Djankuat Glacier Station in the North Caucasus, Russia: A Database of glaciological, hydrological, meteorological observations and stable isotopes sampling results during 2007-2017

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Abstract. The study presents a dataset on long-term multidisciplinary glaciological, hydrological, meteorological observations and isotopes sampling in sparsely monitored alpine zone of the North Caucasus in the Djankuat research basin. The Djankuat glacier which is the largest in the basin, was chosen as representative of the central North Caucasus during the International Hydrological Decade and is one of 30 'reference' glaciers in the world which have annual mass balance series longer than 50 years (Zemp et al., 2009). The dataset features a comprehensive set of variables from 2007–2017 observations and contains the yearly measurements of snow depth and density; dynamics of snow and ice melting; water runoff, conductivity, turbidity, temperature, $\delta^{18}O$, δD at the main gauging station (844 samples in total) with an hourly or subdaily time step depending on the parameter; data on $\delta^{18}O$ and δ^2H sampling of liquid precipitation, snow, ice, firn, groundwater in different parts of the watershed taken regularly during melting season (485 samples in total); precipitation amount, air temperature, relative humidity, shortwave incoming and reflected radiation, longwave downward and upward radiation, atmospheric pressure, wind speed and direction – measured at several automatic weather stations within the basin with 15 min to one-hour step; gradient meteorological measurements to estimate turbulent fluxes of heat and moisture, measuring three components of wind speed at a frequency of 10 hertz to estimate the impulse of turbulent fluxes of sensible and latent heat over the glacier surface by the eddy covariance method. Data was collected during the ablation period (June–September). The observations and were halted in winter. The dataset is available from Pangaea (doi:10.1594/PANGAEA.894807) and will be further updated. The dataset can be useful for developing and verifying hydrological, glaciological and meteorological models for alpine areas, to study the impact of climate

change on hydrology of mountain regions, using isotopic and hydrochemical approaches in hydrology. As the dataset includes the measurements of hydrometeorological and glaciological variables during the catastrophic proglacial lake outburst in the neighboring Bashkara valley in September 2017, it is a valuable contribution to study lake outbursts.

1 Introduction

5   Mountain areas there are highly sensitive to climate change (Dyurgerov, 2003, Weingartner et al., 2007, Auer et al., 2007, Viviroli et al., 2011, Pachauri et al., 2014, Zemp et al., 2015). However, it is widely recognized that there is still a great lack of observational data on climate, glaciers and hydrology of mountain areas (Gietl, 1990, Barry, 1992, Singh et al., 1999, Schaefli et al., 2005, Bales et al., 2006). The density of hydrological stations in the world's mountainous regions is from 3 (in Europe) to 100 (in Asia) times lower than those recommended by the World Meteorological Organization (Viviroli et al., 2011,

10   Bobrovitskaya and Kokorev, 2014). The majority of field observations in mountainous catchments are conducted in Scandinavia, the Alps and the mountains of the USA, while vast Asian territories and the Southern Hemisphere are sparsely monitored (Barry, 1992, Dyurgerov, 2003, Meier et al., 2003, Zemp et al., 2009, Viviroli et al., 2011, Immerzeel et al., 2012). The Great Caucasus used to have a developed observational network during the Soviet Union period. But recently it became also a poorly instrumented terrain lacking high quality glaciological and hydrometeorological data (Barry, 1992, Dyurgerov,

15   2003, Shahgedanova et al., 2005, Bobrovitskaya and Kokorev, 2014).

The specificity of this dataset is a relatively long measurement period of 10 years (2007–2017) including several high discharge events covered in a multi-site measurement program and the extensive set of measured variables, which is unique for the North Caucasus area.

The Djankuat research basin, 9.1 km2 in area, is located at 43.2ºN and 42.75ºE in the alpine zone of the North Caucasus (Russia),

20   between 2600 and 4000 m (Fig. 1). Djankuat glacier, covering 27% of its area, was chosen as representative of the central North Caucasus during the International Hydrological Decade (IHD) - research program on water problems launched by UNESCO in 1965 (Boyarsky, 1978). The mass-balance measurements have been carried out on Djankuat glacier since 1967 till now on a regular basis (www.wgms.ch) based on standard methods (Østrem and Brugman, 1992, Boyarsky, 1978). Detailed hydrological and meteorological measurements were included in the monitoring program of the station during the IHD and came to an end

25   in the late 1970s (Boyarsky, 1978). The comprehensive hydrometeorological observation were resumed in the Djankuat research basin under the initiative of the collective of the authors since 2007. Hydrometeorological measurements were done during the ablation season every year since 2007 and the observational program gradually expanded during 2007–2017 and now goes beyond the standard network hydrological and meteorological observations. The relative cutting of the program in 2011–2012 happened due to a special military regime in Kabardino–Balkaria republic.

30   Automatic Weather Stations (AWS) are installed in 4 main locations in the basin (see Fig. 1, Table 1). All the meteorological stations operate only during the ablation season of each year. Two Campbell AWS are located in the central part of the Djankuat glacier above the ice surface (AWS1) and the debris of the glacier (AWS2). AWS1 operated through the period 2007–2017

(excluding 2011). The second Campbell station, located over the debris (AWS2) was operating for three years (2007–2009). The both stations provide measurements of the air temperature, relative humidity, downward and upward shortwave radiation, downward and upward longwave radiation, wind speed, wind direction, atmospheric pressure. A Davis weather station operated at Base Camp (Base Camp AWS) through 2007–2009 and 2013–2017. The second Davis (AWS3) station was placed on the upper part of the Djankuat glacier in 2017. A DAVIS Gradient mast was placed in the central part of the Djankuat glacier (AWS1) in 2015 to obtain long-term meteorological data series in the surface layer. Turbulent pulsations of wind and acoustic temperature were measured in 2013, 2014 and 2016 with a 3–axis GILL WindMaster sonic anemometer in the central part of the Djankuat glacier (AWS1).

Hydrological measurements at the Djankuat gauging station (see Fig. 1, see Table 1) started from measuring runoff with one-hour step during 2007–2010 ablation seasons. In 2013 the first test measurements of water conductivity, water salinity, water turbidity, and stable isotopes (18O and 2H), as well as first samplings of liquid precipitation, snow, ice, firn in the basin on water conductivity, water salinity, δ18O and δ 2H were carried out. From 2014 to 2017 the stable isotopes sampling, conductivity measurements were done on a regular basis on the Gauging Station and on the watershed. A total amount of 844 samples on stable isotopes were collected on the Djankuat River Gauging station and 485 samples of snow, ice, firn, groundwater and liquid precipitation. At the outlet of Djankuat River turbidity was recorded manually using portable turbiditimeter 5–7 times a day in 2015–2017, water conductivity – during 2014–2017, water temperature – during 2015–2017. The dataset was published on a long-term data repository (doi:10.1594/PANGAEA.894807) and will be updated. Outcomes of the research included studies of glacier mass balance (Zemp et al., 2009, Rets and Kireeva, 2010, Lambrecht et al., 2011, Zemp et al., 2011, Zemp et al., 2015, Popovnin and Pylayeva, 2015) water transport processes and dangerous hydrological phenomena (Rets et al., 2017, Toropov et al., 2017, Chernomorets et al., 2018) and sediment budget issues (Chalov et. al, 2017).

2 Study Area

The Greater Caucasus stretches 1300 km along the border between Russia and Georgia from the Black Sea to the Caspian Sea. The alpine zone extends above the orographic snowline approximately 2000 m above sea level. The Elbrus Mountain has the peak elevation in the Greater Caucasus reaching 5642 m. The climate is moderate continental to high-alpine. The precipitation decreases both southeastwards and with a decrease in elevation. Annual precipitation sum varies from 200–400 mm in Eastern plain part and 600–800 mm in Western plain part to 800–1300 and more in mountainous part (Rets at al., 2018). The water supply in the North Caucasus is strongly dominated by runoff formed in the high mountains, a unit of area at an elevation of 3000–4000 m can be 10 times more productive in terms of water yield than the lowlands. In the most alpine zone of the North Caucasus annual unit discharge varies from 20–30 to 50–60 liters/km2.s. In the foothills mean annual runoff unit discharge sharply declines to 5–15 liters/ km2.s (Rets et al., 2018).

The Djankuat research basin is situated on the northern slope of the central part of the Main Caucasian Ridge (see Fig. 1). It is a typical alpine watershed of 9.1 km^2 with the elevation range 2600 – 4000 m, with steep slopes (more than 20º in average) and

nival-glacial landscape (see Fig. 1). An overall exposition of the basin is the North-North-West. In the 2017 glaciers occupied 27% of the territory of the basin. The main glacier with the same name – Djankuat glacier – is the source of the Djankuat River. It is a valley glacier, with the lowest point of the tongue at approximately 2750 m, the elevation of the bergschrund is at 3600 m. The mean elevation of the glacier is 3210 m, the area is 2.42 km^2 and its length is 3.0 km. The maximum measured thickness of the glacier is 105 m, and the average thickness is 31 m (Lavrentiev et al., 2014). The Djankuat River basin also contains three small glaciers with areas less than 0.5 km^2: Koyavgan, Via-Tau, and Visyachiy. These glaciers contribute runoff to the Djankuat River upstream the main gauging station (see Fig. 1). The Djankuat River is a source of the Adul-Su River – a tributary of the Baksan River which drains into the Caspian Sea via the Terek River.

The uppermost gauging station on the Baksan River was situated 12 km from its source in Usengi. The river basin area at the gauging station is 180 km^2. The mean annual discharge of the Baksan River at Usengi gauging station is 9.9 m^3/sec that amounts to mean unit annual discharge of 55 liters per sec. per km^2 (Rets, Kireeva, 2010). The water-abundant period of the Basksan River in the upstream is prolonged and steady, it extends from May to September–October. The general wave of runoff hydrograph, formed by snow and ice melting, is overlain with sharp peaks of rain floods. The maximum water levels are usually recorded in July. A stable winter low-flow period with minimum monthly discharge of 2.4 m^3/sec is observed in February to March (Rets, Kireeva, 2010). Annual river runoff in the mountainous part of the North Caucasus shows a slight positive trend during 1940–2010. In the most elevated areas the long-term mean value of annual runoff remains stable (Rets et al., 2018).

