Earth Syst. Sci. Data, 10, 151–171, 2018
https://doi.org/10.5194/essd-10-151-2018

Open Access Earth System Science Data

The Rofental: a high Alpine research basin (1890–3770 m a.s.l.) in the Ötztal Alps (Austria) with over 150 years of hydrometeorological and glaciological observations

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Received: 3 August 2017 – Discussion started: 21 August 2017
Revised: 26 November 2017 – Accepted: 18 December 2017 – Published: 24 January 2018

Abstract. A comprehensive hydrometeorological and glaciological data set is presented, originating from a multitude of glaciological, meteorological, hydrological and laser scanning recordings at research sites in the Rofental (1891–3772 m a.s.l., Ötztal Alps, Austria). The data sets span a period of 150 years and hence represent a unique time series of rich high-altitude mountain observations. Their collection was originally initiated to support scientific investigation of the glaciers Hintereisferner, Kesselwandferner and Vernagtferner. Annual mass balance, glacier front variation, flow velocities and photographic records of the status of these glaciers were recorded. Later, additional measurements of meteorological and hydrological variables were undertaken, and over time a number of autonomous weather stations and runoff gauges were brought into operation; the available data now comprise records of temperature, relative humidity, short- and longwave radiation, wind speed and direction, air pressure, precipitation, and river water levels. Since 2001, a series of distributed (airborne and terrestrial) laser scans is available, along with associated digital surface models. In 2016 a permanent terrestrial laser scanner was installed on “Im hintern Eis” (3244 m a.s.l.) to continuously observe almost the entire area of Hintereisferner. The data and research undertaken at the sites of investigation in the Rofental area enable combined research of cryospheric, atmospheric and hydrological processes in complex terrain, and support the development of several state-of-the-art glacier mass balance and hydroclimatological models. The institutions taking part in the Rofental research framework promote their site in several international research initiatives. In INARCH (International Network for Alpine Research Catchment Hydrology, http://words.usask.ca/inarch), all original research data sets are now provided to the scientific community according to the Creative Commons Attribution License by means of the PANGAEA repository (https://doi.org/10.1594/PANGAEA.876120).

1 Introduction

Glaciers in the Rofental, Ötztal Alps, have been under observation since the early 17th century; in particular the Vernagtferner (VF) was known for its dangerous surge-type advances (Richter, 1892) with flow velocities up to $11.5\,\mathrm{m\,day^{-1}}$ (Nicolussi, 2013). In 1599, the tongue of VF reached the valley floor of the Rofental, blocking the valley and forming an ice-dammed lake which burst, causing a catastrophic lake outburst flood (GLOF) on 20 July in 1600. The painting of VF with its lake that was formed again in summer 1601 is the oldest known image of a glacier worldwide (Fig. 1). The lake was ∼ 1700 m in length, and the lake level was at ∼ 2260 m a.s.l. (Nicolussi, 1990). Further advances of VF are documented for the periods around 1680, 1770 (the maximum extent of VF in the little ice age, LIA), 1820 and 1848. Prior to the 19th century, each advance of VF formed the ice dam and lake in the Rofental, and the outflow of this lake was observed due to its dangerous nature (Nicolussi, 2013). The glacier changes were monitored with irregular glacier-front variation recordings.

A milestone in glacier cartography was the map "Der Vernagtferner im Jahre 1889 1 : 10 000", constructed by means of terrestrial photogrammetry (Finsterwalder, 1897). This map showed, for the first time, an entire glacier in large scale with unprecedented details, including the area that became ice-free since the last glacier advance period (Fig. 2a). The first map of Hochjochferner (HJF) (1883) by Blümcke and Hess (1895) and Hintereisferner (HEF) (1894) by Blümcke and Hess (1899) followed shortly afterwards (Fig. 2b). After that, geodetic glacier maps were generated frequently for HEF, KWF and VF (Brunner, 2013; Charalampidis, 2018)[1]. These maps were accompanied by frequent terrestrial photographs of VF between 1897 and 1928, documenting, for example, the last surge of the glacier (1897–1903). From these photographs Weber (2013) and Lindmayer (2015) reconstructed the extent and dynamics of VF for the respective periods. The monitoring of the geometry of the glaciers in the Rofental was accompanied by ice drilling experiments to reconstruct the glacier bed and dynamics (Blümcke and Hess, 1899), and first glacier flow theories were developed (Finsterwalder, 1897; Hess, 1904). With the foundation of the "International Commission for Snow and Ice" (ICSI) (as "International Glacier Commission" in Zürich 1894, renamed in 1948) the observation of glaciers became systemized and internationally coordinated, and the continuous observations of meteorological and hydrological variables began: the first totalizing rain gauge in the Rofental was installed in the village of Vent (1900 m a.s.l.) in 1905, followed by continuous measurements further up in the valley since 1952. The "Combined Water, Ice and Heat Balance Project in the Rofental" became an official initiative of the UNESCO International Hydrological Decade (IHD, 1964–1974) (Hoinkes et al., 1974). Later, it was continued as part of the UNESCO International Hydrological Program (IHP) (http://en.unesco.org/themes/water-security/hydrology). Ablation stakes and pits for mass balance monitoring have been continuously maintained at HEF and Kesselwandferner (KWF) (since 1952), at VF (since 1965), and for short discontinuous periods at HJF. As of 2017, the glacier mass balance time series of HEF, VF and KWF are among the longest uninterrupted series worldwide (Fischer et al., 2015; Mayer et al., 2013a), and several automatic weather stations (AWSs) as well as runoff gauges at VF and in the village of Vent are in continuous operation. These are complemented by a network of historical rain gauges (totalizators) and modern precipitation gauges.

The comprehensive pool of long-term observations available for the Rofental provides the basis for (i) manifold process studies on energy balance, ice dynamics, glacier hydrology and hydraulics (e.g., Kuhn et al., 1985a, b; Kuhn, 1987), (ii) new ground-based and remote sensing monitoring methods (Escher-Vetter and Siebers, 2013; Juen et al., 2013; Helfricht et al., 2014a), (iii) model development and application in glaciological and regional hydrological research (Kaser et al., 2010; Escher-Vetter and Oerter, 2013; Schöber et al., 2014, 2016; Hanzer et al., 2016; Schmieder et al., 2016, 2018), (iv) the evaluation of potential future glacier evolution and changes of the hydrological regime in a changing climate (Weber et al., 2009; Marke et al., 2013; Marzeion and Kaser, 2014; Weber and Prasch, 2015a, b; Hanzer et al., 2017), (v) attributing observed glacier changes to different drivers (Painter et al., 2013; Marzeion et al., 2014a, b) and, finally, (vi) as calibration and validation site for estimating the contribution of glaciers to global sea level rise (Marzeion et al., 2012a, b; Marzeion and Levermann, 2014). For VF, a comprehensive collection of 50 years of significant scientific work of the Commission of Glaciology of the Bavarian Academy of Sciences and Humanities has been edited by Braun and Escher-Vetter (2013). Historical elevation and area changes of HEF, KWF and VF are documented in the Austrian glacier inventories, available for 1969, 1997 and 2006 (Abermann et al., 2009): Between 1969 and 1997, the glacier area in the Rofental decreased from 42.9 to $37.7\,\mathrm{km^2}$, corresponding to 12 % (Kuhn et al., 2006); recently, the retreat of the glaciers has accelerated. The key glaciological results for HEF, KWF and VF are reported annually to the World Glacier Monitoring Service (WGMS, http://wgms.ch). The state of HEF and KWF in 2014 is shown in Fig. 3.

In addition to monitoring glacier mass balance with glaciological, geodetical and hydrological methods as well as the long-term recordings of respective variables, the Rofental has been an open laboratory for the development of new method-

[1] HEF: 1850, 1894, 1920, 1939, 1953, 1962, 1964, 1967, 1969, 1979, 1991, 1997, 2001–2008
KWF: 1939, 1967, 1969, 1979, 1991, 1997, 2001–2008
VF: 1846, **1889**, 1897, 1899, 1901, 1904, 1912, 1938, 1954, 1966, 1969, 1972, **1979**, **1982**, **1990**, 1994, **1999**, 2002, 2003, **2006**, 2009 (bold years available at http://geo.badw.de/vernagtferner-digital/karten.html)

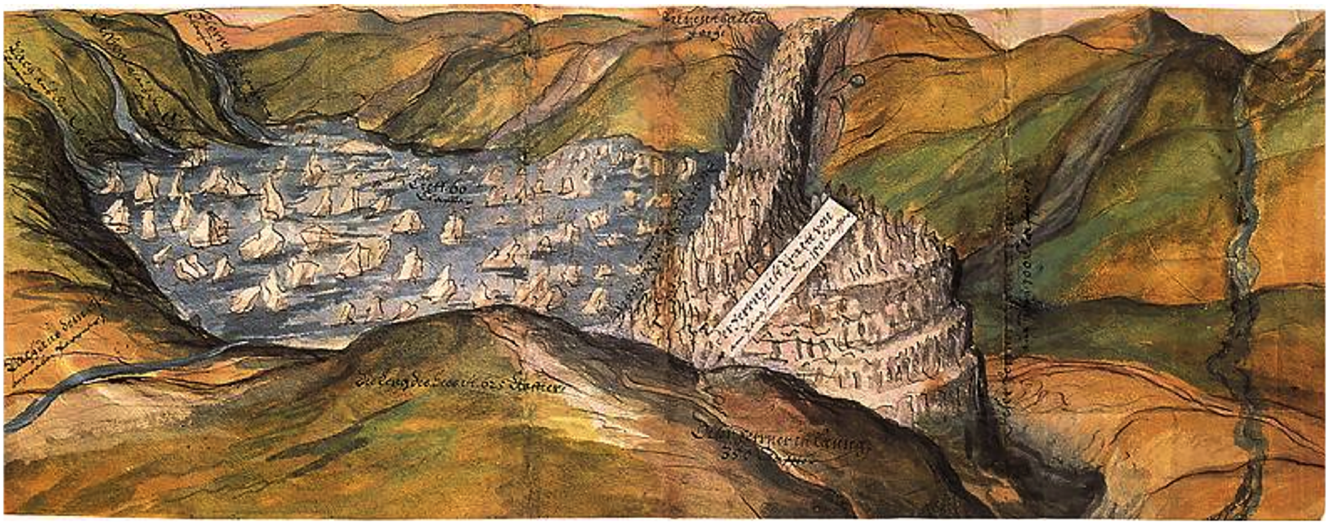

Figure 1. The "Rofentaler Eissee" in 1601, the first known image of a glacier worldwide. Painted in water colors by Abraham Jäger. The original is in the Tiroler Landesmuseum Ferdinandeum in Innsbruck. From Nicolussi (1990).

