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A database of worldwide glacier thickness observations

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ABSTRACT

One of the grand challenges in glacier research is to assess the total ice volume and its global distribution. Over the past few decades the compilation of a world glacier inventory has been well-advanced both in institutional set-up and in spatial coverage. The inventory is restricted to glacier surface observations. However, although thickness has been observed on many glaciers and ice caps around the globe, it has not yet been published in the shape of a readily available database. Here, we present a standardized database of glacier thickness observations compiled by an extensive literature review and from airborne data extracted from NASA's Operation IceBridge. This database contains ice thickness observations from roughly 1100 glaciers and ice caps including 550 glacier-wide estimates and 750,000 point observations. A comparison of these observational ice thicknesses with results from area- and slope-dependent approaches reveals large deviations both from the observations and between different estimation approaches. For glaciers and ice caps all estimation approaches show a tendency to overestimation. For glaciers the median relative absolute deviation lies around 30% when analyzing the different estimation approaches. This initial database of glacier and ice caps thickness will hopefully be further enlarged and intensively used for a better understanding of the global glacier ice volume and its distribution.

Contents

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1. Introduction

Within the global observing programs glaciers are recognized as essential variables in the global climate system with important impacts on environmental, economic and therefore also political issues from local to global scales (UNEP, 2007). Information on ice thickness of the world's glaciers and ice caps is an important boundary condition for the assessment of ice volume, changes therein and the related modeling approaches. Ice volume change affects the hydrological cycle on different scales and contributes to sea-level rise (Vaughan et al., 2013). Estimates of global ice volume and related issues such as the changing global sea-level equivalent are based on different modeling approaches using statistical scaling (e.g., Chen and Ohmura, 1990; Bahr et al., 1997; Cogley, 2012) or glacier surface characteristics and applications of the shallow-ice approximation (e.g., Huss and Farinotti, 2012). The recent estimates of the global sea level equivalent (SLE) of glaciers and ice caps are 0.35 m (Grinsted, 2013), 0.43 m (Huss and Farinotti, 2012) and 0.52 m (Radić et al., 2013); an overview is presented in Cogley (2012) and Grinsted (2013). The varying estimates were derived from different methods. However, the given estimates are calibrated with only a few hundred glacier thickness measurements and uncertainties are therefore difficult to quantify (Vaughan et al., 2013). In addition, all of these studies consider the completeness and quality of global glacier monitoring and of the available ice thickness data as a basic requirement for improving estimates of global glacier volume distribution. Over the past decades, major efforts have gone into the compilation of a worldwide glacier inventory (WGMS, 1989; Raup et al., 2007) improving both data richness (WGMS and NSIDC, 1989/2012; GLIMS and NSIDC, 2005/2012) and global completeness (Pfeffer et al., 2014). In their current realizations inventories are restricted to glacier surface information. Ice thickness, i.e. sub-surface information, was observed on many glaciers around the world and the attempt to collect information on ice thickness is not new. One dataset used in several studies (e.g., Grinsted, 2013) is compiled by Cogley and Hock (unpublished, see Cogley, 2012), but so far no readily available database of worldwide glacier thicknesses exists.

Here, we present the first release of the Glacier Thickness Database (GlaThiDa, doi: 10.5904/wgms-glathida-2014-09), a standardized compilation of glacier and ice cap thickness observations based on an extensive literature review and open access data, including glacier-wide estimates of mean and maximum ice thickness, thickness distribution relative to glacier hypsometry, and point observations, as well as corresponding metadata and source information. In addition, we make a first comparison of the compiled glacier and ice cap thickness observations with results from different area- and slope-dependent approaches to assess the strengths and limitations of methods to estimate glacier thickness and volume at the local and at the glacier-wide scale. The GlaThiDa presented in this paper is made available for future studies and updates through the Global Terrestrial Network for Glaciers (www.gtn-g.org). It builds a substantial basis for the working group on "Glacier ice thickness estimation" (http://www.cryosphericsciences.org/wg_glacierIceThickEst.html), recently formed under the auspices of the International Association of Cryospheric Sciences (IACS).

2. Methods and data

2.1. Data compilation

A considerable number of data compiled and analyzed in this publication is based on an extensive literature review on glacier and ice cap thickness. The review is based on two basic articles about global glacier thickness analysis by Chen and Ohmura (1990) and Bahr et al. (1997) and the sources given therein. In addition, complete series of selected glaciological journals (Annals of Glaciology, Journal of Glaciology, Zeitschrift für Gletscherkunde und Glazialgeologie) were checked systematically. Selected publications from other relevant journals, such as The Cryosphere and Journal of Geophysical Research, were also included. 'Glacier thickness', 'thickness data' and 'ice volume' were mainly used as keywords and phrases for search criteria, but directly searching for relevant methods, such as 'GPR' and 'seismic', also revealed additional literature. A total of 135 publications are considered for this new database GlaThiDa. Beside the literature review, open access data on glacier thickness provided by NASA's Operation IceBridge (OIB) (cf. Li et al., 2012) are included in the database. These data are retrieved from http://nsidc.org/idebridge/portal/, where data and metadata are directly downloadable.

GlaThiDa is structured in three data tables of different levels of detail (see Fig. 1). All tables include the given GlaThiDa_ID, the political unit, glacier name and the year. The first table is the overview table (Table T) containing information on the location and area of the glacier (T1–T10, cf. Fig. 1), estimates of mean and maximum thickness from interpolated observations including accuracies (T11–T14), the survey method and related information (T15–T20), as well as investigator and source of the data (T21–T23). Missing basic information is partly taken from related databases (World Glacier Inventory (WGI), WGMS 1989; Randolph Glacier Inventory (RGI), Pfeffer et al., 2014) and documented in the fields T4 and T5 (see also database documentation (http://www.gtn-g.org/glathida.html)). For surveys with no inter/extrapolation to obtain glacier-wide values (such as all entries from the OIB), only area information is collected here, since mean and maximum thicknesses are not available. The data compiled in the T table reflect the glacier-wide information, which is often used for further studies such as sea level equivalent estimations (e.g., Grinsted, 2013).

The second table (TT, Fig. 1) includes ice thickness data (mean and/or max; TT9–TT12) averaged over surface elevation bands by given lower and upper boundaries (TT5 and TT6) from ice thickness maps or Digital Elevation Models (DEMs). The third table (TTT, Fig. 1) contains point data including a point ID, related coordinates, the elevation at the surveyed point, as well as the thickness value (TTT5–TTT10). Table TTT reflects the original observations which are more or less extensive, depending on the survey method and the level of detail of the data description in the literature. In the given data tables information on accuracies, uncertainties (Table T, TT and TTT) or interpolation methods (Table T) is included if available.

The three tables are linked through the numerical ID (GlaThiDa_ID) which has to be unique for a given glacier and survey. Note that for one glacier or ice cap there can be multiple entries for ice thickness surveys (e.g., at different dates).

2.2. Methods to quantify glacier thickness

2.2.1. Direct explorations

Glacier thickness is generally defined as the vertical distance between the glacier surface and the underlying bed (Cogley et al., 2011). Techniques to measure glacier and ice cap thickness directly are explorations such as ice drillings and excavations. While these methods derive precise point information, they are very time- and cost-consuming and have low spatial representativeness (Haeberli and Fisch, 1984; Sugiyama et al., 2008). From the ice core community, mostly focusing on the reconstruction of climate records, some side-product data on ice thickness are available for a number of ice caps (e.g., Eisen et al., 2003; Herren et al., 2013). These data are not yet included, but will be made available in an updated version of GlaThiDa.

2.2.2. Geophysical soundings

Indirect explorations such as geophysical soundings (radio-echo and seismic investigations) provide mostly profile information with deduced thickness values. While seismic soundings were common until about the 1960s, radio-echo soundings are still frequently applied. A general introduction to environmental geophysics is given in Reynolds (1997), a review of its application in glaciology is provided

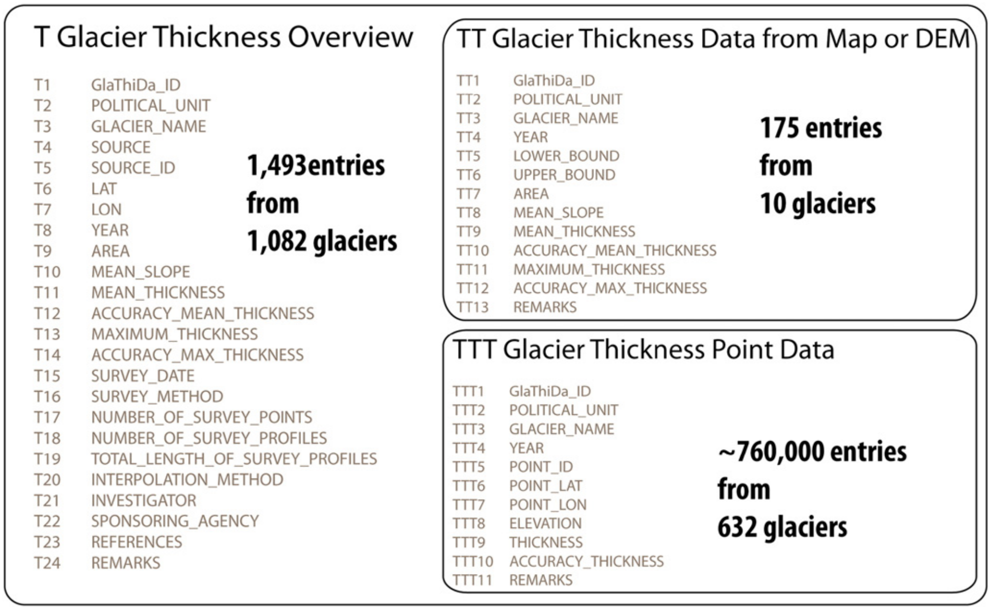


Fig. 1. Overview of the Glacier Thickness Database (GlaThiDa) with the three different data tables T, TT and TTT, including the number of entries and glaciers. More details are given in Section 2.1 as well as in the database documentation (www.wgms.ch/glathida.html).

