Cap	Russian Arctic (9)	20 667	2002–2015
5	Northern Ellesmere Icefield	Arctic Canada North (3)	19 521	1999
6	Prince of Wales Icefield	Arctic Canada North (3)	19 009	1999
7	Agassiz Ice Cap	Arctic Canada North (3)	18 038	1999
8	Southern Patagonian Icefield	Southern Andes (17)	13 326	2000–2007
9	Thurston Island Ice Cap	Antarctic and Subantarctic Islands (19)	11 133	1972
10	Flade Isblink Glacier Complex	Greenland Periphery (5)	9025	2001
Glaciers				
1	Seller Glacier	Antarctic Mainland (19)	7018	2002
2	Thurston Island Glacier No. 1	Antarctic and Subantarctic Islands (19)	5261	1972
3	Alexander Island Glacier No. 1	Antarctic and Subantarctic Islands (19)	4766	1997
4	Alexander Island Glacier No. 2	Antarctic and Subantarctic Islands (19)	3980	1997
5	Mercator Ice Piedmont	Antarctic Mainland (19)	3499	2002
6	Malaspina-Seward Glacier	Alaska (1)	3363	2010
7	Wykeham Glacier South	Arctic Canada North (3)	3176	1999
8	Bering Glacier	Alaska (1)	3025	2010
9	Hubbard Glacier	Alaska (1)	2834	2010
10	Barnes Ice Cap South Dome North Slope Glacier	Arctic Canada South (4)	2771	2002

'Year' indicates the year or range of years the area refers to.
[a]Note that we consider the ice body on the Antarctic Peninsula as a glacier complex although it is connected to the Antarctic Ice Sheet.



REGION		ICE COMPLEX NAME	AREA (km2)
19M	Antarctic Mainland	Antarctic Peninsula Ice Body	80852
19I	Antarctic & Subant. Islands	Alexander Island Glacier Complex	47486
1	Alaska	Malaspina-Seward Glacier Complex	30195
9	Russian Arctic	Severny Island Northern Ice Cap	20667
3	Arctic Canada North	Northern Ellesmere Icefield	19521
17	Southern Andes	Southern Patagonian Icefield	13326
5	Greenland Periphery	Flade Isblink Glacier Complex	9025
7	Svalbard & Jan Mayen	Asgardfonna/ Balderfonna/Olaf V Glacier Complex	8371
6	Iceland	Vatnajökull Ice Cap	8092
14	South Asia West	Siachen Glacier Complex	7401
4	Arctic Canada South	Penny Ice Cap	6508
13	Central Asia	Western Kunlun Icefield	2786
15	South Asia East	Yanong Glacier Complex	955
2	Western Canada & USA	Klinaklini Glacier Complex	905
8	Scandinavia	Jostedalsbreen Icefield	500
18	New Zealand	Tasman Glacier Complex	249
11	Central Europe	Grosser Aletsch Glacier Complex	214
12	Caucasus & Middle East	Bezengi Glacier Complex	153
10	North Asia	Tavan Bogd Icefield	137
16	Low Latitudes	Vilcanota Complex	121

Fig. 3. Overview of the largest glacier complexes in each of the 19 first-order regions, sorted by area (largest to smallest). The region number is listed in the black box. The Region 19 subregions are listed as 19 M (Antarctic Mainland) and 19I (Antarctic and Subantarctic Islands). Glacier complexes are projected in local Universal Transverse Mercator, centered at the polygon's centroid, chosen as a best compromise to minimize distortion in shape and area. Areas are computed using an equal area projection. The area differences between these two coordinate reference systems are <0.1%. Note that we considered the ice body on the Antarctic Peninsula as an ice complex although it is connected to the Antarctic Ice Sheet.

Carolina) or some islands (e.g. Hokkaido (the 21st largest island in the world) or Tasmania), and yet are still orders of magnitudes smaller than the Greenland and Antarctic Ice Sheets, encompassing 1.7×10^6 km^2 (Zwally and others, 2012) and 12.3×10^6 km^2 (Zwally and others, 2012; Fretwell and others, 2013), respectively.