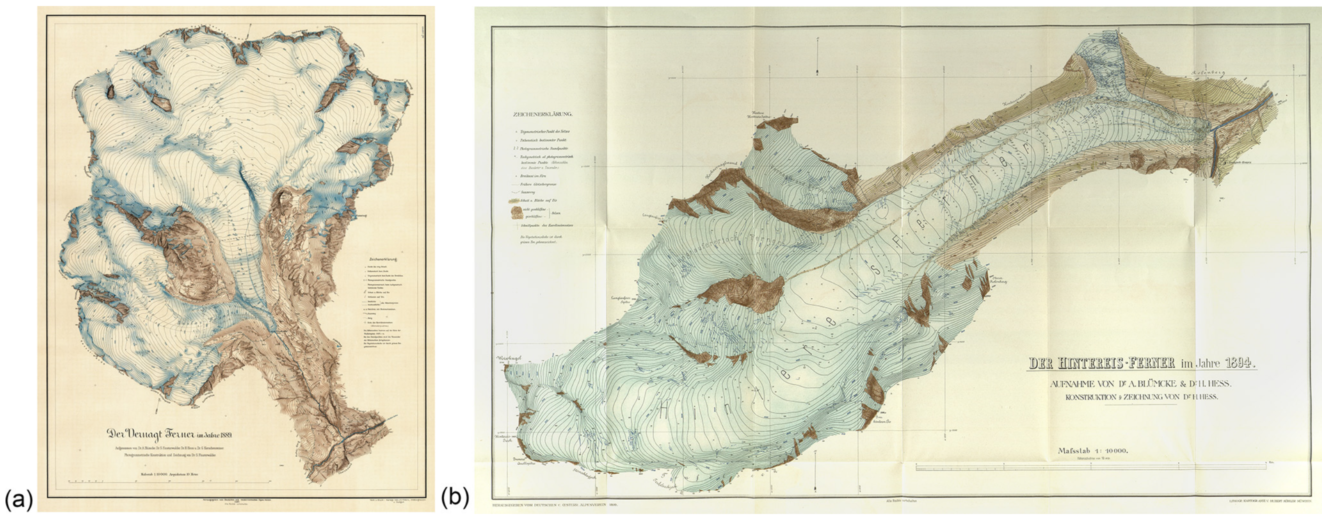

Figure 2. **(a)** The 1889 map of Vernagtferner showing the entire glacier in large scale: "Der Vernagtferner im Jahre 1889 1 : 10 000" (Finsterwalder, 1897). **(b)** "Der Hintereisferner im Jahre 1894" (Blümcke and Hess, 1899).

ologies. For example, a series of airborne lidar-derived high-resolution digital terrain models (DTMs) of HEF and its surroundings has been processed spanning 2001–2011 (Geist and Stötter, 2002; Helfricht et al., 2014b; Klug et al., 2017). They are subject to ongoing evaluations and method comparison studies as well as the monitoring and study of periglacial morphodynamics (Sailer et al., 2012, 2014). Since 2016, a permanent terrestrial laser scanning station is operating at Im hintern Eis (3244 m a.s.l.), allowing for high-resolution, on-demand monitoring of almost the entire surface area of HEF.

All available data for the Rofenal area are placed on a PANGAEA repository (https://doi.org/10.1594/PANGAEA.876120). Recordings of devices which still (as of fall 2017) undergo a test and development phase will be continuously made available in PANGAEA. These data will also be documented as continuation of this publication by means of the ESSD "living data process". The data collection that is already accessible comprises (i) image files, e.g., glacier topography maps, photographs or animations, and diagrams; (ii) raster grids, e.g., spatial data derived from laser scanning, as tab-delimited text files; (iii) time series of point observations, e.g., meteorological and hydrological recordings, as well as calculated results for points or areas such as mass balances, as tab-delimited text files; and (iv) the glacier inventories in ArcGIS shape file format. All data are comprised with the period of coverage, and the exact coordinates of the locations (in latitudes and longitudes). Areas are defined by

Figure 3. State of Hintereisferner (HEF), Kesselwandferner (KWF) and Guslarferner (GF) on 28 September 2014. Aerial photo by Christoph Mayer, view to the south.

latitudes and longitudes of their bounds. The data described in the present publication have been collected by several institutions operationally measuring cryospheric, atmospheric and hydrological variables along with their changes in the framework of their monitoring programs in the Rofental in the Ötztal Alps, Austria. The institutions involved are the University of Innsbruck with the Department of Atmospheric and Cryospheric Sciences (formerly Institute of Meteorology and Geophysics, http://acinn.uibk.ac.at), the Department of Geography (http://uibk.ac.at/geographie), the Bavarian Academy of Sciences and Humanities in Munich (geo.badw.de) and the Hydrographic Service of Tyrol in Innsbruck (http://tirol.gv.at/umwelt/wasser/wasserkreislauf) which is a section of the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW, http://bmlfuw.gv.at).

In this paper, we document the available data from the Rofental area. It is structured in (i) glaciological data, i.e., recordings of glacier volume and geometry changes for HEF, KWF, VF and HJF; (ii) meteorological data as recorded by temporally installed or permanent AWSs; (iii) hydrological data characterizing the water balance of the respective glaciated (sub) catchment; and (iv) airborne and terrestrial laser scanning data. The link to the respective PANGAEA repository parent is https://doi.org/10.1594/PANGAEA.876120. This parent comprises all DOI links to download the data described. Nevertheless, the respective direct DOI links are explicitly referred to here as well.

The selection of data, documented here and available for download from PANGAEA, is only a portion of all the observations that have been collected. Countless documents, photographs, tables and analogue measuring tapes await digitization, and many older digital data still have to be processed and correctly documented. According to the purpose of the INARCH special issue to which this paper belongs we have concentrated our efforts on providing (i) a mostly complete picture of the water balance components of the Rofental – the mass balances of the observed glaciers being an important highlight of these – and (ii) the meteorological data to force a typical hydrological catchment model. Particular attention is paid to the glaciological, meteorological and hydrological processes in the complex Alpine topography and their spatiotemporal variations in the valley.

2 The Rofental – site description

The Rofental (98.1 km^2, Fig. 4) is a glaciated headwater catchment in the central eastern Alps, namely in the upper Ötztal Alps (Tyrol, Austria): as of 2008 approximately one-third of its area is ice-covered (Müller et al., 2009). The valley floor is a narrow discontinuous riparian zone typically less than 100 m in width. The Rofental stretches from 1891 m a.s.l. at the gauge at Vent, the lowest point of the catchment, to 3772 m a.s.l. at the summit of Wildspitze, the highest summit of Tyrol. The average slope is 25° and the average elevation is 2930 m a.s.l.. The Rofenache is a tributary to the Venter Ache, Ötztaler Ache and the Inn and as such contributes to the Danube system (i.e., the Black Sea). The river gauge at Vent (1891 m a.s.l., 46.85694° N, 10.82361° E) has been operated continuously from the Hydrographic Service of Tyrol since 1967. The characteristic water discharges ($m^3\ s^{-1}$, 1971–2013) are NQ = 0.09 (lowest discharge), MQ = 4.6 (mean discharge) and HQ = 109 (highest discharge); further characteristic data are published as annual review in the "Hydrographisches Jahrbuch von Österreich" (e.g., BMLFUW, 2011; available at: http://bmlfuw.gv.at,data-downloadatehyd.gv.at). The runoff regime of the Rofenache has not been modified by any measures of hydropower generation and is dominated by the melt of snow

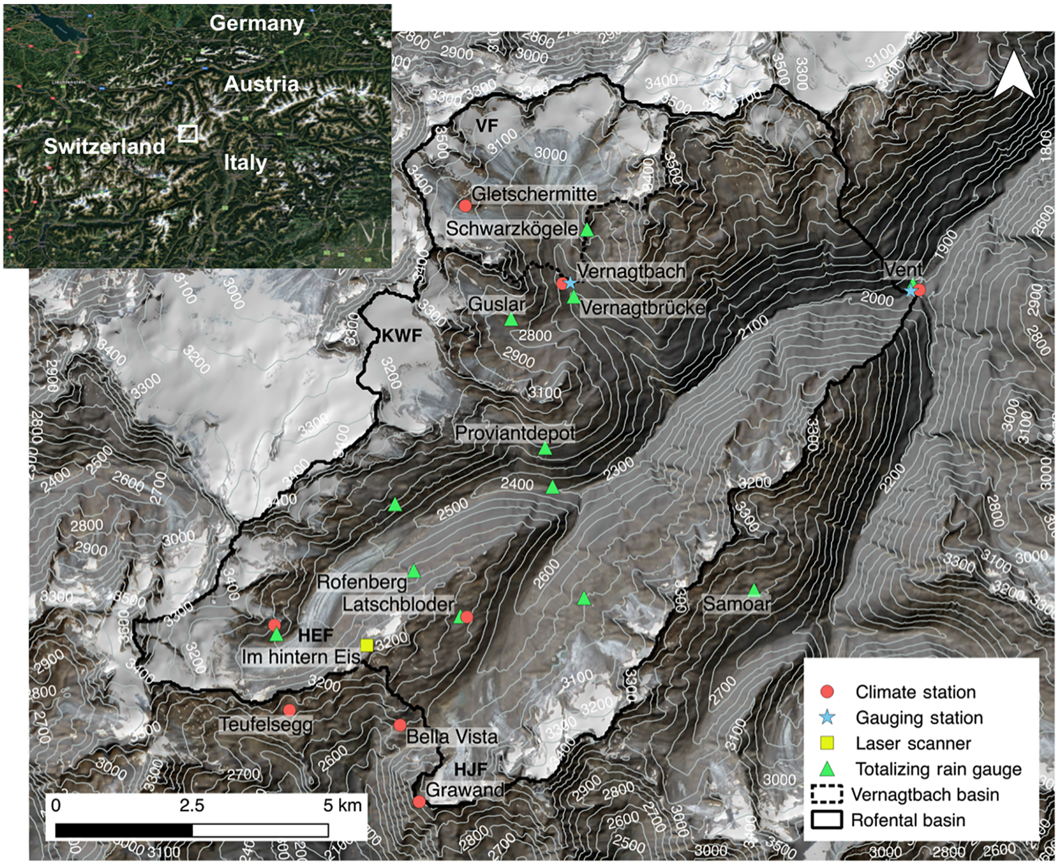

Figure 4. The Rofenache (98.1 km^2) and Vernagtbach (11.44 km^2) catchments with permanent meteorological stations and the runoff gauges. Background satellite image of the top left inset from maps.google.com, copyrights by Google (2009) and TerraMetrics (2017).

and ice during spring and summer, respectively. The early melt-season onset is typically in April. The gauge at Vernagtbach (2635 m a.s.l.) has been operationally maintained by the Bavarian Academy of Sciences and Humanities since 1973 and is the highest streamflow recording site in Austria with measurements also documented at http://ehyd.gv.at (see above) since 2003. The Vernagtbach catchment stretches from 2635 m a.s.l. at the gauge to 3635 m a.s.l. at the summit of Hinterer Brochkogel. According to the glacier inventory of 2006 (https://doi.org/10.1594/PANGAEA.844985), the ice coverage of the Vernagtbach at that time was 71 %. The current rapid decrease of the glaciated area in the Rofental is documented in the WGMS database (http://wgms.ch).