The climate of the Djankuat research basin is characterized by a distinct seasonality in temperature. The mean monthly air temperatures at the Terskol, the closest to the research basin all-year meteorological station, situated 16 km northwest of the study area at an altitude of 2146 m goes below zero during November–December. The warmest months are July and August with mean monthly temperatures above 12 ⁰C (Fig. 2). Monthly precipitation totals are 40–50% higher in the warm period of the year (May–September) than during winter (Fig. 2). The annual precipitation at the Terskol weather station varied from 590 to 1330 mm with a mean annual value of 950 mm. Daily precipitation maxima occur in July to September in response to convective activity triggered by a combination of strong insolation and depressions developing on the Polar front and enhanced by the orographic uplift (Shagedanova, 2002).

The observations in the Djankuat research basin, included in the presented dataset, were carried out under the conditions of slightly warmer summer periods in comparison to the long-term average, and substantially higher amounts of precipitation, especially during the spring period – from March to May (Fig. 2). The strong influence of spring snowfalls during the observation period also is reflected in the results of Djankuat glacier snow sampling for stable isotopes (Rets et al., 2017). The outlined tendency is likely to be the consequence of climate change in the region.

According to the majority of studies (Alekseev et al., 2014, Toropov et al., 2018a, Rets, Kireeva, 2010) a statistically significant positive trend in air temperature amounting to 0.7 – 1 ⁰C per decade is observed during the summer period in the North Caucasus. A slight positive trend in the mean temperature in the ablation period (May to September), 0.3 ⁰C per decade, is observed at the Terskol meteorological station since the end of 1970th. In the winter period the observed tendencies in air temperature in the North Caucasus are very inhomogeneous: Alekseev et al. (2014) report a statistically insignificant positive trend. In the study

by Rets and Kireeva (2010) a decrease in air temperature of the winter period was revealed in the mountainous part of the North Caucasus. According to the on the Terskol meteorological station the value of mean air temperature during the accumulation season (October to April) remains stable in the study area.

According to different studies, a positive trend in annual precipitation sum of 5% per decade is reported by Alekseev et al.
(2014), and no statically significant trend is reported for the most of the North Caucasus by Toropov et al. (2018a). An increase in annual precipitation sum was revealed for the majority of mountainous stations and a number of foothills located in the central part of Northern Caucasus (Rets, Kireeva, 2010). At the Terskol meteorological station the amount of precipitation is constantly rising during the whole observational period. The increase in annual sum is 3.5% per decade is different for the ablation (2.1% per decade) and accumulation (5% per decade) period. The most intensive rise in precipitation is observed in spring (8.6% per decade in March, 7% per decade in April) and autumn (10.3% per decade in October). This result is consistent with the result reported by Alekseev et al. (2014) for the whole territory of the North Caucasus.

The intensive degradation of glaciation is observed in the North Caucasus (Shahgedanova et al., 2014, Zemp et al., 2015). The area of glaciers in the North Caucasus dropped by 12.6% during 1970–2000 (Voitkovskiy et al., 2004), and by 4.7% between 2000 and 2010/2012 (Shahgedanova et al., 2014), amounting to approximately 17% in total during 1970–2012. The glaciers terminus retreat increased from the 1987–2000/2001 period to the 2000/2001–2010 period by the factor 2.5–3.8. (Shahgedanova et al., 2014). Glacier retreat and the increase in supraglacial debris cover is also accompanied by the emergence and growth of proglacial lakes and related increase in proglacial lake outburst floods (Stokes et al., 2007). On the 1ˢᵗ of September 2017 an outburst of Bashkara lake in the upstream of neighboring to the Djankuat basin valley gave a rise to catastrophic mudflow that led to major destructions and human casualties (Chernomorets et al., 2018).

3 Methods and results

3.1 Hydrological measurements

3.1.1 Discharge measurements

Water discharge of the Djankuat River at the gauging station (see Fig. 1, see Table 1) is calculated from the water level using a rating curve Q=f(H) (Table 2a). The water level was recorded with 10 min to hourly time step (depending on the year of observation) by means of an automatic water level logger with a pressure sensor (ADU-02 during 2007–2013, Solinst Level logger in 2014–2017). The level logger is placed with a ripple shield in an artificial bay constructed at the river bank (Fig. 3b). Additionally, manual water level measurements were made 6–7 times a day. Rating curves were drawn for each month on the yearly basis. Dilution method using NaCl as a tracer was used for discharge metering as turbulent flow conditions make it impossible to apply the current meter (Dobriyal et al., 2017).

As there is a possibility of erroneous results due to the loss or incomplete mixing of the tracer arising from the difference in velocity in the upper and lower layers of the stream (Dobriyal et al., 2017), every discharge measurement is repeated twice.

The value is accepted, if the difference between the two simultaneous measurements does not exceed 10%. For the most of the discharge measurements at the Djankuat gauging station this difference was less than 5%. 50–80 water discharges are measured every ablation season to draw a rating curve.

Water discharge at the Djankuat gauging station is observed within a range of 1 to 2 m^3/s in 2007-2017 (Fig. 4a), the mean value of water discharge was 1.39 m^3/s (Table 3). During high discharge events (1% probability) streamflow rates ranged from 3.5 to 8.46 m^3/s. The maximum discharge, 8.46 m^3/s, was observed on the 1st of July 2015 at 9:00 due to heavy rain flood caused by 227 mm of precipitation in sum over 7 days superimposed on an intensive snow and ice melting in the river basin.

The inter-annual fluctuations of the Djankuat River runoff can be quite substantial (Fig. 5). The Djankuat River was the most abundant in water during 2015–2016, the least in 2013. Mean water discharge for June to September in 2015 (1.88 m^3/s) was twice as large as in 2013 (0.97 m^3/s). The Djankuat River is most abundant in water in July (Fig. 5). Mean monthly discharge in this month is 1.3–2.8 m^3/s. June and August are comparable in terms of mean discharge, 0.93 to 1.8 and 1.0 to 2.0 m^3/s, respectively. In September runoff due to ice and firn melting decreases with the decrease in the incoming solar radiation, the seasonal melt water is gradually drained from the Djankuat River basin. Mean monthly discharge is 0.6–1 m^3/s. At the end of September, the ablation period ends with the first stable fresh snow cover on the glacier.

The Djankuat River hydrograph has a saw-tooth shape with a pronounced daily maximum and minimum typical for glacial rivers (Fig. 6). A diurnal fluctuation of discharge is great and can be compared with the overall seasonal fluctuation: up to 1.5–2 m^3/s on a day without rain. The rise of a rain flash-flood can be very intensive: more than 1 m^3/s per hour.

3.1.2 Electrical Conductivity and Salinity

Water salinity is calculated from the conductivity measurements (Table 2a), using a dependency Salinity=f(Cond). The dependency was drawn in 2013 using the data on simultaneous measurement of electrical conductivity and complete chemical analysis in 19 samples with conductivity from 4.2 to 87.5 µS/cm. The Djankuat River water is low-mineralized, the value of electrical conductivity stayed in the range of 55–85 µS/cm for 90% of the time (Table 3, Fig. 4d). The electrical conductivity value strongly depends on the percentage of snow and ice melt water in the total river runoff. During long periods without rain with intensive melting the water of the Djankuat River can be diluted up to 40–50 µS/cm during day time. On the daily minimums of water discharge in early morning, the electrical conductivity rises by 10–30 µS/cm. At the end of the ablation season, when melting is strongly reduced, the electrical conductivity of the Djankuat River reaches values of 110 to 115 µS/cm during night–morning hours, which is close to the value of electrical conductivity of groundwater in the basin.

3.1.3 Water Temperature

Water temperature has a close to a uniform distribution on the duration curve and is mostly within the range of 1.2–4.5 °C (Fig. 4c). Water temperature of the Djankuat River has a great diurnal variation up to 4°C. Diurnal maximum of temperature is usually observed at day time before the beginning of an intensive rise of diurnal wave of meltwater flow. Mean daily value of

water temperature generally rises trough the ablation season (Fig. 6). The maximum value (6.63 °C) was registered on 18th of September 2016 at midday. The minimum values (0.1 °C) are observed during the night in the beginning of the ablation period (Fig. 6).

3.1.4 Water Turbidity

The regularity of turbidity measurement was defined for each month according to the shape of a diurnal hydrograph of the Djankuat River. The measurement Station was done manually using portable turbidity meter. During heavy rainfall events, the measurements were performed every 15 minutes, and averaged in the database of hourly time step. Additionally, water samples were taken manually under various turbidity conditions (in total 19 samples within a range from 66.7 to 36400 NTU) and filtered using 0,45 μm Millipore membrane filters to compute initial suspended sediment concentration (SSC; mg L^{-1}) The values of turbidity were converted to SSC using the above-mentioned lab samples using quadratic regression (Belozerova, Chalov, 2013). The total amount of 1991 measurements is included in the database (Table 3). The Djankuat River turbidity has an extremely uneven distribution (Fig 4b): staying less than 400–500 NTU (250–350 g/m^3) most of the time, water turbidity was abruptly rose to 1000–5000 NTU (750–4000 g/m^3) and 30 000 – 40 000 NTU (25 000–33 000 g/m^3) within short periods of heavy rainfalls (more than 20 mm/day) (Fig. 6). Observed values close a gap in alpine sediment transport observations and correspond to extreme sedimentation processes registered in the World (e.g. Cohen et al., 2014) and are similar to conditions observed in the most unstable volcanic environments (Chalov et al., 2017b); The maximum value of turbidity (45 060 NTU or 37 200 g/m^3) was measured on 1st of September 2017 after 87 mm of rain with average intensity of 30 mm/hour. The same rain event triggered of an outburst of Bashkara lake in the upstream of a neighboring valley, that gave a rise to a catastrophic mudflow (Chernomorets et al., 2018).

