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Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe

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[1] The contribution of glaciers to runoff from large-scale drainage basins in Europe is analyzed for the major streams originating in the Alps: Rhine, Rhone, Po, and Danube. Detailed information on glacier storage change is available from monthly mass balance data of 50 Swiss glaciers for the period 1908–2008. Storage changes are extrapolated to all glaciers in the European Alps. By comparing monthly runoff yields from glacierized surfaces in the summer months with measured runoff at gauges along the entire length of the streams, the relative portion of water from glacier storage change for each month is calculated. Macroscale drainage basins with a size of 100,000 km^2 (1% ice-covered) can show a 25% contribution of glaciers to August runoff over the last century. In the lower Danube (0.06% glacierization) glacier meltwater accounts for 9% of observed runoff in September of the extreme year 2003. The relative importance of glacier contribution to runoff does not scale linearly with the percentage of glacierization, as high glacier runoff in summer dominates lowland areas with little precipitation and high evapotranspiration. Thus, glacial meltwaters are relevant to the hydrological regime of macroscale watersheds and do not only have a regional impact. By transiently modeling future glacier retreat until 2100 using climate scenarios, a reduction of glacierized areas in the Alps to 12% of the current value is found. In consequence, summer runoff contribution from currently glacierized basins will be strongly reduced, intensifying issues with water shortage in summer also in poorly glacierized catchments.

1. Introduction

[2] Glacier meltwater strongly affects the runoff regime of mountainous drainage basins and is an important source of runoff in the summer months [*Kuhn and Batlogg*, 1998; *Jansson et al.*, 2003]. With the expected future retreat of alpine glaciers there is increasing concern about water supply security in the European Alps [*Beniston*, 2003; *Viviroli et al.*, 2011] and, even more importantly, in other dry mountain ranges as the South American Andes or central Asia [*Kaser et al.*, 2003; *Casassa et al.*, 2009; *Immerzeel et al.*, 2010]. The impact of future glacier change on runoff yields, for example in the Himalayas, is discussed with considerable controversy [*Alford and Armstrong*, 2010] and obtains widespread public interest [*Cogley et al.*, 2010]. Future changes in hydrology are likely to have strong socioeconomic impacts on a global scale [*Arnell*, 1999; *Kundzewicz et al.*, 2008; *Kaser et al.*, 2010].

[3] Mountains are often regarded as "water towers" providing vital amounts of water to the streams leading through the densely populated lowland areas to the sea [*Viviroli et al.*, 2007]. According to *Viviroli and Weingartner* [2004] runoff from the mountainous headwaters of the Alps contributes about twice as much water (compared to their areal proportion) to runoff of the four major European streams. But the percentage of ice-covered surfaces in these macroscale watersheds is mostly significantly smaller than 1%. This might lead to the conclusion that glaciers are negligible runoff contributors outside of the Alps. However, due to their high specific runoff in the summer months, glacier meltwater can have an overregional impact that is also recognizable in large basins [*Comeau et al.*, 2009].

[4] The contribution of glaciers to runoff can be quantified based on two different concepts: (1) runoff only due to melt of the bare ice surface is considered, or (2) the glacier storage change ΔS corresponding to the closure of the water balance ($Q = P - E - \Delta S$) is evaluated. Concept 1 requires the application and the careful calibration of a distributed hydrological model in order to separate the quantities of water originating from the snow covered and snow-free parts of the glacier that change their extent continuously. This approach provides process-based portions of melt from snow or ice. This is advantageous for the analysis of changes in the runoff regime because the individual components are revealed. Concept 2 can also be applied without a hydrological model and yields information on the total water yield of glacierized surfaces. The monthly glacier storage change ΔS is made up by snow accumulation (positive), and snow and ice melt (negative). This approach thus takes into account that glaciers do not only contribute to runoff with bare ice melt, but also with reduction of their snow coverage. Snow and ice melt on the glacier surface are

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intrinsically interlinked: Snow that is not melted during 1 year will contribute to a more positive mass balance of the glacier and is transformed into ice. For these reasons, concept 2 considering the glacier storage change to correspond to the contribution of glaciers to the hydrological cycle is emphasized here. Results of concept 1 are also presented for comparison.

[5] Physically-based or conceptual rainfall-runoff models perform well for small, highly glacierized basins, as effects of mountain topography and complex accumulation and ablation processes on glaciers can be accounted for in detail [e.g., *Verbunt et al.*, 2003; *Schaefli et al.*, 2007; *Huss et al.*, 2008; *Koboltschnig et al.*, 2008; *Stahl et al.*, 2008]. The long-term changes in runoff from large-scale drainage basins were also calculated using models with coarser spatial resolution [e.g., *Middelkoop et al.*, 2001; *Weber et al.*, 2010]. Whereas the contribution of snowmelt to runoff can be simulated reasonably well by these models, the representation of glaciers is difficult as they are often much smaller than one grid cell. Thus, the resolution of processes determining the glacier mass balance is prone to a significant uncertainty as these processes may vary over one order of magnitude on short spatial scales. Nested modeling and advanced subgrid parameterization approaches are promising alternatives [e.g., *Soulsby et al.*, 2006; *Weber et al.*, 2010].