The climate of the Rofental is characterized as an inner Alpine dry type (Fig. 5). The mean annual temperature at the station in Vent (1900 m a.s.l., 46.85833° N, 10.91250° E) is 2.5 °C, and total annual precipitation varies between 797 mm in Vent (1982–2003, Kuhn et al., 2006) and > 1500 mm in the higher altitudes around 3000 m a.s.l., confirmed by the recordings at the various totalisators (see Sect. 3.2.3, Table 4). In these higher regions, seasonal snow cover lasts from October until the end of June. Figure 5 shows temperatures and precipitation of the station at Vent at 1900 m a.s.l. for the period 1969–2006.

The geological bedrock in the Rofental area mainly consists of biotite-plagioclase, biotite and muscovite gneisses, variable mica schists, and gneissic schists of the Austroalpine Ötztal nappe (Kreuss, 2012; Moser, 2012). Subordinate lithologies are quartzites and graphite schists. Granitic gneisses, amphibolites and diabase occur as layers ranging from a few meters to a few hundred meters thick within the metasedimentary sequence. Land cover in the Rofental is dominated by mountain pastures and coniferous forests in the lower areas, but these only cover little of the area (source: "Land Tirol", http://data.tirol.gv.at). Permafrost is likely to occur at north-facing slopes at higher altitudes (Klug et al., 2016).

Infrastructure in the valley is very good for monitoring instrumentation and fieldwork. A research station at HEF (built in 1966 in 3026 m a.s.l.) and one at Vernagtbach (built in 1973 in 2637 m a.s.l.) serve as logistic bases for fieldwork on the two glaciers. Several mountain huts are located in the Rofental, namely the "Vernagthütte/Würzburger Haus" (2755 m a.s.l.), the "Hochjoch-Hospiz" (2413 m a.s.l.), the "Brandenburger Haus" (3277 m a.s.l.) and close by the

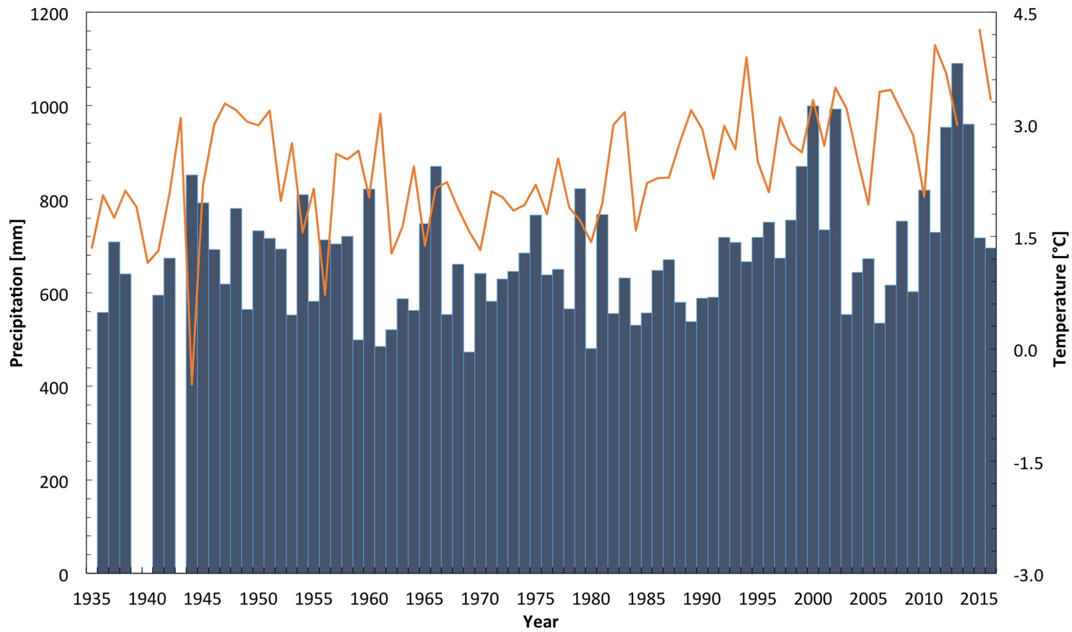

Figure 5. Annual precipitation sums (blue bars) and mean annual temperatures (orange line) 1935–2016 for the valley station "Vent" (1900 m a.s.l.). Data from PANGAEA (1935–2011: https://doi.org/10.1594/PANGAEA.806582 and 2012–2016: https://doi.org/10.1594/PANGAEA.876595).

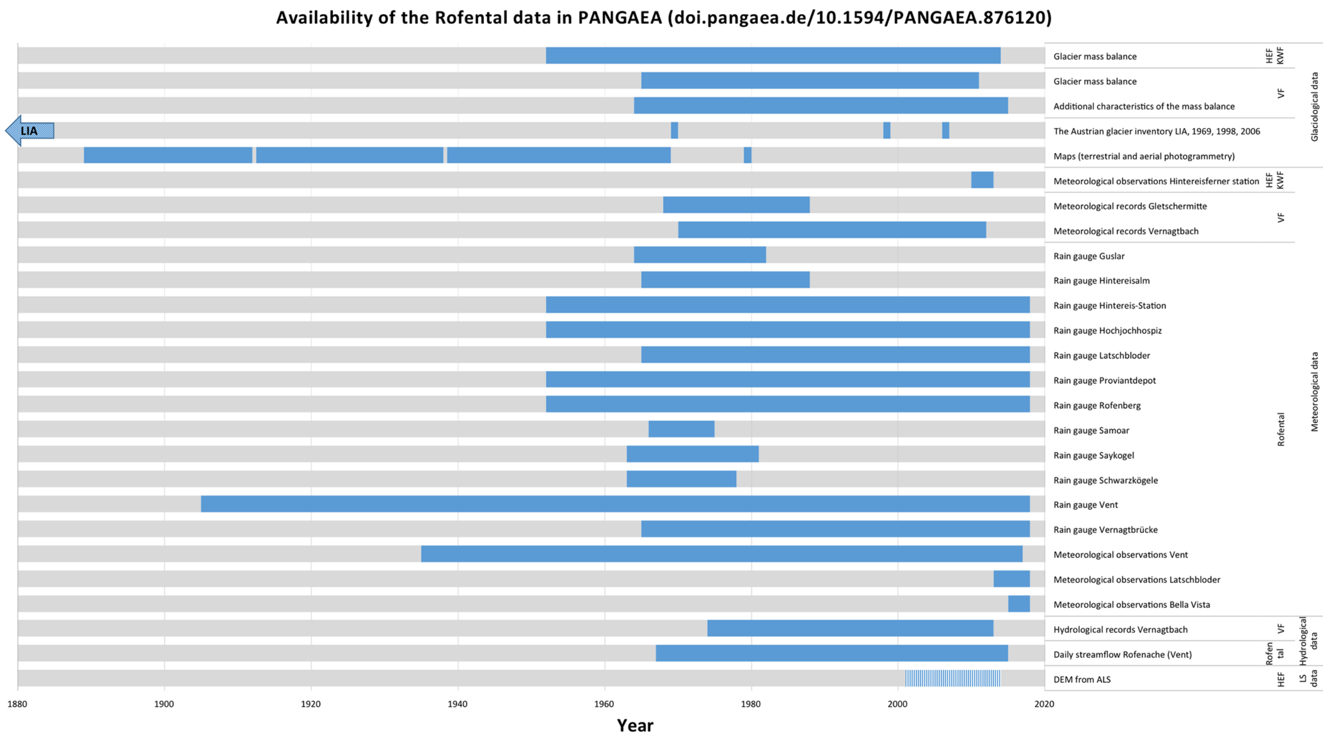

Figure 6. Available data time series for the Rofental in PANGAEA, structured in glaciological data, meteorological data, hydrological data and laser scanning data. LIA = little ice age.

Austrian–Italian borderline at the Hochjoch the "Schöne Aussicht" (also known as "Bella Vista", 2845 m a.s.l.), within the Schnalstal glacier ski resort (http://schnalstal.com/en/glacier). The "Rofenhöfe" (2014 m a.s.l.), the highest permanently settled mountain farm in Austria, is well situated as base camp in the lower valley floor.