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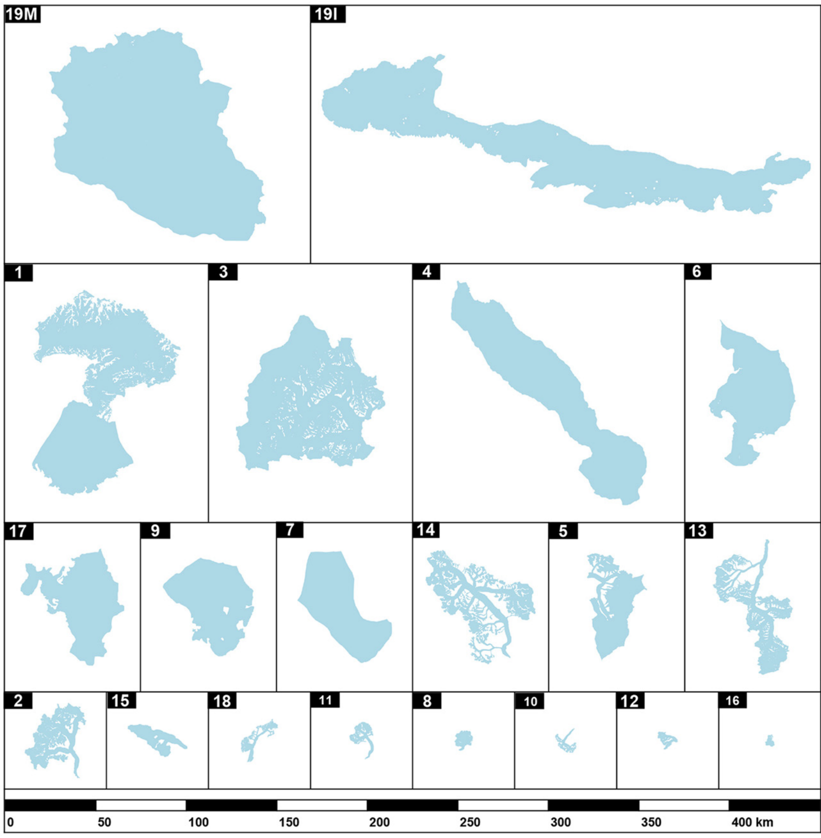

REGION		GLACIER NAME	AREA (km2)
19M	Antarctic Mainland	Seller Glacier	7018
19I	Antarcitc & Subant. Islands	Thurston Island Glacier No. 1	5261
1	Alaska	Malaspina-Seward Glacier	3363
3	Arctic Canada North	Wykeham Glacier South	3176
4	Arctic Canada South	Barnes Ice Cap South Dome N Slope Glacier	2771
6	Iceland	Skeidararjökull	1561
17	Southern Andes	Pio XI Glacier	1345
9	Russian Arctic	Moshnyj Glacier	1257
7	Svalbard & Jan Mayan	Storstraumbreen	1226
14	South Asia West	Siachen Glacier	926
5	Greenland Periphery	Tjalfe Glacier	739
13	Central Asia	Fedchenko Glacier	700
2	Western Canada & USA	Klinaklini Glacier	470
15	South Asia East	Yanong Glacier	180
18	New Zealand	Tasman Glacier	88
11	Central Europe	Grosser Aletsch Glacier	78
8	Scandinavia	Austerdalsisen	55
10	North Asia	Potanin Glacier	37
12	Caucasus & Middle East	Bezengi Glacier	37
16	Low Latitudes	Jancapampa Glacier	16

Fig. 4. Overview of the largest glaciers in each of the 19 first-order regions, sorted by area (largest to smallest). Display methods are the same as Figure 3.

Table 3. The three largest glacier complexes and glaciers for each of the seven geographical continents, excluding ice sheets but including glaciers in their periphery and the ice body on the Antarctic Peninsula

