Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-85
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 August 2017

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

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Abstract. A comprehensive hydrometeorological and glaciological data set is presented, originating from a multitude of recordings at several intensively operated research sites in the Rofental (1891 – 3772 m a.s.l., Ötztal Alps, Austria). The data sets are spanning a period of 150 years and hence represent a unique, worldwide unprecedented pool of high mountain observations. Their collection has originally been initiated to support the scientific investigation of the glaciers Hintereis-, Kesselwand- and Vernagtferner. Later, additional measurements of meteorological and hydrological variables have been undertaken; data now comprise records of temperature, relative humidity, short- and longwave radiation, wind speed and direction, air pressure, precipitation and water levels. For the glaciers, annual mass balance, glacier front variation and flow velocities as well as photographic images of the glacier status have been recorded. Since 2001, a series of distributed (airborne and terrestrial) laserscans has been processed. Most recently, a permanent terrestrial laser scanner installed on "Im hintern Eis" (3244 m a.s.l.) enables to continuously observe almost the entire area of Hintereisferner. The data and research undertaken at the sites of investigation enable combined research of atmospheric, cryospheric and hydrological processes in complex terrain, and support the development of several state-of-the art hydroclimatological and glacier mass balance models. The institutions taking part in the Rofental research framework have joined to a cooperation consortium and promote their site in several international research initiatives. In the framework of 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).

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1. Introduction

In the Rofental, several institutions presently are operationally monitoring atmospheric, cryospheric and hydrological variables along with their changes with particular attention to the related processes in the complex topography and climate setting of the high Alpine environment: as research institutions the University of Innsbruck with the Institute of Atmospheric and Cryospheric Sciences (the former Institute of Meteorology and Geophysics, http://acinn.uibk.ac.at) and the Institute of Geography (https://www.uibk.ac.at/geographie/index.html.en) as well as the Bavarian Academy of Sciences in Munich (http://geo.badw.de/das-projekt.html), and as a public administration institution the Hydrographic Service of Tyrol in Innsbruck (https://www.tirol.gv.at/umwelt/wasser/wasserkreislauf), a section of the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW, https://www.bmlfuw.gv.at/english).

First documents from glaciers in the Rofental date back as far as 1601 (Nicolussi 1993), and regular observations and systematic studies began more than 150 years ago. Geodetic maps were generated since the late 19th century, and the first rain gauges were installed in 1929. The glacier mass balance time series of Hintereis-, Vernagt- and Kesselwandferner (HEF, VF and KWF further on) are among the longest uninterrupted series worldwide. Ablation stakes and pits for mass balance monitoring are maintained at HEF, VF and KWF, and – less regularly – at Hochjochferner (HJF further on). Today, runoff gauges at VF and in Vent as well as several automatic weather stations (AWSs) are in continuous operation in the Rofental, complemented by a network of rain gauges (totalisators). The “Combined Water, Ice and Heat Balance Project in the Rofental” became a core of the UNESCO International Hydrological Decade (IHD 1964–1974) (Hoinkes et al. 1974), as such prolonging into the successive UNESCO International Hydrological Program (IHP) (http://en.unesco.org/themes/water-security/hydrology).

The glaciers in the Rofental provided 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, Schmieder et al. 2016, 2017, Hanzer et al. 2016), (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/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 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, respectively (Abermann et al. 2009): e.g., between 1969 and 1997, the glacier area in the Rofental has decreased from 42.9 km^2 to 37.7 km^2, corresponding to 12 % (Kuhn et al. 2006); after that, the retreat of the glaciers even accelerated. The state of HEF and KWF in 2014 is shown in Fig. 1.

Figure 1: State of Hintereisferner (background/left), Kesselwandferner (center/right) and Guslarferner (foreground/right) in 2014 (Sep 28). Aerial photo by Christoph Mayer, view to the South.

A series of airborne LIDAR-derived high resolution digital terrain models (DTMs) of HEF and its surroundings has been processed since 2001 (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 for monitoring and studying periglacial morphodynamics (Sailer et al. 2012, 2014). Since 2016, a permanent terrestrial laser scanning station is operating "Im hintern Eis" (3244 m a.s.l.), allowing for high resolution and on-demand monitoring of almost the entire area of HEF; a nearby 6 m high tower is presently (summer 2017) equipped for detailed turbulent flux measurements. Key glaciological results are annually reported to the World Glacier Monitoring Service (WGMS, www.wgms.ch), and all available data is placed on the PANGAEA repository (https://doi.org/10.1594/PANGAEA.876120). A research station at HEF (built in 1966 in 3026 m a.s.l., with member status in the Horizon 2020 INTERACT network, http://www.eu-interact.org) and one at Vernagtbach (built in 1973 in 2637 m a.s.l.) serve as logistic bases for fieldwork. Several mountain huts are located in the Rofental, namely the "Vernagthütte" (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 Austrian-Italian borderline at the Hochjoch the "Schöne Aussicht" ("Bella Vista", 2845 m a.s.l.), within the Schnalstal glacier ski resort (http://www.schnalstal.com/en/glacier.html). The "Rofenhöfe" (2014 m a.s.l.) in the lower valley floor are the highest permanently settled mountain farm in Austria.