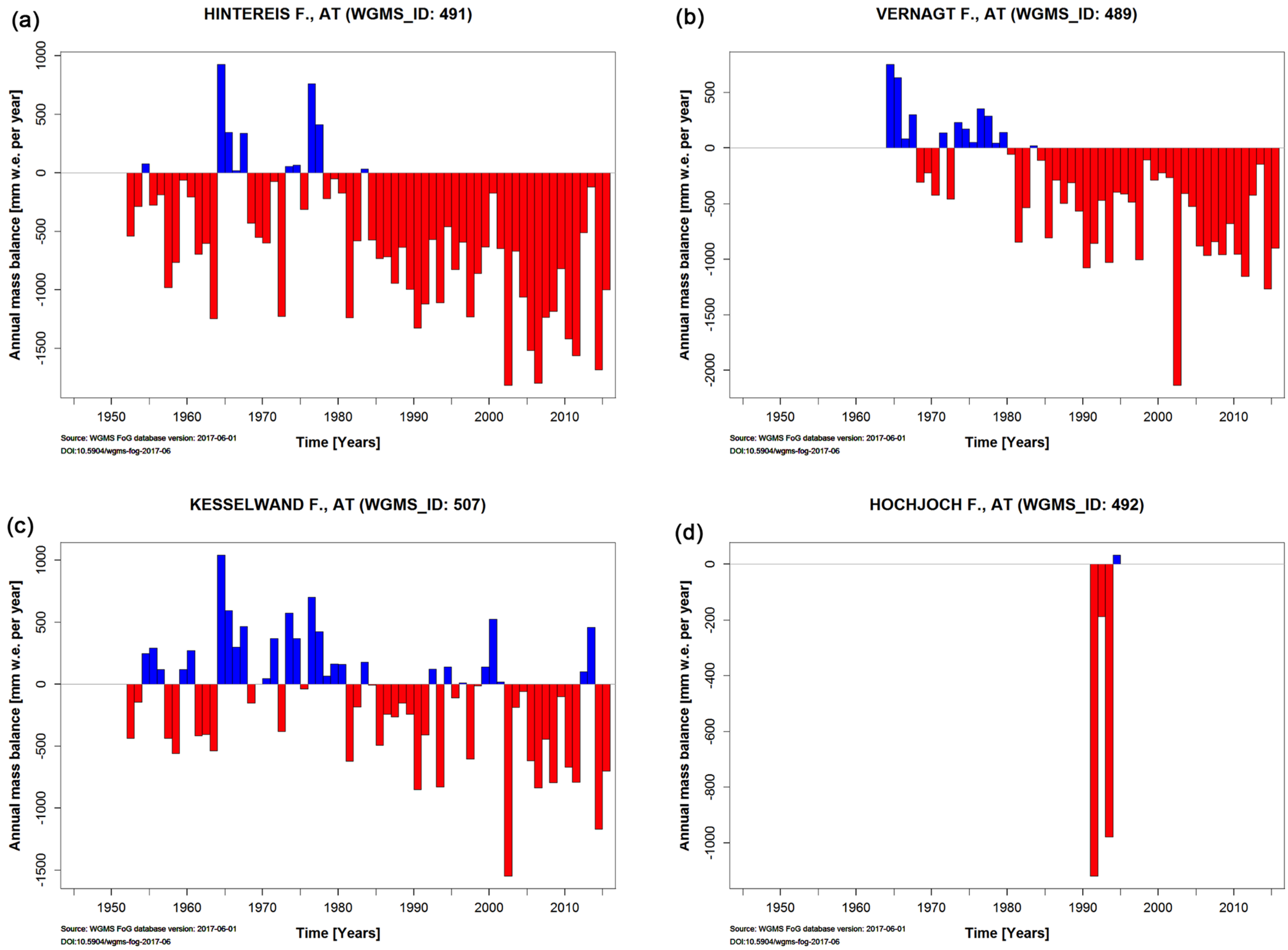

Figure 7. Annual mass balances for Hintereisferner **(a)**, Vernagtferner **(b)**, Kesselwandferner **(c)** and Hochjochferner **(d)** after the glaciological method using stake readings and snow pit data. From WGMS (http://wgms.ch, https://doi.org/10.5904/wgms-fog-2017-06).

3 The data

In the following chapter the Rofental data are presented in the chronological order in which it has been recorded (Fig. 6). First, we describe the long time series of glaciological data (Sect. 3.1). HEF and KWF are monitored by the University of Innsbruck (Austria), whereas VF is monitored by the Bavarian Academy of Sciences and Humanities (Munich, Germany). Next, we describe the meteorological data, again structured by location, i.e., in the order HEF and KWF, VF, and then the valley area (Sect. 3.2). Following that, we describe the hydrological data, firstly in the HEF and KWF catchments, then the VF catchment, and finally, the Rofental as a whole (Sect. 3.3). In the last section (Sect. 3.4), the airborne and terrestrial laser scanning data, which serves glaciological, geomorphological and wider modeling purposes, is described.

3.1 Glaciological data

All glaciers in the Rofental are included in the three Austrian glacier inventories carried out in 1969, 1998 and 2006 (http://glaziologie.at/gletscherinventar.html) and also in the inventory of reconstructed glaciers at the time of the LIA (Kuhn et al., 1999, 2009, 2012; Lambrecht and Kuhn, 2007; Fischer et al., 2015), allowing detailed studies of the deglaciation in the catchments. The parent directory on PANGAEA for the Austrian glacier inventory is https://doi.org/10.5194/tc-9-753-2015, including the LIA maximum (https://doi.org/10.1594/PANGAEA.844987), and the years 1969 (https://doi.org/10.1594/PANGAEA.844983), 1998 (https://doi.org/10.1594/PANGAEA.844984) and 2006 (https://doi.org/10.1594/PANGAEA.844985). Annual reports of the variations of HEF (ID 491, since 1952), KWF (ID 507, since 1966), VF (ID 489, since 1965) and HJF (ID 492, 1991–1995) are provided to the World Glacier Monitoring Service (WGMS; http://wgms.ch) (Fig. 7).

3.1.1 Hintereisferner and Kesselwandferner

Changes in the areas of HEF and KWF have been documented on the basis of maps, aerial photos, and more recently satellite and airborne derived digital elevation models (DEMs) since the early 19th century (Lambrecht and Kuhn, 2007; see also the introduction). The traditional glaciological method of determining glacier-wide mass balance involves spatial extrapolation of local measurements of ablation and accumulation to provide values of the climatic mass balance, encompassing changes at the glacier surface and in the near subsurface (Cogley et al., 2011). Uncertainties in the methods are discussed in Zemp et al. (2013). Since 1952, a network of measurement stakes and pits was continuously maintained at HEF to directly measure the mass balance of the glacier (Hoinkes, 1970). Summer and winter mass balances have been measured separately. Interpretation of the surface mass changes of HEF is supported by the availability of daily images from an automatic camera which views the upper part of the glacier to below the ELA, providing useful information on the distribution of snow cover and the pattern of snow melt over the glacier surface. From 1952–2013 the mass balance of KWF has also been recorded, but with a much smaller number of observations and the assumption that the spatial distribution of the mass balance is analogous to the one of the adjacent HEF. Since summer 2013 a full network of observations is also undertaken and maintained at KWF. The mass balance values of HEF and KWF are available at WGMS (ID 491 and 507, since 1952 and 1966; see Fig. 7) and are also archived in the PANGAEA database (https://doi.org/10.1594/PANGAEA.803830, https://doi.org/10.1594/PANGAEA.803829, https://doi.org/10.1594/PANGAEA.818898 and https://doi.org/0.1594/PANGAEA.818757).

Geodetic determinations of glacier mass balance involve determining the volume change of the whole glacier body, encompassing englacial and basal volume changes. The volume change must then be converted into a mass change which is complicated in the case of a rapidly changing glacier whose surface type can change significantly over the monitoring interval. Apart from the geodetic mass balances on the basis of the glacier inventories, airborne laser scanning images are available for HEF since 2001 (see Sect. 3.4). From these, a time series of geodetic mass balances was derived for 2001–2002 to 2010–2011 (Fig. 8). This method allows for pixel-by-pixel correction of method-inherent discrepancies in the classical glaciological method (Klug et al., 2017).

3.1.2 Vernagtferner

Glaciological mass balance measurements for VF have been available since 1965 (Mayer et al., 2013a). Since the beginning, annual and winter balance was measured separately in order to discriminate ice melt and snow accumulation. The mass balance values are available at WGMS (ID 489, since 1965; see Fig. 7) and are also archived in the PANGAEA database (https://doi.org/10.1594/PANGAEA.853832). The measurements are based on stake readings and snow pits for the annual balance, and snow depth probing and snow pits for the winter balance. The point data are then interpolated on the temporally closest map of the glacier. A summary of the mass balance series for VF is given in Fig. 9. Additional characteristics of the Vernagtferner mass balance for the period 1964–2014 are available at https://doi.org/10.1594/PANGAEA.854639.

In 1976, an automatic analogue camera has been installed on "Schwarzkögele" (3075 m a.s.l., 46.86575° N, 10.83245° E), capturing one picture of VF and its surrounding per day during the ablation period. Since 2010, three digital pictures per day are produced throughout the year (Weber, 2013). A time series of maps is available for VF since 1889, derived from terrestrial and aerial photogrammetry, aerial laser scanning and optical line scanner images; these maps are used to determine area and volume changes of the glacier for longer periods (Table 1 and Mayer et al., 2013b).

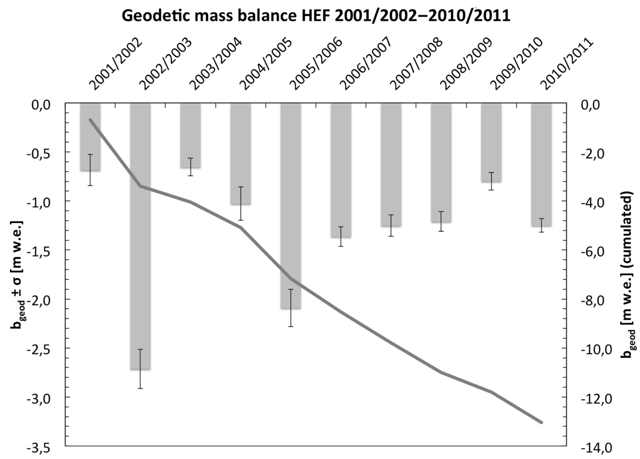

Figure 8. Available geodetic mass balances $b_{\text{geod}} \pm \sigma$ [m w.e.] for Hintereisferner from 2001–2011 and the cumulated balance 2001–2011 (b_{geod} cumulated) as derived from airborne laser scanning measurements (Klug et al., 2017; see also Sect. 3.4).

3.2 Meteorological data

Due to its complex topography, the Rofental is characterized by steep environmental gradients and large spatiotemporal variations of meteorological conditions. An ongoing effort has been undertaken to supplement data available from the lower regions with additional AWS installations in the higher elevations. As of 2017, the Rofental offers a comprehensive pool of valuable observations and model forcing data for mountain catchment hydrology research (Fig. 4; see also the introduction in Sect. 1).

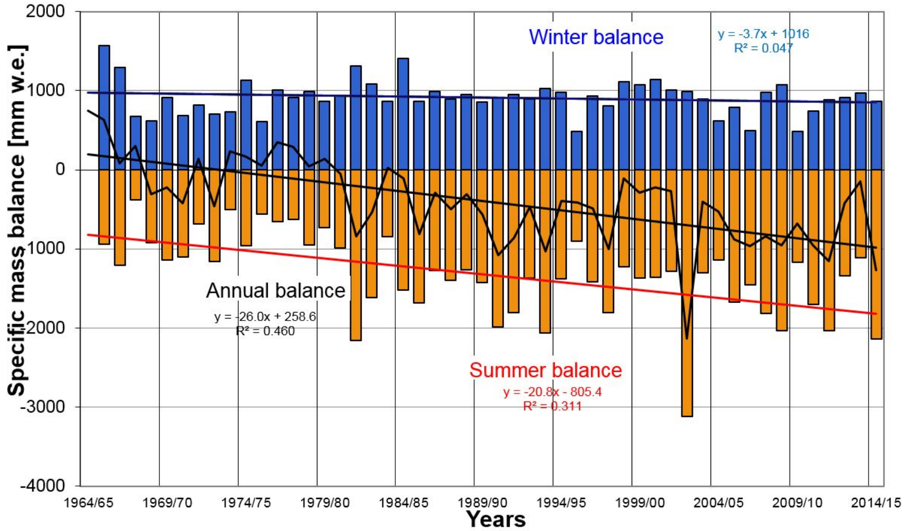

Figure 9. Graphical summary of the seasonal and annual mass balances of Vernagtferner from 1965 until 2014. The vertical bars represent seasonal values and the black line annual values.

Table 1. Available maps of Vernagtferner.

