On thin glacial ice: New Austrian Glacier Inventory shows accelerating glacier shrinkage and 31% area loss within two decades

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Abstract. We present the new Austrian glacier inventory, AGI 5. Glacier outlines were manually digitized from high-resolution orthoimagery and digital elevation models (DEM), using older inventory data as a baseline. The delineation of debris-covered ice was supported by visual analysis of multi-temporal imagery and DEM differencing, depending on data availability. We assessed discrepancies with older inventories and differences in interpretation between analysts using a round robin experiment

5   (mapping of selected glaciers by several analysts). The updated inventory reflects glacier extent in 2023 (55 % of total glacier area in the study region), 2022 (43 %), and 2021 (2 %). The total glacier area in AGI5 is 285 ± 12 km^2. Most glaciers in Austria (87 %) are smaller than 0.5 km^2. These "very small" glaciers comprise 22 % of the total glacier area. Nine glaciers remained larger than 5 km^2 and account for more than a quarter of Austria's glacierized area. Area losses since the previous inventory (2004-2012) amount to 129 ± 23 km^2, corresponding to 31% of the total glacier area. Median area loss rates differ

10   between regions, ranging from 2-3 % per year in more heavily glacierized regions to almost 7 % per year in regions with smaller glaciers. Of 894 glaciers listed in the previous inventory, 95 have disappeared completely or were no longer mappable. Compared to other glacierized regions, Austria's glacier recession since the Little Ice Age (LIA) maximum is well constrained with a LIA inventory, four high-resolution, consistent AGIs from 1969 to 2022/23, and additional coverage in complementary

inventories using different data sources. As glacier loss accelerates, more frequent updates to the AGIs are needed to keep pace

15 with rapid changes.

1   Introduction

Glaciers in the European Alps lost nearly 40 % of their mass between 2000 and 2023 (The GlaMBIE Team, 2025). During recent extreme years, in particular the record breaking summer of 2022, glaciers thinned across all elevation ranges and un-

20 precedented mass loss was recorded throughout the Alps (Berthier et al., 2024b; Voordendag et al., 2023; Hartl et al., 2025a; WGMS, 2025; van Tiel et al., 2026). Regional studies in Austria indicate the same trends, with the complete disappearance of several small glaciers since the mid-2000s, volume change patterns indicative of strong disequilibrium, and progressing disintegration processes of increasingly debris-covered glacier remnants (Kellerer-Pirklbauer and Kulmer, 2019; Fischer et al., 2021a; Hartl et al., 2022, 2025b; Conzelmann et al., 2026). Given the magnitude of the current changes, it is essential that local

25 and regional glacier monitoring continues to keep pace with ongoing ice loss.

Glacier inventories are an integral part of glacier monitoring (e.g., Paul et al., 2007; Zemp et al., 2014). Multi-temporal glacier outlines are an important prerequisite for assessing glacier volume and mass change, support assessments of the impacts of glacier shrinkage on local hydrological systems, runoff patterns, and natural hazards, aid the calibration and validation of glacier evolution models, and ultimately foster sustainable mountain development (Nussbaumer et al., 2017; Gärtner-Roer

30 et al., 2019). To maintain their usefulness for such applications, inventories need to be updated regularly. Paul et al. (2020) suggested decadal updates of global glacier inventories, noting that more frequent updates are required in regions with more rapid change, such as the European Alps. In Switzerland, Linsbauer et al. (2021) stated 6-year repeat inventories as a goal to appropriately monitor regional glacier area evolution.

In Austria, national-scale glacier inventories (AGI) were compiled for glacier state during the Little Ice Age maximum (AGI

35 LIA Fischer et al., 2015b), the late 1960s (AGI1 Patzelt, 1980; Groß, 1987), late 1990s (AGI2 Lambrecht and Kuhn, 2007), and the mid-2000s (AGI 3 Fischer et al., 2015b). The most recent glacier inventories covering all of Austria reflect glacier state in 2015-2016 (Buckel et al., 2018; Paul et al., 2020) but used differing methodological approaches compared to the earlier AGI. A comprehensive inventory update for glaciers in Austria is urgently needed to account for the rapid area losses and progressing glacier disappearance in recent years.

40 This study presents results of a community effort to compile a new Austrian Glacier Inventory along with area change metrics derived from the resulting dataset. The Fifth Austrian Glacier Inventory (AGI5) follows the approach of prior national inventories (AGI 1-3 Fischer et al., 2015b) and is based on manual mapping of glacier outlines from high-resolution orthoimagery and digital elevation models (DEM) derived from airborne laser scanning data. Most glaciers in Austria are small and many are fragmented, partially debris-covered, and no longer have persistent accumulation zones. Despite their relatively small size

45   and limited contribution to total glacier area, data on the distribution of such features provides important context for catchment scale applications related to, for example, hydrology, touristic infrastructure, cartography, or potential hazards (e.g., Intergovernmental Panel on Climate Change (IPCC), 2023; Van Tiel et al., 2021; Mani et al., 2023). In keeping with prior AGI and in contrast to, for example, the Swiss national glacier inventories and many larger-scale inventories (Linsbauer et al., 2021; Paul et al., 2020), we use the term "glacier" to refer to any glacial ice identified in the inventory, regardless of feature size or other

50   characteristics.

The aims of this study are to 1) delineate glacier ice in Austria for the target years 2022-2023 with the highest possible accuracy given the available source data, and to enable direct comparisons with prior AGIs by adhering to established ID-numbering systems and definitions 2) quantify glacier area changes in Austria since the last inventories 3) discuss the main challenges and sources of uncertainties in compiling regional inventories of rapidly receding mountain glaciers.

55   ## 2   Methods and data

2.1   Previous national and regional glacier inventories in Austria

Glaciers in Austria have been mapped at national and regional scales in various iterations. AGI LIA, 1, 2 and 3 contain glacier outlines derived from high-resolution (<1 m - 5 m) orthoimagery, DEMs, and moraine mapping. Refer to Table 1 for an overview of data sources and references. The exact inventory years of the AGIs vary regionally due to varying data

60   availability and survey dates. Naming conventions and the glacier numbering system were applied consistently across AGI1, 2 and 3. In AGI LIA, a "parent ID" system was applied that builds upon the AGI1 IDs and glacier names. In addition to the national inventories, regional GI for individual subregions (Stubai Alps, Ötztal Alps, Silvretta Group) and two Austrian federal provinces (Vorarlberg, Salzburg) were compiled in an approach consistent with prior AGI for varying time periods between 2008 and 2018 (Table 1).

65   The fourth national inventory (AGI4, Buckel and Otto, 2018) contains glacier outlines for 2015 and was compiled from Google Earth imagery. The AGI4 outlines show a slight spatial shift compared to AGI3 due to differences in the underlying source data and the attributes are not fully consistent with AGI3. Therefore, we used AGI3 rather than AGI4 as the baseline for the updated inventory presented in this study.

Austrian glaciers are also included in an Alpine-wide glacier inventory mapped from Sentinel-2 data (10 m resolution)

70   acquired in 2015 and 2016 (Paul et al., 2020) and in the Randolph Glacier Inventory (Pfeffer et al., 2014; RGI Consortium, 2023), which provides glacier outlines for the Alps based on Landsat 5 TM data (30 m resolution) from 2003. Unlike the AGI, the RGI and Paul et al. (2020) apply a minimum feature size of 0.01 km^2 to account for the limits of detection associated with the spatial resolution of the source data (e.g., Paul et al., 2009), and some outlines deviate from the AGI due to the treatment of national borders and slightly differing delineations of drainage basins. Three additional Alps-wide inventories were generated

75   based on the RGI, using Landsat data for 1999–2001 (L5 TM, L7 ETM+), 2011 (L5 TM), and 2013–2015 (L8 OLI) by Sommer et al. (2020).

Table 1. Overview of inventories covering Austria's glaciers at global, Alps-wide, national or regional level.

Name	Inventory Year	Data basis	Coverage	References
AGI LIA	1850	Moraines, historical data	Austria	Fischer et al. (2015b); Groß and Patzelt (2015)
AGI 1	1969	Orthoimagery, DEMs	Austria	Patzelt (1980); Groß (1987); Patzelt (2015)
AGI 2	1996-2002	Orthoimagery, DEMs	Austria	Eder et al. (2000); Lambrecht and Kuhn (2007); Kuhn et al. (2015)
Sommer 2000	1999-2001	L5 TM, L7 ETM+	Alps	Sommer et al. (2020)
RGI	2003	L5 TM	Alps	Paul et al. (2011); Pfeffer et al. (2014); RGI Consortium (2023)
AGI 3	2004-2012	Orthoimagery, DEMs	Austria	Fischer et al. (2015b, a)
Sommer 2011	2011	L5 TM	Alps	Sommer et al. (2020)
Sommer 2014	2013-2015	L8 OLI	Alps	Sommer et al. (2020)
AGI 4	2015	Google Earth Imagery	Austria	Buckel et al. (2018); Buckel and Otto (2018)
Paul 2020	2015-2016	Sentinel-2I	Alps	Paul et al. (2020)
Salzburg	2008-2018	Orthoimagery, DEMs	Federal Province (Austria)	Bertolotti et al. (2025)
Vorarlberg	2017, 2020, 2021, 2022, 2023	Orthoimagery, DEMs	Federal Province (Austria)	Conzelmann et al. (2026); Conzelmann et al. (2026)
Stubai Alps	2017-2018	Orthoimagery, DEMs	Subregion (Austria)	Helfricht et al. (2024b)
Ötztal Alps	2017	Orthoimagery, DEMs	Subregion (Austria)	Helfricht et al. (2024a)
Silvretta Group	2017	Orthoimagery, DEMs	Subregion (Austria)	Fischer et al. (2021b)
AGI 5	2021-2023	Orthoimagery, DEMs	Austria	This study

2.2 Compilation of the fifth Austrian Glacier Inventory (AGI5)

Efforts to compile a new national glacier inventory, AGI5, evolved from discussions within the Austrian glacier monitoring community and were implemented by the same community. In keeping with the prior AGIs, glaciers were grouped by mountain
80 ranges into 20 inventory subregions (Fig. 1), which were assigned to analysts or groups of analysts for outline mapping. Where possible, the mapping of a given subregion was carried out by analysts who were involved in the prior AGIs for that region and/or otherwise familiar with the area.

AGI5 follows the naming conventions and ID number system of AGI1, 2 and 3 (Table 1). An ID number can be associated with multiple separate glacier fragments if the fragments were previously connected and listed under the same ID. In the
85 following, "glacier" refers to all glacier fragments associated with the same ID even if they are no longer connected. This is in line with the approach of the prior AGIs and allows consistent counting of glaciers (the overall number of glaciers does not increase if a glacier splits into two fragments) and per-glacier area change assessments through the AGI time series.
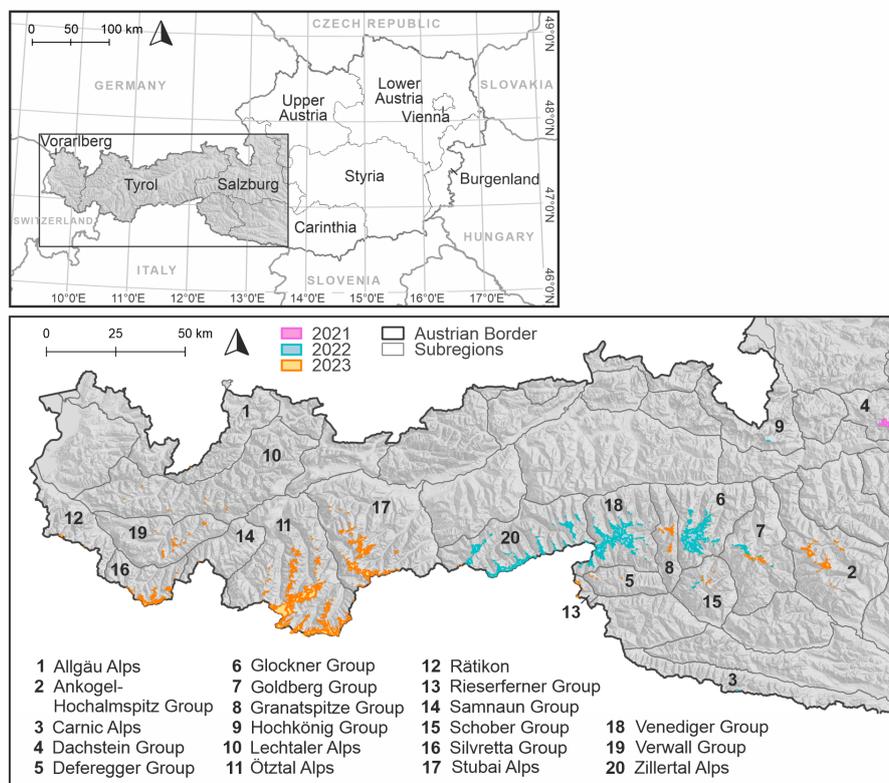

Figure 1. Location of the 20 subregions and glacierized terrain in Austria. Colors indicate acquisition years of the AGI5 source data for the respective glaciers and regions. Background terrain map: Government of Austria (CC BY-SA 2.0 AU), data.bev.gv.at

2.2.1   Data basis and general mapping procedure

Glacier outlines were mapped manually using GIS programs. The AGI3 outlines and, where available, consistent intermediate
90   regional inventories (Table 1) were used as a starting point for the new outlines. The primary data type used for the mapping
process was high-resolution regional orthoimagery (spatial resolution: 10-25 cm). Where available, high-resolution DEMs
(0.5-1 m) and derived products (hillshades from different illumination angles, elevation change rasters) were used as supporting
information or instead of orthophotos depending on data coverage. The georeferenced aerial imagery and DEMs were accessed
through governmental open data services. The DEMs are derived from airborne laserscanning surveys and provided by Austrian
95   regional authorities. High-resolution satellite imagery (Pleiades images, 0.5 m; Planet Labs, 3 m (PBC, 2022)) was used in
some cases to compensate for image quality issues in the orthophotos related to snow cover or shading. Refer to Table 2 for an
overview of the main data sources and acquisition years per subregion.