2. The Rofental – site description

The Rofental (98.1 km^2, Fig. 2) is a glaciated headwater catchment in the central eastern Alps, namely in the upper Ötztal Alps (Tyrol, Austria): approximately 1/3 of its area still is ice-covered (Müller et al. 2009). In the valley floor, a narrow discontinuous riparian zone is formed with 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 gauge at Vent (1891 m a.s.l., 46.85694° N, 10.82361° E) is in continuous operation by the Hydrographic Service of Tyrol since 1967. The characteristic water discharges (in m^3 s^{-1}, 1971–2013) are NQ=0.09, MQ=4.6 and HQ=109. The runoff regime of the Rofenache is dominated by the melt of snow and ice during spring and summer, respectively. The early melt season onset typically is in April. Up to date (summer 2017), the streamflow of the Rofenache is not modified by any measures of hydropower generation. The gauge at Vernagtbach (2635 m a.s.l.), operationally maintained by the Bavarian Academy of Sciences since 1973, is the highest streamflow recording site in Austria with measurements being officially documented in the “Hydrographisches Jahrbuch von Österreich” since 2003 (BMLFUW 2011, http://ehyd.gv.at). The Vernagtbach catchment still is approximately 2/3 ice-covered.

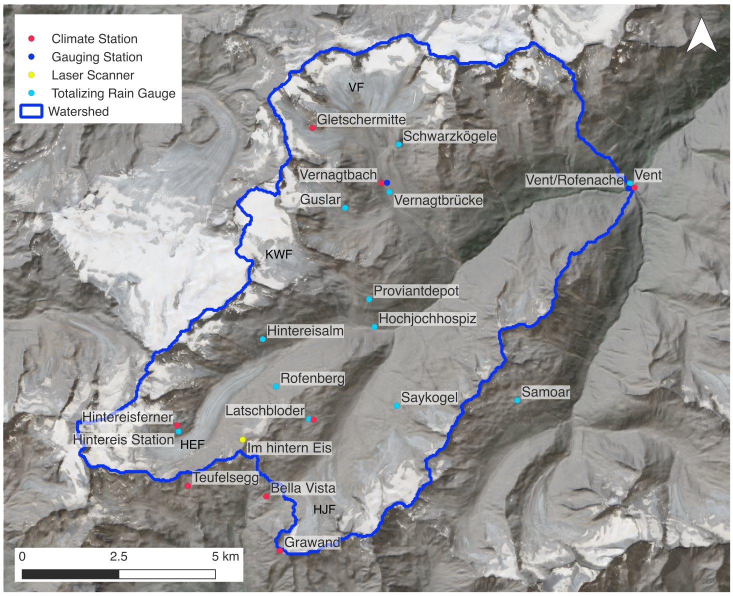

Figure 2: The Rofental catchment with permanent meteorological stations and the runoff gauges at Rofenache and Vernagtbach. The climate station “Vernagt” of the Hydrographic Office of the Civil Protection Agency of the Autonomous Province of Bolzano - South Tyrol is located slighly South of the lower map boundaries.

The climate of the Rofental is of the inner Alpine dry type (Fig. 3). The mean annual temperature at the station in Vent (1900 m a.s.l.) 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 3.1.3, Table 3). In these higher regions, the seasonal snow cover lasts from October until the end of June. Fig. 3 shows temperatures and precipitation of the valley station in Vent at 1900 m a.s.l. for the period 1969–2006.

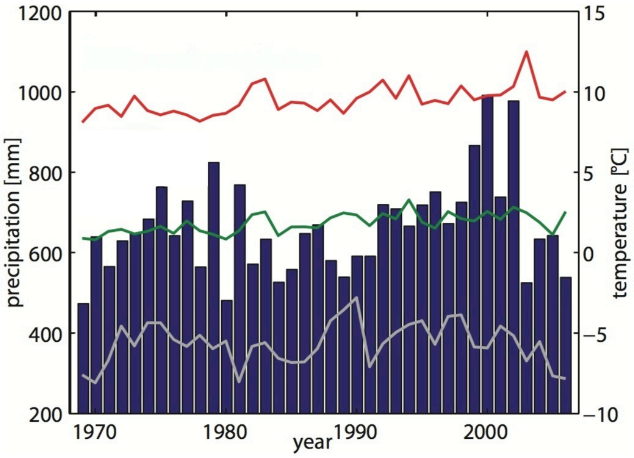

Figure 3: Annual precipitation sums (blue bars) and temperature evolutions: winter (DJF grey), mean (green) and summer (JJA: red) for 1969–2006, valley station "Vent" (1900 m a.s.l.). Modified after Abermann et al. (2009).

Landuse in the Rofental is dominated by grassland, 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 the North-facing slopes in the higher altitudes (Klug et al. 2016). The geological bedrock in the Rofental area mainly consists of biotite-plagioclase, biotite and muscovite gneisses, variable mica schists as well as 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 meter- to a few hundred meter thick layers within the metasedimentary sequence. The Rofenache is a tributary to the Venter Ache, Ötztaler Ache and the Inn and as such contributing to the Danube system (i.e., the black sea).

3. The data

In the following, the data collected in the Rofental area is documented, structured in (i) meteorological data as recorded by temporally installed or permanent AWSs, (ii) glaciological data, i.e. recordings of glacier volume and geometry changes for HEF, KWF, VF and HJF, (iii) hydrological data characterizing the water balance of the respective glaciated (sub-)

catchment, (iv) airborne and terrestrial laser scanning data, and (v) other data, i.e. mainly the Austrian glacier inventories (Abermann et al. 2009). The link to the respective PANGAEA repository parent is https://doi.org/10.1594/PANGAEA.876120. This parent comprises many separate doi links to download the data described. Where appropriate, the respective direct doi link is referred to here explicitely.

The selection of data documented here and downloadable from PANGAEA is only a small portion of the giant wealth of observations that has been collected by the involved research institutions during the past 150 years. Countless documents, photographs, tables, and analogue measuring tapes still await their digitization, and many digital data still have to be processed and correctly documented, but we will continue to make the material available in PANGAEA step by step. For the present publication only a small exemplary collection of this data is described and made available online. We have thereby concentrated our efforts to provide (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. Information about any data that is still being processed and not yet available in PANGAEA can be obtained from the authors.