3.1.5 Stable isotopes

Sampling of stable isotopes content in the Djankuat River was carried out during 2013-2017 (Table 2a). The concentrations of ^{18}O and D expressed in the values of δ: $\delta D = [(^2H/^1H_{sample} - {}^2H/^1H_{standard})/^2H/^1H_{standard}] \times 1000‰$; $\delta 18O = [(^{18}O/^{16}O_{sample} - {}^{18}O/^{16}O_{standard})/^{18}O/^{16}O_{standard}] \times 1000‰$. In 2013 all samples were processed in the Stable Isotope Laboratory of the Geography Department of Lomonosov Moscow State University on a Finnigan Delta-V mass spectrometer. For the measurement, international standards were used: V-SMOW ($\delta^{18}O = 0‰$, $\delta D = 0‰$), GISP ($\delta^{18}O = –24.76‰$, $\delta D = –189.5‰$), SLAP ($\delta^{18}O = –55.5‰$), own laboratory standard MSU (snow glacier Garabashi: $\delta^{18}O = –15.60‰$, $\delta D = –110.0‰$). The measurement precision for $\delta 18O$ was ±0.1‰.

In 2014 to 2016 all samples were processed in Saint Petersburg State University Resource center for Geo-Environmental Research and Modeling (GEOMODEL) on Picarro L-2120i. In 2014 50 control sampless were processed independently by two laboratories: a) Saint Petersburg State University Resource center for Geo-Environmental Research and Modeling (GEOMODEL) on Picarro L-2120i; b) the Stable Isotope Laboratory of the Geography Department of Lomonosov Moscow

State University on a Finnigan Delta-V mass spectrometer. The difference in the definition for the same sample did not exceed 0.2‰.

In 2017 the samples were measured at Climate and Environmental Research Laboratory (CERL) of Arctic and Antarctic Research Institute on laser analyzer Picarro L2140-i that uses Cavity Ring-Down Spectroscopy (CRDS) technique to define the δD and $\delta^{18}O$ ratios in water samples. After each 5 samples we measured our work standard "SPB" (distilled Saint Petersburg tap water) calibrated against the IAEA standards, in order to obtain true values of the samples' isotopic composition. 23 % of randomly chosen samples were re-measured in order to estimate the reproducibility of the results, accordingly to 0.06 per mil for $\delta^{18}O$ and 0,4 per mil for δD, which is 2 orders of magnitude less than the natural variability of the isotopic composition of the studied samples.

In coarse of the first test sampling in 2013 a needed regularity of sampling to get a representative mean daily value of $\delta^{18}O$ and δD was defined. As the daily variation of $\delta^{18}O$ and δD turned out to be low compared to other hydrological parameters of the Djankuat River, sampling was done twice a day in 2014–2017: on the maximum and minimum of water level.

The values of $\delta^{18}O$ and δD in the Djankuat River waters have a relatively even duration curve (Fig 4 e,f). The value of $\delta^{18}O$ stays in range of -13.5…-11.5‰ most of the time, δD in – -95…-80‰. The mean values of $\delta^{18}O$ and δD are correspondingly - 12.5‰ and -86.2‰. Concentration of ^{18}O and D decreases with an increase in share of ice and firn melt in total river flow as shown in the beginning of June and July–August 2017 on Figure 6. Pronounced rises in $\delta^{18}O$ and δD are driven by precipitation events (Fig. 6). The maximum value of $\delta^{18}O$ amounting to -6.7‰ (the content of δD in this sample was -72 ‰) was observed on 16th of June 2016 at 22:00 in the beginning of an ablation season after a heavy rain that doubled the mean daily runoff of the Djankuat River. The minimum values of $\delta^{18}O$ (-14.7‰) was observed on the 17th of July 2016 at 21:00 in course of an intensive snow and ice melting period.

A clear-cut difference in isotopic composition of ice/snow meltwater and liquid precipitation (see the 3.1.6 section of the paper) makes it possible to estimate the ratio of these components it the total river flow. A series of articles was published from the beginning of 1970[s], describing runoff hydrograph separation by nourishment sources with the use of ^{18}O and D (see for example Dincer et al., 1970, Martinec et al., 1974, Fritz et al., 1976, Hermann et al., 1978, Cable, 2011).

A mixing-model approach was tested for the Djankuat River to conduct river hydrograph separation in the study (Rets et al., 2017). Two equation systems were drawn:1) in terms of water routing with salinity as indicator; 2) in terms of runoff genesis with $\delta^{18}O$ as a tracer. In terms of water routing the Djankuat River hydrograph was separated into surface routed and subsurface routed waters. In terms runoff genesis the Djankuat River hydrograph was separated into liquid precipitation and meltwaters. Some 70% of the Djankuat River runoff in August–September 2014 was formed by ice and firn meltwater. Rain water is mostly subsurfacely routed; surface runoff of liquid precipitation is formed only during the most intensive rainfall (more than 20 mm on average). Ice and firn meltwater partly percolates to the glacier bottom and comes through a sub-surface layer. The fast (responsive to weather fluctuations) and regulated components of sub-glacier runoff can be distinguished. Sub-glacier runoff contributed 20–30% to the Djankuat River melt runoff in August 2014 and up to 100% of the Djankuat River melt runoff at the end of September 2014, when ablation stopped (Rets et al., 2017).

3.1.6 Sampling snow, ice, firn, liquid precipitation and groundwater in the basin for stable isotopes and electrical Conductivity

Regular sampling of snow, ice, firn, liquid precipitation and ground water in the Djankuat basin was carried out during 2014–2017. The first test sampling was performed in 2013. Liquid precipitation was sampled on every significant occasion of rainfall (more than 1 mm) that amounts to 25–30 samples a year of the Base camp weather station (Table 1). The snow, ice and firn sampling points were evenly distributed on the Djankuat basin area, the coordinates are given in the database. Samples were taken regularly during the ablation season, 40–150 samples a year. Snow samples were taken from the surface and on different depth of snowpack. The groundwater was sampled: 1) after the end of ablation season in the Djankuat River stream when the total runoff is assumed to be provided by groundwater in 2014; 2) out of the sub-glacial waters spring in 2015; 3) A groundwater-fed spring on the slope of the Djankuat River basin in 2017.

Total amount of samples taken was: 113 samples of liquid precipitation, 218 samples of snow, 116 samples of ice, 22 samples of firn and 16 samples of groundwater. The values of $\delta^{18}O$ and δD were measured in each sample. The proceeding of the samples was the same as for the stable isotopes samples taken at the gauging station (see section 3.1.5). Relative concentrations of ^{18}O and D in precipitation are strongly correlated and defined to a great extent by air temperature, which is called the "seasonal isotope phenomenon" (Dansgaard, 1964). The highest concentrations of ^{18}O and D among the samples collected in the Djankuat River basin are characteristic of liquid precipitation (Table 3, Fig. 7). The $\delta^{18}O$ value lies mostly between -0.5 and -7‰ with a mean value of -4.9‰, The δD value – between 0 and -40‰, the mean value is -26‰. The lowest concentrations of ^{18}O and D were registered in winter snow ($\delta^{18}O$=-28.3‰, δD=-216‰) and Djankuat glacier ice ($\delta^{18}O$=-22.0‰, δD=-159‰). The amount of stable isotopes in snow cover formed during spring snowfalls is higher and closer to the corresponding values in liquid precipitation ($\delta^{18}O$=-9…-5‰, δD=-28…-70‰). The mean concentration of ^{18}O and D is quite similar: the mean $\delta^{18}O$ is -12.2‰ in snow samples, -14.3‰ in ice samples and -11.3‰ in firn; mean δD is -85.5‰, -99.3‰ and -77.1‰ respectively. The surface of a glacier ablation area is always formed by ice layers of different ages, while firn samples represent the climatic conditions of the last 5–10 years. A generally warmer mean isotopic composition of firn and snow compared to ice can indicate a total warming of the climate. Groundwater is a mixture of all the stated above sources, accordingly the points of groundwater samples lie in the middle of the $\delta^{18}O$ vs. δD graph (Fig. 7). The mean concentration of ^{18}O and D in groundwater samples (-13.3‰ and -91‰ correspondingly) indicates a bigger role of meltwater than of summer precipitation in the replenishment of groundwater layers.

The ice, snow and firn samples are ultra-fresh (Table 3). Groundwater is enriched with dissolved salts up to 105 mg/L (114 μSm/cm).

3.2 Glaciological measurements

Glaciological observations were carried out by standard methods during 2007–2017 (Østrem and Brugman, 1992, Boyarsky, 1978). The data on snow depth, snow density and ablation is included in the presented database (Table 2b).

Snow depth on the Djankuat glacier is measured at 250–300 points evenly distributed in all zones of the glacier (Fig. 8). The snow measurement survey usually starts in late May – early June and ends at the end of June. The mean value of measured snow thickness is 3.6 m, the maximum is 11.5 m.

Snow density is measured in 2–4 snowpits placed in different elevation belts of the Djankuat glacier (Fig. 1). Density is measured in each 40–50 cm layer of a snowpack (Fig. 3d). The measurements are repeated 2–5 times during the ablation season. Integral density of snowpack has a low variance; total range of variation is less than 0.2 g/cm^3. The density in the layers of snowpack can greatly vary – from 0.23 to 0.92 g/cm^3 according to the 2007–2017 measurements. The overall mean measured value of snow density in the snowpack, 0.57 g/cm^3, greatly exceeds the density of fresh snow, as the database includes measurements carried out in the midsummer and at the end of the ablation period (Table 3).

35–45 ablation stakes were placed on the Djankuat glacier surface every year (Fig. 8). The time-step between measurements depends on the accessibility of each stake and ranges from 1–5 to 30 days. The values included in the dataset are counted from measured depth of melted snow/firn/ice in cm and corresponding values of density of melting material.

