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QFuego-Patagonia: A comprehensive glacier-related dataset for Patagonia and Tierra del Fuego, South America

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Abstract

Patagonia and Tierra del Fuego (Austral Andes) are the most glacierised regions in the Southern Hemisphere, where glaciers have experienced significant mass changes in recent decades. Understanding glacier–climate–water interactions is crucial for addressing future climate challenges. Open-access data play a key role in advancing geoscience research, improving models and assessing the impacts of hazards and sea-level rise impacts. Here, we present QFuego-Patagonia, a free glacier-related GIS dataset and web portal covering Patagonia and Tierra del Fuego, which provides essential geospatial information across four scientific topics: Glaciology, Atmosphere, Terrain Models, and Glacial Geology and Geomorphology. This initiative aims to foster interdisciplinary research and collaboration, synthesise current knowledge and establish an advanced glacier data repository that will be continuously updated as new data and insights become available.

1. Introduction

Glaciers within the Patagonia and Tierra del Fuego region—hereafter referred to as Fuego-Patagonia, a term established in the mid-19th century (Auer, 1959)—span from 45°S to 56°S and cover approximately 25 000 km^2. This region encompasses the largest icefields in the Southern Hemisphere outside of Antarctica, including the Northern and Southern Patagonia Icefields (NPI and SPI), the Cordillera Darwin and numerous peripheral glaciers, representing around 80% of the total glacierised area in South America (Pfeffer and others, 2014; Fig. 1).

The Fuego-Patagonia glaciers are highly sensitive to climatic and environmental changes, as reflected in widespread negative trends in glacier area and surface elevation (Rivera and others, 2007; Braun and others, 2019; Dussaillant and others, 2019). These dynamic changes drive several associated phenomena, such as increased debris coverage, landslides, glacial lake outburst floods and proglacial lake expansion (Iribarren and others, 2014; Glasser and others, 2016). Despite substantial advances in understanding the region's glaciological evolution and its implications for climate and local communities, significant knowledge gaps remain. Key uncertainties persist in precipitation patterns (Bravo and others, 2019; Sauter, 2020), climatic mass balance estimation (Schaefer and others, 2015), and ice thickness distribution (Fürst and others, 2024), particularly in areas lacking direct observational data (Minowa and others, 2021).

Addressing these challenges requires high-quality, freely accessible datasets that adhere to the Findable, Accessible, Interoperable and Reusable (FAIR) principles (Wilkinson and others, 2016). Open-access geospatial data—such as satellite imagery, terrain models and climate records—play a crucial role in improving glacier and glacio-hydrological models, quantifying glacier changes and evaluating potential hazards and sea-level rise contributions. Ensuring continuous access to such data fosters inclusivity in research, enables more accurate model refinement and enhances our understanding of glacial dynamics and their broader climatic implications.

The Fuego-Patagonia region offers a unique opportunity to study glacial responses to volcanic, tectonic, atmospheric and climatic variability in the Southern Hemisphere. Here, we introduce the QFuego-Patagonia dataset, the first freely available geospatial compilation for this region, integrated into a Geographic Information System (QGIS environment). Following the example set by initiatives such as Quantarctica and QGreenland (Matsuoka and others, 2021; Moon and others, 2023), this dataset consolidates and visualises essential data on Fuego-Patagonian glaciers to enhance accessibility and collaboration within the scientific community. By developing open, well-structured datasets, we aim to support widespread scientific inquiry and facilitate engagement from researchers, stakeholders and the broader public in discussions on the impacts of climate change in this region.

2. Methods

2.1. QFuego-Patagonia GIS data and web mapping portal

QFuego-Patagonia is both a free GIS data compilation for Tierra del Fuego and Patagonia and an interactive web portal that enables downloading data and conducting simple online analyses for this region. The free mapping tool and interactive website will support interdisciplinary research, teaching and scientific collaboration in Tierra del Fuego and Patagonia. The GIS data compilation comprises key glacier datasets in a unified, all-in-one open-source GIS environment, which can be visualised offline and online (Fig. 2). The interactive web portal contains the same dataset as the GIS dataset, allowing users to visualise the layers individually.

2.2. Software selection

QGIS (https://qgis.org/) was chosen for the same purpose as the reference projects Quantarctica and QGreenland (Matsuoka and others, 2021; Moon and others, 2023). Aligned with the outlined methodology (Matsuoka and others, 2021), QGIS proves to be a valuable tool due to the following advantages: (i) it is freely available, (ii) compatible

