We thank the reviewers for their thoughtful and detailed reviews. We have revised the manuscript accordingly. Below, all of their general and specific comments are responded to in turn. Reviewer suggestions are tagged as either accepted ('[Accept]') or rejected ('[Reject]'), in which case a reason is always given. Locations in the original manuscript are referenced in the format '[Page #, Line #]'.

In addition to the reviewer changes, we have updated the references to the data, in anticipation of publication and release of the corresponding v3.1.0 of the dataset (currently residing at https://gitlab.com/wgms/glathida/-/tree/v3.1.0-rc2):

- [Page 1, Line 9] Changed "Archived versions GlaThiDa are available from the World Glacier Monitoring Service (https://doi.org/10.5904/wgms-glathida-2019-03; GlaThiDa Consortium (2019)) and the development version (v3.1.0-rc1, from which this manuscript draft is generated) is available on GitLab (https://gitlab.com/wgms/glathida/-/tree/v3.1.0-rc1)" to "Archived versions of GlaThiDa are available from the World Glacier Monitoring (e.g. v3.1.0, from which this manuscript was generated: https://doi.org/10.5904/wgms-glathida-2020-09; GlaThiDa Consortium (2020)) while the development version is available on GitLab (https://gitlab.com/wgms/glathida)."
- [Page 20, Line 5] Changed "The development version (v3.1.0-rc1, from which this manuscript draft is generated) is available on GitLab (https://gitlab.com/wgms/glathida/-/tree/v3.1.0-rc1)" to "(e.g. v3.1.0, from which this manuscript was generated: https://doi.org/10.5904/wgms-glathida-2020-09; GlaThiDa Consortium (2020))".

Reviewer: Aparna Shukla

General comments

> *The paper focuses on describing the data attributes, characteristics and sources. In my opinion including some illustrations of the data (for certain regions or may be one per method) and field photographs of the glaciers investigated (one from each region) may be included to make the paper more interesting. Since it seems to be the first attempt of the authors to incorporate the field-based thickness measurements in the GlaThiDa v3, adding the same would add more value to the manuscript. [...] Rather than just including the field photograph of the glacier, it would be better to have photos of the estimation methods in-process.*

We have added a new figure with photos illustrating the four main methods for measuring glacier thickness: Ground-based ground-penetrating radar (Johnsons Glacier, Antarctica), aerial ground-penetrating radar (Hansbreen Svalbard), hot water drilling (Rhonegletscher, Switzerland), and seismic reflection (Grubengletscher, Switzerland). We have not added photos of glaciers from each world region, as glaciers from different regions can be indistinguishable.

> *The uncertainty part can be improved further in the dataset as well as in the manuscript. Certain method can be employed to standardize the uncertainty associated with the data. Thereafter the data may be sorted in terms of associated uncertainty such that the end-user may know the error involved, and they may choose the data accordingly*

as per the permissible error-limit of their respective applications. [...] The uncertainty part needs to be given more importance. Ice thickness estimated from a particular method (regardless of analyst or region) should follow same method of uncertainty estimation. It may vary across the ice thickness estimation methods as the parameters introducing error in different methods would differ, however, for each method the parameters to be considered while error estimation should be standardized for uniformity in the database.

Uncertainties are indeed important, but we are not in a position to standardize them further. The uncertainties that we describe in Section 3.2 are those published or submitted to us by many different data providers, and span the history of glacier thickness measurement. We have little control over the methods that were used to estimate these uncertainties. However, we hope to command more leverage on data submissions in the future. Thus we write: [Page 18, Line 2] "As a consequence, we intend to tighten reporting requirements and flag statistically nonconforming uncertainties in future versions of GlaThiDa." Documenting the lack and heterogeneity of published uncertainties is an important first step towards a common understanding and reporting of observational uncertainties.

The data can be sorted and filtered by their uncertainties by using the uncertainties columns in the database tables.

The authors discuss the spatial and temporal coverage of the data in sections 3.1.1 and 3.1.2 respectively. Here they mention that there are certain regions across the globe where the data density is scarce. This mandates that it should also be discussed here that what measures can be taken to improve the data density over these regions and how is it planned to add the temporal data. A discussion on how does these regions of low representation affect the overall quality and import of the database.

We are not a consortium of data collectors, but rather an (unfunded) initiative to collect existing measurements. Ultimately, we are limited to the data that people submit to us or publish in public repositories. As a result, we had limited ourselves to the following recommendations:

- [Page 11, Line 18] "Future efforts should be aimed at increasing spatial coverage and regional representation, both by performing new measurements and by conducting literature surveys and calls for data in underrepresented languages and regions of the world."
- [Page 14, Line 11] "Ideally, all ice thickness surveys would be published in open data portals, then added to GlaThiDa for complete coverage in a standard format."

However, in light of your feedback, we have added the following:

- [Page 11, Line 18] Added "Poor coverage in these regions necessarily limits the quality of local and global glacier volume assessments and predictions of future change".
- [Page 14, Line 11] Added "An assessment of the Arctic data in GlaThiDa v2 by the Integrated Arctic Observation System (INTAROS, 2018) identified missing observations and concluded that pressure must continue to be placed on research

groups to submit their data to the wider community". (see https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-land-and-cryosphere)

> *[e.g. Page 2, Line 21; Page 4, Line 15] At places the fonts are different. If this is on purpose then it is fine but looks quite abrupt and awkward.*

To clarify our use of a monospace font, we have added the following:

[Page 2, Line 23] Added "A monospace font is used throughout the manuscript for software packages (e.g. `git`), files (e.g. `datapackage.json`), database tables (e.g. `T`), database table fields (e.g. `POINT_LAT`), and code samples (e.g. Figure 2)."

Specific comments

> *[e.g. Page 2, Line 10] In general, the manuscript is well-written except for some places the sentences are too long and wordy, making it complicated to understand. This should be checked throughout the manuscript.*

[Page 2, Line 10] Changed "While the Ice Thickness Models Intercomparison eXperiment (ITMIX; Farinotti et al., 2017) only used GlaThiDa v1 (WGMS, 2014) to calibrate one of the participating models, it helped garner support and data for GlaThiDa v2 (WGMS, 2016), which was subsequently used to calibrate ice thickness models and evaluate model performance for an ensemble-based estimate of the thicknesses of all glaciers on Earth (Farinotti et al., 2019)." to "The Ice Thickness Models Intercomparison eXperiment (ITMIX; Farinotti et al., 2017) only used GlaThiDa v1 (WGMS, 2014) to calibrate one of the participating models, but it helped garner support and data for GlaThiDa v2 (WGMS, 2016). GlaThiDa v2 was subsequently used to calibrate all participating models and evaluate model performance for an ensemble-based estimate of the thicknesses of all glaciers on Earth (Farinotti et al., 2019).".

Several of the more confusing sentences were pointed out by other reviewers and subsequently rewritten.

Reviewer: Bruce Raup

General comments

> *Please add a bit of discussion why glacier area being within 1 km of a thickness measurement is important. I understand that this is a good general measure of coverage, and perhaps that is all that is meant. But it seems to be no guarantee that interpolation will be more accurate. For example, there could be a small glacier within 1 km of a thickness measure on a different glacier, perhaps of greatly different size.*

The metric is simply a means to measure and track global data coverage. It is defined as the total glacier area within 1 km of a thickness measurement "located on the same glacier" (see Section 3.1); glacier area is not included if the measurement is on a neighboring glacier. To clarify these points, we have made the following changes:

- [Page 1, Line 5; Page 19, Line 26] Changed "14% of global glacier area is now within 1 km of a thickness measurement" to "14% of global glacier area is now within 1 km of a thickness measurement (located on the same glacier)".
- [Page 12, Line 2] Added "A better measure of data coverage is the area of a glacier that is within a certain distance of a thickness point measurement located on the same glacier."
- [Page 12, Line 2] Changed "More specifically, 36% of the area of these surveyed glaciers (102 030 km2), and 14% of the global area, is within 1 km of a thickness point measurement located on the same glacier" to "Globally, 36% of the area of all surveyed glaciers (102 030 km2), and 14% of global glacier area, is within 1 km of a measurement".

> *The regex for the numbers seems to add friction. Shouldn't "number" refer to the standard ascii representation of floating point values, without reference to a language (regular expressions) that most scientists probably don't use? If someone accidentally deleted a character in the regex and didn't notice, it could mess up code that they're using on the data. Inclusion of the regex for number representation seems needlessly complex, and actually a bit dangerous. Also, the Ahmad post you cite describes regular expressions as if there is only one flavor. There are multiple versions of regular expressions, which is why I think including machine code in the JSON file that is particular to one flavor isn't a good idea. Or, this could be fixed by stating which flavor it is. See https://en.wikipedia.org/wiki/Comparison_of_regular-expression_engines. But that would add even more needless complexity.*

Our use of regular expressions on `number` fields is merely a way to enable automated checks of decimal place limits in the data files. Since Frictionless Data's Table Schema specification does not support this constraint natively (see https://github.com/frictionlessdata/specs/issues/641), we opted for a generic and flexible solution: extending the existing `pattern` constraint to non-string fields by checking the pattern against the raw values (i.e. strings) stored in the data files. Independent checks ensure that each field value is a valid "number", "integer", etc (as defined by the Table Schema specification: https://specs.frictionlessdata.io/table-schema/#types-and-formats).

The data files (`data/*.csv`) can be worked with directly, whether or not the JSON metadata (`datapackage.json`) is valid or present. Users can read the JSON metadata (or the friendlier Markdown equivalent), but they have no need to modify it. Mainly, it is a powerful tool for data maintainers, since it powers detailed and automatic data validation, ensuring the data files delivered to users are sound. Regular expressions are a very precise, compact, and machine-readable way of describing constraints on field values. Thanks to automatic tests, any breaking change made by maintainers to any of the files in the data repository (including changes to the regular expressions) would immediately be detected.

Finally, Frictionless Data's Table Schema specification (https://specs.frictionlessdata.io/table-schema/#constraints) has addressed the question of differing regular expression syntax by requiring `pattern` constraints conform to the standard and barebones XML Schema syntax (http://www.w3.org/TR/xmlschema-2/#regexs).