Continent name	Glacier complex Name	Area (km^2)	Year	Glacier Name	Area (km^2)	Year
North America	Malaspina-Seward Glacier Complex	30 195	1999–2010	Malaspina-Seward Glacier	3363	2010
	Northern Ellesmere Icefield	19 521	1999	Wykeham Glacier South	3176	1999
	Prince of Wales Icefield	19 009	1999	Bering Glacier	3025	2010
South America	Southern Patagonian Icefield	13 326	2000–2007	Pio XI Glacier	1345	2007
	Northern Patagonian Icefield	4018	2000–2007	Upsala Glacier	883	2007
	Cordillera Darwin Icefield	1894	2000–2007	O'Higgins Glacier	883	2007
Europe	Severny Island Northern Ice Cap	20 667	2002–2015	Skeidararjökull	1561	2000
	Asgardfonna-Balderfonna-Olaf V Glacier Complex	8371	1961–2008	Bruarjökull	1429	2000
	Vatnajökull Ice Cap	8092	1999	Moshnyj Glacier	1257	2013
Africa	Northern Icefield Glacier Complex	1	2004	Northern Icefield	<1	2004
	Kersten Glacier Complex	<1	2004	Kersten Glacier	<1	2004
	Stanley Glacier Complex	<1	1990	Stanley Glacier	<1	1990
Asia	Siachen Glacier Complex	7401	1998–2010	Academy of Sciences Ice Cap Basin North Glacier	1244	2006
	Academy of Sciences Ice Cap	5574	2006	Academy of Sciences Ice Cap Basin West Glacier	1033	2006
	Karpinsky-University Glacier Complex	4033	2001	Siachen Glacier	926	2006
Oceania	Tasman Glacier Complex	249	1978–2009	Tasman Glacier	88	2009
	Adams-Lambert Glacier Complex	43	1978	Fox Glacier	34	2009
	Lyell-Ramsay Glacier Complex	31	1978	Franz Josef Glacier	33	2009
Antarctic	Antarctic Peninsula Ice Body[a]	80 852	2002	Seller Glacier	7018	2002
	Alexander Island Glacier Complex	47 486	1979–2001	Thurston Island Glacier No. 1	5261	1972
	Thurston Island Ice Cap	11 133	1972	Alexander Island Glacier No. 1	4766	1997

'Year' indicates the year or range of years the area refers to.
[a]Note that we considered the ice body on the Antarctic Peninsula as an ice complex although it is connected to the Antarctic Ice Sheet.

Glacier size is a function of both climate and underlying topography. In the present study, we show that the largest glaciers are found in the polar regions, where low temperatures and relatively flat topographies have allowed large icefields and ice caps to grow and build major glacier complexes – over long time periods – in spite of low annual precipitation (Braithwaite and Hughes, 2020). Outside the Arctic and Antarctic regions, the largest glacier complexes occur in Alaska, Patagonia and Iceland where glaciers profit from the high annual precipitation of maritime climate regimes (Braithwaite and Hughes, 2020). In High Mountain Asia, steep topography results in well-defined catchments but limits the area of glaciers and the formation of very large glacier

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complexes even though some of the longest glaciers in the world exist in this region (Machguth and Huss, 2014).

5.2 Challenges related to ranking glaciers by area

Which glaciers are the largest in the world? What seems to be a simple question, in fact, is difficult to answer. Not only does one need a clear definition of what a glacier and glacier complex are, but also a globally complete dataset with a consistency that allows for a related comparison. In the following sections, we elaborate on the key challenges to ranking glaciers by area.

5.2.1 Definition

Glaciers form different glacier types depending on topographic and climatic conditions. These conditions differ from region to region and across continents. Consequently, a generally accepted definition is the most fundamental requirement to rank the world's glaciers by area. The 'Glossary of glacier mass-balance and related terms' by Cogley and others (2011) provides consensus definitions (Table 1). In particular, the differentiation between glaciers and glacier complexes emerged as essential. While this differentiation is theoretically reasonable, the related practical implementation comes with some complications. Separating individual glaciers – such as Grosser Aletsch Glacier in the European Alps (Fig. 1a) – is straightforward in regions of steep high-mountain topography with clearly defined hydrological basins. However, the task is more challenging when several glaciers form complexes in regions where the topography is flat, as illustrated by Kronebreen, Infantfonna, Kongsvegen and Sidevegen, which are neighboring glaciers in Svalbard that are calving into Kongsfjord and share a common glacier tongue (Fig. 1d).

In this case, the division might be justified as the individual tongues exhibit different flow dynamics, but other glaciers that merge from individual basins into a common tongue or only touch a trunk glacier as a tributary without contributing to its flow remain undivided. This inconsistency is difficult to solve and might also vary over time, necessitating a time stamp for the outline when size rankings are performed (see Tables 2 and 3).

The complex nature of glacier topography is well demonstrated by the Northern Ellesmere Icefield (Arctic Canada North) where hundreds of glaciers cover the mountainous terrain but are separated by mountain topography in their ablation regions. These glaciers partly share ambiguous ice divides (that change with the DEMs used to calculate them) and have tongues that are fed from accumulation zones in opposite valleys, connecting two icefields to form an even larger glacier complex (Fig. 1c). In addition, we note that glacier names – if available in the global datasets – often originate from regional or national contexts and, hence, are not always consistent with the classification based on topography. For example, the term for 'glacier' in Iceland is 'jökull', but it is used for both an ice cap and its outlet glaciers (Sigurdsson and Williams, 2008). The same is true in Norway for the word 'breen' (Andreassen and Winsvold, 2012). The word 'glacier', then, when affixed to a name, does not always provide a differentiation between a glacier and a glacier complex.