The Djankuat glacier has experienced a general mass loss since the beginning of observation in 1968 (www.wgms.ch). Until 2005, negative mass balance years alternated with positive mass balance years (Fig. 9). After 2006 and during all period that is presented in the dataset, the annual mass balance of Djankuat glacier was negative. The annual mass balance values ranged from -2010 mm w.e. in 2007, that was the lowest value since the beginning of the observation in 1968, to -230 mm w.e. in 2009. The mean value of annual mass balance during 2007–2017 was -900 mm w.e. During 2007–2017 the area of the Djankuat glacier decreased from 2.68 to 2.42 km^2 that amounts to almost 10% of loss (Fig. 8). The front of the glacier retreated by 60– 300 m in different measurement profiles during 2010–2016 (Fig 8), that amounts to 8.5–42.9 m/year retreatment rate. The main reason of the Djankuat glacier retreating during the long-term period is an intensive decrease in summer balance, while accumulation shows a slight positive trend (Fig. 9).

The information on Djankuat glacier mass balance, calculated from the presented dataset, is being published in the Glacier Mass Balance Bulletin, which is issued by the World Glacier Monitoring Service (wgms) at 2-year intervals, and in Fluctuations of Glaciers along with other standardized data on changes in glaciers throughout the world at 5-yearly intervals (see for ex. Popovnin, 2012, 2013).

Some of the glacial measurements data presented in this article was used in global studies on evolution of the Earth's cryosphere (Zemp et al., 2009, Zemp et al., 2011, Zemp et al., 2015). In Popovnin and Pylayeva (2015) snow thickness measurements on Djankuat glacier are used to work out a methodology of estimation of avalanche feeding of a glacier from the total mass of snow accumulation.

3.3 Meteorological measurements

The main purpose of meteorological measurements in the Djankuat research basin is to provide the data needed for calculating the components of the heat balance (Toropov et al., 2017, 2018b), which is a necessary input for physically-based hydrological

models. Aa an example, the presented meteorological data was successfully used to model the melting regime of the Djankuat glacier in 2007 by the A-Melt model of ice and snow melt in alpine areas (Rets, Kireeva, 2010).

The program of meteorological observations in the Djankuat research basin during 2007–2017 included meteorological and radiation measurements and by means of two Campbell AWS placed above ice surface (Gjankuat Glacier AWS1 in Table 1-2, Fig.1, Fig. 3a) and over the debris-covered surface (Gjankuat Glacier AWS2 in Table 1-2, Fig.1). In order to measure the ablation rate at both sites by Sonic Ranger, the sensor was located on a construction drilled into the body of the glacier and measured the distance from the sensor to the ice or snow surface. Standard meteorological characteristics were monitored at the Base Camp by means of DAVIS AWS (Base Camp AWS in Table 1-2, Fig.1, Fig. 3c). In 2017 a Davis AWS was also placed in the upper part of the glacier (Djankuat Glacier AWS 3 in Table 1-2, Fig.1).

Number of experimental observations were carried out at the Gjankuat Glacier AWS1: Gradient observations to obtain turbulent heat fluxes estimations with the Monin–Obukhov method in 2015, that included 4 temperature and humidity sensors and 4 wind sensors located at 0.25, 0.5, 1 and 2 m above the glacier surface; measurements of high frequency turbulent pulsations of wind and acoustic temperature (Fig. 3c).

The Figure 10 shows an example of the course of the average daily values of the basic meteorological variables during the ablation season of 2007 measured by Campbell AWS 1. It is clearly seen that changes in air temperature associated with synoptic events are expressed quite well, their average amplitude is 3 °C (the same values were observed the other years). The average temperature during the ablation period is around 8 °C, while the minimum values almost reach 0 °C annually, and the maximums are 16 to 18 °C. The variability of the radiation balance is determined mainly by cloudiness, which has primarily a pronounced daily variation. The albedo effect is also clearly manifested – especially in June and September, when fresh snow frequently falls on the surface of the glacier. The maximum values of incoming shortwave radiation can reach 1100 W/m². The wind regime is stable to a great extent and varies little from year to year. The average wind speed over the tongue of the glacier is fairly stable at 4-6 m/s. Above the glacier, stable katabatic winds blow, which is characterized by a pronounced diurnal course. The most probable value of the maximum gusts is 10-12 m/s. The absolute maximum for the period under review was 16.6 m/s above the surface of the glacier and 21 m/s above the moraine ridge. The strongest glacial wind is observed in the lower part of the glacier, in the area of the weather station AWS-1, where the maximum slope angle and density contrast between glacial and valley air are combined. The wind decreases down the valley, and in the area of the base camp its gusts rarely exceed 10 m/s. The maximum speed values are associated with foehn winds, observed 3–4 times per season. Table 4 shows the average July values of the main meteorological characteristics.

Figure 11 gives an example of the variability of the main meteorological characteristics in the Djankuat River valley, in the area of the base camp at an altitude of 2640 meters above sea level (Table 1, Fig. 1). The average daily temperature is about 12 °C, the average wind speed is about 2 m/s, despite the fact that the maximum gusts are stronger than over the glacier and reach 18 m/s. This is due to the density difference between the cold air flowing from the glacier and the local air mass forming over the heated alpine meadows and rocks. Heavy rains can be observed in the study area. For example, in 2017, the daily precipitation of about 20 mm was observed 6 times. From August 31 to September 1, about 48 mm of precipitation fell within 48 hours,

which is a very high amount. This rainfall caused the above mentioned outburst of the Bashkara glacial lake in the neighboring valley and the formation of a catastrophic mudflow (Chernomorets et al., 2018).

4 Conclusion

With the detailed measurement program described here, the Djankuat basin is expected to serve as a highly valuable benchmark for evaluating, calibrating and further developing glaciological and hydro-sedimentological catchment models of the alpine catchments. of the North Caucasus and Russian Federation as whole (Konovalov et al., 2018, Stokes et al., 2006, Shagedanova et al., 2005, Hagg et al., 2010). The aim of the multidisciplinary monitoring in the Djankuat basin is not only to fill a "blind-spot" in extremely underreported North Caucasus alpine territories but to provide data for detailed studies of hydrometeorological processes in mountain areas (Rets et al., 2017, Toropov et al., 2017).

The dataset presented here covers the period of 2007–2017 and can be useful to researchers developing and verifying hydrological, glaciological and meteorological models for mountainous territories, studying the recent climate and its impact on the cryosphere and hydrology, using isotopic and hydrochemical approaches to study the source areas of runoff.

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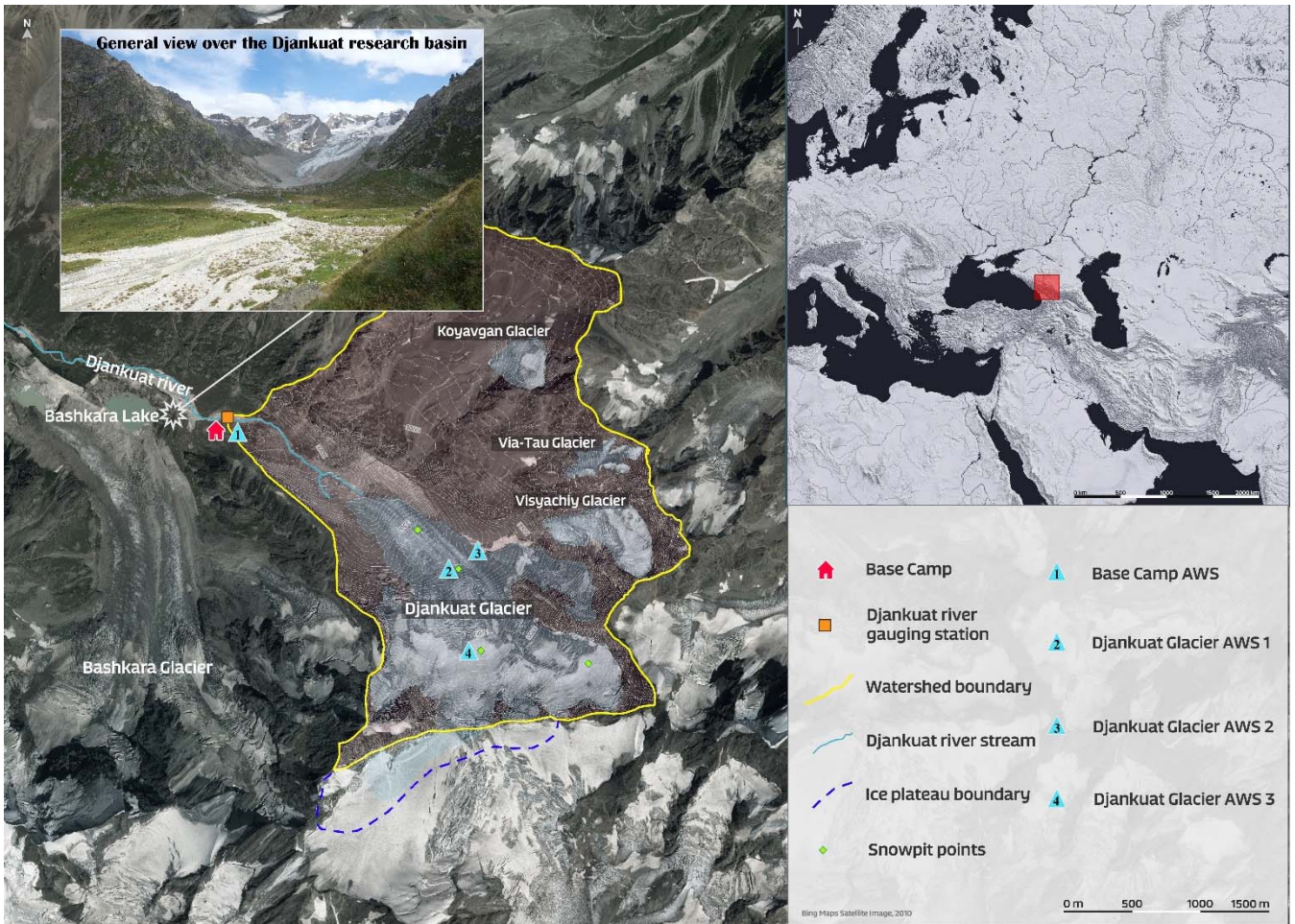