[6] *Lambrecht and Mayer* [2009] evaluated the contribution of glaciers to the hydrological cycle by analyzing their long-term mass balance, that is, their storage change. This method is directly based on field observations and does not require modeling that increases the uncertainty in the results. The approach, however, does neither resolve glacier contributions on a monthly scale, nor the relative importance of snow and ice melt. Glacier contribution to runoff was also inferred by analysis of discharge anomalies in the hot summer of 2003 [*Zappa and Kan*, 2007]. This indicates that also by straightforward runoff data analysis estimates of the importance of glacier melt in the hydrological cycle can be obtained [see also *Pellicciotti et al.*, 2010].

[7] In a recent study, *Kaser et al.* [2010] quantified the relevance of the glacier contribution to the water availability of 17 glacierized large-scale drainage basins on different continents and analyzed the impact on the population. Their method relies on gridded climatologies, but does not include direct observations of glacier melt and runoff. *Kaser et al.* [2010] come to the conclusion that the importance of glaciers in a basin strongly depends on the seasonality of climate. Whereas glacier runoff is vital in arid regions, it is negligible in monsoon climates.

[8] Estimating the present and future contribution of glacier melt to runoff from large-scale catchments is a challenge: Hydrological models for entire basins necessarily have a coarse resolution. Although they may yield good results for the water balance in the lowlands, the representation of the small-scale variability of glacier mass balance is difficult and results in significant uncertainties. More simple approaches based on the annual glacier storage change obtained from mass balance data have the drawback that the monthly contribution is not resolved. Due to the high seasonality of glacier storage change, this is a crucial effect.

[9] In this study, an approach is presented that addresses both above mentioned problems. The method is based on a simple comparison of scales: glacier storage change in monthly resolution for the entire 20th century is obtained from a variety of glacier mass balance data and detailed glaciological modeling for 50 glaciers in the Swiss Alps. Storage changes extrapolated to all European glaciers provide monthly runoff yields in the catchments of all major streams leaving the Alps. The quantity of water provided by glacier storage change in the summer months is compared to measured discharge at several gauges along the Rhine, Rhone, Po and Danube from their source until the mouth taking into account the time delay of meltwater. Drainage basin sizes of up to 800,000 km^2 are included in the evaluation; the catchment glacierization ranges over three orders of magnitude.

[10] Relative contributions of glacier storage change over the 20th century (study period 1908–2008) to runoff from 22 drainage basins in Europe are presented. The main focus is on the month of August. Based on an analysis of the components of glacier storage change (accumulation, snow and ice melt), and the evaluation of their relative importance in different periods, new insights into the dynamics of glacier melt and its impact on overregional runoff are possible. In particular, shifts in glacier contribution during the last two decades and the extreme year of 2003 are emphasized. Results of transient model runs of the 21st century glacier retreat are presented. Based on these data, the future changes in snow and ice melt, and the contribution of glacier storage change to runoff until 2100 is simulated. This allows the future importance of glacier contribution in macroscale drainage basins to be assessed, and provides an important planning basis for adapting to a possible future water shortage in the summer months.

2. Study Sites and Data

2.1. Study Area

[11] This study focuses on the four major European streams originating in the Alps: Rhine, Rhone, Po, and Danube (Figure 1). The head watersheds of all drainage basins are glacierized; however, the percentage of ice coverage decreases toward zero when approaching the mouth of the streams. All streams flow through many countries of the European continent and represent an important economic factor.

[12] The Rhine has its source region in the eastern Swiss Alps, and runs over more than 1000 km through Germany and the Netherlands to the Northern Sea. With a total catchment area of roughly 200,000 km^2 the Rhine is, after the Danube, the most important stream draining water from the European Alps. In the headwaters of the Rhine, the major tributary of the Aare is considered as the main branch in this study due to more important glacierization (Figure 1).

[13] The Rhone has its origin in the central Swiss Alps. Its headwaters have a considerable glacier coverage. The Rhone flows through France southward into the Mediterranean Sea. The size of the entire drainage basin is about 100,000 km^2.

[14] The Po catchment is comparable to the Rhone. The source region of the Po is at the southern flank of the Alps, mostly in Italy. The stream leads into the Adriatic Sea. Due to a scarcity of available runoff data along the Po, this study includes the poorly glacierized Swiss tributary of the Ticino in the headwaters.

