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The 2024 release of the Global Heat Flow Database (GHFDB): quality assessment, metadata standards, and a century of geothermal data

Florian Neumann[1,2], **Ben Norden**[2], **Elif Balkan-Pazvantoğlu**[2,5], **Samah Elbarbary**[2],
Alexey G. Petrunin[2,3], **Kirsten Elger**[4], **Samuel Jennings**[4], **Viktoria Dergunova**[2], **and Sven Fuchs**[2]

[1]MARUM Center for Marine Environmental Sciences, University of Bremen, Bremen, 28334, Germany
[2]Section Geoenergy, GFZ Helmholtz Centre for Geosciences, Potsdam, 14471, Germany
[3]Section Geodynamic Modeling, GFZ Helmholtz Centre for Geosciences, Potsdam, 14471, Germany
[4]Section Data and Information Management, GFZ Helmholtz Centre for Geosciences,
Potsdam, 14471, Germany
[5]Dokuz Eylül University, Department of Geophysical Engineering, Izmir, 35390, Türkiye

Correspondence: Florian Neumann (fneumann@marum.de) and Sven Fuchs (sven.fuchs@gfz.de)

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Abstract. The Global Heat Flow Database is a comprehensive data compilation on published heat-flow measurements dating back to the 1950s. The International Heat Flow Commission first released the database in 1963. Recent activities within the World Heat Flow Database Project (funded by the DFG German Research Association) and the Task Force VIII of the International Lithosphere Program (ILP) have focused on (1) developing a new, modern digital data infrastructure with integrated quality control of the data, (2) creating a new dedicated metadata scheme for reporting heat-flow data, (3) conducting a comprehensive review of the original literature to supplement the original metadata according to the new scheme, and (4) thoroughly adding new measurements from the literature. As a result, the 2024 release presents a substantial update, with the number of heat-flow observations increasing from 58 302 data points in 2012 to 91 182 in 2024, while the number of literature sources simultaneously increased from 572 to 1586 documents. A key part of this process was the introduction of a new, comprehensive metadata scheme and the development of the GHFDB Data Template (Global Heat Flow Data Assessment Group, 2024, https://doi.org/10.5880/fidgeo.2024.014), which facilitates the structured and detailed reporting of heat flow observations in accordance with the new scheme (Fuchs et al., 2025a, https://doi.org/10.5880/fidgeo.2025.042). The GHFDB Data Template captures methodological details, uncertainty estimates, and contextual information, forming the basis for a newly implemented, multi-dimensional quality-assessment system. The improved data submission workflow, now supported by the option of obtaining digital object identifier (DOI), making the newly submitted data citable in literature, as is increasingly required by journals. This service encourages direct contributions from researchers and ensures transparency, attribution, and long-term data stewardship by the partner repository GFZ Data Services. The new heat flow database release marks a significant step towards establishing a global, quality- assured data infrastructure and lays the foundation for more reliable, reusable, and interoperable heat-flow datasets across scientific disciplines.

1 Introduction

The Global Heat Flow Database (GHFDB) is an extensive compilation of geothermal heat-flow measurements and its dependent thermal parameters from across the Earth, dating back to the 1950s. The database is maintained by the International Heat Flow Commission (IHFC, https://www.ihfc-iugg.org, last access: 20 June 2026) of the International Union for Geodesy and Geophysics (IUGG). Heat-flow data is essential in many different fields of research: In geosciences, for example, it helps us to analyze the Earth's thermal and tectonic processes. In polar studies, it enables us to assess the dynamics of permafrost and the ice sheet stability for climate change predictions. In oceanography, it enhances our understanding of seafloor spreading and hydrothermal vents. In biological studies, it provides insights into the adaptations of extremophiles to high-temperature environments (e.g., Cavicchioli et al., 2011; Mashayek et al., 2013; Neumann et al., 2017; Fuchs et al., 2020; Negrete-Aranda et al., 2021; Hopcroft and Gallagher, 2023; Neumann et al., 2023a). Heat-flow data further provide boundary conditions for modeling the lithosphere, the ocean floor and the ice sheets (e.g., Fuchs et al., 2020; Reading et al., 2022; Sobh et al., 2025; Vega-Ramírez et al., 2025). The first global heat-flow data compilation was published by Birch (1954) with basic metadata, such as geographical location, elevation and a heat-flow value. The IHFC was founded in 1963 and published the first GHFDB in the same year (Lee, 1963). Since then, the GHFDB has grown in both heat-flow observations and the metadata properties collected for each observation (see Sect. 3). For details on the historical evolution of the database under the IHFC umbrella, the authors refer to Cermak et al. (2018) and references therein.

Beyond its role as a long-term data repository, the GHFDB has become a critical research infrastructure enabling quantitative, large-scale, and interdisciplinary studies that depend on harmonized and quality-controlled heat-flow information. Recent applications include regional to global assessments of lithospheric thermal structure and heat transport (e.g., Harris et al., 2020; Fuchs et al., 2020; Reading et al., 2022; Neumann et al., 2023a; Zhu and Lui, 2025), geothermal resource assessment and exploration (e.g., Senger et al., 2023; Miranda et al., 2026), and the use of heat-flow boundary conditions in climate, cryosphere, and environmental modeling (e.g., Harris and Chapman, 1997; Brand et al., 2025; Brown et al., 2026). Many of these studies rely on metadata completeness, uncertainty characterization, and consistent parameter definitions that were either absent or inconsistently reported in earlier database versions. The present update therefore represents a necessary step to support reproducible research, uncertainty-aware thermal modeling, and emerging applications that could not be robustly addressed using previous releases of the GHFDB.

The 2024 update of the database covers a wide range of geographical locations, including continental, oceanic, and polar regions. In addition to individual heat-flow values, the GHFDB contains several metadata properties, which have overtime and include geographical, thermal gradient and conductivity information, as well as information about environmental or location-specific disturbances and methodological approaches. The most recent standardization process, which took place between 2019 and 2021, was based on a community effort (Fuchs et al., 2021a). This process laid the foundations of the new, enhanced metadata scheme and a newly developed quality score scheme (Fuchs et al., 2023), the application of which is described in this article. The database itself was compiled from published literature over decades. Given the changes in demand for scientific work over time, documentation of heat-flow data has been inconsistent. Numerous references are inaccessible for verification and include sources such as grey literature, confidential industry reports, personal communications, and unclear citations. The first release with the new database structure was in 2021 (Fuchs et al., 2021b) replacing a release from a decade earlier (Global Heat Flow Compilation Group, 2012), which was based on a 1976 data scheme (Jessop et al., 1976). The 2021 update provided all available data points to date as well as references that were compiled from different custodians. Since then, the Global Heat Flow Data Assessment Group, an association of volunteer scientists who supported the revision of the GHFDB, has published regular updates of the revised data collection in the form of annual or biannual releases of the GHFDB. In addition, several regional data collections have been published as intermediate results of this work (Fuchs et al., 2022; Fuentes-Bustillos et al., 2023; Sidigam et al., 2023; Neumann et al., 2023b; Balkan-Pazvantoğlu et al., 2024; Fuchs et al., 2025b). A reviewer core group supporting the IHFC custodian plays a vital role in maintaining and enhancing the quality of the database. This involves ensuring the consistent application of quality standards, validating new submissions, and identifying gaps in metadata or methodological details. Their ongoing contributions facilitate the integration of high-quality data and metadata, thereby strengthening the database's reliability and usefulness to the scientific community. The group is also overseeing the periodic release of updated and new data, ensuring that the latest high-quality information is made available to the scientific community.

In this article, we present the current state of the thorough revision and systematic assessment of the GHFDB which began in 2019. We provide an overview of the workflow and tools used, as well as the assessment results. The latter includes an analysis of the effect that the application of metadata standards and quality schemes has had on the global dataset and its usability, and an analysis of data quality. We also present the Global Heat Flow Database Data Template (GHFDB Data Template), which was the most important tool during the assessment process and will be essential for future data submissions directly to the GHFDB. Finally, we describe the semi-automated process of publishing heat-flow data via GFZ Data Services.

2 Data and literature collection, quality standards, and initial quality control

Since the IHFC members initiated the revision of the GHFDB at the 2019 IUGG General Assembly, direct access to primary literature sources has been an indispensable foundation for creating an authenticated GHFDB. In order to carry out the global assessment, a complete overview of the available heat-flow literature and access to digital copies of the underlying publications was needed. Building a comprehensive archive of heat flow literature was a tremendous task that also started in 2019. The custodian philosophy here is to acknowledge the original researcher's work and to avoid citation chains. The latter can occur when data are republished in compilations in order to provide a DOI for data that did not have one at the time of publication. The assessment core group at, led by members of the author team, began collecting reference lists from old and curated internet sources (e.g., PANGAEA, outdated IHFC pages, online repositories or institutional data publishing) and from previous data compilations, such as atlases or previous IHFC releases. This effort was expanded on this by conducting extensive online searches using scholarly indexing services (e.g., Web of Science, Scopus and Google Scholar), alongside building an Endnote database for bibliographic information. Document deliveries from the international libraryloan system (SUBITO) supported by the Telegrafenberg library team were also initiated. Over time, many donations of literature from numerous authors, contributors and collaborators in the international heat flow community were received, whom the core group have approached several times for this purpose. Since then, the collection has grown to approximately 4030 items (see Table 1), covering all kinds of reference types. Currently, the literature collection comprises around 2593 peer-reviewed articles, which usually come with comprehensive metadata, including detailed bibliographic information, methodologies, and results. This makes them reliable sources of scientific and technical information. Many of these articles were obtained as scanned copies from colleagues from the community, ensuring access to valuable publications that would otherwise have been difficult to obtain. Additionally, 564 books and book sections that provide extensive coverage of geothermal topics have been acquired. These books are distinguished by the relevant information they contain, including comprehensive bibliographies, thorough indexing, and extensive appendices. This extends their value as research resources by providing detailed context, methodologies, and background knowledge required to comply with properties needed for the new metadata scheme. Books, particularly older and more obscure publications, were obtained via international interlibrary loans. Furthermore, the literature collection has grown thanks to generous donations of hard copies, such as those by Vladimír Čermák from the Geophysical Institute of the Czech Academy of Sciences in 2024. These donations have particularly enriched the collection of Russian literature, which often contains unique data and insights that are not readily available in digital format. Today, the literature collection covers heat-flow research from 1884 to 2025. The collection also includes 193 conference documents from 1967 onwards that focus on the latest advancements in heat flow research. While these documents tend to be brief and contain limited metadata, they may be the only source of specific heat-flow data.

In addition, 381 technical or research reports that describe a wide variety of geothermal studies, regional energy assessments, and marine heat-flow studies were compiled. These reports are generally well-structured, with substantial content and metadata detailing the research methodology, data, and findings. The reports and conference papers were gathered through online searches and downloads, while others were sourced as community copies shared by colleagues and collaborators within the heat flow research community. Cruise reports are particularly valuable for marine heat-flow studies and the majority of these were accessed directly from the websites of the relevant institutes and organizations, or from colleagues who conducted the expeditions. The collection further includes 157 PhD, master and bachelor theses representing significant original research (Table 1). These theses, particularly the PhD theses, are renowned for their thoroughness and depth, featuring extensive metadata such as detailed methodologies, comprehensive data analysis, and in-depth discussions. Their high quality makes them valuable sources of detailed and well-documented information. PhD theses, in many cases, are often easier to obtain as they are frequently available on university library or institutional repository websites. In contrast, obtaining MSc and BSc theses is more challenging, as they are rarely digitized or made publicly accessible, particularly for older documents. Often, even the single copies held in individual university libraries are also not available via interlibrary loan. The majority of these theses were acquired in digital form through generous donations from the scientific community. For PhD theses for which international interlibrary loans to Germany were not possible, colleagues from the countries in which the theses were originally written kindly provided digital copies, ensuring that the data could be included and documented in the GHFDB. The "Other" category, consisting of 118 items, includes datasets, maps, hand-written notes and comments, and personal communications. While these documents may provide valuable context-specific information, their quality can vary and they are generally not peer-reviewed. Nonetheless, they provide supplementary insights that can be relevant for specific research questions. All items in this category were contributed by colleagues, with maps being primarily sent as hard copies. Out of the total collection of about 4030 publications with thermal or heat-flow reference, 1586 documents contain actual heat-flow data that have been compiled for the database release 2024. For the next release, around 1800 relevant publications are anticipated. The remainder utilize the database for different research purposes, often as boundary input or as numerical model calibration. Where maps served as the sole source of heat-flow data, they were digitized using the large-scale map scanner at the GFZ library. Regarding the languages, the collection includes 2833 documents in English and the remaining 1197 have been written in various foreign languages, which poses challenges for the review process. Significant contributions from a total of 13 other languages include Russian (~ 500 documents), Chinese (107), German (73) and smaller numbers in languages such as Japanese, Spanish, Hungarian, Romanian and Portuguese. Note that, for copyright reasons, none of the documents in our collection are publicly accessible; they are stored solely as proof and backup for the published heat-flow data. The documents serve as internal references and verification sources to support and validate the information within the GHFDB of the International Heat Flow Commission. Each heat-flow value in the database is linked to the original reference in the form of a citation. The literature collection comprises more than 4000 publications and reports related to terrestrial and marine heat-flow measurements gathered from international scientific literature, institutional archives, and community contributions. For 89 % of the data records included in the 2024 release, the original source documents were available to the assessment team. It is worth acknowledging the crucial role that the international collaborative network played in the preservation of the impressive memory of legacy publications of thermal and heat-flow research. Despite all technological and organizational efforts, however, the authors must acknowledge that some originals have been lost over the course of history.

The data collection process and initial quality control measurements from the literature, a commercial reference management software (EndNote) was used to organize and manage our bibliographic references and citations. Upon receiving a new document, the core group conducted an initial screening to distinguish those publications containing heat-flow data from those that reference it and assign a unique internal identifier (ID) based on the author and year (e.g., Author_2019; Author_Author_2020; Author_etal._2021). If multiple documents by the same author or authors combination are from the same year, letters are appended to differentiate them (e.g., Author_etal._2021a, Author_etal._2021b).

3 Metadata Schema and GHFDB Data Template

Metadata Schema and GHFDB Data Template since its inception, the Global Heat Flow Database (GHFDB) has experienced substantial growth, expanding from the original 63 heat-flow observations reported by Birch in 1954 to approximately 90 000 in this release 2024. During this time, the metadata properties collected for each observation have increased from 7 to 62 fields (see Table 2). During the initial assessment of parts of the heat-flow database before 2019, it became clear that the few originally collected metadata properties were insufficient for modern methods of heat-flow determination and the requirements of high-quality heat-flow data across many geoscience disciplines. A more detailed description of the data was required to evaluate the data quality. This was the main motivation for the development of a new comprehensive metadata scheme for the Global Heat Flow Database (Fuchs et al., 2021a, 2023). The creation of this scheme, developed in collaboration with the global heat-flow community under the umbrella of the IHFC and ILP, was a critical development in the GHFDB's growth.

To facilitate the provision of high-quality heat-flow data with associated structured metadata following the new metadata scheme, a dedicated data template was developed. The GHFDB Data Template (Fuchs et al., 2025a) serves as the primary tool for the structured documentation and reporting of heat-flow data and associated information. It is designed to capture detailed metadata at multiple levels, ensuring that all essential information required to describe, contextualize, and evaluate heat-flow measurements is systematically recorded. Following the original metadata scheme, the template consists of 62 individual fields, organized into four main categories: heat-flow density, metadata and flags, temperature, and thermal conductivity. Field obligations are divided into 36 mandatory fields used for the quality score calculation, and 20 recommended and a further 6 optional that provide supportive information. This structure facilitates accurate data retrieval, analysis, and comparison across different geographic regions and methodological approaches. The template provides a structured tool that helps both the international assessment team, which works globally as a virtual project group, and any scientist who submits their new data to the GHFDB.