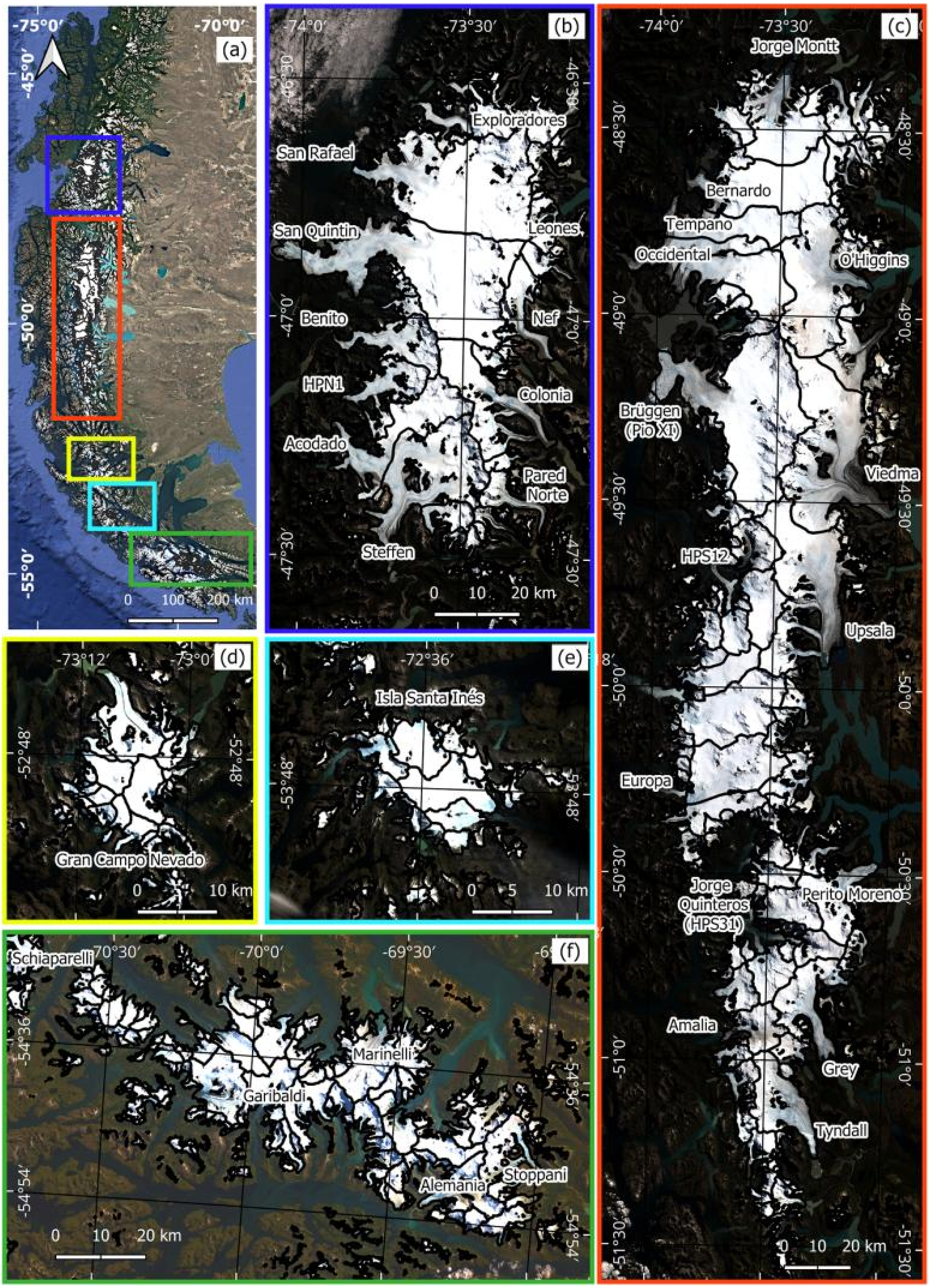

Figure 1. (a) Location of Patagonia and Tierra del Fuego (background: Google Earth image); (b) Northern Patagonia Icefield (NPI); (c) Southern Patagonia Icefield (SPI); (d) Gran Campo Nevado (GCN); (e) Isla Santa Inés (ISI) and (f) Cordillera Darwin (background: Landsat images from 2016 to 2021). Panels (d) and (e) are shown within the yellow box in panel (a).

