glenglat: A database of global englacial temperatures

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Abstract. Measurements of englacial temperatures have been collected since the earliest years of glaciology, with the first measurements dating back to the mid-19$^{\text{th}}$ century. Although temperature is a defining characteristic of any glacier – and is notoriously laborious to collect – no effort had yet been made to gather all existing measurements. In an attempt to make existing ice temperature data more accessible, we present glenglat, a global database of englacial temperature measurements, compiled from 241 literature sources and nine data submissions and composed of 1 142 146 measurements of depth and temperature from 689 boreholes located on 184 glaciers outside of the ice sheets. Alongside recent compilations for the ice sheets (Løkkegaard et al., 2023; Vandecrux et al., 2023), most published englacial temperature measurements are now readily available to the research community.

Here, we review the variety of glacier thermal regimes that have been measured and summarize the spatial, temporal, and climatic coverage of measurements relative to global glacierized area. Measurements of cold and polythermal glacier ice greatly outnumber those of temperate ice. Overall, temperature has been measured in fewer than 1 ‰ of all glaciers, and only 20 % of borehole locations have been measured more than once, highlighting the large potential to investigate changing temperature conditions by repeating past measurements. The database is developed on GitHub (www.github.com/mjacqu/glenglat) and published to Zenodo (https://doi.org/10.5281/zenodo.11518069; Jacquemart and Welty, 2024). It consists of four relational tables and detailed machine-actionable and human-readable metadata. The GitHub repository also provides submission instructions (including a spreadsheet template and validation tools), in the hopes that investigators can help us keep glenglat complete and current going forward. We hope that glenglat can help improve our understanding of glacier thermal regimes, help refine glacier thermo-dynamic models, or shed insight into hazardous glacier instabilities in a warming world.

1 Introduction

The englacial temperature is a defining characteristic of any glacier. It influences glacier flow dynamics and subglacial hydrology, it can be a decisive factor for glacier hazards, and it can serve as an archive of past climate. To illustrate, ice viscosity and deformation rate depend directly on ice temperature (Deeley and Woodward, 1908; Glen, 1954; Cuffey and Paterson, 2010); only temperate (basal) ice permits glacier sliding over the bed (Cuffey and Paterson, 2010); impermeable cold ice can serve as a barrier for water, controlling sub- and englacial water flow and possibly contributing to the formation of hazardous water accumulations within the ice or in glacier sediment beds (Irvine-Fynn et al., 2011; Vincent et al., 2012; Gilbert et al., 2012; Kääb et al., 2018; Gilbert et al., 2018; Jacquemart et al., 2020; Kääb et al., 2021); the warming of a formerly frozen bed can initiate basal sliding that can lead to large ice avalanches (Alean, 1985; Faillettaz et al., 2015; Troilo et al., 2021; Chiarle et al., 2023). Under cold conditions, the variations of temperature with depth are a window into the past evolution of atmospheric temperatures, making englacial temperature changes an important climate variable (e.g., Gilbert et al., 2010). Finally, ice temperature records also serve to validate thermo-mechanical glacier models, which are key to improving our understanding of glacier systems.

Glaciers are typically categorized either as temperate, cold, or polythermal. Temperate ice is at the pressure melting point, cold ice is below the pressure melting point, and polythermal glaciers contain both cold and temperate ice. The pressure melting point depends mostly on the ice overburden pressure (and to a lesser extent, the presence of air bubbles and other impurities), such that under temperate conditions ice temperature decreases with depth at around $6.5 \times 10^{-4}\,°\mathrm{C}$ to $7.5 \times 10^{-4}\,°\mathrm{C}$ per meter (Paterson, 1971; Harrison, 1972; Jania et al., 1996). More generally, the englacial temperature is determined by the complex interaction between the surface energy balance, the geothermal heat flux, and internal heating from ice deformation, basal friction, and refreezing of meltwater (Cuffey and Paterson, 2010). Available heat is transferred through the ice via conduction and advection by ice and water flow. The superposition of these processes can lead glaciers to be fully cold or temperate, or simultaneously contain cold and temperate ice in a wide variety of spatial configurations (Blatter and Hutter, 1991; Irvine-Fynn et al., 2011).

Measuring englacial temperatures is a laborious process; (deep) ice temperature measurements are therefore comparatively rare. Those that exist were typically collected for one of two reasons: To gain an understanding of glacier dynamics and englacial temperatures directly (e.g., Agassiz, 1847; Blatter and Haeberli, 1984; Clarke et al., 1984; Copland et al., 2003; Ryser et al., 2013; Gilbert et al., 2010; Vincent et al., 2020; Troilo et al., 2021; Karušs et al., 2022) or in connection with the retrieval of ice cores used to reconstruct past climatic changes (e.g., Thompson et al., 1990, 2018; Kinnard et al., 2006; Schwikowski et al., 2013; Kinnard et al., 2020). The data resulting from such efforts are largely hidden away in scientific literature spanning more than a century, and are therefore not readily available as a community resource. At the same time, there is an increasing need to understand how englacial temperatures – and their changes over time – relate to glacier dynamics, climate change, and glacier hazards (Kääb et al., 2018; Colgan et al., 2015; Gilbert and Vincent, 2013; Gilbert et al., 2015). In order to make englacial temperature data from glaciers around the world more widely available, we have compiled a database of englacial temperatures sourced – largely, but not exclusively – from published literature. In the following, we describe how englacial temperatures are measured in the field (Sec. 2.1), how we found and compiled these measurements (Sec. 2.2), and how the resulting glenglat database is structured and managed (Sec. 2.3). In Section 3, we present and discuss the content of glenglat (version 1.0), and close with instructions for how others can contribute additional data (Sec. 3.5). We hope that

Figure 1. Photographs illustrating methods for measuring glacier temperatures: (a) drilling a shallow borehole with a handheld mechanical auger on Griesgletscher, Switzerland (photo by Matthias Huss), (b) drilling a deep borehole with a hot water drill and a large array of fuel drums and pumps to heat and pressurize the water on Rhonegletscher, Switzerland (photo by Raphael Moser), and (c) a typical string of thermistors used to measure temperature at different depths in a borehole (photo by Mylène Jacquemart)

glenglat can serve as a community resource to help improve our understanding of ongoing changes in the cryosphere and that it will grow over time with the addition of past and future englacial temperature measurements.