In light of these considerations, we have made the following changes to the text and the data package:

- [Page 5; Line 24] Changed "In the example in Figure 3, the regular expression (Ahmad, 2018) `^\-?[0-9]*(\.[0-9]{1,7})?$` matches a character string representing any positive or negative number with optionally a decimal point

and one to seven decimal places" to "In the example in Figure 3, the description informs users that the field values are stored in the data files with 'up to seven decimal places', while the pattern `\-?[0-9]*(\.[0-9]{1,7})?` (a regular expression conforming, as required by the Frictionless Data specification, to the XML Schema syntax; Biron, 2004) makes possible an automated test that this is indeed the case.". Biron, 2004 is a reference to the XML Schema specification (http://www.w3.org/TR/xmlschema-2/#regexs).

- [Figure 2] Changed pattern `^\-?[0-9]*(\.[0-9]{1,7})?$` to `\-?[0-9]*(\.[0-9]{1,7})?`.
- [`datapackage.json` ; `README.md`] Updated the regular expressions to conform to XML Schema syntax (and updated our test suite accordingly):
    - Removed unsupported start (`^`) and end (`$`) anchors (XML Schema requires strings to match the entire regular expression).
    - Replaced unsupported non-capturing (`(?: )`) with standard (`( )`) groups (these are equivalent for XML Schema, which is only concerned with whether or not strings match the regular expression).
- [`datapackage.json` ; `README.md`] Updated field descriptions to include, in words, any `pattern` constraint:
    - Added 'Cannot contain double quotes (") or whitespace other than space' for `[^"\s]+( [^"\s]+)*` .
    - Added 'Cannot contain double quotes (") or whitespace' for `[^"\s]+` .

Specific comments

> *[Page 1, Line 4] "more than 3000 glaciers": Give precise number.*

[Accept] Changed "more than 3000 glaciers" to "roughly 3000 glaciers" – dropping the "more than" marketing term.

There is not a precise number. A "glacier" is an ambiguous unit of measure (e.g. does a retreating branching glacier, or a large icecap with multiple drainage basins, count as multiple glaciers?). Even if we choose RGI glacier boundaries (which are themselves sometimes arbitrary or inconsistent with respect to drainage basins), some of the measurements fall outside the boundaries (i.e. the list in Section 3.1.1).

> *[Page 1, Line 5] "within 1 km of a thickness measurement": Why is this important? Does that make interpolation easier?*

[Accept] We agree that clarification is needed. Added the following sentence: "Improvements in measurement coverage increase the robustness of numerical interpolations and model extrapolations, resulting in better estimates of regional to global glacier volumes and their potential contributions to sea-level rise.".

> *[Page 1, Line 9] insert "of" into "versions GlaThiDa"*

[Accept] Inserted "of".

> *[Page 2, Line 11] change "only used GlaThiDa v1 to calibrate one of the participating models" to "used GlaThiDa v1 to calibrate only one of the participating models" (?)*

[Reject] We believe our original wording more clearly emphasizes the marginal use of GlaThiDa v1 by ITMIX (in contrast to the central use of GlaThiDa v2 by Farinotti et al. 2019).

> *[Page 2, Line 16] change "over 3 million" to "approximately 3 million" (over = marketing term)*

[Accept] Since "million" already indicates an approximation, changed "over 3 million" to "3 million".

> *[Page 3, Line 3] "manual": Manual in what sense?*

[Accept] Changed "manual data submissions" to "data submissions". "submission" already suggests that the data was submitted to us, as opposed to harvested by us.

> *[Page 4, Line 8] remove "as" in "Equally as important"*

[Accept] For additional clarity, changed "Equally as important as the data itself is the packaging – the physical representation [...]" to "Packaging of data is as important as the data themselves. This includes the physical representation [...]".

> *[Page 4, Line 9] change "data [is much less likely achieve its full potential]" to "a dataset [...]"*

[Accept] For continuity with previous reworked sentence, changed "data is much less likely to achieve its full potential" to "data are much less likely to achieve their full potential".

> *[Page 4, Line 10] change "forthcoming" to "following"*

[Accept] Changed "forthcoming" to "following".

> *[Page 5, Line 1] change header "data/.csv The data" to "Data (data/.csv)"*

[Accept] Changed "data/.csv The data" to "Data (data/.csv)".

> *[Page 5, Line 2] change "The data is" to "The data are"*

[Accept] Changed "The data is" to "The data are".

> *[Page 5, Line 15] change header "datapackage.json The metadata" to "Metadata (datapackage.json)"*

[Accept] Changed "datapackage.json The metadata" to "Metadata (datapackage.json)".

> *[Page 5, Line 18] move "CC-BY-4.0: https://creativecommons.org/licenses/by/4.0" to Table 2*

[Accept/Reject] We have removed this parenthetical mention of the license and added it to the "Data availability" section [Page 20, Line 7]:

"GlaThiDa is licensed under Creative Commons Attribution 4.0 International (CC-BY-4.0: \url{https://creativecommons.org/licenses/by/4.0})."

> *[Page 5, Line 19] change "Crucially, the file" to "The file"*

[Accept] Changed "Crucially, the file" to "The file".

> *[Page 5, Line 20] change "an astonishing number of variants" to "a large number of variants"*

[Accept] Changed "an astonishing number of variants" to "a large number of variants".

> *[Page 5, Line 22] "string, number, or integer". I realize his terminology came from the the Frictionless Data Tabular Data Package specification, but "integer" is a subset of "number", so I think "number (float)" or "decimal number" would be better (more precise).*

[Accept] Changed "string, number, or integer" to "string, floating point number, or integer" to be both more precise and consistent with the terminology used in the Frictionless Data Tabular Data Package specification (and thus in `datapackage.json`).

> *[Page 5, Line 28-29] change "Foreign keys link tables together based on the values of one or more fields: each row of the table must match one (and only one) row in the other ("foreign") table" to "These unique keys can be stored in other tables, where they are called "foreign keys", to link the tables together."*

[Accept] Changed "Foreign keys link tables together based on the values of one or more fields: each row of the table must match one (and only one) row in the other ("foreign") table" to "Unique keys can be stored in other tables (where they are called "foreign keys") to link the tables together.".

> *[Page 8, Line 1] change "README.md The storefront" to "Documentation starting point (README.md)"*

[Accept] Changed "README.md The storefront" to "Documentation (README.md)".

> *[Page 8, Line 3] "dynamically [generate a more human-readable version]": The word "dynamically " makes it sound like an interactive application. Maybe "automatically" would be better.*

[Accept] Changed "dynamically" to "automatically".

> *[Page 8, Line 8] change "CHANGELOG.md The historian" to "Database history (CHANGELOG.md)"*

[Accept] Since not only changes to the "database" are recorded, changed "CHANGELOG.md The historian" to "History (CHANGELOG.md)".

> *[Page 12, Line 8] change "per km2" to "/ km2" or spell out km2*

[Accept] Changed all instances of "per km2" to "km-2".

> *[Page 15, Line 5] change "Operation IceBridge […] are" to "Operation IceBridge […] is"*

[Accept] Changed "Operation IceBridge […] are" to "Operation IceBridge […] is".

> *[Page 15, Line 10] change "on […] and […]" to "on […] or […]"*

[Accept] Changed "on […] and […]" to "on […] or […]".

> *[Page 19, Line 25] "more than 3000": Actual number is better than this marketing expression*

[Accept] Changed "more than 3000 glaciers" to "3000 glaciers" – dropping the "more than" marketing term and letting the rounding communicate that the number is (and is limited to being) an approximation.

Reviewer: Anonymous

General comments

> *It is not clear to me what use the TT level of the data will have, I think the point measurements the TTT file contains the data that the user will make use of, rather than of elevation bands that are not clearly or uniformly defined.*

The `TT` table mainly exists for the rare situations (5 so far, from the literature) when the original point measurements are not available but elevation band summaries are available. To clarify this point, we have made the following change:

[Page 5, Line 6] Added "Although rare, some ice thickness surveys are only available as surface elevation band estimates, their point measurements having been lost or never published.".

We have removed Figure 8 [Page 15] and Figure 11 [Page 18] and made the following changes to the text:

- [Page 12, Line 11] Inserted "(calculated from the surface elevations of point measurements in GlaThiDa and the minimum and maximum glacier surface elevations in RGI)" after "Dividing each glacier into 100 m elevation bands".
- [Page 17, Line 3-11] Rewrote entire paragraph: "A fraction of glacier thicknesses in GlaThiDa were published with uncertainty estimates: 26% of mean glacier thicknesses in table `T` (drawn from about 35 studies, based on the listed references), 19% of mean elevation-band thicknesses in table `TT` (drawn from 4 studies), and 40% of point thicknesses in `TTT` (drawn from 51 studies). By computing percent uncertainties (100 % × uncertainty / thickness), we can compare the distribution of uncertainties by thickness "types". We find that the reported uncertainties are significantly lower for point thicknesses than for the spatial means – an interquartile range of 3.1–5.5 % of the measured value for points versus 9.9–22.8 % and 20–50 % for glacier and elevation band means, respectively. The uncertainties reported by these studies may or may not be realistic. Nevertheless, the relatively high uncertainties reported for spatial means clearly indicates that, for these studies, interpolation errors outweighed any benefit gained from averaging the spatially-independent errors in the point measurements.

- Section 2.2.1: Changed "data/*.csv The data*" to "Data (data/.csv)"
- Section 2.2.2: Changed "datapackage.json The metadata" to "Metadata (datapackage.json)"
- Section 2.2.3: Changed "README.md The storefront" to "Documentation (README.md)"
- Section 2.2.4: Changed "CHANGELOG.md The historian" to "History (CHANGELOG.md)"
- Section 3.1.3: Changed "Future growth" to "Future additions"

Specific comments

[Accept] Changed "validate the data against this description" to "validate the data format and content against this metadata description".

"this description" refers to the use of open-source metadata formats and software tools to describe the data. Both the data format and content is validated against this description. Hopefully the changes clarify these points.

> *[Page 1, Line 9] Something missing before GlaThiDa, insert "of" here?*

[Accept] Inserted "of".

> *[Page 2, Line 6] I find "anticipating" a strange selection of word here, do you mean assessing, or modelling.*

[Accept] Changed "anticipating" to "predicting".

> *[Page 3, Line 7-8] This sentence is not clear and needs editing. What does "intersecting" here mean, is the location of the data points inside a RGI glacier outline?*

[Accept] Changed "These replaced the IceBridge data available in 2014, intersected with Randolph Glacier Inventory (RGI 3.2) glacier outlines \citep{rgiconsortium_2013}, included in GlaThiDa v1." to "These replaced the IceBridge data, located within Randolph Glacier Inventory (RGI 3.2) glacier outlines \citep{rgiconsortium_2013}, added to GlaThiDa v1 in 2014.".