The GHFDB Data Template also forms the foundation of the newly developed quality scoring system that enables a multi-dimensional assessment of heat-flow data (see below and Fuchs et al., 2023).

3.1 Hierarchical Structure: Parent-Child System

The GHFDB Data Template uses a parent-child system to capture information at multiple levels for each heat-flow site, ensuring thorough documentation of both primary site attributes and specific measurements. At the parent level, the template stores essential information about the measurement location, including geographical coordinates (latitude, longitude, elevation), geological setting (onshore or offshore), and exploration purpose and method. It also includes the most (site-) representative heat-flow value (q) and its associated uncertainty, providing the best estimate of vertical terrestrial heat flow at that specific site. Besides the primary site information, contextual information like basic environmental con-

Table 1. Summary of collected relevant heat-flow documents (as of April 2025).

Category	Count	Share (%)	Notes
Peer-reviewed articles	2593	64.3	Primary literature
Books/Sections	564	14.0	Monographs and edited volumes
Reports	381	9.5	Institutional, technical and cruise reports
Conference references	193	4.8	Abstracts and proceedings
Thesis	157	3.9	103 PhD, 48 MSc, 6 BSc
Other	142	3.5	Miscellaneous sources
Total	4030	100	

Table 2. Summary of selected heat-flow observations and metadata for the GHFDB.

Heat-Flow Observations	Metadata Properties	Reference
63	7	Birch (1954)
~ 800	9	Lee (1963)
~ 2000	12	Lee and Uyeda (1965)
~ 2500	16	Simmons and Horai (1968)
~ 5400	24	Jessop et al. (1976)
~ 25 000	18	Pollack et al. (1993)
~ 60 000	43	Hasterok and Chapman (2008)
~ 70 000	19	Lucazeau (2019)
~ 74 000	56	Fuchs et al. (2021a, b)
~ 91 000	62	Release 2024/This study

ditions of the heat-flow determination, general comments, flags for heat production corrections (e.g., from the overburden) or total measured and true vertical depth are provided as additional parent-level properties.

Each parent entry is linked to one or more child entries that store detailed data from individual depth intervals, different measurement techniques or correction statuses. These child entries provide further detailed information from individual measurements, including heat-flow values, uncertainties, methods, interval boundaries, and penetration depths. Child entries also record metadata on the primary publication reference and site-specific flags for various environmental effects (e.g., in-situ thermal properties, temperature corrections, sedimentation, erosion, topographic, and paleoclimatic effects), as well as platform and probe details (e.g., vessel, expedition, probe type, length, and tilt). Other fields capture both corrected and uncorrected temperature gradients, thermal conductivity values, their associated uncertainties, and the methods and conditions used (e.g., saturation, pressure, and temperature). A detailed description of the individual fields can be found in Fuchs et al. (2023). The relevant child field indicates the values that correspond to the parent entry. If multiple child values exist and the original literature does not specify a value, the parent value is calculated as an arithmetic mean of the child values. The hierarchical parent-child structure ensures that depth-dependent and multi-methodological data are effectively captured and analyzed, allowing for a more comprehensive understanding of site-specific conditions.

3.2 Sub-Categories, Properties and Controlled Vocabularies

The GHFDB Data Template is designed to systematically organize and store multiple heat-flow observations ensuring that both site attributes and specific measurements are well-documented. It encompasses four sub-categories, each focusing on different aspects of the data, including heat-flow density, metadata, flags, temperature, and thermal conductivity (see Table 3).

The heat-flow-density field captures the measured heat-flow value (qc) and its associated uncertainty, derived from individual depth intervals, as well as the surface heat-flow value (q), which represents the most representative heat-flow value at a given site. The template also distinguishes between different depths and measurement types by utilizing the heat-flow type field, which categorizes the data as surface heat-flow (q) or child heat-flow (qc).

The metadata and flags fields provide detailed contextual information about the measurement site and the data source. These fields include location data, such as geographical coordinates, elevation, and site descriptions, as well as geological context covering lithological and tectonic settings, depositional environments, and relevant geological history. Additionally, reference and source fields document publication details and any additional references necessary for understanding the dataset. Measurement conditions such as the date of measurement, environmental factors, and site-specific conditions that could influence heat-flow values are also systematically stored.

The template further includes specific flags for known perturbations that may affect the heat-flow values, ensuring that corrections are documented for both environmental and methodological factors like sedimentation, erosion, topographic and paleoclimatic effects, transient surface temperature changes, convection processes, and heat refraction effects. These flags enhance transparency and allow researchers to properly account for these variables when analyzing the data, ensuring that the reported heat-flow measurements reflect the true subsurface conditions.

In addition to the perturbation flags, the template captures information on the research platform, vessel, or expedition used for data collection. This contextual information provides insight into the operational environment of the study area with sources such as cruise reports for marine heat-flow data that contribute additional geophysical and geological data. The template also captures probe specifications, including type, length, probe tilting during measurements, and surface temperature, ensuring methodological transparency and supporting accurate data analysis.

Temperature data is an important component for heat-flow determination, and the GHFDB Data Template includes separate fields for recording the temperature methods, corrected and uncorrected temperature gradients with respective uncertainties, and applied correction methods. The template also captures shut-in or relaxation times after drilling, ensuring that thermal equilibrium is properly documented, along with any method used for temperature stabilization. Separate fields for corrected temperature gradients at both the top and bottom depths of the measured interval ensure accurate reporting of depth-specific variations and potential site-specific influences.

Thermal conductivity, another critical parameter in heat-flow determination, is also comprehensively documented in the template. The relevant fields include thermal conductivity values and their uncertainty for each depth interval, as well as details on the measurement techniques, such as line/-plane source with half-space, or full-space methods. Correction factors for in-situ pressure, temperature, and fluid saturation effects are also included, providing a clearer understanding of the subsurface thermal conditions.

To ensure flexibility and accommodate additional information that may not be captured by the predefined properties, the GHFDB Data Template includes a free-text comment field at both the parent and child levels. This field allows for the inclusion of any supplementary information, observations, or context-specific details that may help understanding and interpretation of the heat-flow data. These free-text entries ensure that unique or unforeseen factors that may have an influence on the data can be adequately documented, contributing to a complete and more nuanced dataset. If multiple entries or methods are used, they are separated by a semicolon (;) within the respective property cell, ensuring that all relevant information is preserved without compromising data structure.

For numerical fields, a defined range of allowed values is enforced to maintain consistency and prevent erroneous entries. For string-based fields, a controlled vocabulary is applied to standardize terminology and ensure consistency across different datasets (Fuchs et al., 2025a, 2023). The controlled vocabulary used in the template can also be found here: https://github.com/ihfc-iugg/ihfc-vocabularies (last access: 20 June 2026, Jennings et al., 2026). Most of these vocabularies were developed in the framework of the collaborative and community-driven standardization process and will be converted to RDF format and registered via dedicated vocabulary servers (e.g., by the Australian Research Data Commons or the German Base4NFDI terminology server) at a later stage. External controlled linked-data vocabularies are already used for naming the lithology (GeoSciML Simple Lithology, http://resource.geosciml.org/classifier/cgi/lithology, last access: 20 June 2026), and the stratigraphy (International Chronostratigraphic Chart of the International Commission on Stratigraphy; https://stratigraphy.org, last access: 20 June 2026, accessed through https://vocabs.ardc.edu.au/viewById/128, last access: 20 June 2026).

Several fields in the GHFDB Data Template are automatically populated using controlled vocabularies or populated using external data services, reducing manual data entry and enhancing consistency. These include administrative fields such as entry ID, parent ID, child ID, and modification history, as well as geographical classifications based on site coordinates, including continent, country, region, and oceanic or continental classification (https://geoportal.un.org/, last access: 20 June 2026). Additionally, the final quality score is automatically added to the dataset after evaluation, using a Python-based script that reads the submitted Excel file (GHFDB Data Template), performs the quality assessment based on predefined rules, and writes the resulting score directly back into the appropriate field of the template. This semi-automated workflow ensures consistent application of the scoring system and facilitates reproducibility of the assessment process.

To ensure data discoverability and long-term accessibility, the GHFDB Data Template is designed to capture and properly format all relevant metadata. It is also the source of automated information integration into the database. Key fields include a unique ID linked to Digital Object Identifiers (DOIs), which connect datasets to their associated publications, ensuring persistent access to the original sources whenever possible. International Generic Sample Numbers (IGSNs) can be added to provide traceability for physical samples associated with heat-flow data, ensuring consistent identification and reference of the physical samples. Citation and attribution fields enable researchers to always properly credit the original publication and the data publication to promote transparency of research results and follow the rules of good research practice.

By systematically capturing detailed metadata at both the parent and child levels, the GHFDB Data Template ensures that heat-flow data is well-documented, traceable, and easy to integrate into regional or global models. The template was extensively tested during the assessment process and will serve as the tool for future data submissions. A primary goal of the GHFDB Data Template is to ensure that newly submitted data is of high quality directly from data producers, reducing the need for extensive data extraction from scien-

Table 3. Summary of database properties.

Sub-category	Properties
Heat flow (8)	Basic geographical environment Flag heat production of the overburden (heat-flow correction) General comments parent level Type of exploration method Original exploration purpose
	Heat-flow method Primary publication reference Relevant child
Metadata and perturbation flags (18)	Flag in-situ thermal properties Flag temperature corrections (instrumental correction) Flag sedimentation effect (temperature/heat-flow correction) Flag erosion effect (temperature/heat-flow correction) Flag topographic effect (temperature/heat-flow correction) Flag paleoclimatic effect (temperature/heat-flow correction) Flag transient surface temperature (temperature/heat-flow correction) Flag convection processes (temperature/heat-flow correction) Flag heat refraction effect (heat-flow correction) Platform, Vessel, Expedition Probe type Probe tilt Probe length Surface/Bottom-water temperature Lithology Stratigraphic age Date of acquisition IGSN
Temperature (7)	Shut-in time (top) Shut-in time (bottom) Temperature method (top) Temperature method (bottom) T correction method (top) T correction method (bottom) Number T recordings
Thermal conductivity (8)	Thermal conductivity source Thermal conductivity location Thermal conductivity method Thermal conductivity saturation Thermal conductivity pT conditions Thermal conductivity pT assumed function TC number TC averaging method

tific publications. The newly developed DOI minting service, created in partnership with GFZ Data Services, encourages researchers to fulfil data publication requests, thereby ensuring that datasets are properly archived, documented, and accessible for future research.

4 Heat flow – quality evaluation scheme

The evaluation scheme of heat-flow data (HFD) focuses on determining the reliability of the collected information, creating a comprehensive and comparable database, and improving the understanding of the Earth's lithospheric thermal conditions. To achieve this, Fuchs et al. (2023) proposed a quality evaluation scheme that identifies the most accurate heat-flow values and ensures a consistent, high-quality HFD. This scheme incorporates three key components: uncertainty quantification (U-Score), methodological rating (M-Score), and the assessment of various perturbation effects (P-flags), which combined offer a comprehensive evaluation of data reliability and methodological rigor of heat-flow data expressed by an overall quality score (applied in the 2024 release of the Global Heat Flow Database; Global Heat Flow Data Assessment Group et al., 2024). It also reflects effects that might perturb technically reliable and methodologically perfectly executed heat-flow measurements; for example, effects on temperature gradients from erosion, sedimentation, topographical elevation or transient climate effects. These quality scores are particularly crucial for managing older data with missing metadata, allowing such data to remain in the database while being flagged appropriately. The multi-dimensional quality flags enhance users' ability to understand and assess the data, contributing to a more transparent and reliable database overall.

4.1 Automated evaluation of heat-flow data

The *quality_scores* Python script originally developed by Chishti et al. (2025) was subsequently updated by Dergunova et al. (2026). The script automates the assessment of heat-flow data reliability by computing three key components: the U-score, M-score, and P-flags, based on the framework outlined by Fuchs et al. (2023). Detailed definitions of the U-score and M-score quality classes, as well as the scoring criteria and implementation, are provided in Fuchs et al. (2023), Chishti et al. (2025), and Dergunova et al. (2026). The U-score quantifies numerical uncertainty in heat-flow data using the relative coefficient of variation (COV), which expresses the uncertainty of the mean heat-flow density (HFD-mean) as a percentage. This uncertainty (HFDunc) is derived through error propagation of uncertainties in thermal conductivity and temperature gradient measurements. The COV classification assigns a U-score ranging from U1 (excellent) to U4 (poor), ensuring a standardized evaluation of heat-flow data precision.

The M-score assesses methodological quality by evaluating the reliability of temperature gradient and thermal conductivity measurements. It accounts for differences between shallow probe-sensing techniques (marine) and borehole/mine-based (mainly continental) methods by assigning penalties and bonuses based on metadata completeness and measurement conditions. The scoring starts at 1.0 and is adjusted based on factors such as penetration depth, number of temperature points, data source reliability, measurement type and source, saturation, and p-T conditions for thermal conductivity and corrections for temperature. Final M-scores are categorized into four quality classes (M1–M4), with an "x" suffix (e.g., M3x) indicating incomplete metadata. In particular, the designation Mx is used when the type of exploration method is missing.