Year	Type	Area (km^2)	Volume change (km^3)	DOI
1889	Terrestrial photogrammetry	11 549		https://doi.org/10.1594/PANGAEA.834873
1912	Terrestrial photogrammetry	11 509	−2.137	https://doi.org/10.1594/PANGAEA.834873
1938	Terrestrial photogrammetry	10 410	−4.382	https://doi.org/10.1594/PANGAEA.834873
1954	–	9474	−4.543	*
1969	Aerial photogrammetry	9466	0.634	https://doi.org/10.1594/PANGAEA.834873
1979	Aerial photogrammetry	9397	1.840	https://doi.org/10.1594/PANGAEA.771301
1990	Aerial photogrammetry	8982	−4.931	*
1999	Aerial photogrammetry	8680	−7.888	*
2003	Aerial photogrammetry	8430	−3.355	*
2006	Optical line scanner	8173	−8.970	*
2009	Optical line scanner	7748	−8.403	*

* Data set will be uploaded to PANGAEA as soon as it is processed, quality checked and documented.

For all stations, the height of the sensors above ground is at least 1.5 m; in winter, the distance between the snow surface and the sensors can become much smaller, and in extreme snow-rich periods the instruments even can become completely snow-covered. Such periods can be recognized in the data by typical recordings of zero wind speed and increasing dampening of the other meteorological variables.

3.2.1 Hintereisferner and Kesselwandferner

The first meteorological observations at HEF and its surrounding began in 1968 and are documented in Kuhn et al. (1979). Short term projects, dedicated to measuring the surface mass balance of snow and ice on the glacier involved temporary installations of AWSs on the glacier (e.g., Siogas, 1977a; Harding et al., 1989; Obleitner, 1994). Since 2010, automatic meteorological measurements have been carried out at station “Hintereisferner” (3026 m a.s.l., 46.79867° N, 10.76042° E) (Fig. 10). The installation as of 2017 is detailed in Table 2.

Since 2014 an AWS has been seasonally operated on the glacier terminus, providing the meteorological data for surface energy balance assessments of the ice surface, complemented by surface height change observations with a sonic ranger.

From summer 2017, the permanent meteorological measurements at Hintereisferner will be complemented by recordings of the sensors on a 6 m high tower that has been equipped for detailed turbulent flux measurements (see Sect. 3.2.3). This new station is situated close to the permanent terrestrial laser scanner on Im hintern Eis (3244 m a.s.l., 46.79586° N, 10.78277° E; see Sect. 3.4.2).

Figure 10. The Hintereisferner AWS and research station in June 2013 (3026 m a.s.l., 46.79867° N, 10.76042° E), view to the northeast. Photo by Christian Wild.

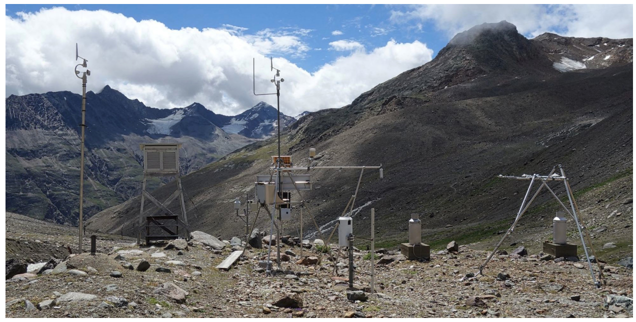

Figure 11. The Vernagtbach AWS in July 2017 (2640 m a.s.l., 46.85663° N, 10.82857° E), view to the southeast. Photo by Ludwig Braun.

For KWF, only the meteorological observations on the glacier from 1958 by Ambach and Hoinkes (1963) are documented.

3.2.2 Vernagtferner

After the start of the glacier monitoring program by the Bavarian Academy of Sciences and Humanities, meteorological observations were initiated at the glacier forefield with the installation of a precipitation gauge in 1970. With the completion of the gauging station "Vernagtbach" (2635 m a.s.l., 46.85675° N, 10.82886° E; see Sect. 3.3.2), additional meteorological parameters have been observed since 1974 at the Vernagtbach climate station close by (2640 m a.s.l., 46.85663° N, 10.82857° E) (https://doi.org/10.1594/PANGAEA.775113). In 1975 hourly measurements of air temperature, relative humidity, air pressure, wind speed and direction were started. The same instruments were installed at the station "Gletschermitte" (3078 m a.s.l.), situated on a rock outcrop in the western part of the glacier at 46.86894° N, 10.80299° E, where hourly meteorological observations were collected during the summer months from 1968 until 1987 (with a varying beginning and end from year to year). The observed parameters were air temperature, relative humidity, wind speed and direction, and precipitation (https://doi.org/10.1594/PANGAEA.832562). Radiation sensors were installed at Vernagtbach in 1976. However, especially during winter, data gaps frequently occurred. The situation was considerably improved by installation of a first digital data logger in 1984. Since then, all-year data records are available from the Vernagtbach station (Escher-Vetter and Siebers, 2013). The meteorological observations were revised in 2002 with the installation of a modern AWS (Fig. 11), and since then all data are automatically transferred to the Bavarian Academy of Sciences and Humanities via GSM and a satellite network. In August 2010, the Hydrographic Service of Tyrol extended the installation with a separate temperature sensor and an unheated Pluvio 2 pluviometer (2630 m a.s.l., 46.85667° N, 10.82861° E). Details about the most recent sensor configurations are given in Table 3.

On "Schwarzkögele" (3075 m a.s.l., 46.86575° N, 10.83245° E), a summit in the vicinity of VF, an autonomous climate station has been in operation since 1976 (Braun et al., 2013). Data recorded there comprise air temperature, relative humidity, global radiation, wind speed and direction as well as precipitation. After digitization these measurements will be made available in PANGAEA. Experiments and special investigations in the catchment of VF are listed in Escher-Vetter and Siebers (2013); since 2003, the meteorological observations have been extended to the ice surface of the glacier itself. Whereas in the first years these data have gaps (mainly in winter), they are mostly continuous since 2011.

3.2.3 Rofental apart from the glaciers

In the Rofental several totalizing rain gauges have are used to collect precipitation data, the first of which was installed in 1905 (see Fig. 6). The totalizing rain gauges are operated by the Department of Atmospheric and Cryospheric Sciences of the University of Innsbruck with financial support by the Hydrographic Service of Tyrol. These totalizing rain gauges provide a valuable picture of the historical evolution and temporal variability of precipitation, and they support the development of precipitation fields derived from interpolation of the recordings (Hoinkes and Steinacker, 1975), which is particularly important for distributed modeling exercises. Evaporation and freezing of the devices is inhibited by annual additions of oil and salt to the gauge reservoir. Readings of totals are undertaken every 2 months in summer with a 4-month break in winter. These totals are then redistributed to monthly values using the recordings of the weighing rain gauge in Vent. Altitude, geographical location and the period

Table 2. Weather and snow variables recorded by the sensors installed at the station Hintereisferner (3026 m a.s.l., 46.79867° N, 10.76042° E) in 2010, 2011 and 2012. Accuracy according to technical data sheets of the manufacturers. Original temporal resolution of the data records is 10 min.

Variable	Sensor	Period of operation	Accuracy	Unit
Air temperature	Vaisala HMP45AC	Since October 2010–present	±0.13 °C	°C
Relative humidity	Vaisala HMP45AC	Since October 2010–present	±2 % RH for 0–90 % RH, ±3 % RH for 90–100 % RH	%
Wind speed and direction	Young Wind Monitor	Since October 2010–present	0.5–1 $m\,s^{-1}$; ±3°	$m\,s^{-1}$ and °
Shortwave and longwave radiative fluxes	Kipp & Zonen CNR 4	Since October 2010–present	±10 % (outgoing) < 10 % (incoming)	$W\,m^{-2}$
Atmospheric pressure	Setra CS 100	Since October 2010–present	±0.1 hPa	hPa
Soil and snow temperature	BetaTherm 100K6A	Since October 2010–present	±0.3 °C	°C
Snow depth	Campbell SR50A	Since October 2010–present	1 cm (or 0.4 % of distance)	cm

Data 2010: https://doi.org/10.1594/PANGAEA.809091; 2011: https://doi.org/10.1594/PANGAEA.809094; 2012: https://doi.org/10.1594/PANGAEA.809095.

Table 3. Sensors and sampling intervals of the AWS Vernagtbach (2640 m a.s.l., 46.85663° N, 10.82857° E)*.

Variable	Sensor	Period of operation	Interval	Unit
Air temperature (ventilated)	Thies PT-100	Since 2002	5 s 10 min^{-1}	°C
Air temperature (unventilated)	PT-100	Since 2002	5 s 10 min^{-1}	°C
Relative humidity	Thies hair hygrometer	Since 2002	20 s 10 min^{-1}	%
Wind speed	Thies cup anemometer	Since 2002	5 s 10 min^{-1}	$m\,s^{-1}$
Wind direction	Thies wind vane	Since 2002	5 s 10 min^{-1}	°
Shortwave downward radiation	Kipp & Zonen CM7B unventilated	Since 2002	5 s 10 min^{-1}	$W\,m^{-2}$
Shortwave upward radiation	Kipp & Zonen CM7B unventilated	Since 2002	5 s 10 min^{-1}	$W\,m^{-2}$
Longwave downward radiation	Schenk Pyradiometer 8111 unventilated	Since 2002 (summer only)	5 s 10 min^{-1}	$W\,m^{-2}$
Longwave upward radiation	Schenk Pyradiometer 8111 unventilated	Since 2002 (summer only)	5 s 10 min^{-1}	$W\,m^{-2}$
Precipitation sum	Belfort weighing gauge	Since 2002	5 s 10 min^{-1}	mm
Precipitation difference	Gertsch tipping bucket, unheated	Since 2002	Sum in 10 min	mm
Air pressure	Druck RPT 410	Since 2002	20 s 10 min^{-1}	hPa
Snow depth	Campbell SR50	Since 2002	120 s 10 min^{-1}	mm

* Further technical details can be found in Escher-Vetter and Siebers (2012). The additional temperature and rainfall recordings of the Hydrographic Service of Tyrol have been separately available since August 2010, visualized online at http://apps.tirol.gv.at/hydro/#/Niederschlag/?station=197075; data upon request.

of operation of these totalizing rain gauges are given in Table 4.

Meteorological observations have been made in close proximity to the village of Vent since 1934 (Lauffer, 1966; Siogas, 1977b). This long-term station provides a valuable reference for shorter series of meteorological observations and also the lower boundary conditions on the likely variation of meteorological variables with elevation across the catchment. Data are available for 1935–2011 at https://doi.org/10.1594/PANGAEA.806582, and for 2012–2016 at https://doi.org/10.1594/PANGAEA.876595. In September 2015 the weather station installation was updated and the position changed by a horizontal displacement of 102 m (new position: 1907 m a.s.l., 46.85745° N, 10.91288° E). The recordings of this station comprise the meteorological variables air temperature, relative humidity, wind speed and direction (since February 2016), and atmospheric pressure (since September 2016; same instruments and specifications as for station Hintereisferner, Table 2). Precipitation is recorded with a heated Ott Pluvio 2 in millimeters per hour with an accuracy of 0.1 $mm\,h^{-1}$.

