ECMWF COPERNICUS REPORT

Copernicus Climate Change Service

Product User Guide and Specification

Cryosphere Service: Glaciers ECV - Elevation and Mass Change

D3.GL.8-v3.0

Issued by: UZH / Frank Paul

Date: 06/07/2021

Ref: C3S_312b_Lot4.D3.GL.8-v3.0_Product_User_Guide_Specification_Change_i1.0.docx

Official reference number service contract: 2018/C3S_312b_Lot4_EODC/SC2

IMPLEMENTED BY ECMWF

This document has been produced in the context of the Copernicus Climate Change Service (C3S).
The activities leading to these results have been contracted by the European Centre for Medium-Range Weather Forecasts, operator of C3S on behalf of the European Union (Delegation Agreement signed on 11/11/2014). All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose.
The user thereof uses the information at its sole risk and liability. For the avoidance of all doubts, the European Commission and the European Centre for Medium-Range Weather Forecasts has no liability in respect of this document, which is merely representing the authors view.

Contributors

UNIVERSITY OF ZURICH

1. Frank Paul
2. Michael Zemp
3. Philipp Rastner
4. Jacqueline Bannwart

History of modifications

Issue	Date	Description of modification	Author
i0.1	21/12/2020	Created based on C3S_312b_Lot4.D3.GL.8-v2.0_202001_Product_User_Guide_Specification_v1.0. Split document into area and change version. Revision to executive summary. Removal of all text referring to Glacier Area. Removal of Adaptor 3 text (was only relevant to C3S 312a activity).Minor revisions to section 1.1. and 1.2. Text describing product (Section 2.2. and Section 2.3) is brought in from TRGAD v2.0. Data Citation revised to point to recent WGMS FoG database. Revision of Data access information	FP
I1.0	25/02/2021	Approved. Finalised. To OTC	RK

List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
D3.GL.5-v3.0	Glacier Elevation Change CDR v3.0	CDR	Brokered from FoG v6 (v202008)	31/01/2021
D3.GL.6-v3.0	Glacier Mass Change CDR v3.0	CDR	Brokered from FoG v6 (v202008)	31/01/2021

Related documents

Reference ID	Document
RD1	WGMS FoG Versions, incl. attribute description (https://wgms.ch/data_databaseversions/)
RD2	GCOS Implementation Plan 2016 (https://unfccc.int/sites/default/files/gcos_ip_10oct2016.pdf)
RD3	Mass balance Analysis (https://doi.org/10.5194/tc-7-1227-2013)
RD4	(D1.S.1-2020) Target Requirements and Gap Analysis Document, Soil Moisture Service, Glaciers Service, Lakes Service, Ice Sheets Service
RD5	(D2.GL.1-v3.0) Product Quality Assurance Document Cryosphere Service: Glaciers ECV - Area, v3.0

Acronyms

Acronym	Definition
DEM	Digital Elevation Model
FoG	Fluctuations of Glaciers
GMBB	Glacier Mass Balance Bulletin
GTN-G	Global Terrestrial Network for Glaciers
PSFG	Permanent Service on Fluctuations of Glaciers
WGMS	World Glacier Monitoring Service
WGS	World Geodetic System

General definitions

This document[1] refers to the following versions of the datasets in the Climate Data Store (**CDS**):
Glacier change service: **FoG database 20200824**

[1] Results presented in earlier versions of this document (v1, v2 and v3 of C3S_312a & v1 and v2 of C3S_312b) are kept.

Table of Contents

Scope of the document

This document is the Product User Guide and Specification (PUGS) for the glacier elevation and mass change products from the glacier change service. .It describes the baseline product (CDR) provided to the CDS, which is an extract from the Fluctuations of Glaciers (FoG) database that is brokered from WGMS (wgms.ch).. For the detailed product description and usage, we refer to the freely available reference documents [RD1/2/3].

Executive summary

This document provides a description of the dataset (CDR) provided by the C3S Glacier Change Service to the Climate Data Store (CDS), the Fluctuations of Glaciers (FoG) database containing glacier elevation and mass changes.

In Section 1, we first provide a description of the database, target requirements from GCOS and limitations of data usage. Details of the technical specifications and data fields are described in the following Section 2. These were formerly described in the TRGAD [RD4]. Information on data access is provided at the end in Section 3.