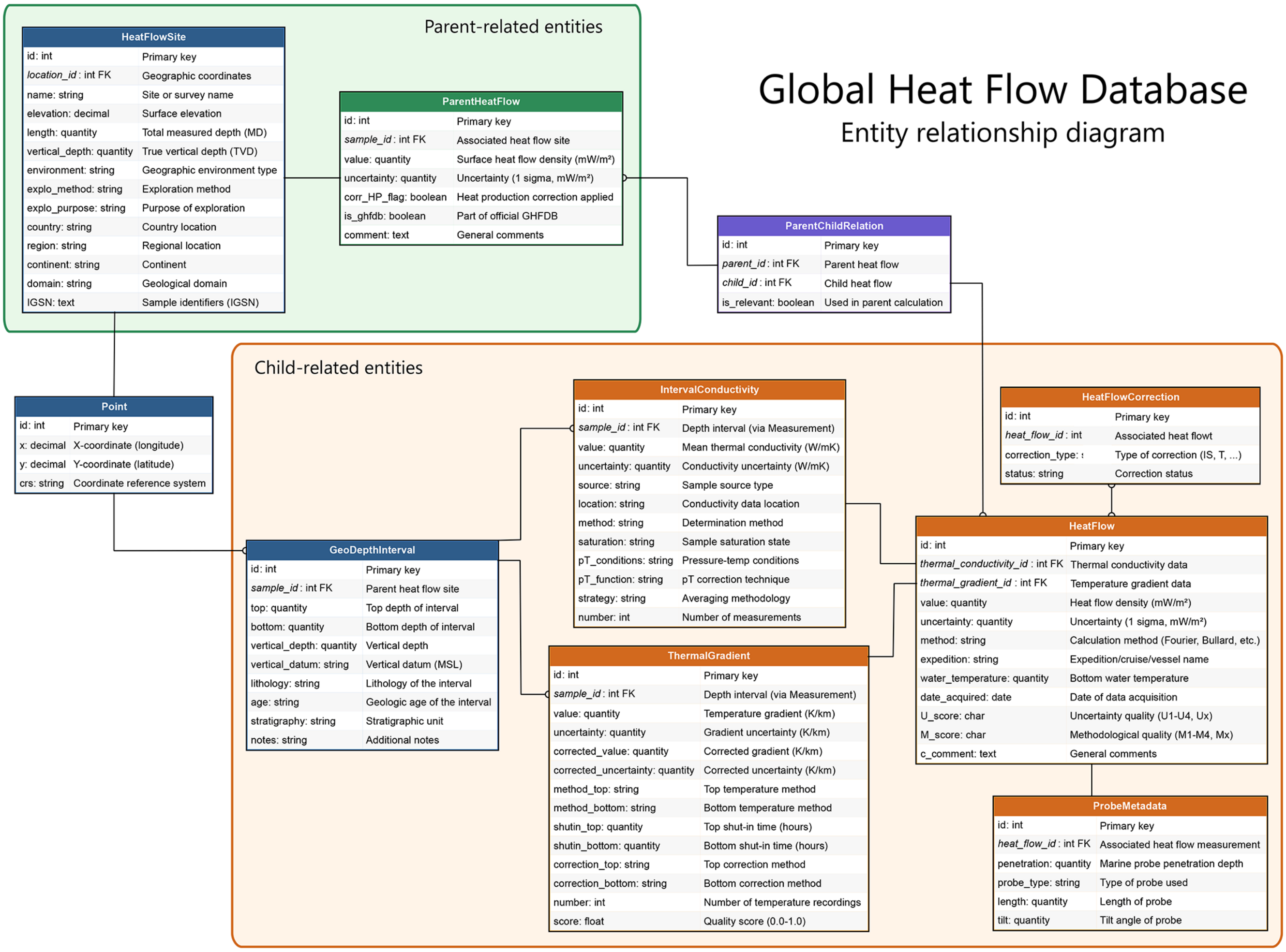
The P-flags provide a site-specific indicator of potential perturbation effects that may influence heat-flow measurements. Because site-specific corrections often require additional data not stored in the database, this system offers a pragmatic approach to flagging recognized perturbations. The P-flag consists of a seven-letter code representing different types of perturbations: Surface processes effects include sedimentation (S/s), erosion (E/e), and topography/bathymetry (T/t), while time-dependent surface temperature effects account for paleoclimate/glaciation (P/p), surface/bottom water temperature variations (V/v), and convection/fluid flow/hydrate dynamics (C/c). Additionally, structural effects such as heat refraction (R/r) are considered. Each perturbation is marked with an uppercase letter if it was corrected, a lowercase letter if it was recognized but not corrected, an uppercase "X" if it was assumed to be insignificant, and a lowercase "x" if it was not recognized or assumed absent. If information is missing, a "-" is used. The final quality score offers a detailed assessment of the data's reliability and applicability. For instance, a score of U2M2.ScXx-x- indicates that the U2 score shows the uncertainty in the measurements falls within an acceptable range, ensuring the data is reliable for analysis. The M2 score highlights a solid methodological approach, confirming that the measurements are backed by appropriate correction processes and sufficient metadata, which reinforces the dataset's credibility. The P-flags reveal that environmental factors were considered, but not all were fully corrected. Specifically, the sedimentation effect (S) was addressed, groundwater flow (c) was recognized but not corrected, and topographic effects (X) were deemed negligible. The "x" for glaciation suggests no major influence. Other environmental factors were either not flagged or left unassessed. The inclusion of "ScXx-x-" emphasizes the need for caution when interpreting the results, particularly where perturbations were not fully addressed. Overall, this quality score indicates that while the dataset is dependable and robust in terms of methodology and uncertainty, there are external factors that may affect the data quality. Further improvements in handling these factors could refine the dataset and improve its overall reliability.

5 The new research data infrastructure of the GHFDB

To make use of the full potential of the new database, the GHFDB has been developed as a new digital research data infrastructure for an online domain-specific community portal. It will transform the database from a desktop and file-based collection into a fully integrated online database system that acts as a one-stop shop for all kinds of information around heat-flow research. The web portal (https://www.heatflow.world, last access: 20 June 2026) is built on stable, open-source technology and is hosted on servers managed by GFZ. It is developed using the Django web framework and is powered by a PostgreSQL database instance. Containerization and management of multiple required services is maintained via Docker and ensures consistent deployment across different environments. Continuous integration tools including GitHub workflows, pre-commit hooks and code coverage tools help to maintain high code quality. The open-source codebase, along with configuration files for deployment, are available for inspection, feedback and contributions from the open-source community. The underlying relational database structure and the hierarchical organization of the heat-flow data are illustrated schematically in the Entity–Relationship Diagram (ERD; Fig. 1).

The portal serves two primary purposes: (1) enabling easy and open access to high-quality heat-flow data and (2) providing analytics tools that facilitate online data exploration. Users of the portal can explore individual datasets through the user interface, paging through entries that match desired filters or keywords. Data may also be consumed programmatically via a RESTful API, which caters to automated systems and can be easily integrated into external workflows. In addition, thanks to the strict metadata definitions and enforced data conformity, the portal also offers tabular data views that allow users to browse through individual data tables that span across many different datasets. In terms of analytical capability, the portal provides a custom-built mapping application that allows both casual and advanced users to visually explore and analyze the latest release of the Global Heat Flow Database. The interactive mapping tool allows users to view geographic distributions of heat-flow data. It provides filtering and analytical capabilities, allowing users to highlight regional variations and trends without the need to download and master specialized software.

A secondary goal of the portal is to migrate the ongoing maintenance and growth of the Global Heat Flow Database from a custodian-driven approach to a community-driven effort led by domain experts. To promote a community-driven



HeatFlowSite	
id: int	Primary key
location_id : int FK	Geographic coordinates
name: string	Site or survey name
elevation: decimal	Surface elevation
length: quantity	Total measured depth (MD)
vertical_depth: quantity	True vertical depth (TVD)
environment: string	Geographic environment type
explo_method: string	Exploration method
explo_purpose: string	Purpose of exploration
country: string	Country location
region: string	Regional location
continent: string	Continent
domain: string	Geological domain
IGSN: text	Sample identifiers (IGSN)

ParentHeatFlow	
id: int	Primary key
sample_id : int FK	Associated heat flow site
value: quantity	Surface heat flow density (mW/m²)
uncertainty: quantity	Uncertainty (1 sigma, mW/m²)
corr_HP_flag: boolean	Heat production correction applied
is_ghfdb: boolean	Part of official GHFDB
comment: text	General comments

ParentChildRelation	
id: int	Primary key
parent_id : int FK	Parent heat flow
child_id : int FK	Child heat flow
is_relevant: boolean	Used in parent calculation

Point	
id: int	Primary key
x: decimal	X-coordinate (longitude)
y: decimal	Y-coordinate (latitude)
crs: string	Coordinate reference system

IntervalConductivity	
id: int	Primary key
sample_id : int FK	Depth interval (via Measurement)
value: quantity	Mean thermal conductivity (W/mK)
uncertainty: quantity	Conductivity uncertainty (W/mK)
source: string	Sample source type
location: string	Conductivity data location
method: string	Determination method
saturation: string	Sample saturation state
pT_conditions: string	Pressure-temp conditions
pT_function: string	pT correction technique
strategy: string	Averaging methodology
number: int	Number of measurements

HeatFlowCorrection	
id: int	Primary key
heat_flow_id : int	Associated heat flowt
correction_type: :	Type of correction (IS, T, ...)
status: string	Correction status

GeoDepthInterval	
id: int	Primary key
sample_id : int FK	Parent heat flow site
top: quantity	Top depth of interval
bottom: quantity	Bottom depth of interval
vertical_depth: quantity	Vertical depth
vertical_datum: string	Vertical datum (MSL)
lithology: string	Lithology of the interval
age: string	Geologic age of the interval
stratigraphy: string	Stratigraphic unit
notes: string	Additional notes

HeatFlow	
id: int	Primary key
thermal_conductivity_id : int FK	Thermal conductivity data
thermal_gradient_id : int FK	Temperature gradient data
value: quantity	Heat flow density (mW/m²)
uncertainty: quantity	Uncertainty (1 sigma, mW/m²)
method: string	Calculation method (Fourier, Bullard, etc.)
expedition: string	Expedition/cruise/vessel name
water_temperature: quantity	Bottom water temperature
date_acquired: date	Date of data acquisition
U_score: char	Uncertainty quality (U1-U4, Ux)
M_score: char	Methodological quality (M1-M4, Mx)
c_comment: text	General comments

ThermalGradient	
id: int	Primary key
sample_id : int FK	Depth interval (via Measurement)
value: quantity	Temperature gradient (K/km)
uncertainty: quantity	Gradient uncertainty (K/km)
corrected_value: quantity	Corrected gradient (K/km)
corrected_uncertainty: quantity	Corrected uncertainty (K/km)
method_top: string	Top temperature method
method_bottom: string	Bottom temperature method
shutin_top: quantity	Top shut-in time (hours)
shutin_bottom: quantity	Bottom shut-in time (hours)
correction_top: string	Top correction method
correction_bottom: string	Bottom correction method
number: int	Number of temperature recordings
score: float	Quality score (0.0-1.0)

ProbeMetadata	
id: int	Primary key
heat_flow_id : int FK	Associated heat flow measurement
penetration: quantity	Marine probe penetration depth
probe_type: string	Type of probe used
length: quantity	Length of probe
tilt: quantity	Tilt angle of probe

Figure 1. Entity–Relationship Diagram (ERD) of the Global Heat Flow Database (GHFDB), providing a detailed schematic representation of the relational database structure described in the text. The model illustrates the hierarchical parent–child organization of heat-flow data, separating parent-related entities (green) from child-related entities (orange). The junction table ParentChildRelation (purple) links parent and child heat-flow records and identifies which child values contribute to the parent heat-flow calculation via the is relevant field. Primary keys are shown at the top of each entity, and foreign keys are italicized, while crow's-foot notation indicates one-to-many relationships. Color coding highlights entity roles within the schema: blue entities represent relatively stable site and depth-interval metadata, whereas orange and green entities capture measurement-specific information. Purple elements denote relational infrastructure. The schema enables provenance tracking from primary measurements (e.g., thermal gradients and thermal conductivities), through derived child heat-flow estimates including corrections and probe metadata, to quality-controlled parent heat-flow values at the site level.

approach, the portal provides several features aimed at engaging heat-flow researchers and convincing them to actively participate. These features include the ability to showcase historic or promote ongoing heat flow research projects, provide commentary on publicly available datasets and to follow the work of other heat-flow researchers from around the world. These features aim to promote networking, sharing of knowledge and hopefully nurture future scientific collaborations within the international community. Regarding future growth of the Global Heat Flow Database, the portal encourages community members to submit both past and future heat-flow datasets via dataset creation and upload functionality. Submitted datasets are always validated programmatically by the server to ensure adherence to the defined metadata structure, and then again by a core team of heat flow experts to moderate for scientific validity. Once reviewed, datasets are made publicly available via the portal and will be included in future releases of the Global Heat Flow Database. This semi-automated workflow aims to place the onus for future contributions on individual researchers rather than a dedicated team of database admins. Contributors who submit datasets that are eventually made public will also gain the ability to formally publish their work and receive a DOI through semi-automated systems that link the portal to the domain repository GFZ Data Services.

6 The Assessment Process

From the beginning, the assessment process was designed as a collaborative approach of the international heat-flow community. This approach requires coordination and control by a core team. The assessment begins with a thorough review of the guidelines for the new database structure, field definitions, and review protocols to ensure a clear understanding of the required standards (Fuchs et al., 2023). The core team of reviewers then selects literature, which is carefully analyzed, and the corresponding values in the database are updated using the GHFDB Data Template (Fuchs et al., 2025a). For certain types of literature, the extraction process is relatively straightforward because the data are already available in digital tables within the document or as supplementary information. In such cases, the relevant data can be directly copied into the template, significantly reducing processing time. Any missing metadata or contextual information is then obtained from the text itself, ensuring that the extracted data are complete and accurately documented. However, for other documents, the extraction process is more labor-intensive, requiring data to be manually copied or typed into the template. This is often necessary for older publications, handwritten notes, or scanned reports where the data are not available in digital format. Despite the additional effort required, this meticulous process ensures that valuable heat-flow information is preserved and integrated into the database with the highest possible level of accuracy. For maps, the process involves digitization followed by georeferencing using GIS software to align the extracted information with accurate geographic coordinates. Heat-flow data points are then meticulously extracted, ensuring that the digitized values maintain their original spatial accuracy and scientific relevance. All data and information were extracted by either heat-flow experts or trained geoscientists and always reviewed by the core team. Text recognition OCR was used for automated table digitization, but all numbers were subsequently eye-checked by humans. Artificial intelligence and large language models were not suitable and not used to categorize contextual information according to the metadata scheme. The review process was strongly supported by the ILP Task Force and additional funding, which enabled the hiring of international staff. This support was particularly essential for revising literature that was not available in English, allowing for an inclusive assessment of the heat-flow data. A large impact was generated by fellows within the *heatflow.fellowship* program of the IHFC. The program offers travel grants to PhD and early-career scientists focused on heat-flow research, enabling them to receive training and contribute to assessments at designated host institutes. This program proved highly effective, as the assessment project benefited from country-specific information. Fellows were able to more easily identify additional local literature, and upon returning home, they were well-equipped to contribute to the standardization of heat-flow data, either through their own future submissions or by serving as peer reviewers. Once a review is complete, the results are uploaded to the database. If multiple entries for the same location are available, the document with the most reliable surface heat-flow value is chosen as the parent entry, following the guidelines outlined by Fuchs et al. (2023). The selection of parent entries is based on factors such as the completeness of metadata, the applied corrections and the overall reliability of the reviewed document. Where multiple publications refer to the same locations, this process is often challenging due to inconsistencies in geographical coordinates, site names, and other metadata reported across different sources. The selection process is not automated but is carried out by the database custodian and the core reviewer team, who carefully evaluate these factors to make an informed decision. This process is iterative, with reviewers continually repeating these steps to ensure that the database remains accurate, comprehensive, and up-to-date. To ensure data accuracy and consistency, a script called *vocabulary_check* is used to verify that all mandatory fields are correctly filled, that unique IDs are properly assigned, and that multiple entries are separated by semicolons. Any missing mandatory fields are flagged and output for review. This script also validates the controlled vocabulary used across the properties, and verifies that numerical values (floats) fall within acceptable ranges. The *quality_scores* script computes the final quality score based on the framework outlined by Fuchs et al. (2023) and ensures that the assigned quality codes accurately reflect the robustness of the data. Both scripts are implemented through a Python-based approach (https://github.com/viktoriadergunova/hfqa_tool, Dergunova et al., 2026).

7 Heat-flow data publication process

Over the past decades, heat-flow compilations have been published occasionally by the IHFC (see Table 2). Since 2021, the full collection of the GHFDB has been frequently published with open access and digital object identifiers (DOI) via GFZ Data Services (Fuchs et al., 2021b; Global Heat Flow Data Assessment Group et al., 2023, 2024). Each release also reflects the actual status of the GHFDB assessment (see below) and makes it publicly available to the community. It includes citations for all sources in the DataCite metadata files as well as detailed technical data description documents. All data to date have been manually extracted from publications and other data sources as described in Sect. 2 of this article. This manual data integration, however, is not scalable for the future maintenance of the GHFDB for and with the community. Proposed changes include the strong recommendation to directly submit heat-flow data to the GHFDB and the additional incentive to obtain a DOI for the new data by GFZ Data Services. The publication of data underlying scientific results via (domain) research data repositories is increasingly required by journals and publishers and supported by the Coalition for Publishing Data in the Earth, Space and Environmental Sciences (COPDESS, Hanson et al., 2015; Stall et al., 2018, https://copdess.org, last access: 20 June 2026).

