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What is the global glacier ice volume outside the ice sheets?

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Abstract

A recent study (Millan and others, 2022*a*, *Nature Geoscience* 15(2), 124–129) claims that ice volume contained in all glaciers outside the ice sheets and its potential contribution to sea level is 20% less than previously estimated. However, the apparent decrease is largely due to differences in choice of domain, as the study excludes 80% of the glacier area in the Antarctic periphery that was included in previous global glacier volume estimates. The issue highlights the difficulty in separating glaciers from the ice-sheet proper, especially in Antarctica, and the need for both the glacier and ice-sheet communities to develop standards and protocols to avoid double-counting in global ice volume and mass-change assessments and projections. Process-based inversion models have replaced earlier scaling methods, but large uncertainties in global glacier volume estimation remain due to the ill-posed nature of the inversion problem and poorly constrained parameters emphasizing the need for more direct ice thickness observations.

1. Introduction

Knowledge of total glacier ice volume outside the ice sheets in Antarctica and Greenland is important for a range of studies, such as the assessment of the world's freshwater resources or the potential contribution of glaciers to sea-level change (IPCC, 2019). However, direct observations of ice thickness based on, for example, ground-penetrating radar or boreholes, are scarce, available only for <5000 of the world's >200 000 glaciers (Pelto and others, 2020; Welty and others, 2020), and satellites are currently not capable of measuring ice thickness of these glaciers. Thus, global ice volume is estimated indirectly from surrogate variables (see Table 1 for references). Earlier estimates were based on scaling methods, such as volume–area scaling (Bahr and others, 1997). Although the validity of power-law scaling has been demonstrated by dimensional, directional and stretching analyses (Bahr and others, 2015), results characterize the average behavior over a population of glaciers rather than an accurate ice volume of individual glaciers. In the absence of a globally complete inventory, earlier estimates also had to be further upscaled to include all glaciers in a region (e.g. Radić and Hock, 2010). When the globally complete Randolph Glacier Inventory (RGI) became available (Pfeffer and others, 2014) including individual glacier outlines mostly around year 2000, Huss and Farinotti (2012) were the first to use a process-based approach to invert the ice thickness distribution of every glacier based on principles of mass conservation and ice flow dynamics. Farinotti and others (2019) provided an updated, much refined global-scale 'consensus' estimate based on an ensemble of five ice thickness inversion models, which has widely been used in glacier studies (e.g. Watson and others, 2020; Rounce and others, 2021).

2. Have previous studies overestimated global glacier ice volume?

Recently, Millan and others (2022*a*) presented a re-estimation of the global ice volume and its sea-level potential by inverting ice thickness for every glacier based on a novel regional scale (rather than glacier-by-glacier) 2-D inversion scheme. The inversion was driven by surface slope and newly derived, globally almost complete surface ice velocity maps for 2017 and 2018 with an unprecedented sampling resolution of 50 m. The authors conclude that the potential global glacier contribution to sea-level rise is 20% less than the previous estimate by Farinotti and others (2019).

However, we note that Millan and others' global estimate excludes large areas in the Antarctic periphery (RGI region 19 'Antarctic and Subantarctic'), which were previously included (Fig. 1). Thus, the two estimates are not directly comparable. In total, 106 701 km^2 (80.3%) of 132 867 km^2 of ice-covered area in this region were excluded by Millan and others (2022*a*) (see their Fig. S13), as these glaciers were considered to belong to the ice sheet. If these glacier areas were included, consistent with Farinotti and others (2019) and most other previous estimates (Table 1), the difference between these two latest global estimates is just 1 cm sea-level equivalent (SLE) or 4% (0.31 ± 0.10 m SLE by Millan and others (2022*a*) versus 0.32 ± 0.08 m SLE by Farinotti and others (2019)). Hence the apparent decrease in global glacier potential contribution to sea-level rise postulated in Millan and others (2022*a*) is largely

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Table 1. Summary of published estimates of area and ice volume, and associated sea-level equivalent (SLE) of all glaciers on Earth excluding the ice sheets. Estimates including and excluding the glaciers in the periphery of the Greenland and Antarctica ice sheet are given. Where reported, ocean area (A_{sea}, 10^6 km^2), ice density (ρ_{ice}, kg m^{-3}) and ocean water density (ρ_w, kg m^{-3}) used to convert ice volumes to SLE are given. Unless specified otherwise, SLE estimates do not account for the effect of ice below sea level already displacing ocean water. Three estimates (Huss and others, 2012; Farinotti and others, 2019; Millan and others, 2022*a*) are based on thickness inversion using process-based models, while all other estimates are based on scaling methods.