1. The Fluctuations of Glaciers Database (FoG)

1.1 Product description

Internationally coordinated glacier monitoring began in 1894, with the periodic publication of compiled information on glacier fluctuations starting one year later (Forel, 1895). In the beginning, glacier monitoring focused mainly on observations of glacier front variations, and after the late 1940s, on glacier-wide mass balance measurements (Haeberli, 1998). Beginning with the introduction of the Fluctuations of Glaciers series in the late 1960s (PSFG 1967, WGMS 2012, and volumes in between), standardised data on changes in glacier length, area, volume and mass have been published at pentad intervals. At the beginning of the 1990s, the Glacier Mass Balance Bulletin (GMBB) series (WGMS, 1991; WGMS, 2013, and issues in between) was designed in order to speed up access to information on glacier mass balance at two-year intervals. Since the late 1980s, glacier fluctuation data have been organised in a relational database (Fluctuations of Glaciers database; Hoelzle and Trindler, 1998) and are available in electronic form through websites of the WGMS (https://www.wgms.ch) and GTN-G (https://www.gtn-g.org). The new Global Glacier Change Bulletin series merges the former Fluctuations of Glaciers (Vol. I–X) and Glacier Mass Balance Bulletin (No. 1–12) series. It aims to provide an integrative assessment of global glacier changes every two years. In Figure 1, a global overview of the glacier distribution and fluctuation measurements is depicted.

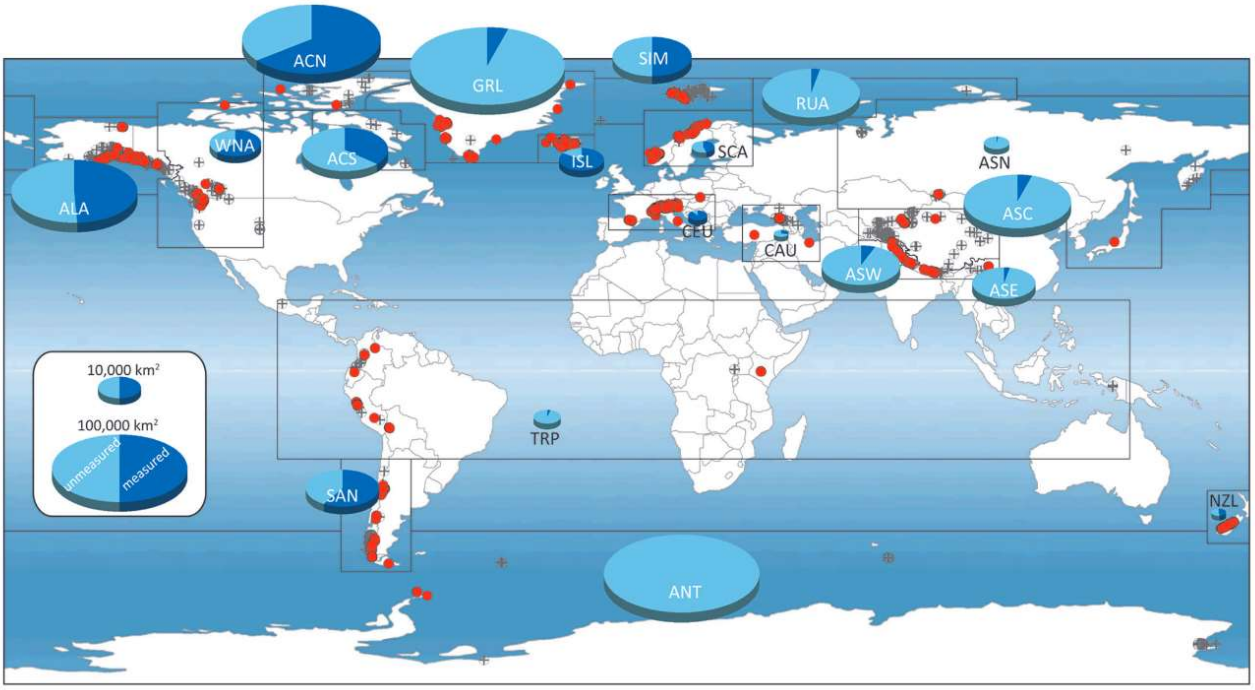

Figure 1: Distribution of glacier area and fluctuation records in 19 regions. The pie charts show the regional glacier area (excluding the ice sheets in Greenland and Antarctica) and the fraction covered by available observations of changes in glacier length, volume and mass. The dots show the location of continued (red) and interrupted (black cross) series with respect to the latest data report covering the observation period 2005/06–2009/10 (from Zemp et al. 2015).