To facilitate the data submission workflow and guarantee that the data and metadata are harmonized and follow the GHFDB quality standards (Fuchs et al., 2023), the data will be submitted via GHFDB Data Template, which also includes essential metadata properties required for DOI registration and data discovery. Once the data are reviewed by the custodians of the GHFDB, who also add the quality scores and include the data in the GHFDB infrastructure, a predefined set of metadata properties will be directly exported to GFZ Data Services where the formal data curation and publication is done by the curators of GFZ Data Services. The data publication is normally timely correlated with the publication of a related article. In addition to the bibliographic information, the metadata properties enrich the DataCite metadata includes several disciplinary keywords related to the data type that are directly exported from the GHFDB and ensures the consistent use of keywords (e.g. temperature gradient, thermal conductivity, geospatial domain, lithology, stratigraphic age, methods). Physical samples assigned with International Generic Sample Numbers (IGSN) as well as related text, data or software publications will be cited using DataCite's metadata property "related identifier". Once the DOI of a new dataset is registered, it will be included as a new data source in the GHFDB. The data provision with the GHFDB Data Template will reduce the loss of information during the data transfer from publications to the database and increase the speed with which data is integrated in the global data compilation. Beyond that, it is expected that the DOI service for citable data publications provided by GFZ Data Services represents an attractive incentive to increase the availability of heat-flow data. In many cases, heat-flow data or underlying temperature and property data are collected as secondary information in studies with varying scientific focus. Often these data are not analyzed in detail and thus not implemented in final scientific reports. Here, the new heat-flow data publication workflow represents an important incentive to secure such heat-flow data and make it available to the global geoscience community in citable form.

8 The assessment results

The following chapter describes the results of the assessment (status and impact of metadata enrichment) and the application of the quality code on the overall quality of heat-flow observations compiled in the GHFDB. The statistical evaluation (Sect. 8.1) illustrates the current state of the assessment, the distribution of continental and marine heat flow observations, the global coverage for each continent and how the metadata completeness for the heat flow observations increased during the assessment. Section 8.2 presents the results of analyses of the data quality based on the newly applied quality flags (Fuchs et al., 2023). Subsections address the quantification of uncertainty, the evaluation of methodological quality and the results of perturbation effects. Finally, Sect. 8.3 discusses the impact of quality indicators on the quality of the data and metadata of the entire GHFDB, representing a typical use case for historical data collections.

8.1 Heat flow – statistical evaluation

The 2012 release of the GHFDB included 58 302 data points (Fig. 2a). By 2021, this number had increased to 74 548 data points across 1403 references, with 55 % (around 40 870 data points, Fuchs et al., 2021a) from continental domains and 45 % (about 33 678 data points) from oceanic domains. The 2023 release featured 73 033 heat-flow data points from 1414 publications, maintaining a similar distribution between continental (approximately 40 082 data points) and oceanic (about 32 951 data points) domains (Global Heat Flow Data Assessment Group et al., 2023). This update included the removal of data points lacking documented references and the addition of 2831 new data points.

The latest release 2024 (Global Heat Flow Data Assessment Group et al., 2024) marks a significant expansion, featuring 91 182 heat-flow data points from 71 934 locations and 1586 publications. Of the 2024 release, approximately 46 % (41 922 data points) have undergone quality assessment, while 13 % (12 113 data points) are have been newly added and also quality-assessed. Of the data points included in this release, 57 % are from the continental domain and 43 % are from the marine domain, which includes lakes, rivers, seas, and oceans (see Fig. 2b). We expect the next release to include more than 100 k data points from over 1700 publications.

It is also important to assess the relative coverage of heat-flow measurements for the continents and oceans, not only in terms of both numbers and area. The data in Table 4 highlight the disparity in measurement coverage between continental and marine regions, with data coverage at a resolution of $0.5° \times 0.5°$. Relative coverage is calculated as the percentage of grid cells containing at least one heat-flow measurement within the respective domain. Although continental measurements exhibit a higher relative percentage (12.8 %) than marine regions, the much larger area of the oceans, compared to continental regions, results in a larger global percentage (4.2 % marine compared to 3.7 % continental). The overall global measurement of 7.9 % indicates significant gaps in heat-flow-data coverage (see Petrunin et al., 2026).

Figure 3 illustrates the relative coverage of heat-flow measurements across continents, showing the percentage of measurements relative to each continent's land area. For obvious reasons, Antarctica has the least coverage, which limits the ability to reliably interpolate heat flow across its surface. This is one reason for the many statistical and geophysical inversion studies here (e.g., Shapiro and Ritzwoller, 2004; An et

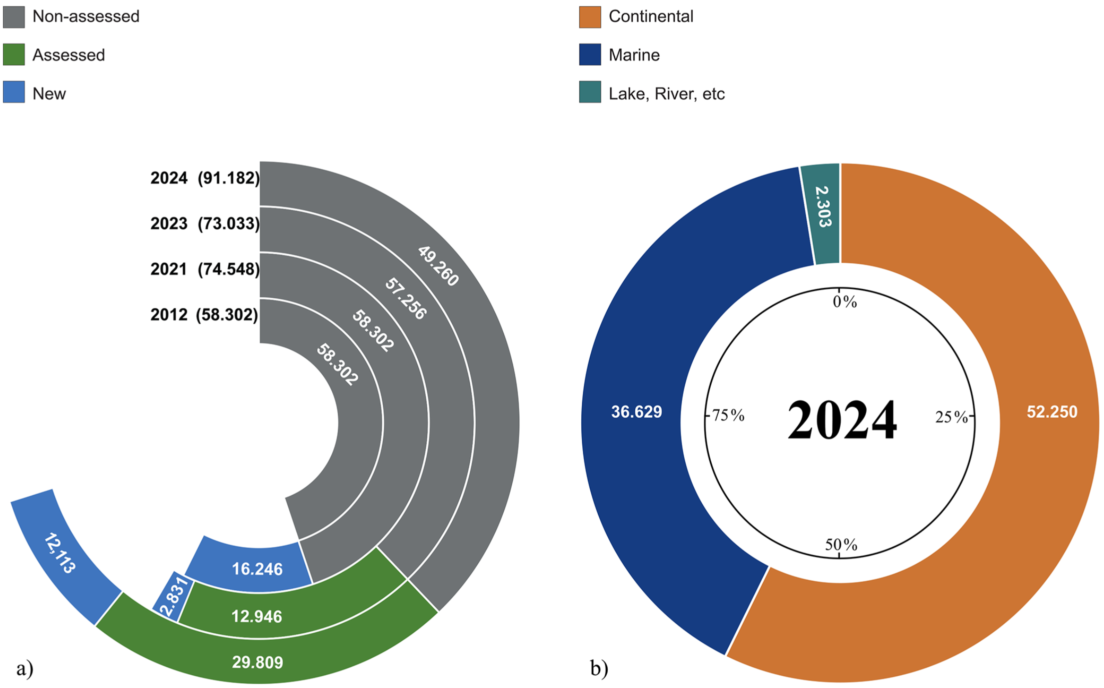


Figure 2. **(a)** Comparison of heat-flow data releases from 2012 to 2024. The figure illustrates the total number of heat-flow data points for each release, highlighting the distribution of non-assessed, assessed, and newly added and assessed data. **(b)** Distribution of heat-flow data points in the 2024 release. 57 % from the continental domain and 43 % from the marine domain.

Table 4. Percentage of the Earth's surface using a 0.5° × 0.5° resolution covered by heat-flow measurements compared to the total surface area of the Earth (Global, %) and continental/marine areas (Relative, %).

Domain	Global coverage (absolute), %	Relative, %
Continental	3.7	12.8
Marine	4.2	5.9
Total	7.9	

al., 2015; Martos et al., 2017). Europe has the highest coverage at 30.7 %, reflecting its denser measurement network. In contrast, Asia, despite its vast land area, has only about 11 % coverage. Oceania shows a higher coverage percentage than Asia, highlighting the impact of regional size on measurement density. The statistical analysis methodology is outlined in Petrunin et al. (2026).

Figure 4 shows the substantial improvements to the database and its metadata between 2021 and 2024, with the 2024 update making a significant contribution. The total number of heat-flow data points increased from 58 302 in 2019, before the assessment began, to 91 182 in 2024, reflecting the dataset's considerable growth. This expansion was accompanied by a notable enhancement in metadata completeness, with the percentage of filled fields rising from 14 % in 2021 to 41 % in 2024. The 2024 release included 41 922 fully assessed data points, for which approximately 70 % of metadata fields were populated on average. This highlights the important part that data assessment plays in improving the quality and reliability of heat-flow information (Global Heat Flow Data Assessment Group et al., 2024). The assessment process also ensures the completeness of the mandatory fields, as shown in bold, which are crucial for reliably evaluating the parent heat-flow. The remaining ∼ 30 % of metadata fields are solely attributable to missing information in the source literature.

In the 2024 release, approximately 63 272 heat-flow data points are linked to individual heat-flow child elements, which are derived from 1275 references. However, only 25 % (15 973 data points from 448 references) of these data points have been assessed. The assessment process ensures that the most reliable heat-flow values are selected, particularly when multiple measurements are available for the same location. The majority of assessed entries include one to three child elements, though some locations have more than eight heat-flow-child elements, with a few reaching up to 39, indicating detailed multi-measurement evaluations (Fig. 5).

Overall, the 2024 release significantly contributes to the Global Heat Flow Database by not only increasing the volume of data but also enhancing the quality and completeness of the metadata, thereby providing a more robust foundation for geophysical research and analysis (Fig. 2, Table 1).

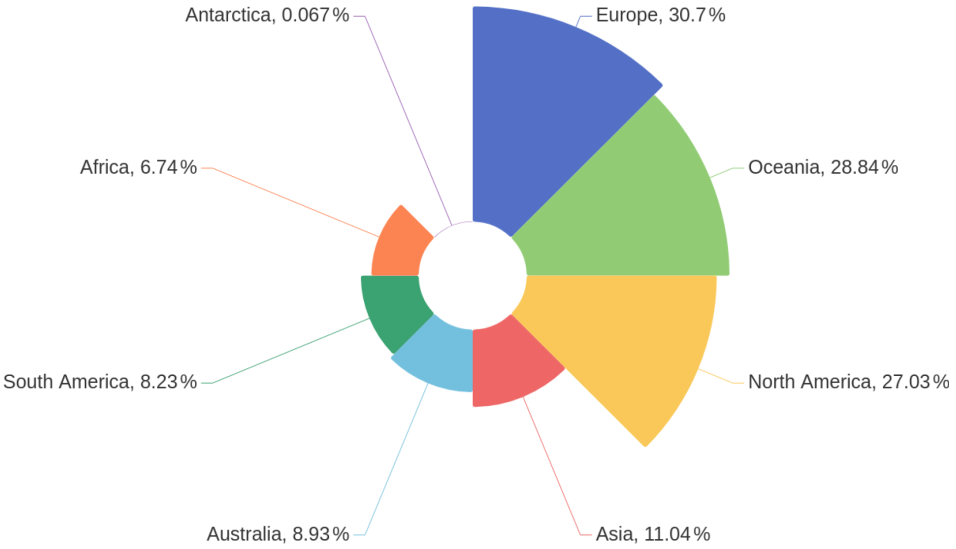


Figure 3. Coverage by measurements percentage for continents relative to its area.

8.2 Heat-flow quality evaluation

The quality evaluation scheme described in Sect. 4 was systematically applied to all heat-flow entries included in the 2024 GHFDB release. Each data point was assessed using the uncertainty score (U-Score), methodological score (M-Score), and perturbation flags (P-flags), resulting in an integrated quality score that enables consistent comparison across regions, measurement types, and publication periods. The application of this framework allows technically sound but environmentally perturbed measurements to be distinguished from data affected by methodological limitations or incomplete documentation. Implementation of the scheme reveals clear differences in data quality related to measurement era, acquisition method, and metadata completeness. In particular, legacy data frequently exhibit acceptable temperature measurements but elevated uncertainty or perturbation flags due to missing corrections for effects such as topography, sedimentation, erosion, fluid advection, or transient climatic signals. Rather than excluding such data, the evaluation framework preserves them within the database while transparently communicating their limitations to users.

8.2.1 Uncertainty quantification (U-score)

Heat-flow data are categorized by coefficient of variation (COV) to assess data reliability (Fig. 6a). Data with a COV of less than 5 % are assigned a U1 score, representing high reliability and low variability, and include 2162 entries, or 2.4 % of the dataset. Data with a COV between 5 % and 15 % are assigned a U2 score, indicating good reliability with moderate variability, and comprise 6085 entries, or 6.7 % of the dataset. Data with a COV between 15 % and 25 % are assigned a U3 score, reflecting moderate reliability with higher variability, and include 2328 entries, or 2.5 % of the dataset. Data with a COV exceeding 25 % receive a U4 score, denoting lower reliability due to significant variability, and encompass 1440 entries, or 1.6 % of the dataset. The Ux category includes entries where the COV is not applicable or where data is missing. This accounts for 79 167 entries, or 86.8 % of the dataset. The global U-score distribution is shown in Fig. 6b. This classification provides a detailed assessment of data reliability based on variability and completeness. Future efforts to improve U-scores should focus on refining error estimation techniques, particularly through advanced statistical modeling and more precise measurements of temperature gradients and thermal conductivity. Additionally, adopting standardized data reporting practices and re-analyzing historical datasets using modern methodologies will further enhance the reliability of heat-flow data.

8.2.2 Methodological quality evaluation (M-score)

The M-score assesses the quality of heat-flow data from a methodological perspective, taking into account the accuracy of temperature gradient and thermal conductivity (TC) measurements. The scores are categorized into four quality classes: M1 (Excellent), M2 (Good), M3 (Ok), and M4 (Poor), with an additional Mx class for data where the methodological quality cannot be determined or is missing.

The distribution of M-scores in the 2024 release, reveals that a significant proportion of the dataset falls into the lower-quality categories (see Fig. 6a). Specifically, M1, which represents excellent quality, accounts for 2474 entries, or 2.7 % of the total dataset and shows high methodological reliability. M2, indicated good quality and includes 4747 entries (5.2 % of the total dataset). M3, which signifies an acceptable standard and encompasses 12 821 entries (14.1 % of all data).

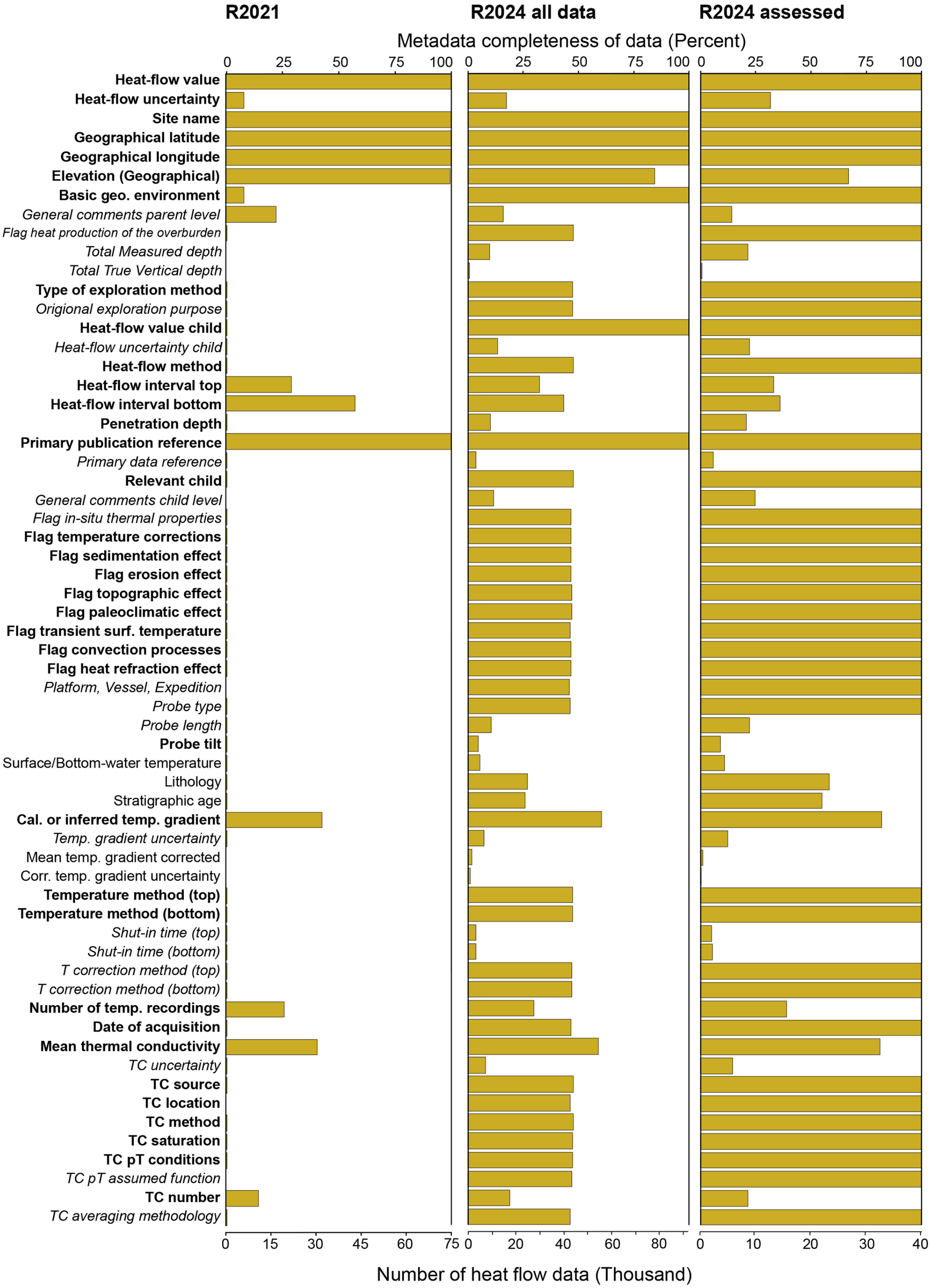


Figure 4. A comparison of metadata completeness of data in the IHFC Global Heat Flow Database structure in percentage between **(a)** Release 2021, **(b)** Release 2024, and **(c)** assessed data for the Release 2024. The mandatory database fields are represented in bold font, recommended fields in italic, and optional fields in normal font (see details in Fuchs et al., 2023).