	Global		Excl. Antarctic and Greenland periphery[a]		
Reference	Volume in km^3 m SLE	Area km^2	Volume in km^3 m SLE	Area km^2	Remark
Millan and others (2022*a*)[b]	140 600 ± 40 400 [0.311 ± 0.099]	705 253 (RGI 6.0)	94 000 ± 27 600 [0.223 ± 0.073]	482 823 (RGI 6.0)	SLE excl. ice below floatation; A_{sea} = 361.8 ρ_{ice} = 917 ρ_w = 1027
	109 000 ± 32 130 [0.257 ± 0.085][c]	598 552[c]	"	"	
Farinotti and others (2019)	158 170 ± 41 030 [0.324 ± 0.084]	705 253 (RGI 6.0)	96 020 ± 24 920 [0.221 ± 0.057]	482 823 (RGI 6.0)	SLE excl. ice below sea level; A_{sea} = 62.5 ρ_{ice} = 900 ρ_w = 1028
Radić and others (2014)	209 973 [0.522]	736 989	144 207 [0.301]	516 312	A_{sea} = 362 ρ_{ice} = 900
Grinsted (2013)	140 778 ± 28 155 [0.35 ± 0.07]	734 933 (RGI 2.0)	92 511 [0.230]	513 881 (RGI 2.0)	A_{sea} = 362 ρ_{ice} = 900
Huss and Farinotti (2012)	170 214 ± 20 688 [0.43 ± 0.06]	734 856 (RGI 2.0)	113 646 ± 12 383 [0.282 ± 0.030]	513 918 (RGI 2.0)	A_{sea} = 362.5 ρ_{ice} = 900
Marzeion and others (2012)	–	–	137 841 ± 7531 [0.343 ± 0.019][d]	504 700 ± 1590d	A_{sea} = 362 ρ_{ice} = 900
Radić and Hock (2010)	241 430 ± 29 229 [0.600 ± 0.073]	741 448 ± 68 186	164 044 ± 13 349 [0.408 ± 0.032]	514 309 ± 2429	A_{sea} = 362 ρ_{ice} = 900
Raper and Braithwaite (2005)	–	–	87 000 ± 10 000 [0.241 ± 0.026]	522 000 ± 2000	A_{sea} = 362
Dyurgerov and Meier (2005)	260 000 ± 65 000 [0.65 ± 0.16]	785 000 ± 10 000	133 000 ± 20 000	540 000 ± 300 000	A_{sea} = 362
Ohmura (2004)	–	–	56 000 [0.15]	512 000	
Meier and Bahr (1996)	180 000 ± 40 000 [0.50 ± 0.10]	680 000	–	–	

[a]For studies based on the RGI, the area excluded is defined by RGI primary regions 19 (Antarctic and Subantarctic) and 15 (Greenland periphery). Where not provided in the reference, we computed uncertainties from the regional uncertainties of all RGI regions outside Greenland and Antarctica assuming regional errors either fully correlated (Huss and Farinotti, 2012; Farinotti and others, 2019; Millan and others, 2022*a*, 2022*b*) or independent (Radić and Hock, 2010; Marzeion and others, 2012) consistent with each study's approach.
[b]Numbers include the corrections reported in Millan and others (2022*b*).
[c]Global estimate excludes 80.3% of glacier area in RGI region 19 (Antarctic and Subantarctic) since these glaciers were considered to belong to the ice sheets.
[d]Estimates extracted for 2009 from transient mass-balance model run starting in 1901.

due to relabeling glaciers as ice sheet rather than pointing to an overestimation in the previous estimate, and thus simply a matter of accounting.

In addition, the spatial coverage in Millan and others (2022*a*) is not complete in several other regions (see their Table 1), but the regional volume estimates were not upscaled to account for the missing area. The regions with the largest percent volume differences compared to Farinotti and others (2019) (North Asia and Low Latitudes, Fig. 2a) are regions with low areal coverage of ice velocity data (63 and 82%, respectively). If volumes were compared over the same glacier area, the differences in these regions would change from −22 to −1% and from −27 to −15%, respectively (see the Supplementary material).