The C3S glacier change service is an extract of the Fluctuations of Glaciers database providing the core datasets on changes in glacier elevation (as derived from the geodetic method; Cogley et al. 2011, Zemp et al. 2013) and mass (as derived from glaciological measurements; Cogley et al. 2011, Zemp et al. 2013) to the C3S CDS. More information is provided in WGMS (2017; and earlier reports as available from https://wgms.ch/literature_published_by_wgms). The wider context and history of the Fluctuations of Glaciers database are summarised in Zemp (2012).

1.2 Target requirements

The target requirements for the elevation and mass change products from the glacier change service are described in the TRGAD [RD4]. We, thus, only refer here to the requirements for glaciological mass balance measurements and geodetic volume changes as listed in GCOS (2016) and repeated in Table 1. In the following, a short description of the related entries is added.

Table 1: GCOS requirements for the ECV Glaciers.

Terrestrial ECV Product Requirements								
ECV	Products	Frequency	Resolution	Required measurement uncertainty	Stability (per decade unless otherwise specified)	Standards/ References	Entity (see Part II section 2.2).[95]	
							Satellite	In Situ
Glaciers	Glacier area	Annual (at end of ablation season)	Horizontal 15-30m	5%		IGOS (2009) Paul et al. (2009) Zemp et al. (2013)	WGClimate	GCW
	Glacier elevation change	Decadal	Horizontal 30m-100mx Vertical 1m	2m/decade	1m/decade		WGClimate	GCW
	Glacier mass change	seasonal to annual (the latter at end of ablation period)	Vertical: 0.01m or 10kg/m^2 (at point location)	better than 200kg/m^2/year (glacier-wide)			WGClimate	GCW

Glacier elevation change is measured in-situ and remotely sensed using the geodetic method (Cogley et al. 2011, Zemp et al. 2013). The frequency "decadal" refers to the length of the time period needed between two geodetic surveys in order to safely apply a density conversion from volume to mass change (cf. Huss 2013, Zemp et al. 2013). The targets for horizontal and vertical resolutions refer to requirements for differences of digital elevation models (dDEM) in mountainous terrain (e.g. Joerg and Zemp, 2014). The required measurement uncertainty refers to the glacier-wide uncertainty estimate based on a quality assessment of the dDEM product over stable terrain. The value of "2 m per decade" (= 0.2 m m^{-2} a^{-1}) is set in relation to the corresponding uncertainty requirement of the glaciological method. The stability of "1 m/decade" refers to a bias in the glacier-wide change of 0.1 m m^{-2} a^{-1}, which is about 1/3 to 1/2 of the average annual ice loss rate over the 20th century (Zemp et al. 2015) and good enough for validation of glaciological series [RD3].

Glacier mass change is measured in-situ by the glaciological method (Cogley et al. 2011, Zemp et al. 2013). The frequency "seasonal to annual" refers to the measurement campaigns, which ideally are carried out at the time of maximum accumulation (in spring) and of maximum ablation (at the end of hydrological year). The vertical resolution "0.01 m or 10 kg/m^2" refers to the precision of ablation stake and snow pit readings at point locations. The required measurement uncertainty "200 kg m^{-2} a^{-1}" (= 0.2 m w.e. m^{-2} a^{-1}) refers to the glacier-wide annual balance, which is interpolated from the point measurements. The target value was selected based on a review of long-term mass balance measurement series [RD3]. The stability can be assessed by validation and – if necessary – calibration of a glaciological times series with decadal results from the geodetic method. As a rule of thumb, stability is recommended to be better than 300 kg m^{-2} a^{-1} [RD3].

As described in the PQAD [RD5], the glacier datasets, as delivered to the CDS, consist of a global compilation of research data from in-situ, air and space borne methods. The classical concept of calibration and validation as applied to global satellite products, hence, cannot be applied. Instead, the validation of the global glacier products (i.e. the glacier CDRs) is limited to three general levels: (i) peer-review system of original data publication in an academic journal, (ii) plausibility checks during upload into the international databases within the GTN-G, and (iii) evaluation of uncertainty information submitted with the data. A global analysis of the product and a discussion of related uncertainties are found in Zemp et al. (2015) and [RD3], respectively. The datasets (ICDRs) being produced within C3S will all have the required uncertainty information attached.