2 Methods and Data

2.1 Measurement methods

Englacial temperature measurements are typically made by placing one or more thermistors in a borehole (Fig. 1. Boreholes are drilled with either mechanical (reviewed in Talalay, 2016) or thermal (reviewed in Talalay, 2020) drills, or a combination thereof. The advantage of mechanical drilling is that temperatures can be reliably measured after a short time. Thermal drilling (e.g., steam or hot water) significantly raises the temperature of the borehole, which subsequently needs time to re-adjust to the temperature of the surrounding ice (typically a several days to a few weeks Laternser, 1992; Miles et al., 2018). Depending on the measurement techniques and objectives, borehole temperatures are measured only once, or the thermistor chain is left in the hole (which is allowed to freeze up or kept open with a casing or fluid) and either remeasured manually or equipped with an automatic logger. A recent innovation replaces discrete thermistors with a fibre optic cable (distributed temperature sensing (DTS), Law et al., 2021), which can provide measurements with an unprecedented vertical resolution, especially in deep boreholes where the required number of thermistors would be prohibitively expensive.

2.2 Data compilation

Most data included in glenglat are sourced from published literature and datasets. Publications were initially found by searching Google Scholar (https://scholar.google.com) and Google Dataset Search (https://datasetsearch.research.google.com) for combinations of the English words glacier, ice, temperature, thermal, regime, englacial, borehole, drill(ing), measurement, and record, as well as 冰川温度钻孔 and скважина температуры ледника ("glacier borehole temperature" in Chinese and Russian, respectively). We then recursively sought out publications referenced in previously-identified publications, striving to find the most complete and original data source for each measurement. Tracking down references was made more difficult by the practice of journals (primarily European and North American ones using Latin script) of not publishing references in their original form (e.g., "термический"), but only translations ("temperature") or phonetic transcriptions ("termicheskiy"). Finding these often involved reconstructing the original reference, since the modified form did not appear in search results. When we were unable to find the full text of a publication online or in print in nearby libraries, we requested it from the Swiss Library Service Platform (SLSP) document delivery service through the University of Bern (ub.unibe.ch). In addition to extracting data from publications, we solicited data submissions on CRYOLIST (cryolist.org), at the 2023 Alpine Glaciology Meeting in Birmensdorf, Switzerland, and through personal communications. References to all our data sources can be found in the bibliography of this publication and within glenglat itself (Sec. 2.3).

For this first version of glenglat, we selected only firn and/or ice temperature measurements with a well-defined depth. This means that we did not take into account measurements made in tunnels dug into glaciers at undefined depths. We largely omitted shallow measurements known to be only in seasonal snow (though occasionally including them if found alongside deeper measurements). We also focused on glaciers and omitted measurements from the Antarctic and Greenland ice sheets, in large part because data from the ice sheets have already been compiled by Løkkegaard et al. (2023) and Vandecrux et al. (2023).

For each measurement, we extracted depth and temperature data and their associated metadata (see below). Submitted or published data in machine-readable formats were added directly to the database, data published numerically in text or tables were transcribed with the help of Optical Character Recognition (OCR), and data represented graphically (e.g., as a plot of temperature versus depth) were digitized using the open-source software Plot Digitizer (https://plotdigitizer.sourceforge.net/). For plots that used points to indicate each measurement (Fig. 2a), we digitized the values at each point. For plots using a continuous line (Fig. 2b), such that the locations of the measurements along the line are unknown, we used a point density sufficient to reproduce the original line.

Metadata associated with the temperature measurements were compiled from one or more sources to the best of our abilities (see Tables 1 – 4). For example, borehole coordinates were either extracted directly from text, digitized from a map with defined axes (e.g., latitude and longitude) using Plot Digitizer, digitized from a map (without such axes) visually georeferenced to a global basemap usingthe QGIS Freehand Raster Georeferencer plugin (https://plugins.qgis.org/plugins/FreehandRasterGeoreferencer/), or approximated on global basemaps with the help of terrain features, glacier morphology, or elevation information. Borehole elevation was published as text in most cases, though we did occasionally have to approximate elevation from provided contour lines or by comparison to an independent topographic map. Other metadata included the measurement and drilling dates, the drill type (mechanical, thermal, or combined), the depth of the firn-ice interface (i.e., whether the measurements are in firn, ice, or both), whether the borehole reached the glacier bed, and the accuracy of the temperature measurements. Some columns were added later in the data compilation process, therefore not all field are equally well populated.

2.3 Data structure and management

Glenglat is packaged and described following the Frictionless Tabular Data Package standard (Walsh et al., 2017), version-controlled and tested on GitHub (https://github.com/mjacqu/glenglat), and published to Zenodo (https://doi.org/10.5281/zenodo.11518069). Data and metadata are stored using common text file formats to ensure that they are human-readable, machine-actionable, and compatible with line-based version-control systems like Git.

The data are structured as a four-table relational database stored as CSV (comma-separated values) files (Tables 1 – 4). The source table contains a full reference to each data source that we used. Names in non-Latin scripts (Cyrillic, Hangul, and Chinese characters) are accompanied by a latinized form, and non-English titles are accompanied by an English translation. The borehole table describes the drill site – including the location, elevation, drill method, and reported accuracy of the temperature measurements. The profile table describes each temperature-depth profile – including the timing of the measurement and whether or not the measurement was made after the borehole was known to have reached thermal equilibrium. Finally, the measurement table contains the measurements of temperature with depth. To improve manageability of the csv files, data from boreholes with time-series measurements (i.e., with hundreds of profiles), the profile and measurement tables are stored in separate, source-specific csv files. Supporting these tabular data are files that, for each source, document how and from where the data were extracted. For submissions, these include data files and email correspondence. For publications, these include the key text passages, tables, maps, or figures that served as the sources for the data. Additional files document how numeric values were digitized from maps and figures using Plot Digitizer (*.xml) or georeferenced and digitized using QGIS (*.pgw, *.{png|jpg}.aux.xml, and *.geojson).

The tabular data are described in a single YAML (https://yaml.org) metadata file (datapackage.yaml). This file lists general attributes of the database – like name, description, version, license, and contributors – as well as a detailed description of the structure and content of each tabular data file. The CSV Dialect (Pollock, 2021) specifies how exactly the CSV files are structured, while the Table Schema (Walsh and Pollock, 2021) specifies the name and data type of each column, the constraints on each column's values, and the foreign-key relations between tables.

This metadata architecture allows data maintainers and contributors to use Frictionless Framework (https://framework.frictionlessdata.io) to test that the metadata is correctly structured and that the data are consistent with the metadata. These tests are run automatically in a continuous-integration pipeline on GitHub using Frictionless Repository (https://repository.frictionlessdata.io), ensuring the integrity of the database whenever any file is modified. Additional custom tests, which cannot be expressed by the metadata, further verify the integrity of the dataset, for example that all people who contributed data (referenced as a personal communication in table source) are listed as contributors in datapackage.yaml. Using software built on the Frictionless Tabular Data Package standard (https://github.com/ezwelty/tablecloth), we can also render the metadata as an interactive spreadsheet template with dropdown menus and real-time validation, lowering the bar for future data contributors.