3. How to distinguish glaciers from the ice sheets?

However, the issue raises the broader question of how to distinguish 'glaciers' from the ice-sheet proper. Following IPCC (2013), in this context glaciers are defined as all glacier ice (including ice caps) distinct from the ice sheets. The RGI excludes the ice-sheet proper but it includes the glaciers in their periphery (Fig. 1). In Greenland, the RGI defines three connectivity levels (CL) differentiating entirely unconnected (CL = 0), dynamically weakly connected (CL = 1) and dynamically strongly connected glaciers (CL = 2) to the ice sheet following Rastner and others (2012). Global glacier assessments (see summary in Hock and Huss, 2021) and projections (Hock and others, 2019; Marzeion and others, 2020; Rounce and others, 2023) have only included the glaciers with CL = 0 and 1 (in total 89 717 km^2), but excluded those with CL = 2. Also Citterio and Åhlstrøm (2013) mapped the Greenland ice masses distinguishing 'local glaciers and ice caps' from the ice sheet for the mid-1980s (Citterio and Åhlstrøm, 2013).

In Antarctica, the RGI includes only glaciers on the surrounding islands (132 867 km^2) excluding ice rises and ice shelves, and any glaciers on the mainland (Fountain and others, 2016; Huber and others, 2017) based on Bliss and others (2013). Connectivity levels were not defined in this region since the island glaciers were considered separate from the continental ice sheet, although in many cases the ice sheet and island glaciers are connected by ice-sheet-fed ice shelves.

The question of distinguishing glaciers and ice sheets is not just an academic one, but has practical implications. Glaciers are much smaller in size than the ice sheets, often occupying complex mountain topography, and they are generally more sensitive to climate change (Oerlemans and Fortuin, 1992; Dyurgerov, 2003; Hock and others, 2009). Hence, the types of suitable

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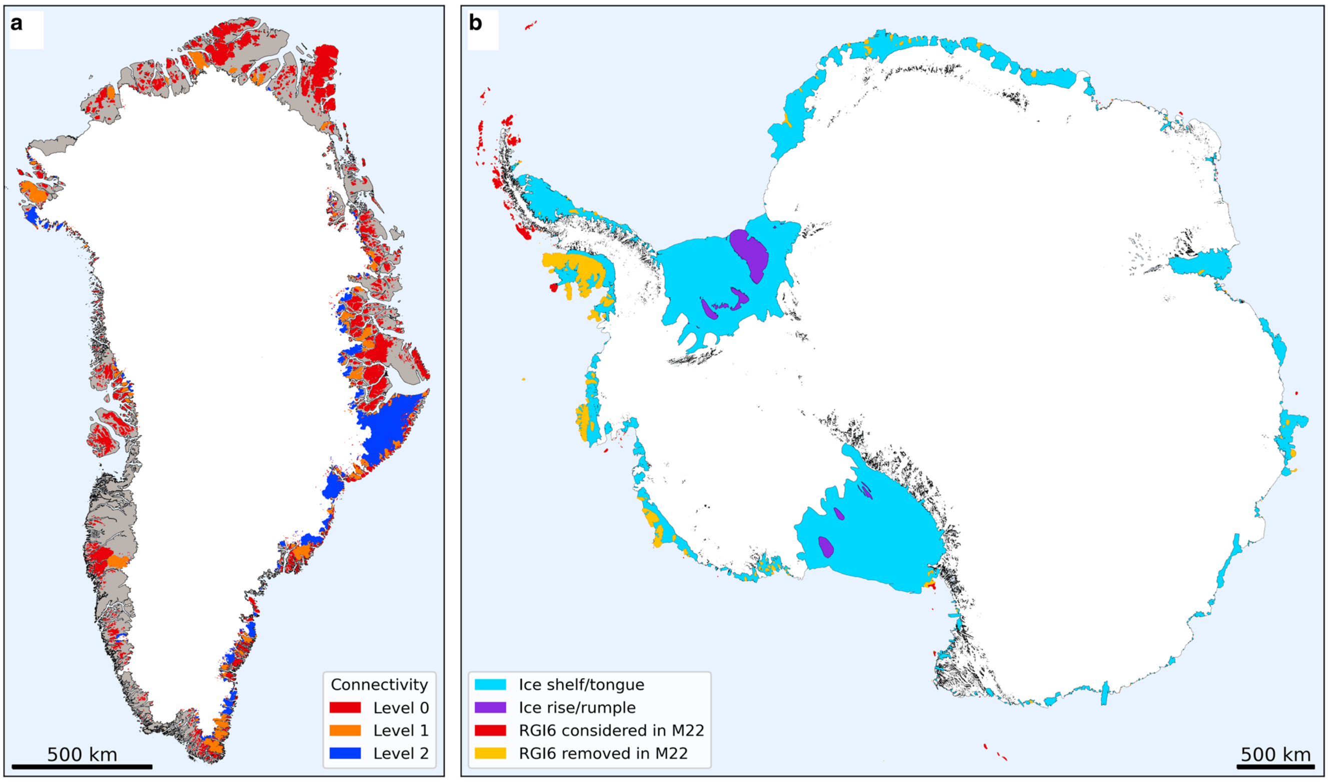