1.3 Data usage information

The data provided through the Glacier Change Service consists of two data layers:

1) ELEVATION_CHANGE_SERIES in shapefile-format with related ELEVATION_CHANGE_DATA in csv-format.
2) MASS_BALANCE_SERIES in shapefile-format with related MASS_BALANCE_DATA in csv-format.

The shapefiles are in the World Geodetic System 1984 (WGS84) datum and contain the glacier location as point shapefiles. The csv-files contain the individual glacier change series linked to the corresponding point shapefile through the WGMS_ID. More detail about the dataset including a full attribute description is given in Section 2.

For the integration into the C3S Climate Date Store, the following basic query and plotting functions are recommended:

- Query and plotting of individual data series according to the following examples for Hintereisferner, Austria, WGMS_ID 491:
  - Mass balance series: https://www.wgms.ch/data/min-data-graphs/491_MB_ann.png
  - Elevation change series: https://www.wgms.ch/data/min-data-graphs/491_TC_ann.png
  - Note that the mass balance series consist of usually continuous annual balance measurements.
  - The elevation change series consist of multi-annual changes with sometimes overlapping survey periods. For plotting, multi-annual ELEVATION_CHANGE needs to be converted to ANNUAL CHANGE RATES.
- Query and plotting of regional annual averages according to Figure 3.8.1 in the Global Glacier Change Bulletin No. 3: http://wgms.ch/downloads/WGMS_GGCB_03.pdf. Note that for combining mass balance and elevation change data in one regional plot, the elevation changes (a) need again to be converted to annual change rates and (b) need to be converted to mm, i.e. using a density conversion factor, e.g. 850 kg m^{-3} (cf. Huss 2013).

2. Technical details of the provided products

2.1 Background

The Copernicus Glacier Change Service is providing two types of datasets, time series of glacier elevation and mass changes in CSV format, and meta-information for each glacier in the respective time series in shape file format. The basic structure and contents is adopted from the Fluctuations of Glaciers (FoG) database that is brokered from WGMS. Each new FoG version is provided to the CDS. The new dataset includes all previous datasets, possible corrections, an extension with the latest measurements and new datasets. The following descriptions have been adopted from the attribute description of the FoG database (version doi: 10.5904/wgms-fog-2016-08) hosted by WGMS [RD2] and still valid for the latest version of the dataset (doi: 10.5904/wgms-fog-2020-08).

2.2 Technical Specification of the dataset

The time series of glacier-wide changes in elevation and mass are provided as individual CSV files. Meta-information about each glacier in the respective time series is provided in shape file format (.shp with accompanying .dbf, .prj and .shx files) and contains the location of the glacier label point in geographic coordinates and some general statistic information about the glacier. Each of the two CSV files has its own meta-information shape file, but the entries in the shape file are the same. In the following section we first describe the entries of the shape file (summarized in Table 1.1) and then each entry of the two CSV files (Tables 1.2 and 1.3).

2.3 Data fields

Data fields of the shape file presenting the meta-information for each glacier in the GLACIER_MASS_BALANCE_SERIES and GLACIER_ELEVATION_CHANGE_SERIES

POLITCAL UNIT [alphabetic code; 2 digits]
Name of country or territory in which glacier is located (for 2 digit abbreviations, see ISO 3166 country code, available at www.iso.org).

GLACIER NAME [alpha-numeric code; up to 60 digits]
The name of the glacier, written in CAPITAL letters. Format: max. 60 column positions.

WGMS ID [numeric code; 5 digits]
5-digit key identifying glaciers in the Fluctuations of Glaciers (FoG) database of the WGMS. For new glacier entries, this key is assigned by the WGMS.

LATITUDE [decimal degree North or South; up to 6 digits]
The geographical coordinates refer to a point in the upper ablation area; for small glaciers, this point may lie outside the glacier. Latitude is given in decimal degrees, positive values indicating the northern hemisphere and negative values indicating the southern hemisphere, the datum is WGS1984. Latitude is given to a maximum precision of 4 decimal places.

LONGITUDE [decimal degree East or West; up to 7 digits]
The geographical coordinates refer to a point in the upper ablation area; for small glaciers, this point may lie outside the glacier. Longitude is given in decimal degrees, positive values indicating

east of zero meridian and negative values indicating west of zero meridian, the datum is WGS1984. Longitude is given to a maximum precision of 4 decimal places.
GLACIER REGION [alphabetic code; 3 digits]
3-digit code assigning each glacier to one of 19 first-order regions. For new glacier entries, this key is assigned by the WGMS.