5.2.2 Availability of synchronous data

Ideally, the ranking of the largest glaciers could be directly derived from a globally homogeneous dataset of glacier outlines from the same reference year. Indeed, this is difficult to achieve as adverse snow and cloud conditions can make it difficult to retrieve satellite imagery for the same year for all glacierized regions in the world. Historically, the first, nearly complete, global inventory only became available with RGI 1.0 in 2012 (Pfeffer and others, 2014), so it was difficult to answer the question about the world's largest glaciers before then. RGI 6.0 – used for this study – was published in 2017 and provides a snapshot inventory, mostly for the beginning of the 21st century. However, its glacier outlines still span several decades in some regions and more than half a century in the most extreme case. This timing issue can influence rankings due to glacier area changes, which currently range from close to zero to several percent per year depending on the region (Vaughan and others, 2013; Cogley, 2016; Zemp and others, 2019). In most cases, this will not affect the ranking since relative area change is typically smallest for larger glaciers (e.g. Yang and others, 2020). However, the ranking of ice complexes may change if an ice complex is abruptly split into two or more smaller complexes when the connections between individual outlet glaciers are lost due to retreat (Fig. 5).

In addition, asynchronous glacier outlines can have a major effect on glacier ranking when glaciers change rapidly due to dynamically induced retreats or advances, for example, caused by rapid tidewater glacier retreats (McNabb and Hock, 2014) or surge or tidewater advances (Sevestre and Benn, 2015; Brinkerhoff and others, 2017). In the present study, we tried to minimize the temporal spread by complementing RGI 6.0 with GLIMS, which contains some more recent outlines.

5.2.3 Data quality

Ranking glaciers by area depends also on the uncertainty in the outlines used. Glacier extents can be overestimated due to wrongly mapped seasonal snow, underestimated due to missed glacier ice in shadowed areas, or both over and under estimated when debris cover on glaciers is wrongly interpreted. In general, uncertainties decrease as glacier size increases and are on the order of a few percent for glaciers with a size of a few square kilometers (Paul and others, 2013; Raup and others, 2014). Thus, for the largest glaciers in a region, this only plays a minor role. More severe is the impact of the quality of the available DEMs on glacier extent. Elevation errors, especially in relatively flat accumulation zones, can have major effects on the location of the automatically computed ice divides, which influence the separation of glacier complexes into glaciers.

Mapping precision is most relevant for glaciers with complex outlines and for very small glaciers. When size differences are smaller than a few percent, the uncertainties become significant, and hence, the related glaciers may share the same rank. Consequently, the Asgardfonna-Balderfonna-Olaf V Glacier Complex (8371 km^2) in Svalbard, Vatnajökull (8092 km^2) in Iceland and Austfonna Ice Cap (8067 km^2) in Svalbard could all be considered to be the second largest glacier complex on the European continent after the Severny Island Northern Ice Cap (20 667 km^2) in the Russian Arctic.

5.2.4 Data consistency

Finally, a glacier ranking should ideally be based on a consistent interpretation of glacier extents. In reality, GLIMS and RGI are a compilation of regional or national glacier inventories that originate from different investigators with various implementations of glacier definitions, data sources (platform, sensor and media) and time periods. As a consequence, our glacier ranking might be impacted by interpretation differences across regions.

For glacier complexes, subjective decisions in the mapping of outlines can result in major differences in glacier area and, hence, influence our glacier ranking. For example, the Hans Tausen Ice Cap – the second largest glacier complex in Greenland – is connected with the Bure Ice Cap through a relatively small glacier confluence in the ablation region (Fig. 5a). Separating the two ice caps would reduce the total area of the Hans Tausen glacier complex from 4114 to 3721 km^2 but, in this case, not change the ranking in Greenland. A similar situation is seen with the Karpinskiy and University Ice Caps in the