Fig. 1. Location of glaciers in the periphery of the (a) Greenland (RGI region 5) and (b) Antarctic ice sheet (RGI region 19) as defined by the RGI 6.0 (RGI Consortium, 2017). All outlines displayed in (b) are obtained from Bliss and others (2013). In Greenland only RGI glaciers with connectivity levels 0 and 1 (89 717 km^2) have been considered in previous RGI-based ice volume estimates. In Antarctica the glaciers in the RGI that were excluded in Millan and others (2022*a*, M22) are shown in yellow. Subantarctic island glaciers outside the plotted domain cover 3476 km^2 (2.6% of total area of 132 867 km^2 in RGI 6.0 region 19).

observing systems to assess, and models typically used to simulate large-scale mass changes are generally different for glaciers and ice sheets. Therefore, traditionally glaciers and ice sheets have been treated separately when estimating past (e.g. The IMBIE team, 2018; Hugonnet and others, 2021) and projecting future large-scale mass changes (Nowicki and others, 2016, 2020; Marzeion and others, 2020). This separation also enables partitioning of global ice mass change. For example, Horwath and others (2022) found that 45 ± 2% of the cryospheric mass input into the ocean between 1993 and 2016 originated from glacier mass loss with the remainder coming from the ice sheets.

Glacier and ice-sheet mass-change estimates need to be combined in global sea-level assessments, a central topic, for example, in Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC; e.g. Oppenheimer and others, 2019). However, the separation between glaciers and ice sheets is ambiguous, and care must be taken to avoid double-counting or omissions in global assessments and projections. For example, ice-sheet mass-change assessments based on gravimetry measurements provided by the Gravity Recovery and Climate Experiment (GRACE; e.g. Groh and others, 2019; Velicogna and others, 2020) cannot distinguish unambiguously the glaciers in the ice-sheet periphery from the ice-sheet proper due to methodological limitations (e.g. signal leakage due to limited spatial resolution). In contrast, altimetry-based observations (The IMBIE Team, 2018) allow a clear separation of ice masses. However, which peripheral glaciers exactly are covered, varies among studies (e.g. Schröder and others, 2019; Hanna and others, 2020; Shepherd and others, 2020; Simonsen and others, 2021), hampering unambiguous merging with independent glacier estimates based on the RGI (e.g. Gardner and others, 2013; Hugonnet and others, 2021). Hansen and others (2022) investigated how different ice masks defining the ice-covered area in Antarctica in regional climate models (Mottram and others, 2021) affect the modeled surface mass balance. Despite small differences in the total area (<3%), modeled surface mass balances differed substantially solely due to different ice mask definitions (up to 6% of the ensemble mean balance, which corresponds to the total Antarctic mass imbalance). This finding corroborates generally higher sensitivity of peripheral glaciers to climate change, and thus the need to assess and model these glaciers properly.

A similar problem arises for ice-sheet modeling studies. While recent global glacier projections compute every glacier in the Greenland and Antarctic periphery based on the RGI, and thus the domain is standardized and well-defined, this is not the case for ice-sheet modeling. Some ice-sheet projections include all or some glaciers in the periphery, while others restrict their simulations to the ice-sheet proper (Goelzer and others, 2020; Seroussi and others, 2020). Which domain is covered depends on many factors including input dataset, model grid discretization and model initialization procedure (see e.g. model characteristic tables in Goelzer and others, 2020; Seroussi and others, 2020). For example, the use of regular grids in some ice-sheet models hampers clear separation where irregularly shaped boundaries between glaciers and ice sheet occur, and the problem is aggravated for coarse grids. Also, long-term interglacial model spin-up may lead to different ice-covered areas than model initializations to present-day ice-sheet extent (Nowicki and others, 2013*a*, 2013*b*; Goelzer and others, 2018; Seroussi and others, 2019).