GLACIER SUBREGION [alpha-numeric code; 6 digits]
6-digit code assigning each glacier to one of 90 second-order regions. For new glacier entries, this key is assigned by the WGMS.

PHOTO URL [alphabetic code; up to 255 digits]
URL to photo of the corresponding glaciers stored at WGMS or NSIDC. These images are typically provided in JPG or PNG format.

PHOTO INFO [alphabetic code; up to 255 digits]
Meta-data related to the photo given under PHOTO URL. The information is provided in the format "GLACIER-NAME (PU), DD.MM.YYYY, PHOTOGRAPHER-NAME".

CITATION [alpha-numeric; up to 255 digits]
General reference of the current version of the FoG database which must be cited when using the data. Note that full details to principal investigators, sponsoring agencies, and references are given with the individual observations.

Table 1: Entries of the attribute table included in the shape file of the glaciological and geodetic datasets.

GLACIER_MASS_BALANCE_SERIES			
Item (short)	**Item (full)**	**Unit**	**Format**
PU	Political Unit	n/a	txt
NAME	Glacier name	n/a	txt
WGMS_ID	WGMS ID	n/a	Integer
LATITUDE	Latitude	deg	Float
LONGITUDE	Longitude	deg	Float
GLACREG1	Glacier Region Code	n/a	txt
GLACREG2	Glacier Sub-region Code	n/a	txt
PHOTO_URL	Photo Link	n/a	png/jpg
PHOTO_INFO	Photo Info	n/a	txt
CITATION	Citation for this data series	n/a	txt

Data fields of the CSV file presenting GLACIER_MASS_BALANCE_DATA
WGMS ID [numeric code; 5 digits]
5-digit key identifying glaciers in the Fluctuations of Glaciers (FoG) database of the WGMS. For new glacier entries, this key is assigned by the WGMS.

SURVEY DATE [numeric; 8 digits]

Date of present survey. For each survey, the complete date in numeric format (YYYYMMDD) is indicated. Missing data: For unknown day or month, “99” is put in the corresponding position(s).

REFERENCE DATE [numeric, 8 digits]
Date of previous survey. For each survey, the complete date in numeric format (YYYYMMDD) is indicated. Missing data: For unknown day or month, “99” is put in the corresponding position(s).

AREA [km^2]
Glacier area (in horizontal projection) in the survey YEAR.

ANNUAL BALANCE [mm w.e.]
Annual mass balance of glacier divided by the area of the glacier.

ANNUAL BALANCE UNCERTAINTY [mm w.e.]
Estimated random uncertainty of reported annual balance.

INVESTIGATOR [alpha-numeric; 255 digits]
Name(s) of the person(s) or agency doing the field work and/or the name(s) of the person(s) or agency processing the data.

SPONSORING AGENCY [alpha-numeric; 255 digits]
Full name, abbreviation and address of the agency where the data are held.

REFERENCE [alpha-numeric; 255 digits]
Reference to publication related to above data and methods. Use short format such as: Author et al. (YYYY); Journal, V(I), X-XX p.

REMARKS [alpha-numeric]
Any important information or comments not included above.

Table 2: Overview of the attribute data provided in the CSV file of the glaciological dataset.

GLACIER_MASS_BALANCE_DATA			
Item (short)	**Item (full)**	**Unit**	**Format**
WGMS_ID	WGMS ID	n/a	Integer
SURVEY_DATE	Survey date	n/a	yyyymmdd
REFERENCE_DATE	Reference date	n/a	yyyymmdd
AREA	Area	km^2	Float
ANN_BAL	Specific annual balance	mm w.e.	Integer
ANN_BAL_UNC	Specific annual balance uncertainty	mm w.e.	Integer
INVESTIGATOR	Principal investigator(s)	n/a	txt
SPONS_AGENCY	Sponsoring agency	n/a	txt
REFERENCE	Reference to related publication(s)	n/a	txt
REMARKS	Remarks	n/a	txt

Data fields of the CSV file representing GLACIER_ELEVATION_CHANGE_DATA

WGMS ID [numeric code; 5 digits]
5-digit key identifying glaciers in the Fluctuations of Glaciers (FoG) database of the WGMS. For new glacier entries, this key is assigned by the WGMS.