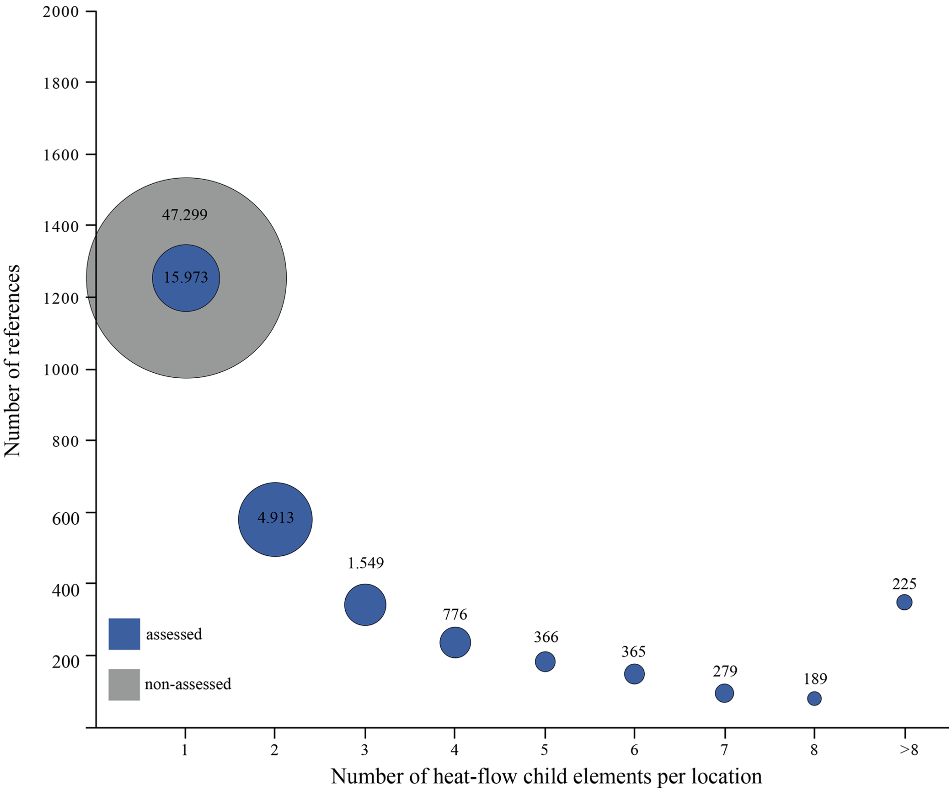


Figure 5. Relationship between the number of heat-flow child elements per location and number of references. The size of each bubble varies according to the number of locations.

The M4 class represents poor quality and comprises 22 094 entries, or 24.2 % of the total dataset. This highlights the significant proportion of data with lower methodological reliability and reflects the heterogeneity in the collected literature. Furthermore, the Mx class, which includes data with unknown or missing methodological quality, comprises 49 046 entries (53.8 % of all data).

In total, the 2024 release comprises 91 182 heat-flow data points, of which 41 922 have been evaluated for quality. A significant proportion of these data points, particularly those classified as M4, highlight areas where methodological rigor could be enhanced. The dominance of lower-quality data (M4) among the assessed entries emphasizes the need to refine and improve the methodologies used in heat-flow data collection and reporting. The global distribution of the M-scores (Fig. 6c) also sheds light on geographical variations in data quality, enabling researchers to focus on regions where data-collection methods require improvement.

8.2.3 Perturbation effects (P-flags)

Perturbation flags (P-flags) are used to identify potential site-specific effects that could influence heat-flow measurements. Figure 7 provides a detailed overview of these flags within the 2024 dataset, categorizing them into three main types as explained in detail above. A significant proportion of the data falls into the unspecified category, indicating a lack of detailed information on these perturbation effects in the original literature sources. Specifically, 66 % of sedimentation effects, 91 % of erosion effects, 65 % of topographic effects, 81 % of paleoclimatic effects, 82 % of transient surface temperature effects, 78 % of convection processes, and 84 % of heat refraction effects are unspecified. This means that the effect is neither actively recognized nor mentioned as having been corrected. The U-score shows that the unspecified category predominantly consists of Ux data, and the M-score shows that M4 is the most common category among the assessed data. Sedimentation and topography effects are corrected for slightly more than 20 % of U (1–4) and M (1–4) category HFDs (Fig. 7).

The detailed breakdown is as follows: The effects of sedimentation have been corrected for 3285 entries but not yet for 6880. For 1394 entries this parameter is not significant, for 2789 entries it is not recognized, and for 27 574 entries it is unspecified. The effects of erosion show that 152 entries have been corrected, 622 have not been corrected, 705 are not significant, 2183 have not been recognized, and 38 260 are unspecified. The topographic effects include the following: 4365 entries were corrected; 4705 entries were not corrected, 2775 entries were not significant, 2969 entries were not recognized, and 27 108 entries were unspecified. Paleo-

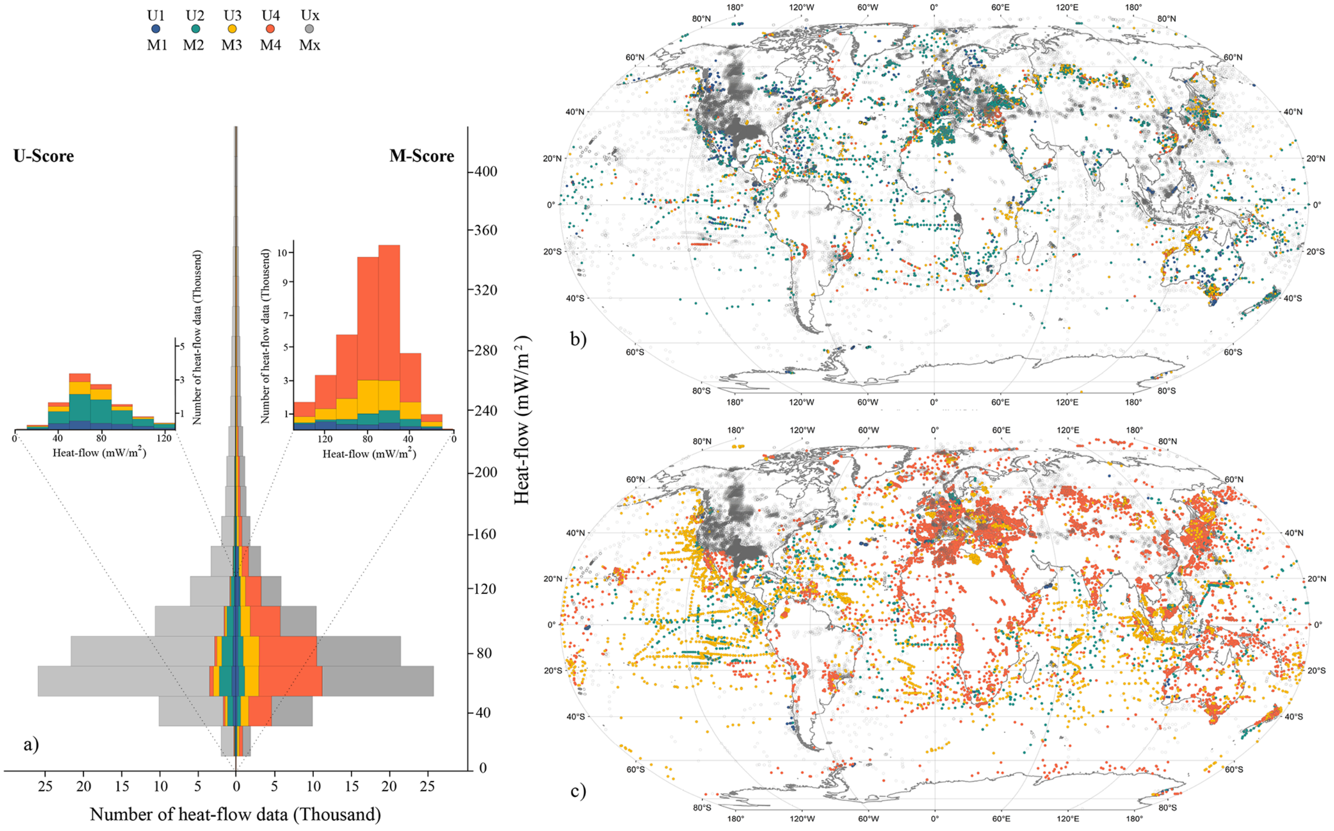


Figure 6. **(a)** Horizontal mirrored histogram showing the distribution of heat-flow data categorized by uncertainty (U-score) on the left and methodological (M-score) on the right. The close-up view emphasizes data distribution across U-scores (U1–U4) and M-scores (M1–M4), highlighting the prevalence of lower-quality scores. **(b)** Map of heat-flow data distribution based on U-scores and **(c)** map based on M-scores, both using the Robinson (1974) projection. These maps illustrate spatial patterns in data quality, pinpointing regions with concentrated high-reliability data (U1, M1) and areas dominated by lower-quality scores, providing insights into the geographic variability in data reliability and methodological rigor across the GHFDB.

climatic effects have been corrected for 2725 entries. Not yet corrected for 2097 entries. Not significant: 1153 entries. Not recognized: 1979 entries. Unspecified: 33 968 entries. The transient surface temperature effects include 953 entries that have been corrected, 2074 that have not been corrected, 2396 that are not significant, 1995 that are not recognized, and 34 504 that are unspecified. Convection processes show 1485 corrected entries, 2465 uncorrected entries, 1408 not significant, 3827 unrecognized, and 32 737 unspecified. There are 1298 entries for heat refraction effects that have been corrected, 2365 that have not been corrected, 1060 that are not significant, 1821 that are not recognized, and 35 378 that are unspecified.

This classification illustrates the extent to which perturbation effects impact the reliability of heat-flow data. It is important to recognize and correct these perturbations in order to accurately determine surface heat flow (parent entry), particularly when dealing with multiple valid measurements from the same location (child entries). It is also important to document the presence or absence of these effects as an author's opinion.

8.3 Impact of the quality score

Quality scores are crucial for evaluating the reliability and usefulness of heat-flow data in both scientific research and practical applications. A statistical evaluation of heat-flow data from various database releases spanning from 2012 (before the first assessment) to 2024 (the last release) highlights the importance of rigorous quality assessment. Over this period, the GHFDB has undergone significant updates, reflecting a commitment to continually improving data quality. Each release has refined the dataset by incorporating advanced quality metrics and methodologies, thereby enhancing the usability and accuracy of heat-flow data.

For example, the latest update introduced U-scores, M-scores, and P-flags, which allow for a multidimensional evaluation of data reliability. U-scores assess the numerical variability in heat-flow measurements, M-scores evaluate the methodological and technical rigor in temperature gradient

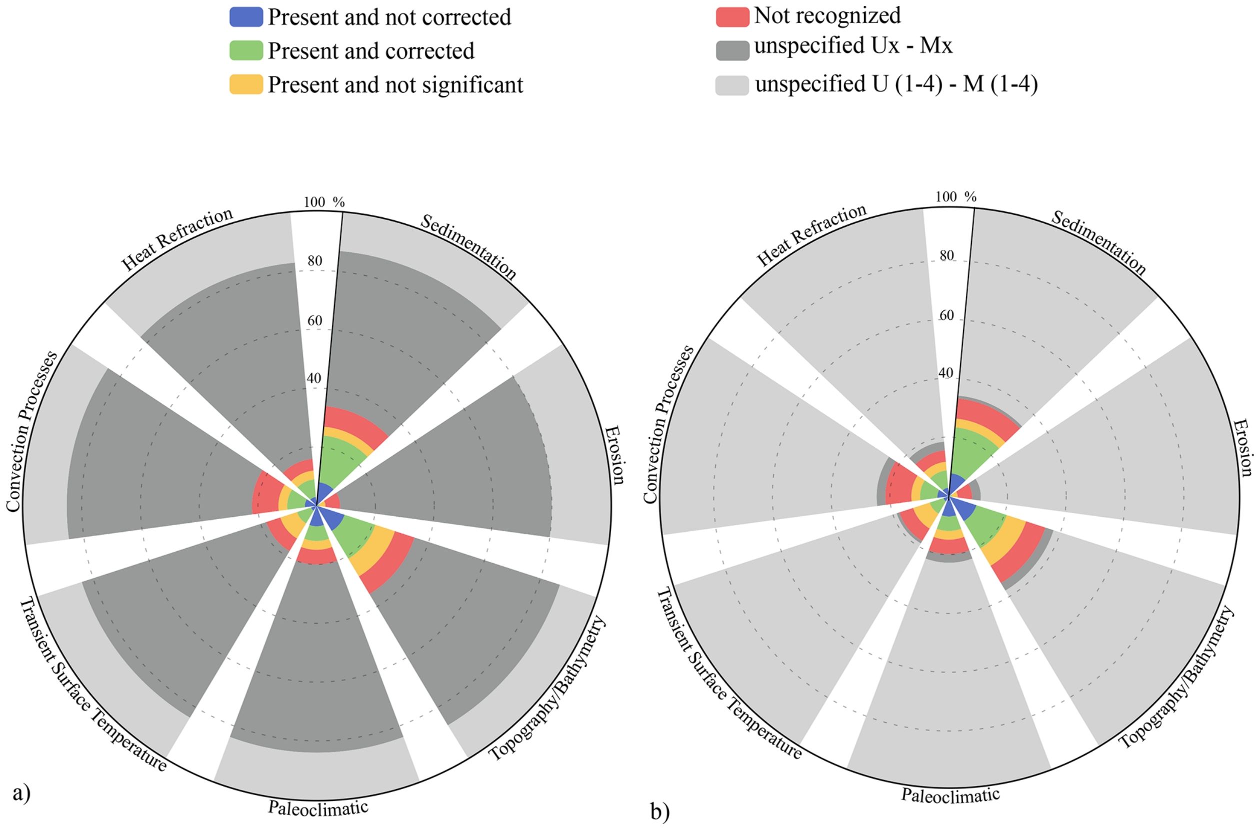


Figure 7. Circular chart illustrating the distribution of perturbation effects (P-flags) identified as a result of the assessed dataset for the 2024 release. The perturbation flags are classified into five categories: corrected, not corrected, not significant, not recognized, or unspecified. The unspecified category is further classified based on **(a)** U-score and **(b)** M-score.

and thermal conductivity determinations, and P-flags identify potential overruling site-specific perturbations. Together, these components enhance the robustness of the dataset, ensuring that the collected data reflects as much of the original research as possible and is therefore relevant for various applications.