The GitHub repository is linked to Zenodo such that a new version is published on Zenodo automatically whenever a new release is created on GitHub. A .zenodo.json file in the repository, generated automatically from the data and metadata, controls and enhances the metadata that is transferred to Zenodo – for example to include machine-actionable references to all sources with a persistent identifier like a DOI (Digital Object Identifier) or other URL (Uniform Resource Locator). Zenodo manages the DOIs for glenglat, registering a concept DOI encompassing all versions (concept-doi) and a version DOI for each new version (version-doi).

Table 1. Main columns of the source table (data/source.csv); a full description is provided in datapackage.yaml. Column names and categorical values closely match the Citation Style Language (CSL) 1.0.2 specification (Zelle et al., 2015). The primary key is indicated with a *

Column	Type / Units	Description
id*	string	Unique identifier, constructed from author name and year (e.g., zagorodnov1981), referenced from other tables either formally in a foreign key or informally within free-form text.
author	string	Author names (optionally followed by their ORCID in parentheses) as a pipe-delimited list.
year	YYYY	Year issued (published, communicated, last updated)
type	string	Type (e.g., journal article, book chapter, dataset, personal communication)
title	string	Title of the work
container_title	string	Title of the container (e.g., journal, book, data repository)
url	string	URL (DOI if available)

Table 2. Columns of the borehole table (data/borehole.csv). Primary keys are indicated with a *, foreign keys with a °.

Column	Type / Units	Description
id*	integer	Unique identifier
source_id°	string	Identifier of the source of the earliest temperature measurements (and the source of all borehole metadata, unless otherwise stated in notes).
glacier_name	string	Glacier or ice cap name (as reported).
glims_id	string	Global Land Ice Measurements from Space (GLIMS) glacier identifier.
location_origin	string	Origin of location (latitude, longitude): - submitted: Provided in data submission - published: Reported as numbers in original publication - digitized: Digitized from published map with complete axes - estimated: Estimated from published plot by comparing to a map - guessed: Estimated with difficulty (e.g., by comparing elevation to a map)
latitude	degrees	Latitude in the EPSG 4326 spatial reference system.
longitude	degrees	Longitude in the EPSG 4326 spatial reference system.
elevation_origin	string	Origin of elevation; same categories as for location_origin.
elevation	meters	Elevation above sea level of the drilling site.
label	string	Borehole name (e.g., as labeled on a plot).
date_min	YYYY-MM-DD	Begin date (or first possible date) of drilling (e.g., 2019: 2019-01-01).
date_max	YYYY-MM-DD	End date (or last possible date) of drilling (e.g., 2019: 2019-12-31).
drill_method	string	Drilling method: mechanical, thermal, or combined.
ice_depth	meters	Starting depth of ice. Infinity (INF) indicates that ice was not reached.
depth	meters	Total borehole depth (not including drilling in the underlying bed).
to_bottom	boolean	Whether the borehole reached the glacier bed.
temperature_accuracy	degrees Celcius	Thermistor accuracy or precision (as reported). Typically understood to represent one standard deviation.
notes	string	Additional remarks about the study site, the borehole, or the measurements therein.
curator	string	Names of people who added the data to the database, as a pipe-delimited list.

Table 3. Columns of the profile table (data/profile.csv and data/**/profile.csv). (Composite) primary keys are indicated with a *, foreign keys with a °.

Column	Type / Units	Description
borehole_id*°	integer	Borehole identifier.
id*	integer	Borehole profile identifier (starting from 1 for each borehole).
source_id°	integer	Source identifier.
measurement_origin	string	Origin of measurements:
		- submitted: Provided as numbers in data submission
		- published: Numbers read from original publication
		- digitized: Digitized from published plot(s) with Plot Digitizer
date_min	YYYY-MM-DD	First possible date of measurement (e.g., 2019: 2019-01-01).
date_max	YYYY-MM-DD	Last possible date of measurement (e.g., 2019: 2019-12-31).
time	hh:mm:ss	Measurement time.
utc_offset	hours	Time offset relative to Coordinated Universal Time (UTC).
equilibrated	boolean	Whether temperatures have equilibrated following drilling.
notes	string	Additional remarks about the profile or the measurements therein.

Table 4. Columns of the measurement table (data/measurement.csv and data/**/measurement.csv). (Composite) primary keys are indicated with a *, foreign keys with a °.

Column	Type / Units	Description
borehole_id*°	integer	Borehole identifier.
profile_id*°	integer	Borehole profile identifier.
depth*	meters	Depth below the glacier surface.
temperature	degrees Celsius	Measured temperature.

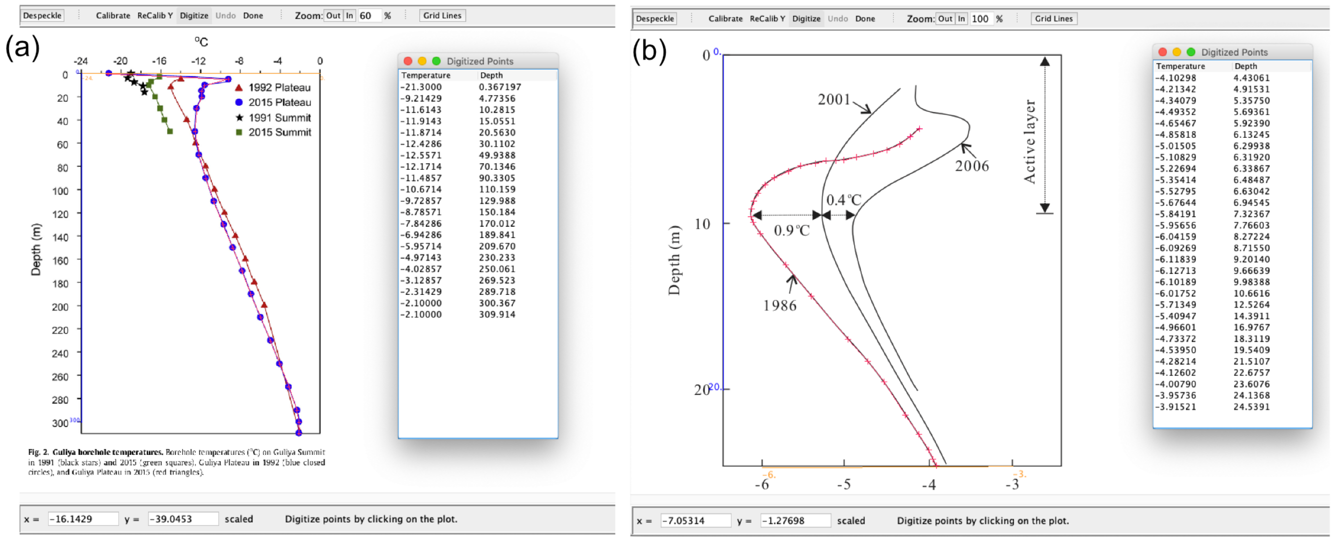

Figure 2. Screenshots of the digitization process with Plot Digitizer, where temperature versus depth is either plotted as (a) discrete points for each measurement or (b) a continuous line with unknown measurement locations. Data is from (a) 古里雅冰帽 (Guliya Ice Cap, GLIMS ID G081455E35226N) and (b) 天山1号冰川 (Urumqi Glacier No. 1, GLIMS ID G086810E43111N).