[15] The Danube is the longest stream in central Europe (almost 3000 km) and drains an important part of south-

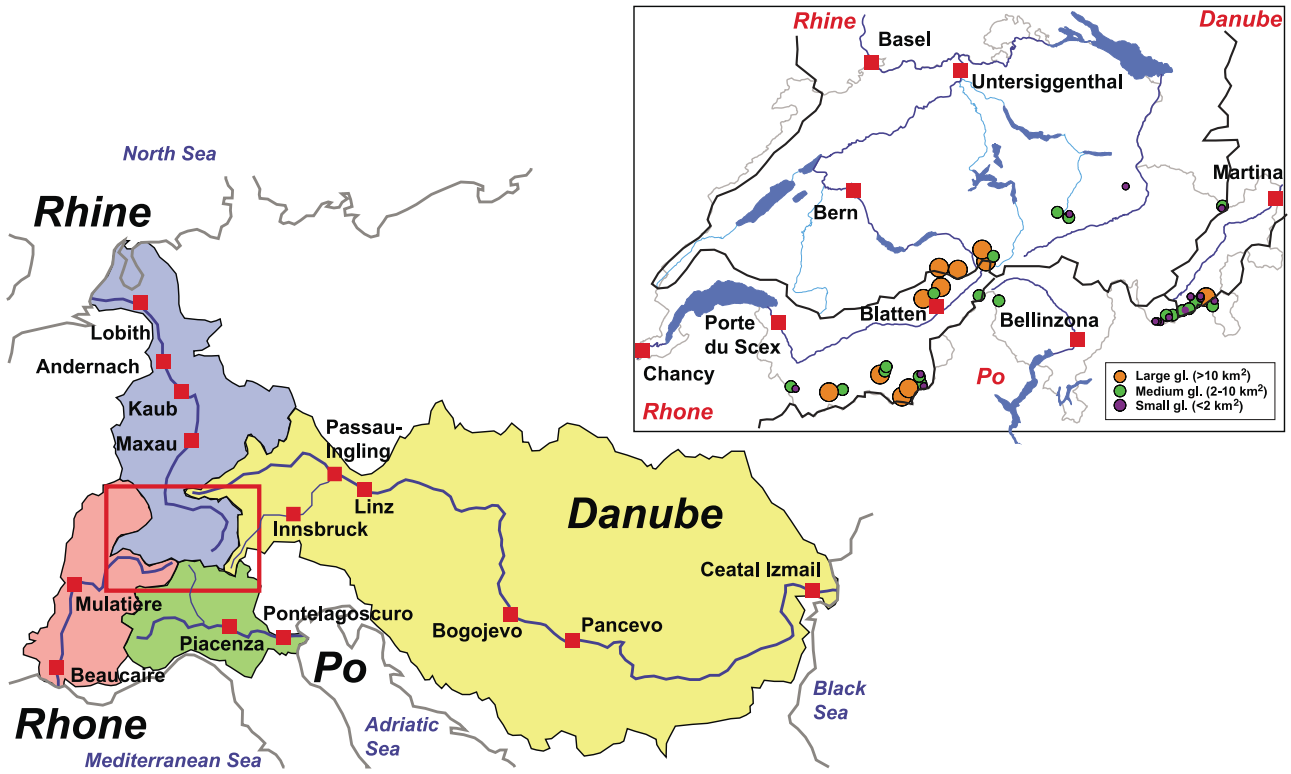

Figure 1. Overview map of investigated drainage basins (Rhine, Rhone, Po, and Danube) and runoff gauges (squares). The box containing Switzerland with the glacierized headwaters of all streams is enlarged. The location of the 50 glaciers with mass balance data is shown and their size is indicated.

eastern Europe into the Black Sea. Compared to the basin size of 800,000 km^2, glacier cover is very limited and concentrated in the Austrian Alps. The main branch of the Danube headwaters is not glacierized. Therefore, a major tributary, the Inn, is considered as the origin of the Danube in this study (Figure 1).

2.2. Glacier Data

[16] Mass balance data for 50 glaciers in the Swiss Alps (Figure 1) are central to this study. For all of these glaciers, monthly glacier storage changes are available from a combination of field data and modeling [*Huss et al.*, 2010a, 2010b] (see section 3). In total, 18% of the currently glacierized area in the European Alps is covered by the data set.