3.1 Meteorological data

Due to its complex topography, the Rofental is characterized by steep environmental gradients and high spatio-temporal variations of the meteorological conditions over short distances in both space and time (e.g. shortwave radiation, wind speed). An ongoing effort has been undertaken over the years to supplement the available data from the lower regions by recordings of additional AWS in the higher elevations. The Rofental is now an enormous pool of valuable observations and model forcing data for mountain catchment hydrology research.

3.1.1 Hintereis- and Kesselwandferner

Meteorological measurements have been carried out at Station "Hintereisferner" (3026 m a.s.l., 46.79867° N, 10.76042° E) since 2010. Before, short term projects were dedicated to measure the surface mass balance of snow and ice on the glacier (e.g. Obleitner 1994, Harding et al. 1989, Siogas 1977a). The present day installation is detailed in Table 1. In summer 2017, the station is subject to general overhaul and upgrade with a permanently registering pluviometer. In addition to the automatic recordings, 2014 to 2016 several AWSs have been seasonally operated on the glacier terminus providing the meteorological data for a full surface energy balance assessment of the ice surface, and also monitoring surface height changes with a sonic ranger.

In summer 2017 a permanent terrestrial laser scanner has been installed at "Im hintern Eis" (3244 m a.s.l.) high over the interfluve between the east and west parts of the upper Rofental (46.79586° N, 10.78277° E, see chapter 3.4.2). The small container hut hosting the laser scanner instrument will be further equipped with sensors on a 6 m high tower to allow near surface boundary layer processes to be investigated. It is foreseen to install a METEK 3D ultrasonic anemometer, a

Campbell Krypton hygrometer, a Kipp & Zonen net radiometer, a Campbell ultrasonic snow depth sensor, and – in a vertical profile arrangement – 3 Lufft Ventus 2D ultrasonic anemometers as well as 2 Rotronic temperature/humidity sensors.

Table 1: Weather and snow variables recorded by the sensors installed at the station "Hintereisferner" (3026 m a.s.l., 46.79867° N, 10.76042° 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	Accuracy	Unit
Air temperature	Vaisala HMP45AC	Since Oct 2010 – present	± 0.13° C	° C
Relative humidity	Vaisala HMP45AC	Since Oct 2010 – present	± 2 % RH for 0–90 % RH, ± 3 % RH for 90–100 % RH	%
Wind speed and direction	Young Wind Monitor	Since Oct 2010 – present	0.5–1 m s^{-1}; ± 3°	M s^{-1} and °
Shortwave and longwave radiative fluxes	Kipp & Zonen CNR 4	Since Oct 2010 – present	± 10 % (outgoing) < 10 % (incoming)	W m^{-2}
Atmospheric pressure	Setra CS 100	Since Oct 2010 – present	± 0.1 hPa	hPa
Soil and snow temperature	BetaTherm 100K6A	Since Oct 2010 – present	± 0.3° C	° C
Snow depth	Campbell SR50A	Since Oct 2010 – present	1 cm (or 0.4 % of distance)	cm

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

3.1.2 Vernagtferner

The first continuous meteorological observations in the VF basin were collected at the station "Gletschermitte" (3078 m a.s.l.) during the summer months 1968 until 1987. It was situated on a rock outcrop in the western part of the glacier at 46.86894° N, 10.80299° E. The observed parameters were wind speed and direction, air temperature, humidity and precipitation. Over the major part of the period, the same instruments were used as at the "Vernagtbach" climate station (2640 m a.s.l., 46.85663° N, 10.82857° E), installed in 1974. Soon after the start of the glacier monitoring program by the Bavarian Academy of Sciences, meteorological observations were initiated at the glacier fore field with the installation of a Fueß precipitation gauge in 1970. Additional meteorological parameters are observed since 1974, after the completion of the gauging station "Vernagtbach" close by (2635 m a.s.l., 46.85675° N, 10.82886° E, see 3.3.2). At that time, continuous air temperature and air humidity measurements were started and complemented by air pressure, wind speed and direction sensors in 1975. The installation of radiation measurements followed in the years 1976 and 1979. During this period, data gaps frequently occurred, especially during winter. 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 until now (Escher-Vetter and Siebers, 2013). The meteorological observations were revised in 2002 with the installation of a modern AWS. Today, all data are automatically transferred to the Bavarian Academy of Sciences via GSM and 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 2.

Table 2: Sensors and sampling intervals of the AWS "Vernagtbach" (2640 m a.s.l., 46.85663° N, 10.82857° E)[1].

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

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

On "Schwarzkögele" (3075 m a.s.l., 46.86575° N, 10.83245° E), a summit in the vicinity of VF, an autonomous climate station is in operation since 1976 (Braun et al. 2013). Data recorded there comprises air temperature, relative humidity, global radiation, wind speed and direction as well as precipitation. These measurements are currently digitized and will soon be made available in PANGAEA. Experiments and special investigations in the catchment of VF are listed in Escher-Vetter and Siebers (2013); recently, continuous meteorological observations have been extended to the ice surface of the glacier itself.

3.1.3 Rofental apart from the glaciers

In the Rofental several totalizing rain gauges have been measuring two-monthly in the summer months with a four months break in winter, starting with the first one in 1905. These rain gauges are operated by the University of Innsbruck (Institute of Atmospheric and Cryospheric Sciences) with financial support by the Hydrographic Service of Tyrol. These totalizing rain gauges are capable to provide a valuable picture of the historical evolution and temporal variability of precipitation, and they support the spatial densification of the precipitation fields derived from interpolation of the AWS recordings (Hoinkes and Steinacker 1975) which is particularly important for distributed modelling exercises. Evaporation and freezing of the rain gauge is inhibited by annual additions of oil and salt to the gauge container; for that purpose, the instruments are visited and serviced during field campaigns every year. Altitude and geographical location of these totalizing rain gauges are given in Table 3.