> *[Page 4, Table 1] What data is the last line, 17 surveys, 0 points and no thickness measurement, why is this included in the table?*

[Accept] Removed last line of Table 1.

These are poorly-documented surveys, pulled from the literature, for which we know neither the survey method, survey date, nor have any point measurements (only mean, and sometimes maximum, glacier thickness).

> *[Page 4, Line 10] Add "to" before "achieve"? something missing in sentence*

[Accept] Changed "is much less likely achieve" to "is much less likely to achieve".

> *[Page 5, Line 21] "n" missing in "unnecessary"*

[Accept] Changed "unecessary" to "unnecessary".

> *[Page 9, Line 13-14] something missing in sentence, it is strange*

[Accept] Changed ""Issues", which can be posted by anyone with a free account, track bug reports, feature requests, and other community dialogue" to ""Issues" – which can be posted by anyone with a free account – track bug reports, feature requests, and other community dialogue".

[Accept] Changed "This wide range enables comparisons through time for those glaciers with repeat surveys […]. However, it also complicates comparisons between

glaciers with different survey dates" to "This wide range of survey dates enables glaciers with repeat surveys ([…]) to be compared over time. However, it also complicates regional and global studies, which must account for thickness measurements spanning multiple years".

[Accept] Changed "known ice thicknesses coincident with the glacier outlines" to "measured ice thicknesses coincident in time with any glacier outlines".

[Accept] Changed "the glacier outlines, surface elevations, and other time-varying data used to initialize the model" to "measured glacier outlines, surface elevations, and other time-varying parameters (e.g. surface mass balance, rates of ice thickness change, and surface velocities) used to initialize the model".

Typically, both surface elevations and glacier outlines (i.e. the line at which glacier thickness reaches 0) are measurements.

[Accept] Changed "For large-scale analysis, however, this is rarely possible" to "For analysis spanning many glaciers (or all of the world's glaciers), it is not possible to ensure that all these data are coincident in time".

[Accept] Changed "their corresponding RGI outlines" to "their spatially coincident RGI outlines".

[Reject] It is unclear to us why this would be necessary, since often we are referring to the physical attribute rather than a measurement of it. However, as reported above and below, we have added "measured" or "measurement" to some instances of

"surface elevation".

> *[Page 14, Line 2-4] "synchronous surface elevations" is not clear, suggest "surface elevation measurement from the same time as thickness measurements". The remainder*
> *of sentence is also not clear, suggest to edit to something like "with bed elevation measurement any surface elevation measurement at later time will provide a thickness measurement"*

[Accept] Changed "synchronous surface elevations" to "temporally coincident ice thickness and surface elevation measurements".

> *[Page 14, Line 5] suggest to edit section title, it is not clear what "growth" is referring to here, probably the database, but this can be clarified.*

[Accept] Changed "Future growth" to "Future additions".

> *[Page 14, Line 9] suggest to replace "from" with "in"*

[Accept] Changed "missing from GlaThiDa" to "missing in GlaThiDa".

> *[Page 14, Line 9] it is not clear what "This" is referring to, suggest to clarify data base, but this is not clear in the text, suggest to clarify*

[Accept] Changed "This is evidenced, for example, by the 460 glacier surveys, pulled from the literature for v1 (Gärtner-Roer et al., 2014), that are still missing […]" to "For example, 460 glacier surveys pulled from the literature for v1 (Gärtner-Roer et al., 2014) are still missing […]".

> *[Page 17, Line 6] suggest to replace "thicknesses" with "thickness measurements"*

[Reject] We prefer to keep "point thicknesses", since that is how they are referred to in the previous sentence. We would rather not create a false dichotomy by suggesting that spatial means are not also "measurements".

> *[Page 17, Line 6-8] This sentence needs editing, "glacier and elevation band thicknesses" is not clear, probably refers to database categories?*

[Accept] Changed "glacier and elevation band thicknesses" to "glacier and elevation band means", to clearly reference the categories set out earlier in the revised paragraph (see General comments) where the direct link is now made to each database table.

[Page 17, Line 8-11] This sentence also needs editing, uncertainties are not "correct" but possible "realistic", "deemed to outweigh any benefit gained from averaging out random errors" also not clear and needs clarification

[Accept] Changed "correct" to "realistic" and reworded entire sentence (see revised paragraph in General comments).

[Page 17, Line 10-11] this sentence is not clear, not clear how a distribution on Figure provides estimate of uncertainty. "thickness type" is also not a good term, refer to database categories

[Accept] Removed sentence (see revised paragraph in General comments).

[Page 18, Figure 11] is not very useful and needs better explanation and editing of figure caption, suggest to delete figure and convey information of the figure in text and safe space

[Accept] Removed figure (see revised paragraph in General comments).

[Page 18, Line 5] suggest to edit section title

[Reject] We think that "Data management > Error detection" is an appropriate title for this section. What would you suggest?

[Page 19, Line 5] "number of changes" what is meant here, corrections in the database or additional input?

[Accept] Inserted "Every change, addition, and subtraction made to a file in the data package is tracked by git".

We mean any change made to any of the files in the data package, including corrections to existing data, the addition of new data, etc.

[Page 19, Line 5] suggest to add "will" before "grow"

[Accept] Changed "git repositories inevitably grow in size" to "the git repository will inevitably grow in size".

Worldwide version-controlled database of glacier thickness observations

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Abstract.

Although worldwide inventories of glacier area have been coordinated internationally for several decades, a similar effort for glacier ice thicknesses was only initiated in 2013. Here, we present the third version of the Glacier Thickness Database (GlaThiDa v3), which includes 3 854 279 thickness measurements distributed over ~~more than~~ roughly 3 000 glaciers worldwide.

5   Overall, 14 % of global glacier area is now within 1 km of a thickness measurement (located on the same glacier) – a significant improvement over GlaThiDa v2, which covered only 6 % of global glacier area, and only 1 100 glaciers. Improvements in measurement coverage increase the robustness of numerical interpolations and model extrapolations, resulting in better estimates of regional to global glacier volumes and their potential contributions to sea-level rise.

In this paper, we summarize the sources and compilation of glacier thickness data and the spatial and temporal coverage

10   of the resulting database. In addition, we detail our use of open-source metadata formats and software tools to describe the data, validate the data ~~against this~~ format and content against this metadata description, and track changes to the data following modern data management best-practices. Archived versions of GlaThiDa are available from the World Glacier Monitoring Service (~~; ?) and the development version~~ (e.g. v3.1.0~~-rc1~~, from which this manuscript ~~draft is generated)~~ was generated: https://doi.org/10.5904/wgms-glathida-2020-09; GlaThiDa Consortium (2020)) while the development version is available on

15   GitLab (https://gitlab.com/wgms/glathida).

1   Introduction

A central challenge of glaciology is assessing the distribution and total ice volume of the world's glaciers. Increasingly detailed and globally-complete inventories of the world's glaciers (WGMS and NSIDC, 2012; GLIMS and NSIDC, 2018; RGI Consortium, 2017) have been compiled with great effort over the last few decades. However, these inventories have been limited to glacier extent and surface elevation. The Glacier Thickness Database (GlaThiDa), launched by the World Glacier Monitoring Service (WGMS, https://wgms.ch) and supported by the International Association of Cryospheric Sciences (IACS) Working Group on Glacier Ice Thickness Estimation (https://cryosphericsciences.org/activities/ice-thickness), complements these existing efforts by compiling and publishing a freely-accessible database of glacier thickness observations (Gärtner-Roer et al., 2014).

Knowing the thickness of glacier ice is critical for ~~anticipating~~ predicting the rate and timing of glacier retreat and disappearance, the subsequent effects on local and regional hydrologic cycles and global sea level, and the associated environmental and social impacts. As the only worldwide repository of its kind, GlaThiDa plays an important role in local, regional, and global studies of glaciers, glacier ice volumes, and their potential sea-level rise contributions (e.g. Thorlaksson, 2017; Farinotti et al., 2017, 2019; Meyer et al., 2018; Fischer, 2018; Ayala et al., 2019; Werder et al., 2020). ~~While the~~ The Ice Thickness Models Intercomparison eXperiment (ITMIX; Farinotti et al., 2017) only used GlaThiDa v1 (WGMS, 2014) to calibrate one of the participating models, but it helped garner support and data for GlaThiDa v2 (WGMS, 2016)~~, which~~. GlaThiDa v2 was subsequently used to calibrate ~~ice thickness~~ all participating models and evaluate model performance for an ensemble-based estimate of the thicknesses of all glaciers on Earth (Farinotti et al., 2019).

GlaThiDa v3 represents a major step forward for the database. We have more than doubled the spatial coverage and more than quadrupled the number of observations relative to v2, released in 2016, adding ~~over~~ 3 million thickness measurements either submitted by researchers (46 % of new measurements) or imported from the IceBridge Data Portal (54 %, https://nsidc.org/data/icebridge). In addition to summarizing the spatial and temporal coverage of the database, we present a case study on how simple open-source metadata formats and software tools can be used to implement modern data management practices. In the sections that follow, we describe a development environment for data – based on universal text-based file formats and the distributed version-control system `git` (Chacon and Straub, 2014) – that maximizes data access and interoperability, automatically tracks and archives every change made to the dataset, continuously validates the structure and contents of the data, and facilitates dialogue with (and bug reports by) data users. A monospace font is used throughout the manuscript for software packages (e.g. `git`), files (e.g. `datapackage.json`), database tables (e.g. `T`), database table fields (e.g. `POINT_LAT`), and code samples (e.g. Figure 3).

2 Methods and data

2.1 Data sources

2.1.1 Data compilation

Since the release of GlaThiDa v1 in 2014 (Gärtner-Roer et al., 2014), which focused on gathering glacier mean and maximum thickness estimates from published literature, a large number of thickness measurements have been submitted by members of the research community in response to two calls for data, one for version 2 in 2016 and another for version 3 in 2018. In all, researchers from institutions in Europe, North and South America, Oceania, and Asia have contributed data from Antarctica, Africa (Kenya, Tanzania), Asia (China, Georgia, India, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Russia, Tajikistan), Europe (Austria, Germany, Greenland, Svalbard, Iceland, Italy, Norway, Sweden, Switzerland), Oceania (New Zealand), North America (Canada, United States), and South America (Bolivia, Chile, Colombia, Peru).