In the uppermost parts of the Hochjoch valley, two AWSs have been more recently brought into operation: “Latschbloder” (2919 m a.s.l., 46.80106° N, 10.80659° E), installed in September 2013, and Bella Vista (2805 m a.s.l., 46.78284° N, 10.79138° E), installed in June 2015. The data of these two fully automatic stations complement the spatial picture of the meteorological variables in the upper zones of the Rofental. Both stations collect 10 min values of temperature, precipitation (unheated, but also recording by the type of precipitation), wind (mean and maximum speed and direction), relative humidity, radiative fluxes (incoming and outgoing short- and longwave) and air pressure (Table 5). The Latschbloder station is about 25 m from the totalizing rain gauge at the same site (see Table 4). Three continuous years of consistent records are available for 2014,

Table 4. Totalizing rain gauges in the Rofental.

Station	Altitude (m a.s.l.)	Lat. (° N)	Long. (° E)	Period of operation	DOI
Vent	1900	46.85766	10.91127	1905–present	https://doi.org/10.1594/PANGAEA.876532
Hochjochhospiz	2360	46.82310	10.82616	1952–present	https://doi.org/10.1594/PANGAEA.876525
Vernagtbrücke	2600	46.85461	10.82979	1965–present	https://doi.org/10.1594/PANGAEA.876533
Proviantdepot	2737	46.82951	10.82407	1952–present	https://doi.org/10.1594/PANGAEA.876527
Rofenberg	2827	46.80847	10.79344	1952–present	https://doi.org/10.1594/PANGAEA.876528
Latschbloder	2910	46.80118	10.80561	1965–present	https://doi.org/10.1594/PANGAEA.876526
Hintereis station	2964	46.79727	10.76096	1952–present	https://doi.org/10.1594/PANGAEA.876523
Saykogel	2990	46.80491	10.83459	1963–1980	https://doi.org/10.1594/PANGAEA.876529
Schwarzkögele	3075	46.86575	10.83245	1963–March 1977	https://doi.org/10.1594/PANGAEA.876531
Guslar	2920	46.85060	10.81489	October 1964–September 1981	https://doi.org/10.1594/PANGAEA.876522
Samoar	2650	46.80708	10.87539	1966–1974	https://doi.org/10.1594/PANGAEA.876530
Hintereisalm	2900	46.81941	10.78842	1965–September 1987	https://doi.org/10.1594/PANGAEA.876524

2015 and 2016 (mean annual temperature −1.3, −1.5 and −2.2 °C (WXT520), and annual precipitation: 1590, 1311 and 1118 mm (Pluvio 2 unheated)).

The weather station at Bella Vista includes a heated Ott Pluvio 2, supplied with main power from the "Schöne Aussicht-Hütte" approximately 90 m away. This site also includes fuller snow instrumentation (Table 6) to measure: snow water equivalent (by means of a snow pillow), snow depth (by means of an ultrasonic ranger) and snow temperature profile (by means of a series of temperature sensors at different height levels). These snow sensors are still undergoing technical examination and development, and as yet no check for consistency has been undertaken (e.g., by using the data as input in a snow model as in Morin et al., 2012). In 2016, mean annual temperature at the station was −0.4 °C, and annual precipitation was 1605 mm. The Bella Vista weather and snow monitoring station is one of the highest of its kind in the Alps. During summer 2017 an automatic camera that has the station in its field of view has been installed (Fig. 12).

In summer 2017, a 6 m high tower close to the permanent terrestrial laser scanner on Im hintern Eis (3244 m a.s.l., 46.79586° N, 10.78277° E; see Sect. 3.4.2) was equipped for detailed turbulent flux measurements with the following sensors: three Lufft Ventus 2-D Sonic wind sensors at 1.5, 3 and 6 m altitude; two ventilated Rotronic HC2-S3 temperature–humidity sensors at 3 and 6 m altitude; a Campbell SR50 AH heated ultrasonic snow depth sensor in 1.5 m altitude; a Campbell Krypton hygrometer at 3 m altitude (only for specific campaigns); a Kipp & Zonen CNR4 net radiometer at 1.5 m altitude; a Metek USA-1 3-D sonic turbulence sensor at 3 m altitude; and a Setra 278 barometric pressure sensor in the logger box. The data of these sensors will be made available in PANGAEA as soon as first tests have proven the installation to be reliable, and a time series of at least a year of data is available.

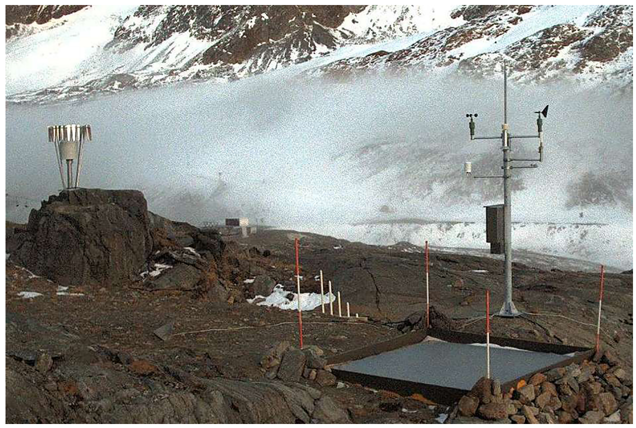

Figure 12. Webcam picture of the Bella Vista weather station (2805 m a.s.l., 46.78284° N, 10.79138° E), view to the East. Left: Ott Pluvio 2 with wind shelter. Center: temperature profiler. Right: snow pillow (foreground) and mast with sensors (background) for wind speed and direction, snow height, temperature/humidity and radiative fluxes. The most recent picture is available at http://alpinehydroclimatology.net.

Three additional AWSs are located south of the Rofental, in the Italian Schnalstal: "Teufelsegg" (3035 m a.s.l., 46.7847° N, 10.7647° E) close to the accumulation area of HEF, "Grawand" (3220 m a.s.l., 46.7703° N, 10.7966° E) in the Schnalstal glacier ski resort and "Vernagt" (1950 m a.s.l., 46.7357° N, 10.8493° E) close to the village and the lake with the same name. These stations are maintained by the Hydrographic Office of the Civil Protection Agency of the Autonomous Province of Bolzano – South Tyrol. Their data are available at http://daten.buergernetz.bz.it/de/dataset/misure-meteo-e-idrografiche.

Table 5. Climate and snow variables recorded by the sensors installed at the station Latschbloder (2919 m a.s.l., 46.80106° N, 10.80659° E). Accuracy according to technical data sheets of the manufacturers. Original temporal resolution of the data records is 10 min.

Variable	Sensor	Period of operation	Resolution and accuracy	Unit
Air temperature	Vaisala WXT520	Since September 2013	0.1 °C ± 0.3 °C	°C
Relative humidity	Vaisala WXT520	Since September 2013	0.1 % ± 3 % RH for 0–90 % RH, 0.1 % ± 5 % RH for 90–100 % RH	%
Wind speed and direction	Vaisala WXT520	Since September 2013	0.1 $m\,s^{-1}$ ± 3 % (speed) 1° ± 3 % for 10 $m\,s^{-1}$ (direction)	$m\,s^{-1}$ and °
Radiative fluxes (short- and longwave)	Kipp & Zonen CNR 4	Since September 2013	10–20 $W\,m^{-2}$ (incoming) 5–15 $W\,m^{-2}$ (outgoing)	$W\,m^{-2}$
Precipitation	Vaisala WXT520 Friedmann tipping bucket Ott Pluvio 2 v. 200 with wind shelter	Since September 2013 September 2013 to June 2014 Since July 2014	0.01 $mm\,h^{-1}$ ± 5 %* (not yet known) 0.01 $mm\,h^{-1}$ ± 1 %	mm
Atmospheric pressure	Vaisala WXT520	Since September 2013	0.1 hPa ± 0.5 hPa for 0–30 °C 0.1 hPa ± 1.0 hPa for −52–60 °C	hPa

* for hailstorm: 0.1 hit cm^{-2}. The Vaisala WXT520 records rain and hail as well as their durations and intensities, but cannot recognize snowfall.
Data 2013: https://doi.org/10.1594/PANGAEA.879215; 2014: https://doi.org/10.1594/PANGAEA.879216; 2015: https://doi.org/10.1594/PANGAEA.879217; 2016: https://doi.org/10.1594/PANGAEA.879218; 2017: https://doi.org/10.1594/PANGAEA.879219.

Table 6. Weather and snow variables recorded by the sensors installed at the station Bella Vista (2805 m a.s.l., 46.78284° N, 10.79138° E). Accuracy according to technical data sheets of the manufacturers. Original temporal resolution of the data records is 10 min.

Variable	Sensor	Period of operation	Resolution and accuracy	Unit
Air temperature	E+E EE08 Vaisala WXT520	Since July, 2015	< 0.5 °C[1] 0.1 °C ± 0.3 °C	°C
Relative humidity	E+E EE08 Vaisala WXT520	Since July, 2015	±2 % RH for 0–90 % RH, ±3 % RH for 90–100 % RH 0.1 % ± 3 % RH for 0–90 % RH, 0.1 % ± 5 % RH for 90–100 % RH	%
Wind speed and direction	Vaisala WXT520 Kroneis 262	Since July 2015	0.1 $m\,s^{-1}$ ± 3 % (speed) 1° ± 3 % for 10 $m\,s^{-1}$ (direction)	$m\,s^{-1}$ and °
Radiative fluxes	Kipp & Zonen CNR 4	Since July 2015	10–20 $W\,m^{-2}$ (incoming) 5–15 $W\,m^{-2}$ (outgoing)	$W\,m^{-2}$
Precipitation	Vaisala WXT520 Ott Pluvio 2 v. 200 with wind shelter	Since July 2015 Since July, 2015	0.01 $mm\,h^{-1}$ ± 5 %[2] 0.01 $mm\,h^{-1}$ ± 1 %	mm
Atmospheric pressure	Vaisala WXT520	Since July, 2015	0.1 hPa ± 0.5 hPa for 0–30 °C 0.1 hPa ± 1.0 hPa for −52–60 °C	hPa
Snow water equivalent	Sommer snow pillow 3 × 3	(still experimental)[3]	(still experimental)	mm
Snow depth	Sommer USH-8	(still experimental)[3]	1 mm ± 0.1 %	mm
Snow temperature	Pilz temperature profiler	(still experimental)[3]	(still experimental)	°C

[1] depending on air temperature; see technical data sheet of the manufacturer. [2] for hailstorm: 0.1 hit cm^{-2}. The Vaisala WXT520 records rain and hail as well as their durations and intensities, but cannot recognize snowfall. [3] data not yet downloadable from PANGAEA. Data 2015: https://doi.org/10.1594/PANGAEA.879210; 2016: https://doi.org/10.1594/PANGAEA.879211; 2017: https://doi.org/10.1594/PANGAEA.879212.