2.4 Errors from digitization and data reproduction

In addition to the errors of the original measurement, errors are introduced when measurements are reproduced in tables or figures (henceforth "reproduction error"), and again when these reproductions are digitized (henceforth "digitization error"). Such errors can multiply if the data is shared between researchers or digitized from older publications and reprinted in subsequent publications. In 80 cases, we acquired the same temperature profile from two different sources (e.g., data submission and published figure, published figure and published table), allowing us to assess the magnitude of reproduction errors. In order to quantify the digitization error, 177 temperature profiles were digitized by two different people. This exercise also allowed us to refine our method by identifying avoidable human errors and software quirks (e.g. wrong scaling of an axis, misplaced points).

3 Results and Discussion

As far as we know, glenglat is the largest collection of englacial temperature measurements. It contains 1 142 146 measurements of depth and temperature, organized into 147 582 profiles from 689 boreholes (Fig. 3). We included 17 873 profiles (for 79 boreholes) from nine data submissions. The remaining data were extracted from 175 primary sources, with an additional 66 secondary sources helping to further populate the metadata. Non-English sources make up 28 % (49) of all primary sources but 40 % (40) of those published before the year 2000.

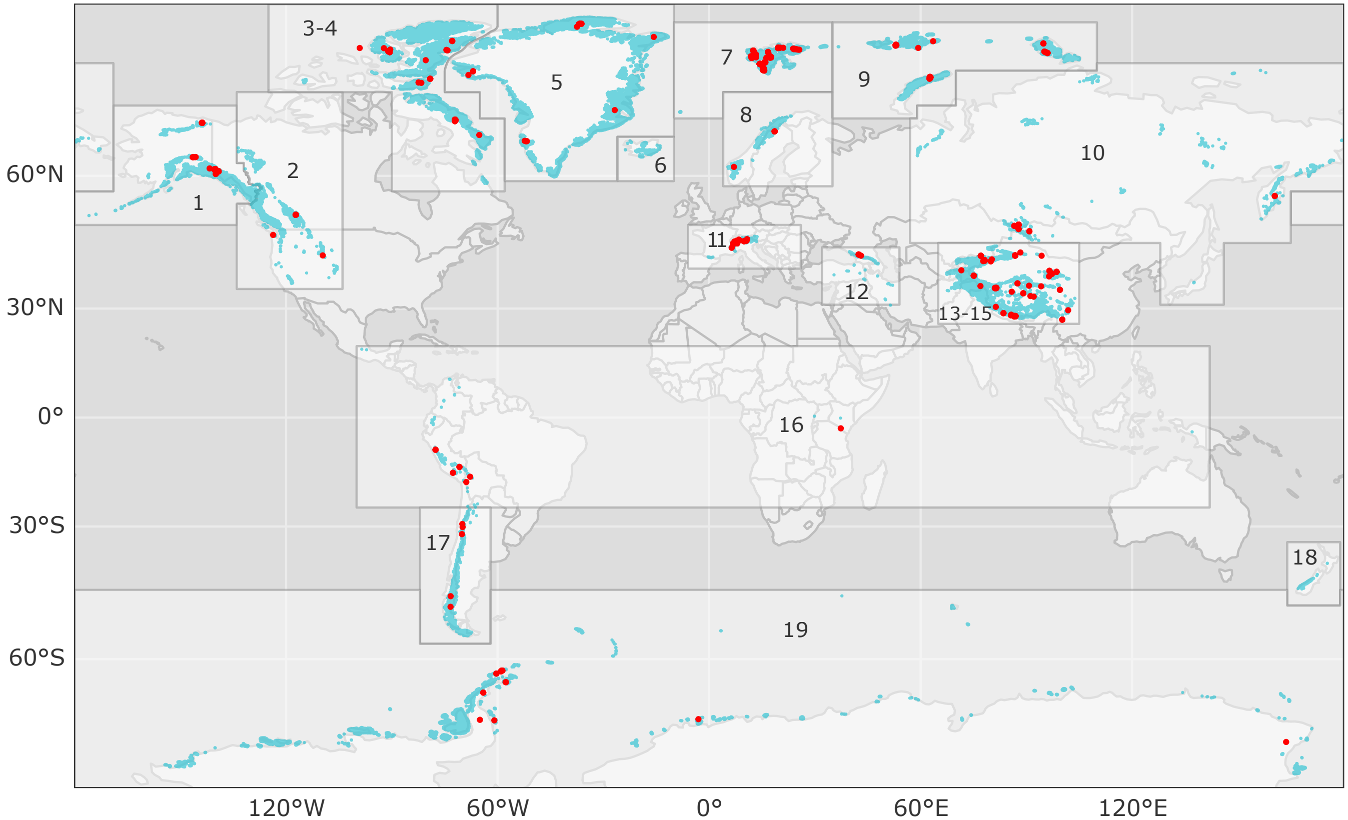

Figure 3. Spatial distribution of temperature measurements recorded in glenglat. Boreholes are plotted in red, glaciers in light blue (according to the Randolph Glacier Inventory 7.0; RGI Consortium, 2023) in light blue. The RGI region numbers correspond to those referenced in Fig. 5.

3.1 Thermal regimes and borehole depths

A variety of thermal structures can be identified in the temperature profiles (Fig. 4). The borehole from the Devon Ice Cap (Nunavut, Canada; data from Paterson and Clarke, 1978) is an example of fully cold conditions. At depth, the temperature increases at a rate largely determined by the geothermal heat flux (heat conduction from the Earth's interior). In contrast to the fully cold conditions, profiles can be fully temperate, such as on Hansbreen (e.g., Svalbard; data from Jania et al., 1996) where the ice temperature decreases with depth in accordance with the lowering of the pressure melting point. Between these two endmembers, there is a lot of variety. At Grenzgletscher (Switzerland; data from Ryser et al., 2013; Hoelzle et al., 2011) and White Glacier (Axel Heiberg Island, Canada; data from Blatter, 1987), for example, the ice in the accumulation area is colder than the ice in the ablation area, indicating that the cold ice is warmed (e.g., by shear heating and latent heat release) as it advects down from the accumulation area. The opposite is true at Kongsvegen (Svalbard; data from Björnsson et al., 1996), where the