Data availability and acquisition years vary between subregions and Austrian federal provinces. The target year for AGI5
glacier outlines was 2023. Data acquired in 2021 or 2022 was used if no suitable coverage for 2023 was available. Outlines for
100   2023 were produced for 60 % of glaciers in the study region (55 % of total glacier area). Outlines for 2022 were produced for
39 % of glaciers (43 % of total area). The remaining 1 % of glaciers (2 % of area) were mapped with data acquired in 2021.
For the glaciers in the federal province of Vorarlberg, outlines for 2023 produced for a province-level inventory (Conzelmann
et al., 2026) were incorporated into AGI5.

About 95 % of total glacier area in the study region was mapped using primarily aerial images. The remaining area was
105   mapped mainly based on DEM derived products (hillshades, difference rasters; approx. 4 % of area), or high resolution satellite
imagery (1 % of area), typically with orthophotos as auxiliary data. In most cases, analysts reported using more than one data
type. This mainly refers to using hillshades or elevation change rasters in combination with aerial or satellite imagery, using
satellite imagery instead of orthophotos if snow conditions were more favourable in the former, or using imagery from multiple
years to assess glacier evolution (e.g., Fig. 2). As a general guideline and following the approach of AGI3, analysts were asked
110   to use a maximum zoom scale of 1:3000 in both aerial imagery and DEM derivatives as a starting point for mapping. Most
analysts mentioned using a higher zoom level for very small features and cases they considered challenging. Fig. 2 shows
examples of the different available data types for Großelend Kees in the Ankogel-Hochalmspitze Group and Nördlicher Schalf
Ferner in the Ötztal Alps. Großelend Kees (Fig. 2a-d) was mapped using mainly information derived from a 2023 DEM,
whereas Nördlicher Schalf Ferner (Fig. 2e-h) was mapped based on multi-temporal orthoimagery.

115   Information from field surveys of the glacier margins and relevant local knowledge was incorporated at the discretion of
the analysts. Such terrain knowledge was available mainly for glaciers with in situ monitoring programs and a subregion of
the Ötztal Alps where an analyst documented debris-covered ice outside of older AGI outlines during site visits over multiple
years.

Table 2: Main data sources for the 20 subregions of AGI5

Region	Federal Province	Main data source	Additional data
Allgäu Alps	Tyrol	Orthoimagery Province of Tyrol (2023)[1]	-
Ankogel –Hochalm- spitze Group	Salzburg, Carinthia	Lidar DEM Hillshade Province of Salzburg (2023)[3]; Carinthia (2023)[4]	DoD (Difference of DEMs) (2023-2010); Planet Scope Orthoimagery (2023), Orthoimagery Province of Salzburg[3]; Carinthia[3] (2021; 2022)
Carnic Alps	Carinthia	Lidar DEM Hillshade Province of Carinthia (2022)[4]	Orthoimagery Province of Carinthia[4] (2021); Planet Scope Orthoimagery (2023)
Dachstein Group	Salzburg, Upper Austria, Styria	Orthoimagery provided by BEV[2] for Salzburg (2021); Upper Austria (2021); Styria (2021)	Orthoimagery provided by BEV[2] for Salzburg; Upper Austria; Styria for 2022 and 2024; Lidar DEM Hillshade provided by BEV[2] for Salzburg; Upper Austria; Styria
Deferegger Group	Tyrol	Orthoimagery Province of Tyrol (2023)[1]	-
Glockner Group	Salzburg, Tyrol, Carinthia	Orthoimagery provided by BEV[2] for Tyrol (2022); Carinthia (2022); Orthoimagery Province of Salzburg (2022)	Pléiades Orthoimagery (2022), Planet Scope Orthoimagery (2023); DEM (2023) provided by BEV[2] for Salzburg; Tyrol; Carinthia; Hillshade (2023); DoD (2023-2009)
Goldberg Group (Sonnblick Group)	Salzburg, Carinthia	UAV Orthoimagery from Geosphere Austria (2023), Lidar DEM Hillshade Province of Salzburg (2022, 2023)[3], Orthoimagery Province of Salzburg (2022, 2023)[3]; Province of Carinthia(2022)[4]	Lidar DEM Hillshade Province of Salzburg (2022, 2023)[3]; UAV Orthoimagery and Hillshade from Geosphere Austria (2023); Orthoimagery Province of Salzburg (2022, 2023)[3]; Province of Carinthia(2022)[4]
Granatspitze Group	Salzburg, Tyrol	DEM/ Hillshade Province of Salzburg (2023)[3]; Tyrol (2023)[1]	Orthoimagery Province of Tyrol[1]; Salzburg[3] (2022)

Hochkönig Group (Salzburg Limestone Alps)	Salzburg	Orthoimagery from Planet Labs: Satellite Imagery and Earth Data Analytics (2022)	Orthoimagery Province of Salzburg[3] (2022)
Lechtaler Alps	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol (2023)[1]; Vorarlberg (2023)[5]	Orthoimagery from 2009-2016; Lidar DEM and Hillshade Province of Tyrol[1]; Vorarlberg[5]; DoD (2027-2023)
Ötztal Alps	Tyrol	Orthoimagery Province of Tyrol (2023)[1]	In situ knowledge for individual glaciers; Orthoimagery Province of Tyrol[1] for previous years; DEM Province of Tyrol[1]; Pleiades DoD (2017-2022 Berthier et al., 2024a)
Rätikon	Vorarlberg	Orthoimagery Province of Vorarlberg (2023)[5]	Lidar DEM and Hillshade Province of Vorarlberg[5]; DoD (2017-2023)
Rieserferner Group	Tyrol	DEM Hillshade Province of Tyrol (2023)[1]	Orthoimagery Province of Tyrol[1] (2021)
Samnaun Group	Tyrol	Orthoimagery Province of Tyrol (2023)[1]	Hillshade Province of Tyrol[1] (2018)
Schober Group	Tyrol, Carinthia	DEM Hillshade Province of Tyrol (2022)[1], Province of Carinthia (2023)[4]	Orthoimagery Province of Tyrol[1] (2021)
Silvretta Group	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol (2023)[1]; Vorarlberg (2023)[5]	Lidar DEM and Hillshade Province of Vorarlberg[5]; DoD (2017-2023) Orthoimagery Province of Tyrol[1] for previous years; DEM Province of Tyrol[1] (2018)
Stubai Alps	Tyrol	Orthoimagery Province of Tyrol (2023)[1]	ALS DEM Province of Tyrol[1] (2017/18); Orthoimagery Province of Tyrol[1] for previous years; DoD (2006-2017/18)
Venediger Group	Salzburg, Tyrol	Orthoimagery Province of Tyrol (2022)[1]; Salzburg (2022)[3]	Planet Scope Orthoimagery (2024); DoD (2012-2023), Hillshade and DEM Province of Tyrol[1]; Salzburg[3] (2023)

Verwall Group	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol[1] (2023); Vorarlberg (2023)[5]	Lidar DEM and Hillshade Province of Vorarlberg5; DoD (2017-2023); Orthoimagery Province of Tyrol[1] for previous years
Zillertal Alps	Tyrol, Salzburg	Orthoimagery Province of Tyrol[1] (2022, 2023); Salzburg (2022)[3]	Hillshade Province of Tyrol[1] (2021)

1 Federal Province of Tirol: Land Tirol - data.tirol.gv.at; 2 BEV: Federal Office of Metrology and Surveying - data.bev.gv.at; 3 Federal Province of Salzburg - salzburg.gv.at; 4 Federal Province of Carinthia - kagis.ktn.gv.at

2.2.2 Metadata and quality metrics

120 For each glacier ID and corresponding outline, the AGI5 attribute tables list information related to the source data (acquisition date, data type, image identifiers). Categorical flags indicating potentially detrimental image characteristics (e.g., snow cover or shadows), a qualitative level of uncertainty of the outline, and general scores for debris cover and visible crevasses were also recorded (Tab. 3). An additional attribute flag indicates cases where AGI5 outlines overlap with the outlines of the most recent Austrian Rock Glacier Inventory (ROGI, Wagner et al., 2020).

125 The AGI5 attribute table further contains the area of each glacier, the number of fragments per glacier, and elevation statistics. Minimum, maximum, and median elevation of all pixels within a given outline were extracted from a 10 m x 10 m resolution DEM provided by the Austrian Federal Office of Metrology and Surveying (BEV). This DEM is a resampled product from original high-resolution DEM data (0.5 - 1 m) derived from airborne laserscanning produced for the individual provinces of Austria. It includes data from different undisclosed epochs around 2015 and is available through the Austrian open government 130 data platform (Geoland.at, 2015).

2.2.3 Vanishing glaciers

In keeping with the previous AGI, no minimum size threshold for glaciers or fragments of glaciers was applied in AGI5. Analysts were asked to map the remaining glacial ice patches in their subregions to the best of their abilities regardless of feature size. Experience with recent regional inventories showed that very small, highly debris-covered features can be difficult 135 to map even with very high-resolution imagery and auxiliary DEM-derived information (Fischer et al., 2021a; Conzelmann et al., 2026). To account for this, analysts had the option to flag glaciers or glacier fragments that they considered impossible to map but assumed may still contain ice as "vanishing features". For these features, no new outline was mapped and the AGI3 centroid coordinates were recorded.

Two possibilities for further handling of such "vanishing features" were incorporated in the processing workflow:

140 – Case 1: A single glacier ID was associated only with "vanishing features". That is, there were no longer any "mappable" fragments of a given glacier but it was assumed that ice may still be present, for example under debris cover. In this case,
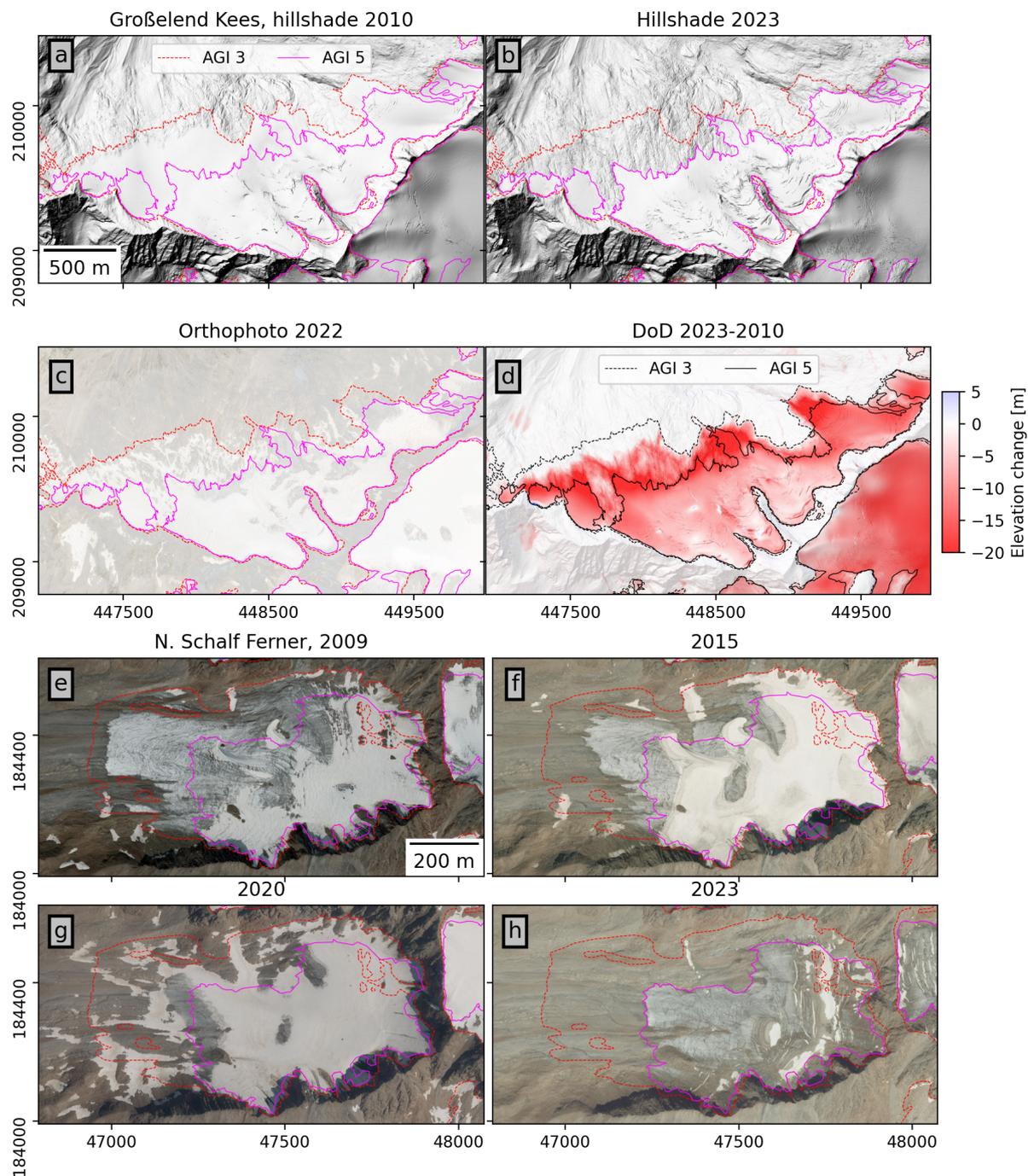
Figure 2. a, b: Großelend Kees (Ankogel-Hochalmspitz Group) as seen in hillshades generated from 2010 and 2023 DEMs (August 2010 and September 2023; Province of Carinthia, CC BY 4.0) c) Großelend Kees in a 2022 orthophoto (June 19, 2022; Province of Carinthia, CC BY 4.0) d) Großelend Kees elevation change 2023-2010. e-f: Multitemporal orthophotos of Nördlicher Schalf Ferner (Ötztal Alps; 3. August 2015, 28. July 2020, 19. August 2023; Province of Tyrol; CC BY 4.0 AT). a-d: EPSG: 31258; e-f: EPSG: 31287. Grid in meters.