5   **Figure 1: The Djankuat River basin with the depicted location of the Base camp, main weather stations, snowpits and the Djankuat River gauging station.**

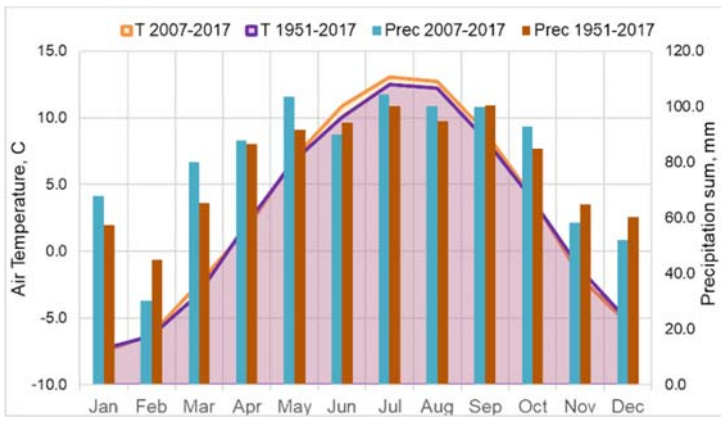
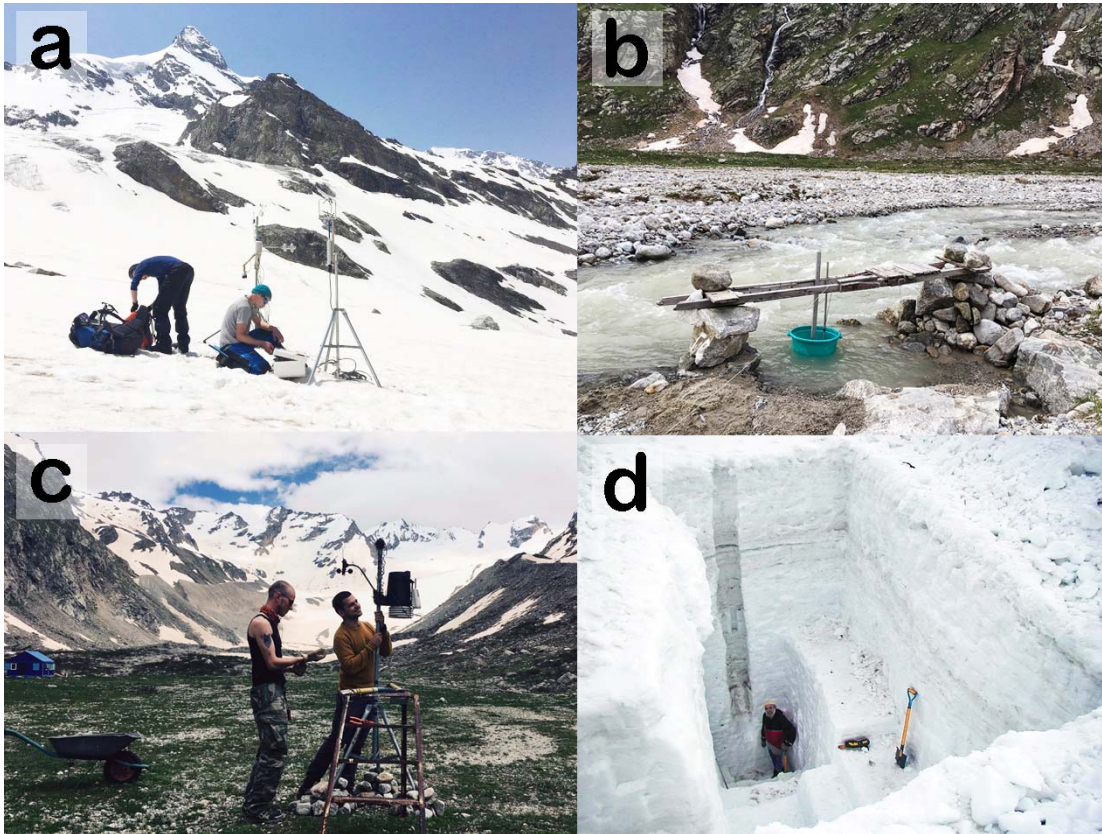



Figure 2: Monthly distribution of air temperature and precipitation for the period of the dataset (2007–2017) compared to the long-term period (1951–2017) on the nearest to the Djankuat research basin all-year weather station Terskol (2146 m).

5   **Figure 3: (a) Campbell meteorological complex with a set of Kip & Zonen radiometers and GILL three-component acoustic anemometer at the Djankuat GlacierAWS1 location; (b) the construction of the Djankuat Gauging Station; (c) Djankuat Base Camp AWS - Davis meteorological station; (d) Snow density measurement in a snowpit at the stake 49.**

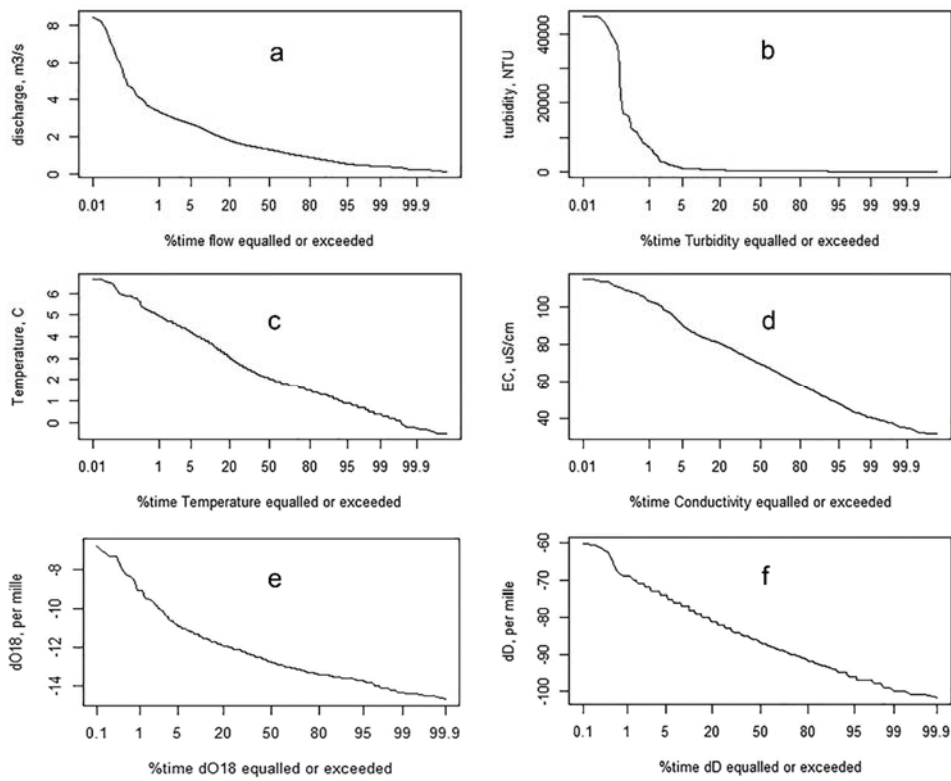
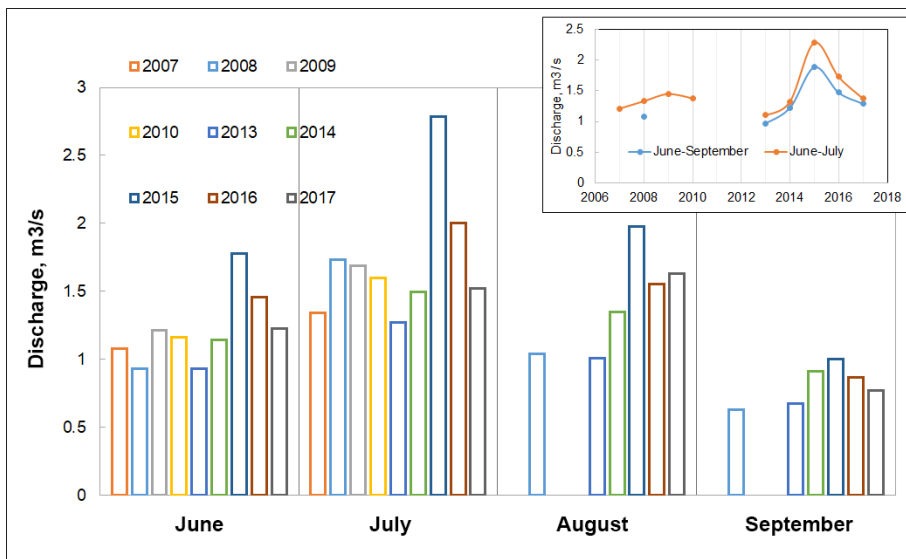



Figure 4: Duration curves of the parameters measured during 2007–2017 on the Djankuat Gauging Station: (a) Water discharge, (b) Optical turbidity, (c) Water temperature, (d) Water Electrical Conductivity, (e) δ18O, (f) δD.