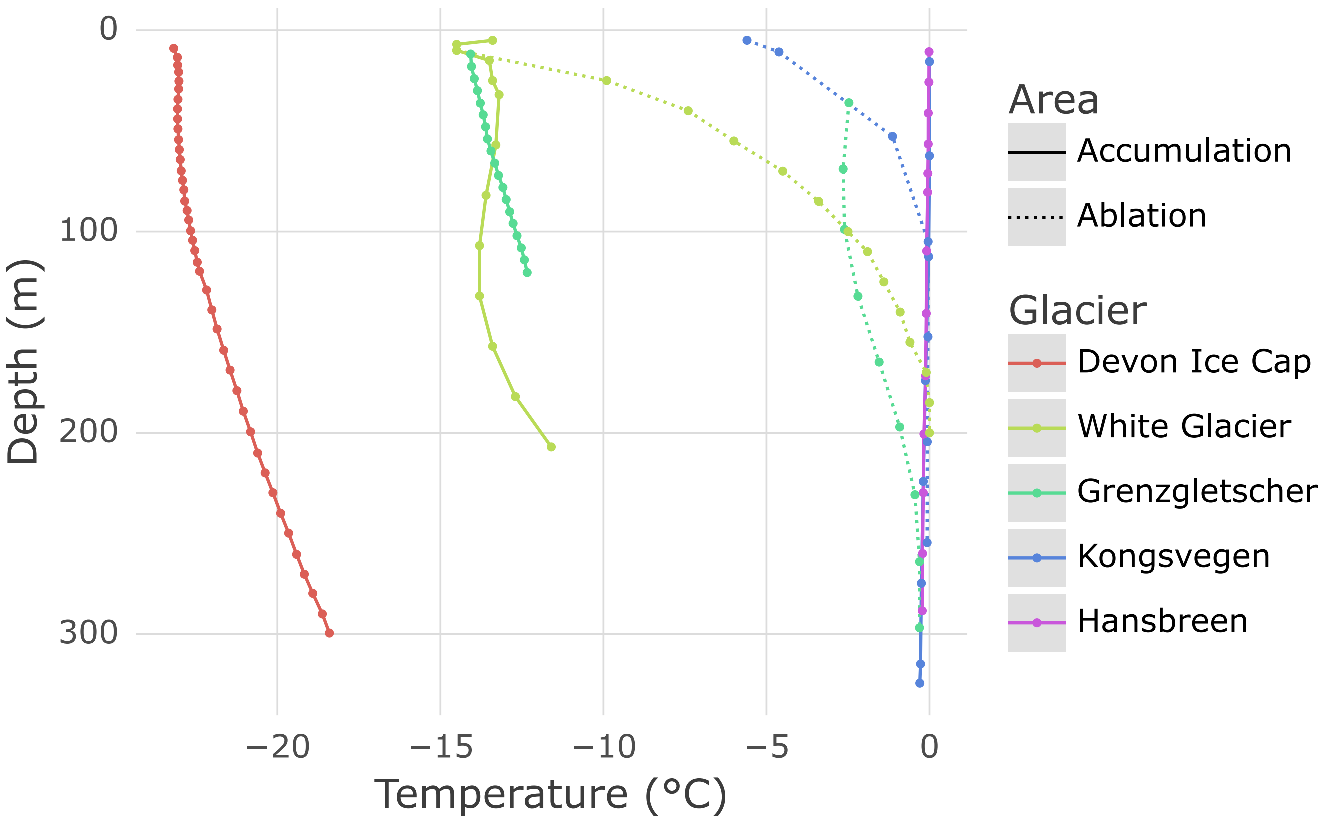

Figure 4. Measured profiles demonstrating the range of englacial temperatures and some typical profile shapes – from fully cold (Devon Ice Cap) to fully temperate (Hansbreen). Measurements from accumulation areas are plotted with solid lines, those from ablation areas with dotted lines.

latent heat release of refreezing meltwater and precipitation is large enough to eliminate the winter cold wave and create temperate firn and ice in the accumulation area. In the ablation area lower on the glacier, meltwater and precipitation can run off, allowing the near-surface ice to cool into a layer of cold ice superimposed on the temperate ice.

The temperatures measured in the boreholes range from temperate (i.e., at the pressure melting point) to −33.5 °C. The majority (75 %) of boreholes deeper than 15 m are in cold or polythermal ice (defined as those where the maximum measured temperature is colder than −0.5 °C), with only about 7 % of all boreholes showing fully temperate conditions (i.e., the lowest measured temperature is warmer than −0.5 °C). This is not surprising. For one, temperate (or even partially temperate) ice is of little interest to ice-core investigations because it does retain a memory of past climatic conditions. Secondly, temperate ice measurements are deemed less interesting, therefore, englacial temperature measurements are rarely carried out on glaciers that are assumed to be fully temperate, and if temperate

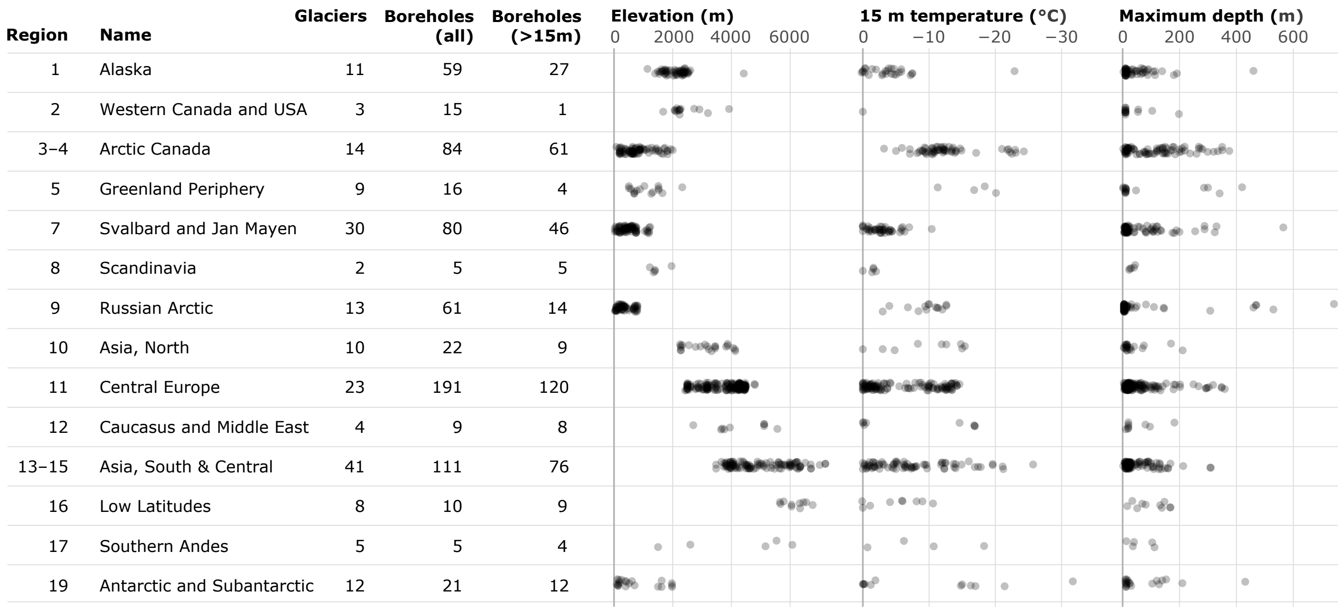

Figure 5. Overview of borehole counts (all and those deeper than 15 m) and surface elevation, 15 m temperature, and maximum measured depth for each borehole (each represented by a dot) by RGI region (see Fig. 3).