SURVEY DATE [numeric; 8 digits]
Date of present survey. For each survey, the complete date in numeric format (YYYYMMDD) is indicated. Missing data: For unknown day or month, "99" is put in the corresponding position(s).

REFERENCE DATE [numeric, 8 digits]
Date of previous survey. For each survey, the complete date in numeric format (YYYYMMDD) is indicated. Missing data: For unknown day or month, "99" is put in the corresponding position(s).

AREA SURVEY YEAR [km^2]
Glacier area of each altitude interval (in horizontal projection) in the survey YEAR.

AREA CHANGE [1000 m^2]
Area change for each altitude interval.

ELEVATION CHANGE [mm]
Specific ice thickness change for each altitude interval.

ELEVATION CHANGE UNCERTAINTY [mm]
Estimated random uncertainty of reported thickness change.

INVESTIGATOR [alpha-numeric; 255 digits]
Name(s) of the person(s) or agency doing the field work and/or the name(s) of the person(s) or agency processing the data.

SPONSORING AGENCY [alpha-numeric; 255 digits]
Full name, abbreviation and address of the agency where the data are held.

REFERENCE [alpha-numeric; 255 digits]
Reference to publication related to above data and methods. Use short format such as: Author et al. (YYYY); Journal, V(I), X-XX p.

REMARKS [alpha-numeric]
Any important information or comments not included above.

Table 3: Overview of the attribute data provided in the CSV file of the geodetic dataset

GLACIER_ELEVATION_CHANGE_DATA			
Item (short)	**Item (full)**	**Unit**	**Format**
WGMS_ID	WGMS ID	n/a	Integer
SURVEY_ID	SURVEY ID	n/a	Integer
SURVEY_DATE	Survey date	n/a	yyyymmdd
REFERENCE_DATE	Reference date	n/a	yyyymmdd
AREA_SURVEY_YEAR	Area survey year	km^2	Float
AREA_CHANGE	Area change	1000 m^2	Integer
ELEV_CH	Specific thickness change	mm	Integer
ELEV_CH_UNC	Elevation change uncertainty	mm	Integer
INVESTIGATOR	Principal investigator(s)	n/a	txt
SPONS_AGENCY	Sponsoring agency	n/a	txt
REFERENCE	Reference to related publication(s)	n/a	txt
REMARKS	Remarks	n/a	txt

2.4 Data sources

The glaciological method (cf. Cogley et al. 2011), based primarily on ablation stake and snow pit measurements, provides mass-budget estimates that are integrated within glacier-wide averages of mass changes in metres of water equivalent (m w.e.). The glaciological method provides quantitative results at high temporal resolution, which are essential for understanding climate–glacier processes and for allowing the spatial and temporal variability of the glacier mass balance to be captured, even with only a small sample of observation points. It is recommended to periodically validate and calibrate annual glaciological mass-balance series with decadal geodetic balances in order to detect and remove systematic biases.

The geodetic method (cf. Cogley et al. 2011) provides overall glacier volume changes over a longer time period by repeat mapping from ground, air- or spaceborne surveys and subsequent differencing of glacier surface elevations. The geodetic method includes all components of the surface, internal and basal balances and can be used for a comparison with the glaciological (surface-only) mass budgets of the same glacier (Zemp et al. 2013) and for extending the glaciological sample in space and time (Cogley 2009). For the conversion of geodetic results to glaciological mass-balance units (m w.e.), a glacier-wide average density of 850±60 kg m^{-3} is commonly applied (cf. Huss 2013). The results of the glaciological and the geodetic methods provide conventional balances, which incorporate climatic forcing and changes in glacier hypsometry and represent the glacier contribution to runoff (cf. Cogley et al. 2011).

2.5 Data citation requirement

The data are an extract from the WGMS Fluctuations of Glacier (FoG) database, version: https://doi.org/10.5904/wgms-fog-2020-08.

The use of the dataset requires the following citation:
WGMS (2020): Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich, Switzerland. DOI:10.5904/wgms-fog-2020-08.

3. Data access information

The various versions of the FoG database provided to the CDS can be found on the WGMS website (https://wgms.ch/data_databaseversions/) in their original form, and are described in related documentation that is provided in the download package. Shapefiles can be visualised by a range of commercial (e.g. ESRI ArcGIS) and freely available (e.g. QGIS) software packages. A generalised overview on the available datasets is also possible using the GTN-G browser that can be found at https://www.gtn-g.ch/data_browser. For questions regarding the FoG or any other GTN-G dataset, please contact the WGMS staff via wgms@geo.uzh.ch.