by Plewes and Hubbard (2001). Beside in situ explorations, remote sensing methods (mostly airborne or helicopter based) have developed rapidly and have resulted in improved acquisition techniques, with good spatial coverage and easily accessible data (e.g. Zamora et al., 2009; Finn et al., 2012). Already in 1978, the first airborne radio-echo sounding system for the exploration of temperate glaciers was constructed and tested on Columbia Glacier, Alaska (Watts and Wright, 1981).

2.2.2.1. Ground Penetrating Radar. Ground Penetrating Radar (GPR) is an active measurement technique that uses electromagnetic waves to acquire information on subsurface characteristics and structures. The different subsurface materials (air, water, sediment, ice) and in particular the interfaces between them, have specific electromagnetic properties; any dielectric discontinuity is detected (Plewes and Hubbard, 2001). The principle of radar methods is based on the transmission and reflection signal of each interface, as well as the velocity of propagation, which decrease with increasing relative permittivity, and material losses (Daniels, 2007). The vertical resolution of GPR data is mainly a function of frequency; at lower frequencies, resolution decreases and vice versa. Advantages of GPR are the relatively easy application and the limited processing that are required for basic data interpretation. A potential drawback of GPR is the sometimes limited signal penetration; a lower frequency can increase penetration but results in a lower resolution (Van Dam, 2010). In glacier studies, low frequencies (approx. 2–220 MHz) are suitable for ice thickness observations (Cogley et al., 2011). Maximum depths of about 4000 m in cold ice and 1500 m in temperate ice have been sounded (Plewes and Hubbard, 2001). A direct comparison of radar measurements with hot water drillings and borehole electrodes indicated that thicknesses derived from radar measurements are usually within ± 5% of the measured ice thickness (Haeberli and Fisch, 1984). Fischer (2009) estimated the uncertainty of thicknesses for the Austrian glaciers as 5–10% of the measured value. Zamora et al. (2009) applied airborne GPR on Tyndall glacier (Patagonia, Argentina) and observed a maximum ice thickness of 670 m, with an accuracy of ± 50 m when comparing the results to existing thickness information.

Currently, a large number of thickness data is provided by OIB (Koenig et al., 2010; Li et al., 2012). Ice thickness data are derived from the Multichannel Coherent Radar Depth Sounder/Imager (MCoRDS/I), which was developed by the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas (Allen, 2010; Shi et al., 2010). The radar system operates at the center frequency of 195 MHz with a bandwidth of 30 MHz; for technical details see Li et al. (2012). About 90% and 50% of the surface area ice thickness in Antarctica and Greenland, respectively, were retrieved so far; the recently released ice thickness maps for the two ice sheets (Bamber et al., 2013; Fretwell et al., 2013) are mainly based on OIB data. In Antarctica, airborne radar data are cross-validated with ground-based radio-echo soundings from the British Antarctic Survey DEep-LOok-Radar-Echo-Sounder (DELORES) and indicated a good agreement (Farinotti et al., 2014). In this study the median absolute deviation between the two datasets was 17 m (2.8% of the local ice thickness) and maximum discrepancy was 44 m (7.2%).

2.2.2.2. Seismics. The principle of seismic methods is based on elastic waves traveling through different materials at different velocities. The propagation of seismic waves through layered ground is determined by the reflection and refraction of the waves at the layer interface. When the wave reaches the interface some energy is refracted into the deeper layer, while the reflected wave directs energy back into the upper layer (Schrott and Sass, 2008). A strong benefit of seismic methods over other geophysical methods is the penetration depth. For example on Taku Glacier (Alaska, USA), with a thickness of 350 m to 1450 m, Nolan et al. (1995) and Pelto et al. (2008) applied seismic methods to reach the glacier bed. They found good agreement taking into account both the deterministic measurement error as well as the temporal difference. The disadvantages are the time consuming and costly data collection of high resolution seismic data. Hence, seismic soundings are less common in glaciology (cf., Table 1).

2.2.2.3. Gravimetry. The gravimetric method to estimate ice thickness was first used by Martin (1949) and extensively applied in the 1960s; nowadays it is rarely used. Up to now, no gravimetric data are included in the database, but will probably be available in an updated version of GlaThiDa. The method is convenient to determine the general relief of the underlying bedrock, since the observed gravity represents a mean

Table 1
Overview of the data contained in Table T of the database. The second column indicates the number of entries related to a specific method given in the first column. The third column shows the number of glaciers covered by the respective entries. All subsequent columns indicate the number of values related to the methods. h is the ice thickness.

Method	Entries	Glaciers	h_{mean} (m)	h_{max} (m)	Publications
OIB, airborne radio echo sounding	933	617	0	0	2
Airborne radio-echo sounding	214	172	131	160	22
Terrestrial radio-echo sounding	274	265	210	262	72
Seismic	41	36	39	18	25
Direct drilling	4	4	1	3	4
Unknown + other	23 + 4	22 + 4	22 + 4	9 + 4	8 + 4
All	1493	1082	407	456	137

value in the area around the station (Casassa, 1987). The accuracy of the method is described as 7–20% of the measured ice thickness, strongly influenced by the roughness of the topography (Casassa, 1987).

2.3. Estimation approaches for glacier thickness and volume

In order to calculate glacier thickness without direct measurements, various estimation approaches have been developed and applied in several studies. Here we select three often used estimation approaches for the comparison with results from in situ observations. We first apply the so-called volume–area-scaling (Chen and Ohmura, 1990; Bahr et al., 1997) with different parameters based on the formula

$$V = cA^{y}, \tag{1}$$

where V (km^3) is the total ice volume of a glacier with surface area A (km^2), and c and y are the empirical constants. While the scaling parameters used by Radić and Hock (2010) are based on Bahr et al. (1997), which considers ice dynamics on a theoretical basis, Grinsted (2013) applies an empirical fitting using existing ice-thickness data from an unpublished dataset (compiled by Cogley and Hock, see Cogley, 2012). The two studies use different relations for calculating mountain glacier and ice cap volumes: Radić and Hock (2010) calculate glacier volume with $c = 0.0365$, $y = 1.375$ and ice caps with $c = 0.0538$, $y = 1.25$, while Grinsted (2013) calculates glaciers with $c = 0.0433$, $y = 1.29$ and ice caps with $c = 0.0432$, $n = 1.23$.

Besides this area-dependent approach, we apply two slope-dependent estimation approaches. The approach by Haeberli and Hoelzle (1995) calculates mean glacier thickness with

$$\frac{\pi}{4} * \frac{\tau_f}{f \rho g \sin \alpha}, \tag{2}$$

hmean = ... formula

where τ is the mean basal shear stress, ρ is the mean glacier density, g is the acceleration due to gravity and α is the average surface slope along the central flowline. Based on empirical data, basal shear stress is parameterized by a polynomial fit with an upper bound value of 150 kPa for the largest glaciers with an elevation range greater than 1600 m. The surface slope is calculated from elevation range and glacier length. The original approach is suitable for valley glaciers and less feasible for ice caps, because an (radial) ice cap has no clearly-defined length (Cogley et al., 2011).

The two above methods, only provide an estimate for the total glacier volume, whereas the third approach by Huss and Farinotti (2012) also provides spatially distributed results. This method calculates ice thickness for every grid cell of a digital elevation model based on an inversion of estimated ice volume fluxes along the glacier using the shallow ice approximation. A number of variables are described in a process-based way (for details, see Huss and Farinotti, 2012):

$$h_i = \sqrt[n+2]{\frac{(1-f_{sl}) * q_i}{2A_f(T)} * \frac{n+2}{\left(F_{s,i} \rho g \sin \overline{\alpha}_i\right)^n}}, \tag{3}$$

where n is the exponent of flow law, f_{sl} is the fraction of sliding, q_i is the ice flux normalized with glacier width for the individual elevation band, $A_f(T)$ is the rate factor of flow law (temperate glacier), $F_{s,i}$ is the valley shape factor, p is the ice density, g is the acceleration due to gravity and α_i is the average slope.