Hence, in contrast to the glacier modeling community, there is no adopted standard in the ice-sheet modeling community which part of the glacierized area in Greenland and Antarctica should be modeled, and thus targeted in model initialization to the present-day state. Consequently, a wide range of domains have been modeled. For example, in Greenland, modeled domains have ranged from a low estimate including only the main ice sheet (as defined by Rastner and others, 2012) to a high estimate including all

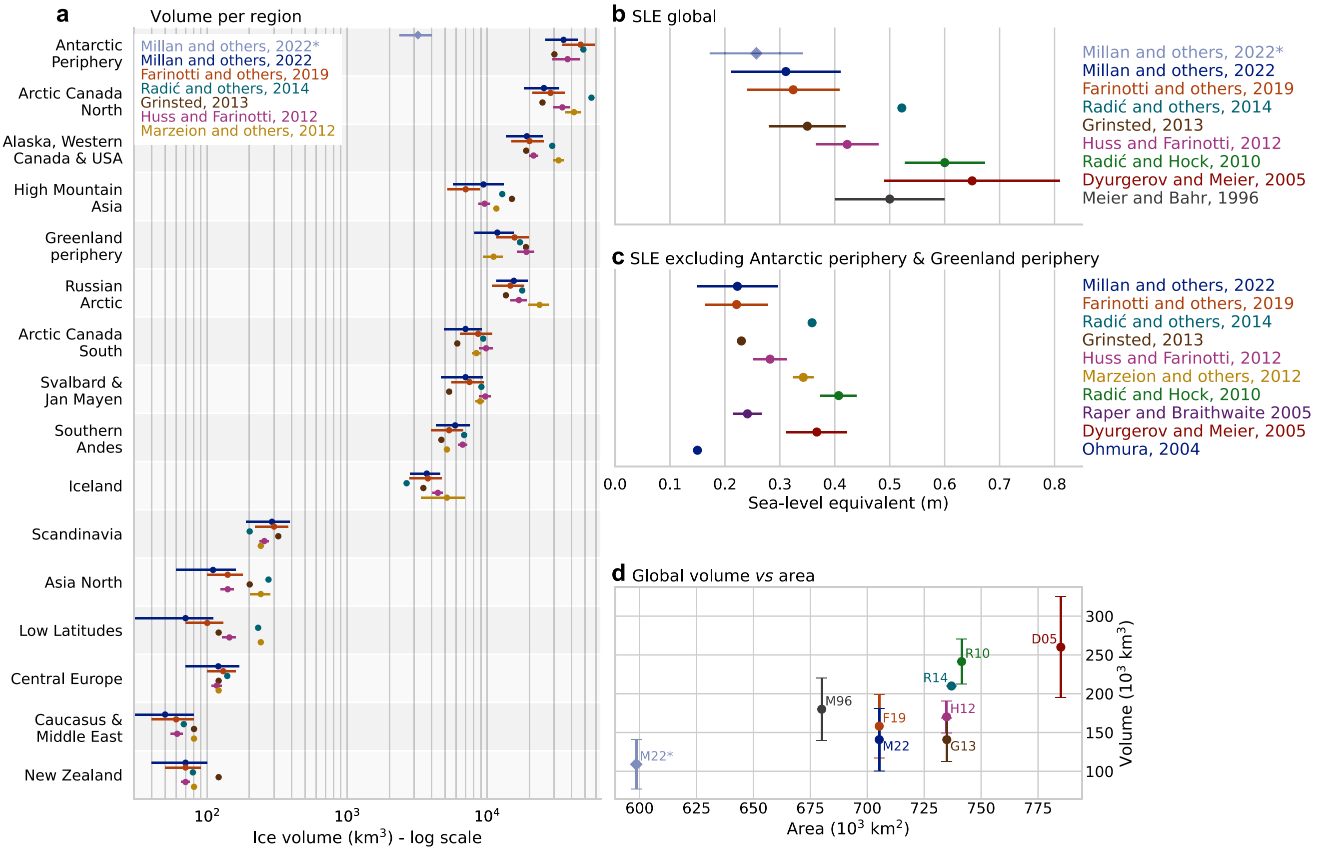

Fig. 2. Published estimates of glacier ice volume. (a) Regional estimates for the primary regions of the RGI 6.0 (RGI Consortium, 2017) sorted by the total glacier area. High Mountain Asia includes RGI regions 13–15. RGI regions 1 (Alaska) and 2 (Western Canada and USA) are combined following Millan and others (2022*a*). Estimates of sea-level equivalent (SLE) for (b) all glaciers globally and (c) all glaciers excluding the Antarctic and Greenland periphery (Table 1). Studies are sorted by publication year. (d) Global glacier volume as a function of the inventoried or estimated glacier area for the studies shown in (b), abbreviated by first letter of first author and year. The global volume and area estimate by Millan and others (2022*a*)* excludes 80.3% of the area in the Antarctic periphery as defined by the RGI 6.0 (region 19, Fig. 1) and thus is considerably lower than their estimates when this area is included (Table 1). Note that their numbers include the corrections reported in Millan and others (2022*b*). Uncertainties are shown where reported.

peripheral glaciers (Morlighem and others, 2017; see Fig. 2 in Goelzer and others, 2020). To ensure that the multiple ice-sheet models were consistent in their definition of the Greenland ice sheet and to avoid double-counting in global sea-level projections, the Ice Sheet Model Intercomparison Project (ISMIP6, Nowicki and others, 2016, 2020) normalized ice-sheet mass change per grid-cell by the area fraction of the glaciers in the RGI (Goelzer and others, 2020).

In Antarctica, despite generally fair agreement between simulated and observed ice extents as defined by the Reference Elevation Model of Antarctica (REMA, Howat and others, 2019), modeled present-day areal extents varied by 6% (13.6–14.5 × 10^6 km^2) among the ISMIP6 Antarctica models (Seroussi and others, 2020), which is more than six times the area of the peripheral glaciers (based on RGI 6.0). Unlike for Greenland, there was no attempt in