Table 3: Totalizing rain gauges in the Rofental.

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

In close proximity to the village of Vent (1890 m a.s.l., 46.85833° N, 10.91250° E) meteorological observations have been made since 1934 (Lauffer 1966, Siogas 1977b). This long-term station provides a valuable context for shorter series of meteorological observations and also the lower boundary conditions on the likely variation of meteorological variables with elevations across the catchment. In September 2015 the weather station installation was updated and the position slightly changed (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 1). Precipitation is recorded with a heated Ott Pluvio 2 in mmh^{-1} with an accuracy of 0.1 mmh^{-1}.

In the valley of the Hochjochbach, two new automatic weather stations have been 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. Even though the former is solely powered by solar energy, it is in continuous operation since its installation, collecting 10-minute values of temperature, precipitation (unheated, but also recording by the type of precipitation), wind (mean/maximum speed and direction), relative humidity, radiative fluxes (incoming and outgoing short- and longwave) and air pressure (Table 4). The "Latschbloder" station is about 25 m beside the totalizing rain gauge North of the small lake (see Table 3). For "Latschbloder" three continuous years of consistent records are already available, namely for 2014, 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).

Table 4: 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 Sep, 2013	0.1° C ± 0.3° C	° C
Relative humidity	Vaisala WXT520	Since Sep, 2013	0.1 % ± 3 % RH for 0–90 % RH, 0.1 % ± 5 % RH for 90–100 % RH	%
Wind speed and direction	Vaisala WXT520	Since Sep, 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 Sep, 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 Sep, 2013 Sep 2013 to June 2014 Since July 2014	0.01 mm h^{-1} ± 5 %[1] (not yet known) 0.01 mm h^{-1} ±1 %	mm
Atmospheric pressure	Vaisala WXT520	Since Sep 2013	0.1 hPa ± 0.5 hPa for 0–30° C 0.1 hPa ± 1.0 hPa for -52–60° C	hPa

[1] 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: doi:10.1594/PANGAEA.879215; 2014: doi:10.1594/PANGAEA.879216; 2015: doi:10.1594/PANGAEA.879217; 2016: doi:10.1594/PANGAEA.879218; 2017: doi:10.1594/PANGAEA.879219.

The new weather station at "Bella Vista" is supported with an electric cable from the hut (distance approximately 90 m). Hence precipitation can there be measured with a heated device, the Ott Pluvio 2. At "Bella Vista", the standard recordings of the meteorological variables are supplemented by snow measurements (Table 5): 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). In 2016, mean annual temperature at the station was -0.4° C (EE08), and annual precipitation was 1605 mm (Pluvio 2 heated). The "Bella Vista" weather and snow monitoring station is one of the highest of its kind in the Alps. However, the data of the "Bella Vista" station are yet to be considered as experimental, particularly the snow sensors are still in technical examination and development, and no check for consistency has been undertaken so far (e.g. by using the data as input in a snow model as in Morin et al. 2012). During summer 2017, the station will undergo a general technical overhaul, and the pictures of an automatic camera which has the station in its view field will be available via internet (later in 2017). For all the data of the "Latschbloder" and "Bella Vista" stations, the height of the sensors above ground is at least 2 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.

Table 5: 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 3x3	(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 hitcm^{-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: doi:10.1594/PANGAEA.879210; 2016: doi:10.1594/PANGAEA.879211; 2017: doi:10.1594/PANGAEA.879212.

Three additional AWS 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 is available at http://daten.buergernetz.bz.it/de/dataset/misure-meteo-e-idrografiche.

3.2 Glaciological data

All glaciers in the Rofental are included in the three Austrian glacier inventories carried out in 1969, 1998 and 2006 (http://www.glaziologie.at/gletscherinventar.html) and also in the inventory of reconstructed glaciers at the time of the little ice age (Fischer et al. 2015, Kuhn et al. 2009, 2012; Kuhn et al. 1999, Lambrecht and Kuhn 2007), allowing detailed studies of the deglaciation in the catchments. The parent directory on PANGAEA for the Austrian glacier inventory is doi:10.5194/tc-9-753-2015, including the little ice age maximum (doi:10.1594/PANGAEA.844987), and the years 1969 (doi:10.1594/PANGAEA.844983), 1998 (doi:10.1594/PANGAEA.844984) and 2006 (doi:10.1594/PANGAEA.844985). Annual reports of the variations of HEF (ID 491, since 1952) and KWF (ID 507, since 1966) are provided to the World Glacier Monitoring Service WGMS (www.wgms.ch), including mass balance, thickness change and front variation (Fig. 4).