References

Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P., Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp (2011): Glossary of Glacier Mass Balance and Related Terms. IHP-VII Technical Documents in Hydrology No. 86, UNESCO-IHP, Paris.

Forel, F.A. (1895): Les variations périodiques des glaciers. Discours préliminaire. Extrait des Archives des Sciences physiques et naturelles XXXIV, p. 209-229.

GCOS (2016): GCOS Implementation Plan 2016. GCOS-200. WMO, Geneva, 315 pp. Available at https://library.wmo.int/opac/doc_num.php?explnum_id=3417

Haeberli, W. (1998): Historical evolution and operational aspects of worldwide glacier monitoring. In: W. Haeberli, M. Hoelzle and S. Suter (eds.): Into the second century of worldwide glacier monitoring: prospects and strategies. Studies and Reports in Hydrology 56, UNESCO–International Hydrological Programme, Paris, 35-51.

Hoelzle M and Trindler M (1998) Data management and application. In: W. Haeberli, M. Hoelzle and S. Suter (eds.): Into the second century of worldwide glacier monitoring: prospects and strategies. Studies and Reports in Hydrology, 56, UNESCO–International Hydrological Programme, Paris, 53-73.

Huss, M. (2013): Density assumptions for converting geodetic glacier volume change to mass change. The Cryosphere, 7(3), 877–887.

Joerg, P. C., & Zemp, M. (2014). Evaluating Volumetric Glacier Change Methods Using Airborne Laser Scanning Data. *Geografiska Annaler: Series A*, 96, 135–145. DOI: 10.1111/geoa.12036

PSFG (1967): Fluctuations of Glaciers 1959-1965 (Vol. I). P. Kasser (ed.), IASH (ICSI) / UNESCO, Permanent Service on Fluctuations on Glaciers, Zurich, Switzerland: 52 pp.

WGMS (1991): Glacier Mass Balance Bulletin No. 1 (1988-1989). W. Haeberli and E. Herren E. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 70 pp.

WGMS (2012): Fluctuations of Glaciers 2005-2010 (Vol. X). Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F. and W. Haeberli (eds.), ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 336 pp. Publication based on database version: doi: 10.5904/wgms-fog-2012-11

WGMS (2013): Glacier Mass Balance Bulletin No. 12 (2010-2011). Zemp, M., Nussbaumer, S.U., Naegeli, K., Gärtner-Roer, I., Paul, F., Hoelzle, M. and Haeberli, W. (eds.), ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland: 106 pp., publication based on database version: doi: 10.5904/wgms-fog-2013-11.

WGMS (2017): Global Glacier Change Bulletin No. 2 (2014-2015). Zemp, M., Nussbaumer, S.U., Gärtner-Roer, I., Huber, J., Machguth, H., Paul, F., and Hoelzle, M. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 244 pp. Based on database version: doi: 10.5904/wgms-fog-2017-10.

Zemp, M. (2012): The monitoring of glaciers at local, mountain, and global scale. Habilitationsschrift zur Erlangung der Venia Legendi, Faculty of Science, University of Zurich, Switzerland: 72 pp & Appendix.

Zemp, M., E. Thibert, M. Huss, D. Stumm, C. Rolstad Denby Nuth, S.U. Nussbaumer, G. Moholdt, A. Mercer, C. Mayer, P.C. Joerg, P. Jansson, B. Hynek, A. Fischer, H. Escher-Vetter, H. Elvehøy and L.M. Andreassen (2013): Reanalysing glacier mass balance measurement series. The Cryosphere, 7, 1227-1245.

Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, et al. (2015). Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology, 61(228), 745–762. http://doi.org/10.3189/2015JoG15J017

Zemp, M. and 14 others (2019): Global glacier mass balances and their contributions to sea-level rise from 1961 to 2016. Nature, 568, 382-386.

Zemp, M., Huss, M., Eckert, N., Thibert, E., Paul, F., Nussbaumer, S.U. and Gärtner-Roer, I. (2020): Brief communication: Ad hoc estimation of glacier contributions to sea-level rise from latest glaciological observations. The Cryosphere, 14, 1043-1050.

Copernicus Climate Change Service

ECMWF - Shinfield Park, Reading RG2 9AX, UK

Contact: info@copernicus-climate.eu

climate.copernicus.eu copernicus.eu ecmwf.int