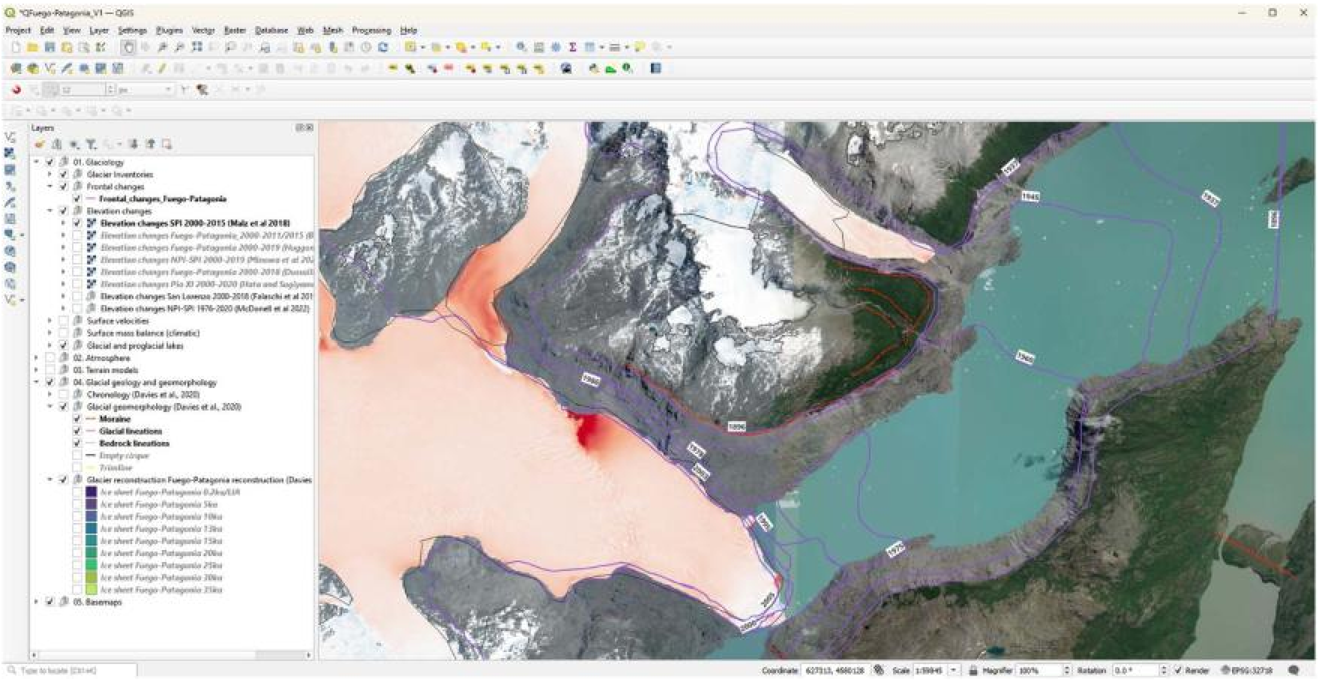

Figure 2. Example view of the QFuego-Patagonia dataset stored in QGIS (Figure 1c). The layers can be displayed by clicking on the selection box on the left. The colour scale represents the values of each specific field (e.g. the 'elevation changes' field). Users can display and rearrange the order of data layers that lie on top of basemaps, satellite imagery and terrain models at a user-chosen, continuously adjustable map scale.

with most computer operating systems, (iii) usable offline, (iv) features a user-friendly interface, (v) offers a wide array of tools, (vi) supports common geographical data formats, (vii) enables advanced cartographic capabilities, (viii) allows for high-quality map production, (ix) is actively maintained and developed, (x) follows a transparent bug-fixing process, (xi) benefits from an active user community and extensive knowledge base and (xii) can be bundled with datasets for standalone offline use.

2.3. Data selection

The interconnected disciplines in the scope of the QFuego-Patagonia project were identified and prioritised to build the database using a two-step methodology: (1) freely accessible and publicly available data in different repositories were reviewed, and then, (2) our project contributors and editorial team provided additional data from the included topics. In the first version, QFuego-Patagonia comprised 161 data layers, of which 135 represented four glacier-related scientific datasets (Table 1) to establish a long-term dataset that will require further revisions as future QFuego-Patagonia versions are developed. The first version consists of several regional datasets (e.g. atmosphere) that are compiled into a single dataset in upcoming versions to improve their usability. The data used for basemaps, satellite data and miscellaneous base layers were selected from a wide range of available products, prioritising those most up-to-date in terms of detail, integrity and relevance.

2.4. Mapping reference system and file format

The EPSG:32718 and EPSG:32719 coordinate systems were primarily used for this project, corresponding to UTM zones 18S and 19S. Also, the EPSG:4326 coordinate system was used to extend the study area (e.g. atmospheric data). The datasets were obtained from diverse sources, resulting in two file formats. To ensure uniformity, all vector data were maintained in Shapefile format, and all raster data were kept in GeoTIFF format. It is worth noting that, except for reprojection, the original data remains unchanged.

Table 1. Overview of the topics and basemaps included in the QFuego-Patagonia dataset.

Topics	Number of data layers	Total data size (MB)
1. Glaciology	86	13 300
2. Atmosphere	17	13.6
3. Terrain models	13	5760
4. Glacial Geology	19	22.9
Basemap	26	9 830
Total	161	29 040

2.5. Metadata

The metadata contains an overview of the dataset's general information, including references to the source scientific publication, comments and other details about the data. Additionally, it includes essential attributes such as dataset identification, the dataset's categories, access information, licenses, restrictions on use, the dataset author's contact information and a link to the project's website. The quality and impact of datasets like QFuego-Patagonia heavily depend on freely accessible, contributed data. Therefore, we strongly encourage citing the original data source and QFuego-Patagonia when these are used in scientific work and