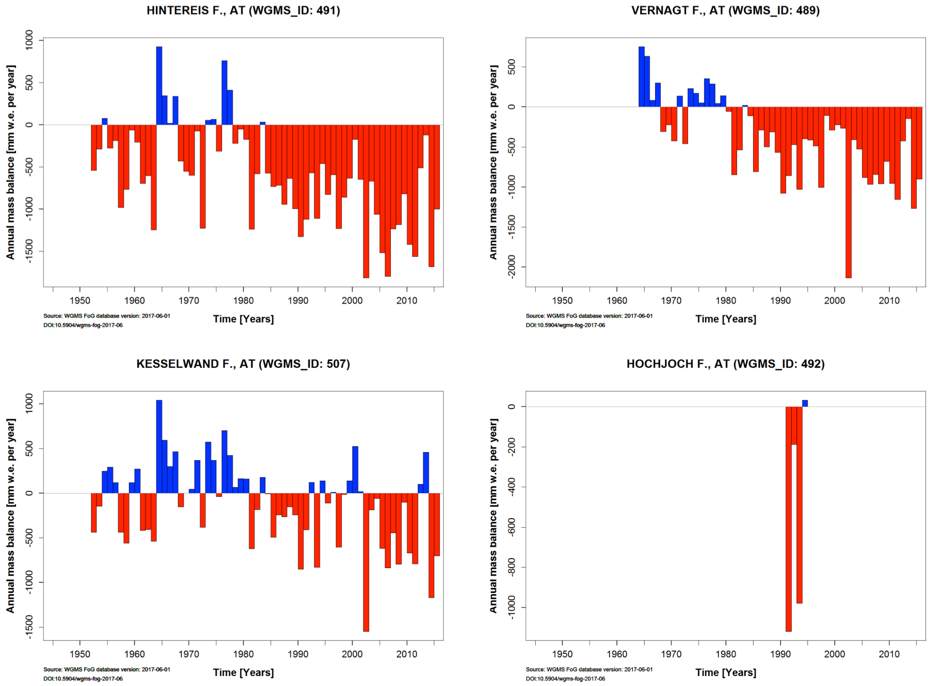

Figure 4: Annual mass balances for Hintereisferner (top left), Vernagtferner (top right), Kesselwandferner (bottom left) and Hochjochferner (bottom right) after the glaciological method. From WGMS (www.wgms.ch, https://doi.org/10.5904/wgms-fog-2017-06).

3.2.1 Hintereis- and Kesselwandferner

Change in the areas of HEF and KWF have been documented on the basis of maps, aerial photos and more recently satellite and airborne derived DEMs since the early 19th century (Lambrecht and Kuhn 2007). In the dawn of the International Geophysical Year 1957, multidisciplinary scientific work at HEF was initiated. At that time, a network of stakes and pits was established to directly measure the mass balance (Hoinkes 1970). This traditional glaciological method of determining glacier-wide mass balance involves spatial extrapolation of point measurements of ablation and accumulation to provide values of the climatic mass balance, encompassing changes at the glacier surface and in the near sub-surface (Cogley et al. 2011). Today, the HEF mass balance record represents one of the longest glacier mass balance series in the world (since 1952).

From 1966–2013 the mass balance of KWF has also been recorded based on a much smaller number of observations and the assumption that the spatial distribution of mass balance is analogous to the adjacent HEF, and since 2013 a full network of observations is also undertaken and maintained at KWF. The 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 snowmelt over the glacier surface. The mass balance values of HEF and KWF are available at WGMS (ID 491 and 507, since 1952 and 1966, see Fig. 4) and are also archived in the PANGAEA data base (doi:10.1594/PANGAEA.803830, doi:10.1594/PANGAEA.803829, doi:10.1594/PANGAEA.818898 and doi:10.1594/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 not trivial in the case of a rapidly changing glacier whose surface type can change significantly over the monitoring interval. Geodetic mass balances for HEF are available for a number of intervals since observations began (Table 6).

Table 6: Available geodetic mass balances $b_{geod} \pm \sigma$ [m w.e.] for Hintereisferner from 2001–2011, mean annual mass balance (01/11) and the cumulated balance (01/11 cum.) as derived from airborne laser scanning measurements (Klug et al. 2017). See section 3.4 for the method and the available data sets.

01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	01/11	01/11 cum.
-0.685 ± 0.16	-2.713 ± 0.20	-0.654 ± 0.09	-1.028 ± 0.17	-2.091 ± 0.19	-1.363 ± 0.10	-1.252 ± 0.11	-1.209 ± 0.10	-0.798 ± 0.09	-1.249 ± 0.07	-12.450 ± 0.20	-12.990 ± 0.78

3.2.2 Vernagtferner

First observations of the VF date back to the 17th century due to its surge activities during this time (drawing of Abraham Jäger from 1601, Tiroler Landesmuseum; Nicolussi 1993). A first accurate map of the glacier and the adjacent Guslarferner was produced by Sebastian Finsterwalder in 1889 (Finsterwalder 1897). Terrestrial photographs are available for VF between 1897 and 1928, documenting the last surge of the glacier (1987–1903). In 1976, an automatic camera has been installed on “Schwarzkögele” (3075 m a.s.l., 46.86575° N, 10.83245° E), capturing one picture per day during the ablation period, and three digital pictures per day throughout the year since 2010 (Weber 2013). Today, a 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 7 and Mayer et al. 2013b).

Glaciological mass balance measurements for VF are 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. 4) and are also archived in the PANGAEA data base (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. Uncertainties of the methods are discussed in Zemp et al. (2013). A summary of the mass balance series for VF is given in Fig. 5.

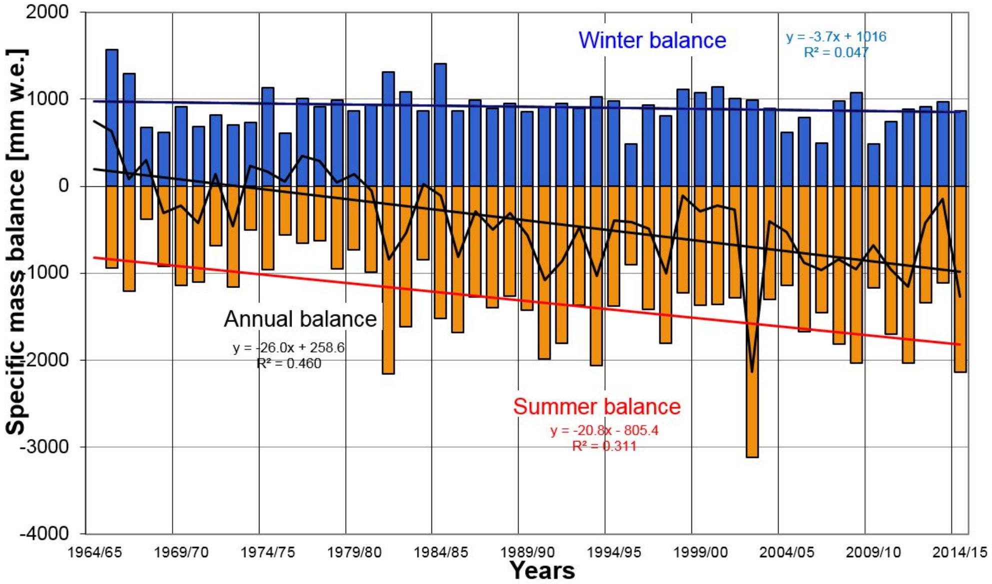

Figure 5: Graphical summary of the seasonal and annual mass balances of Vernagtferner from 1965 until 2014.