Table 3. Categorical scores included in the data attributes of each AGI5 glacier outline, indicating potential image quality issues, estimated outline quality, debris cover, the presence of crevasses, and overlap with a nation-wide rock glacier inventory (Wagner et al., 2020). A full list of attributes is provided in the supplement.

Image quality flag	Categorical value indicating whether snow, shading, or image errors/artifacts affect outline mapping
0 ("good")	No snow cover and no shading over any part of the glacier, no relevant image errors/artifacts.
1 ("medium")	Snow cover and shading allow mapping but parts of the feature are affected by shadows, snow, or image errors/artifacts.
2 ("poor")	Snow cover, shading, or image errors/artifacts do not allow good confidence assessment of the glacier outline.
Outline quality flag	Categorical value indicating issues not related to the quality of the images that affect outline mapping, typically related to debris cover over very small features
0 ("good")	The outline of the feature can generally be mapped with good confidence (e.g., debris cover may be present in some parts but does not substantially obscure the feature boundary, or the boundary can be determined despite debris cover)
1 ("medium")	Some fragments of the feature (single polygons with the same id number) cannot be mapped with confidence (e.g., debris cover obscures part of the boundary)
2 ("uncertain")	The entire feature (all polygons associated with the id number) cannot be mapped with confidence (e.g., fully debris-covered or otherwise obscured boundary)
3 ("very uncertain")	Very high uncertainty: the feature probably still contains some ice (e.g. a small ice body under debris cover) but it is not possible to determine this with certainty and the extent of the feature cannot be mapped with confidence
Debris flag	Categorical value to approximately indicate the amount of debris cover
0	no debris cover (usage: no continuous debris cover on any part of the glacier. Individual rocks are not considered debris cover)
1	partial debris cover (for example: sections of the terminus are debris-covered)
2	mostly debris-covered (most of the feature is debris-covered)
3	fully debris-covered (the entire feature is debris-covered)
4	not possible to determine (e.g. due to snow cover)
Crevasse flag	categorical value to indicate whether there are visible crevasses
0	no visible crevasses
1	visible crevasses
2	not possible to determine (e.g., due to snow cover)
ROGI	indicates overlap of the feature with the rock glacier inventory
0	no overlap
1	up to 20 % of the feature area overlaps with a feature in the rock glacier inventory
2	more than 20 % of the feature area overlaps with a feature in the rock glacier inventory

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the respective glacier was considered a "vanishing glacier" close to disappearance. As the outlines of these features are not mappable with the given source data, they were not included in the main inventory dataset. Centroid coordinates are provided in a separate file.

145   – Case 2: A glacier ID was associated with fragments that could still be mapped as well as "vanishing fragments", which may still contain ice but could not be outlined. In such cases, the outlines of the remaining "mappable" fragments were included in the inventory dataset and the possible existence of "vanishing fragments" was flagged in the dataset attribute table.

Analysts categorized glaciers as "vanished" if they found no evidence of remaining ice within the previous glacier outline. We
150 acknowledge that the distinction between "vanished" and "vanishing" is not always clearcut and categorization as one or the other can depend on the data type available for mapping and the subjective interpretation of the analyst. The decision to include a "vanishing" category was based on feedback by analysts, who indicated that uncertainties in mapping the outlines of very small, debris-covered features can effectively be as large as the remaining area of said features. Hence, attempting to map the outlines of such features does not result in an improved estimate of overall glacier area.

155   The centroid coordinates of the glaciers that were categorized as "vanishing" or "vanished" are provided as an extra file in the AGI5 dataset publication and the two categories can be distinguished in the data file based on the attributes. To improve the readability of this manuscript, we refer to both categories as "vanishing" in the following.

2.2.4   Treatment of errors in prior outlines

In some cases, analysts found that the imagery and data used to delineate AGI5 outlines showed ice where none was mapped
160 in prior outlines, resulting in local increases of mapped glacier area. Such increases do not represent actual glacier growth but are due to varying image quality, snow cover, and/or differences in interpretation between analysts. It is assumed that these kinds of discrepancies are inevitable given the varying quality of the source data and uncertainties inherent to the method (e.g., Kellerer-Pirklbauer et al., 2005; Fischer et al., 2014, 2021a; Strudl, 2024; Conzelmann et al., 2026). The prior outlines were not modified in these instances.

165   The AGI5 mapping process also revealed several errors in prior inventory attributes, mainly related to wrongly assigned or mistyped ID numbers. Corrections for these cases were issued as updates to the existing AGI3 data publication (Fischer et al., 2015a). For AGI1 and AGI2, any identified inconsistencies in ID-numbering were adjusted to match AGI3 for the change assessment analysis presented in this study. These cases were not corrected in the respective published datasets.

2.3   Special cases

170   ### 2.3.1   Glacier ski resorts

The study region contains nine ski resorts located in glacierized terrain. The resorts apply white reflective coverings to locally reduce melt and preserve particular patches of ice and snow relevant to resort operations (e.g., for snow storage or to maintain

lift tracks, see examples in Fig. 3). Such patches of covered ice and snow were included in the outline mapping if they were connected to a remaining uncovered feature. Covered patches not connected to uncovered ice were not included. The overall
175 area of glacier ice covered in this manner is negligible (<0.2 % of total area), but there are noticeable impacts locally where coverings were placed near the glacier margins (Fig. 3b, d).

2.3.2 Ice divides and country borders

We maintained the AGI3 ice divides in AGI5 to enable consistent area change assessments and due to the challenges associated with accurately determining the current location of the divides. The ice divides were initially defined for AGI1 (Patzelt, 1980;
180 Groß, 1987) and largely applied in the same way in AGI2 and AGI3. We note that the true location of the ice divides may have shifted since AGI1 due to ice losses.

Some of the glaciers in the study region border on neighboring glaciers in Italy. Country borders along the main chain of the Alps are generally defined based on drainage divides. That is, the country border mostly follows the ice divides in the glacierized regions of the Ötztal, Stubai, and Zillertal Alps. Regulatory texts defining the border between Italy and Austria
185 have been updated to reflect that ice divides and, hence, borders may change due to glacier recession.

For the practical purposes of AGI5, we consider the country border to be equivalent to the ice divides as defined in AGI1. The main exceptions to this are Hochjoch Ferner and Niederjoch Ferner in the Ötztal Alps. Here, the country border locally deviates from the drainage divides and the glaciers extend across the border. For consistency with AGI3, we continue to include the Italian parts of the respective glaciers in AGI5.

190 ## 2.4 Area uncertainty estimation

Mapping glacier outlines is subject to various sources of uncertainty, which result in uncertainties in the derived glacier area. Building on approaches by previous studies (Abermann et al., 2010; Fischer et al., 2015b; Conzelmann et al., 2026), we applied different area uncertainty estimates to glaciers of different size classes and outline quality categories. Regional uncertainty values were calculated as the sum of the individual glacier uncertainties (that is, uncertainties always cumulate), in keeping
195 with AGI3 (Fischer et al., 2015b).

The relative uncertainties based on glacier size categories correspond to uncertainties applied by Conzelmann et al. (2026), who used uncertainties determined by Abermann et al. (2010) as a starting point for their assessment (±1.5 % for glaciers larger than 1 km^2, ±5 % for smaller glaciers). The values of Abermann et al. (2010) were also applied in the uncertainty estimates of AGI3 (Fischer et al., 2015b). However, Conzelmann et al. (2026) found higher uncertainties for very small, highly debris-
200 covered features based on multi-analyst mapping comparisons (referred to as "Round-Robin" experiments in the following), similar to the results of Paul et al. (2013). Accordingly, they adjusted the uncertainty estimates of Abermann et al. (2010), adding smaller size categories with higher relative uncertainties (±10 % and ±25 % for features smaller than 0.1 km^2 and 0.05 km^2, respectively). We used the same approach for AGI5 and additionally accounted for cases flagged by the analysts as highly uncertain by incorporating the outline quality attribute.
205 For outline quality 0 or 1 ("good" and "medium"), relative area uncertainties were assigned solely based on size categories:
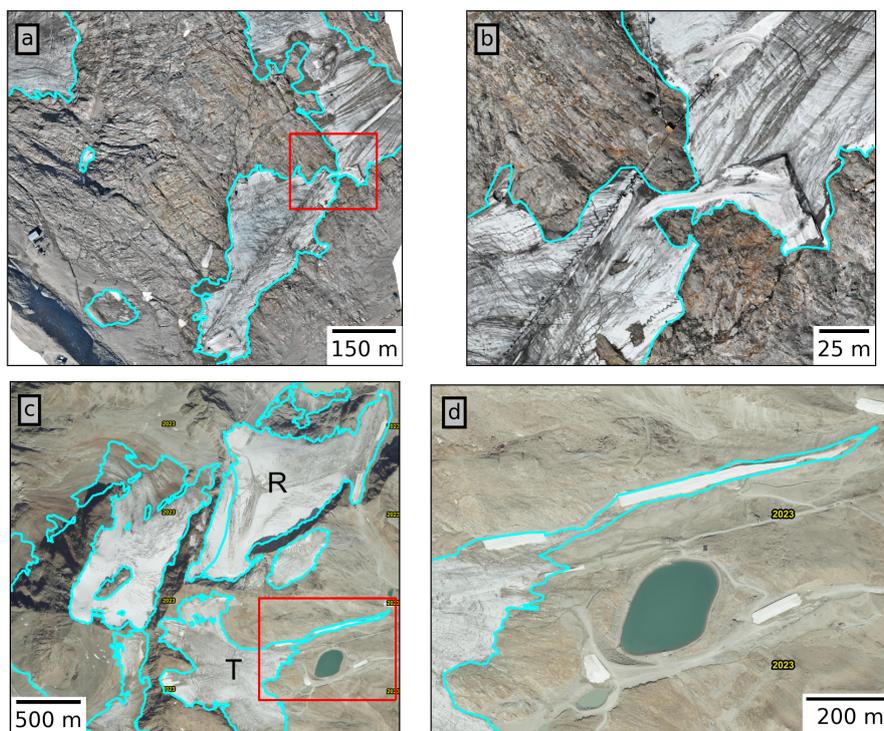
Figure 3. a: Wurtenkees in the Goldberg Group with the Mölltaler Gletscher ski resort (Carinthia). The red box marks the subset shown in b. b: Zoomed in view of Wurtenkees; reflective coverings are applied to reduce ice melt in this sector in the vicinity of resort infrastructure. c: The ski resort of Sölden (Tyrol) maintains infrastructure and ski runs on glacierized terrain in the central Ötztal Alps, mainly on Tiefenbach Ferner (T) and Rettenbach Ferner (R). The red box marks the subset shown in d. d: Reflective coverings on the terminus of Tiefenbach Ferner. Background image a, b: 2023 UAV orthophoto, courtesy of Geosphere Austria. c, d: 2023 orthophoto mosaic, Province of Tyrol (CC BY 4.0 AT)

- Glacier area > 1 km^2: ±1.5 %

- Glacier area 0.1 km^2 - 1 km^2 : ±5 %

- Glacier area 0.05 km^2 - 0.1 km^2 : ±10 %

- Glacier area < 0.05 km^2: ±25 %

210 For outline quality 2 and 3 ("uncertain", "very uncertain") the following relative uncertainties were applied regardless of glacier size:

- Outline quality 2: ±25 %

- Outline quality 3: ±50 %

To assess differences in interpretation between analysts and enable comparisons of uncertainty estimates between AGI5 and
215 similar studies, we carried out a Round-Robin (RR) experiment. The outlines of six glaciers of different sizes and characteristics
were digitized independently by 15 analysts using the AGI5 imagery and the AGI3 outlines as a starting point. The selection
of glaciers for the RR reflects the abundance of small (<1 km^2) and very small (<0.5 km^2) glaciers in the study region and
intentionally included cases that were considered challenging due to debris cover, vanishing status, and discrepancies between
AGI3 and AGI5. Refer to Section 1 of the supplementary material for figures showing the RR glaciers.