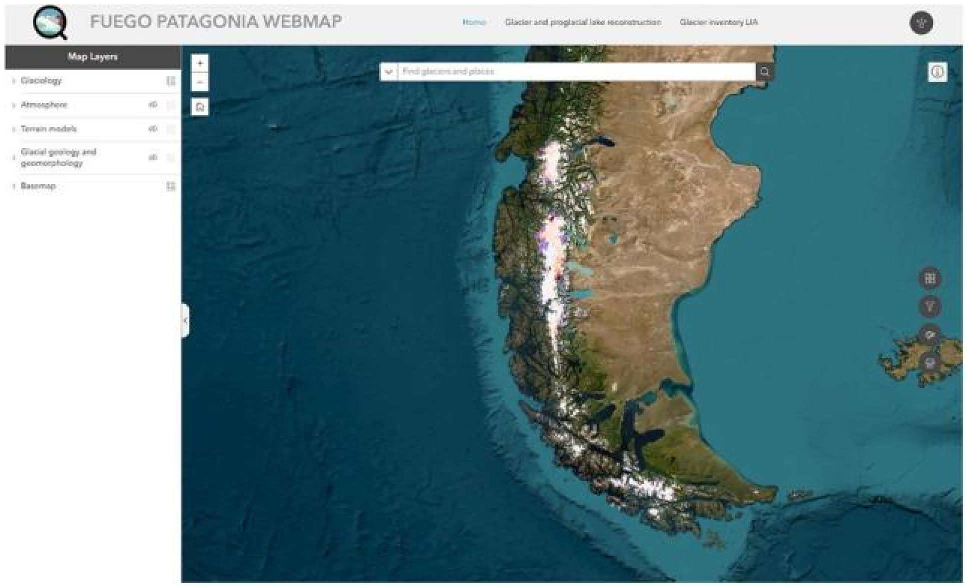

Figure 3. Example view of the QFuego-Patagonia web map. This online map provides a visualisation of existing data, enabling easy, rapid analysis.

publications. This citation information is provided in the abstract section of the metadata.

2.6. Implementation of the web mapping

ESRI ArcGIS products were used to develop the web mapping interface for the QFuego-Patagonia platform (Fig. 3). First, the datasets were assembled on a single platform; second, the original files were adapted and modified to comply with ESRI system requirements, refining the scope and enhancing functionality. The project was consistently integrated into the online platform. To optimise performance, raster data were converted into image tile caches. Leveraging ArcGIS Experience Builder facilitated the seamless construction of the web map, eliminating the need for manual coding. This tool offers templates and an intuitive drag-and-drop interface, enabling the creation of immersive web experiences adaptable to diverse screen sizes.

3. Datasets

The first version of the QFuego-Patagonia includes four glacier-related disciplines in a GIS environment (Fig. 2 and Table 1). All data layers are stored in a folder structure, allowing individual data files and their associated metadata to be easily located. The complete list of data included in QFuego-Patagonia is provided in Tables S1–S5. A user guide was also provided to adjust QGIS to the QFuego-Patagonia workspace.

3.1. Glaciology data

Glaciological data comprise the most extensive volume of data in QFuego-Patagonia, composed of several sub-fields, such as (1) glacier inventories, (2) frontal changes, (3) elevation changes, (4) surface velocities, (5) surface mass balance (SMB), and (6) glacial and proglacial lakes (Table S1). Studies on elevation changes and mass changes conducted in this region have employed diverse techniques, mostly estimated by differencing digital elevation models (DEMs) generated with interferometry techniques like Shuttle Radar Topography Mission (SRTM) and TerraSAR-X-Add-on for Digital Elevation Measurements (TanDEM-X; Malz and others, 2018; Abdel Jaber and others, 2019; Braun and others, 2019) or photogrammetric methods utilising Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), declassified satellite images (e.g. KH-9), and SPOT images, but with different post-processing techniques (Willis and others, 2012; Dussaillant and others, 2019; Hugonnet and others, 2021; Minowa and others, 2021; McDonnell and others, 2022). The dataset resolution for these fields is 30 m. Figure 4a illustrates an example of the elevation changes of NPI.

Glacier inventories and frontal changes have been estimated by several authors (e.g. Aniya, 1988; Rivera and Casassa, 2004; 2007; 2008; Bown and others, 2014). These datasets have been generated using remote sensing techniques ranging from band ratios and band-composition methods to historical reports and aerial photograph interpretation (Rivera and Casassa, 2004; Rivera and others, 2007, 2008, 2012; DGA, 2011; Bown and others, 2014). QFuego-Patagonia includes two versions of glacier inventories (IPG2014_v1 and IPG2022_v2) of the Dirección General de Aguas (DGA) of Chile (DGA, 2022), the Argentinian glacier inventory stored in GLIMS (Global Land Ice Measurements from Space) (Zalazar and others, 2020) and the glacier inventory by Meier and others (2018), who mapped glacier extension from the Little Ice Age to the present. The Randolph Glacier Inventory version 6 (Pfeffer and others, 2014; RGI Consortium, 2017), which has been widely used for global estimates of elevation changes and surface velocities, was also included (Friedl and others, 2021; Hugonnet and others, 2021).

Surface velocities are provided in GeoTIFF format with resolutions ranging from 50 to 200 m. Most studies used radar and optical remote sensing techniques to estimate surface velocities across the Fuego-Patagonia region (Mouginot and Rignot, 2015; Friedl and others, 2021; Minowa and others, 2021; Millan and others, 2022). QFuego-Patagonia includes regional velocities from two authors (Friedl and others, 2021; Millan and others, 2022), while the remainder are from NPI and SPI only (Mouginot and Rignot, 2015; Minowa and others, 2021).