Table 7: Available maps of Vernagtferner.

Year	Type	Area (km^2)	Volume change (km^3)	doi
1889	Terrestrial photogrammetry	11549		doi:10.1594/PANGAEA.834873
1912	Terrestrial photogrammetry	11509	-2.137	doi:10.1594/PANGAEA.834873
1938	Terrestrial photogrammetry	10410	-4.382	doi:10.1594/PANGAEA.834873
1954	–	9474	-4.543	[1]
1969	Aerial photogrammetry	9466	0.634	doi:10.1594/PANGAEA.834873
1979	Aerial photogrammetry	9397	1.840	doi:10.1594/PANGAEA.771301
1990	Aerial photogrammetry	8982	-4.931	[1]
1999	Aerial photogrammetry	8680	-7.888	[1]
2003	Aerial photogrammetry	8430	-3.355	[1]
2006	Optical line scanner	8173	-8.970	[1]
2009	Optical line scanner	7748	-8.403	[1]

[1] this dataset is currently processed and will be uploaded to PANGAEA thereafter.

3.3 Hydrological data

3.3.1 Hintereis- 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 exemplarily for many other short and longer term experiments carried out in the Rofental. The respective catchment was 26.6 km^2 in size, with a fraction of 58 % being covered by the glaciers. Annual recorded streamflow amounted to 1848 mm (1957/58) and 1770 mm (1958/59). The glacier contribution (24 % and 20 %, respectively) was extraordinarily high, due to strong negative mass balances in this period. Winter runoff (Oct through Mar) only was 5 % and 10 % of the annual amount, whereas the three summer months (Jul through Sep) provided 76 % and 72 %. Highest monthly streamflow amounts were registered in August 1958 (575 mm) and July 1959 (559 mm). The frequency distribution of daily streamflow for 1957/58 shows a period of daily low flows of less than 0.5 m^3s^{-1} (18.8 $l\ s^{-1}\ km^{-2}$) for 217 days (Oct through May). Higher daily streamflow of more than 6.0 m^3s^{-1} (225 $l\ s^{-1}\ km^{-2}$) only occured during July and August. The observed maximum daily streamflow amounted to 55 mm. The exponential decrease of the hydrograph in fall to the minimum in spring suggests that the winter streamflow mainly origins in delayed melt water of the previous season from the glaciers. The increase in the water flows after the beginning of the snowmelt period occurs with a certain time delay – due to the refreezing of melt water, and its retention in the snow cover.

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” (2635 m a.s.l. – the highest streamflow gauge in Austria) since 1974 by different means. The water level is continuously monitored in the gauge, while water-level-to-discharge calibrations are conducted regularly by the salt injection method. Simultaneously the water level is determined by three sonic rangers distributed across the runoff channel, in order to detect the 2D surface geometry of the water flow. Also, the surface velocity is monitored by a Doppler-system. The total catchment area covers 11.44 km², while 7.3 km² were glacierized in 2015 (63.8 %). The vertical extent ranges from 2635 m a.s.l. at the gauge to 3631 m a.s.l. at the summit of Hinterer Brochkogel. The discharge values are available as hourly mean values (https://doi.org/10.1594/PANGAEA.829530).

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- and icemelt with a significant maximum in July and August (Fig. 6); the glaciated area has decreased from 44 % (in 1969) to 38 % (in 2009; Müller et al. 2009). However, it is expected to further drop to almost zero during the course of the 21st century, due to the rapidly changing climatic conditions (Hanzer et al. 2017). The co-existence of the “Vernagtbach” gauge in the VF headwatershed allows for combined hydrological investigations (see also Fig. 2). Episodical recordings at smaller tributaries of the Rofenache were obtained during the spring snowmelt season in 2014 (Schmieder et al. 2016) and during the glacier melt season in 2016 (Schmieder et al. 2017).

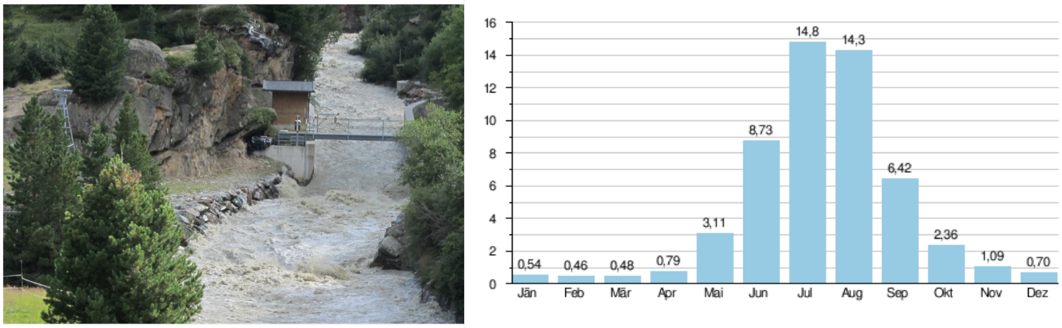

Figure 6: The rainfall totalisator and the gauge at Vent (left; Photo: Hydrographic Service of the Tyrol), and mean monthly streamflow of the Rofenache 1971–2009 (right, in m^3 s^{-1}). Data from the Hydrographisches Jahrbuch (BMLFUW 2011).