Statistical analyses reveal trends and improvements in data quality over time, demonstrating the progressive increase in the database's value through methodological refinements and updated quality standards. As the GHFDB continues to evolve, it is becoming an increasingly valuable resource for geophysical research, resource management, and climate studies. This highlights the importance of maintaining high-quality data standards.

Figure 8 provides an analysis of the distribution and quality of heat-flow data across various categories, demonstrating the impact of the quality assessment scheme. Figure 8a examines the distribution of heat-flow data points across different application categories, categorized by U-scores. This chart shows that categories such as "Research/Mapping" (17 710 data points) and "Hydrocarbon" (12 989 data points) have more entries, while categories like "Geothermal" (1465 data points) and "Others" (52 data points) have fewer. The data is divided into U-Score categories, with U1 representing the highest reliability and Ux indicating data for which quality metrics are either undetermined or missing. As the chart shows, a significant proportion of the data falls into the lower U-Score categories (U2, U3, and Ux), particularly in applications such as "unspecified" and "Mining". This variation reflects differences in data reliability across application areas and underscores the need to carefully consider data quality in diverse research and practical contexts.

Figure 8b focuses on the distribution of heat-flow data by M-scores, which assess the methodological quality of the data. Categories such as Drilling (24 483 data points) and Probing (Offshore/Marine) (13 981 data points) have the highest numbers of entries, whereas categories like unspecified (31 data points) have very few. The M-scores range from M1, which indicates excellent methodological quality, to Mx, which indicates data with an undetermined or missing quality score. The chart shows that a significant proportion of the data falls into the M4 and Mx categories, particularly in categories like "unspecified" and "Other". This distribution emphasizes the prevalence of poor-quality and uncertain data, highlighting the methodological issues and gaps that affect the dataset as a whole.

Overall, Fig. 8 illustrates the impact of the quality assessments on the dataset by showing how data quality varies across different application categories and methodological contexts. It emphasizes the importance of U-scores and M-scores in evaluating the reliability and usability of heat-flow data for scientific research and practical applications.

Figure 9 illustrates an examination of the assessed heat-flow data, examining the distribution of U- and M-scores in relation to temperature measurement methods, TC methods, and TC saturations. The U-score evaluation reveals that just 3 % of the assessed data falls into the U1 category, indicating the lowest level of numerical uncertainty. By contrast, 78 % of the assessed data falls into the Ux category, indicating missing or unspecified information on the uncertainty of measured temperatures or conductivities. Specifically, 47.6 % of the assessed data lacks information on temperature measurement methods, 27 % lacks details on TC methods, and 50 % lacks data on TC saturation. This highlights a significant lack of detailed methodological information, which is crucial for evaluating the reliability of the heat flow measurements (Fig. 9a).

Figure 9b shows how the data are distributed based on M-scores, which assess the methodological quality of the data. Approximately 52 % of the assessed data is categorized as M4, indicating poor methodological quality. The high proportion of low-quality data highlights the challenges of achieving methodological rigor across the dataset and emphasizes the need for improved data collection and reporting standards.

Overall, Fig. 9a and b reveal the high impact of the quality assessment scheme on the heat-flow dataset. They demonstrate that, although a small fraction of the data is classified as highly reliable (U1) or methodologically excellent (M1), a substantial amount remains with unspecified or poor-quality metrics. This highlights the urgent need for improved reporting and methodological consistency to enhance the overall quality and usability of the Global Heat Flow Database.

Figure 10 gives a detailed look into the assessed heat-flow data based on U-score and M-score for various temperature measurement methods and TC methods and TC saturation. The total number of assessed heat-flow data that have been classified as "unspecified" is 21 632 for the temperature measurement method, 11 320 for the TC method, and 22 708 for TC saturation. The proportion of data attributed to these three mandatory fields has fluctuated over time. In earlier periods, particularly between 1966 and 1995, a lower proportion of data was assessed for these fields, resulting in a higher percentage of unspecified data points.

Figure 11 illustrates the unspecified category presented in Figs. 9 and 10, focusing on the temperature measurement methods (bottom), TC method, and TC saturation. The aim of this figure is to determine whether the clarity of the data provided by the authors has improved over time regarding these aspects.

Specifically, there has been a marked decrease in the percentage of unspecified data from 2005 to 2025 (Fig. 11). This suggests that information related to temperature measurement methods, TC methods, and TC saturation has become clearer and more consistently reported by authors.

This trend reflects advancements in scientific methods and better documentation. As it continues, future datasets are expected to be clearer and better organized, making them more valuable for researchers and enabling them to draw meaningful conclusions in heat-flow studies.

9 Discussion

The Global Heat Flow Database has seen substantial growth since its early compilations in the 1950s. Initially containing only basic metadata, such as geographical location and heat-flow values (Birch, 1954), the database has evolved to include more comprehensive and detailed information.

From the initial 63 observations with seven metadata properties, the database expanded significantly through subsequent updates, reflecting advancements in data collection and quality over the decades. Before the current revision started in 2019, the database included around 58 302 observations. The 2024 release further increased this to approximately 91 182 observations with 62 metadata properties.

This growth demonstrates an increased focus on data quality and detail over time, enabling more precise analyses and applications in geophysical research and practical fields. The ultimate aim is to create an authenticated database that is interoperable with other well-structured geo-datasets.

9.1 GHFDB Data Template

The introduction of the GHFDB Data Template marks a major step forward in ensuring high data quality already at the point of submission. By guiding contributors through a well-structured reporting process based on the standardized metadata scheme, the template significantly reduces the likelihood of incomplete or inconsistent metadata. This proactive approach helps to prevent common issues seen in historical data compilation, particularly those related to missing methodological information or ambiguous measurement conditions, and shifts the focus towards high-quality, transparent, and reusable data from the outset.

One of the key strengths of the GHFDB Data Template is its ability to capture the full complexity of heat-flow observations in a consistent, structured way. It accommodates detailed methodological data, uncertainty estimates, and environmental context, and uses a hierarchical parent-child structure to document multiple depths, corrections, or methods per site. The template helps contributors understand and meet quality expectations by clearly distinguishing between mandatory, recommended, and optional fields. It serves both as a reporting tool and a guide to best practices.

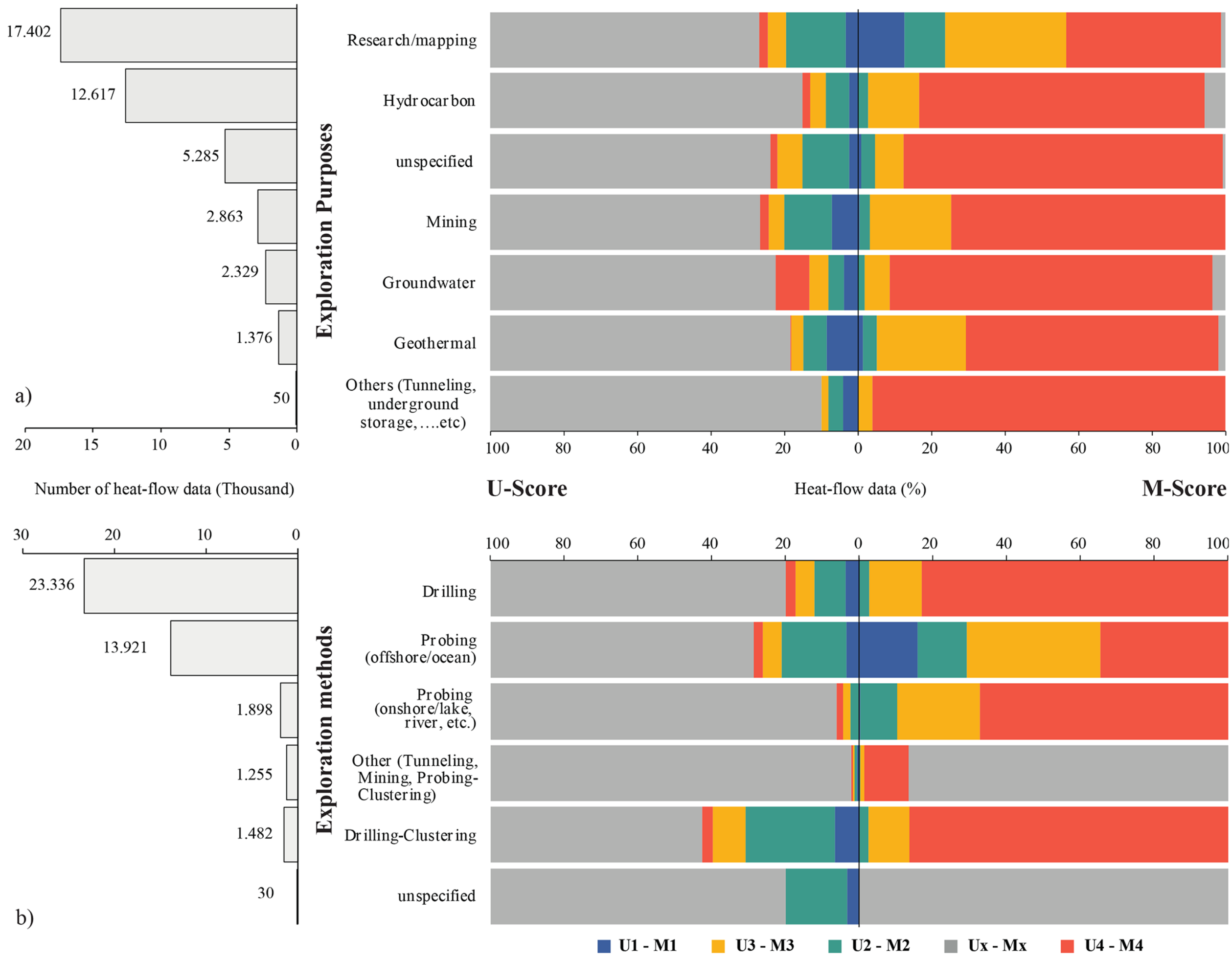


Figure 8. Distribution of the assessed heat-flow data for U- and M-scores based on **(a)** exploration purposes and **(b)** exploration methods. The left panel shows the number of assessed data points, while the right panel displays the distribution in percentages, highlighting the categorization of heat-flow data according to U-scores and M-scores.

This is especially important for a globally diverse research community with varying expertise. To encourage high-quality submissions further, the web portal will offer DOI registration for datasets submitted via the template. This provides formal recognition and citation opportunities, which align with open science principles and increase the visibility of contributors' work.

The structured submission process and DOI service work together to foster a dynamic and collaborative database environment. They support the integration of new, well-documented data while progressively reducing incomplete or low-quality entries and enhancing both scientific reliability and long-term value.

Thus, the GHFDB Data Template is not just a technical tool, it is essential for building a transparent, high-quality, and community-driven global heat-flow database.

9.2 Quality Assessment and Improvement of the GHFDB

The GHFDB's reliability and utility have been significantly enhanced by the quality assessment and improvement of the dataset from 2019 to 2024. Systematic evaluation of data quality by domain experts has been crucial in refining the database, establishing its trustworthiness, and increasing its value for scientific and practical applications. This process marks the transformation from a data collection with unknown content and quality towards an authenticated database with proven content and documented quality.

The quality assessment has been addressed comprehensively through various metrics. The U-scores, which indicate the reliability of data based on the coefficient of variation (COV), reveal that while some data is highly reliable (U1), a substantial portion remains in the Ux category. This points to incomplete or unclear variability information and highlights

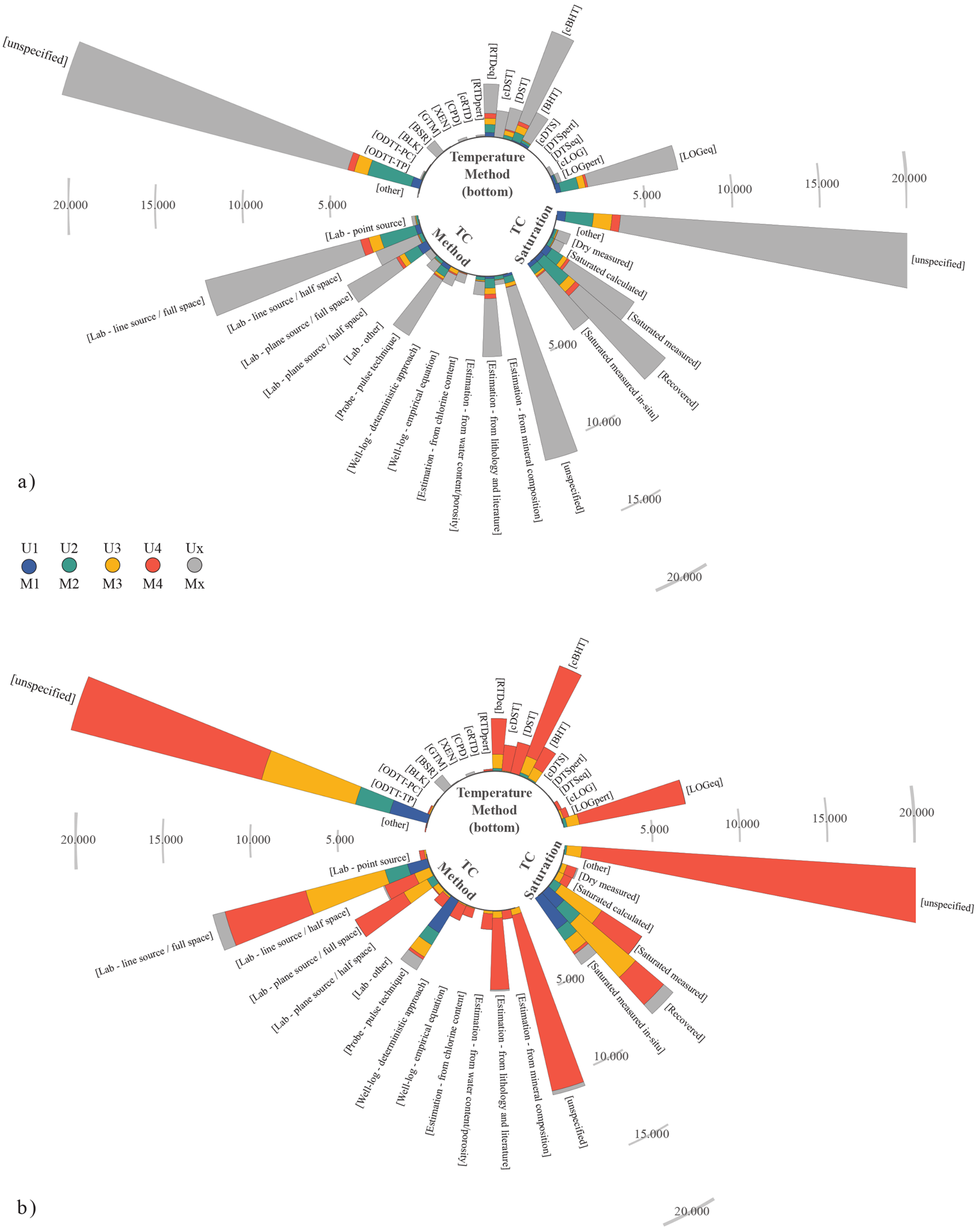


Figure 9. Distribution of the assessed heat-flow data based on **(a)** U-score and **(b)** M-score. These radial charts provide insights into the quality scores of the assessed data across various temperature measurement methods (bottom) and thermal conductivity (TC) methods and saturations.