ISMIP6 to correct for differences in simulated ice-covered area in the Antarctic multi-model ensemble or to avoid possible double-counting with projections by the Glacier Model Intercomparison Project (GlacierMIP; Hock and others, 2019; Marzeion and others, 2020). This decision was based on many factors, including the typically coarser ice-sheet grid used in Antarctic models, and the use of mask datasets that only distinguish between ocean, ice-free land, grounded ice (including glacier) and floating ice (see e.g. Morlighem and others, 2020).

Due to the different treatment of peripheral glaciers in Greenland and Antarctica in ISMIP6, the IPCC's Sixth Assessment Reports (e.g. IPCC, 2019, 2021) distinguishes between peripheral glaciers in Greenland but not in Antarctica. While many glaciers in the Antarctic periphery, in particular larger ice caps, appear to be modeled by ISMIP6, it remains unclear in how far their sensitivity to climate change is captured properly by coarse-grid ice-sheet models instead of the glacier-by-glacier modeling approach adopted by GlacierMIP (Hock and others, 2019; Marzeion and others, 2020), and how important any omissions of peripheral glaciers on islands further away from the mainland are.

4. Other causes for discrepancies in global ice volume estimates

Apart from the issue of separating glaciers from the ice sheets, other inconsistencies and methodological issues can contribute to differences between the existing global and regional glacier ice volume estimates (Table 1). For example, ice volume estimates are often reported in SLE, but different approaches (and values for ocean area (Cogley and others, 2012) and ice and water densities) have been used to convert ice volume to SLE (Table 1). Earlier studies simply spread the water equivalent of the ice volume equally over the ocean area, while the most recent two studies account for the displacement of water by ice below sea level, although in different ways. The latter only became possible when estimates of the fraction of ice located below sea level (~15%; Farinotti and others, 2019) became available. Farinotti and others (2019) subtracted the ice volume below sea level from their global ice volume estimate, while Millan and others (2022*a*) adopted a slightly different approach and removed only the ice volume below flotation. The latter is more accurate since

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a small portion (∼10%) of the ice below sea level would contribute to sea-level rise if melted.