3.4 Laser scanning data

Laser scanning is an active remote sensing technique which uses a laser beam to acquire 3D point data, representing the surface and objects on that surface. Both geometrical and spectral information derived from the point cloud are in general of high spatial accuracy and spatial resolution. DTMs derived from laser scanning measurements become 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). Both airborne laser scanning (ALS) and terrestrial laser scanning (TLS) are the most common methods for LiDAR data collection (Telling et al. 2017).

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 m to 0.20 m, mainly dependent on the slope angle (Beraldin et al. 2010, Bollmann et al. 2011). Such 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 of 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). 1x1 m digital elevation models (DEMs) 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.

ALS measurements can be used to study the volume changes of HEF complementary to direct glaciological mass balance measurements. At least one scan was performed at the end of the glacier mass balance year (end of September). In 2001/2002, 2002/2003, 2007/2008, 2008/2009 and 2010/2011 project-based intermediate campaigns were carried out, too. An overview of the data (UTM32N, WGS84) including the technical details is given in Table 8. 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 (Table 6). As expected, the most negative balance year is 2002/03 with a mean specific mass balance of -2.713 ± 0.20 m water equivalent (w.e.). In the subsequent mass balance year 2003/04, the lowest 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 -1.299 m w.e. was calculated with the HEF ALS data set (Klug et al. 2017).

Using the ALS data sets described in Table 8, 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 8: Overview of the available HEF ALS data with flight dates, used sensors, mean flight heights above ground [m], pulse repetition rates [Hz], across track overlaps [%], mean point densities [points per m^2], and vertical accuracies [m]. Data is are available at https://doi.org/10.1594/PANGAEA.875889.

Flight date	Optech Sensor	Mean height AGL [m]	Max. scanning angle [°]	Pulse repetition rate [Hz]	Across track overlap [%]	Mean point density [pnts m^{-2}]	Vertical accuracy STDV [m]	Funding[1]
11.10.2001	ALTM 1225	900	20	25000	24	1.1	0.11	Ω
09.01.2002	ALTM 1225	900	20	25000	24	1.2	0.14	Ω
07.05.2002	ALTM 1225	900	20	25000	24	1.2	0.14	Ω
15.06.2002	ALTM 1225	900	20	25000	24	1.3	0.14	Ω
08.07.2002	ALTM 1225	900	20	25000	24	1.4	0.15	Ω
19.08.2002	ALTM 1225	900	20	25000	24	1.4	0.10	Ω
18.09.2002	ALTM 3033	900	20	33000	24	1.0	0.10	Ω
04.05.2003	ALTM 2050	1150	20	50000	40	0.8	0.10	Ω
12.08.2003	ALTM 2050	1150	20	50000	40	0.8	0.10	Ω
26.09.2003	ALTM 1225	900	20	25000	24	1.0	0.06	Ω
05.10.2004	ALTM 2050	1000	20	50000	24	2.0	0.07	TWF
12.10.2005	ALTM 3100	1000	22	70000	50-70	3.4	0.07	TWF
08.10.2006	ALTM 3100	1000	20	70000	37-75	2.0	0.08	IfG
11.10.2007	ALTM 3100	1000	20	70000	37-75	3.4	0.06	FFG asap
07.08.2008	ALTM 3100	NA	NA	NA	NA	NA	NA	FFG asap
09.09.2008	ALTM 3100	1000	20	70000	40-45	2.2	0.06	FFG asap
07.05.2009	ALTM 3100	–	–	–	–	–	–	FFG asap
30.09.2009	ALTM 3100	1100	20	70000	31-66	2.7	0.05	ACRP
08.10.2010	ALTM Gemini	1000	25	70000	62	3.6	0.03	FFG Comet
04.10.2011	ALTM 3100	1100	20	70000	25-75	2.9	0.04	FFG asap
11.05.2012	ALTM 3100	1200	20	70000	31-66	2.8	0.06	FFG Comet
03.09.2013	ALTM Gemini	1200	20	70000	59-80	4.2	0.04	FFG Comet

[1] Funding provided by: Ω: EU Project OMEGA (Operational Monitoring of European Glacial Areas, project no: EVK2-CT-2000-00069); FFG asap: Austrian Research Promotion Agency (FFG), Austrian Space Applications Programme projects ALS-X and SE.MAP (project no: 815527 and 840109); ACRP: Austrian Climate Research Programme C4AUSTRIA (project no: A963633); TWF: financial support of the Tyrolean Science Foundation, IfG: Institute of Geography, University of Innsbruck; FFG Comet: in cooperation with alpS GmbH Compentence Center (funding agency: Austrian Research Promotion Agency FFG).

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

In 2017, a permanent TLS was installed in a climate controlled container (46.79586° N, 10.78277° E) at an altitude of 3244 m a.s.l. m close to the summit "Im hintern Eis", protected by an especially designed protective housing. The 3D Laser Scanner VZ-6000 (manufactured by RIEGL Laser Measurement Systems GmbH) offers an extremely long measurement range of more than 6000 m and operates with beam divergence of 0.12 mrad at a wavelength of 1050 nm for snow and ice related applications. Hence, the instrument is predestinated for topographic (static) applications such as monitoring of glaciological and geomorphological processes in high mountain terrain. Due to the large field of view (60° vertical, 360° horizontal), nearly the entire HEF catchment area is captured by the instrument; only a very small part of the terminus and small flat areas in the upper glacier zones are not sampled by the sensor. The TLS surface point cloud is accompanied by high quality optical imagery. This installation allows high temporal and spatial resolution glacier volume changes for HEF to be determined (Fig. 7). In addition, the high spatial resolution can be used to monitor surface features such as crevasses, the evolving surface roughness, the supraglacial drainage network as well as geomorphodynamically induced surface changes (e.g. debris flows) or snow avalanches. Currently, the VZ-6000 is operating with an angular step width of 0.01° for a field of view of 60° vertically and 120° horizontally (South-West to North-East) and a laser pulse repetition rate of 30 kHz, equivalent to an effective measurement rate of 23000 measurements per s, 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. Seven scans have been carried out during the test phase (September 2016 to April 2017).