5 **Figure 5: Fluctuations of mean monthly and mean seasonal runoff of Djankuat River during the whole period of observation (2007–2017).**

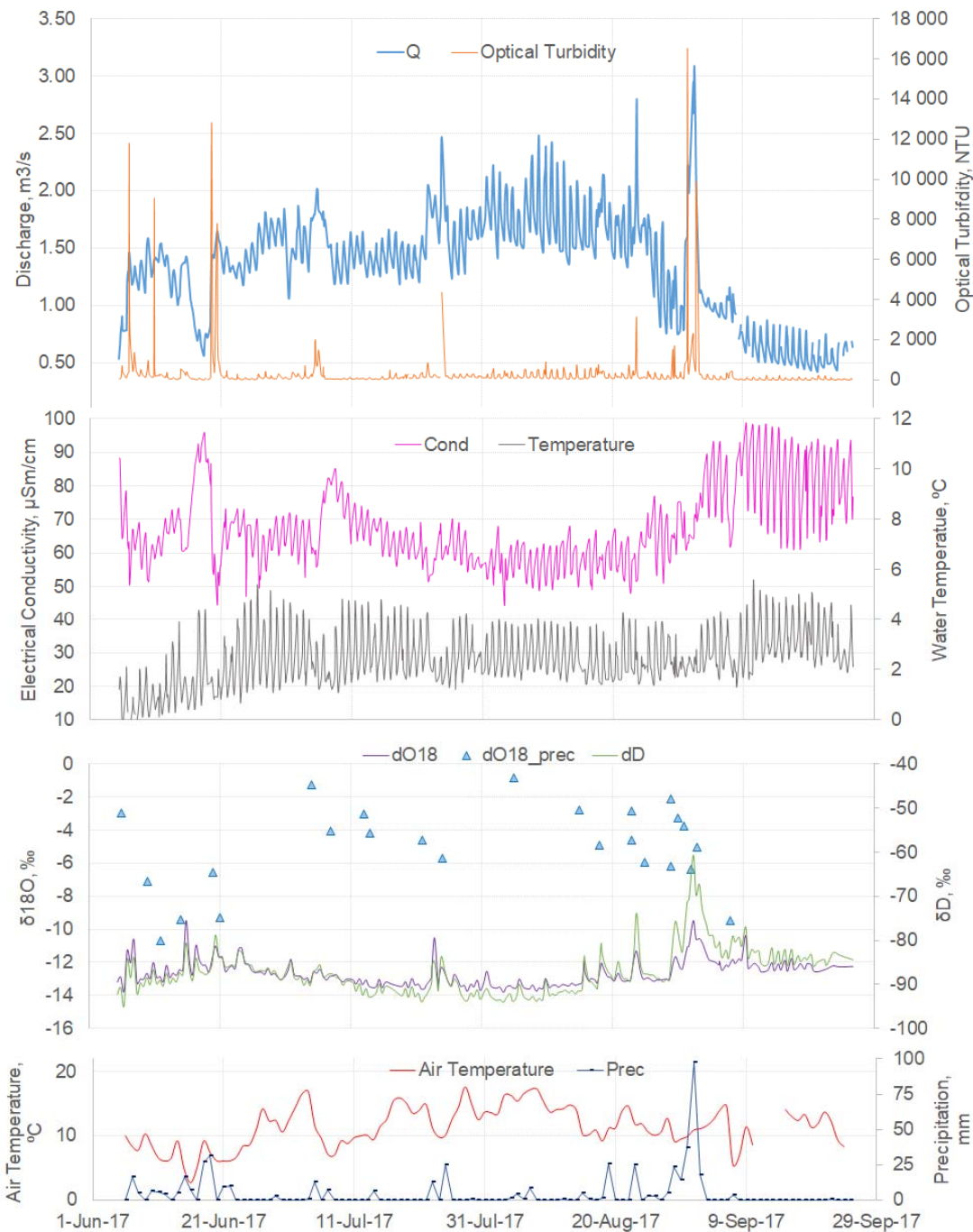



Figure 6: Example of the fluctuations of the water discharge (Q), optical turbidity (Optical Turbidity), electrical conductivity (Cond), water temperature (Temperature), δ¹⁸O (dO18), δD, (dD) in Djankuat River during the ablation season accompained with mean daily air temperature (Air Temperature), precipitation amount (Prec) and δ¹⁸O in liquid precipitation (dO18_prec). Drawn using the observational data for June–September 2017.

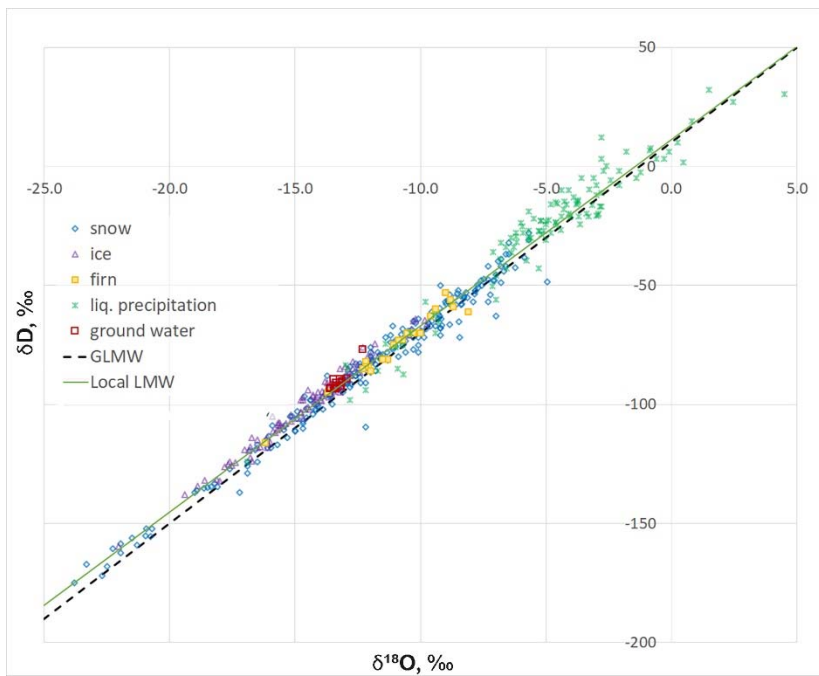
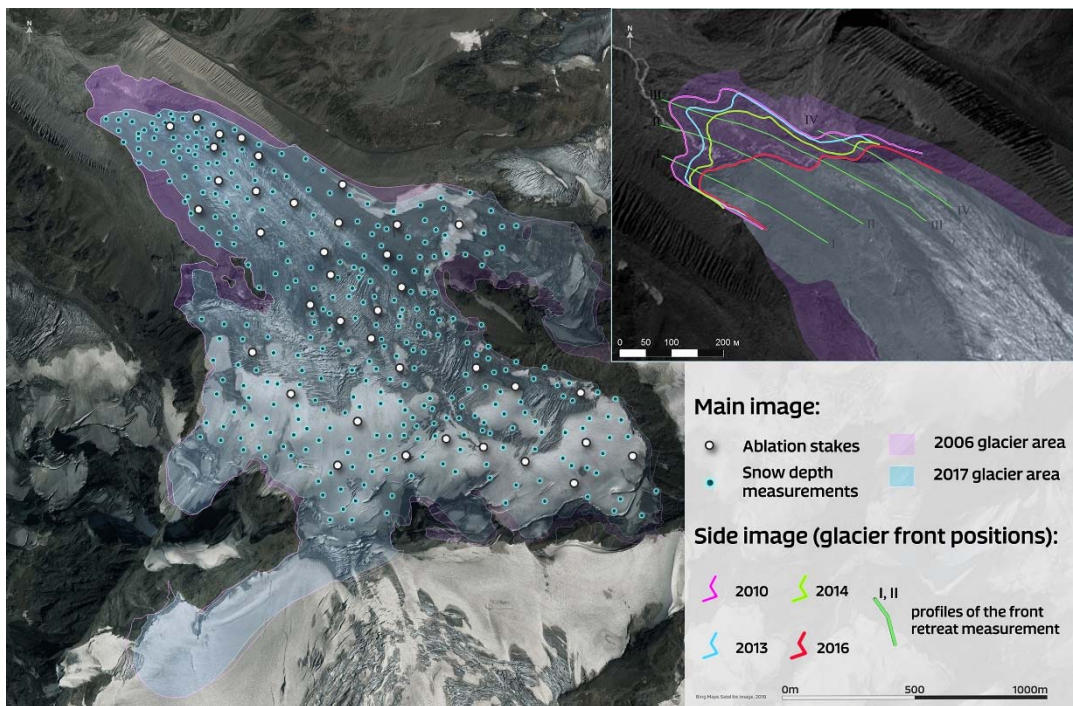



Figure 7: δ¹⁸O vs. δD graph for the samples of snow, ice, firn, liquid precipitation and groundwater collected in the Djankuat River basin in 2013–2017, plotted with a global and local meteoric water line.

5   **Figure 8: The spatial distribution of ablation stakes and snow thickness measurement points, change in the Djankuat glacier area during the study period and glacier front position.**

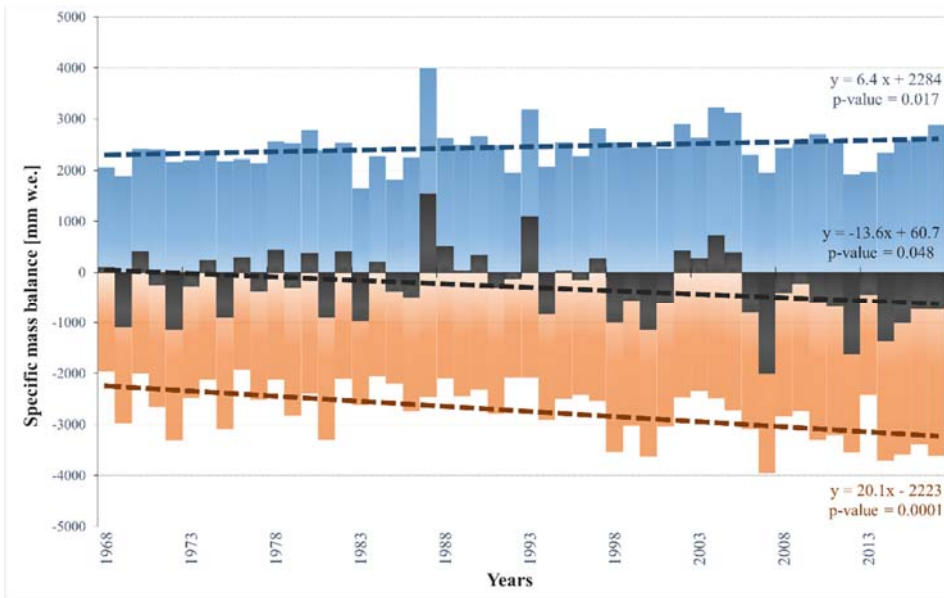



Figure 9: Fluctuations of the Djankuat glacier mass balance components in mm of water equivalent (mm w.e.) since the beginning of the observations in 1968 (www.wgms.ch).