Alongside these ~~manual~~ data submissions, airborne glacier thickness profiles collected by National Aeronautics and Space Administration (NASA) Operation IceBridge were retrieved from the corresponding National Snow and Ice Data Center (NSIDC) data portals. Since these campaigns were primarily focused on the Greenland and Antarctic ice sheets, only measurements within Randolph Glacier Inventory (RGI 6.0) glacier outlines (RGI Consortium, 2017) were included in GlaThiDa. These replaced the IceBridge data~~available in 2014, intersected with~~, located within Randolph Glacier Inventory (RGI 3.2) glacier outlines (RGI Consortium, 2013), included in GlaThiDa v1 ~~.~~ in 2014.

2.1.2 Measurement methods

The surveys in GlaThiDa span the history of glacier ice thickness measurement, and thus include several different survey methods, summarized in Table 1 and illustrated in Figure 1. The most direct methods involve excavating or drilling through the ice. Although these typically produce a precise measurement, they do so only for a single point and at a great expense of time and money; correspondingly, these account for only 0.35 % of surveys in GlaThiDa (here, a "survey" roughly represents one measurement campaign on one glacier). The drilling surveys added in v3 (compiled by Fürst et al., 2018a, Table S3) were carried out in Svalbard in the 1970s through 1990s to map the thermal structure of glaciers (e.g. Jania et al., 1996) or to extract paleoclimate records (e.g. Kotlyakov et al., 2004). No drilling surveys were added in v2.

More often, ice thickness is measured indirectly using geophysical methods. For example, seismic soundings employ the propagation properties of elastic waves to determine the structure of the subsurface (described in Susstrunk, 1951). Although common in the 1950s through 1980s, they are expensive and time-consuming to collect; correspondingly, these account for only 0.84 % of surveys in GlaThiDa. No seismic surveys were added in v3; of those already in the database, the majority were carried out in the Austrian Alps up until the 1970s (reviewed in Aric and Brückl, 2001). Only one seismic survey – of Tasman Glacier, New Zealand from 1971 (Anderton, 1975) – was added in v2.

The most common geophysical method is radar (i.e. radio detection and ranging, also known as "radio-echo sounding" or "ground-penetrating radar"), which is based on the transmission, reflection, and subsequent detection of radio waves (reviewed

Table 1. Number of glacier surveys and point measurements, interquartile range of point thicknesses~~(if any)~~, and full range of survey years by survey method. In the database, a "survey" roughly represents one measurement campaign on one glacier, and a "point" represents a single ice thickness measurement (as opposed to a spatial mean).

Method	Surveys	Points	Thickness (m)	Years
Radar (airborne)	4 624	3 064 055	104–456	1968–2017
Radar (terrestrial)	412	700 066	87–330	1970–2018
Radar (both or unknown)	25	87 481	179–323	2006–2016
Seismic	43	31	218–440	1953–1993
Drilling	18	35	40–135	1935–2007
Electromagnetic	2	2 611	47–86	2002–2002
~~Unknown 17 0~~ height				

in Schroeder et al., 2020). Radar measurements can be collected quickly, from the ice surface or from airborne platforms, and account for 98.44 % of surveys in GlaThiDa. Of the radar surveys added in v3, a majority are provided by NASA Operation IceBridge (Koenig et al., 2010), which sponsored a series of airborne radar platforms: the Multichannel Coherent Radar Depth Sounder (MCoRDS; Paden et al., 2011, 2018; Shi et al., 2010), High-Capability Airborne Radar Sounder (HiCARS; Blankenship et al., 2017a, b), Pathfinder Advanced Radar Ice Sounder (PARIS; Raney, 2010), and Warm Ice Sounding Explorer (WISE; Rignot et al., 2013a, b). Other large additions in v3 include terrestrial and aerial radar surveys in Svalbard (compiled by Fürst et al., 2018a, Table S2) from the early 1980s (e.g. Dowdeswell et al., 1984, 1986) to the present day (e.g. Martín-Español et al., 2013; Navarro et al., 2014; Lindbäck et al., 2018), and helicopter-borne radar surveys in the Swiss Alps (Rutishauser et al., 2016). Large additions in v2 include extensive terrestrial radar surveys of glaciers in the Italian and Austrian Alps (Fischer et al., 2015a, b).

Geophysical techniques less commonly used for measuring glacier ice thickness include geoelectric (e.g. electrical resistivity tomography) and electromagnetic (e.g. magnetotellurics, controlled-source induction) methods which invert variations in electrical resistivity with depth to map the subsurface. The only examples of these in the database (0.04 %), added in v1, are helicopter electromagnetic surveys of two Cascade Range volcanoes (Finn et al., 2012). The methods of the remaining surveys (0.33 %) are unknown because the original source is either not known or cannot be found. All studies included in GlaThiDa are acknowledged in the database; the studies cited above are only provided as examples.

2.2 Data package structure

~~Equally~~ Packaging of data is as important as the data ~~itself is the packaging — the~~ themselves. This includes the physical representation of the data within files, the design of the metadata that describes the data, and the distribution of the data package to prospective users. Without proper packaging, data ~~is~~ are much less likely ~~achieve its~~ to achieve their full potential.

4

Figure 1. Field photographs illustrating different methods for measuring glacier thickness. (a) Ground-penetrating radar measurements on Johnsons Glacier, Antarctica, in January 2020. The white sledge contains a radar transmitter, receiver, shielded antennas, control unit, and recording system. A Global Navigation Satellite System receiver antenna is mounted to the sledge. Credit: Francisco Navarro. (b) Aerial ground-penetrating radar measurements over Hansbreen, Svalbard, in spring 2011 (Navarro et al., 2014). The radar transmitter, receiver, and antennas are mounted to a wooden frame hung from the helicopter. Credit: Antoine Kies. (c) Hot water drilling on Rhonegletscher, Switzerland, in August 2018 by ETH Zurich's Glacier Seismology Group. Although used mostly for characterizing bed conditions, the drillings measure ice thickness as a side product. Credit: Johannes Landmann. (d) Seismic reflection measurements on Grubengletscher, Switzerland, using a sledgehammer as a seismic energy source. The black seismic line connects geophones to the recording system. Credit: Bernd Kulessa.

The approach described in the ~~forthcoming~~ following sections implements (and extends) the FAIR guiding principles: scientific data should be Findable, Accessible, Interoperable and Reusable for both machines and people (Wilkinson et al., 2016). Our implementation, built on simple text files, was designed to meet the following criteria:

– Widely-supported, open, human- and machine-readable file formats to maximize interoperability and ease of use (Cerri and Fuggetta, 2007).

– Compatible with line-based version control systems like `mercurial` and `git` to automatically track and store changes (Blischak et al., 2016), facilitate collaboration between multiple authors (Ram, 2013), and continuously release new versions as the dataset evolves over time (Rauber et al., 2015).

– Described according to existing metadata standards to facilitate data interpretation, validation, and future contributions (Fowler et al., 2017), as well as reuse by software applications like the Global Terrestrial Network for Glaciers (GTN-G) data browser (http://www.glims.org/maps/gtng).

2.2.1 Data (`data/*.csv`)

The data ~~is~~ are structured as three relational database tables ordered in increasing level of detail (Figure 2). The first, overview table (`T`) contains information on the location, identity, and area of the surveyed glacier, the survey method used, and details about the authors and sources of the data. Glacier mean and maximum thickness, estimated from point measurements, are also included when available from data providers. The second table (`TT`) contains any mean and maximum thicknesses, estimated from point measurements, for surface elevation bands. Although rare, some ice thickness surveys are only available as surface elevation band estimates, their point measurements having been lost or never published. The third table (`TTT`) contains point thickness measurements. All tables include a survey identifier (`GlaThiDa_ID`, unique in `T`) that links entries between the tables, as well as a country code (`POLITICAL_UNIT`) and glacier name (`GLACIER_NAME`) which are replicated in `TT` and `TTT` as a convenience to users. Structural changes since GlaThiDa v1, described in the changelog (Section 2.2.4), have been limited to adding fields (e.g. `PROFILE_ID` in v3 to group point measurements by survey profile) and renaming fields (e.g. `DEM_DATE` to `ELEVATION_DATE` in v3 to clarify that provided surface elevations need not be from a digital elevation model).

Following FAIR principles, the three tables are stored as CSV (comma-separated values) files, a universally-supported text format for representing tabular data. To maximize machine-readability, the files do not contain any non-data content other than a single header line with field names. Data documentation is performed by a separate metadata file, described below.

2.2.2 Metadata (`datapackage.json`)

The structure and content of the data package is described in a single JSON (JavaScript Object Notation) file which conforms to the Frictionless Data Tabular Data Package specification (Walsh et al., 2017). This file contains general metadata like the package's name, version, description, and license~~(CC-BY-4.0:)~~, a list of contributors, and links to published source datasets.

6

Table T. Glacier thickness: Overview

5 141 glacier surveys

```
GlaThiDa_ID
POLITICAL_UNIT
GLACIER_NAME
GLACIER_DB
GLACIER_ID
LAT
LON
SURVEY_DATE
ELEVATION_DATE
AREA
MEAN_SLOPE
MEAN_THICKNESS
MEAN_THICKNESS_UNCERTAINTY
MAXIMUM_THICKNESS
MAX_THICKNESS_UNCERTAINTY
SURVEY_METHOD
SURVEY_METHOD_DETAILS
NUMBER_OF_SURVEY_POINTS
NUMBER_OF_SURVEY_PROFILES
TOTAL_LENGTH_OF_SURVEY_PROFILES
INTERPOLATION_METHOD
INVESTIGATOR
SPONSORING_AGENCY
REFERENCES
DATA_FLAG
REMARKS
```

Table TT. Glacier thickness: By elevation band

412 entries from 41 surveys

```
GlaThiDa_ID
POLITICAL_UNIT
GLACIER_NAME
SURVEY_DATE
LOWER_BOUND
UPPER_BOUND
AREA
MEAN_SLOPE
MEAN_THICKNESS
MEAN_THICKNESS_UNCERTAINTY
MAXIMUM_THICKNESS
MAX_THICKNESS_UNCERTAINTY
DATA_FLAG
REMARKS
```

Table TTT. Glacier thickness: Point measurements

3 854 279 entries from 4 681 surveys

```
GlaThiDa_ID
POLITICAL_UNIT
GLACIER_NAME
SURVEY_DATE
PROFILE_ID
POINT_ID
POINT_LAT
POINT_LON
ELEVATION
THICKNESS
THICKNESS_UNCERTAINTY
DATA_FLAG
REMARKS
```

Figure 2. Fields and overall contents of the three database tables `T`, `TT`, and `TTT`. Detailed field descriptions are provided in the metadata file described in Section 2.2.2.

```
{
  "format": "csv",
  "mediatype": "text/csv",
  "encoding": "utf-8",
  "dialect": {
    "header": true,
    "delimiter": ",",
    "lineTerminator": "\n",
    "quoteChar": "\"",
    "doubleQuote": true
  },
  "schema": {
    "missingValues": [""]
  }
}
```

Figure 3. Sample JSON from `datapackage.json` specifying the file format (format: "csv"), character encoding (encoding: "utf-8"), and structure of the data files – for example, that the first line of each file contains field names (header: true), values are separated by a comma (delimiter: ","), and missing values are exclusively represented by empty strings (missingValues: [""]).