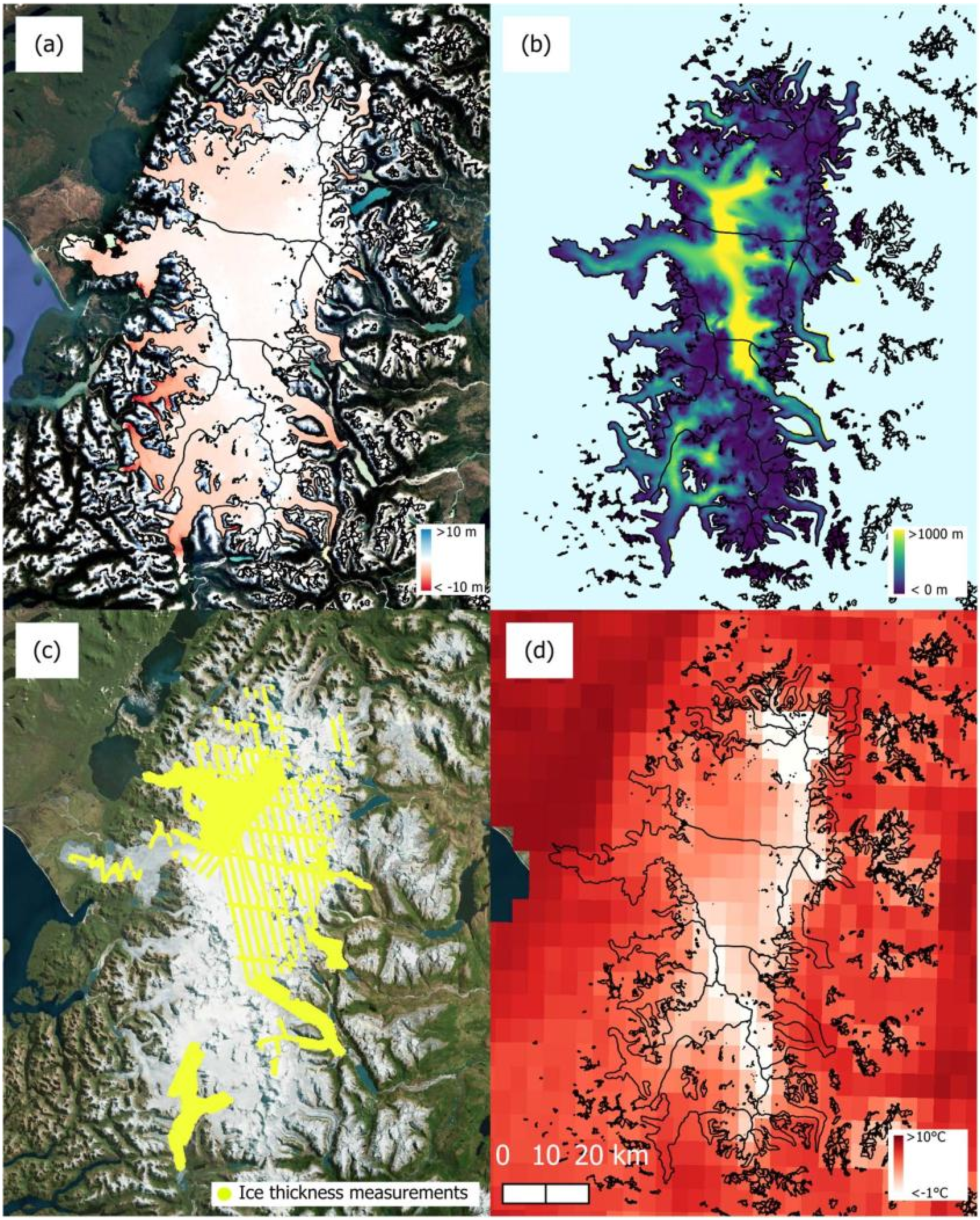

Figure 4. Example data contained in the QFuego-Patagonia for NPI: (a) elevation changes (Braun and others, 2019), (b) modelled ice thickness (Fürst and others, 2024), (c) compilation the tracks of the effective ice thickness measurements (Table S3 shows the list of the studies) and (d) mean annual temperature °C (Aguayo and others, 2024a).

SMB data from direct mass-balance measurements using glaciological methods are scarce for individual glaciers in the Fuego-Patagonia region. Various modelling efforts, utilising downscaled global climate data and applying SMB models of varying complexities, have been undertaken only in NPI and SPI, which are included in QFuego-Patagonia (Schaefer and others, 2013; 2015; DGA, 2014; Bravo and others, 2021; Carrasco-Escaff and others, 2023). Accumulation estimations (Schaefer and others, 2013; 2015; Bravo, 2019; Carrasco-Escaff and others, 2023) and SMB projections using different RCP scenarios (Bravo and others, 2021) were also included in the SMB field. Observations and simulations of SMB for the Tierra del Fuego are available for Sarmiento Massif (Temme and others, 2023) and the entire Cordillera Darwin (Temme and others, 2025).

Glacial and proglacial lakes include two sub-fields. Glacial and proglacial lake inventories were compiled using the aforementioned remote sensing techniques and historical reports (e.g. Loriaux and others, 2013; Wilson and others, 2018). The files include those of Wilson and others (2018), a point shapefile of changes in lake area, and Loriaux and Casassa (2013), which document changes in lakes between 1944/45 and 2011 at NPI (Table S1).