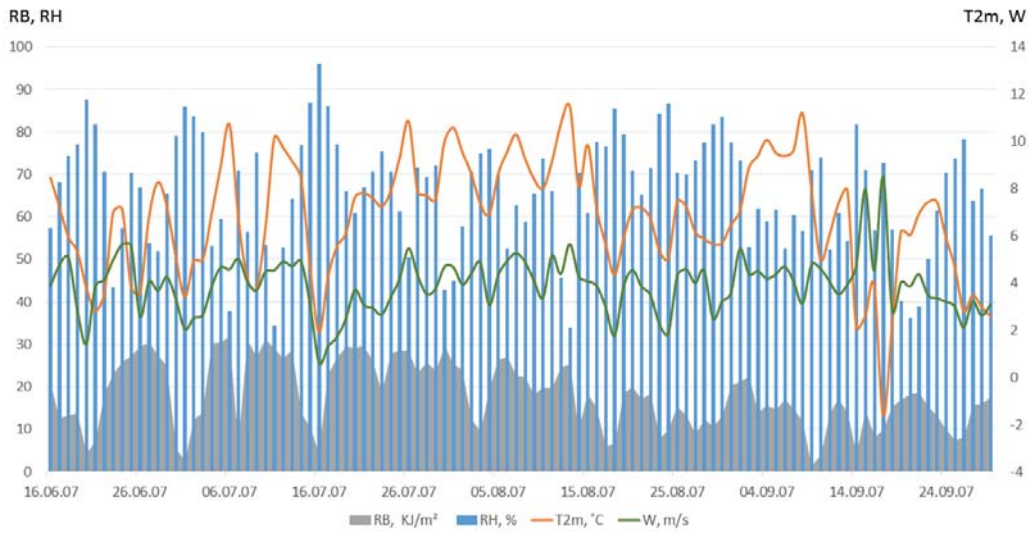



Figure 10: An example of temporal variability of average daily values on the Djankuat glacier (measured in Djankuat glacier AWS-1 location) in 2007: RB – radiation balance, KJ/m², RH – relative humidity,% T2m – air temperature, °C, W – wind speed, m/s.

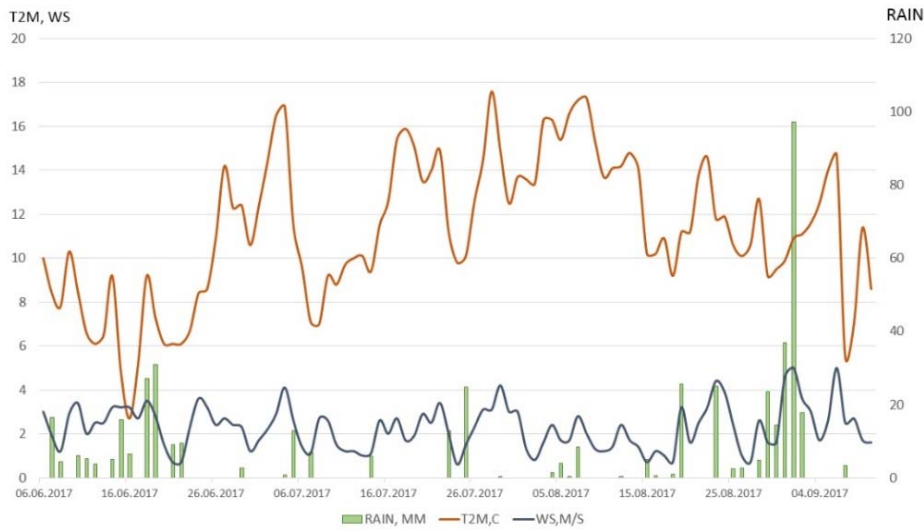



Figure 11: An example of temporal variability of average daily temperature, wind speed and precipitation sum on base camp (point AWS–«base camp»): RAIN –precipitation, mm/day, T2m – air temperature, ⁰C, WS – wind speed, m/s.

5 **Table 1: Location of main Sites within the Djankuat research basin**

#	Name	x (longitude), decimal degrees	y (latitude), decimal degrees	Elevation, m
1	Djankuat Base Camp	42.735	43.208	2635
2	Djankuat Base Camp AWS	42.736	43.208	2640
3	Djankuat Glacier AWS 1	42.757	43.198	3000
4	Djankuat Glacier AWS 2	42.759	43.2	3050
5	Djankuat Glacier AWS 3	42.759	43.193	3200
6	Djankuat River Gauging Station	42.736	43.209	2630

Table 2a: Hydrological characteristics measured in the Djankuat research basin and included in the database

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements (with number of days in brackets)
1	Djankuat River Gauging Station	Water Discharge	m³/s	1 hour	<10%	Calculated from water level measurements (see in the text)	15.06.07 – 12.07.07 (28) 06.06.08 – 15.09.08 (102) 15.06.09 – 19.07.09 (35) 14.06.10 – 14.07.10 (31) 10.06.13 – 26.09.13 (109) 08.06.14 – 30.09.14 (115) 09.06.15 – 19.09.15 (103) 14.06.16 – 27.09.16 (106) 03.06.17 – 25.09.17 (115)

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements (with number of days in brackets)
2		Water Temperature	°C	1 hour step or 6-7 times daily	0.5		28.06.08 – 26.07.08 (29) 15.06.09 – 19.06.09 (5) 09.06.15 – 19.09.15 (70) 09.06.16 – 18.09.16 (74) 03.06.17 – 25.09.17 (115)
3		Water Electrical Conductivity	μS/cm		2%	Electrical conductivity meter Econics Expert-002	28.06.08 – 26.07.08 (29) 15.06.09 – 19.06.09 (5)
4		Water Salinity	mg/L		-	Calculated from Electrical conductivity (see in the text)	10.06.13 – 19.09.13 (4) 19.06.14 – 30.09.14 (104) 09.06.15 – 19.09.15 (67) 09.06.16 – 18.09.16 (74) 03.06.17 – 25.09.17 (115)
5		Optical Turbidity	NTU	6-7 times daily	2%+0.02 NTU	Portable turbidity meter HACH 2100P	28.06.08 – 17.07.08 (20) 10.06.13 – 20.06.13 (5)
6		Turbidity in weight units	SSC		-	Calculated from Turbidity measured in NTU (see in the text)	31.08.14 – 08.09.14 (9) 08.06.15 – 19.09.15 (104) 09.06.16 – 19.09.16 (103) 03.06.17 – 25.09.17 (115)
7		^{18}O concentration as δ-notion	‰	2 times daily	0.06-0.1	2013:mass spectrometer, 2014-2016:laser-based spectrometer; 2017 - Cavity Ring-Down Spectroscopy (see text for details)	11.06.2013 – 19.09.13 (4) 08.06.14 – 30.09.14 (115) 08.06.15 – 18.09.15 (98) 06.06.16 – 18.09.16 (105) 03.06.17 – 25.09.17 (115)
8		^{2}H concentration as δ-notion	‰		0.4-2	2014-2016:laser-based spectrometer; 2017 - Cavity Ring-Down Spectroscopy (see text for details)	08.06.14 – 30.09.14 (115) 08.06.15 – 18.09.15 (98) 06.06.16 – 18.09.16 (105) 03.06.17 – 25.09.17 (115)
9	Snow, Ice, Firn, Ground water, Liquid precipitation samples in different parts of the watershed	Water Electrical Conductivity	μS/cm	60-200 samples of each Snow, Ice, Firn, Ground water, Liquid precipitation a year	2%	Electrical conductivity meter Econics Expert-002	8 samples in 2013 104 samples in 2014 64 samples in 2015 100 samples in 2016 209 samples in 2017
10		Water Salinity	mg/L		-	Calculated from Electrical conductivity (see in the text)	
11		^{18}O concentration as δ-notion	‰		0.06-0.1	2013:mass spectrometer, 2014-2016:laser-based spectrometer; 2017 - Cavity Ring-Down Spectroscopy (see text for details)	
12		^{2}H concentration as δ-notion	‰		0.4-2	2014-2016:laser-based spectrometer; 2017 - Cavity Ring-Down Spectroscopy (see text for details)	

Table 2b: Glaciological characteristics measured in the Djankuat research basin and included in the database

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements
1	At 250–300 evenly distributed points on the Djankuat Glacier Surface	Snow thickness	cm	1 time yearly	5	Probe poles	12.06.07 – 30.06.07 12.06.08 – 07.07.08 08.06.09 – 07.07.09 19.05.10 – 10.07.10 04.06.12 – 06.07.12 05.06.13 – 01.07.13 04.06.14 – 04.07.14 04.06.15 – 12.07.15

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements
							26.05.16 – 15.07.16 04.06.17 – 11.07.17
2	At 35–45 evenly distributed points on the Djankuat Glacier Surface	Ablation	mm of water equivalent	1-30 days	2	Ablation stakes	12.06.07 – 10.09.07 16.05.08 – 07.10.08 08.06.09 – 25.09.09 18.06.10 – 02.10.10 03.06.12 – 04.10.12 05.06.13 – 21.09.13 04.06.14 – 30.09.14 04.06.15 – 20.09.15 26.05.16 – 20.09.16 03.06.17 – 24.09.17
3	Stake 9, 18, 49, 65/68	Snow density	g/cm³	1-5 times in each snowpit yearly	0.01	Snow sampling cylinder	19.05.07 – 13.06.07 16.05.08 – 14.07.08 03.06.09 – 01.09.09 21.05.10 – 06.07.10 04.06.12 – 06.07.12 06.06.13 – 22.06.13 05.06.14 – 02.09.14 05.06.15 – 04.09.15 29.05.16 – 07.10.16 06.06.17 – 10.08.17