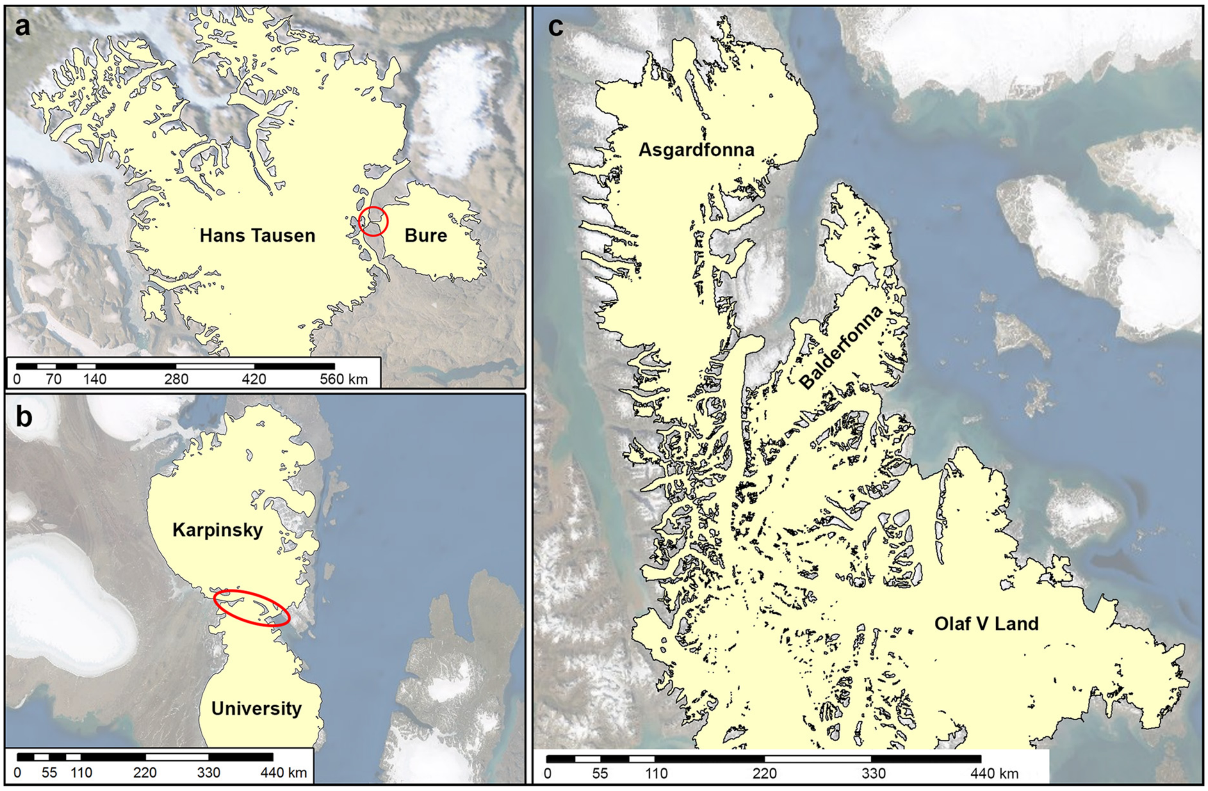

Fig. 5. Examples of glacier complexes with limited connections. (a) Hans Tausen Ice Cap and Bure Ice Cap in Greenland; (b) Karpinskiy Ice Cap and University Ice Cap on October Revolution Island, Severnaya Zemlya; (c) Asgardfonna, Balderfonna and Olaf V Icefields on Svalbard, Norway. Red circles highlight small glacier confluences connecting the ice caps; the background image is the ESRI World Imagery base map (ESRI, 2022).

Russian Arctic (Fig. 5b). Here, separating the two ice caps would still keep Karpinskiy Ice Cap as the third largest glacier complex. In Svalbard, the largest glacier complex is formed by the Asgardfonna, Balderfonna and Olaf V icefields. All three are connected in the ablation region through common outlet glaciers (Fig. 5c) but regionally often considered as individual ice bodies (Liestøl, 1993), as they are dynamically independent and have separate accumulation zones. Thus, the corresponding glacier complex ranks first in this region. Separating these connections would result in different rankings for the complexes. Without separation, the largest glacier complexes in Svalbard are the Asgardfonna-Balderfonna-Olaf V Glacier Complex (8371 km^2), Austfonna Ice Cap (8067 km^2) and Holtedalfonna-Isachsenfonna Glacier Complex (5377 km^2). Were the glacier complexes separated, the largest would become Austfonna Ice Cap (8067 km^2), Vestfonna Ice Cap (2372 km^2) and Asgardfonna Icefield (1587 km^2). For the purposes of this study and for consistency across all regions, we have chosen not to separate the glacier complexes by these connections in order to show the size of the largest contiguous ice bodies in the world based on the currently available databases.