~~Crucially, the~~ The file also contains a detailed description of both the contents and structure of the tabular data files. In practice, CSV files come in ~~an astonishing~~ a large number of variants; by making the format and character encoding explicit, we help both software and human users avoid ~~unecessary~~ unnecessary guesswork (Figure 3).

5   Each table field is described in turn, including its name and description, the data type it represents (~~e.g. string, number, or integer~~string, integer, or floating point number), and any constraints on the values it can take (e.g. whether a value is required, falls within a numeric range, or matches a search pattern). In the example in Figure 4, the ~~regular expression (Ahmad, 2018)~~ ~~^\-?0-9*(\.0-9{1,7})?$~~ ~~matches a character string representing any positive or negative number with optionally a decimal point and one~~ description informs users that the field values are stored in the data files with "up to seven decimal

10   places", ~~while the pattern~~ \-?[0-9]*(\.[0-9]{1,7})? (a regular expression conforming, as required by the Frictionless Data speci makes possible an automated test that this is indeed the case.

Finally, relations within and between tables are defined following relational database nomenclature. A unique key is a field (or set of fields) whose values must be unique for each row in the table. ~~Foreign keys link tables together based on the values of one or more fields: each row of the table must match one (and only one) row in the other ("foreign") table~~Unique keys can be stored in other tables (where they are called "foreign keys") to link the tables together. In the example in Figure 5, each row of table `TTT` (point measurements) is uniquely identified by the combination of a survey identifier (`GlaThiDa_ID`), profile identifier (`PROFILE_ID`), and point identifier (`POINT_ID`). Each of these point measurements is linked to the corresponding

```
{
  "name": "POINT_LAT",
  "title": "Point latitude (, WGS 84)",
  "description": "Latitude in decimal degrees (, WGS 84),
    with up to seven decimal places. Positive values indicate the northern
    hemisphere and negative values indicate the southern hemisphere.",
  "type": "number",
  "constraints": {
    "required": true,
    "minimum": -90,
    "maximum": 90,
    "pattern": "^\\-?[0-9]*(\\.[0-9]{1,7})?$"
    "pattern": "\\-?[0-9]*(\\.[0-9]{1,7})?"
  }
}
```

Figure 4. Sample JSON from `datapackage.json` specifying the name, title, description, data type, and value constraints for the field `POINT_LAT` in table `TTT`.

5   row in table `T` (survey overviews) by the value of its survey identifier (`GlaThiDa_ID`), along with the replicated fields for country code (`POLITICAL_UNIT`) and glacier name (`GLACIER_NAME`).

2.2.3   Documentation (`README.md`)

The data package is fully described in `datapackage.json`, but the JSON format may not be familiar or welcoming to some users. Therefore, we ~~dynamically~~ automatically generate a more human-readable version from the contents of `datapackage.json`.

10   The resulting `README.md` is a text file structured with Markdown, a widely-supported markup language (Gruber, 2004). As a result, it is both easy to read as plain text and readily converted to other formats such as HTML (Hypertext Markup Language) or PDF (Portable Document Format). The choice of file formats increases user access while their shared JSON origin eliminates the risks and overhead associated with manually maintaining multiple files.

2.2.4   History (`CHANGELOG.md`)

15   All notable changes made to the data or metadata are recorded in a chronological list formatted in Markdown, `CHANGELOG.md`. This includes the update or removal of existing data records, additions of new data records, and changes to the file structure or data schema. The goal is to provide a variety of user groups with important information about the history of the dataset. Future maintainers can review past changes, developers can evaluate whether and how to update their processing chain based on structural changes, and users can discover what data have been added or updated since the last version.

9

```
{
  "uniqueKeys": [
    ["GlaThiDa_ID", "PROFILE_ID", "POINT_ID"]
  ],
  "foreignKeys": [
    {
      "fields": ["GlaThiDa_ID", "POLITICAL_UNIT", "GLACIER_NAME"],
      "reference": {
        "resource": "T",
        "fields": ["GlaThiDa_ID", "POLITICAL_UNIT", "GLACIER_NAME"]
      }
    }
  ]
}
```

Figure 5. Sample JSON from `datapackage.json` specifying the unique keys and foreign keys for table `TTT`.

2.3 Product development cycle

The Glacier Thickness Database (GlaThiDa) is a community effort that grows as more data is collected. For an evolving dataset like ours, the ability to revise and review collaboratively – to track changes and share those changes with others – is of great benefit to the communities that contribute to, maintain, and use the data. The development environment should therefore support the following activities:

– Receive, review, and discuss issues with the dataset from and with the community.

– Automatically track all changes made to the dataset by a distributed team of contributors.

– Continuously validate the dataset as changes are made.

– Release new versions on a rolling basis, to be archived – with a unique DOI (digital object identifier) —— for distribution, citation, and safekeeping in a scientific data repository (Paskin, 2005).

2.3.1 Tooling

To achieve the goals listed above, we have adopted tools, widely used for open-source software development, for open-data development. In our case, the dataset is stored as a file repository managed by the distributed version-control system `git`, and hosted on GitLab (https://gitlab.com), an open-source equivalent of GitHub (https://github.com), the popular online platform for collaborative software development. The underlying `git` software tracks changes (or "commits"), while GitLab provides interactive tools for garnering and managing input from the community. "Issues" , which can be posted by anyone with a free

account ‚ track bug reports, feature requests, and other community dialogue. "Releases" tag a snapshot of the dataset, at any stage in the development cycle, as a numbered version. These snapshots can then be assigned a DOI and placed in a scientific data repository for citing and safekeeping.

10   Version control systems like `git` are line-based; that is, they track changes to text files on a line-by-line basis. Storing all data and metadata as text files, rather than binary files, allows us to automatically track all changes to the dataset. When fixes are made to existing data records, the change consists of the updated lines. When new records are added, the change consists of the appended lines. In this way, we avoid making a new copy of a file each time a change is made. Only versions published for download by users are compressed to a binary format, to reduce bandwidth.

2.3.2   Versioning

15

The project follows the Semantic Versioning Specification (Preston-Werner, 2013) for software, adapted for data. Given a version number `major.minor.patch`, the `major` version is incremented for new data, the `minor` version is incremented for changes to existing data, and the `patch` version is incremented for changes to metadata only.

Note that our versioning scheme does not communicate compatibility with downstream software dependencies, which is the

20   primary purpose of Semantic Versioning. A proposed software-oriented alternative (Pollock and Walsh, 2017) is to increment the `major` version for incompatible changes (e.g. field removed, field constraint made more restrictive), the `minor` version for backwards-compatible changes (e.g. data added, field constraint made less restrictive), and the `patch` version for backwards-compatible fixes (e.g. fix data errors, update field description). However, we believe our data-oriented versioning is better aligned with our users and contributors, who are primarily concerned with the addition of new data following each call for

25   submissions.

2.3.3   Schema validation

A major benefit of describing the data with machine-readable metadata (i.e. `datapackage.json`) is the ability to automatically validate the data against this description. This includes relations between tables, uniqueness within tables, and whether field values match field types and constraints: for example, whether dates match the expected format (~~"YYYYMMDD"~~ YYYYMMDD)

30   and latitude and longitude are numbers within the allowed limits ($[-90, 90]$ and $[-180, 180]$). Furthermore, by using a standard format for the metadata, we can automatically validate the metadata itself against this standard.

That said, all metadata standards have their limits; they cannot express all the possible constraints we may wish to impose on our data. In addition to tests of single fields, validation of GlaThiDa includes tests across multiple fields – for example, that country codes (`POLITICAL_UNIT`) and point measurements (`TTT.POINT_LAT`, `TTT.POINT_LON`) are spatially consistent with the provided coordinates for the glacier center point (`T.LAT`, `T.LON`), or that survey method details (`T.SURVEY_METHOD_DETAILS`) are provided if the survey method (`T.SURVEY_METHOD`) is "other". The latter test, im-

5   plemented in Python, is shown in Figure 6 as an example.

Continuous Integration (CI) is a standard software development practice wherein changes to the code are verified by automated tests to detect and fix issues as quickly as possible (Fowler, 2006). In our case, we use CI pipelines integrated into

11

```
def test_has_details_if_survey_method_other():
    df = tables['T']
    mask = df['SURVEY_METHOD'] == 'OTH'
    assert df[mask]['SURVEY_METHOD_DETAILS'].notna().all()
```

Figure 6. Sample Python code testing whether `SURVEY_METHOD_DETAILS` is provided whenever `SURVEY_METHOD` is "OTH" (other).

Table 2. Total number of rows (surveys, elevation bands, or point measurements) and number of surveys represented in each table, by GlaThiDa version ("v", with the release year in parentheses). Since not all glacier surveys have a mean glacier thickness in table `T`, such surveys are counted separately.

Table	v1 (2014)	v2 (2016)	v3 (2019)
`T`. Glacier thickness: Overview			
Surveys (all)	1 493	1 601	5 141
Surveys (with mean glacier thickness)	407	504	500
`TT`. Glacier thickness: By elevation band			
Surveys represented	10	33	41
Elevation bands	175	376	412
`TTT`. Glacier thickness: Point measurements			
Surveys represented	948	1 080	4 681
Point measurements	759 629	820 370	3 854 279

GitLab to automatically validate data and metadata whenever a change is made to the repository, catching issues early in the development cycle and, crucially, before the next release.