Table 2c: Meteorological characteristics measured in the Djankuat research basin and included in the database

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements (with number of days in brackets)
1		Air temperature at 2 m	°C		0.2	Campbell AWS - Vaisala MT300 sensor	
2		Relative humidity at 2 m	%		5		
3		Wind speed at 2 m	m/s		(0.5+0.05W)	Campbell AWS - wind sensor	15.06.07 – 30.09.07 (107)
4		Wind diection at 2 m	°		10		17.06.08 – 30.09.08 (105)
5		Atmospheric pressue	hPa		1	Campbell AWS - Vaisala pressure sensor	01.07.09 – 30.09.09 (91) 09.07.10 – 29.09.10 (82) 10.07.12 – 05.08.12 (26)
6		Incoming shortwave radiation	Wt/m²			Campbell AWS - KEEP & ZONNEN radiometers	07.07.13 – 09.09.13 (64) 19.06.14 – 30.09.14 (103)
7		Reflected shortwave radiation	Wt/m³		15		07.07.15 – 04.09.15 (59)
8		Downward longwave radiation	Wt/m⁴				20.06.16 – 05.09.16 (77)
9		Upward longwave radiation	Wt/m²				19.06.17 – 02.09.17 (75)
10		Sensor-surface distance	m		0.01	Campbell AWS - Sonic Ranger sensor	
11		Air temperature at 0.25, 0.5, 1 and 2 m	°C		±0,4		
12		Relative humidity at 0.25, 0.5, 1 and 2 m	%		±10		
13		Mean wind speed at 0.25, 0.5, 1 and 2 m	m/s		±0.5 – 2		05.07.15 – 15.08.15 (41)
14		Maximum wind speed at 0.25, 0.5, 1 and 2 m	m/s				
15		Wind direction at 0.25, 0.5, 1 and 2 m	rhumb	15 min	-	DAVIS AWS	
16	Djankuat Glacier AWS 1	Three components of wind speed	m/s		0.05 – 0.1	Sonic anemometer GILL	12.07.13 – 03.08.13 (22) 09.08.13 – 16.08.13 (7)
17		T - acoustic temperature	°C	10 Hz			26.08.13 – 06.09.13 (42)

#	Site	Characteristic	Unit	Sampling intervals	Accuracy modulus	Method	Period of measurements (with number of days in brackets)
							30.06.14 – 30.07.14 (30) 17.06.16 – 01.08.16 (45)
18		Air temperature at 2 m	°C		0.2	Campbell AWS - Vaisala MT300 sensor	
19		Relative humidity at 2 m	%		5		
20		Wind speed at 2 m	m/s		(0.5+0.05W)	Campbell AWS - wind sensor	
21		Wind diection at 2 m	°		10		
22		Atmospheric pressue	hPa		1	Campbell AWS - Vaisala pressure sensor	17.06.07 – 07.09.07 (82) 02.07.08 – 26.09.08 (86) 23.06.09 – 02.10.09 (101)
23		Incoming shortwave radiation	Wt/m²			Campbell AWS - KEEP & ZONNEN radiometers	
24		Reflected shortwave radiation	Wt/m³		15		
25		Downward longwave radiation	Wt/m⁴				
26		Upward longwave radiation	Wt/m²				
27	Djankuat Glacier AWS 2	Sensor-surface distance	m	15 min	0.04-0.06	Campbell AWS - Sonic Ranger sensor	
28		Air temperature	°C		0.4		
29	Djankuat Glacier AWS 3	Relative humidity	%	15 min	10		19.06.17 – 21.08.17 (63)
30		Wind speed	m/s		(0.6+0.06W)		
31		Wind diection	°		15	DAVIS AWS	
32		Air temperature	°C		0.4		17.06.07 – 14.09.07 (90) 12.06.08 – 20.09.08 (101) 26.06.09 – 04.10.09 (101) 08.06.13 – 07.09.13 (92) 09.06.14 – 01.10.14 (115) 09.06.15 – 18.09.15 (102) 09.06.16 – 01.10.16 (115) 06.06.17 – 25.06.17 (112)
33		Relative humidity	%		10		
34	Base Camp AWS	Wind speed	m/s	15 min	(0.6+0.06W)		
35		Wind diection	°		15		
36		Atmospheric pressue	hPa		1	DAVIS AWS	
37		Liquid precipitation	mm	24 hours	5% of total	Rain Gauge	

Table 3: Mean value and range of some of the parameters measured in the Djankuat research basin

Parameter	Site	Unit	Number of values	Mean	Max	Min
Water Discharge		m³/s	16971	1.39	8.46	0.11
Water Temperature		ºC	3259	2.26	6.63	0.1
Optical Turbidity	Djankuat River Gauging Station	NTU	1991	468	45060	6.9
Weight Turbidity		g/L	1991	368	37164	28
Water Electrical Conductivity	Djankuat River Gauging Station	µS/cm	3464	56.76	115	31.7
	Snow samples		218	9.3	37.2	0.3
	Ice samples		116	14.8	63.7	0.7
	Firn samples		22	13.7	23	4.1
	Groundwater samples		16	109	115	104
δ¹⁸O	Djankuat River Gauging Station	‰	844	-12.6	-6.7	-14.7
	Snow samples		218	-12.2	-5	-28.3
	Ice samples		116	-14.3	-9.8	-22
	Firn samples		22	-11.3	-8.1	-16.2
	Liquid precipitation samples		113	-4.9	5.6	-16.9
	Groundwater samples		16	-13.3	-12.3	-13.6

	Djankuat River Gauging Station		842	-86.2	-60	-102
	Snow samples		218	-85.5	-28	-216
	Ice samples		116	-99.3	-64	-160
	Firn samples		22	-77.1	-53	-116
	Liquid precipitation samples		113	-26.2	32	-124
δD	Groundwater samples	‰	16	-91.1	-77	-93.5
Snow thickness		cm	2932	360	1155	7
Ablation		mm w.e./day	5045	47	387	0
Mean snow density for the snowpack		g/cm^3	66	0.57	0.64	0.46
Snow density by layers of the snowpack	Djankuat Glacier	g/cm^3	434	0.57	0.92	0.23
	Base Camp AWS		5340	10.2	24.2	-1.10
	Djankuat Glacier AWS 1		17551	6.60	17.6	-8.97
Air temperature at 2 m_hourly	Djankuat Glacier AWS 2	°C	4901	6.37	15.8	-4.22
	Base Camp AWS		5340	65.0	95.0	12.5
	Djankuat Glacier AWS 1		17526	68.4	100.0	13.9
Relative humidity at 2 m_hourly	Djankuat Glacier AWS 2	%	4901	68.0	100.0	10.5
	Base Camp AWS		5095	1.93	10.8	0.10
	Djankuat Glacier AWS 1		17469	3.95	16.6	0.00
Wind speed at 2 m_hourly	Djankuat Glacier AWS 2	m/s	6095	5.50	21.1	0.01
	Djankuat Glacier AWS 1		13728	273.8	1150.0	0.0
Incoming shortwave radiation_hourly	Djankuat Glacier AWS 2	Wt/m^2	3706	330.2	1160.0	0.0
	Djankuat Glacier AWS 1		16920	295.4	407.9	161.5
Downward longwave radiation_hourly	Djankuat Glacier AWS 2	Wt/m^2	6466	286.6	382.5	156.0
	Djankuat Glacier AWS 1		17548	313.7	408.9	171.7
Upward longwave radiation_hourly	Djankuat Glacier AWS 2	Wt/m^2	6466	353.1	494.9	156.8
Liquid precipitation daily sum	Base Camp AWS	mm/day	232	11.2	97.2	0.1

Table 4. July daily averaged meteorological variables on Djankuat glacier in 2007–2017 (with RMS in brackets)

Year	Air temperature, °C			Relative humidity, %		Wind speed, m/s		Components of radiation balance, Wt/m^2 Albedo A, %				
	Mean	Min	Max	Mean	Min	Mean	Max	SW+	SW-	LW+	LW-	A, %
2007	8.0(±2.6)	0.4	13.5	66 (±19)	13	3.8 (±1.7)	8.4	247(±99)	68(±39)	280(±27)	314(±3)	19
2008	8.1(±2.1)	2.3	13.9	72 (±15)	24	4.2 (±1.8)	9.3	237(±105)	88(±58)	291(±26)	315(±4)	32
2009	6.0(±2.5)	-0.5	14.2	76 (±13)	36	3.8 (±1.7)	9.0	225(±88)	71(±48)	286(±29)	313(±8)	23
2010	8.3(±2.2)	2.9	15.2	68 (±14)	31	4.2 (±1.3)	8.5	265(±84)	43(±15)	293(±21)	317(±5)	18
2012	7.7(±2.0)	1.7	15.2	71 (±15)	31	3.9 (±1.6)	7.9	267(±104)	57(±25)	290(±19)	323(±3)	21
2013	5.0(±2.2)	-0.7	10.7	77 (±12)	40	3.5 (±2.0)	10.5	225(±98)	53(±30)	300(±22)	325(±4)	24
2014	7.6(±2.1)	2.4	14.7	67 (±16)	18	3.6 (±1.6)	8.3	274(±111)	47(±18)	306(±18)	293(±6)	19

2015	8.8(±2.8)	-0.1	17.9	65 (±17)	15	4.0 (±1.8)	8.9	308(±78)	75(±22)	357(±10)	332(±5)	24
2016	7.6(±2.8)	0.2	15.1	69 (±16)	24	3.8 (±1.9)	9.0	235(±92)	65(±23)	305(±15)	315(±6)	23
2017	8.3(±2.3)	0.5	17.6	63 (±15)	20	4.2 (±2.0)	10.1	224(±98)	54(±30)	301(±22)	324(±4)	25
Mean	7.6(±2.3)	1.1	14.5	68 (±17)	25	3.9 (±1.7)	8.9	231(±94)	63(±25)	300(±10)	317(±5)	24