The required input data (e.g., elevation range, length, area) are taken from WGI (WGMS 1989) and RGI (Pfeffer et al., 2014); digital outlines are taken from the RGI (updated, version RGIv3.2) as well as from various DEMs (see references in Huss and Farinotti (2012)).

3. Results

3.1. The glacier thickness database GlaThiDa

GlaThiDa is structured into three data tables of different levels of detail. The overview table (Table T) includes 1493 entries for 1082 glaciers, as illustrated in Table 1. 933 entries thereof derive from the OIB and provide area information only, since no mean thickness values are available. The remaining 560 entries comprise 465 different glaciers. These entries are derived from 135 referenced publications. For 70 glaciers multiple entries from different publications (multitemporal) are stored. A spatial overview is given in Fig. 2, showing that mean and/or maximum thickness data is available for all 19 regions (based on Pfeffer et al., 2014).

In total, six different survey methods (including 'unknown' and 'other') are reflected in the database. While the majority is derived from airborne GPR surveys (1147 entries, 933 from OIB), 274 entries result from terrestrial GPR measurements. 41 entries are compiled from seismic measurements and for 27 entries the method is unknown or another. Only 4 entries are obtained from direct drilling. Mean ice thickness is available for more than 400 entries. For 398 entries both glacier surface area and mean thickness values are given. Maximum ice thickness is compiled for about 450 entries (cf. Table 1).

The second database table (TT, cf. Appendix A) includes ice thickness data averaged over surface elevation bands, e.g. from ice thickness maps or Digital Elevation Models (DEMs). Here, 175 entries – representing the elevation band information – from 10 different glaciers in the European Alps are available so far. This number will probably increase in the near future.

The third table (TTT, cf. Table 2) contains point data. While about 727,000 entries originate from the OIB and cover 617 glaciers and ice caps in the periphery of Antarctica and Greenland, as well as in Arctic Canada, 32,632 entries are compiled from publications covering 15 different glaciers from four countries (Germany, Mongolia, Switzerland, and United States). The number of studies contributing point data is small, since the raw data are often not included in the publications. The large quantity of point information is related to the measuring principles of radio-echo sounding and does not allow direct inferences on data quality or on spatial coverage.

Besides the OIB data, information from 135 articles is assessed and compiled in GlaThiDa. While the first reference goes back to 1936, a considerable amount of data was published in the 1980s (25 publications, or 19%) and during the last five years (2008–

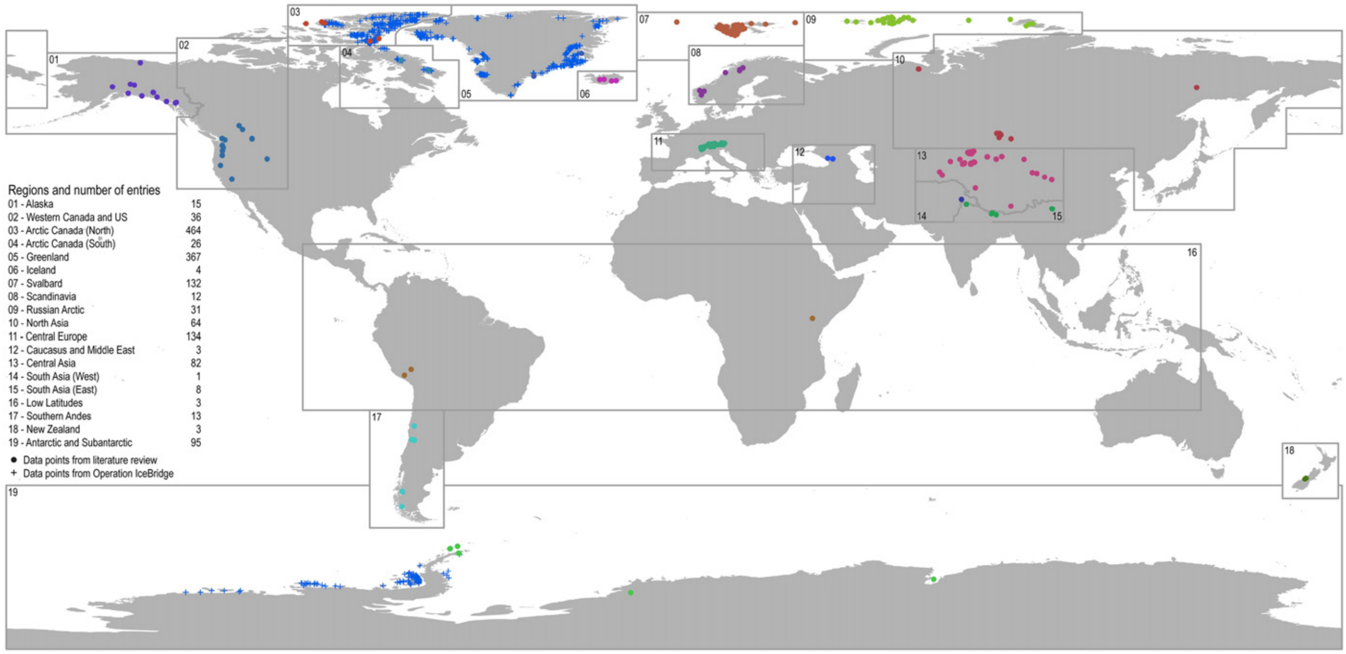


Fig. 2. Global and regional distribution of all compiled thickness observations. The crosses represent data from the Operation IceBridge. The dots represent data from literature review; the different colors underline the 19 different regions as based on Pfeffer et al. (2014).

2012; 46 publications, or 34%). Based on all available data in GlaThiDa, the spatial coverage and the temporal pattern (survey year) of the compiled data are analyzed. Glacier thickness information is available for all 19 regions (Fig. 2) with a strong bias to the northern hemisphere. Most observations on glacier thickness are available for Arctic Canada (490) and Greenland (367), followed by Central Europe (134) and Svalbard (132) (cf. Fig. 2). From all glaciers with mean thickness information, 339 (or 83%) have a mean thickness of ≤100 m and only 6 glaciers (1.5%) are thicker than 300 m. From the literature review, area information is available for 541 observations. 274 or 51% of the glaciers are smaller than 5 km^2; 134 (25%) glaciers have a small to medium size (5–50 km^2). The majority of the glaciers covered with OIB data are small to medium (5–50 km^2) or medium to large (50–500 km^2) with 298 (32%) and 342 (37%) respectively; only 7 (1%) are larger than 5000 km^2. An overview is provided in Table 3.

3.2. Data limitations

Theoretical or location-specific uncertainties of ice thickness measured from individual methods are listed in Section 2.2. Actual uncertainties of the data contained in GlaThiDa depend on a variety of additional factors that need to be derived from the metadata contained in the cited literature. However, the level of detail in method descriptions and the amount of information on measuring accuracy are rather limited for most sources. While 73% of the published studies mention the mean ice thickness and 81% provide a value for the maximum glacier thickness, only 15% provide an estimate of accuracy. Furthermore, only 4% of the studies comment on the applied interpolation method (see Appendix A).

The lack of background information makes it impossible to provide a general estimate of accuracy for the data contained in GlaThiDa. To raise awareness of data limitations we instead highlight the major factors controlling accuracy of the measurements and provide examples. The factors can be divided into two main categories and their potential impact on GlaThiDa is discussed in the following.

a. *Accuracy of data interpretation*: Several parameters such as basal conditions and internal structures of glaciers impact on geophysical measurements of ice thickness and render data interpretation challenging (Plewes and Hubbard, 2001). For instance, Macheret and Zhuravlev (1982) measured ice thickness for a considerable number of glaciers on Svalbard and obtained consistently low

Table 2
Overview of the data contained in Table TTT. The second column indicates the number of entries related to a specific method shown in the first column. Thereby one entry refers to the ice thickness at one point on one glacier. The third and fourth columns show the number of glaciers covered by the respective entries and the number of sources.

Method	Entries	Glaciers	Publications
OIB, airborne radio-echo sounding	726,997	617	2
Airborne radio-echo sounding	13,221	1	1
Terrestrial radio-echo sounding	16,700	11	10
Direct drilling	8	1	1
Other	2703	2	1
All	759,629	632	15

Table 3
Overview of the glacier area information as reflected in GlaThiDa.