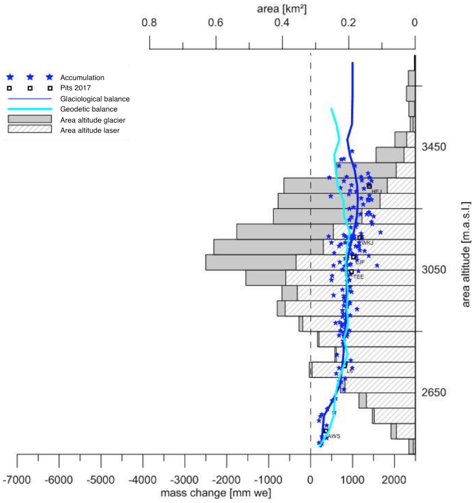

Figure 7: Vertical mass balance profile (vbp) of the winter mass balance of Hintereisferner (1.10.2016 – 30.4.2017, 892 mm we) compared to vbp derived from two TLS (24.9.2016 – 29.4.2017). Mean density of snow is derived from 6

snow pits (353 – 388 kg m^{-3}, 5.5.2017). Above 3100 m a.s.l. the TLS covers less than 45 % of the glacier area (due to cloud cover in September 2016) which might explain the underestimation of the TLS mass balance (791 mm we).

The utility of TLS in performing high resolution glacier observations was tested on the 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. This work was carried out under the auspices of the hiSNOW project in which the TLS data, along with coincident optical imagery from the onboard camera, was used to produce high resolution surface classifications to map snowcover extent, and to explore the spatial patterns of the surface mass balance of HJF (Prantl et al. 2017).

4. Data availability

The datasets presented here are available freely from PANGAEA (https://doi.org/10.1594/PANGAEA.876120). However, these datasets represent only a small fraction of what has been observed and collected during the past decades. The data from the Rofental have been widely used for process studies and all kind of method and model development activities. Many measurements have been conducted during special field campaigns and are not yet documented to get published. E.g., 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, 2017). Other data still await digitization and processing. Such data, originally published in analogous printwork, 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) and many energy balance investigations (Jaffé 1958, 1960; Hoinkes and Untersteiner 1952; Hoinkes 1953a/b; Ambach and Hoinkes 1963; Wendler 1967; Wagner 1979, 1980). 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 documentation of the used data, methods and models. The long-term field experiments on VF are described in Moser et al. (1987). Runoff data of the gauge “Vent” has been widely used in hydrological studies, the most recent ones including Schmieder et al. (2016) and Hanzer et al. (2016, 2017). At regional scales, the Rofental data contributed to modelling exercises for future scenario climatic conditions and their effect on simulated river discharge (Marke et al. 2011, 2013). The Hydrographic Service of Tyrol visualizes its data online at https://apps.tirol.gv.at/hydro, and provides their download at http://ehyd.gv.at. The data of the sites “Latschbloder” and “Bella Vista” are used in several ongoing research projects and also supply valuable experimental data for application in various student courses.

The efforts to provide these data to the scientific community according to the Creative Commons Attribution License will continue. In the meantime all the data, and many more that are not documented here, can be obtained on request from the authors.

5. Conclusions and outlook

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 (https://words.usask.ca/inarch); it also belongs as a research catchment to ERB Euro-Mediterranean Network of Experimental and Representative Basins (http://erb-network.simdif.com), and the Rofental also represents a regular complex site in the LTSER platform Tyrolean Alps (http://www.lter-austria.at/ta-tyrolean-alps/) which belongs to the national and international long term ecological research network (LTER-Austria, LTER Europe and ILTER). Station Hintereis is part of the EU Horizon 2020 INTERACT framework of Arctic (and few Alpine) research stations (http://www.eu-interact.org/field-sites/austria/hintereisferner-research-station). To connect our research activities and datasets collected to other Alpine altitude research sites, we will apply with the Rofental to the "Virtual Observatory of the Alps", where stations in Italy, France, Slovenia, Switzerland, Austria and Germany are bundled (http://www.schneefernerhaus.de/en/forschung/vao-ii/alpine-environmental-data-analysis-centre-alpendac.html).

Acknowledgements

Much of the instruments and the monitoring activities presented here have been supported by the institutions the authors belong to, and countless research programs funded by DFG (Deutsche Forschungsgemeinschaft), ÖAW (Austrian Academy of Sciences), the European Region Tyrol – South Tyrol – Trentino, the Autonomous Province of Bolzano – South Tyrol, the Austrian Federal of Agriculture, Forestry, Environment and Water Management (BMLFUW, section IV/4-water cycle) and others. 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 University of Innsbruck and the Bavarian Academy of Sciences generously supported the instrumentation of the site. 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. Paul Grüner provided local support in many administrative issues, and practical help in the maintenance of the technical infrastructure around the "Schöne Aussicht" ("Bella Vista") mountain hut. Michael Stipp (Innsbruck) provided the description of the bedrock geology of the basin. Rainer Sieger (Bremerhaven) supported the data upload and checked the manuscript, as did Johannes Schöber (Innsbruck).

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