conditions are measured, the results are rarely published. However, such measurements would be very valuable to train and calibrate models that predict glacier thermal regimes at regional to global scales. At present, it may be possible to train a model to accurately identify cold or polythermal glaciers, but it would be harder to constrain the boundaries – in terms of elevation, latitude, mean air temperature, etc. – between cold and temperate ice.

The median of the maximum-measured-depths in all boreholes in glenglat is 22 m (see Fig. 5). A total of 485 boreholes (70 %) were measured at depths greater than 15 m, and 148 (21 %) deeper than 100 m. Only 134 (19 %) are known to have reached the glacier bed, including the deepest, an 724 m ice core borehole drilled on Ледник Академии Наук (Akademii Nauk Ice Cap, Severnaya Zemlya, Russia; Kotlyakov et al., 2004).

Of 165 boreholes with a reported ice surface depth (an attribute that was added later and thus likely incomplete with respect to the available literature), 92 actually reached ice, whether at 0 m depth (for 68 boreholes) or below a maximum of 34 m of snow and firn on 慕士塔格冰川(Muztagh Glacier, Xinjiang, China 李真[Li Zhen] et al., 2004). Unfortunately, whether a borehole was drilled into snow, firn, ice, or a combination thereof is not always known. For applications where this is relevant, the stratigraphy can often be estimated – if not explicitly reported – from the depth of the borehole and its location on the glacier (e.g., ablation or accumulation area). Further complicating borehole stratigraphy, repeat measurements in the same borehole typically define depth relative to the glacier surface at the time of the initial drilling or thermistor installation, despite accumulation and ablation that may occur in the interim. This can lead to spurious and above-zero temperature measurements if thermistors melt out over time.

3.2 Climatic conditions

Compared to the average climatic conditions at the locations of all glaciers in the Randolph Glacier Inventory 7.0 (RGI Consortium, 2023), the locations selected for englacial temperature measurements are biased towards cold and dry conditions (Fig. 6a). Most boreholes are in locations where the total annual precipitation is less than $1\,\mathrm{m\,yr^{-1}}$ and the mean annual air temperature is below $-5\,°\mathrm{C}$. This focus on regions with a continental climate is again not surprising, because the high accumulation rates and warmer air temperatures of maritime climates are more likely to lead to temperate ice – which is considered less interesting – or high ice fluxes – which are not desirable for ice core measurements.

To explore the controls on englacial temperatures, we take the 15 m temperature – the depth at which seasonal temperature variations have mostly disappeared (see Fig.7) – as an indicator of the local glacier thermal regime. Comparing these borehole temperatures to the mean annual air temperature taken from (Muñoz Sabater, 2019) of the ten years prior to the borehole measurement reveals that temperate ice can occur over a wide range of surface air temperatures (Fig. 6b). Englacial temperatures generally increase with increasing air temperature, but they are also consistently warmer than the temperatures at the surface. This is expected, given the numerous processes that can deliver heat into the glacier(latent heat release and geothermal, frictional, and strain heating). This warm bias is smallest at the coldest surface temperatures (presumably because there is little melt) – but can still be up to $+10\,°\mathrm{C}$ at $-20\,°\mathrm{C}$. It reaches a maximum of $+15\,°\mathrm{C}$at $-15\,°\mathrm{C}$, before gradually decreasing towards warmer temperatures only because ice cannot be any warmer than the melting-point.

Temperate ice does not seem to occur where the mean annual air temperature is below $\sim\!-15\,°\mathrm{C}$. It is unclear, however, whether the absence of temperate ice in colder climates is real or due to the undersampling of temperate glaciers. In reality, englacial temperatures are controlled by much more than mean annual air temperature and precipitation, and the consideration of 15 m temperatures ignores that: i) temperate ice can exist at deeper locations within the ice even under very cold conditions (e.g., due to shear heating Blatter, 1987), ii) ice temperatures can be controlled by glacier dynamics more than by climate (e.g., emergence of cold ice in the ablation area of a glacier in a temperate climate Ryser et al., 2013), and iii) ice at depth has a memory of past surface temperatures, which can lead to complex patterns of englacial temperatures that are not reflected in the 15 m temperature. Despite these caveats, the large number of englacial temperature measurements available in glenglat makes it possible, for the first time ever, to investigate global patterns of englacial temperatures and hopefully find more robust ways of predicting the thermal regime of all glaciers in a region or worldwide.

3.3 Spatial, temporal, and elevation distributions

The 689 boreholes in glenglat are located on 184 individual glaciers (based on their GLIMS IDs) scattered across the world (see Figs. 3 and 5). This represents less than 1 ‰ of all glaciers worldwide, illustrating both how laborious englacial temperature measurements are and how interest in this glacier variable remains relatively limited. Two