Data source	≤5 km^2	5–50 km^2	50–500 km^2	500–5000 km^2	>5000 km^2
Literature review	51%	25%	19%	4%	2%
OIB	11%	32%	37%	20%	1%
All	26%	29%	30%	14%	1%

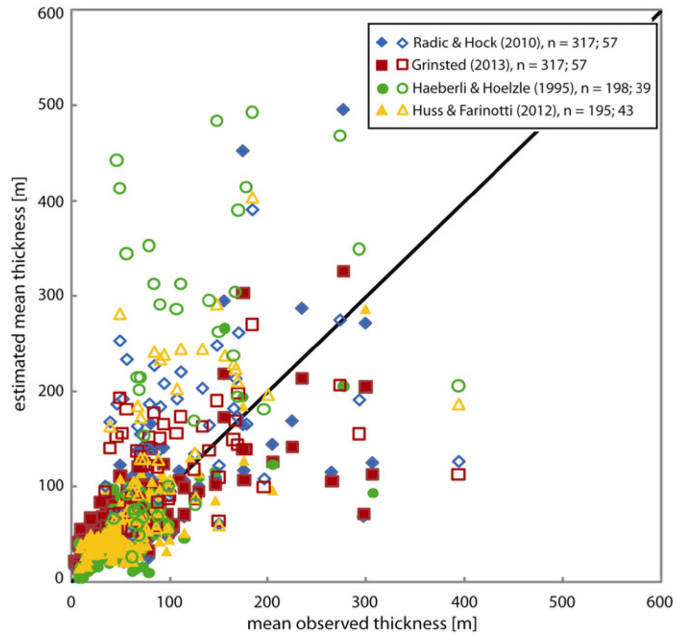


Fig. 3. Comparison of mean observed thickness and estimated mean thickness of glaciers. Symbols represent the different estimation approaches; filled symbols depict realistic entries, while blank symbols depict unrealistic entries (corresponding numbers of the dataset are given in the legend).

ice thicknesses. A counterstatement was later published by Dowdeswell et al. (1984), stating that the radar data were misinterpreted. According to Dowdeswell et al. (1984) the thickness of the polythermal glaciers was underestimated systematically because Macheret and Zhuravlev (1982) interpreted the prominent signal return generated at the interface of cold and temperate ice as the signal from the glacier bed. Later this was acknowledged by the authors and several glaciers were omitted from their study (Zhuravlev, 1985).

The data by Macheret and Zhuravlev (1982) are included in GlaThiDa but flagged as unreliable by a reference to the publication of Dowdeswell et al. (1984) in the remarks field (T24). We do not expect that similar misinterpretations are frequent in GlaThiDa. Nevertheless it is difficult to detect erroneously

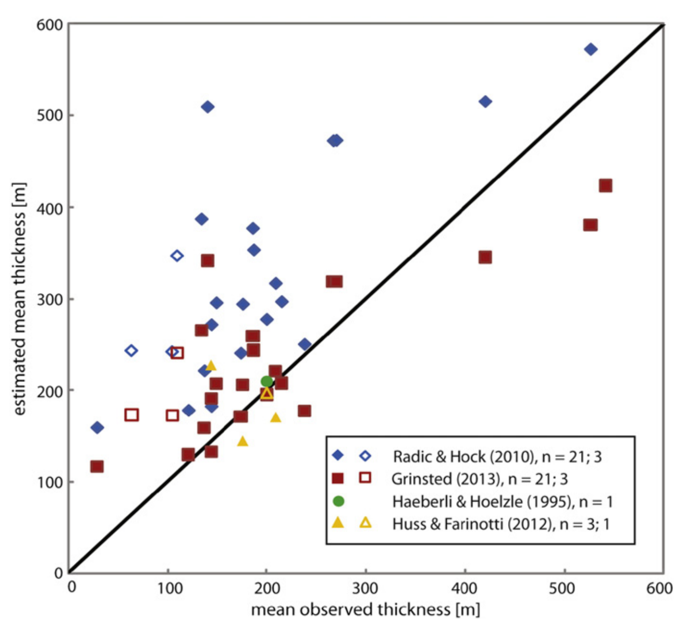


Fig. 4. Comparison of mean observed thickness and estimated mean thickness of ice caps. Symbols represent the different estimation approaches; filled symbols depict realistic entries, while blank symbols depict unrealistic entries (corresponding numbers of entries are given in the legend).

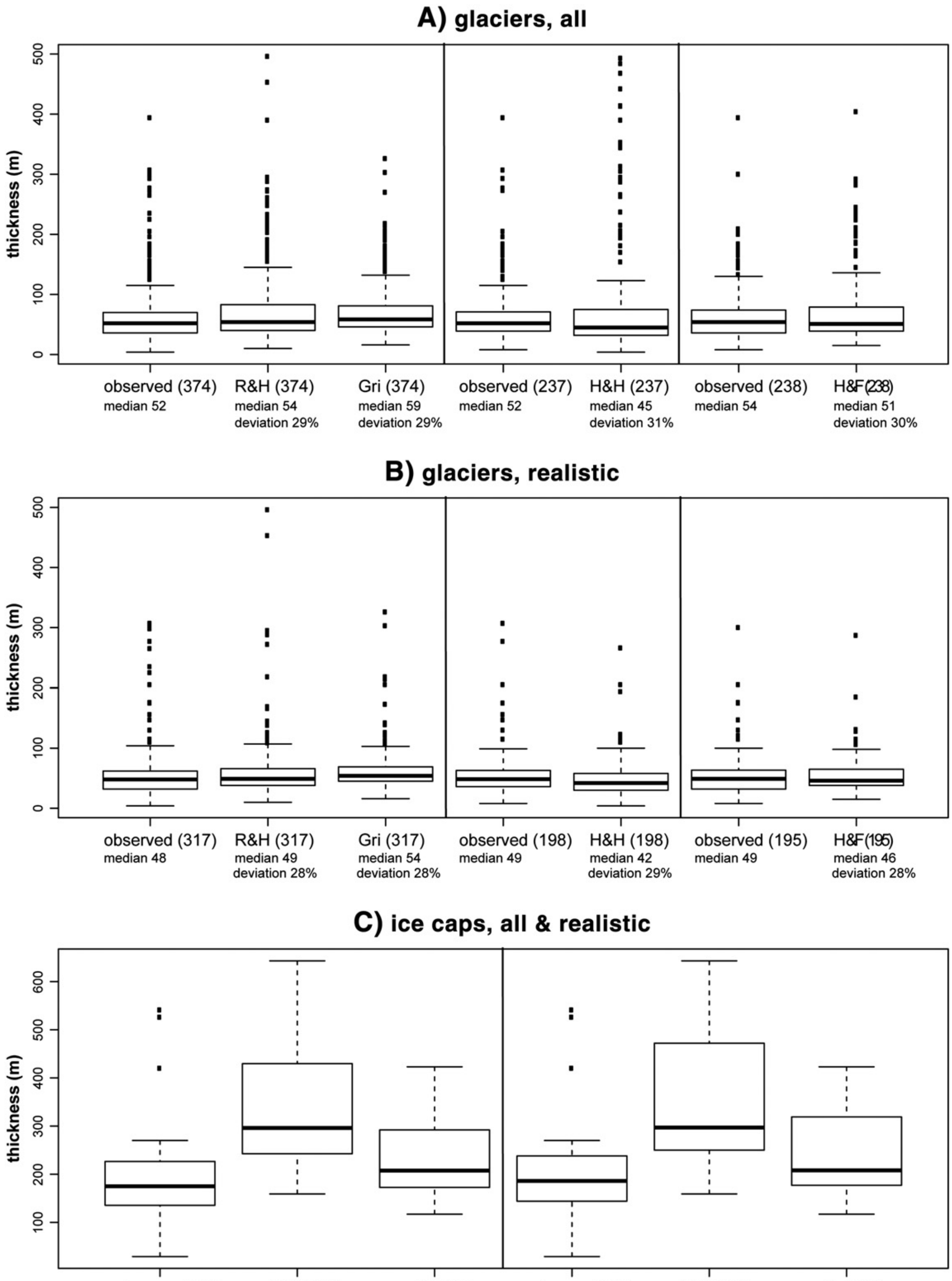


Fig. 5. Box-plot diagrams based on the comparison of mean observed and estimated mean thicknesses, for glaciers (upper diagrams A, B) and ice caps (lower diagram C). The box-plots depict the median value (thick line), the lower and upper quartile (box), the minimum and maximum values (brace), as well as outlier values. The different estimation approaches are represented by the following abbreviations: R&H = Radić and Hock (2010); Gri = Grinsted (2013); H&H = Haeberli and Hoelzle (1995); H&F = Huss and Farinotti (2012). The upper diagram A) statistics for all glacier entries (including the flagged data; cf. Fig. 4), B) only the realistic data (cf., Fig. 4), and C) the performance of volume–area-scaling approaches for ice caps (all data to left and realistic to the right). Corresponding number of entries are given in brackets. Median thicknesses (in m) and median of relative absolute deviations to the observed values (in %) are given for each data series.

interpreted data without any attempt of reproducing the measurements. The example illustrates that uncertainty in ice thickness measurements in GlaThiDa can potentially be higher than theoretical or site-specific uncertainties as listed in Section 2.2.

b. *Data coverage and adequateness of interpolation*: The vast majority of the entries in GlaThiDa is derived from radio-echo sounding, an approach allowing the measurement of ice thickness either at point locations or along transects. To obtain mean or maximum thickness values for a glacier or ice cap, the measurements have to be inter and extrapolated from the point or profile information, ideally based on a dense array of measurements. However, the measurement density is often less than ideal, as when the array consists of a one to a few profiles or even just a small number of boreholes (Cogley et al., 2011). Clear criteria such as method and survey setup, including observation density, are still missing and depend on individual glacier types. Hence, uncertainty in the interpolated ice thickness distribution is influenced by (i) the data coverage (i.e. are the measurements distributed to represent most areas of the glacier), and (ii) by the adequacy of the chosen interpolation method. The aim is to acquire data and observations conforming to the entire glacier.