Table 1. Glacier Size Classes and Glacier Data Coverage[a]

	Size Class (km^2)	A_{gl} (km^2)	n_{gl}	R_d (%)	$\overline{b_{1908-2008}}$ (m w.e.)	ΔA (%)
I	<0.5	266.3	7	0.8	−0.26	−51.1
II	0.5–1.0	204.6	6	3.2	−0.26	−27.9
III	1.0–3.0	470.2	11	6.0	−0.23	−20.1
IV	3.0–6.0	336.1	11	18.9	−0.25	−11.4
V	6.0–10.0	307.3	4	11.6	−0.36	−11.9
VI	10.0–20.0	349.7	8	45.9	−0.29	−8.2
VII	>20.0	271.2	3	55.3	−0.45	−7.7
Total		2205.4	50	17.5	−0.28	−21.7

[a] A_{gl} refers to the total glacierized area in the size class according to inventory data reduced to the year 2008, n_{gl} is the number of glaciers with data, and R_d is the percentage of glacier area represented by mass balance series in the data set. The value $\overline{b_{1908-2008}}$ is the mean specific glacier mass balance in a 100 year period given in meters water equivalent (w.e.) according to *Huss et al.* [2010a, 2010b], and ΔA is the relative glacier area change in the period 1970–2008.

Glaciers are represented best for the Rhone and the Rhine catchments. Mass balance data are somewhat less dense for the Danube and the Po. 10 glaciers with storage change data are situated in the Rhine basin, 19 in the catchment of the Rhone, 9 are drained by the Po, and 12 by the Danube. The glaciers have different sizes (0.08–80 km^2), regional climate conditions and exposures. They are thus assumed to be a representative sample of all glaciers in the European Alps allowing extrapolation of storage change to unmeasured glaciers.

[17] Glaciers were divided into seven size classes (Table 1 and Figure 2). Each size class contains about the same

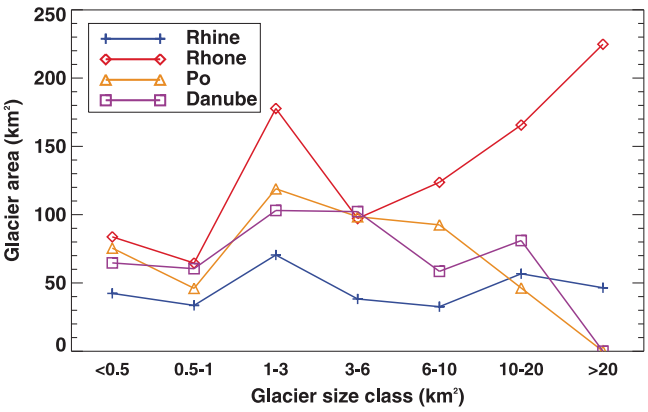

Figure 2. Glacier size distribution in the catchments of Rhine, Rhone, Po, and Danube according to the WGI reduced to 2008 (Table 1).

Table 2. Compilation of Long-Term Runoff Measurements and Catchment Glacierization[a]

River	ID	Station	Period	Nation	A_c (km^2)	A_{gl} (km^2)	Glacierization (%)	t_w (days)	n_{gl}	R_d (%)
Rhine (Aare)	Ri1	Bern	1917–2008	CH	2969	190.7	6.42	2	3	29.9
Rhine (Aare)	Ri2	Untersiggenthal	1935–2008	CH	17625	272.5	1.55	5	3	20.9
Rhine	Ri3	Basel	1869–2008	CH	35930	320.4	0.89	6	10	22.8
Rhine	Ri4	Maxau	1921–2008	D	50196	320.4	0.64	8	10	22.8
Rhine	Ri5	Kaub	1930–2008	D	103488	320.4	0.31	12	10	22.8
Rhine	Ri6	Andernach	1930–2008	D	139549	320.4	0.23	15	10	22.8
Rhine	Ri7	Lobith	1901–2007	NL	160800	320.4	0.20	17	10	22.8
Rhone (Massa)	Ro1	Blatten	1938–2008	CH	196	115.9	59.09	1	3	94.3
Rhone	Ro2	Porte du Scex	1905–2008	CH	5220	620.8	11.89	1	19	40.9
Rhone	Ro3	Chancy	1904–2008	CH	10299	715.9	6.95	5	19	35.5
Rhone	Ro4	La Mulatière	1900–1972	F	50200	754.6	1.50	8	19	33.7
Rhone	Ro5	Beaucaire	1920–1999	F	95590	937.3	0.98	12	19	27.1
Po (Ticino)	P1	Bellinzona	1920–1999	CH	1515	4.2	0.28	1	0	0.0
Po	P2	Piacenza	1924–1985	I	42030	382.3	0.91	8	1	0.6
Po	P3	Pontelagoscuro	1918–1998	I	70091	477.8	0.68	12	9	4.9
Danube (Inn)	D1	Martina	1974–2008	CH	1945	57.4	2.95	1	12	62.8
Danube (Inn)	D2	Innsbruck	1951–2006	AT	5792	263.3	4.55	1	12	13.7
Danube (Inn)	D3	Passau-Ingling	1920–2007	D	26084	369.0	1.41	3	12	9.8
Danube	D4	Linz	1931–1999	AT	79490	369.0	0.46	6	12	9.8
Danube	D5	Bogojevo	1931–2003	RS	251593	469.9	0.19	19	12	7.7
Danube	D6	Pancevo	1931–2003	RS	525009	469.9	0.09	29	12	7.7
Danube	D7	Ceatal Izmail	1921–2008	RO	807000	469.9	0.06	43	12	7.7