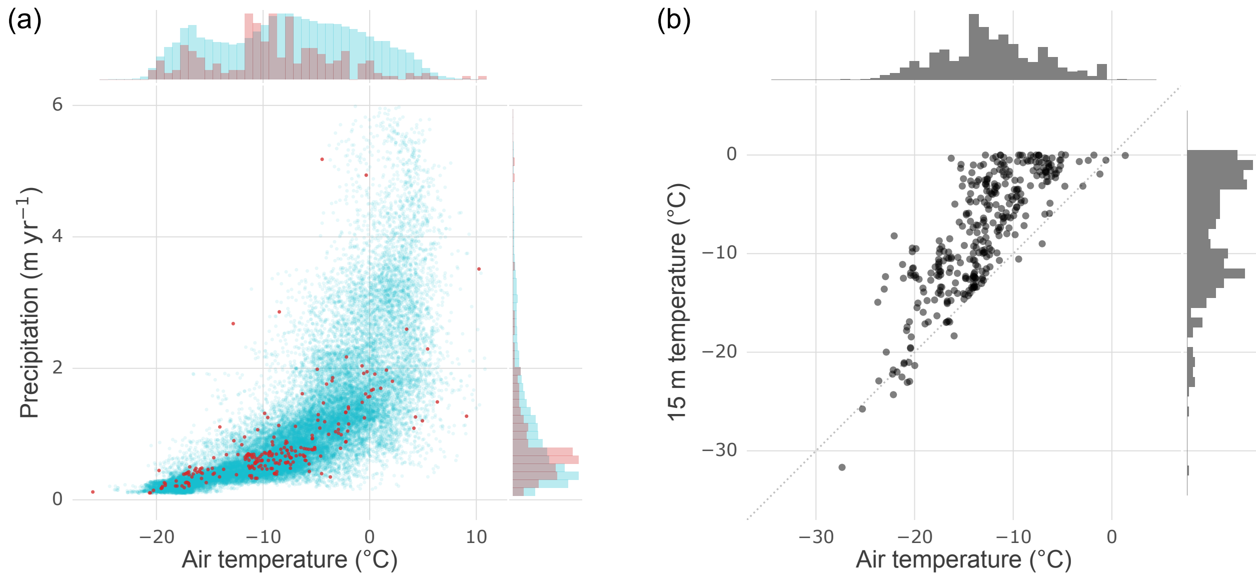

Figure 6. a) Distribution of 2000-2019 mean annual 2 m air temperature and total annual precipitation for the locations of glenglat boreholes (red) and locations of all RGI 7.0 glaciers (blue). b) Englacial temperatures (1950 to present) at 15 m depth versus mean annual air temperature at the borehole location for the ten years prior to the borehole measurement. Air temperatures were adjusted to the elevation of the borehole using a lapse-rate of $-6.5\,^{\circ}\mathrm{C\,km^{-1}}$. The climate data is from ERA5-Land (Muñoz Sabater, 2019).

thirds of all boreholes (68 %) are in either Arctic Canada (84), Svalbard and Jan Mayen (80), Central Europe (191 – albeit with 79 on a single glacier: Grenzgletscher), and South and Central Asia (111). Conversely, there are only five boreholes in all of Scandinavia or the Southern Andes, and none in Iceland or New Zealand.

The surface elevations of boreholes in glenglat range from 25 m (Erikbreen, Svalbard; Ødegârd et al., 1992, (elevation above sea level assumed henceforth)) to 7200 m (Dasoupu Glacier, China; Yao Tandong et al., 2002). Compared to the elevation distribution of glaciers worldwide (as represented by RGI 7.0), elevations above 2000 m are oversampled while elevations between 750 m and 1500 m are undersampled (Fig. 8). This sampling bias may have several causes. Topographic saddles and summits of very high elevation glaciers (> 4500 m) are of particular interest to ice core science because ice flow and melt are minimal and a maximum number of annual ice layers can be preserved. The middle elevations (2000 m to 4500 m) are likely oversampled because they circumvent many of the challenges of work at very high elevations, allowing for simpler (helicopter) logistics and reasonable working conditions. Additionally, this is the elevation range of glaciers in Central Europe (region 11, see Figs. 3 and 5), which are historically overstudied compared to other regions. Below 2000 m, most of the data comes from Svalbard and Jan Mayen (region 7) and Arctic Canada (regions 3-4). Though there are many measurements from these regions, lower elevations remain undersampled, likely because i) there is a very large glacierized area in this elevation band, ii) there is lack

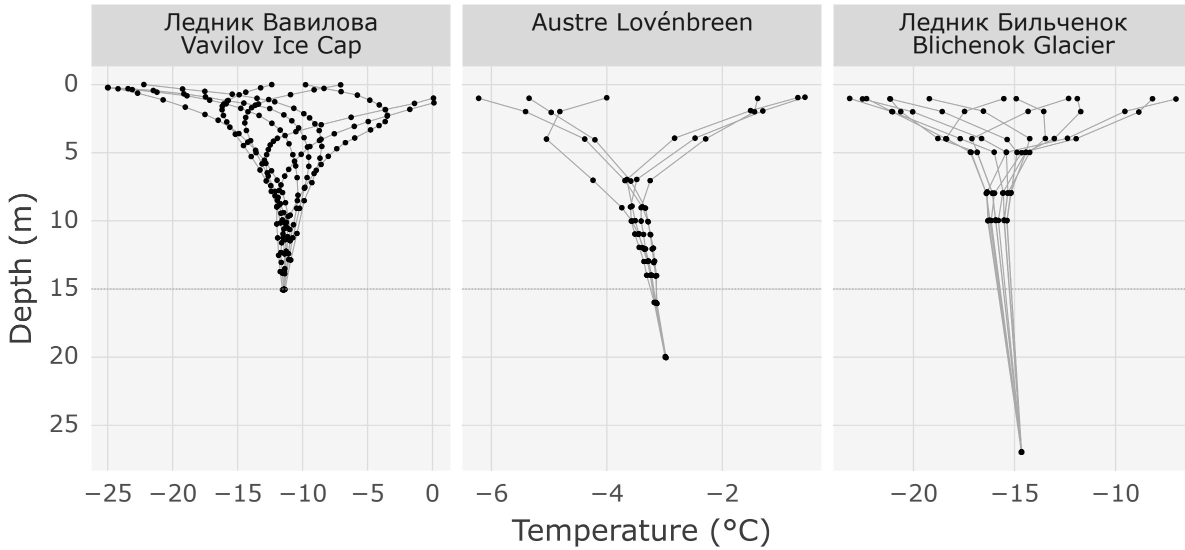

Figure 7. Examples of temperature profiles measured in the same borehole at different times of year, showing the elimination of seasonal surface temperature variations at a depth of around 15 m. Data from Vavilov Ice Cap (Н. И. Барков [N. I. Barkov] et al., 1988), Austre Lovénbreen (孙维君[Sun Weijun] et al., 2016), Blichenok Glacier (Shiraiwa et al., 2001).

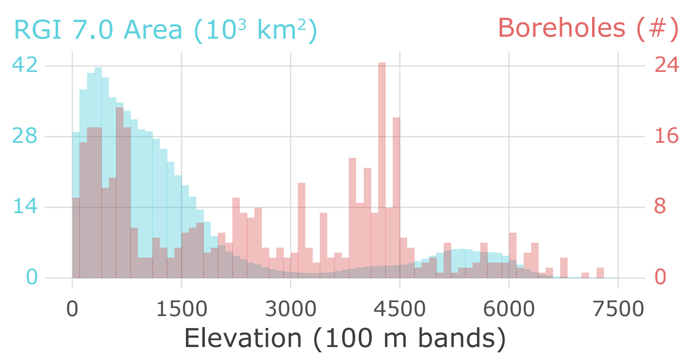

Figure 8. Elevation distribution of glenglat boreholes (red) compared to the elevation distribution of all RGI 7.0 glaciers (blue). Higher elevations, especially between 2000 m and 4500 m, are oversampled while low elevations are undersampled.

of interest in measurements from temperate ice (e.g., the large low-lying glaciers along the west coast of Alaska), iii) the tongues of tidewater glaciers – which make up a large portion of this band – are notoriously difficult to access, and iv) when accessing land-terminating glaciers in these remote regions, working on their low-elevation tongues is easier than accessing the higher accumulation areas (750 m to 1500 m).