We assume that a considerable amount of the data on mean ice thickness and maximum ice thickness present in GlaThiDa has been derived from raw data that do not optimally cover the respective glaciers. In most cases this issue is simply related to practical constraints: In situ measurements are difficult to carry out in steep, crevassed, avalanche or debris covered areas of a glacier. Therefore, surveys are mainly conducted on flat and crevasse-free (and thick) glacier tongues and might thus not be representative for the entire glacier (Linsbauer et al., 2012).

The impact of different levels of data coverage was investigated for Barnes Ice Cap (Northern Canada), an almost axisymmetric ice cap with a simple geometry and an area of almost 6000 km^2 (Abdalati et al., 2004). Barnes Ice Cap is covered by a rather dense (approx. 10 km horizontal spacing) array of OIB profiles which can be considered a good coverage. Knecht (2014) calculated the mean ice thickness for the ice cap and thereby analyzed how interpolated mean ice thickness varies when the number of profiles used for the interpolation is reduced. It could be shown that a reduction to a grid of 20 km and 30 km spacing, respectively, reduced mean ice thickness by 10% and 22% compared to the value based on all ice thickness data. The example cannot simply be considered representative for other glaciers or ice caps. Glacier geometry and the choice of an interpolation scheme define for each individual glacier what data coverage is needed for a reliable calculation of ice thickness. However, as stated above, for many glaciers the data coverage is likely below an optimal level and interpolated mean or maximum ice thickness can be subject to a considerable uncertainty.

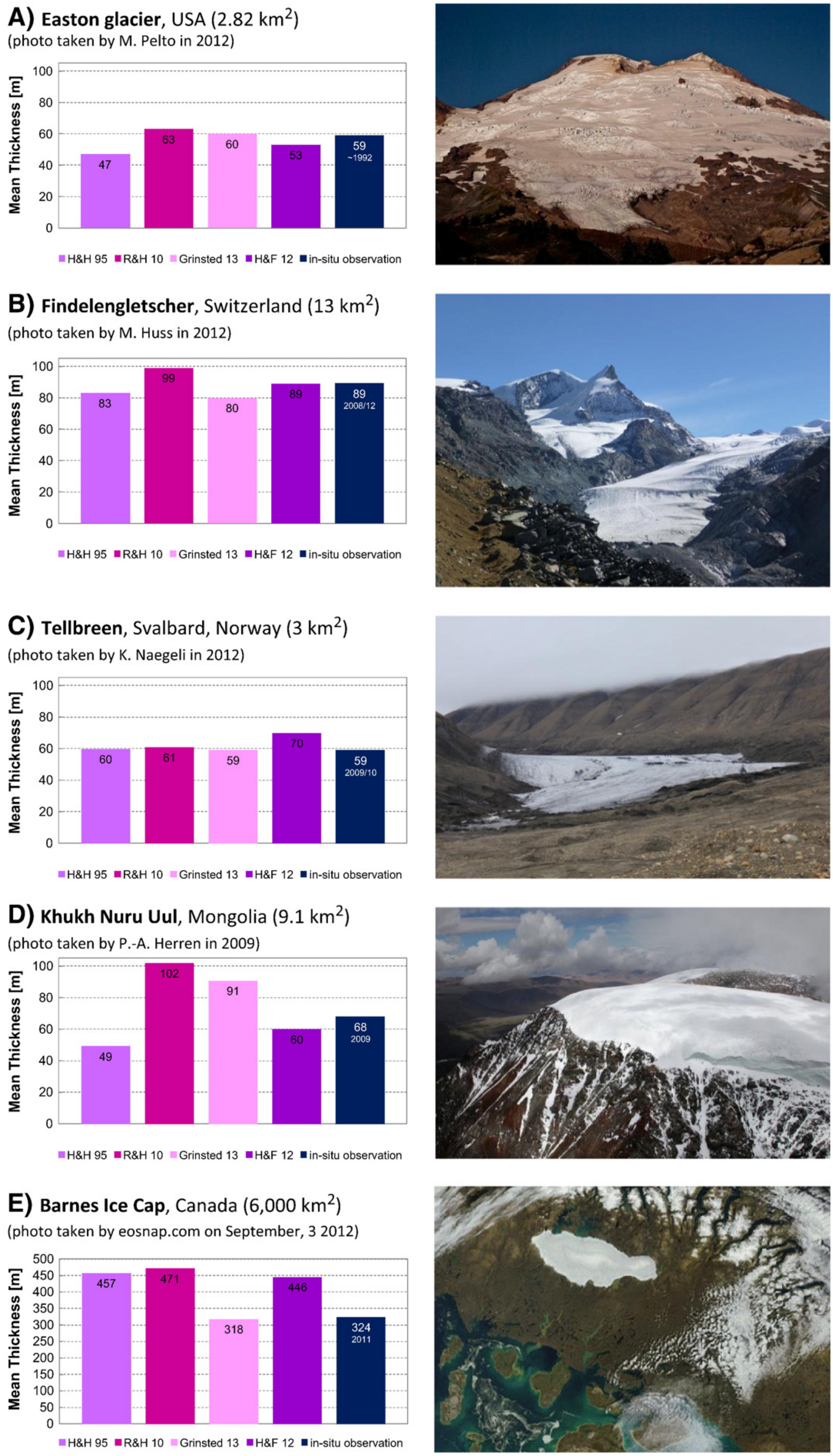
The examples above refer to the application of radio-echo sounding, but other methods applied to measure ice thickness are subject to similar or additional challenges. We recommend that the users of GlaThiDa consider theoretical and site-specific uncertainties of individual methods (Section 2.2) as a minimum estimate for the uncertainties inherent to the point data (Table TTT). Glacier mean ice thickness, maximum ice thickness and elevation interval mean ice thickness (Tables T and TT) need to be considered as being subject to uncertainties substantially larger than the method-specific uncertainties listed in Section 2.2.

3.3. Application and evaluation of glacier thickness and volume estimation methods

A comparison of the results from the different estimation methods with observations is given in Figs. 3 and 4. Mean observed thicknesses from the database, typically derived from interpolations, are compared to estimated mean thicknesses calculated from area- and slope-dependent approaches. Thereto, the results from area–volume-scaling (Radić and Hock, 2010; Grinsted, 2013) are divided by the glacier area. The slope-dependent approaches (Haeberli and Hoelzle, 1995; Huss and Farinotti, 2012) directly provide mean glacier thicknesses. The comparison with volume–area-scaling is performed for 374 glaciers; this number is reduced to 317 glaciers, when excluding the data that is flagged as unrealistic in the database (e.g., based on review articles). These data are mostly from Svalbard (Macheret and Zhuravlev, 1982) and are likely erroneous as explained in Section 3.2. The numbers are smaller for the other comparisons, since the attribution to related datasets (WGI, RGI) was not possible for all glaciers. Due to their different characteristics, the comparison was performed separately for glaciers (Fig. 3) and ice caps (Fig. 4). An overview of the statistical performance of the different datasets (observed and estimated thicknesses) is given in Fig. 5. The box-plot diagrams show the spread of the data around the median value, the minimum and maximum values, as well as the outliers. This analysis is performed for all data (including the flagged data), as well as for the realistic data only.

For glaciers (Fig. 3), the results of all estimation approaches indicate a moderate agreement for glaciers with small thicknesses (up to 50 m), while the spread becomes larger for thicker glaciers. In comparison to the observed glacier thicknesses, all approaches have a tendency to overestimation. The two area-dependent approaches both overestimate glacier thicknesses by about 30% (for Radić and Hock (2010) 30%, for Grinsted (2013) 38%, respectively, for the entire dataset, and 24% and 37%, respectively, when excluding the flagged data). The slope-dependent approaches show a less pronounced trend. Haeberli and Hoelzle (1995) overestimate by 20% for the entire dataset and underestimate by 2% when using the realistic data only, while Huss and Farinotti (2012) overestimate by 27% (all data) and 20% (realistic data only). All datasets show a large number of outliers, which are only partly removed by excluding the flagged data. Nevertheless, the variance is reduced by this exclusion, as is best seen in the datasets of Radić and Hock (2010) and Haeberli and Hoelzle (1995) (Fig. 5). The statistics for the volume–area scaling approaches show that the relative absolute deviation of observed and estimated thicknesses has a median of 29% for all data and of 28% when excluding the flagged data (cf. Fig. 5). For Haeberli and Hoelzle (1995) the relative absolute deviation of the median is 31% (all data) and 29% (without flagged data). For the estimation approach by Huss and Farinotti (2012) this results in relative differences of the median values of 30% (all data) and 28% (without flagged data). The standard deviation is largest for the approach by Haeberli and Hoelzle (1995) and smallest for Grinsted (2013). It has to be mentioned, however, that the parameters of the latter have been obtained by statistical fitting on (mostly) the same source data as used for this evaluation, which reduces the comparability of these results to a certain extent.