3.2. Atmospheric data

The atmospheric dataset in QFuego-Patagonia is primarily based on the PatagoniaMet v1.1 grid, which provides a reliable representation of mean precipitation and temperature across the Fuego-Patagonia region (Aguayo and others, 2024a). It includes annual mean precipitation and temperature data (0.05° resolution, 1990–2019) and seasonal values (Aguayo and others, 2024a). The dataset also integrates additional precipitation grids (Schaefer and others, 2013; 2015; Carrasco-Escaff and others, 2023), covering NPI and SPI. Figure 4d is an example of the gridded mean temperature at 2 m for NPI (Aguayo and others, 2024a).

The dataset's value lies in its inclusion of data from various sources, providing a comprehensive view of atmospheric conditions (Table S2). However, there is potential for expanding the spatial and temporal coverage in future versions. Collaborative efforts to include more atmospheric variables, enhance modelling techniques and acquire additional data at higher elevations (e.g. icefield plateaus) would improve its utility for climate studies and reduce uncertainties in hydrological projections (Aguayo and others, 2024b).

3.3. Terrain models data

Terrain model data in QFuego-Patagonia include modelled ice thickness, ice thickness measurements, subglacial topography and bathymetry (Table S3). Modelled ice thicknesses were obtained through mass conservation, perfect plasticity assumptions and the shallow-ice approximation (SIA; Carrivick and others, 2016; Farinotti and others, 2019; Millan and others, 2022; Fürst and others, 2024), some of which include ground-truth data (Millan and others, 2022; Fürst and others, 2024). These models provide critical insights into ice dynamics, though data gaps in certain regions (e.g. the Cordillera Darwin) underscore the need for further investigation.

Ice thickness observations, primarily collected via terrestrial or airborne ground-penetrating radar, seismic measurements and gravimetry, provide important validation of modelled ice thicknesses—initial attempts included gravimetric point measurements on Nef and Soler glaciers (e.g. Casassa, 1987). NPI and SPI were measured using the Warm Ice Experiment Sounder (WISE) radar sounder (Rignot and others, 2013). Airborne gravimetry surveys in 2012 and 2016 provided extensive spatial coverage for the interior of the Northern Patagonian Icefield (NPI; Millan and others, 2019). Figures 4b and 4c show examples of the modelled ice thickness and NPI thickness measurements.

Ground Penetrating Radar measurements dating back to 1990 have been conducted on Tyndall Glacier and Paso Cuatro Glaciares (Casassa, 1992; Casassa and Rivera, 1998; Rivera and Casassa, 2002). Dense ice-thickness grid surveys on several NPI and SPI glaciers using helicopter-borne radar are included (Blindow and others, 2012; DGA, 2012, 2016; Pętlicki and others, 2023). However, NPI presents a better helicopter-borne radar coverage than SPI. A few samples of seismic cross-profiles in the Perito Moreno glacier were also included in this dataset (Stuefer, 1999; Sugiyama and others, 2011)· As for Cordillera Darwin, there are no ice thickness measurements; only a small section of Schiaparelli Glacier was measured in the near-front area (Gacitúa and others, 2021). This highlights the importance of collaborative efforts to expand the coverage and reliability of ice thickness data.

Bathymetry data consists of fjord, glacial and proglacial lake measurements. The dataset integrates various oceanographic observations from cruises and historical records, providing a detailed perspective on the underwater landscape. The bathymetric fjords data are composed of three large regional datasets: (1) Baker-Martinez fjord bathymetry (Piret and others, 2017), (2) Beagle channel bathymetry (Giesecke and others, 2021) and (3) a compilation of depth sounding acquired over many years by the Hydrographic service of the Chilean Navy (SHOA) in the western fjords of SPI. The Baker-Martinez fjord data set (Fig. 5a) is a comprehensive ensemble of diverse bathymetric data sets compiled by Piret and others (2017). It includes multibeam echosounder data from Baker channel and Steffen fjord and Baker River delta, single beam echosounder data from Martinez channel (R/V Sur-Austral 2015/2016) and Jorge Montt fjord (Rivera and others, 2012; Moffat, 2014), as well as additional bathymetric data contributed by C. Moffat and individual points digitised from two SHOA nautical charts (SHOA). The Beagle Channel is a vital interoceanic passage spanning approximately 270 km and is connected to the glaciers of Cordillera Darwin through tributary fjords. The Beagle Channel bathymetry measurement (Fig. 5b) was generated by Giesecke and others (2021), who used an ensemble of different oceanographic observations derived from cruises and historical records. The bathymetric data provided by SHOA for the region west of the SPI is a shapefile containing depth soundings surveyed by hydrographic vessels used in nautical charts of the area, and therefore presents a minimum depth in their vicinity.