The earliest measurement in glenglat stems from 1842, when Louis Aggasiz and colleagues drilled a 60 m borehole in temperate ice on Unteraargletscher (Agassiz, 1847) in Switzerland (see Fig. 9). With the exception of other early outliers (1911, Vallot (1913): 1938, Hughes and Seligman (1939); 1948, Sharp (1951)), wide-spread measurement does not begin until the late 1950s – to a large part motivated by the 1957/1958 International Geophysical Year – by when drilling technology and motorized transport were developed enough to allow increasingly ambitious expeditions to remote areas. Mid-century measurements likely remain underrepresented in glenglat because of early and obscure publications that were never indexed or published online. After sustained activity since the 1970s, measurements decline beginning in 2015, which may be the result of a lag between data collection and publishing, reduced interest and funding for complex field campaigns, a shift of focus from glaciers to ice sheets, or increased emphasis on modeling and remote sensing.

In only 156 boreholes (20 %) were temperatures measured more than once. The most frequently measured borehole is on Hintergrat Glacier (Italy; Carturan et al., 2023a), with five years of hourly measurements (2011-2016). The longest monitored borehole is CG05-1 on Grenzgletscher (Switzerland; Hoelzle, 2014; Darms, 2009; Hoelzle, 2017), drilled in 2005 and measured 4 times over 8 years (2007-2015). The lifetime of a single borehole is limited by creep closure, internal deformation, and other forces that inevitably lead to equipment failure, so to achieve longer records, a new borehole is drilled and instrumented nearby. A cursory review of boreholes within ∼100 m reveals only a few locations with multi-borehole records spanning more than 20 years, all of which are the result of deliberate repeat studies (Vincent et al., 2020; Hoelzle et al., 2011; Thompson et al., 2018; В. Н. Михаленко [V. N. Mikhalenko] et al., 2005b; Rabus and Echelmeyer, 2002), although clusters of more distant boreholes suggest opportunities for retroactive comparisons. The wide range of measurement dates in glenglat could present a challenge for training or calibrating numerical models, as it requires longer model runs and inputs (e.g., climate reanalysis) from earlier periods with less and lower-quality data. Conversely, the low percentage of boreholes that have been measured more than once indicate that there is a large potential for repeat measurements that would yield insight into how englacial temperatures have changed.

3.4 Error analysis

The reported temperature accuracy addresses measurement error (mean 0.14 °C), but not the additional errors that may have crept in when the data was reproduced or when it was finally digitized for glenglat (Fig. 10). Comparing measurements from the same profile retrieved from different sources (e.g., published table versus published figure), we find that reproduction errors (standard deviation 0.48 °C) are on par with the reported measurement errors at depths larger than 15 m (standard deviation 0.18 °C, median absolute deviation 0.06 °C). Because of the steep temperature gradients near the surface, the comparison of different sources can be heavily influenced by whether and which near-surface measurements were included in each source. Comparing the result of two different people digitizing the same measurements, we find that digitization errors, are even smaller (standard deviation 0.132 °C, median absolute deviation 0.025 °C) so as to be negligible. Overall, this indicates that the data available through

Figure 9. Number of measured boreholes (top) and number of measured glaciers (bottom) for each year. We assume that early measurements are still underrepresented, because some publications were not archived. The drop-off towards more recent years may be due to the lag between drilling and publication.

Figure 10. Distribution of reproduction errors (comparing the same measurement from different sources) and digitization errors (comparing the digitization of the same measurement by two different people). These errors are on par with the reported accuracy of the original measurements. The y-axis uses square-root scaling to accentuate differences near 0 °C.

glenglat as suitable for quantitative analysis as data collected directly, even though they have been drawn from one (or several iterations of) publications.

3.5 Future additions

We hope that glenglat can serve not only as a valuable resource for glaciological research today but also as a long-lived data repository for additional (past) and future englacial temperature measurements. The dataset is currently hosted at https://github.com/mjacqu/glenglat. To encourage and facilitate submissions, we have included detailed instructions, a Microsoft Excel spreadsheet template, and a tutorial showing how to self-validate the data prior to submission using the Frictionless Python package.

4 Conclusions & Outlook

Based on an extensive literature search and data submissions, we have created glenglat, the first (to our knowledge) englacial temperature database for all glaciers outside of the ice sheets. Together with the recent compilations of deep boreholes in Greenland by Løkkegaard et al. (2023) and of shallow measurements for Greenland and Antarctica compiled in the SUMup collaborative database (Vandecrux et al., 2023), most published englacial temperature measurements are now readily available to researchers. Depending on community needs, it may be worth combining these datasets into one, for lower maintenance overhead, ease of use, and because the distinction between ice sheet and glacier will become increasingly arbitrary as glaciers detach from the retreating ice sheet margins. Subsurface variables like density (as in SUMup) or stratigraphy (as in glenglat, but only for the depth of the snow/firn-ice transition) may be worth adding, especially since these are often measured alongside temperature. Another enhancement would be to include qualitative temperature information, namely whether a borehole was measured as temperate (but no actual measurements were reported) and the presence and depth of a cold-temperate transition surface (often extracted from ice-penetrating radar profiles as an indicator of the glacier thermal regime).

We believe that glenglat can contribute to better modelling and understanding of englacial temperatures, their spatial distribution, and their changes in a warming world – most directly as an unparalleled source of observational data for model training and validation. For measurements to better reflect global glacier conditions, however, we see a general need for more measurements (or reporting thereof) from temperate glaciers, warmer climates, elevations between 750 m and 1500 m, and underrepresented regions (e.g., Iceland, New Zealand, Scandinavia). Glenglat also presents new opportunities to investigate changes in englacial temperatures over time, both by making more evident the existence of repeat measurements and documenting a century of early measurements that could now be deliberately repeated.

5 Data availability

Glenglat is maintained as a Git repository hosted at https://github.com/mjacqu/glenglat. Published versions – those with an assigned DOI (digital object identifier) – are hosted by Zenodo (e.g., v1.0.0-rc2, to which this manuscript refers: https://doi.org/10.5281/zenodo.11518069, Jacquemart and Welty, 2024). Glenglat is licensed under Creative Commons Attribution 4.0 International (CC-BY-4.0: https://creativecommons.org/licenses/by/4.0).

Author contributions. MJ conceived the project, and together with EW, designed, implemented, and populated the database. MJ and EW wrote the manuscript.

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