In addition, ice volumes are rapidly changing in response to climate change, but it is currently impossible to assign a single date to the global glacier ice volume estimates. In particular, the most modern methods (Table 1) require a large array of observational datasets such as ice velocity fields, surface topography, surface slope and area to derive ice thickness, as well as ice thickness observations for calibration. However, available datasets refer to different years, sometimes decades apart, and dates also vary within a region for the same type of data.

Furthermore, ice thickness inversion models are sensitive to the assumptions on model parameters, in particular those related to ice flow, but ice thickness observations are currently too scarce and unevenly distributed between regions to constrain these parameters. The inversion models (Huss and Farinotti, 2012; Farinotti and others, 2019; Werder and others, 2020; Jouvet and others, 2022; Van Wyk de Vries and others, 2022; Millan and others, 2022*a*) are constrained by surface data as information on basal conditions is widely lacking. However, despite significant methodological advances, such as by Millan and others (2022*a*), thickness inversions remain ill-posed problems (Bahr and others, 2015), and the ill-posed inversion can exponentially increase any errors due to poorly constrained parameters. In fact, due to ill-posed inversion errors, inversion methods have been found to have the same volume resolution as scaling methods (Bahr and others, 2015). In addition, the shallow-ice approximation adopted in the recent inversion techniques (Table 1) can further increase errors considerably (Bahr and others, 2015), since most of the world's glaciers have geometries and related aspect ratios that are not compatible with the shallow ice approximation. For these reasons, current ice thickness inversions are likely subject to large biases, and far more direct observations on ice thickness and basal boundary conditions from glaciers around the world are urgently needed to better constrain model parameters. Recent developments in airborne radar techniques provide new promising opportunities to increase the number of observations in remote regions (Pritchard and others, 2020).

In addition, global ice volume estimation depends on the accuracy of glacier outlines in the underlying inventories. For example, Li and others (2022) found differences in ice volume of 2–8% in the Tien Shan using two different inventories. The influence of the choice of digital elevation model appeared to be negligible at the regional scale. Another uncertainty is the volume contained in very small glaciers not included in the different glacier inventories used in previous studies. Bahr and Radić (2012) showed that in some regions the omission of glaciers <0.01 km^2 can lead to errors in regional ice volume in the order of 10% emphasizing the need for regionally complete inventories. The RGI applies a minimum size threshold of 0.01 km^2. However, the actual threshold differs regionally and between versions since higher minimum thresholds have been imposed in some of the underlying inventories.

5. Conclusions

Overall, tremendous progress has been made in the last decade in our ability to determine regional and global glacier ice volume as physics-based inversion techniques are replacing empirical scaling methods, and glacier area data with unprecedented accuracy and coverage have become available through the globally complete RGI (RGI Consortium, 2017). However, large uncertainties remain, especially on regional and smaller scales due to the ill-posed nature of current inversion schemes with lack of information on basal conditions, reliance on shallow-ice assumptions and scarcity of ice thickness observations. Since glacier area is a strong prognostic variable for glacier volume, it is likely that future updated glacier inventories will also have an impact on volume estimates (Fig. 2d).

In Greenland and especially in Antarctica significant ambiguities remain with respect to how to separate glaciers from the ice sheets hampering direct comparability of results from different studies as highlighted by the incorrect claim by Millan and others (2022*a*) of considerably lower global glacier ice volume compared to Farinotti and others (2019; Table 1, Fig. 2). While objective separation may be elusive and may also vary depending on purpose or applied observational or modeling tools, care needs to be taken to guarantee direct comparability between studies. As alluded to in Goelzer and others (2020) and Hansen and others (2022), there is an urgent need for a joint effort of the ice-sheet and glacier modeling community to develop standards for present-day ice masks for glacier and ice-sheet modeling, and protocols to avoid double-counting while also ensuring that glaciers in the ice-sheets´ periphery are not omitted, and especially that their sensitivity to climate change is properly accounted for. While pertaining to both Greenland and Antarctica, these issues are most pressing in Antarctica, and ice masks and standards used in both communities should be revisited and reconciled.

Supplementary material. The Supplementary material for this article can be found at https://doi.org/10.1017/jog.2023.1.

Data. Data tables including glacier volumes recalculated from the ice thickness data set by Millan and others (2022a) and upscaled to the regional glacier area in the RGI 6.0 as well as code to generate the results and figures are available at https://doi.org/10.5281/zenodo.7492152 (Maussion and Hock, 2022).

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