For individual glaciers, the largest source of inconsistency most likely comes from the division of glacier complexes in the original inventories. Similarly, digital outlines for many ice caps and icefields are only mapped as single glacier complexes but not, or only partly, divided into glaciers. For example, the Vatnajökull Ice Cap in Iceland is stored as ~30 glaciers in RGI 6.0 but as one single ice cap in GLIMS (Fig. 1b). We have chosen to use the individual outlines for glacier rankings as provided in the RGI dataset (the blue lines in Fig. 1b) and are aware that this is somewhat inconsistent. In other regions, in particular the Antarctic and Subantarctic Islands, many glacier complexes are not, or are insufficiently, divided into glaciers. Hence, this may result in glaciers that are inappropriately too large in our ranking. Further, we chose to use connectivity levels 0 and 1 from Rastner and others (2012) for the Greenland Periphery and exclude glaciers with connectivity level 2. However, Rastner and others (2012) is a first attempt at a consistent solution to distinguish glaciers that are separate from the Greenland Ice Sheet; but as they note in their paper, this is not always in agreement with other inventories. Thus, if one were to include glaciers with connectivity level 2, the list of the ten largest glaciers in the world might change slightly.

5.3 Outlook on future work

To improve the ranking of glaciers by area, we recommend that ice caps and icefields be consistently split into individual glaciers in the GLIMS glacier database rather than only stored as glacier complexes as is currently the case for many ice bodies. Separation based on drainage divides should be built on the highest resolution DEMs available, and where possible, be guided by high-resolution ice velocity data to reduce ambiguities. Such a homogenized glacier inventory will allow a largely automated ranking of the world's glaciers. We acknowledge that creating drainage divides can be a considerable effort and, thus, recommend storing the divides in a separate data layer with polygon topology, as already recommended by Paul and others (2002), so that it may be used again with a dataset from a different point in time and allow for consistent change assessment. These individual glaciers can then be merged into glacier complexes using suitable methods, thus providing a consistent basis for their ranking.

We recommend that global datasets such as future versions of RGI provide both the inventory of individual glaciers as well as a derived inventory of glacier complexes. In addition, rankings should be derived from outlines as close as possible to a common reference year, and thus global inventories should strive for consistency in outline dates at least over a period of ~5–10 years. We acknowledge that this can be difficult to achieve in many regions with adverse cloud conditions and long-lasting seasonal snow where suitable images are simply not available. Storage of multi-temporal outlines of glaciers with common reference years will allow for future work that investigates how rankings change through time as glaciers respond to climate change. Lastly, as glacier inventory data become more internally consistent, this and other such global analysis tasks can be further automated and our analysis can be extended to rankings with respect to glacier length (Machguth and Huss, 2014) or volume and mass (Huss and Farinotti, 2012; Farinotti and others, 2019).

6. Conclusions

The question of which glaciers are the largest in the world has not been previously answered. Here, we revisited established terminology and used available inventories (i.e. GLIMS and RGI) to provide a systematic and reproducible ranking, differentiated for the seven geographical continents and the 19 first-order glacier regions. A basic requirement for such a ranking is delimiting glacier boundaries based on hydrological basins as well as having a clear differentiation between glaciers and glacier complexes.

We find that the largest glacier complexes cover areas larger than 10 000 km^2, exceed the size of the largest glaciers by one order of magnitude, and are located in the polar regions and in the Southern Andes. The largest glacier complexes cover areas the size of smaller countries (such as Bhutan or Austria) but are still orders of magnitudes smaller than the Greenland and Antarctic Ice Sheets and their drainage basins.

Ranking glaciers is highly uncertain and depends on the way the ice is divided, which is subjective and depends on the quality of available data. Ranking requires not only clearly defined glacier terminology but also depends on the availability, quality and consistency of digital glacier outlines at a global scale. Consequently, our rankings are most consistent for glacier complexes and within regions but are subject to larger uncertainties for glaciers and across regions.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2022.61

Data. Access to the digital glacier outlines is provided by NSIDC for the largest glaciers from this study (https://doi.org/10.7265/0k6 h-yn09; Windnagel and Zemp, 2022), RGI 6.0 (https://doi.org/10.7265/N5-RGI-60; RGI Consortium, 2017) and the GLIMS V20190304 database (https://doi.org/10.7265/N5V98602; GLIMS Consortium, 2005). The outlines of the 19 glacier regions are available from the GTN-G (https://doi.org/10.5904/gtng-glacreg-2017-07).

Code availability. GitHub: https://github.com/windnage/wgms-glacier-project

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References

Allison I and 5 others (2019) IACS: past, present, and future of the International Association of Cryospheric Sciences. *History of Geo- and Space Sciences* **10**(1), 97–107. doi: 10.5194/hgss-10-97-2019

Andreassen LM and Winsvold SH (2012) Inventory of Norwegian glaciers. NVE Rapport 38 Norwegian Water and Energy Directorate, Oslo, Norway.