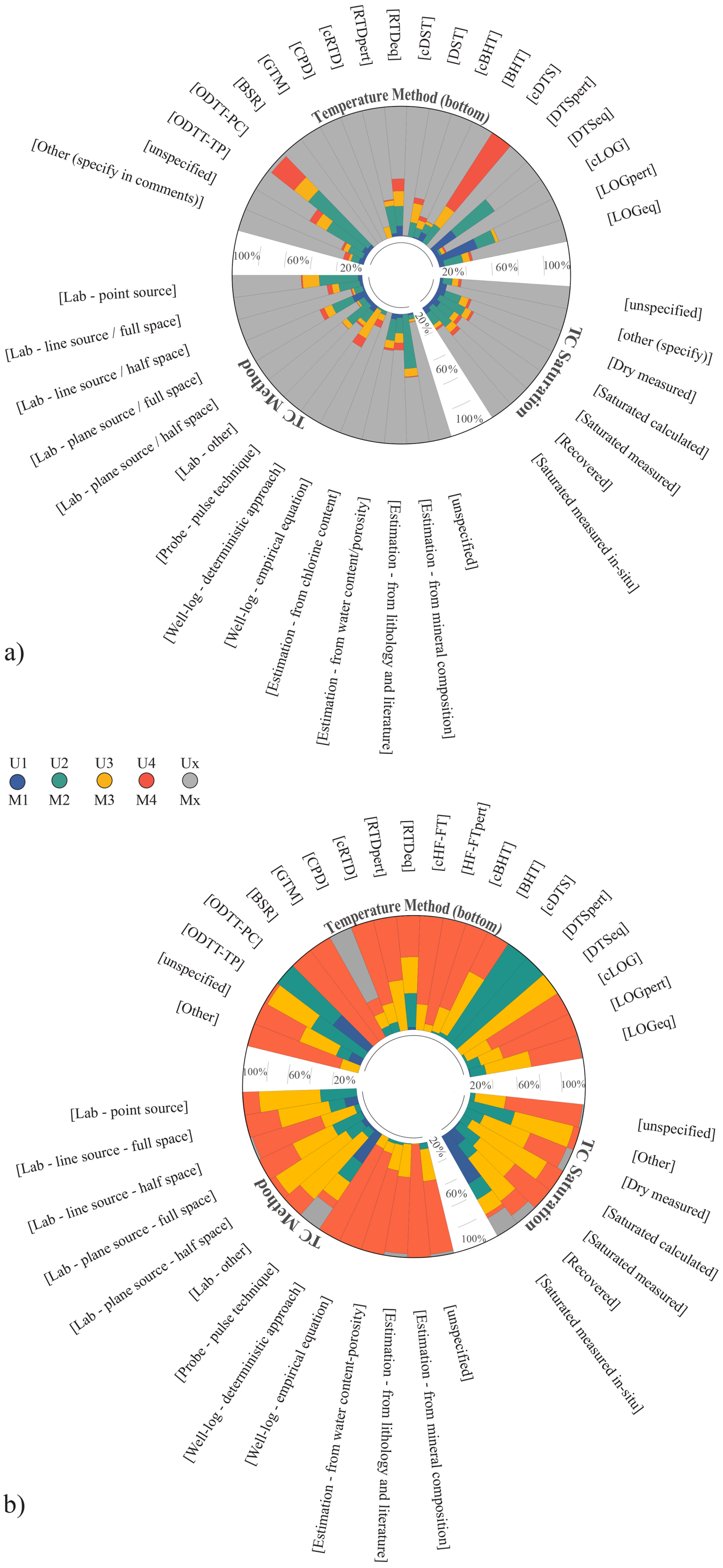


Figure 10. Distribution of the assessed heat-flow data as a percentage for temperature measurement methods (bottom) and TC methods and TC saturation. The data are classified based on **(a)** U-score and **(b)** M-score. These radial charts provide a detailed view of the uncertainty and methodological quality evaluation of the assessed data, demonstrating the predominant scores within the assessed dataset.

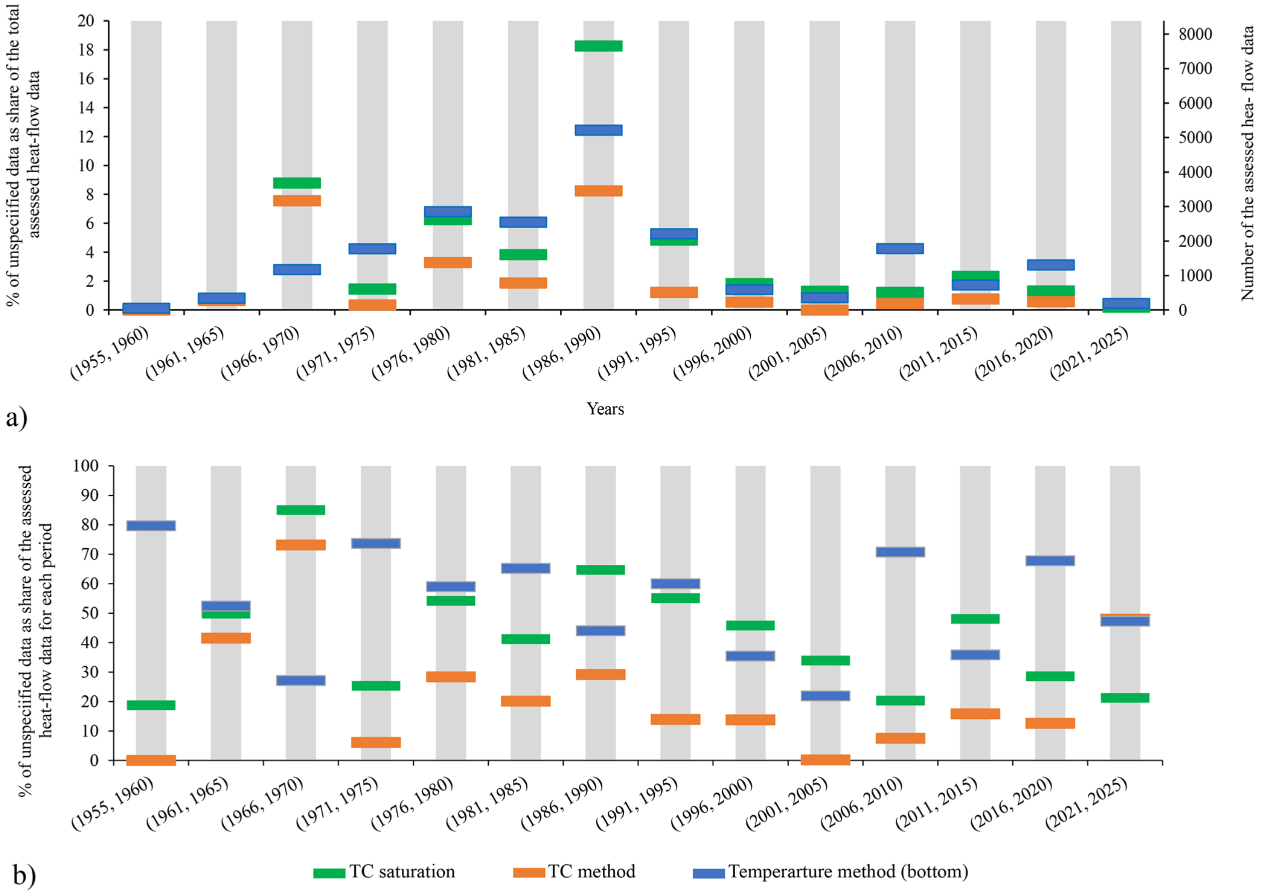


Figure 11. The figure presents the percentage of heat-flow data assessed categories as unspecified for TC method, TC saturation, and temperature measurement method, relative to **(a)** the total number of the assessed heat-flow data over time, **(b)** the total number of the assessed heat-flow data for each specified period of years from 1955 to 2025.

the need for improved documentation and quality control in earlier datasets.

The methodological evaluation through M-scores reflects the accuracy of temperature gradient and thermal conductivity measurements. The 2024 release shows that a significant proportion of data is in the M4 category, which denotes poor methodological quality. A large amount is classified as Mx, indicating undetermined quality due to missing information. This highlights ongoing challenges with methodological consistency and the need for improved measurement techniques and standardized reporting. The GHFDB Data Template presented here is intended to assist scientists in reporting comprehensive and consistent datasets.

The effects of perturbation, as assessed through P-flags, have also been a key focus. Data from the 2024 release show that a significant proportion of entries have unspecified perturbation effects, such as surface processes and time-dependent factors. This suggests that detailed evaluations of site-specific conditions are often lacking. This aspect of quality assessment is crucial for understanding and mitigating potential biases in heat-flow measurements.

Enhanced documentation and rigorous assessment practices have led to a decrease in the percentage of unspecified data and improved categorization. However, a significant proportion of data, particularly from earlier periods, still lacks comprehensive methodological details. Generally speaking, the flags can be used as selector variables to apply overarching correction approaches to these perturbation effects.

These advancements in quality assessment have a profound impact on the reliability and applicability of heat-flow data. Higher quality standards increase confidence in the data and support more precise geophysical research and practical applications, such as geothermal energy exploration and environmental assessments. The overall trend towards better data quality is essential for robust scientific conclusions and informed decision-making in applied fields.

Looking ahead, further efforts are needed to address the remaining data quality issues within the GHFDB releases. Future updates should prioritize reducing the proportion of unspecified data, improving methodological consistency, and continuously refining the quality assessment framework. Addressing these challenges will ensure that the GHFDB continues to evolve as a valuable and reliable resource for both scientific research and practical applications, meeting the needs of researchers and practitioners across various fields.

The direct data submission by researchers via the GHFDB Data Template (as described in Sect. 3) can be an important tool for ensuring high data quality from the outset, particularly given the additional incentive of obtaining a DOI for these new data submissions.

9.3 Global Heat-Flow Data Interpolation

To improve the usability and visualization of the GHFDB for researchers, the data has been interpolated across the globe. Interpolating data scattered over the Earth's surface is challenging due to its spherical shape. Projecting the data onto a flat surface (e.g., the Mercator projection) introduces distortions, particularly near the poles, which can result in inaccurate interpolation. A common approach to address this issue is to divide the Earth's surface into subdomains and interpolate data within each.

For the global interpolation in spherical coordinates, the PyKrige Python library (Murphy et al., 2021), which allows continuous interpolation over the Earth's surface was used. In addition, an orthographic projection is used to represent the interpolation in the two polar domains. For each domain, the Kriging method was applied. The heat-flow data for the interpolation was prepared according to the method described in Petrunin et al. (2026).

Kriging is a widely used geo-statistical interpolation technique in geoscience. It provides a robust method for predicting spatially distributed variables based on the distance and degree of variation between known data points (variogram function). This method not only yields the interpolated values but also provides the Kriging variance, which reflects the confidence level of the predictions.

The results of the interpolation of the heat-flow data are presented in Figs. 12–14. The interpolated map has a resolution of 0.5° in both longitude and latitude. It is important to note that we are not presenting a world heat-flow map, as has been done previously (e.g., Lucazeau, 2019; Mareschal et al., 2017; Davies, 2013; Goutorbe et al., 2019; Davies and Davies, 2010), but rather the results of the interpolation of the available data and the standard deviation of the values at the interpolation nodes. This also depends on the interpolation method and its parameters. The standard deviation map estimates potential errors in the interpolation results. Many of the aforementioned publications also include specific model assumptions for the cooling of the oceanic lithosphere, which result in mid-ocean ridge-specific shapes on the global heat-flow map. More recent studies focus on using enhanced statistical methods (e.g., machine learning, AI) to produce maps based on more geophysical input data. We will consider these approaches as valuable as soon as the GHFDB is updated and fully quality-controlled.

In our mapping, several regions that have been extensively studied, such as North America and Europe, the Sea of Japan, and the Sea of Okhotsk, are characterized by low standard deviation values of less than 3–5 $\mathrm{mW\,m^{-2}}$ and high data density (2). For such regions, our interpolation can be used as a regional heat-flow map.

We used the orthographic projection in a regular grid with a resolution of 50 × 50 km to perform robust interpolation in the polar regions (see Figs. 13, 14). As the distribution of measurements in the north-polar region is very uneven, the standard deviation of the interpolated data ranges from 1 to 12 $\mathrm{mW\,m^{-2}}$. Most of the measurements in the Arctic Ocean are located along the East Greenland Rift Basin, and the Gakkel, Lomonosov, and Mendeleev Ridges. The northwestern part of North America has been studied in the most detail, with a very dense cluster of measurements. In these areas, the standard deviation is generally less than 3 $\mathrm{mW\,m^{-2}}$. Conversely, there is a significant gap in measurements at the same latitude in Greenland, the Canadian Basin, the Kara Shelf, and the north-eastern part of North America, where the standard deviation of the interpolation reaches 10–12 $\mathrm{mW\,m^{-2}}$.

Antarctica remains the least studied region. Most heat-flow measurements are concentrated along the coast, particularly in the bays of the Ross, Amundsen, and Amery Seas. This distribution is insufficient to reliably interpolate heat flow over the Antarctic continent. In contrast, marine measurements in the Southern Ocean surrounding Antarctica are more detailed. However, the standard deviation here averages 5–12 $\mathrm{mW\,m^{-2}}$.

9.4 Community engagement and outreach

Active engagement with the international heat-flow research community is central to the GHFDB's mission and long-term adoption. Since 2019, the team has organized and participated in multiple forms of community interaction, including online workshops, presence at international meetings, and dedicated summer schools. Regular sessions at conferences such as EGU, IUGG, and IHFC-specific workshops (including the *Cermak 7* meeting) provide forums for presenting updates, discussing best practices, and soliciting feedback on metadata standards, quality scoring, and data submission procedures. In 2024, the first *Global Heat Flow Day* was held, a 24 h series of short talks from contributors worldwide, promoting exchange of research results, methodological insights, and collaborative opportunities. All talks were recorded, and videos, along with supporting materials, have been made available on the project portal (http://www.heatflow.world, last access: 20 June 2026) to maximize accessibility and long-term impact. Through these activities, the GHFDB team fosters broad participation, builds trust, and encourages adoption of the database by ensuring transparency, training, and active collaboration across the global heat-flow community.