[a] A_c is the size of the catchment, A_{gl} is the glacierized area in 2008, and t_w is the estimated transit time of water flow through the catchment (see equation (2)). The number of glaciers with mass balance data n_{gl} and their relative area coverage R_d within the basin is given.

glacierized area and is represented by a sufficient number of glaciers with mass balance data. A relatively low percentage of the glacier size classes I-III is covered with data due to the large number of glaciers of this size, but more than half of the area of glaciers larger than 20 km^2 is contained in the data set (Table 1).

[18] For obtaining information on the entire glacierized area in the European Alps and the distribution of glacier sizes, the World Glacier Inventory (WGI) was used [*National Snow and Ice Data Center*, 2009]. The WGI provides consistent and complete information on all glaciers in the study area. However, its origin is between 1960 and the 1970s for the European Alps. In order to update glacier extent to the present-day level (2008), relative area changes for all glacier size classes were evaluated based on the 50 glacier data set that provides repeated information on glacier extent since the beginning of the 20th century [*Huss et al.*, 2010a, 2010b]. Percent area changes in 1973–1999 were compared to an evaluation of satellite images for the Swiss Alps [*Paul et al.*, 2004]. Slightly smaller relative area changes were found in the present study, but the trends (important area loss for small glaciers, small changes for large glaciers) were similar (Table 1).

2.3. Runoff Data

[19] Runoff data were provided by the Global Runoff Data Center (GRDC). Monthly discharge series were obtained for 22 stations (Table 2). Some of the runoff series were completed using information provided by the Swiss Federal Office for the Environment. Seven stations are used along the Rhine and the Danube, five along the Rhone and three along the Po. The stations gauge catchments with sizes between 196 km^2 and 807,000 km^2. Glacierization varies from 60% to 0.06%. In most catchments more than 10 glaciers mass balance series are available (Table 2).

[20] Some of the runoff series do not include the entire study period 1908–2008. On average, 82% of the 100 year time frame is covered. Periods with missing data were filled by superimposing relative monthly offsets from the long-term mean on the average monthly runoff. Offsets were obtained from the next measurement station. This simple procedure of runoff data extrapolation in time was validated by comparing estimated values with measured data at selected stations. Absolute deviations are 12% on average.

3. Methods

3.1. Monthly Glacier Storage Change

[21] One hundred year glacier mass balance series for 50 glaciers in the Swiss Alps (see Figure 1) have been derived by *Huss et al.* [2010a, 2010b]. These data are based on the combination of distributed modeling with a comprehensive field data basis covering the entire 20th century. The time step of the model is 1 day, and its spatial resolution is 25 m. The model is driven by daily temperature and precipitation obtained from different meteorological stations.

[22] For each of the 50 glaciers repeated Digital Elevation Models (DEMs) are available, providing information about past changes in glacier ice volume and glacier extent. Between three and ten DEMs per glacier in intervals of some years to several decades were established [*Bauder et al.*, 2007]. In addition, more than 10,000 direct measurements of point mass balance over both seasonal and annual periods have been compiled [*Huss et al.*, 2010a] based on extensive glaciological investigations on almost two dozens of Swiss glaciers throughout the 20th century. For each glacier a distributed accumulation and temperature-index melt model [*Hock*, 1999] is calibrated individually using a semiautomated procedure in order to maximize agreement with the field data. Most importantly, the model is tuned to exactly reproduce the observed ice volume changes in every time interval between subsequent DEMs. In situ point mass balance data constrain the altitudinal mass balance gradients, the seasonal variability of accumulation and ablation in the course of a year.

[23] The calibrated model thus provides monthly glacier mass balances (glacier storage changes) for each year of the study period 1908–2008. Moreover, it separates the components of the storage change: (1) snow accumulation dominating the winter season, (2) snowmelt most important in spring and early summer, and (3) bare ice melt occurring in late summer when the snow line has risen to high elevation.

3.2. Future Glacier Retreat

[24] The calculation of future glacier runoff is a challenge due to the dynamic reaction of glaciers to a change in climate. Whereas small glaciers normally adapt fast to new climatic conditions by decreasing their size, large glaciers have a longer response time and take several decades to lose their low-lying tongues [*Jóhannesson et al.*, 1989]. Therefore, the dynamic response of the ice mass needs to be accounted for in runoff forecasts for glacierized drainage basins that aim at representing glaciers in a mass conserving way [*Huss et al.*, 2008].