Bamber JL, Westaway RM, Marzeion B and Wouters B (2018) The land ice contribution to sea level during the satellite era. *Environmental Research Letters* **13**(6), 063008.

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

Braithwaite RJ and Hughes PD (2020) Regional geography of glacier mass balance variability over seven decades 1946–2015. *Frontiers in Earth Science* **8**, 119–132. doi: 10.3389/feart.2020.00302.

Brinkerhoff D, Truffer M and Aschwanden A (2017) Sediment transport drives tidewater glacier periodicity. *Nature Communications* **8**(1), 1–8. doi: 10.1038/s41467-017-00095-5

Cogley JG (2016) Glacier shrinkage across High Mountain Asia. *Annals of Glaciology* **57**(71), 41–49. doi: 10.3189/2016AoG71A040

Cogley JG and 10 others (2011) Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2. UNESCO-IHP, Paris, France. Available at unesdoc.unesco.org/images/0019/001925/192525e.pdf.

ESRI (2022) 'World Imagery' [basemap]. 1 m scale. Available at https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9 (February 25, 2022).

Farinotti D and 6 others (2019) A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience* **12**(3), 168–173. doi: 10.1038/s41561-019-0300-3

Forel FA (1895) Les variations périodiques des glaciers. Discours préliminaire. *Archives des Sciences Physiques et Naturelles* **XXXIV**, 209–229.

Fretwell P and 59 others (2013) Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* **7**(1), 375–393. doi: 10.5194/tc-7-375-2013

Gleick PH (1996) Water resources. In Schneider SH (ed.), *Encyclopedia of Climate and Weather*. New York: Oxford University Press, pp. 817–823.

GLIMS Consortium (2005) GLIMS Glacier Database, Version 1, 20190304. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.7265/N5V98602.

GTN-G (2017) GTN-G glacier regions. doi: 10.5904/gtng-glacreg-2017-07

Haeberli W (2008) Changing views of changing glaciers. In Orlove B, Wiegandt E and Luckman BH eds. *The Darkening Peaks: Glacial Retreat in Scientific and Social Context*. Oakland, CA: University of California Press, pp. 23–32.

Huber J, Cook AJ, Paul F and Zemp M (2017) A complete glacier inventory of the Antarctic Peninsula based on Landsat 7 images from 2000 to 2002 and other preexisting data sets. *Earth System Science Data* **9**(1), 115–131. doi: 10.5194/essd-9-115-2017

Huss M and Farinotti D (2012) Distributed ice thickness and volume of all glaciers around the globe. *Journal of Geophysical Research – Earth Surface* **117**(F4), 1–10. doi: 10.1029/2012JF002523

Huss M and Farinotti D (2014) A high-resolution bedrock map for the Antarctic Peninsula. *The Cryosphere* **8**(4), 1261–1273. doi: 10.5194/tc-8-1261-2014

Huss M and Hock R (2015) A new model for global glacier change and sea-level rise. *Frontiers in Earth Science* **3**(September), 1–22. doi: 10.3389/feart.2015.00054

IMBIE Team (2018) Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* **558**(7709), 219–222. doi: 10.1038/s41586-018-0179-y

Immerzeel WW, van Beek LPH, Konz M, Shrestha AB and Bierkens MFP (2012) Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climactic Change* **110**(3), 721–736. doi: 10.1007/s10584-011-0143-4

IPCC (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental

Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liestøl O (1993) Glaciers of Europe – glaciers of Svalbard, Norway. In Williams RS and Ferrigno JG eds. *Satellite Image Atlas of Glaciers of the World*. Washington D.C: US Geological Survey, pp. 127–151.

Machguth H and Huss M (2014) The length of the world's glaciers – a new approach for the global calculation of center lines. *The Cryosphere* **8**(5), 1741–1755. doi: 10.5194/tc-8-1741-2014

Maussion F and 14 others (2019) The open global glacier model (OGGM) v1.1. *Geoscientific Model Development* **12**(3), 909–931 doi: 10.5194/gmd-12-909-2019

McNabb RW and Hock R (2014) Alaska tidewater glacier terminus positions, 1948–2012. *Journal of Geophysical Research – Earth Surface* **119**(2), 153–167. doi: 10.1002/2013JF002915

Morlighem M and 26 others (2017) BedMachine v3: complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. *Geophysical Research Letters* **44**(21), 11–051. doi: 10.1002/2017GL074954

Morlighem M and 37 others (2020) Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience* **13**(2), 132–137. doi: 10.1038/s41561-019-0510-8

OpenStreetMap and Contributors (2021) OpenStreetMap. Available at https://www.openstreetmap.org/.