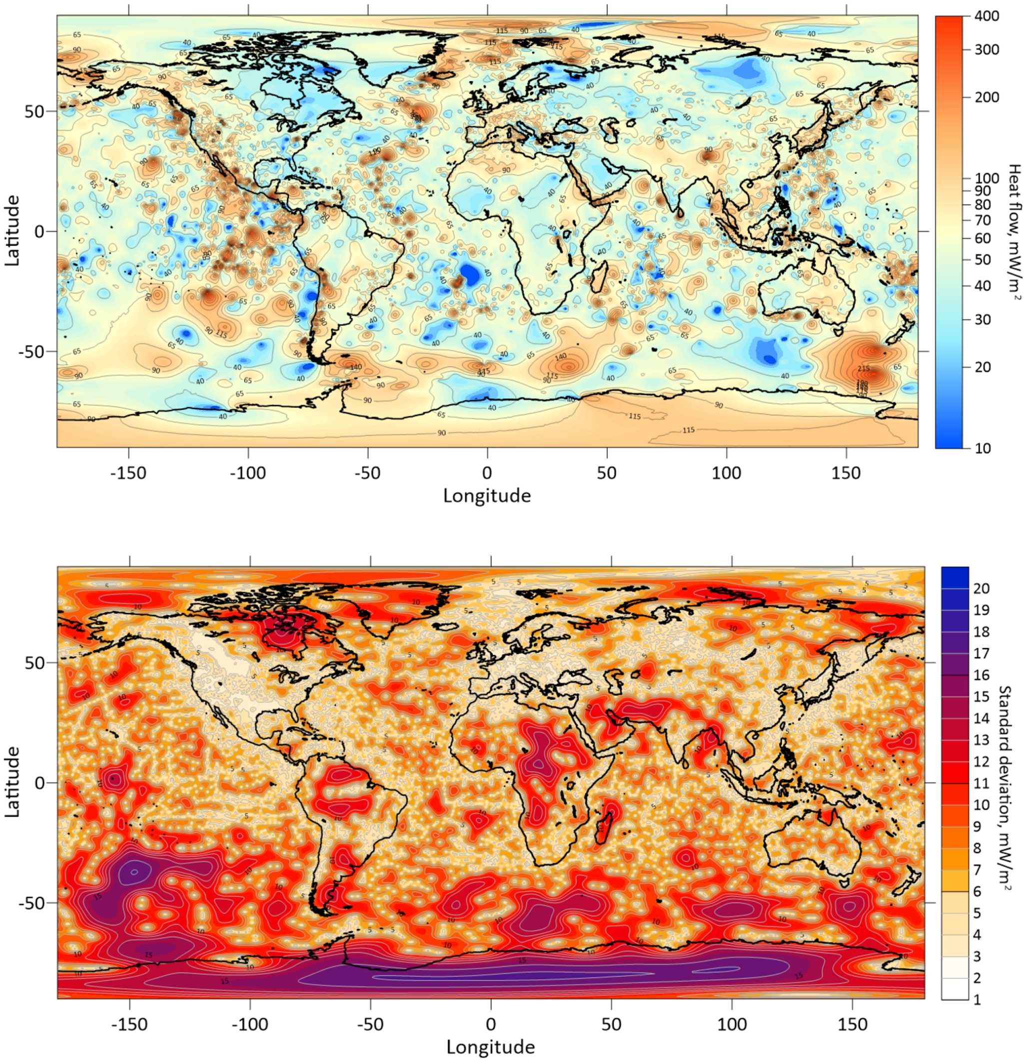


Figure 12. Median heat flow interpolated by Kriging and standard deviation of the interpolation. Data files are available in Petrunin et al. (2026).

9.5 Limitations and outlook of the GHFDB

Despite its extensive coverage, the GHFDB has several limitations. Where data exist, there are generally gaps and uncertainties in the metadata, particularly in regions with high percentages of unspecified (Ux) data or missing methodological details. This can affect the dataset's overall reliability and interpretation. In some cases, the raw measurements themselves may be of high quality, but the reported heat-flow values were not corrected for local or transient processes that bias estimates of the conductive heat-flow. Such effects include topographic influences (Blackwell et al., 1980), palaeoclimate perturbations (e.g., Birch, 1948; Powell et al., 1988), advective heat transport by fluids (Beardsmore and Cull, 2001), and the thermal effects of erosion and sedimentation (Powell et al., 1988). Additionally, inconsistencies can be introduced by the variability of different measurement techniques, calibration methods, and data processing practices can lead to inconsistencies, making it challenging to compare heat-flow data across studies. Regional disparities also pose a limitation. While the database has more comprehensive coverage of certain areas, such as the North Atlantic and North Pacific oceans, other regions remain underrepresented. This uneven distribution coupled with the fact that less than 10 % of the Earth's surface is covered by measurements on a 0.5° × 0.5° raster, can limit the applicability of the data for global-scale studies and highlights the need for additional data collection in underrepresented areas. It may also lead to the overrepresentation of certain geological environments (e.g., Stål et al., 2022) and pose a risk to extended statistical approaches that use these data to create maps based on further geophysical input. Incomplete or inadequate documentation of measurement methods and conditions further complicates the use of the data. Despite im-

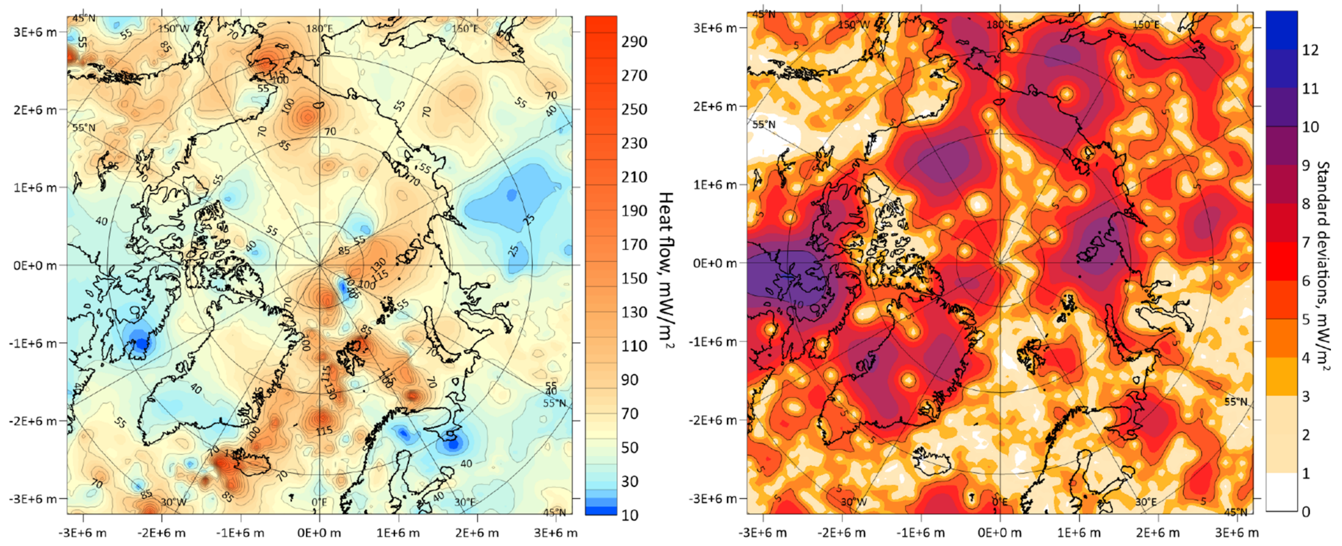


Figure 13. Median heat flow interpolated by Kriging and standard deviations. Orthographic North Pole projection. Data files are available in Petrunin et al. (2026).

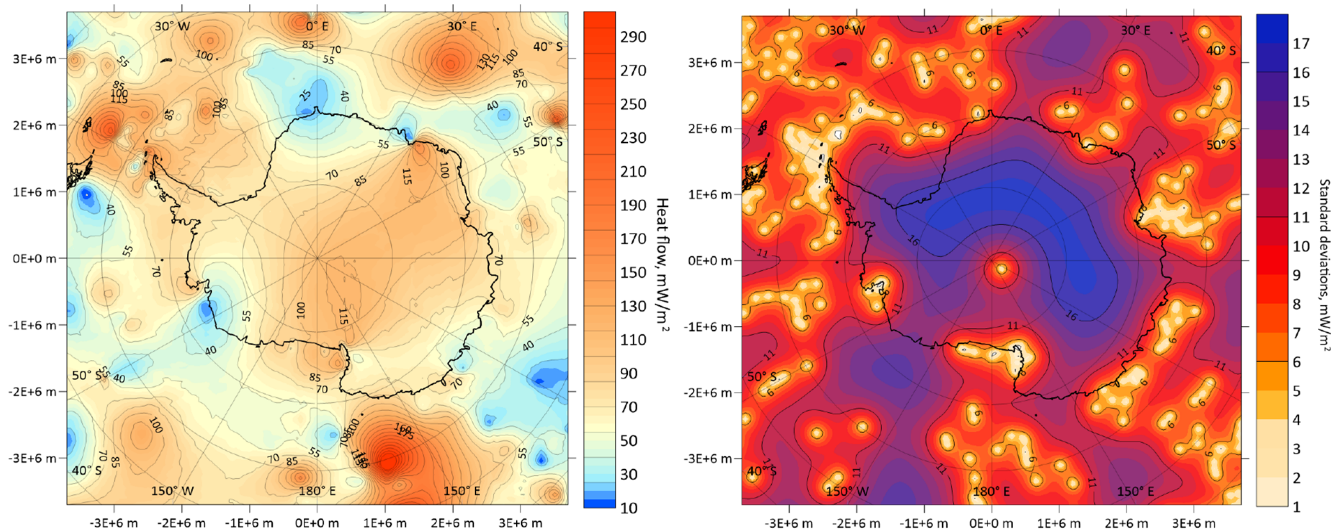


Figure 14. Median heat flow interpolated by Kriging and standard deviations. Orthographic South Pole projection. Data files are available in Petrunin et al. (2026).

provements in quality standards, a significant proportion of the legacy data still lacks detailed methodological information, which can hinder accurate assessment and application. However, the IHFC standards, which reflect the current state of knowledge and data analysis on heat flow, are applied to the legacy data representing methodological and technical development, as well as changes in scientific documentation principles and style, from almost a century of geoscience. Much of the metadata and information that is valued today, was not considered in the past. The absence of this information in past studies cannot be resolved and will persist. To ensure that the identified standards are acknowledged and supported as a minimum threshold in academia and in the scientific review process of publishers, knowledge transfer and education efforts are required for future heat flow studies.

Looking ahead, there are several ways in which the GHFDB could be enhanced. Expanding the geographical coverage particularly in regions with limited data, will address regional disparities and improve the dataset's comprehensiveness. Efforts to standardize measurement and data reporting methods will enhance consistency and comparability across studies, resulting in a more reliable dataset. Improving data quality and documentation remains a priority. Increasing the proportion of data with detailed methodological information while reducing the percentage of unspecified or poorly documented entries will enhance the GHFDB's overall reliability. Integrating heat-flow data with other geophysical datasets, such as seismic, gravimetric and magnetic data, will provide a more comprehensive understanding of the Earth's subsurface and support the development of more detailed geophysical models. For industrial geoenergy applications, such as basin and reservoir models in hydrocarbon or geothermal systems, the development of the GHFDB will provide high-quality model inputs and reduce uncertainties in the subsequent calculations. Technological advancements will continue to play a crucial role in improving the accuracy and resolution of heat-flow measurements. Innovations in instrumentation, remote sensing, and data analysis will contribute to more precise and reliable data, thereby enhancing the GHFDB's utility for scientific research, geothermal exploration, and environmental studies.

In summary, although the GHFDB has grown and improved significantly, addressing its limitations and pursuing future advancements will enhance its value and applicability even further. Such efforts will ensure that the database continues to be a valuable resource for understanding the Earth's thermal processes and supporting the development of sustainable energy.

10 Data availability

The GHFDB collection is available at GFZ Data Services.

- Release 2024 (Global Heat Flow Data Assessment Group et al., 2024, https://doi.org/10.5880/fidgeo.2024.014)
- Release 2023 (Global Heat Flow Data Assessment Group et al., 2023, https://doi.org/10.5880/fidgeo.2023.008)
- Release 2021 (Fuchs et al., 2021b, https://doi.org/10.5880/fidgeo.2021.014)
- GHFDB Data Template (Fuchs et al., 2025a, https://doi.org/10.5880/fidgeo.2025.042)
- IHFC 2024 Global Heat Flow Database (GHFDB v2024): Quality-Assessed Measurements, Gridded Products and Kriging Interpolation (the data underlying Figs. 12–14 and the Jupyter Notebook developed to extract and visualize the data) are available as Petrunin et al. (2026, https://doi.org/10.5880/GFZ.KHAG.2026.004).
- IHFC Controlled Vocabularies for the Global Heat Flow Database, (Jennings et al., 2026, https://doi.org/10.5880/fidgeo.2026.065).

The data are provided in comma-separated value format (.csv) together with comprehensive technical descriptions.

11 Code availability

The Heat Flow Quality Analysis Toolbox (Dergunova et al., 2026, https://doi.org/10.5880/fidgeo.2026.032) is a Python package for the application of heat flow quality standards that was designed based on the framework outlined by Fuchs et al. (2023). The capabilities developed in this tool provide an opportunity for quick and smooth adaptation of heat-flow data for accurate quality score calculations. The package includes two main functions: *vocabulary_check* to ensure vocabulary precision and *quality_scores* to compute the quality score for heat-flow datasets. It can either run in Jupyter Notebooks or through the Python terminal. It is released under the MIT License, allowing free reuse, modification, and distribution of the code. Further details on the code structure and functionality can be found in the README.md file within the repository. Each script is well-documented with in-line comments explaining key steps and functions.

In addition, we provide the Jupyter Notebook *Interpolation_Kriging_PyKrige.ipynb* was developed for Kriging interpolation of geophysical data It demonstrates the application of Ordinary Kriging for interpolating geophysical data (e.g., heatflow measurements) onto a global grid. It uses the PyKrige library for kriging, pandas for data handling, matplotlib and cartopy for plotting, and netcdf4 for output (https://doi.org/10.5880/GFZ.KHAG.2026.004, Petrunin et al., 2026).

12 Summary and Conclusion

From 2012 to 2024, the Global Heat Flow Database has grown and improved substantially. The dataset has expanded from 58 302 data points prior to the 2019 assessment to 91 182 by 2024, reflecting a significant rise in both the volume and diversity of heat-flow data. This growth has been accompanied by a substantial increase in the number of contributing publications, which reached 1586 by 2024 and is expected to grow further in the coming years.

The implementation of rigorous quality standards has significantly improved the GHFDB. In the 2024 release, around 46 % of the data points have been assessed for quality, including 13 % that were newly added and also assessed. The quality assessment framework includes uncertainty (U-scores), methodological (M-scores), and perturbation flags (P-flags), which provide a comprehensive evaluation of data reliability and methodological rigor. The enhanced QC documentation will allow users to create bespoke datasets and maximize the productive use of subsurface thermal data. By 2026, the core group anticipate having assessed, quality-controlled and integrated 90 % of the known heat-flow data from Earth.

The quality classification system reveals a clear improvement in the reliability of the data. The U-score evaluation shows that, although only 3 % of the assessed data is rated as highly reliable (U1), a significant proportion (78 %) is categorized as unspecified (Ux), indicating missing or incomplete information on critical methodological details. This highlights the ongoing challenge of ensuring comprehensive documentation and the need for future actions to establish these procedures in the daily work of heat flow researchers. Similarly, the M-score analysis shows that around 66 % of the assessed data is categorized as M4, indicating poor methodological quality, which emphasizes the need for continued efforts to improve methodological quality. We recommend that publishing journals establish a more rigorous review process, setting these standards as a threshold for the publication of heat-flow data.

Including perturbation flags (P-flags) further improves the quality assessment by identifying potential site-specific perturbation effects. They also provide valuable information about the nature of reported heat flow data, i.e., whether it reflects the heat from Earth's interior or overruling effects. Despite the significant proportion of unspecified data, the overall trend indicates improvements in data documentation and categorization.

Overall, the advancements in the development and application of quality standards and documentation in the past five years have strengthened the GHFDB's utility as a scientific and practical resource for academia and industry. Reducing unspecified data and improving categorization enhances the reliability of the dataset, thus increasing confidence in heat-flow research and its applications. These improvements not only reflect the progress made in data quality but also underscore the importance of ongoing efforts to maintain and enhance the quality of the global heat-flow dataset. Completing the enormous task of compiling a quality-checked and authenticated global compilation of heat-flow data will enable us to contribute significantly to discussions about the Earth's internal heat budget, and help us to develop a better understanding of subsurface thermal processes and the evolution of the Earth.

Author contributions. FN: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Data curation. BN: Conceptualization, Methodology, Writing – review & editing. EBP: Conceptualization, Methodology, Writing – review & editing. SE: Conceptualization, Methodology, Writing – review & editing, Visualization, Data curation. AGP: Conceptualization, Methodology, Writing – review & editing, Visualization, Maps & Grids. KE: Conceptualization, Methodology, Writing – review & editing. SJ: Conceptualization, Methodology, Writing – review & editing. VD: Code development, Writing – review & editing. SF: Conceptualization, Methodology, Writing – review & editing., Data curation, Supervision, Project administration, Funding acquisition.

Competing interests. At least one of the (co-)authors is a member of the editorial board of *Earth System Science Data*. The peer-review process was guided by an independent editor, and the authors also have no other competing interests to declare.

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