3 Results and discussion

3.1 Spatial and temporal coverage

GlaThiDa v3 is the most comprehensive public database of glacier thickness measurements to date. We have added 3 million new thickness measurements relative to GlathiDa v2, released in 2016 (Table 2). The new data, submitted by researchers or imported from the IceBridge data portal (https://nsidc.org/data/icebridge), includes glaciers in Antarctica, Alaska, Canada, China, Greenland, Kazakhstan, Norway, Svalbard, Switzerland, and Tanzania.

Table 3. GlaThiDa coverage for each glacier region mapped in Figure 7. The count and total area (km^2) of RGI glacier outlines with at least one (point, elevation band, or glacier-wide) thickness is listed for GlaThiDa v2 (2016) and v3 (2019) alongside the total for all RGI glaciers.

Region	Name	v2 (count)	v3 (count)	RGI (count)	v2 (km^2)	v3 (km^2)	RGI (km^2)
1	Alaska	14	41	27 108	4 469	21 141	86 725
2	Western Canada and USA	38	45	18 855	118	142	14 524
3	Arctic Canada, North	239	476	4 556	57 783	72 351	105 111
4	Arctic Canada, South	24	251	7 415	10 633	13 943	40 888
5	Greenland Periphery	295	1 361	20 261	51 290	63 594	130 071
6	Iceland	4	4	568	2 161	2 161	11 060
7	Svalbard and Jan Mayen	79	232	1 615	9 582	26 318	33 959
8	Scandinavia	99	103	3 417	800	813	2 949
9	Russian Arctic	22	32	1 069	3 606	5 716	51 592
10	Asia, North	20	61	5 151	82	144	2 410
11	Central Europe	128	175	3 927	498	768	2 092
12	Caucasus and Middle East	2	3	1 888	5	36	1 307
13	Asia, Central	48	79	54 429	1 466	1 401	49 303
14	Asia, South West	0	1	27 988	0	17	33 568
15	Asia, South East	8	8	13 119	69	98	14 734
16	Low Latitudes	6	9	2 939	12	29	2 341
17	Southern Andes	35	39	15 908	733	735	29 429
18	New Zealand	3	3	3 537	112	112	1 162
19	Antarctic and Subantarctic	69	131	2 752	76 481	89 622	132 867
	World	1 133	3 054	216 502	219 900	299 141	746 092

3.1.1 Spatial coverage

To evaluate the spatial coverage of GlaThiDa with respect to the world's roughly 217 000 glaciers (RGI Consortium, 2017), we assigned each survey to glaciers in the Randolph Glacier Inventory (RGI 6.0) by intersecting point measurements and nominal glacier centerpoints with RGI glacier outlines. The result is that 3 054 RGI glaciers have thickness measurements in GlaThiDa (a large increase from 1 133 RGI glaciers in version 2). Out of 5 141 glacier surveys, only 11 (0.2 %) do not fall within an RGI glacier outline. Of these, most are for glaciers not included in RGI 6.0 – specifically, very small glaciers in the European Alps (Blauschnee and Glacier de Tsarmine, Switzerland; Schwarzmilzferner, Austria) and glaciers that may be considered part of the Antarctic Ice Sheet (Lambert Glacier, Starbuck Glacier, and Scharffenbergbotnen). The remaining do not intersect an RGI outline because either the corresponding RGI outline is incorrect (Nördlicher Schneeferner, Germany) or the glacier has retreated since the survey was conducted (Columbia Glacier, Alaska).
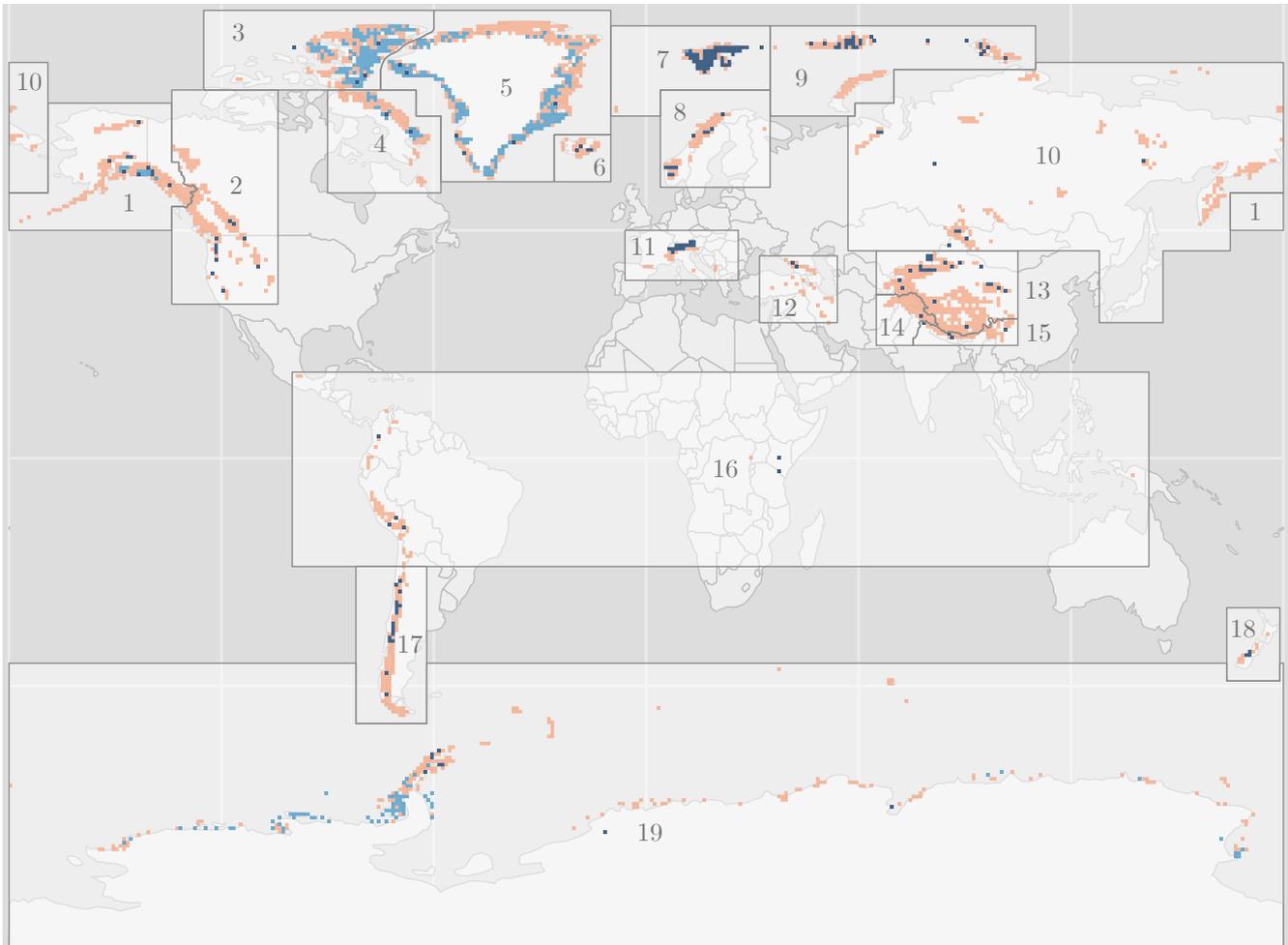
Figure 7. Map comparing GlaThiDa coverage to global glacier coverage according to the Randolph Glacier Inventory (RGI 6.0). Each grid cell represents $78.7\,\mathrm{km} \times 78.7\,\mathrm{km}$ (roughly $1^\circ \times 1^\circ$) in a cylindrical equal-area map projection. Light blue cells contain GlaThiDa data from IceBridge, while the overlaying dark blue pixels contain GlaThiDa data from other sources. Numbered grey polygons correspond to the glacier regions (GTN-G, 2017) listed in Table 3.

Figure 7 shows the coverage of intersected RGI glaciers on a world map. Table 3 lists the number and total area of intersected RGI glaciers by glacier region (GTN-G, 2017). While the proportion of intersected glaciers in a region is at most 14 % (region 7: Svalbard and Jan Mayen), the proportional area of intersected glaciers is much higher, up to 77 % (again, for Svalbard and Jan Mayen) – a result of larger glaciers being preferentially selected for measurement. The coverage in Svalbard is so high in v3 thanks to a recent regional compilation of available measurements (Martín-Español et al., 2015; Fürst et al., 2018b). The regions with the next best area coverage are those with substantial contributions from NASA Operation IceBridge: Arctic Canada, Antarctica, and Greenland. Despite these advances, large gaps persist in GlaThiDa, especially throughout Asia, the Russian Arctic, and the Andes. <u>Poor coverage in these regions necessarily limits the quality of local and global glacier volume assessments and predictions of future change.</u> Future efforts should be aimed at increasing spatial coverage and regional representation, both by performing new measurements and by conducting literature surveys and calls for data in underrepresented languages and regions of the world.

Overall, RGI glaciers with at least one thickness measurement account for 40 % ($299\,141\,\text{km}^2$) of the global RGI area of $746\,092\,\text{km}^2$ (RGI Consortium, 2017). ~~More specifically~~<u>A better measure of data coverage is the area of a glacier that is within a certain distance of a thickness point measurement located on the same glacier. Globally</u>, 36 % of the area of ~~these~~ <u>all</u> surveyed glaciers ($102\,030\,\text{km}^2$), and 14 % of ~~the global~~ <u>global glacier</u> area, is within 1 km of a ~~thickness point measurement~~<u>located on the same glacier</u><u>measurement</u>. Although this represents a significant improvement over GlaThiDa v2 (6 %), this nevertheless means that the thickness of the vast majority of global glacier area must still be estimated through extrapolation, scaling methods (reviewed in Bahr et al., 2015), or models (reviewed in Farinotti et al., 2017).

The spatial coverage of point thickness measurements varies greatly by glacier. While 14 % of glaciers in GlaThiDa with point measurements have more than 100 point measurements ~~per km²~~ km^{-2} on average, 50 % have fewer than 18 points (Figure 8). Although measurements are often sparse with respect to total glacier area, measurements tend to be well distributed across glacier surface elevations, since measurements are often collected along longitudinal profiles. Dividing each glacier into 100 m elevation bands <u>(calculated from the surface elevations of point measurements in GlaThiDa and the minimum and maximum glacier surface elevations in RGI)</u>, 50 % of glaciers with point measurements have measurements in at least half of their elevation bands and 11 % have measurements in all of their elevation bands~~(Figure ??)~~. Glaciers with few measurements but well distributed along their length can still be very useful for validating modeled ice thicknesses (Castellani, 2019), which are often computed along longitudinal ice-flow lines (reviewed in Farinotti et al., 2017).