3.3 Hydrological data

3.3.1 Hintereisferner and Kesselwandferner catchment

During the International Geophysical years 1957 to 1959 a gauging station was in operation at "Steg Hospiz" (2287 m a.s.l.), registering the combined streamflow from HEF and KWF (Lang, 1966). The measurements of this campaign are described here as an example for the many short- and longer-term monitoring activities carried out in the Rofental. The Steg Hospiz catchment is 26.6 km^2 in size, with a fraction of 58 % being covered by the glaciers at that time. Mean annual recorded streamflow for the catchment area amounted to 1848 mm (1957–1958) and 1770 mm (1958–1959), respectively (millimeters are equivalent to liters per square meter per year). Winter runoff (October through March) only was 5 and 10 % of the annual amount, whereas the three summer months (July through September) provided 76 and 72 %. Highest mean monthly streamflow amounts were registered in August 1958 (575 mm) and July 1959 (559 mm). The frequency distribution of daily streamflow for 1957–1958 shows a period of daily low flows of less than 0.5 $m^3 s^{-1}$ (18.8 $L s^{-1} km^{-2}$) for 217 days (October through May). Higher daily streamflow $> 6.0\, m^3 s^{-1}$ (225 $L s^{-1} km^{-2}$) only occurred during July and August. The observed maximum daily streamflow was 16.9 $m^3 s^{-1}$. The glacier contribution, determined as the fraction of (observed) negative mass balance to recorded streamflow, was relatively high in this period: 24 and 20 % of annual streamflow, respectively. The exponential decrease of the hydrograph in fall to the minimum in spring suggests that the winter streamflow mainly originates as delayed meltwater of the previous season from the glaciers. The increase in the water flows after the beginning of the snow melt period occurs with a certain time delay – due to the refreezing of meltwater, and its retention in the snow cover (Lang, 1966).

As of 2017, neither HEF nor KWF are equipped with a permanently registering discharge gauge; this is projected for future initiatives.

3.3.2 Vernagtferner catchment

The VF catchment is one of the very few glacierized catchments where simultaneous measurements of glacier mass balance and discharge exist for several decades since 1974 (Escher-Vetter and Reinwarth, 2013). Discharge is measured at the gauge Vernagtbach (46.85675° N, 10.82886° E), which at 2635 m a.s.l. is the highest streamflow gauge in Austria (Fig. 13). The water level is continuously monitored in the gauge since 1974, and water-level-to-discharge calibrations are regularly conducted by the salt injection method. The water level is simultaneously determined by three sonic rangers distributed across the runoff channel in order to detect the 2-D surface geometry of the water flow, and surface velocity is monitored by a Doppler system. The total catchment area covers 11.44 km^2, 7.3 km^2 of which was glacierized in 2015 (63.8 %). The vertical extent ranges from 2635 m a.s.l. at the gauge to 3635 m a.s.l. at the summit of "Hinterer Brochkogel" (see also Fig. 4). The discharge values are available as 5 min values for 2002 to 2012 (https://doi.org/10.1594/PANGAEA.829530). Hourly hydrological records for the Vernagtbach catchment are available for the period 1974 to 2001 at https://doi.org/10.1594/PANGAEA.775113. Monthly averages of discharge are available at https://doi.org/10.1594/PANGAEA.832432, and yearly values are available for the period 1974 to 2012 at https://doi.org/10.1594/PANGAEA.832429.

Figure 13. The Vernagtbach gauging station in 2006 (2635 m a.s.l., 46.85675° N, 10.82886° E), view to the northwest. Photo by Ludwig Braun.

3.3.3 Rofental catchment

Streamflow in the Rofental catchment is recorded at the gauge "Vent–Rofenache" (1891 m a.s.l., 46.85722° N, 10.91083° E, 98.1 km^2) at the outlet of the catchment (https://doi.org/10.1594/PANGAEA.876119). Vent–Rofenache is one of the highest operational observation sites of the Hydrographic Service of Tyrol, providing a continuous time series of streamflow and sediment transport recordings since 1967 and 1999, respectively. The regime is dominated by snow melt and ice melt with a significant maximum in July and August (Fig. 14); the glaciated area has decreased from 44 % (in 1969) to 38 % (in 2009; Müller et al., 2009) and is expected to drop to almost zero during the course of the 21st century, due to the rapidly changing climatic conditions (Hanzer et al., 2017). The coexistence of the Vernagtbach gauge in the VF head watershed allows for combined hydrological investigations. Episodical recordings at smaller tributaries of the Rofenache were obtained during the spring snow melt season in 2014 (Schmieder et al., 2016), and during the glacier melt season in 2016 (Schmieder et al., 2018).

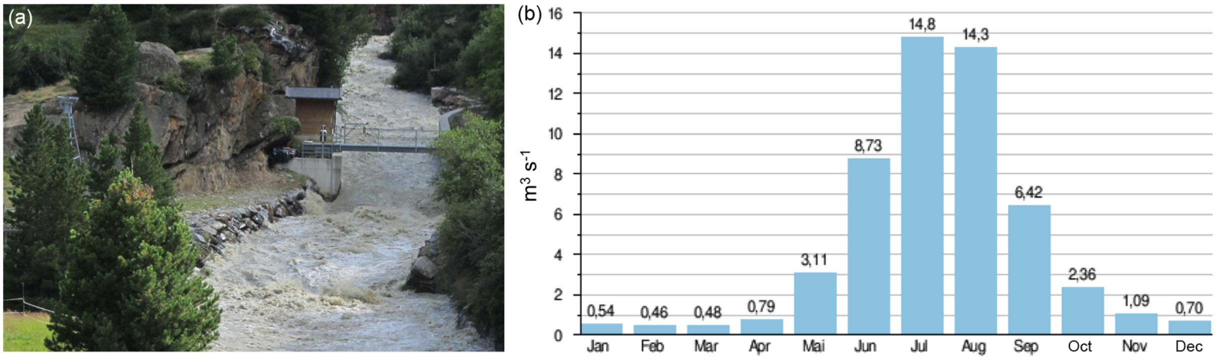

Figure 14. The rainfall totalisator and the gauge at Vent (1891 m a.s.l., 46.85722° N, 10.91083° E) (**a**; Photo: Hydrographic Service of the Tyrol), and mean monthly streamflow of the Rofenache 1971–2009 **(b)**. Data from the Hydrographisches Jahrbuch (BMLFUW 2011).

3.4 Laser scanning data

Laser scanning is an active remote sensing technique which uses a laser beam to acquire 3-D point data, representing the surface and objects on that surface in high spatial resolution. In addition to high accuracy and resolution, additional information on the spectral properties intensity and reflectance of the scanned surface in the wavelength of the specific scanner is recorded. The DTMs derived from laser scanning measurements are becoming increasingly important for glaciological and geomorphological studies. DTM differencing is an important method for detection and quantification of surface changes and mass budget calculations (Sailer et al., 2014; Klug et al., 2017). Airborne laser scanning (ALS) and terrestrial laser scanning (TLS) are the most common methods for lidar data collection (Telling et al., 2017). The Rofental has been an intensive experimental site for both types of laser scanning data processing and analysis.

3.4.1 Airborne laser scans

ALS is well-suited for remote mountain areas, because no external light source is required and, due to overlapping flight strips, the entire surface is captured, even in very steep terrain (Höfle and Rutzinger, 2011). The vertical accuracy is in the order of 0.05 to 0.20 m, mainly dependent on the slope angle (Beraldin et al., 2010; Bollmann et al., 2011). Low vertical errors of 0.05 m were observed in the HEF catchment for areas with slope angle $< 40°$ by comparison of an ALS-derived DTM with dGNSS (differential global navigation satellite system) measurements. For the areas with slope angle $> 40°$, an exponential increase of the vertical error was observed (1.0 m for 80°, Bollmann et al., 2011; Geist et al., 2005; Sailer et al., 2012).

The HEF data set is built from 21 separate ALS acquisitions from 2001 to 2013, covering an area of 32 km^2, including HEF (approx. 6.8 km^2 in 2011), KWF (approx. 3.8 km^2 in 2011), "Langtaufererjochferner" (approx. 1.1 km^2 in 2011) and "Stationsferner" (approx. 0.3 km^2 in 2011). DEMs of 1×1 m were generated by calculating the z value (altitude) from the mean z value inside the respective grid cell by excluding 5 % of the smallest and largest observations of the ALS points. For the provision of the GeoTIFF (UTM32N) raster files the high-resolution DEMs were resampled to DEMs with a cell size of 10×10 m, applying bilinear interpolation. The resulting DEMs are available at https://doi.org/10.1594/PANGAEA.875889.

The available ALS measurements for HEF were used to study the volume changes of the glacier complementary to direct glaciological surface mass balance measurements. At least one scan was performed at the end of every glacier mass balance year (end of September). From these, a time series of geodetic mass balances was derived for 2001–2002 to 2010–2011 (see Fig. 8). In 2001–2002, 2002–2003, 2007–2008, 2008–2009 and 2010–2011 additional project-based intermediate campaigns were carried out. An overview of the data (UTM32N, WGS84) including the technical details is given in Table 7. Klug et al. (2017) corrected the surface models as well as glacier mass balance data by considering method-inherent uncertainties originating from snow cover, survey dates and density assumptions to calculate corrected annual geodetic mass balances. The most negative balance year is 2002–2003, with a mean specific mass balance of -2.713 ± 0.20 m water equivalent (w.e.). In the subsequent mass balance year 2003–2004, the smallest mass loss is observed (mean specific mass balance -0.654 ± 0.09 m w.e.). For the entire observation period (2001 to 2011) a mean mass balance of -1.3 m w.e. was calculated with the HEF ALS data set (Klug et al., 2017).

With the same ALS data sets as described in Table 7, Helfricht et al. (2014b) investigated the spatial snow distribution and its interannual persistence for a partly glacierized mountain area including HEF and KWF (~ 36 km^2).

Table 7. Overview of the available HEF ALS data with flight date, used Optech sensor, mean flight height above ground (m), maximum scanning angle (°), pulse repetition rate (Hz), across-track overlap (%), mean point density (points m^{-2}) and vertical accuracy (m). Data are available at https://doi.org/10.1594/PANGAEA.875889.