For ice caps (Fig. 4), the number of data points is much smaller. Nevertheless, a clear pattern is visible in the comparison of measured and estimated mean thicknesses. Both volume–area parameterizations clearly overestimate the thicknesses of ice caps. The approach by Radić and Hock (2010) gives an average overestimation of around 130% for both datasets. The values compiled from Grinsted (2013) indicate a better performance; for all data the values are overestimated by 127%, but by the exclusion of unrealistic data, the overestimation decreases to 19%. The analysis indicates that a more detailed investigation of the scaling parameters for V–A scaling of ice caps might be needed. The two approaches based on the shallow ice approximation were applied to a smaller number of ice caps since the required additional information (e.g. surface topography) could not be


A) Easton glacier, USA (2.82 km2)
(photo taken by M. Pelto in 2012)
Mean Thickness [m]
47
63
60
53
59
~1992
H&H 95
R&H 10
Grinsted 13
H&F 12
in-situ observation
B) Findelengletscher, Switzerland (13 km2)
(photo taken by M. Huss in 2012)
Mean Thickness [m]
83
99
80
89
89
2008/12
H&H 95
R&H 10
Grinsted 13
H&F 12
in-situ observation
C) Tellbreen, Svalbard, Norway (3 km2)
(photo taken by K. Naegeli in 2012)
Mean Thickness [m]
60
61
59
70
59
2009/10
H&H 95
R&H 10
Grinsted 13
H&F 12
in-situ observation
D) Khukh Nuru Uul, Mongolia (9.1 km2)
(photo taken by P.-A. Herren in 2009)
Mean Thickness [m]
49
102
91
60
68
2009
H&H 95
R&H 10
Grinsted 13
H&F 12
in-situ observation
E) Barnes Ice Cap, Canada (6,000 km2)
(photo taken by eosnap.com on September, 3 2012)
Mean Thickness [m]
457
471
318
446
324
2011
H&H 95
R&H 10
Grinsted 13
H&F 12
in-situ observation

extracted from the WGI/RGI for areas consistent with the perimeter covered by the direct measurements. The comparison indicates only small differences, but due to the limited sample size, any interpretation would be speculative.

In order to exemplify the performance of ice thickness estimation methods in more detail, three glaciers and two ice caps are selected from our database and the measured thickness is compared to the estimated value. The glaciers and ice caps are selected based on available detailed information as well as on their different thermal and geometric characteristics.

(A) Easton Glacier (Mount Baker, North Cascade range, USA; Fig. 6A) is a valley glacier situated on an active stratovolcano. The glacier ranges from 1700 m a.s.l. up to 2900 m a.s.l., has a length of 3.95 km and has an area of 2.82 km^2 (Pelto, 2006; WGMS, 2012). The measured mean thickness is 59 m (Harper, 1993 in Finn et al., 2012). (B) Findelengletscher is a temperate valley glacier, situated in Southern Switzerland (Fig. 6B). Its maximum elevation is at 3906 m a.s.l. and its terminus at 2560 m a.s.l. (Joerg et al., 2012). The glacier covers about 13 km^2. The mean thickness is 89 m (Huss et al., 2014). (C) Tellbreen, situated in Central Spitsbergen (Svalbard, Norway; Fig. 6C), is a cold-based valley glacier. It ranges from 340 m a.s.l. up to 800 m a.s.l. (Hagen et al., 1993), has an area of about 3 km^2 and has a mean thickness of 59 m (Bælum and Benn, 2011). (D) Khukh Nuru Uul is a small ice cap with distinct outlet glaciers in the Tsambagarav mountain range in the Mongolian Altai (Fig. 6D). It has an area of 9.1 km^2 (in 2002) and ranges from 2900 to 4130 m a.s.l. The ice cap is cold-based (Herren et al., 2013). Mean thickness of the ice cap is calculated to be 68 m (Machguth, 2012) and is based on a 2 km long GPR profile that stretches over most of the ice cap but excludes the two outlet glaciers. (E) Barnes Ice Cap is situated on central Baffin Island, Arctic Canada (Fig. 6E). It covers close to 6000 km^2 and has well-defined margins (Svoboda and Paul, 2009). It extends from about 500 m a.s.l. up to over 1100 m a.s.l. (Jacobs et al., 1993). The ice cap is a remnant of the Laurentide ice sheet, which covered much of Canada during the last ice age (Svoboda and Paul, 2009). Most probably it has a polythermal regime, as it is indicated by the climatic conditions (Abdalati et al., 2004). Most of the selected examples (A–D) have a mean thickness of 60–90 m, similar to most of the glaciers in the GlaThiDa, in contrast to example e, which has a mean thickness of about 300 m (Knecht, 2014).

For the five selected glaciers and ice caps mean thicknesses are calculated using the three different estimation approaches described above. Glacier outlines are obtained from the RGIv3.2 and thus date between the years 2000–2010. The comparison of estimated versus measured ice thicknesses shows differences and analogies (Fig. 6). The ice thicknesses derived from the estimation approach by Haeberli and Hoelzle (1995) indicate generally lower values, but rather close to the in situ observations, especially for Findelengletscher and Tellbreen (lilac columns Fig. 6B, C). Higher differences are found for the Easton Glacier and the two ice caps (Fig. 6A, D, E). Volume–area scaling based on the parameters by Radić and Hock (2010) rather overestimates the measured mean ice thickness, but is close to the in situ values, except for the two ice caps (magenta columns Fig. 6D, E). The results from the approach by Grinsted (2013) show a relatively good agreement for all five examples (pink columns Fig. 6A–E); greatest differences appear for Khukh Nuru Uul (Fig. 6D). Ice thicknesses calculated based on Huss and Farinotti (2012) show a relatively good agreement for most of the glaciers (purple columns Fig. 6A–E), except for Barnes Ice Cap. In general, it appears that Tellbreen is best reflected by all models (Fig. 6C). Largest differences are calculated for the two ice caps.

4. Discussion

4.1. The glacier thickness database GlaThiDa

The quality and especially the level of detail of GlaThiDa reflect the limitations of a literature review study and of the published glacier data itself. The database cannot be stated as fully complete, since there are other data on ice thickness available, e.g. from the ice core community, mostly focusing on the reconstruction of the global climate record (e.g., Eisen et al., 2003; Herren et al., 2013), or from isolated ice thickness measurements not covering the entire glacier. Other studies with ice thickness data probably exist that we are not aware of. Together with the most recent publications (e.g., Rignot et al., 2013; Zhu et al., 2014), we aim at including these data in an updated version of GlaThiDa.

Regarding the global distribution of published glacier thickness data, the representativeness of the regional numbers is partly problematic. In our database, this is especially valid for the number of observation given for the Caucasus, and the whole of High Mountain Asia. While scientists from North America, New Zealand and Europe are used to publishing their results in English and in international journals, scientists from other countries often publish their results in mother tongue and in national journals and reports. We partly included such publications, e.g. in Russian, in the database, but we are aware that probably much more data is around, but unavailable in English. This is obviously related to the method of a literature review and might be improved by an additional call for data to the glacier community.

The quality of the values of mean ice thickness is strongly influenced by the glacier or ice cap geometry and the applied observation design. For example, Thyssen and Ahmad (1969) investigated the thickness of Aletschgletscher, the largest glacier of the European Alps. They applied seismic measurements in the area of the Konkordiaplatz, a large confluence zone with a distinct overdeepening, and derived a mean thickness for this area of 500 to 600 m. More recent studies confirm maximum thicknesses of 890 m, with an error of about 5%, by ice drillings at the same location (Hock et al., 1999). However, these high thicknesses are limited to the confluence zone, while the mean thickness of the entire glacier would be around 190 m, as calculated from sparse radio-echo soundings combined with modeling (Farinotti et al., 2009). Related misinterpretations often occur when observations are not clearly conforming to the entire glacier. Nevertheless, only a collection of all published glacier thickness data in an open access database allows for the analysis of this data and the spotting of problematic as well as useful thickness data.

The level of detail given is strongly related to the type and focus of the corresponding publication. While technical papers concentrate more on the potentials and limits of the applied exploration method, other authors just compute an average value of glacier thickness to perform related impact studies. In addition, the increasing interest in sensitivity studies came up only recently. Due to missing data on methodological accuracy as well as interpolation accuracy (cf. Appendix A), it is not possible to quantify general database accuracy.

Fig. 6. A–E: The left column depicts the comparison of estimated (different purple colors) versus measured (blue) mean ice thickness (note the different scale in case E). The numbers in the bars give the estimated/measured values; the date in the blue bar gives the year of the in situ exploration. The right column gives a picture from each of the five different glaciers.

Most of the glaciers and ice caps investigated have a relatively small size and a mean thickness of ≤100 m. These numbers are obviously related to the feasibility of conducting in situ measurements. With an increasing number of airborne explorations as well as further technical innovations, the accessibility plays a minor role.