~~Number of RGI glaciers with point measurements in GlaThiDa by the percentage of elevations (discretized into 100m bands) with one or more point measurements. The median (50%) is marked with a grey line. Calculated from the surface elevations of point measurements reported in GlaThiDa and the minimum and maximum glacier surface elevations reported in RGI.~~

3.1.2 Temporal coverage

The glacier thickness surveys in GlaThiDa span the years 1935–2018 (Table 1). This wide range ~~enables comparisons through time for those~~ <u>of survey dates enables</u> glaciers with repeat surveys ~~–~~(such as the example in Figure 9<u>) to be compared over time</u>. However, it also complicates ~~comparisons between glaciers with different survey dates~~<u>regional and global studies, which must</u>
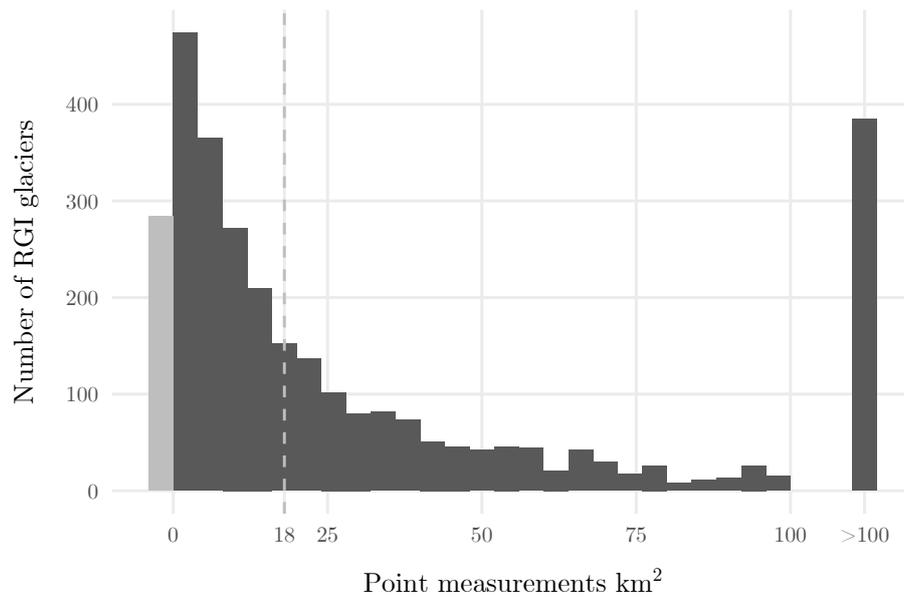
Figure 8. Number of RGI glaciers with point measurements in GlaThiDa by the average number of point measurements ~~per~~ km^{2} $^{-2}$. The median (18 points ~~per~~ km^{2} $^{-2}$) is marked with a grey dashed line. Glaciers with a mean or maximum thickness but no point measurements are shown in the grey bar to the left of 0 ~~per~~ km^{2} $^{-2}$.

account for thickness measurements spanning multiple years. Ideally, modeled ice thicknesses are evaluated against ~~known~~ measured ice thicknesses coincident ~~with the~~ in time with the measured glacier outlines, surface elevations, and other time-
10 varying ~~data~~ parameters (e.g. surface mass balance, rates of ice thickness change, and surface velocities) used to initialize the model (Farinotti et al., 2017). For ~~large-scale analysis , however, this is rarely possible~~ analysis spanning many glaciers (or all of the world's glaciers), it is not possible to ensure that all these data are coincident in time. For example, the median survey year for RGI glacier outlines is 2002, a decade earlier than the 2012 median for GlaThiDa surveys (Figure 10), and the offset between surveys in GlaThiDa and their ~~corresponding~~ spatially coincident RGI outlines is 11–17 years (interquartile range).
15 As for surface elevations, the majority (88 %) of point thickness measurements in GlaThiDa include corresponding surface elevations, 85 % of which were measured the same year as the ice thickness. When available, ~~synchronous surface elevations~~ temporally coincident ice thickness and surface elevation measurements can be used to calculate the elevation of the glacier bed (independent of the survey date over decades to centuries) and thus the ice thickness relative to a glacier surface surveyed at any other time.

3.1.3 Future ~~growth~~additions

5 Our intention is for GlaThiDa to continue to grow and improve as errors are found and fixed, new measurements are made, and more data is found or submitted. Several datasets already published in open data portals (e.g. https://data.npolar.no, https://pangaea.de, https://arcticdata.io, https://nsidc.org, and https://www.usap-dc.org) are slated for inclusion in a future version.
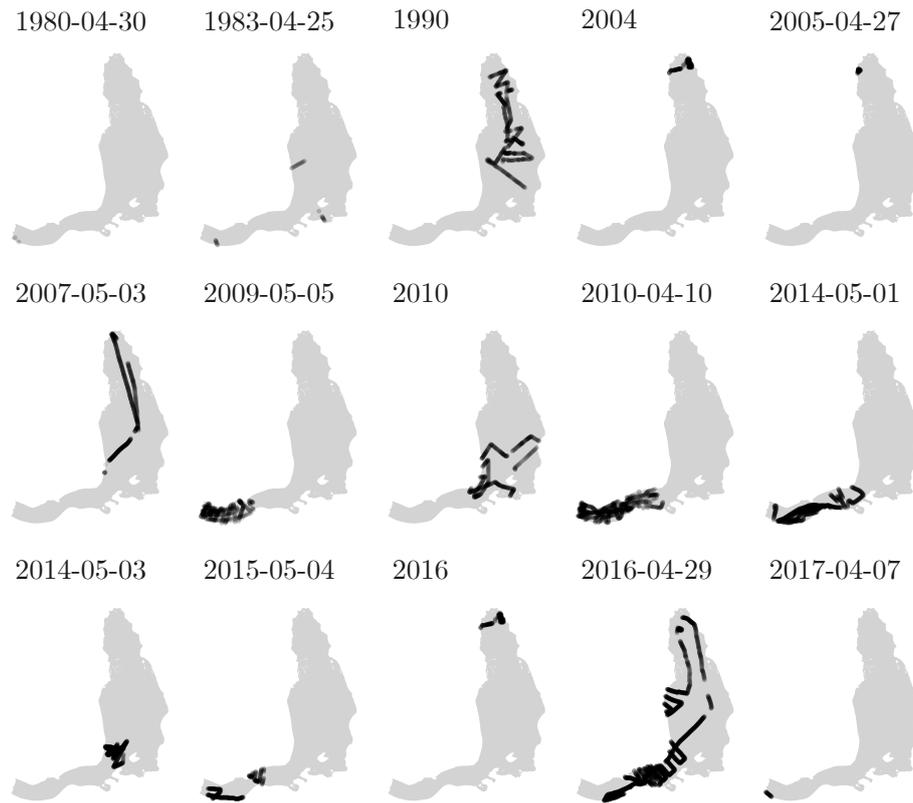
Figure 9. All thickness point measurements in GlaThiDa intersecting the RGI outline (RGI60-07.01464) for Kronebreen, Svalbard (78.992°N, 13.384°E), by survey date (or year, if the date is unknown). The corresponding studies referenced in GlaThiDa are Dowdeswell et al. (1984, 1986); Björnsson et al. (1996); Lindbäck et al. (2018); Kristensen et al. (2008); Paden et al. (2018).

However, these account for only a small number of the glacier thickness measurements still missing ~~from GlaThiDa. This is evidenced, for example, by the~~ in GlaThiDa. For example, 460 glacier surveys ~~,~~ pulled from the literature for v1 (Gärtner-Roer et al., 2014) ~~, that~~ are still missing the original point measurements from which the reported glacier-wide estimates were derived. An assessment of the Arctic data in GlaThiDa v2 by the Integrated Arctic Observation System (INTAROS, 2018) identified missing observations and concluded that pressure must continue to be placed on research groups to submit their data to the wider community. Ideally, all ice thickness surveys would be published in open data portals, then added to GlaThiDa for complete coverage in a standard format.

To streamline data aggregation going forward, GlaThiDa may need to be restructured such that data is primarily organized by campaign or dataset, rather than by glacier. The data tables were originally designed to accommodate mean glacier thicknesses pulled from the literature (Gärtner-Roer et al., 2014). Thus, each survey (i.e. each entry in table `T`, and thus each `GlaThiDa_ID`) is expected to contain measurements gathered on one visit to one glacier – even though each associated point (i.e. each entry in `TTT`) is also encoded with temporal and spatial coordinates. This data model complicates the addition of
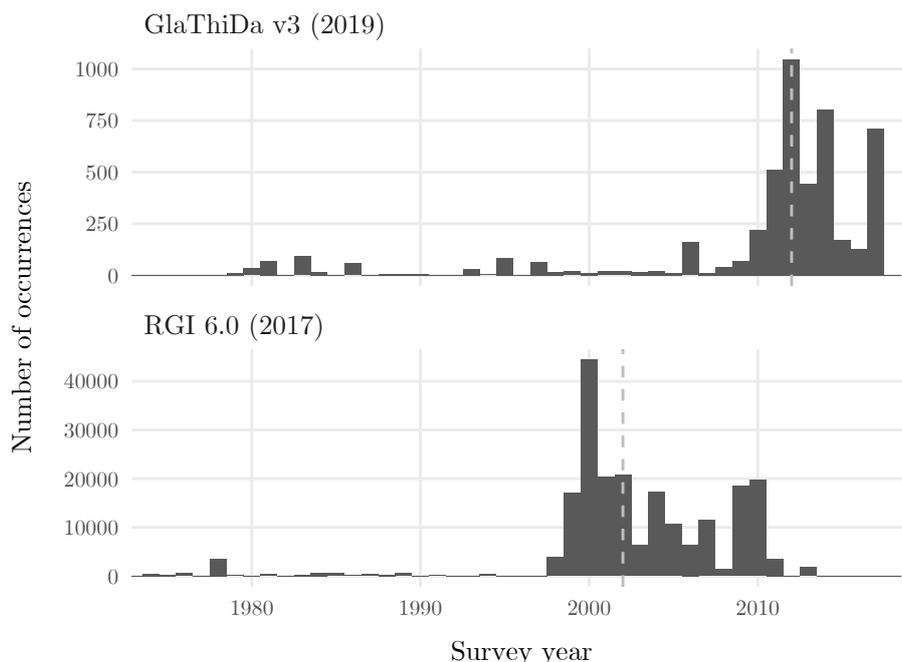
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Figure 10. Comparison of the distribution of survey years between GlaThiDa (top) and RGI (bottom). Medians are marked with grey dashed lines. Only survey years since 1975 are shown.

large campaigns and introduces confusing redundancy to the database. For example, the six datasets from Operation IceBridge had to be split across 4 124 "glacier surveys" by date and by intersection with RGI glacier outlines.