[25] The most important initial condition for the transient modeling of glacier retreat is the ice volume, and its spatial distribution. Here, the initial ice thickness distribution is obtained based on an inversion of glacier surface topography similar to a method presented by *Farinotti et al.* [2009]. For every elevation band of 10 m, mean ice thickness is calculated as follows: Balance ice volume flux along the glacier is derived using the hypsometry and apparent altitudinal mass balance gradients [see *Farinotti et al.*, 2009]. Apparent mass balance gradients prescribing the ice flux in the model are varied according to glacier size as smaller ice masses tend to have lower basal shear stress [*Haeberli and Hoelzle*, 1995]. Ice thickness h_i in elevation band i is calculated using an inversion of Glen's flow law as

$$h_i = \sqrt[5]{\frac{q_i}{2A} \cdot \frac{n+2}{\left(S_f \rho g \sin \alpha_i\right)^n}}, \tag{1}$$

where q_i is the ice flux normalized with the glacier width, A is the rate factor of the ice flow law [*Glen*, 1955] with $n = 3$, S_f is a factor accounting for the valley shape [*Nye*, 1965], ρ is the ice density, g the acceleration of gravity, and α_i the local slope of the glacier surface. According to *Kamb and Echelmeyer* [1986] the local basal shear stress $\tau_i = \rho g \sin \alpha_i$ (elevation band i) should be smoothed over a distance of about 10 times the ice thickness in order to correctly account for longitudinal stress variations. After smoothing, equation (1) is solved again until convergence is achieved. A stable solution for h_i is found after about five iterations and yields profiles of the ice thickness, S_f and τ along the glacier.

[26] Transient evolution of 3D glacier geometry, and thus ice volume, is modeled using a simple parameterization of glacier retreat [*Huss et al.*, 2010c]. Based on a site-specific function, simulated annual mass changes on the glacier surface are redistributed in order to account for the effects of ice flow. The parameterization has been shown to yield results for future glacier geometry change that agree well with 3D finite element ice flow modeling for different Alpine glaciers [*Huss et al.*, 2010c].

[27] Based on the calibrated mass balance model, future glacier retreat, monthly glacier storage change and its components are simulated for each of the 50 glaciers until 2100. Results of regional climate scenarios in seasonal resolution provided by the PRUDENCE project are used [*Christensen and Christensen*, 2007]. Sixteen Regional Climate Models (RCMs) are driven by the SRES A2 and B2 emission scenarios. *Frei* [2007] performed a probabilistic evaluation of 16 RCMs for Switzerland. The RCMs revealed trends of above average temperature increase in the summer months together with a reduction in precipitation. Conversely, a slight increase in winter precipitation is expected. Simulations of future glacier storage change are performed using three scenarios. Scenario 2 represents the median change in temperature and precipitation, Scenario 1 (cold/wet) and Scenario 3 (warm/dry) are extreme changes contained in the 95% confidence interval of expected climate change [see also *Huss et al.*, 2010c]. Scenario 2 (Scenario 1/Scenario 3) assumes an annual mean air temperature increase of +4.2°C (+2.2/+7.8) by 2100 compared to 1990 and a change in annual precipitation of −7% (+19%/−32%). In order to warrant comparability with the past, future storage change is calculated over the area that is currently ice-covered. Thus, also if the glaciers in the basin have completely disappeared, there can be storage changes in summer due to the reduction of winter snow.

3.3. Glacier Storage Change Versus Runoff

[28] The calculation of the relative contribution of glacier storage change to runoff from macroscale watersheds is based on a simple comparison of scales. Runoff provided by the storage change term in the water balance equation is compared to measured discharge.

[29] First, mass balance series of the individual glaciers need to be extrapolated to all ice-covered areas within a catchment (obtained from the WGI). As the mass balance response to the same climatic forcing can vary considerably between adjacent glaciers [e.g., *Kuhn et al.*, 1985] this is not a trivial task. The mass changes of the 50 glaciers do not show any spatial correlation; mean mass balances in the catchments of the four streams are not significantly different. However, some dependence of long-term mean mass balance on glacier size is evident (Table 1). In general, large glaciers show faster rates of mass loss than small glaciers [e.g., *Paul and Haeberli*, 2008; *Huss et al.*, 2010a]. For these reasons, the extrapolation is based on the seven glacier size classes (Table 1).

[30] For each size class the mean monthly storage change is evaluated by arithmetically averaging the monthly mass balance of all elements of the 50 glacier data set within the size class irrespective of the location of the glacier. Glacier area in the past is updated annually for each size class based on observed area changes in the data set. The annual cycle of storage change is similar for all size classes (Figure 3). Large glaciers, however, exhibit slightly faster mass loss in summer and less accumulation in early winter, both favored by their altitudinal extent (glacier tongue at low elevation). Although the monthly differences between the size classes may seem negligible (Figure 3), they sum up to significant differences in the annual mass balance (Table 1).