The other sub-field, (2) glacial lake bathymetry, mainly includes recent data from glaciers in the eastern part of SPI, such as O'Higgins, Viedma, Perito Moreno, Grey and Tyndall (Sugiyama and others, 2016, 2021; Minowa and others, 2023). The bathymetric datasets exhibit varying degrees of coverage. These datasets are essential for understanding the interaction between glaciers and their surrounding aquatic environments. Efforts to fill data gaps, enhance resolution and expand spatial coverage, particularly in the glacial lake bathymetry, will further improve the dataset's utility. Emerging technologies, such as autonomous underwater vehicles, can play a crucial role in future iterations of the dataset.

3.4. Glacial Geology and geomorphology

The geological data layers integrated into QFuego-Patagonia originate from the PATICE project (Davies and others, 2020), a GIS database that compiles Patagonian glacial geomorphology and recalibrated chronological data from various studies across the

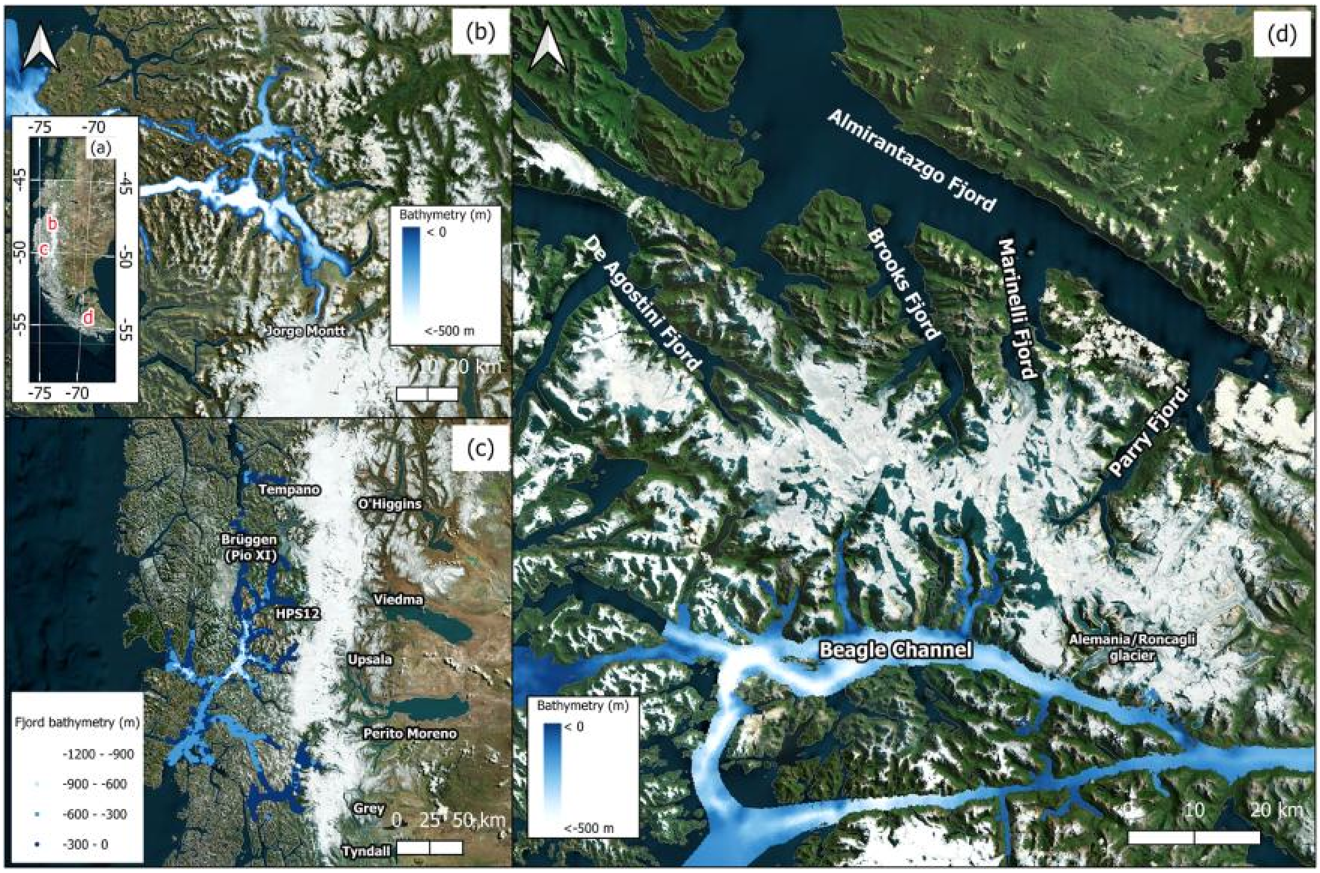

Figure 5. Bathymetric datasets included in QFuego-Patagonia: (a) general location of the data coverage, (b) Baker-Martinez Fjord bathymetry (Piret and others, 2017), (c) soundings from nautical charts of the Hydrographic service of the Chilean Navy (SHOA) and (d) Beagle Channel (Giesecke and others, 2021).