Operation IceBridge, the source of 61 % of the thickness point measurements in GlaThiDa, ~~are~~ is ending operation in 2020. The airborne mission was designed to avoid a gap in measurements between the ICESat satellite (2003–2009) and its successor ICESat-2, which was launched in 2018. However, the ICESat satellites only measure surface elevation, not ice thickness, therefore ending a decade-long ice thickness campaign. In the absence of a successor to Operation IceBridge, future updates to GlaThiDa may not include as many new measurements as the latest version. However, since RGI 6.0 does not include glaciers on the Antarctic Peninsula mainland (Huber et al., 2017) ~~and~~ or in the McMurdo Dry Valleys (Frank Paul, personal communication, 2020), IceBridge data for those glaciers were not included in GlaThiDa v3; these remaining IceBridge data will be added in a future version.

3.2 Thickness uncertainties

The uncertainty of a glacier thickness measurement varies widely with the method used, the characteristics of the site, and the interpretation of the raw data (reviewed in Gärtner-Roer et al., 2014, Section 3.2). For example, sources of error for radar measurements (reviewed in Lapazaran et al., 2016a, Section 3.1) include the radio-wave velocity, the timing of the reflection, and migration (inverting for the reflection surface immediately below, rather than to the side), which can fail in or near steep

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terrain (Welch et al., 1998). Errors in the measurement position (e.g. due to the accuracy, placement, and movement of the GPS receiver) also translate to thickness errors proportional to the local thickness gradient (reviewed in Lapazaran et al., 2016a,

10   Section 3.2). This is a larger issue for older data, especially those transformed from poorly-defined coordinate systems or digitized from printed maps (e.g. Andreassen et al., 2015).

The uncertainty of a spatially-averaged thickness further varies with the adequacy of the interpolation (and extrapolation), the assumed glacier boundary, and most importantly, the spatial coverage of the measurements (reviewed in Lapazaran et al., 2016b). Thickness measurements are typically acquired along sparse profiles, with coverage biased towards gentler terrain.

15   Rarely, if ever, do they approximate a dense grid blanketing the whole glacier. From the law of error propagation, we would expect measurement errors to be smaller for spatial means. In practice, however, the opposite is more commonly the case, since measurement errors are often partly spatially dependent (Martín-Español et al., 2016), rather than truly random, and point coverage is often far from ideal.

A fraction of glacier thicknesses in GlaThiDa were published with uncertainty estimates: 26 % of mean glacier thicknesses

20   in table `T` (drawn from about 35 studies, based on the listed references), 19 % of mean elevation-band thicknesses in table `TT` (drawn from 4 studies), and 40 % of point thicknesses in table `TTT` (drawn from 51 studies). ~~Figure ?? compares the distribution of the~~ By computing percent uncertainties (100 % × uncertainty/thickness)~~reported for each thickness type. The~~, we can compare the distribution of uncertainties by thickness "type". We find that the reported uncertainties are significantly lower for point thicknesses than for the spatial means – an interquartile range of 3.1–5.5 % of the measured value for points

25   versus 9.9–22.8 % and 20–50 % for glacier and elevation band ~~thicknesses~~means, respectively. ~~Whether or not the uncertainties reported by these studies are correct, clearly the interpolation errors were deemed to outweigh~~ The uncertainties reported by these studies may or may not be realistic. Nevertheless, the relatively high uncertainties reported for spatial means clearly indicates that, for these studies, interpolation errors outweighed any benefit gained from averaging ~~out random (~~the spatially-independent ~~)~~ measurement errors~~. For thicknesses in GlaThiDa without uncertainties, the distributions in Figure ?? provide a~~

30   ~~first-order estimate of uncertainty for each thickness type~~errors in the point measurements.

In practice, the statistical definition of the uncertainties reported in GlaThiDa are likely to vary considerably. For example, many studies do not specify whether or not a reported error is the standard deviation. Others may not necessarily provide a full error estimate, but rather the "resolution of the measurements", as in the case of some IceBridge datasets (MCoRDS, HiCARS, and PARIS). As pointed out by Martín-Español et al. (2016), based in part on two studies included in GlaThiDa (Pettersson

5   et al., 2011; Saintenoy et al., 2013), errors for spatial means (e) in the literature can vary by orders of magnitude between two extreme assumptions: (underestimate) local errors (e_i) are spatially independent, such that $e = \bar{e}_i/\sqrt{n}$ (where $\bar{e}_i$ is the mean of the local errors and n is their number), or (overestimate) local errors are linearly dependent, such that $e = \bar{e}_i$ (i.e. the mean of the local errors is taken as the error of the mean). As a consequence, we intend to tighten reporting requirements and flag statistically ~~non-conforming~~ nonconforming uncertainties in future versions of GlaThiDa.

10   ~~Cumulative distribution of percent ice thickness uncertainties (100 % × uncertainty/thickness) by thickness type: point (solid black line), glacier mean (grey solid line), and elevation band mean (dashed grey line). For example, about three quarters of glacier mean thicknesses report uncertainties of 25% of the thickness or better.~~

3.3 Data management

3.3.1 Error detection

15 As recorded in the changelog, we fixed a large number of errors introduced in previous versions and in the initial compilation of the current version. Many were trivial to fix once discovered, others required reviewing published literature and datasets, checking original submissions, and if necessary, corresponding with the data provider. Most errors were detected by the suite of automated validation tests described in Section 2.3.3. Checks of field-level constraints identified missing values in required fields, duplicate values in unique fields, out-of-range values in numeric fields, invalid characters in text fields, invalid values in

20 enumerable fields, and future or non-existent dates in date fields. Checks of table-level constraints identified duplicate values in unique keys (e.g. duplicate combinations of survey and point identifiers in `TTT`), and missing values in foreign keys (e.g. survey identifiers in `TT` and `TTT` missing in `T`). More complex tests identified missing values that were required by logical implication (e.g. thickness missing when thickness uncertainty provided), values that were invalid by logical implication (e.g. glacier identifier not present in the glacier database to which it refers), and values that were invalid by spatial implication (e.g. glacier

25 coordinates outside assigned country or far from associated point measurements). Additional tests will necessarily need to be added proactively as the data evolves, and retroactively as unforeseen errors are introduced and later discovered.

3.3.2 Data storage and version control

Every change, addition, and subtraction made to a file in the data package is tracked by `git`. As the number of changes grows over time, the `git` ~~repositories~~ repository will inevitably grow in size. Cloud-storage hosts place storage limits on free

30 accounts: GitLab.com limits repositories to 10 gigabytes (GB) compressed; GitHub.com limits repositories to 100 GB and each file to 100 megabytes (MB) uncompressed. To keep repositories small in the presence of large files, `git-lfs` (git Large File Storage) was developed to track files in the repository while storing them externally (Carlson and Schneider, 2019). However, whether the file is binary or text, a new copy of the file is made for each change – no matter how small the change. By storing our data as text files in the repository, changes are stored incrementally, which imparts significant storage benefits. At the time of writing, the repository is only ~~46.4~~47.7 MB compressed despite ~~103~~113 changes, including 8 versions of `TTT.csv` (294 MB uncompressed, 42.3 MB compressed). Reaching the 10 GB storage limit on GitLab.com would require adding (or changing) roughly one billion point measurements. If this limit were ever reached, it could be lifted by migrating to a self-hosted GitLab

5 installation.

Nevertheless, line-based version control systems like `git` are not optimized for tracking changes to tabular data. A change to a single cell is recorded as a change to the entire row, and swapping the order of two columns is recorded as a change of every row in the table (Fitzpatrick, 2013). Changes to tabular data can be described more compactly (and legibly) using specialized syntax (e.g. Tabular Diff Specification; Fitzpatrick, 2014), but these impart no storage benefit unless the underlying

10 version control systems were rewritten to use them to store changes internally. Alternatively, many changes can be described as operations rather than as changes to file content, such as a log of Structured Query Language (SQL) commands to a relational

database or the change history tracked by OpenRefine (Hirst, 2013). However, these would require specific software and a strict (and non-standard) workflow to make changes to the data.

4 Conclusions

The Glacier Thickness Database (GlaThiDa) has been established as the international data repository for glacier ice thickness observations. Version 3 contains standardized data for ~~more than~~ roughly 3 000 glaciers worldwide, collected from in-situ and airborne measurements. Overall, 14 % of global glacier area is now within 1 km of a thickness measurement (located on the same glacier), although large regional gaps persist, especially in Asia, the Russian Arctic, and the Andes. Thanks to simple metadata formats and a development environment based on open-source software, GlaThiDa fulfills the FAIR principles (Findable, Accessible, Interoperable and Reusable for both machines and people) and surpasses them with automatic version-control, continuous validation, and an interface for community dialogue. Hosted by the World Glacier Monitoring Service (WGMS), GlaThiDa will continue to serve the glaciological community as a trustworthy dataset.

5 Data availability

GlaThiDa is maintained as a `git` repository hosted at https://gitlab.com/wgms/glathida. Bug reports, data submissions, and other issues should be posted to the issue tracker at https://gitlab.com/wgms/glathida/-/issues. Published versions of GlaThiDa – those with an assigned DOI (digital object identifier) – are hosted by the World Glacier Monitoring Service (WGMS) in Zürich, Switzerland (~~; ?).The development version (~~e.g. v3.1.0~~-rc1~~, from which this manuscript ~~draft is generated) is available on GitLab (~~was generated: https://doi.org/10.5904/wgms-glathida-2020-09; GlaThiDa Consortium (2020)). GlaThiDa is licensed under Creative Commons Attribution 4.0 International (CC-BY-4.0: https://creativecommons.org/licenses/by/4.0).

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