[31] The transit time of glacial meltwater from its source to the mouth of the streams can be considerable and needs to be accounted for when evaluating the glacier contribution far downstream. As the variation in water flow speed along the streams depends on numerous factors, and, moreover,

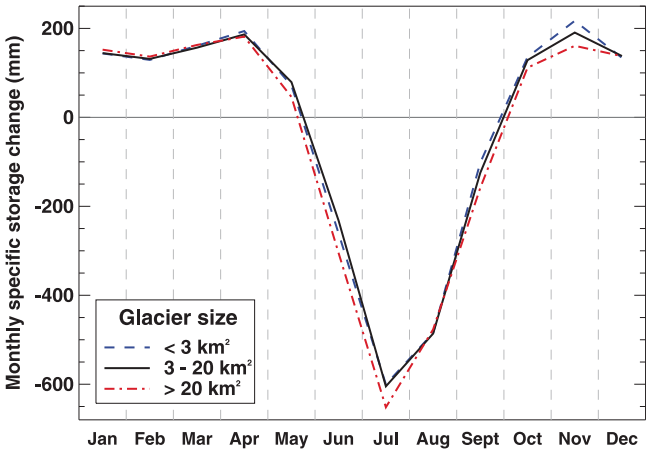

Figure 3. Monthly specific glacier storage change as a mean over the last century (1908–2008) for different glacier size classes.

is difficult to be measured, an empirical approach is employed [see, e.g., *Soballe and Kimmel*, 1987; *Nieuwenhuyse*, 2005]. Following this approach, an empirical relation (equation (2)) was fitted to transit time data for the lower 80% of the length of the Rhine and the Danube based on tracer experiments [*Leibundgut et al.*, 1993], and the propagation of flood waves [*Liepolt*, 1967]. The fit explains 90% of the variance in observed t_w (n = 12). The transit time of water t_w (days) is estimated based on catchment area A_c (km^2), mean discharge Q (m^3 s^{-1}) and basin slope β (m km^{-1}). An additional time t_{lakes} (days) is added that accounts for the time delay of the pressure pulse by large lakes that are present in the headwaters of most streams considered:

$$t_w = 0.055 \cdot A_c^{0.50} \cdot Q^{-0.10} \cdot \beta^{-0.35} + t_{lakes}. \quad (2)$$

The value t_w does not refer to particle velocity in the streams, but to the speed of the pressure pulse (kinematic wave velocity). Thus, t_w is expected to be smaller by a factor between 1.5 and 1.25 compared to particle velocity (tracer experiments) in the streams. As the speed of kinematic wave depends on water depth [*Singh*, 1996], it is assumed to be much faster than the particle velocity in lakes. The increase in t_w induced by the presence of large lakes was estimated based on inflow and outflow data around two major flood events in Switzerland. Outflow responded almost immediately to a perturbation of inflow and reached a peak 2 days after the inflow peak at maximum. Thus, time delays t_{lakes} of 1–3 days were estimated depending on the size and the number of the lakes in the respective catchments.

[32] Reservoirs used for hydropower production are present in many glacierized basins and could potentially have a significant impact on the transit times of the glacier meltwater pulse. As it is however difficult to obtain detailed data on the management of hydropower reservoirs on the scale of the European Alps this factor was not directly accounted for in the calculation of t_w. An in depth discussion of the considerable uncertainties in t_w, and its impacts on the results is provided in section 5.2.

[33] The estimated transit times vary between 1 day for the small and steep catchments in the headwaters and about 6 weeks for the Danube at the Black Sea. Total transit times for the other streams are in the order of 2–3 weeks (Table 2). Thus, runoff near the mouth of the streams is affected by glacier melt occurring several weeks earlier in the year.

[34] The relative contribution $C_{\Delta S,m}$ (%) of glacier storage change to runoff measured at a gauge in month m is calculated as

$$C_{\Delta S,m} = (-1) \cdot \frac{q_{\Delta S,m(t_w)} \cdot A_{gl}}{q_m \cdot A_c} = (-1) \cdot \frac{V_{\Delta S,m(t_w)}}{V_m}, \quad (3)$$

where $q_{\Delta S,m(t_w)}$ is the specific glacier storage change over the presently glacierized area A_{gl} according to the closure of the water balance. The time delay t_w of glacier meltwater is accounted for by considering a weighted average of specific storage change over the months contained in a period that is shifted by t_w (Table 2). If, for example, t_w = 31 days, glacier mass change in July is used to calculate the glacier contribution to August runoff. The temporal allocation of the glacier storage change used in equation (3) is thus a function of t_w. q_m is the specific monthly discharge (total discharge divided by catchment area) over the entire area of the basin area A_c in month m. This results in a comparison of the runoff volumes V given by storage change and overall monthly catchment discharge. In general, $C_{\Delta S,m}$ is negative during winter due to positive glacier storage change (Figure 3), and positive over the summer months.