220 The outlines generated in the RR experiment enable an alternative approach to uncertainty estimation similar to the "buffer
method" applied by, e.g., Granshaw and Fountain (2006); Bolch et al. (2010); Mölg et al. (2018); Paul et al. (2020), in which
glacier area is computed with buffers of varying sizes applied to the outlines to obtain a likely area range. In large-scale
inventories derived from 10 m to 30 m resolution satellite imagery, typical buffer sizes are in the range of 0.5 pixels for clean
ice and 1 to 2 pixels for debris-covered ice (e.g., Mölg et al., 2018; Paul et al., 2020). We explored how well the AGI5 RR
225 outlines are aligned by determining the fraction of outlines that fall within a set of buffers (±2 m, ±2-5 m, ±5-10 m, ±10-20
m, ±20-40 m, . . .) around the main AGI5 outline (supplement Section S2). This yields a buffer distance for clean ice glacier
margins with a derived range of likely glacier area, and a larger buffer and area range for debris-covered margins. We applied
the smaller buffer (±2 m) to glaciers with low debris cover scores (0 or 1, Tab. 3) and the larger buffer (±20 m) to mostly or
fully debris-covered glaciers (debris score 2 or higher, Tab. 3) to generate an alternative area uncertainty estimate.

230 In a separate experiment, we additionally compared two sets of outlines (A, B) for a subset of glaciers in the Ötztal Alps.
Outline dataset A was mapped based on aerial imagery and extensive local terrain knowledge, whereas dataset B was mapped
exclusively from aerial imagery by analysts without detailed field experience at these sites. Statistics computed from the
comparison of these datasets serve as a first-order assessment of potential biases in identification of debris-covered ice without
ground truth (e.g., Racoviteanu et al, 2009, Paul et al. 2013).

2.5 Change analysis

Area change since AGI3 was assessed for all glaciers in the study region. Average annual change rates were computed for
each glacier based on the ID numbering system of the AGIs, and for the 20 subregions of the inventory. To account for the
variability in inventory years in both AGI3 and AGI5, change rates were computed on a per-glacier basis and regional values
are given as the median change rate of the sample. Vanishing glaciers were included in the change analysis with an area of zero
240 in 2023 (AGI5). That is, a "vanishing year" of 2023 was assumed for the computation. The true vanishing years are generally
not known. Uncertainties in area change were computed as the sum of the respective AGI3 and AGI5 uncertainties.

In subregions where regional inventories represent a consistent intermediate time step between AGI3 and AGI5, additional
change rates for individual glaciers were computed. This refers to the province-level inventories of Vorarlberg and Salzburg,
and regional inventories for the Silvretta Group, and the Ötztal and Stubai Alps (Tab. 1).

245 Per-glacier change rates for AGI1 and AGI2 were computed to present a complete overview of the AGI time series. Regional
glacier area change since 1850 was assessed for the subregions contained in all AGIs (some of the smaller regions were omitted
in AGI LIA and AGI1).

3 Results

3.1 Glacier distribution in the Austrian Alps

250 The updated inventory (AGI5) contains 799 glaciers covering a total area of 285 ± 12 km^2. Five subregions contain 88 % of Austria's glacier area, namely the Ötztal Alps (35 %), the Venediger Group (18 %), the Glockner Group (14 %), the Stubai Alps (11 %), and the Zillertal Alps (10 %, Tab. 4). Most glaciers in Austria (87 %) are smaller than 0.5 km^2. These "very small" glaciers (Huss and Fischer, 2016) comprise 22 % of the total glacier area (Fig. 4a, b). Ten glaciers are larger than 4 km^2 in AGI5 and account for more than a quarter of Austria's glacier-covered area (Fig. 4c). Most of the glacier area is located

255 between about 2800 and 3200 m a.s.l. (60 % of total area ; Fig. 5a). The AGI5 glacier area extends from a minimum altitude of 1880 m.a.s.l. (Boggenei Kees, Glockner Group) to a maximum altitude of 3755 m (Rofenkar Ferner, Ötztal Alps).

Analysts identified 82 completely debris-covered glaciers, and an additional 158 glaciers were classified as "mostly" debris-covered (Tab. 3). These glaciers comprised about 1 % and 4 % of the total glacier area, respectively. The fully and mostly debris-covered glaciers are substantially smaller on average (median area 0.02 and 0.04 km^2, respectively) than the glaciers

260 with no or only partial debris cover (median area 0.08 and 0.10 km^2, respectively; supplementary Table S2). Crevasses were visible on 404 glaciers. These glaciers are roughly an order of magnitude larger (median area 0.19 km^2) than glaciers without visible crevasses (363 glaciers, median area 0.02 km^2).

Image quality was mostly considered "good" or "medium", indicating that snow and shadows caused only minor issues in the mapping process (see flag descriptions in Tab. 3; supplementary Fig. S11). About a third of all glaciers (32 %) in the study

265 region were classified as "uncertain" or "very uncertain", mainly due to debris cover (outline quality 2 and 3, Tab. 3). These glaciers accounted for 5 % of the total glacier area (supplementary Tab. S2).

3.2 Glacier area change since AGI3

The new glacier inventory (AGI5) indicates a reduction of glacier area in the Austrian Alps by -129 ± 23 km^2 compared to AGI3. This corresponds to an area loss of 31 % (relative to AGI3) within a period of about 15 years (area weighted inventory

270 year for AGI3: 2007.5; AGI5: 2022.5), or roughly 2.1 % yr^{-1}. The median per-glacier area loss rate is 3.4 % % yr^{-1} (Tab. 4). 72 % of area loss occurred in an altitudinal range between 2500 and 3000 m. Altitudes above 3000 m contributed 22 % of area loss (Fig. 5a).

Regionally, the greatest absolute losses since AGI3 occurred in the Ötztal Alps with -37.5 ± 7.1 km^2 followed by the Stubai Alps with -19.0 ± 3.0 km^2. In relative terms, two regions (Hochkönig Group and Rätikon) lost over 80 % of their AGI3 area.

275 This amounts to absolute losses of 0.96 ± 0.08 km^2 and 1.25 ± 0.04 km^2, respectively. An additional six regions lost more than 50 % of their AGI3 area (Schober Group, Samnaun Group, Allgäu Alps, Rieserferner Group, Deferegger Group, Granatspitz Group; Fig. 5b, Tab. 4). One region (Carnic Alps) showed a slight area increase (Fig. 5b). This region consists of a single glacier (Eiskar Ferner, 0.126 ± 0.006 km^2 in AGI5, 0.093 ± 0.005 km^2 in AGI3). The positive area change here is due to differences in interpretation of debris-covered areas in the AGI3 and AGI5 outlines and does not represent actual glacier growth.

Table 4. Glacier area mapped in AGI5 by region in km^2 and as a percentage of total area. Percentage change refers to the difference in area between AGI5 and AGI3 relative to AGI3 total area. Loss rates were computed per glacier and the median value is reported for each region. The number of glaciers in AGI5 is exclusive of the vanished and vanishing features.

| Region	Glacier area (km^2)	Percent of total area (%)	Area loss (km^2)	Percentage loss (%)	Loss rate (% yr^{-1})	Number of glaciers	Number of vanishing glaciers	AGI3 outline years	AGI5 outline years
Ötztal Alps	99.812±3.821	34.96	-37.54±7.067	-27.3	-2.5	185	20	2006	2023
Venediger Group	51.591±1.454	18.07	-17.67±2.951	-25.5	-3.3	88	11	2007-2009	2022
Glockner Group	41.246±1.331	14.45	-10.39±2.577	-20.1	-3.2	74	4	2009	2022
Stubai Alps	30.108±1.454	10.55	-19.03±2.959	-38.7	-3.4	108	9	2006	2023
Zillertal Alps	28.346±1.518	9.93	-16.85±2.93	-37.3	-5.3	126	10	2007-2011	2022-2023
Silvretta Group	10.606±0.504	3.72	-7.87±1.101	-42.6	-3.2	40	5	2004-2006	2023
Ankogel Group	7.127±0.293	2.50	-4.79±0.639	-40.2	-4.6	43	1	2009	2023
Dachstein	4.439±0.379	1.55	-0.64±0.493	-12.5	-2.0	8	0	2012	2021
Goldberg Group	4.403±0.34	1.54	-3.49±0.735	-44.2	-3.7	30	0	2009	2022-2023
Granatspitz Group	2.727±0.314	0.96	-2.75±0.545	-50.2	-3.9	23	7	2009	2023
Verwall Group	2.148±0.264	0.75	-1.93±0.468	-47.3	-2.6	27	8	2006	2023
Rieserferner Group	1.18±0.072	0.41	-1.56±0.167	-57.0	-6.9	5	5	2009	2023
Schober Group	0.629±0.095	0.22	-1.94±0.223	-75.5	-5.8	16	10	2007-2009	2022-2023
Lechtaler Alps	0.315±0.087	0.11	-0.27±0.116	-46.1	-2.5	11	3	2006	2023
Rätikon	0.303±0.017	0.11	-1.25±0.042	-80.50	-4.7	2	0	2006	2023
Hochkönig Group	0.2±0.019	0.07	-0.96±0.077	-82.8	-6.6	2	1	2009	2022
Deferegger Group	0.142±0.065	0.05	-0.16±0.08	-53.0	-3.3	6	1	2009	2023
Carnic Alps	0.126±0.006	0.04	0.03±0.011	35.70	2.7	1	0	2009	2022
Allgäu Alps	0.02±0.005	0.01	-0.05±0.008	-69.50	-4.1	1	0	2006	2023
Samnaun Group	0.018±0.008	0.01	-0.05±0.011	-73.50	-3.2	3	0	2006	2023
Total	285.486± 12.046	100	-129.162±23.2	-31.15	-3.4	799	95	2004-2012	2021-2023
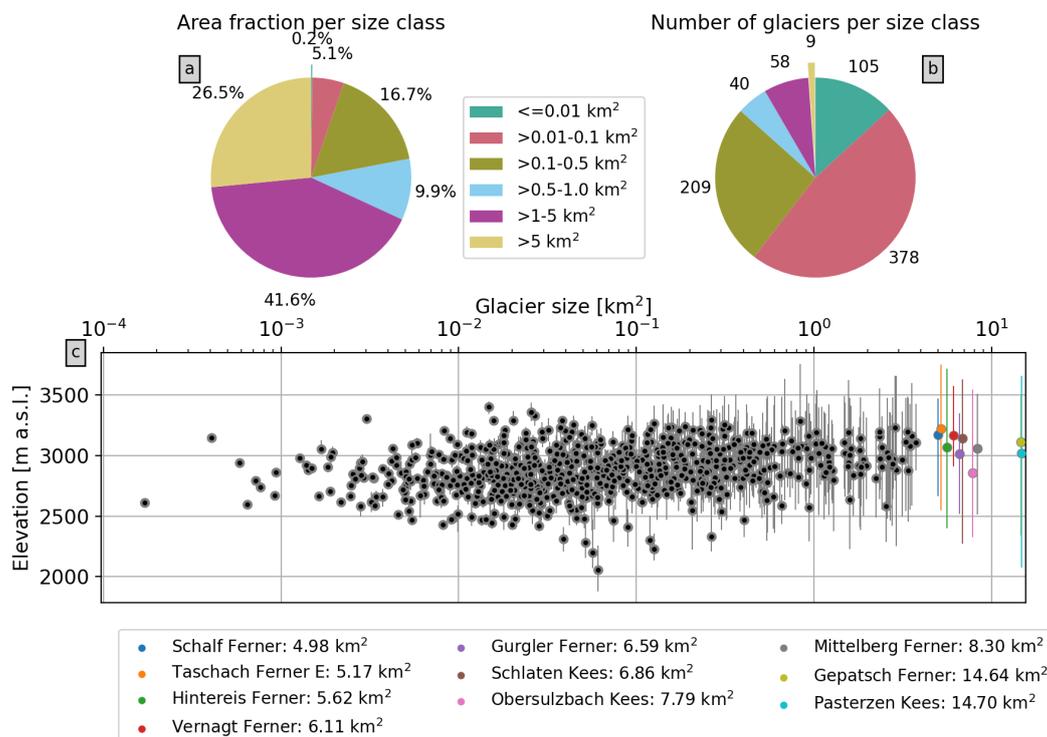
Figure 4. a: Area of all glaciers in the given size classes as percentage of the total glacier area in the study region. b: Number of glaciers per size class. c: Glacier area (log scale), median elevation (circular markers) and elevation range (max. and min. elevation, vertical lines) for all 799 glaciers in the study region. The names and sizes of the 10 largest glaciers are indicated in the legend.

The highest median area loss rates were found in the Rieserferner Group with -6.9 % yr^{-1} (Tab. 4). The Schober Group, Hochkönig Group, and Zillertal Alps also had median loss exceeding -5 % yr^{-1}. The lowest median loss rates were found in the Dachstein Group with -2.0 % yr^{-1}. Here, the AGI5 inventorisation was carried out with imagery from 2021. Accordingly, the change assessment does not include the very negative melt seasons 2022 and 2023.