Flight date	Optech Sensor	Mean height above ground (m)	Maximum scanning angle (°)	Pulse repetition rate (Hz)	Across-track overlap (%)	Mean point density (points m^{-2})	Vertical accuracy (m)
11 Oct 2001	ALTM 1225	900	20	25 000	24	1.1	0.11
9 Jan 2002	ALTM 1225	900	20	25 000	24	1.2	0.14
7 May 2002	ALTM 1225	900	20	25 000	24	1.2	0.14
15 Jun 2002	ALTM 1225	900	20	25 000	24	1.3	0.14
8 Jul 2002	ALTM 1225	900	20	25 000	24	1.4	0.15
19 Aug 2002	ALTM 1225	900	20	25 000	24	1.4	0.10
18 Sep 2002	ALTM 3033	900	20	33 000	24	1.0	0.10
4 May 2003	ALTM 2050	1150	20	50 000	40	0.8	0.10
12 Aug 2003	ALTM 2050	1150	20	50 000	40	0.8	0.10
26 Sep 2003	ALTM 1225	900	20	25 000	24	1.0	0.06
5 Oct 2004	ALTM 2050	1000	20	50 000	24	2.0	0.07
12 Oct 2005	ALTM 3100	1000	22	70 000	50–70	3.4	0.07
8 Oct 2006	ALTM 3100	1000	20	70 000	37–75	2.0	0.08
11 Oct 2007	ALTM 3100	1000	20	70 000	37–75	3.4	0.06
9 Sep 2008	ALTM 3100	1000	20	70 000	40-45	2.2	0.06
7 May 2009	ALTM 3100	–	–	–	–	–	–
30 Sep 2009	ALTM 3100	1100	20	70 000	31–66	2.7	0.05
8 Oct 2010	ALTM Gemini	1000	25	70 000	62	3.6	0.03
4 Oct 2011	ALTM 3100	1100	20	70 000	25–75	2.9	0.04
11 May 2012	ALTM 3100	1200	20	70 000	31–66	2.8	0.06
3 Sep 2013	ALTM Gemini	1200	20	70 000	59–80	4.2	0.04

3.4.2 Terrestrial laser scans – the permanent laser scanner on Im hintern Eis

The utility of TLS in performing high-resolution glacier observations was tested for HJF from 2013–2015 when both glaciological and geodetic mass balances were measured. Likewise, a Riegl VZ-6000 TLS was used to produce surface models within 0.1 m of coincident high-accuracy ALS data for approx. 80 % of the surface of HJF. The TLS surface models are of higher spatial resolution and surface details than the ALS. The TLS data were used – along with coincident optical imagery from the onboard camera – to produce high-resolution surface classifications to map snow-cover extent, and to explore the spatial patterns of the surface mass balance of HJF (Prantl et al., 2017).

In 2016, a permanent TLS was installed in a climate controlled container at 3244 m a.s.l. close to the summit Im hintern Eis (46.79586° N, 10.78277° E). The 3-D laser scanner VZ-6000 (manufactured by RIEGL Laser Measurement Systems GmbH) offers a long measurement range of more than 6000 m and operates with beam divergence of 0.12 mrad at a wavelength of 1050 nm, particularly suited for snow- and ice-related applications. The device operates with an angular step width of 0.01° for a field of view of 60° vertically and 120° horizontally and a laser pulse repetition rate of 30 kHz, equivalent to an effective measurement rate of 23 000 measurements s^{-1}, leading to a point density of approx. 10 pts m^{-2} for a distance of 1000 m, and to approx. 1 to 2 pts m^{-2} for the remote areas at a distance of > 3500 m. Hence, the instrument is ideal for static topographic applications such as monitoring of glaciological and geomorphological processes in high mountain terrain. Due to the large field of view, nearly the entire HEF catchment area can be covered by the instrument (Fig. 15); only a very small part of the terminus and small flat areas in the upper glacier zones cannot be sampled. The TLS surface point cloud is accompanied by high-quality optical imagery (5 megapixel). This installation not only allows high temporal and spatial resolution glacier volume changes for HEF to be determined; in addition, the high spatial resolution supports the monitoring of surface features such as crevasses, evolving surface roughness, the supraglacial drainage network and geomorphodynamically induced surface changes (e.g., debris flows) or snow avalanches. Seven scans have been carried out during the test phase (September 2016 to April 2017).

4 Data availability

The data sets presented here are available freely from PANGAEA (https://doi.org/10.1594/PANGAEA.876120). The data from the Rofental have been widely used for process studies and all kinds of method and model development ac-

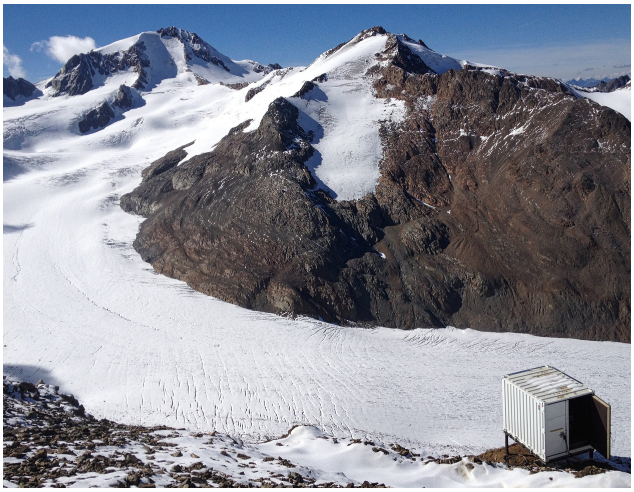

Figure 15. The terrestrial laser scanner in its container housing at Im hintern Eis (3244 m a.s.l., 46.79586° N, 10.78277° E). View to the west over the upper areas of Hintereisferner to the summit of Weisskugel (3739 m a.s.l.) and Langtauferer Spitze (3529 m a.s.l.). Photo by Rudolf Sailer.

tivities. These data sets, however, represent only a small fraction of what has been observed and collected during the past few decades. Many measurements have been conducted during special field campaigns and are not yet documented for online data publication. For example, hydrological investigations have been conducted in the valley of the Hochjochbach, including streamflow observations with pressure sensors and tracer experiments since 2014 (Schmieder et al., 2016, 2018). Other data await digitization and processing. Originally published in analogue printwork, these data include 3 years of hourly ice temperatures from HEF (Markl and Wagner, 1978), observations of sublimation of ice and snow at HEF (Kaser, 1982, 1983), firn investigations at KWF (Ambach et al., 1978), remote sensing experiments and many energy balance investigations at HEF (Jaffé, 1958, 1960; Hoinkes and Untersteiner, 1952; Hoinkes, 1953a, b; Ambach and Hoinkes, 1963; Wendler, 1967; Kuhn et al., 1979, Wagner, 1979, 1980), and many others. For VF, the situation is similar; a comprehensive overview of the research work has been published by Braun and Escher-Vetter (2013), including various descriptions and documentations of the used data, methods and models. Older long-term field experiments at VF are described in Moser et al. (1986). Runoff data of the gauge "Vent" have been widely used in hydrological studies, the most recent ones including Schmieder et al. (2016) and Hanzer et al. (2016, 2017). On a regional scale, the Rofental data contributed to modeling exercises for future scenario climatic conditions and their effect on simulated streamflow discharge (Marke et al., 2011, 2013). The Hydrographic Service of Tyrol visualizes its data online at apps.tirol.gv.at/hydro, and provides their download at http://ehyd.gv.at. As of 2017, data of the sites Latschbloder and Schöne Aussicht are used in several ongoing research projects (listed at http://alpinehydroclimatology.net), and also provide valuable experimental material for application in various student courses.

Several initiatives are also ongoing at the international research network level. Apart from its long history within UNESCO IHP (http://en.unesco.org/themes/water-security/hydrology), the Rofental recently became a research basin in the framework of the GEWEX INARCH project (http://words.usask.ca/inarch). It is a research catchment of the ERB Euro-Mediterranean Network of Experimental and Representative Basins (http://erb-network.simdif.com), and a regular complex site in the LTSER platform Tyrolean Alps (http://lter-austria.at/ta-tyrolean-alps), which belongs to the national and international long term ecological research network (LTER Austria, LTER Europe and ILTER). Hintereisferner station is part of the EU Horizon 2020 INTERACT framework of Arctic (and a few Alpine) research stations (https://eu-interact.org/field-sites/station-hintereis/).

The efforts to provide the Rofental data to the scientific community will continue in all of the currently involved institutions.

5 Conclusions and outlook

The Rofental in the Ötztal Alps (Austria) is a unique, high Alpine research basin (98.1 km^2, 1890–3770 m a.s.l.) with available time series of 150 years of glaciological and hydrometeorological observations. The glaciers in the Rofental attracted early attention and were – for centuries – observed due to the dangerous nature of frequently occurring glacier lake outburst floods. Over the last 100 years, the glacier monitoring has been accompanied by systematic recordings of meteorological and hydrological variables. Today, a glaciological and hydrometeorological data set is available for the Rofental that is without comparison worldwide, with regard to both its amount and temporal coverage. The Rofental data sets support manifold investigations in the context of coupled climate and glacier evolution, snow and glacier hydrology, water resources availability in mountainous regions, or method development like laser scanning or modeling. The scales of such research range from local, like particular micrometeorological assessments at a single observation site, to global, e.g., the estimation of the glacier contribution to sea level rise. This paper gives an overview of what has been measured and what is available already. All the data described are comprehensively documented and made freely available according to the Creative Commons Attribution License by means of the PANGAEA repository (https://doi.org/10.1594/PANGAEA.876120).

This paper covers availability of data as of fall 2017. There are still many manual and analogue historical recordings which are being digitized, processed and documented. After completion they will be made available via PANGAEA and will add to the extension of the records back in time (left side of the bars in Fig. 6). New and future data will continue to further build on the available Rofental database (right side of the bars in Fig. 6). This process of continuous enlargement of the data described here is ensured by the living data process as conceived by the journal.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Hydrometeorological data from mountain and alpine research catchments". It is not associated with a conference.

Acknowledgements. Many of the instruments and the monitoring activities presented here have been supported by the institutions to which the authors are affiliated to, and by countless research programs. These have been funded by the Bavarian Academy of Sciences and Humanities (BAdW), the Deutsche Forschungsgemeinschaft (DFG), the Austrian Academy of Sciences (ÖAW; project HydroGeM^3), the European Region Tyrol – South Tyrol – Trentino (project CRYOMON-SciPro – IPN 10-N33), the Autonomous Province of Bolzano – South Tyrol (project hiSnow – 23/40.3), the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW, section IV/4-water cycle), and others. The laser data acquisition and processing has been funded by the European Union (project OMEGA – EVK2-CT-2000-00069), the Austrian Research Promotion Agency FFG ASAP (Austrian Space Applications Programme; projects ALS-X – 815527 and SE.MAP – 840109), the Austrian Research Promotion Agency FFG COMET (Competence Centers for Excellent Technologies) in cooperation with the alpS GmbH (project MUSICALS – 826388), the Austrian Climate Research Programme (ACRP; project C4AUSTRIA – A963633), the Tyrolean Science Foundation (TWF) and the Department of Geography, University of Innsbruck.

All these funding institutions provide the support to continue our efforts in the monitoring of the water balance and climate elements of the Rofental in the long term. The authors gratefully acknowledge all the contributions and support from their countless colleagues in maintaining the instruments in the field, being so many that they cannot be listed here by name. Without their engagement, the long-term monitoring in the Rofental would never have been possible.

Edited by: Danny Marks
Reviewed by: Stefan Pohl, Samuel Morin, Patrick Kormos, and Adam Winstral

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