4.2. Application: estimation approaches versus in situ observations

The comparison of all available thickness values from glaciers and ice caps with three different estimation approaches (Radić and Hock (2010), Grinsted (2013), Haeberli and Hoelzle (1995), Huss and Farinotti (2012)) indicates that the uncertainty in ice thickness estimates based on surface information is considerable and confirms the earlier studies (e.g., Brückl, 1970; Müller et al., 1976; Cogley, 2012). By evaluating comments in the database, unrealistic values are excluded from the dataset and analyzed separately (see Figs. 3, 4, 5).

For glaciers the comparison indicates that the uncertainties are large (median relative absolute deviation of around 30%). In addition, all estimation approaches show a tendency of overestimation by 20–30% (Fig. 5). For ice caps the comparison of observed and estimated mean thicknesses depicts a distinct tendency to overestimation by the two volume–area scaling approaches, but the dataset is small and the uncertainties are large.

Besides the fact that the estimation approaches are best suitable for large samples (Cogley, 2012), we also show and discuss the basis results calculated for individual glaciers in order to exemplify the strengths and limitations of existing estimation approaches (Fig. 6). Looking in detail, it becomes apparent that the largest differences result in two ice caps. Reasons for the large differences in calculated ice volume at Khukh Nuru Uul might be the erroneous glacier outlines contained in the RGIv3.2 and the limited amount of GPR profiles that do not represent the entire glacier surface. The example demonstrates that the data need to be used with care and that deviations cannot be simply attributed to inaccuracies in the parameterizations.

In conclusion, our comparison indicates that the different parameterizations appear to be less suitable for estimating the thickness of ice caps. Since this cannot simply be concluded from the comparison given here, it has to be analyzed in more details including a higher number of glaciers or ice caps, with detailed information. In addition, the comparison of observed and estimated point and profile data might be an interesting next step to evaluate corresponding estimation approaches on that corresponding scale (e.g., Huss and Farinotti, 2012).

5. Conclusion

A global database of measured glacier and ice cap thicknesses is compiled from literature review and from OIB data with the goal of the data becoming available for purposes such as, for instance, the calibration and validation of estimation approaches. The database is not complete, but provides a good overview of existing thickness measurements and their quality. The accuracy of the mean thickness values is subject to a considerable spread due to large variety in the chosen measurement set-up, data interpretation and applied interpolation methods. With these limitations in mind the database can be used for a comparison with established estimation approaches. The outcome of the data presented here and its application for a model comparison reveal the following main results:

1) We present a global database of glacier thicknesses for about 1100 glaciers compiled by different survey methods. Point information is given for 632 glaciers (about 760,000 entries). Data is available for all 19 regions with a bias to the northern hemisphere. Most of the glaciers investigated in the literature review (83%) have a mean thickness of ≤100 m. 26% of all glaciers included in the T table have a size of ≤5 km^2; 29% and 30% of the glaciers investigated have a size of 5–50 km^2 and 50–500 km^2, respectively. These numbers are obviously related to the feasibility of conducting in situ and airborne measurements to derive glacier thickness.
2) The original measurements are compiled and documented in different levels of detail. Most observations are based on measurements at point locations and along profile lines. As a consequence, these observations do not provide glacier-wide results (such as mean and maximum thickness). Corresponding estimates are subject to both observational and extrapolation uncertainties. Only a very limited number of studies give full details, such as point information and interpolation method (cf. Appendix A). Therefore, a quality assessment of the database is limited to single case studies and qualitative evidences.
3) The comparison of observed and estimated ice thicknesses (for glaciers and ice caps) from different estimation approaches reveals large uncertainties at both the glacier-wide and the local scale. For glaciers, the median relative absolute deviation lies around 30% when analyzing the different estimation approaches. Main limitations seem to be glacier outlines used for the estimation approaches and/or temporal shifts between in situ observations and estimation input data.
4) The increasing number of point information resulting from airborne radar campaigns such as OIB, additionally allows for direct validation (and calibration) of recently published estimation methods for the spatial ice thickness distribution along profiles and, hence, has a large potential for improving our understanding on the global distribution of glacier ice volume.

Regardless of its limitations, our glacier thickness database represents a substantial overview of existing data and appropriate exploration methods. In addition, it provides data for the validation and calibration of modeling studies, which are applied to estimate global ice volume, its change and related impacts. Based on our findings, future comparisons should include different glacier types in order to check their representativeness in different estimation approaches and to further improve local and regional assessments.

GlaThiDa is a first step toward compiling the large number of ice thickness observations but requires joint efforts of the monitoring organizations and the scientific community. The present database is available online and will be updated and extended regularly. Hence, it is a living document allowing the use of the data as well as the implementation of additional data for further improvement. The glacier community is invited to contribute to and benefit from the database.

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Appendix A

Overview of all compiled thickness observations (values represent the number of entries, *italics* = unpublished; blue = point data available; italic & blue = Operation IceBridge data).

REFERENCES	T	TT	TTT	Mean Slope	Mean Thickness	Mean Thickness Accuracy	Maximum Thickness	Maximum Thickness Accuracy	Survey Method	Interpolation Method
Aðalgeirsdóttir et al., (2011). TC.	1				1		1		1	
Aleynikov et al., (2002). Nor. Hydr.	1				1		1		1	
Andreassen et al., (2006). NVE Rapp.	2				2				2	
Araos et el., (2007). Rev. Geo. Nor. Gran.	1				1		1		1	
Aric, K. and Brückl, E., (2001). ZAMG. based on Aric, K. and Brückl, E., (1987). ZAMG. and Steinhauser, F. (1987). ALGB.	3				3		3		3	
Aric, K. and Brückl, E., (2001). ZAMG. based on Bittmann et al., (1973). ZAMG. and Brockamp, B., (1958). IASH Publ. and Steinhauser, F. (1987). ALGB.	1				1		1		1	
Aric, K. and Brückl, E., (2001). ZAMG. based on Brückl et al., (1971). ZAMG.	1				1				1	
Aric, K. and Brückl, E., (2001). ZAMG. based on Brückl et al., (1980). ZAMG.	2				2				2	
Aric, K. and Brückl, E., (2001). ZAMG. based on Brückl, E. and Bittmann, O., (1977). ZAMG.	4				4				4	
Aric, K. and Brückl, E., (2001). ZAMG. based on Brückl, E. and Gangl, G., (1972). ZAMG. and Steinhauser, F. (1987). ALGB.	1				1		1		1	
Aric, K. and Brückl, E., (2001). ZAMG. based on Förtsch, O., (1958). ZfG.	1				1				1	
Aric, K. and Brückl, E., (2001). ZAMG. based on Miller, H., (1972). ZGG.	2				2				2	
Azam et al., (2012). Jour. Glac.	1						1	1	1	
Baelum and Benn, (2011). TC.	1				1				1	
Bahr et al., (1997). JGR.	13			1	13		4			
Bahr et al., (1997). JGR. and Clarke, G.K. and Goodman, R.H., (1975). Jour. Glac.	1				1					
Bahr et al., (1997). JGR. and Harper, J.T., (1993). AAAR.	1		1	1	1		1		1	
Bahr et al., (1997). JGR. and Miller, M. M. and Pelto, M. S., (1999). Geogr. Ann.	1			1	1		1		1	
Bahr et al., (1997). JGR. and Narod, B.B and Clarke, G.K.C. (1980). Jour. Glac.	1				1		1			
Bahr et al., (1997). JGR. based on Heinrichs et al., (1995). USGS.	1				1		1		1	
Bahr et al., (1997). JGR. based on Kuzmichenok (1996). MGI.	4			4	4				4	
Bahr et al., (1997). JGR. based on Macheret et al., (1988). MGI.	2			2	2				2	
Bahr et al., (1997). JGR. based on Nafz and Smith (1993).	1				1		1		1	
Bahr et al., (1997). JGR. based on Narozhniy (1998). MGI.	4			4	4				4	
Bahr et al., (1997). JGR. based on Sikonia (1982).	1				1		1		1	
Bahr et al., (1997). JGR. based on Zhuravlev, A.B., (1985). MGI.	6			6	6				6	
Bhatt et al., (1980). ZGG.	1				1	1	1	1	1	
Binder et al., (2009). Ann. Glac.	2				2	2	2	2	2	2
Binder, D., (2009). Diploma Thesis.	2				2	2	2	2	2	
Bindschadler et al., (1977). Jour. Glac.	1			1	1		1		1	
Björnsson et al., (1996). Jour. Glac.	4						4		4	
Björnsson et al., (2006).	1						1		1	
Björnsson, H., (1981). Geogr. Ann.	3				3		3		3	
Björnsson, H., (1986). Ann. Glac.	1				1	1	1	1	1	
Blindow et al., (2012). Int. Conf. GPR.	2				2		2		2	2
Bogorodsky and Federov, (1970). nown.	6				6				6	
Brown et al., (2010). Glob. Plan. Chn.	1			1	1		1		1	1
Brückl et al., (1971). ZAMG. and Steinhauser, F. (1987). ALGB.	3	3			3		3		3	
Campbell et al., (2012). Jour. Glac.	1						1		1	
Chen, J. and Ohmura, A., (1990). IAHS Publ.	6				6				6	
Conway et al., (2009). Ann. Glac.	1						1	1	1	
Davis et al., (1973). Jour. Glac.	1						1		1	