Median glacier area across the study region decreased from 0.10 km^2 in AGI3 to 0.06 km^2 in AGI5, and median glacier elevation increased from 2849 to 2882 m a.s.l. (Fig. 6a, b). Grouping glaciers by size, the highest median loss rates occurred in the smallest category (<=0.01 km^2) with -5.9 % yr^{-1}. Median loss rates decrease with increasing glacier size, dropping to less than -2 % yr^{-1} for glaciers larger than 1 km^2 (Fig. 6c).

3.3 Vanishing glaciers

AGI5 contains 799 individual glaciers compared to 894 in AGI3. The 95 "missing" glaciers were classified as vanishing between AGI3 and AGI5. That is, analysts found no remaining evidence of ice or considered it impossible to determine an outline for potential remnants of debris-covered ice. The vanishing glaciers had a median size of 0.028 km^2 in AGI3, which
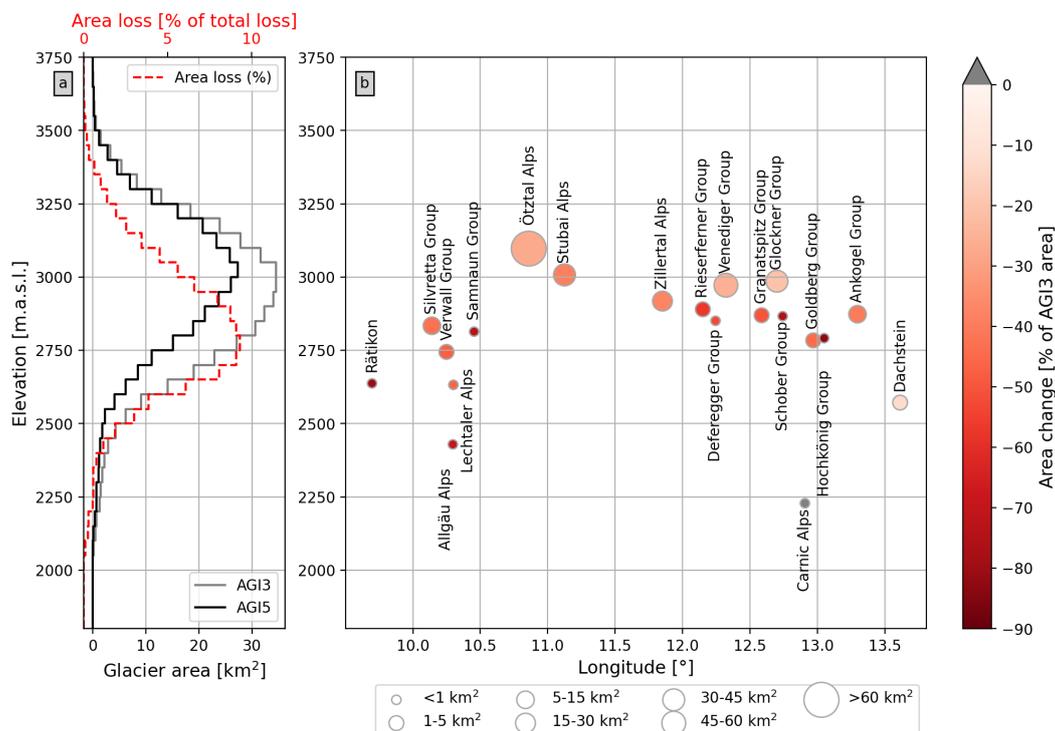
Figure 5. a: Glacier area per 50 m elevation bands in AGI3 and AGI5, and distribution of area loss per elevation band (contribution to total loss per elevation band, red line). b: Median elevation of the 20 subregions (vertical axis) from west to east (horizontal axis) with regional area loss (marker color indicates percentage of AGI3 area lost; positive change due to different interpretation of debris covers in the Carnic Alps shown in grey). Marker size indicates regional glacier area in AGI5.

is about 70 % smaller than the AGI3 median (Fig. 6a). Of 95 vanishing glaciers, 80 were between 0.01 and 0.1 km^2 in AGI3 (Fig. 6 c). The area loss from the vanishing glaciers amounts to 3.702 km^2, equivalent to 2.9 % of total area loss between AGI3 and AGI5. Glaciers have vanished across most of the altitudinal range in the study region (median elevation in AGI3 between 2363 m and 3356 m). The median elevation of the vanishing glaciers was 44 m lower than the AGI3 median and 77 m lower than the AGI5 median (Fig. 6b, d). Fig. 7 and Tab. 4 indicate the location of the vanishing glaciers and their distribution across the subregions. The disappearance of 95 glaciers between AGI3 and AGI5 represents a substantial increase in disappearances compared to AGI1 to AGI2 (5) and AGI2 to AGI3 (11, Fig. 7).

3.4 Area change rates over time

Comparing AGI LIA with the more recent AGIs up to AGI5 shows an area reduction of 68 % since AGI LIA (note: this takes account only the subregions that were included in all AGI). Median area loss rates of Austrian glaciers have increased continuously since AGI1 (Table 5). Median loss rates amounted to approximately -1 % yr^{-1} from 1969 (AGI1) to the late
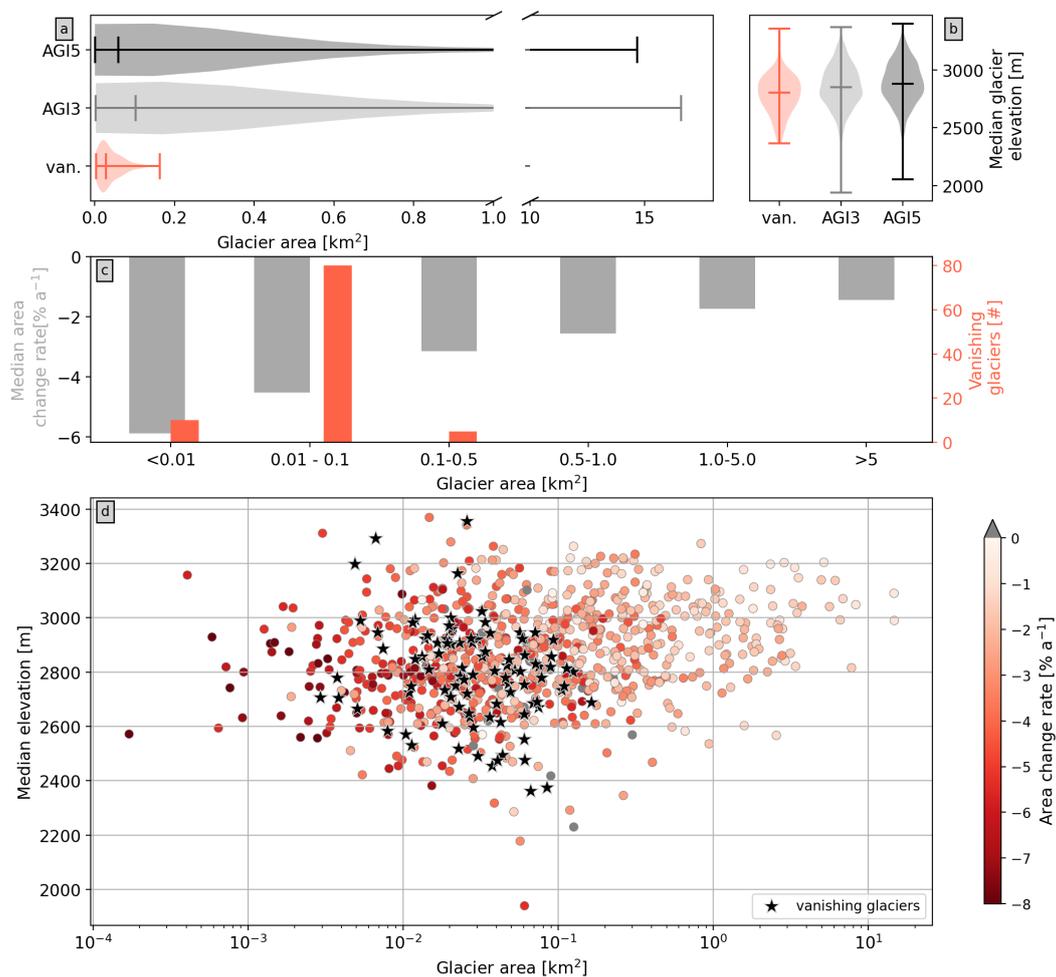
19

Figure 6. a: Violin plots for glacier area in AGI5, AGI3, and the AGI3 area of the vanishing glaciers. b: Median glacier elevation in AGI5, AGI3, and the vanishing glaciers (AGI3 elevation). c: Median area change rates for glaciers grouped by size categories (left axis) and number of vanishing glaciers per size category (right axis). d: Median glacier elevation plotted against glacier area (log-scale) for all AGI5 glaciers. Colors indicate area change rates. Black stars show AGI3 area and elevation of the vanishing glaciers.
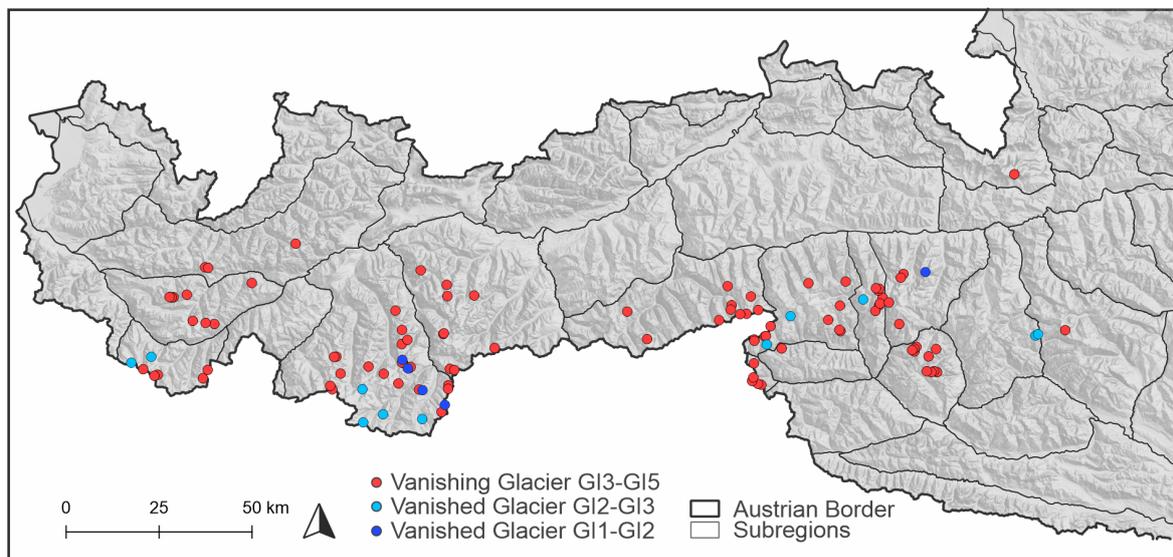
Figure 7. Location of vanishing glaciers in Austria as identified in comparisons of AGI1 and AGI2 (dark blue markers), AGI2 and AGI3 (light blue), and AGI3 and AGI5 (red). Data sources of borders and background terrain map as in Fig. 1 (CC BY-SA 2.0 AU, data.bev.gv.at).

1990s (AGI2) and increased to -1.6 % yr^{-1} between the late '90s and mid-2000s (AGI3) and to -3.4 % yr^{-1} for AGI3 to AGI5. The intermediate regional inventories available for the time frame around 2017/18 show even higher median loss rates of -4.8

305 % yr^{-1} for the most recent subperiod. The histograms of per-glacier change rates for AGI1-2, AGI2-3, and AGI3-5 in Fig. 8b - d indicate increasing variability and more frequent occurrences of extremely negative change rates in the most recent period, in addition to the higher median losses. In absolute terms, loss rates increased from -3.1 km^2 yr^{-1} (AGI1-AGI2) to -5.8 km^2 yr^{-1} (AGI2-AGI3) and -8.8 km^2 yr^{-1} since AGI3 (Table 5).

There are 13, 12, and 17 instances of positive change rates in the three timesteps, respectively, which are attributed to
310 differences in interpretation of outlines, imagery revealing ice that was previously not visible, or inclusion of knowledge gained from in situ surveys (Table 5, supplementary material Section S3). For the subregions with an intermediate inventory for 2017/18, 49 of 511 glaciers show positive change rates, some of which are substantially larger than typical positive change rates associated with subjective differences in interpretation of images between analysts. This is primarily related to the inclusion of debris-covered areas based on local knowledge in AGI5 for glaciers in the Ötztal Alps (refer to supplementary material Section
315 S3 for more information on this subset of glaciers).