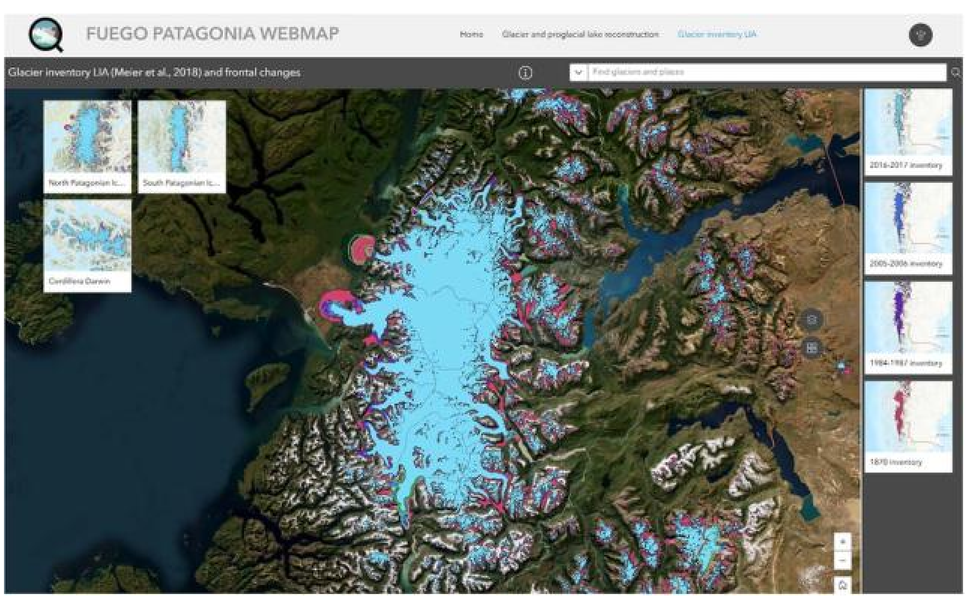

Figure 6. Visualisation example showing glacier reconstruction and frontal shifts from the Little Ice Age (Meier and others, 2018).

region. Three key subfields from PATICE were incorporated: (1) chronology, (2) glacial geomorphology and (3) glacier reconstructions (Table S4).

The chronology subfield encompasses dating techniques such as dendrochronology, cosmogenic exposure dating using ^{10}Be, ^{26}Al, ^{36}Cl and ^{3}He, optically stimulated luminescence, and radiocarbon dating. These datasets provide a temporal framework for past glaciations and landscape evolution. The curation process involved integrating disparate dating records into a standardised format, ensuring chronological accuracy and geospatial consistency.

The glacier reconstruction subfield provides insights into historical glacial extents and lake formations over the past 10 000–35 000 years, as well as reconstructions of the Fuego-Patagonia Ice Sheet over the last 35 000 years (Davies and others, 2020) (Fig. 6). The curation process included refining spatial boundaries to align with QFuego-Patagonia's study area, thereby ensuring the dataset's relevance to the region.

The integration of these geological datasets into QFuego-Patagonia facilitates multi-disciplinary studies on glacier history, landscape evolution and paleoclimate reconstructions (Glasser and others, 2008; Davies and others, 2020). Future work should prioritise expanding chronological records and refining spatial reconstructions using emerging dating techniques and high-resolution geomorphic mapping.

3.5. Basemaps

The basemap layers include data that allow intercomparison, planning and visualization, including satellite images, toponymy information and UTM grids (Table S5). A separate RGI V6 layer is also included, serving as a common reference area for various estimations such as elevation changes, velocities, ice thickness and more.

4. Conclusions

QFuego-Patagonia is a free glacier-related GIS Package for Tierra del Fuego and Patagonia (45°–56 S°) compatible with QGIS 3.16 on multiple platforms, without an internet connection. The GIS package comprises 135 layers across four topics and 26 basemap layers. The compressed package is ∼3.5GB, while the uncompressed dataset is ∼29GB. The QFuego-Patagonia package is available for download from the official website and from PANGAEA. An interactive version is hosted on the ESRI platform and can be accessed without requiring a local download. This project provides a diverse set of datasets derived using different techniques, enriching options for model calibration, data comparison and use in specific tasks or teaching. The database aims to offer an extensive data collection that (1) facilitates an overview of the current state of knowledge in the study region, where the integration of multiple datasets enhances the understanding of present-day glacial dynamics; (2) promotes intercomparison of data with different spatial and temporal resolutions and (3) helps identify priorities for future research.

In the era of big data, the availability of free and accessible datasets in QFuego-Patagonia not only enriches our understanding of the Fuego-Patagonia glaciers but also exemplifies a commitment to harnessing the transformative potential of data for the betterment of society. Furthermore, data accessibility fosters collaboration among diverse stakeholders, including scientists, policymakers and local communities, thereby promoting inclusivity in the scientific process and facilitating the development of effective mitigation and adaptation strategies. We are committed to enhancing QFuego-Patagonia by continually integrating and consolidating the package with new datasets and by cultivating a cutting-edge knowledge repository for the region, which provides a clear overview of our current knowledge and emerging high-quality studies.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2025.10110.

Data availability statement. The QFuego-Patagonia package is available for download at the official website (https://qfuego-patagonia.org/download-data/), as well as PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.983754) under the Creative Commons Attribution-NonCommercial 4.0 International licensed. An interactive version of the package is hosted on the ESRI platform and can be accessed at: https://experience.arcgis.com/experience/be61ce26335e4f02967071a6479e0dff/

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