Dowdeswell et al., (2002). JGR.	2						2		2	2
Driedger, C.L., and Kennard, P.M., (1986a). Ann. Glac. and Bahr et al., (1997). JGR.	8				8		6		5	
Driedger, C.L., and Kennard, P.M., (1986a). Ann. Glac. and Driedger, C.L., and Kennard, P.M., (1986b). U.S.G.S. and Bahr et al., (1997). JGR.	16				16		15		16	
Driedger, C.L., and Kennard, P.M., (1986a). Ann. Glac. based on Driedger, C.L., and Kennard, P.M., (1986b). U.S.G.S. and Bahr et al., (1997). JGR.	1				1		1		1	
Driedger, C.L., and Kennard, P.M., (1986a). Ann. Glac. based on Hodge (1979). Jour. Glac. and Bahr et al., (1997). JGR.	1				1		1		1	
Driedger, C.L., and Kennard, P.M., (1986a). Ann. Glac. based on Trembley written com. (1985)	1				1					
Driedger, C.L., and Kennard, P.M., (1986b). U.S.G.S. and Bahr et al., (1997). JGR.	2				2		2		2	
Engel et al., (2012). Jour. Glac.	2				2	2	2	2	2	2
Farinotti et al., (2009). Jour. Glac.	4				4		4		4	
Finn et al., (2012). Jour. Glac.	2		2		2		2		2	
Fischer et al., (2013). EGU Poster.	11				11		11		11	
Fischer, A. and Kuhn, M., (2013). Ann. Glac.	64				64	64	64	64	64	
Förtsch et al., (1955). BzG.	1				1				1	
Förtsch et al., (1955). BzG. and Giese, P., (1963). IAHS Publ.	1				1		1		1	
Förtsch, O. and Vidal, H. (1956). BzG.	1				1		1		1	
Förtsch, O. and Vidal, H. (1957). BzG.	1				1	1			1	
Förtsch, O. and Vidal, H. (1958). ZGG.	1				1	1			1	
Förtsch, O. and Vidal, H. (1968). ZGG.	1				1				1	
Funk et al., (1997). BHS.	1				1		1		1	
Gabbi et al., (2013). HESS.	5				5	5	5	5	5	5
Gades et al., (2000). IAHS. Publ.	2						2	2	2	
Gades et al., (2012). Jour. Glac.	1			1			1		1	
Gergan et al., (1999). Curr. Scie.	1			1	1		1		1	
Giesen, R.H. and Oerlemans, J., (2010). TC.	1						1		1	
Goodman et al., (1975). Jour. Glac.	1						1		1	
Haeberli, W. and Fisch, W., (1984). Jour. Glac.	1						1	1	1	
Haerberli et al., (1988). ZGG. and Lüthi, M.P., (2000). PhD Thesis.	1				1		1		1	
Hagg et al., (2008). ZGG.	4	4	4	4	4	4	4	4	4	4
Hagg et al., (2012). Erdkunde.	1	1	1	1	1	1	1	1	1	1
Herzfeld, U. C. and Holmlund, P., (1988). ZGG.	1						1	1	1	1
Hochstein et al., (1995). NZ J. Geol. and Geoph.	3						3		3	
Holmlund, P., (1986). Geogr. Ann.	1			1			1	1	1	
Hubbard et al., (1998). Jour. Glac. based on Sharp et al., (1993). ESPL.	1						1			
Huss et al., (2008). Jour. Glac. based on Blatter and Kappenberger (1988). Jour. Glac.	1						1		1	
Huss et al., (2012). Unpublished based on GPR data from 2008 (ETHZ) and 2012 (UZH, UFR).	*1*	*1*	*1*	*1*	*1*		*1*		*1*	
Huss, M., (2010). Geo. Hel.	1	1	1	1	1	1	1	1	1	1
Kennett et al., (1993). Ann. Glac.	1			1			1	1	1	
Klingbjer, P. and Neidhart, F., (2006). AAAR.	1						1		1	
Knudsen, N.T. and Hasholt, B., (1999). AAAR.	1				1	1	1	1	1	
Koerner, R.M. and Paterson, W.S.B., (1974). Quart. Res.	1						1		1	
Kotlyakov, V.M. and Macheret, Y.Y., (1987). Ann. Glac.	24						24		24	
Kotlyakov, V.M. and Macheret, Y.Y., (1987). Ann. Glac. Based on Dowdeswell, J.A. and Drewry, D.J., (1984). Jour. Glac.	19						19		19	
Kutuzov et al., (2012). EGU Poster	1				1	1	1	1	1	
Lapazaran et al., (2013). Pol. Re.	1				1	1	1	1	1	1
Li et al., (2012). JGR.	5						5		5	2
Ma et al., (2008). Jour. Glac. Geocr.	1				1		1		1	1

Appendix (*continued*).

Ma et al., (2010). CSB.	1				1		1		1	1
Macheret et al., (1985). PGG.	19						19		19	
Macheret et al., (1988). MGI.	41			32	41				40	
Macheret et al., (1999). ZGG.	26				12		26		26	
Macheret et al., (2009). Ann. Glac.	1				1		1		1	
Machguth, H., (2012). Unpublished Data. and Schwikowski et al., (2010). PSI-ETH and UniBe Rep.	*1*		*1*		*1*		*1*		*1*	
Makarevich, K.G., (1962). IHAS Publ.	2				2		2			
March, R.S., (2000). USGS.	1		1		1		1		1	
Morgan, V.I. and Budd, W.F., (1975). Jour. Glac.	1						1		1	
Navarro et al., (2005). Ann. Glac.	1				1		1		1	
Navarro et al., (2009). Ann. Glac.	2				2	2	2		2	
Nikitin et al., (2000). MGI.	56				56		56		56	
Nolan et al., (1995). Jour. Glac. and Pelto et al., (2008). TC.	1						1	1	1	
Park, M., (2011). Msc Thesis.	1		1				1		1	
Pattyn et al., (2009). Ann. Glac.	1				1				1	1
Peduzzi et al., (2010). TC.	1				1	1			1	
Pettersson et al., (2011). Geogr. Ann.	1				1		1		1	1
Popovnin, V.V., (1999). Geogr. Ann.	1						1		1	
Rabatel et al., (2011). TC.	4						4		4	
Raymond et al., (2005). Jour. Glac.	1						1		1	
Rivera, A. and Cassassa, G., (2010). Int. Rep.	4						4		4	
Rückamp, M. and Blindow, N., (2011). EAASS. and Blindow et al., (2010). Ann. Glac.	1				1		1		1	1
Saetrang, A.C. and Wold, B., (1986). Ann. Glac.	1				1		1		1	
Saintenoy et al., (2011). Proc. IWAGPR 2011. and Saintenoy et al., (2012). Draft.	1				1		1		1	1
Salzmann et al., (2012). TC.	1						1		1	
Sanders et al., (2010). AJS.	1				1		1		1	
Span et al., (2005) Öst. Meteo & Geophysik	2						2		2	
Sugiyama et al., (2008). BGR.	1		1						1	
Thyssen, F. and Ahmad, M., (1970). Polarfor.	1						1		1	
Thyssen, F. and Kohnen, H., (1968). Polarfor.	1				1				1	
Tucker et al., (2009). Geol. Soc. US.	1		1				1	1	1	
Yafeng et al., (2008). SPSP.	25						25		25	
Zamora et al., (2009). Jour. Glac.	1						1		1	
Zhuravlev, A.B., (1981). MGI. and Macheret, Y.Y. and Zhuravlev, A.B, (1982). Jour. Glac. and Zhuravlev, A.B., (1988). MGI.	57				57		57		57	
Zhuravlev, A.B., (1981). MGI. and Macheret, Y.Y. and Zhuravlev, A.B, (1982). Jour. Glac. and Zhuravlev, A.B., (1988). MGI. and Ekman, S.R., (1971). Geogr. Ann.	2				2		2		2	
Gogineni, Prasad. 2012. CReSIS Radar Depth Sounder Data, Lawrence, Kansas, USA. Digital Media. http://data.cresis.ku.edu/.	*257*		*257*						*257*	
Gogineni, Prasad. 2012. CReSIS Radar Depth Sounder Data, Lawrence, Kansas, USA. Digital Media. http://data.cresis.ku.edu/. and Allen, C. 2010, updated 2013. IceBridge MCoRDS L2 Ice Thickness. Antarctica. Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center.	*676*		*676*						*676*	
TOTAL #	**1493**	**10**	**948**	**64**	**407**	**91**	**456**	**96**	**1470**	**30**
TOTAL %	**100**	**1**	**63**	**4**	**27**	**6**	**31**	**6**	**98**	**2**

Appendix (*continued*).

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