3.5 Round Robin experiment

Table 6 lists the glaciers used for the RR experiment with median glacier area and standard deviation (SD) of the outlines produced by the analysts. Refer to the supplementary material (Section S1) for overview maps of all test cases with the RR outlines and summarized commentary by the analysts. The standard deviation of the RR outlines ranges from 0.006 to 0.269
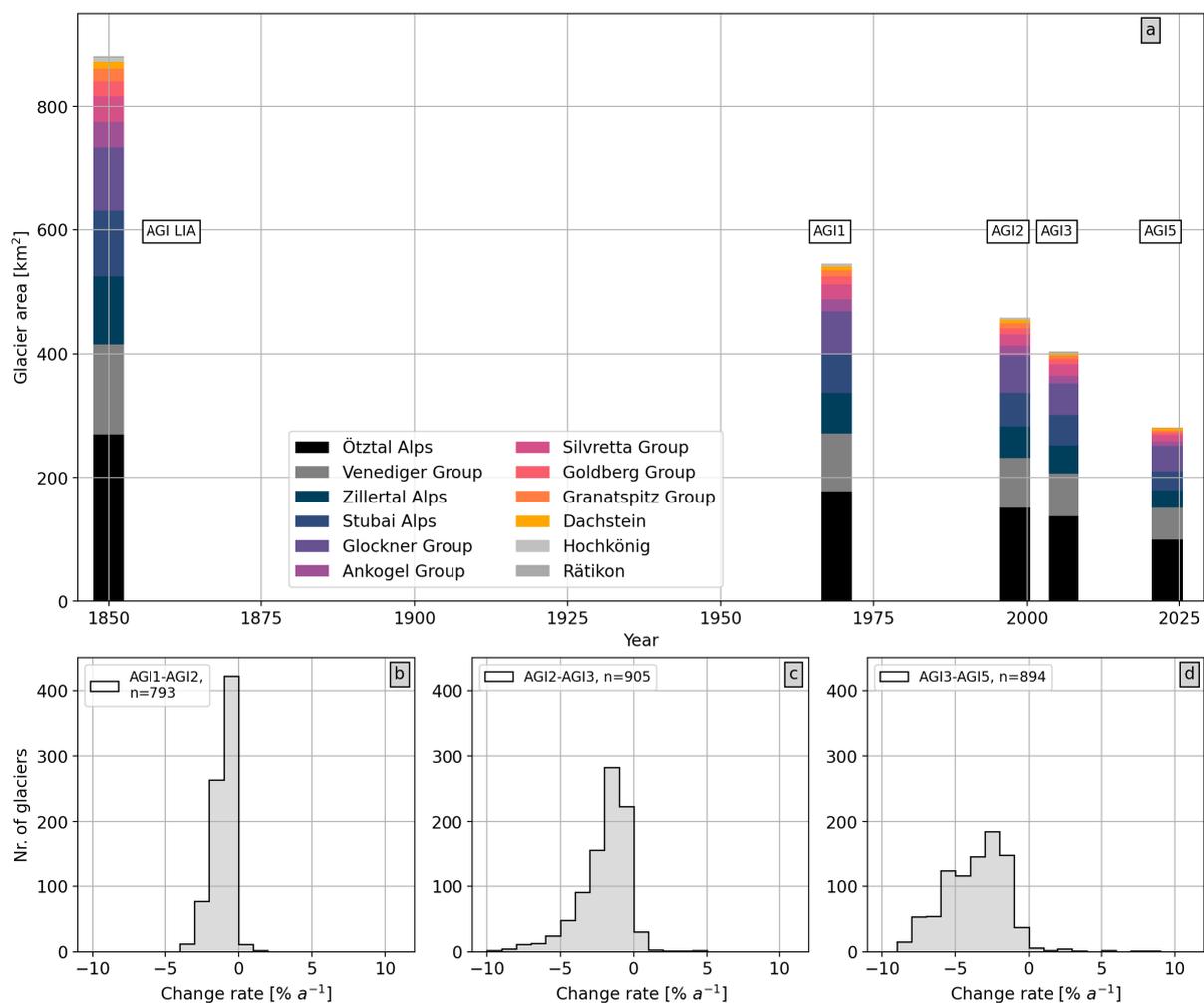
Figure 8. a: Regional area for AGI LIA, 1, 2, 3, and 5 for the subregions included in all AGI (AGI LIA and AGI 1 did not include all 20 subregions). Vertical lines indicate the central years of the AGI. b, c, d: Histograms of relative area change for AGI1-AGI2 (b), AGI2-AGI3 (c), and AGI3-AGI5 (d). The legend indicates the number (n) of glaciers assessed in each time period.

Table 5. Change rates since AGI1 expressed as percentages per year and in km^2 per year. The median and total values are computed from the glacier-wise change rates. That is, different inventory years at individual glaciers are taken into account.

Inventory period	Median change rate (% yr^{-1})	Total change rate (km^2 yr^{-1})	Number of glaciers with positive area change (total number of glaciers)
AGI1-AGI2	-0.9	-3.065	13 (793)
AGI2-AGI3	-1.6	-5.789	12 (905)
AGI3-AGI5	-3.4	-8.760	17 (894)
AGI3-intermediate*	-2.6	-4.461	0 (511)
intermediate*-AGI5	-4.8	-6.440	49 (511)

*intermediate inventories available for some of the subregions

320 km^2, with generally larger SD with increasing glacier size (Tab. 6). The SD reaches up to 50 % of the median for the smallest test case not classified as vanishing by the majority of analysts. SD decreases with glacier size and drops to less than 2 % of the median for the largest test case (Fig. 9e). In absolute terms, the difference between the smallest and largest area values derived from the analysts' outlines ranges from 0.15 km^2 (Fig. 9e) to more than 1 km^2 for the largest test case (Pasterze, Fig. 9f), where analysts had different interpretations of the lake-terminating, partly debris-covered glacier tongue. At Arvental Kees (Fig. 9c),

325 9 of 15 analysts identified ice beyond the AGI3 outlines, leading to an increase in mapped area between AGI3 and AGI5.

The RR test cases included three glaciers that were classified as vanishing by at least one analyst. Madlein Ferner, the smallest of the RR glaciers in AGI3, was classified as vanishing by 14 of 15 analysts (Fig. 9a). The second-largest glacier was classified as vanishing by two analysts, and the third-largest by one analyst (Fig. 9b, c). That is, most analysts agree on the status of these glaciers but there are individual outlier opinions in both directions. The largest area estimates at all six test

330 glaciers were produced by either analyst 4 or analyst 11 (Fig. 9), who included larger debris-covered areas. Analysts 7 and 13 produced the lowest estimates for the three larger RR glaciers.

In general, agreement between the analysts is high in sections of the outlines that can clearly be identified as debris-free. Fig. 10 shows examples from Seekarles Ferner (Fig. 9e) to illustrate the decrease in alignment of the identified ice margins in ambiguous or debris-covered sections. In Fig. 10b, the glacier outline can clearly be delineated with little variation among

335 the 15 analysts where it borders a bedrock outcrop, whereas there are substantial discrepancies in a neighbouring section where loose rocks obscure the margin. Similarly, in Fig. 10c, there is good agreement between the analysts along the largely debris-free upper margin of the glacier despite shading and snow cover. Agreement decreases along the lower margin, which is partially debris-covered and shaded.

Applying distance buffers to the outlines confirms good alignment of the RR outlines with each other and with the main

340 AGI5 outline in clean ice sections of the glacier margins, and heterogeneous results in debris-covered sections (Fig. 10b, c; supplementary material Sections S1, S2). At Seekarles Ferner and Wurten Kees, 57 % and 59 % of RR outlines are within
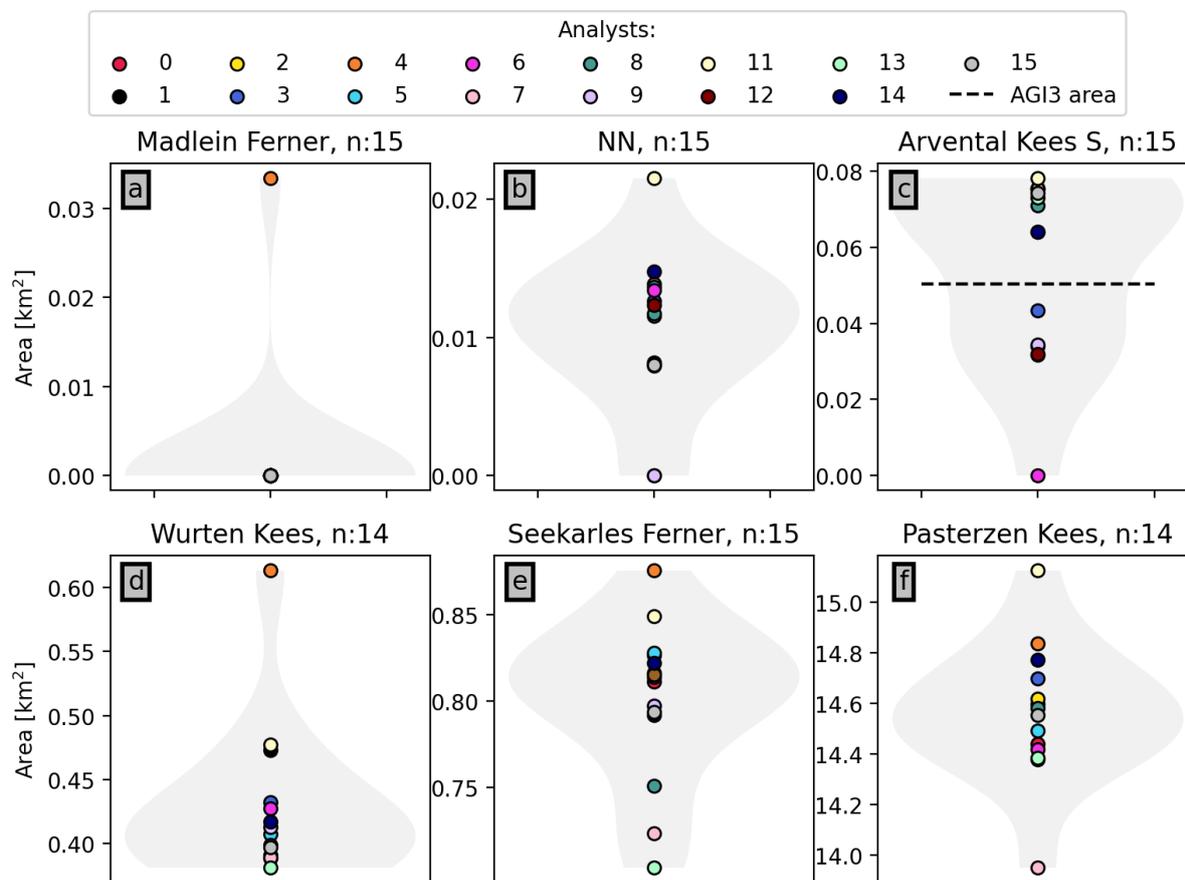
Figure 9. Glacier area derived from the outlines digitized by the analysts (n=number of analysts) for the six test cases in the RR experiment. Grey shading denotes corresponding violin plots. In panel c, the AGI3 area is included for comparison because the AGI5 outlines were mapped beyond the extent of the AGI3 outlines in this case. The AGI3 area was larger than all RR results for the other examples shown.

± 2 m of each other (Tab. 6). At Pasterze, outlines deviate along the large, partly debris-covered and lake-terminating glacier tongue so that only 46 % of the RR outlines are aligned within ± 2 m. At the small, nameless glacier (NN) this value drops to 20 %. A buffer size of ± 40 m covers 90 % of the RR outlines at this glacier (supplementary material Section 2).