Paul F and 9 others (2009) Recommendations for the compilation of glacier inventory data from digital sources. *Annals of Glaciology* **50**(53), 119–126. doi: 10.3189/172756410790595778

Paul F and 19 others (2013) On the accuracy of glacier outlines derived from remote-sensing data. *Annals of Glaciology* **54**(63), 171–182. doi: 10.3189/2013AoG63A296

Paul F, Kääb A, Maisch M, Kellenberger TW and Haeberli W (2002) The new remote-sensing-derived Swiss glacier inventory: I. Methods. *Annals of Glaciology* **34**, 355–361. doi: 10.3189/172756402781817941

Pfeffer WT and 18 others (2014) The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of Glaciology* **60**(221), 537–552. doi: 10.3189/2014JoG13J176

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

Raup BH and 20 others (2014) Quality in the GLIMS glacier database. In *Global Land Ice Measurements from Space*. Berlin: Springer-Praxis, pp. 163–182.

Raup B and 5 others (2007) The GLIMS geospatial glacier database: a new tool for studying glacier change. *Global and Planetary Change* **56**(1–2), 101–110. doi: 10.1016/j.gloplacha.2006.07.018

RGI Consortium (2017) Randolph Glacier Inventory – a dataset of global glacier outlines: version 6.0, technical report.

Seibert J, Vis MJP, Kohn I, Weiler M and Stahl K (2018) Technical note: representing glacier geometry changes in a semi-distributed hydrological model. *Hydrology and Earth System Sciences* **22**(4), 2211–2224. doi: 10.5194/hess-22-2211-2018

Seroussi H and 10 others (2020) ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere* **14**(9), 3033–3070.

Sevestre H and Benn DI (2015) Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging. *Journal of Glaciology* **61**(228), 646–662. doi: 10.3189/2015JoG14J136

Sigurdsson O and Williams RS (2008) *Geographic Names of Iceland's Glaciers: Historic and Modern*. Virginia, USA: USGS, Reston.

Thornton TF (2012) Haa Léelk'w Has Aaní Saax'ú: Our Grandparents' Names on the Land. Seattle: University of Washington Press, in association with the Sealaska Heritage Institute.

Vaughan DG and 13 others (2013) Observations: Cryosphere. Stocker, TF, and 9 others (eds.) Climate Change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 317–382.

WGMS (1989) World glacier inventory – status 1988. IAHS(ICSI)/UNEP/UNESCO, World Glacier Monitoring Service, Zurich, Switzerland.

WGMS (2021) *Fluctuations of Glaciers Database*. Zurich, Switzerland: World Glacier Monitoring Service. doi: 10.5904/wgms-fog-2021-05.

WGMS and NSIDC (2012) World Glacier Inventory. Compiled and made available by the World Glacier Monitoring Service, Zurich, Switzerland, and the National Snow and Ice Data Center, Boulder CO, USA. doi: 10.7265/N5/NSIDC-WGI-2012-02

Windnagel AK (2022) A summary of the global glacier landscape: the largest glaciers and glacier complexes in the 19 glacial regions of the world. NSIDC Special Report 23. National Snow and Ice Data Center, Boulder CO, USA. https://nsidc.org/sites/nsidc.org/files/technical-references/NSIDC-Special-Report-23.pdf

Windnagel AK and Zemp M (2022) *Largest Glaciers and Glacier Complexes in the World*. Boulder, Colorado, USA: NSIDC: National Snow and Ice Data Center. https://doi.org/10.7265/0k6 h-yn09.

Yang R, Hock R, Kang S, Shangguan D and Guo W (2020) Glacier mass and area changes on the Kenai Peninsula, Alaska, 1986–2016. *Journal of Glaciology* **66**(258), 603–617.

Zemp M and 10 others (2014) Global glacier monitoring – a long-term task integrating in situ observations and remote sensing. In Kargel JS, Leonard GJ, Bishop MP, Kääb A and Raup BH (eds), *Global Land Ice Measurements from Space*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–21. doi: 10.1007/978-3-540-79818-7

Zemp M and 14 others (2019) Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**(7752), 382–386. doi: 10.1038/s41586-019-1071-0

Zwally HJ, Giovinetto MB, Beckley MA and Saba JL (2012) Antarctic and Greenland drainage systems. Available at http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php.