345   For the entire study region (total area 285.5 km^2), applying a ± 2 m buffer yields an area range of 279.7 - 292.7 km^2, or an approximate uncertainty of $\pm$ 6.5 km^2 (± 2.3 %). With a $\pm$ 20 m buffer, the range increases to 231.2 km^2 - 347.7 km^2 ($\pm$ 58 km^2, or ± 20 %). A $\pm$ 40 m buffer corresponds to a ± 37 % area uncertainty. Accounting for differing amounts of debris cover by incorporating the debris attributes (Tab. 3) in the calculation results in a regional area uncertainty of ± 13.9 km^2 (± 4.8 %) using a ± 20 m buffer for mostly or fully debris-covered glaciers and ± 2 m for the mostly or entirely clean ice cases. With a

350   ± 40 m buffer the uncertainty increases to ± 20.5 km^2 (± 5.9 %).
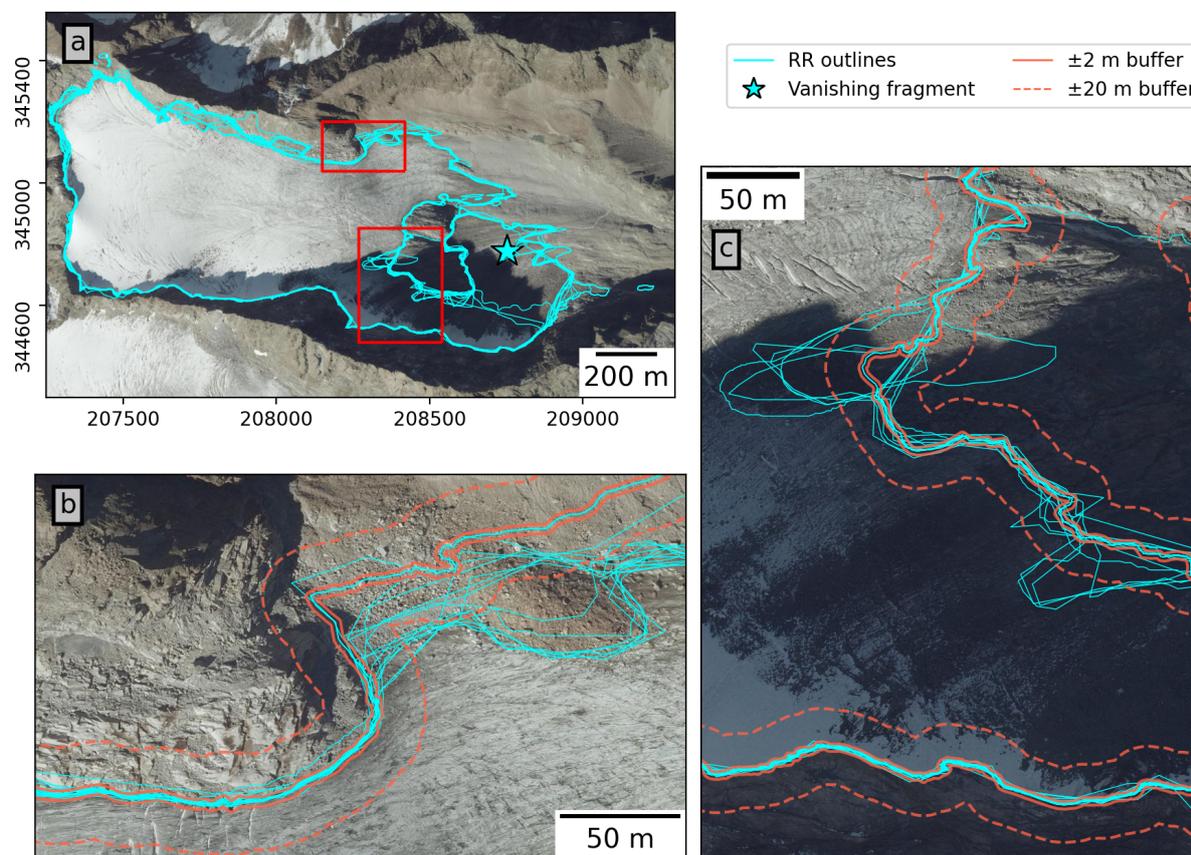
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Figure 10. a: The outlines of Seekarles Ferner produced for the RR experiment by 15 analysts. The star marks a "vanishing fragment" placed by one analyst on the debris-covered sector of the tongue (may contain ice, cannot be mapped with confidence). Two analysts excluded this sector entirely, whereas the remaining 12 analysts included it. The red boxes indicate the close-up views shown in panels b and c. Panels b and c: close up views of Seekarles Ferner outlines highlighting good alignment for bare ice margins and reduced agreement between analysts for debris-covered sections. The solid and dashed red lines respectively indicate a ± 2 m and ± 20 m buffer around the AGI5 outline.

Table 6. Glaciers used in the RR experiment, with regions, size in AGI3, standard deviation (SD), SD divided by median area, and notes on characteristics relevant to the mapping process. All listed glaciers were digitized by at least 14 analysts. Figures showing each glacier and the RR outlines are provided in the supplementary material (Section S1).

Name (ID)	Region	Lon, Lat (centroid)	Size GI3 km^2 (year)	Median size (km^2)	SD (km^2)	SD/median (%)	Outlines within ±2 m (%)	Comments
Madlein Ferner (13029)	Verwall	10.250, 47.020	0.036 (2006)	0.0	0.009	-	-	Highly debris-covered in AGI5 imagery; snow patches but no visible ice. Overlap with rock glacier inventory.
NN* (3028)	Stubai Alps	11.203, 46.978	0.044 (2006)	0.012	0.006	50.0	20	Very small feature, mostly clean-ice in AGI5 imagery.
Arvental** Kees S (6013)	Venediger Group	12.158, 47.01	0.050 (2007)	0.064	0.024	37.5	45	Fragmented and partially debris-covered. AGI5 outline mapped beyond the AGI3 extent based on 2023 imagery.
Wurten Kees (4038)	Goldberg Group	13.01, 47.037	0.916 (2009)	0.41	0.061	14.9	59	Multiple fragments, mostly clean-ice.
Seekarles Ferner (14033)	Ötztal Alps	10.809, 46.976	1.106 (2006)	0.814	0.045	5.5	57	Debris-covered sector near the terminus. One analyst identified a "vanishing fragment" that may still contain ice but cannot be delineated with confidence (Fig. RRmap a).
Pasterzen Kees (4027)	Glockner Group	12.695, 47.101	16.316 (2009)	14.568	0.269	1.8	46	Largest glacier in the study region; partly debris-covered tongue; lake-terminating.

* nameless glacier, * also known as Affental Kees

4   Discussion

4.1   Uncertainties and inherent limitations

4.1.1   Uncertainties in outline mapping

In general terms, we follow an epistemic approach to uncertainties. That is, "the best value is that which is most credible, from
355   the current perspective of knowledge" (Bokulich and Parker, 2025). Uncertainty estimates in this context can be interpreted as
a measure of the extent that our knowledge of glacier area - at the glacier-level and regionally - remains inexact. Considering
the RR experiment, we assume the most credible value for each glacier is the median of the sample. However, the RR approach
is a measure of precision rather than accuracy in the sense that we do not know the "true" area value. Rather, we are assessing
how closely the analysts' interpretations of the source data are aligned (see Section 3.5).

360   The AGI5 uncertainties should be understood as fallible epistemic products that can and should be iteratively improved
(Bokulich and Parker, 2025). Notably, improvement does not necessarily mean a decrease in uncertainty. The AGI5 uncertain-
ties provide an estimate of potential errors introduced by differences in interpretation between analysts, but they do not account
for potential systematic biases, for example related to debris cover identification, and are hence fallible for glaciers that may
be affected by such biases. The AGI5 uncertainty estimates build upon prior work, adapting the approaches of Abermann et al.
365   (2010) and Conzelmann et al. (2026), and have been iteratively improved by incorporating feedback from analysts, who are
arguably in the best position to estimate how inexact their outlines may be for a given glacier. The uncertainty estimates could
be further improved in the future by explicitly including additional sources of uncertainty as related knowledge improves, for
example regarding quantitative bias-estimates for debris cover identification.

The "outline quality" and debris attributes assigned by the analysts (Tab. 3), indicate that about a third (259) of all glaciers
370   in the study area have high outline uncertainties due to debris cover or otherwise obscured ice margins. Although the attributes
are also affected by subjective interpretations (e.g., partially vs. mostly debris-covered), this clearly reflects the most common
challenges in manually mapping glacier outlines from orthoimagery and is aligned with expectations given the numerous
very small glaciers in the study region. Findings by other studies similarly indicate that surface conditions, timing of image
acquisition, quality and resolution strongly affect the visibility and delineation of glacier margins (e.g., Paul et al., 2016; Prinz
375   et al., 2018; Leigh et al., 2019; Fischer et al., 2021a; Andreassen et al., 2022; Hinzmann et al., 2024; Conzelmann et al., 2026).

Discrepancies in manual mapping between different analysts (or the same analyst mapping a glacier multiple times) are to
be expected and it is assumed that they cannot be avoided completely. Round Robin experiments are a standard approach to
estimating the general magnitude of the uncertainties introduced by such discrepancies (e.g., Abermann et al., 2010; Paul et al.,
2013; Fischer et al., 2015b; Paul et al., 2020; Linsbauer et al., 2021; Diaconu et al., 2025). Measures of variability in the area
380   derived from RR outlines are typically used as uncertainty metrics. For example, the 2010 Swiss Glacier Inventory (SGI 2010,
Fischer et al. (2014)) found uncertainties of ± 7.6 % for glaciers smaller than 1 km^2 and uncertainties between ± 3 % and ± 5
% for larger glaciers. For SGI 2016, Linsbauer et al. (2021) reported a standard deviation of glacier area between multiple
analysts of 23.8 % for a "very small glacier in a shadowed, snow-covered north face" and values between 0.3 % and 7.1 %

385 in other cases. In their glacier inventory for Vorarlberg, Conzelmann et al. (2026) found uncertainties of over ±50 % in very challenging (small, mostly debris-covered) cases, which is generally in line with studies assessing outlines of debris-covered or otherwise challenging glaciers mapped from satellite imagery (e.g., Paul et al., 2013; Mölg et al., 2018).

Once uncertainty estimates for individual glaciers are determined (often derived from RR comparisons), they are frequently used to estimate region-wide uncertainties in a second step. For example, Linsbauer et al. (2021) applied an area weighted average uncertainty derived from the RR experiment to obtain the total regional uncertainty of SGI 2010. For AGI3, Fischer
390 et al. (2015b), applied relative area uncertainty estimates to individual glaciers (following Abermann et al. (2010), see section 2.4) and summed uncertainties to produce a region-wide uncertainty value.

The regional uncertainties given for AGI3 (Fischer et al., 2015b) and SGI2016 (Linsbauer et al., 2021) are in the range of 2-3 % of glacier area in Austria and Switzerland, respectively (Austria: 415.11 ± 11.18 km^2, Switzerland: 961 ± 22 km^2, as per the above studies). Uncertainty estimates for AGI5 are slightly higher with ±4.2 % (285.5 ± 12.0 km^2). This increase
395 compared to AGI3 can be explained with the higher relative uncertainties applied to highly debris-covered or otherwise very uncertain glaciers. In AGI5, the glaciers with the highest assumed uncertainties account for about 5 % of total area.

The buffer approach derived from the RR outlines yields uncertainty estimates comparable to the uncertainties computed from the tiered system based on glacier size and outline quality scores (Section 2.4), with higher values depending on how debris cover is treated. Outlines of clean ice margins in our RR experiment are generally aligned within ±2 m of each other.
400 Extrapolating this to the study region yields a regional area uncertainty of around ±2 % (i.e., similar values to AGI3 and SGI2016). In debris-covered sections of the glacier margins, relative uncertainties derived from the buffer approach reach up to around ±40 % (i.e., similar values as in Tab. 6 and as found by Linsbauer et al. (2021) and Conzelmann et al. (2026)for challenging cases).

4.1.2 Takeaways from the AGI5 Round-Robin experiment

405 The results of the AGI5 RR experiment (Fig. 9, Table 6) are broadly in line with the uncertainty magnitudes reported by the studies discussed above and confirm that uncertainties increase with debris cover and decreasing glacier size. Generalizing the comments provided by the analysts regarding the RR experiment (supplement Section S1), the main sources of discrepancies in the RR are differing interpretations of debris cover. Most analysts incorporated geomorphological process understanding in their mapping approach and relied on visible surface features (e.g., changes in surface structure, presence of snow or water)
410 that they considered indicative of subsurface ice to delineate debris-covered ice margins. Other analysts focused more on ice that could be visually identified in the imagery and incorporated less detailed process thinking. The RR experiment showed a general tendency towards smaller glacier area for the latter approach but this is not universally true for all test cases and analysts.

In some cases, analysts provided somewhat contrasting process-based interpretations (e.g., Arvental Kees), or had generally
415 similar interpretations of the geomorphology that nonetheless lead to different conclusions regarding the outline or glacier status (e.g., Madlein Ferner, supplement Section S1). In practice, most of the AGI5 glacier outlines were checked by multiple people and analysts discussed challenging cases among each other. Some of the low outlier cases in the RR (e.g., lowest area

estimate for Pasterze, "vanishing" status for Arvental Kees) would likely have been identified as anomalous and revised in such quality control settings. The high outlier cases are all related to interpretations of debris cover and are difficult to refute

420   or verify. Improved mapping consistency might be achieved with agreed upon, detailed guidelines regarding identification of debris-covered areas. However, improved consistency does not necessarily mean improved accuracy, for example if the majority opinion is subject to unknown or unquantifiable systematic biases.

In discussions prior to the main AGI5 mapping effort, it was agreed that all available information, including relevant process understanding, should be used, as opposed to only mapping visible ice. The latter would likely have produced more consistent

425   results in the RR (and the overall AGI outlines), but would have underestimated the debris-covered area. Similarly, setting an initial zoom-scale of 1:3000 was a measure intended to improve consistency and reduce effort spent on very small-scale details. Most analysts reported deviating from this scale to check for evidence of subsurface ice in challenging cases and considered closer zoom levels to result in improved accuracy.

4.1.3   Likely underestimation of debris-covered area without ground truth

430   As evidenced above, accurately mapping debris-covered ice from remote sensing is challenging even with very high-resolution imagery, and independent ground truth is rarely available (e.g., Racoviteanu et al., 2009; Zandler et al., 2025). Including local terrain knowledge (where available) in the compilation of AGI5 caused area change discrepancies at individual glaciers due to the greater inclusion of debris-covered area compared to AGI3 (supplement Section S3). However, we consider the approach more accurate and, as above, found this more important than maintaining "consistency" with the previous data by omitting the

435   field observations. The same principle (accuracy over consistency with prior outlines) was applied when AGI5 imagery showed evidence of ice beyond the extent of AGI3 (e.g., Eiskar Ferner in the Carnic Alps, Tab. 4; or Arvental Kees in the Venediger Group Fig. 9).

For the subset of glaciers for which detailed local knowledge was available in AGI5 (supplementary material Section 3), the comparison with outlines mapped exclusively from aerial imagery suggests a systematic underestimation of debris-covered

440   area, similar to previous work in the same region (Strudl, 2024). However, the magnitude of the bias is difficult to quantify at larger scales and it is unknown how frequently overestimations or classification errors, for example of periglacial ice (e.g., Haeberli et al., 2024), may occur. The tendency towards underestimation of debris-covered area is in line with findings from neighboring South Tyrol (Alto Adige, Northern Italy), where Galos et al. (2025) reported an underestimation of glacier area by 2.3 % in their 2017 glacier inventory compared to a subsequent inventory for 2023. They suggest the underestimation is

445   mainly related to debris cover and assume a similar underestimation is present in outlines produced with 2023 imagery. Given the comparable source data and mapping approaches, AGI5 underestimations of this type can be assumed to be of similar magnitudes. We note that the opposite scenario (overestimation of debris-covered area) may also occur but this is hard to verify and generally cannot be determined from optical imagery alone (e.g., Paul et al., 2013).

Incorporating DEM-derived products or other auxiliary information in glacier outline mapping can support the identification

450   of debris-covered ice margins (e.g., Strudl, 2024; Diaconu et al., 2025; Zandler et al., 2025). Discussing specifically manual mapping with very high-resolution DEM-derived and optical information at the scale of individual mountain ranges (as applied

in this study), Abermann et al. (2010) and Fischer et al. (2021a) highlighted that surface elevation change and geometric information improve confidence in outline detection under debris cover. Inventory studies from Switzerland have similarly noted that surface elevation change information reduces debris-related uncertainties (Fischer et al., 2014; Linsbauer et al., 2021).

However, even with very high-resolution data (sub-meter pixels), challenges remain. Snow cover during DEM acquisition, avalanches, or rock fall can create locally positive elevation change signals even if glacier ice was lost over the same time period, making such data difficult to interpret especially for very small glaciers close to disappearance (examples in Conzelmann et al. (2026)). In AGI5, analysts used surface elevation change data where available, usually in addition to optical imagery. Feedback on this was mixed - some found the additional information helpful, but others noted that data were inconclusive in their regions, for example because it was not possible to distinguish loss of ground ice from loss of glacier ice, or due to ambiguities in areas where ice cover was lost completely during the elevation change epoch (i.e., an elevation change signal is present but no ice remains at the end of the epoch). In practical terms, on-site inspections of glacier margins would often be beneficial for accurate mapping but are not feasible at larger scales. Lake-terminating glaciers such as Pasterze (Supplement Section S1, Fig. S7) can pose an additional mapping challenge if ice extends below the water level (Kellerer-Pirklbauer et al., 2021).

In summary, it seems likely that debris-covered area is systematically underestimated in glacier inventories compiled from optical imagery, including AGI5, but this remains hard to quantify exactly. Contextual information (surface elevation change, other data types) has the potential to improve delineation of debris-covered glacier margins but needs to be assessed within the specific geomorphological setting. Geophysical investigations would be needed to clearly identify the ice margins beneath thick debris cover.

4.1.4 Classification challenges and conceptual uncertainties

In addition to differences in interpretation and approach between analysts, "classification errors" and "conceptual errors" are two main sources of uncertainties in remote sensing of glacier outlines (Racoviteanu et al., 2009). The former refers to "misidentified features" and the latter is used for a variety of challenges, e.g., "glacier definition issues such as ice divides, perennial snowfields, minimum size, and fragmentation" (Racoviteanu et al., 2009).

Applying these ideas to AGI5, the conceptual issues related to glacier definitions were addressed in the same way as in prior AGIs. That is, there is no explicit distinction between glaciers, ice patches or perennial snow patches; ice divides were maintained since AGI1; and glacier fragments retain their initial ID number. A relevant classification error may be found in the distinction between glaciers, rock glaciers, and other periglacial landforms. Comparing the AGI5 outlines with the Austrian Rock Glacier inventory (Wagner et al., 2020) shows 29 cases where AGI5 and the rock glacier inventory outlines overlap. About half of these have only minimal overlap indicative of different landform types existing in close spatial proximity (i.e., the outlines "touch"). The remaining cases have more than 20 % area overlap and may represent classification errors of rock glaciers misidentified as glaciers or vice versa. Although these distinctions can be challenging for individual landforms, especially in highly debris-covered cases, the low number of overlapping cases between AGI5 and the rock glacier inventory suggests that this is a relatively minor error source for both data sets.

Whether a glacier can and should be classified as "vanished" or "vanishing" might be considered a classification issue as well as a conceptual one. Classification requires consistent inventories or other forms of record keeping that allow a comparison over time to determine if a glacier that was previously present has disappeared. A conceptual definition of a "vanished glacier" requires a common understanding of the term "glacier" that is consistent at least across the inventories used for the comparisons

490   (e.g., Raup et al., 2025; Linsbauer et al., 2025; Pope, 2025; Carlson et al., 2026)).

In their recent compilation of vanished glaciers in Switzerland, Linsbauer et al. (2025) and GLAMOS (2025) consider glaciers that were larger than 0.01 km^2 in the SGI of 1979 and were no longer included in the SGI2016, or the forthcoming SGI2023 (GLAMOS, 2025). That is, they classify glaciers as "vanished" if they no longer meet the size requirements for inclusion in the SGIs. Unlike the SGIs, the AGIs do not apply a minimum size requirement. In AGI5, we allow a "fuzzy"

495   classification as "vanishing" for cases that may still contain ice but cannot reasonably be mapped with the AGI methodology. Of the 95 vanishing glaciers in AGI5, 85 were larger than 0.01 km^2 in AGI3.

Our RR experiment showed that analysts mostly but not always agree whether a glacier has disappeared. Considering the example of Madlein Ferner (Tab. 6, Supplement Section 1), we suggest that phrasing such as "14 of 15 analysts agree this glacier is vanishing" or "this glacier has disappeared with over 90 % confidence" can serve as an adequate expression of

500   uncertainty (Bokulich and Parker, 2025) depending on the application. Such an approach would benefit from more extensive RR-type experiments designed specifically to assess vanishing glaciers and the limits of their detection.

In addition to the minimum size requirement, the recent SGIs (Linsbauer et al., 2025; GLAMOS, 2025) apply criteria related to "evidence of flow" such as crevasses and deformation features to exclude ice bodies that do not meet the definition of a glacier as per Cogley (2011). Similar approaches are described in, e.g., Leigh et al. (2019) and Fountain et al. (2023). In AGI5, filtering

505   by size (>0.01 km^2) and the "visible crevasses" attribute, 396 glaciers covering an area of 265 km^2 remain. That is, almost half of the features included in AGI5 would not meet the criteria for inclusion in the SGI. Although the impact of the filter on glacier count is large, the impact on total area is limited with excluded features accounting for only 7 % of total AGI5 area. Despite the differing criteria, AGI3 and AGI5 and SGI2016 and SGI2023 (forthcoming, (GLAMOS, 2025)) both indicate the disappearance of about 11 % of the total glacier count in the respective inventories.

510   How to treat disappeared or vanishing glaciers in inventories, how to define when a glacier has disappeared, and what to call glacial remnants that may no longer meet common definitions of a "glacier" are matters of current discussion within the glaciological community (e.g., Pope, 2025). Following the approach of previous AGI, AGI5 includes all glacier ice identified in the study region, regardless of size or other criteria. Comparability with other approaches, such as that of the SGI, is achieved with the various data attributes that allow users to filter depending on their use-cases. We concur with Pope (2025), who points

515   out that when a glacier has disappeared depends on "who is asking and why", and hope that AGI5 can contribute to answering this question in Austria for different types of users and applications.

4.2 Comparison with other inventories and outlook

Comparing total glacier area in Austria in the AGI time series and other inventories, overall area loss trends are consistent although absolute area can vary substantially. For example, AGI2 and AGI3 indicate a larger total glacier area than the roughly

520   contemporary RGI 7 (RGI Consortium (2023) - Austrian RGI glacier outlines are mainly based on Paul et al. (2011)) and the

inventories of Sommer et al. (2020). This is likely due in large part to the comparatively coarse resolution of the Landsat source

imagery. Paul et al. (2020) noted improved mapping of small features in their 2015-16 Sentinel-2 inventory, which led to the

inclusion of "new" glaciers compared to the RGI. This is reflected by a glacier count of over 1000 in Austria in Paul et al.

(2020) versus 800 in the RGI and an improved alignment of the outlines in Paul et al. (2020) with AGI 2.

525   The number of individual glaciers counted in different inventories generally varies widely, highlighting the influence of

different approaches to fragmentation and exclusion of glaciers based on size criteria. Excluding glaciers <0.01 km^2 from the

AGIs only marginally affects total glacier area but has noticeable impacts on glacier counts. This calls for pursuing a uniform

and consistent inventory strategy, at least at the national level. Arguably, the number of glaciers in a given region is not essential

for typical applications focusing on hydrology or regional glacier area change. However, such numbers are often included in

530   public communication for general audiences, in particular regarding the number of glaciers that have disappeared in a given

time period (e.g., Boyer and Howe, 2025). Depending on the use-case, care should be taken to contextualize glacier counts by

explaining what specifically was counted and how "glaciers" are defined (e.g., Pope, 2025; Huss et al., 2025).

Glaciers in Austria are expected to largely disappear well before the end of the century under current warming trajectories,

with the greatest losses expected in the coming two to three decades (Hartl et al., 2025b). This overall trend is apparent from all

535   available observational data and from projected future glacier evolution in regional and global modeling studies (e.g., Hanzer

et al., 2018; Zekollari et al., 2019; Rounce et al., 2023; Zekollari et al., 2024; Hartl et al., 2025a; Tricht et al., 2025). Since

AGI2, updates to the AGIs were compiled in roughly decadal intervals. With recenzt median area loss rates of near 5 % yr^{-1}

and changes expected to accelerate as deglaciation progresses, more frequent updates are needed to provide adequate input for

hydrological modeling at catchment scales, biotic succession studies, cartographic material, and other applications that rely

540   on up to date information about local to regional glacier coverage. As has been noted in Alps-wide studies (Paul et al., 2020)

and is evident from the effort to compile AGI5 and previous AGI, variable data availability means that inventories often span

multiple years and it is rarely possible to obtain complete coverage of a larger region from one year. In Austria, new high-

resolution orthoimagery and DEMs become available at irregular intervals, usually on a province-level rather than nationally.

Targeted airborne campaigns that combine optical and laserscanning acquisitions during low-snow conditions and centralized

545   data processing and digitization efforts would be very beneficial for systematic inventory updates, but require considerable

financial resources.

Besides the availability of adequate source data, the workload required for manual digitization of glacier outlines is a key

challenge for increasing the update frequency of glacier inventories. Combining manual calibration and quality control with

automatic approaches has the potential to substantially reduce the workload. Object based image analysis and deep learning

550   approaches (Strudl, 2024; Diaconu et al., 2025; Maslov et al., 2025) can incorporate auxiliary information in addition to

optical imagery, potentially improving the detection of debris-covered ice. Glacier outlines produced for 2015/16 and 2023

in an automated, deep learning-based approach (Diaconu et al., 2025) indicate area loss rates in a similar range as for the

AGI3 to AGI5 period in Austria. However, data coverage is limited and model reliability appears to decrease for very small,

debris-covered features.

555   For further method development aimed at automation, independent reference inventories compiled from high-resolution data sources, such as the AGIs, can serve to quantify potential biases introduced by methodological differences and support model evaluation. Debris cover is likely to remain a central and difficult to quantify source of uncertainty in manual mapping as well as any automated approaches that might be operationalized in the future.

5   Conclusions

560   AGI5 provides an updated status report on Austria's glaciers, highlighting ongoing glacier recession in all regions. Since AGI3, over 30 % of glacier area has been lost and 95 glaciers have disappeared completely or are no longer mappable. Area loss in the highest altitudinal zones above 3000 m is substantial and contributed 22 % of the total losses, indicating that many former accumulation zones have reached a stage of rapid recession and mass loss. The main source of uncertainty in delineating glacier area for AGI5 was the identification of debris-covered glacier ice. The resulting uncertainties for very small glaciers can be
565   large (> ±50 %) but the glaciers with the greatest uncertainties contribute only marginally to total glacier area (approx. 5 %).

With accelerating disintegration processes and glacier disappearance, mapping challenges related to very small, debris-covered features will gain in relative importance for estimating how much glacial ice remains in individual catchments and at regional scales. Inventories compiled from high-resolution source data, ideally taking into account both optical imagery and elevation change information, can help track changes as well as constrain uncertainties.

570   Observational data documenting ongoing, progressing regional deglaciation is essential for model development and local and regional planning and adaptation processes. We recommend more frequent updates to Austrian glacier inventories than in the past to match the accelerating rates of change. Ideally, such inventories would extend beyond national borders. This poses challenges related to data availability, which might be mitigated by greater integration of high resolution satellite imagery. The compilation of AGI5 showed the potential of community initiatives to coordinate inventory updates. In the future, such efforts
575   - at national or Alps-wide scales - would benefit from targeted data acquisition campaigns, improved automation in glacier detection, and systematic support from established monitoring structures.

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