[35] Complementary to the glacier storage change contribution $C_{\Delta S,m}$ (equation (3)), the contribution of meltwater originating only from the snow-free surface of a glacier (ice melt *IM*) is defined:

$$C_{IM,m} = \frac{V_{IM,m(t_w)}}{V_m}. \quad (4)$$

Analogous to equation (3), $V_{IM,m(t_w)}$ is the water volume provided by bare ice melt shifted by t_w in comparison to the measured runoff volume V_m in month m at the gauges. This definition only focuses on one component of glacier storage change. Ice melt does not achieve a closure of the water balance and has no linear relation with glacier mass balance. The ice melt component is however purely glacier-specific and unrelated to normal snowmelt runoff occurring in nonglacierized parts of the basin as well. Thus, differences between $C_{\Delta S,m}$ and $C_{IM,m}$ are discussed, and a complete set of results for $C_{IM,m}$ is given in the auxiliary material (see Table S2).[1]

4. Results

4.1. Seasonal Characteristics of Storage Change and Runoff

[36] The components of glacier storage change show a strong variation throughout the year (Figure 4). Accumulation (solid precipitation) reaches maximum values in May and April, as well as in November. Less accumulation occurs during the cold winter months December to February. Snowmelt over glacierized surfaces is significant between May and September and is maximal in July. Bare ice melt is shifted by 1 month compared to snowmelt and is most important in August, when 30%–40% of the glacier surface

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010WR010299.

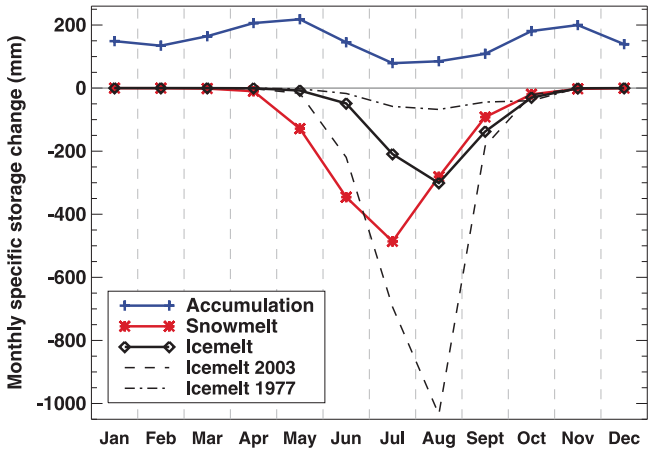

Figure 4. Monthly components of glacier storage change (accumulation/solid precipitation, snowmelt, ice melt) as a mean over 1908–2008 and the 50 glaciers. Ice melt for the extreme years of 1977 (cold and wet summer) and 2003 (hot, dry) is shown separately (dashed lines).

is snow-free in years with a balanced mass budget [*Gross et al.*, 1977].

[37] Glacier storage change components exhibit a large year-to-year variability, which is most pronounced for ice melt. In cool and snow-rich years almost the entire glacier surface can remain snow covered throughout large parts of the summer, thus, inhibiting bare ice melt. In hot years, however, the bare ice area, characterized by lower albedo, can already be completely exposed in July. Glacier storage change then consists purely of ice melt. Figure 4 shows examples of the quantity of ice melt in two extreme years, 1977 with positive mass balance and 2003 with extreme mass losses in the European Alps. Ice melt in August 2003 was more than three times above the mean, and higher by one order of magnitude compared to 1977 (Figure 4).

[38] Discharge data used in this study are shown in Figure 5. Whereas total runoff increases with catchment size, specific discharge is highest for the small mountainous basins, and decreases when moving away from the Alps. This agrees with the function of mountains as "water towers," characterized by high precipitation and little evaporation due to lower air temperatures and longer snow coverage [*Viviroli et al.*, 2007]. Conversely, the plains in the lower reaches of the large-scale catchments show little precipitation due to the lacking effect of orographic uplift, and high rates of evapotranspiration leading to particularly low specific discharge during the summer months. The runoff regime thus changes form nivo-glacial to pluvial when following the course of the streams from their sources in the Alps to their mouths (Figure 5). Glacier storage changes are anticorrelated to the water stress in the lowlands: In the summer period, glaciers release the largest quantities of meltwater that was brought into intermediate or long-term storage during wintertime or cold and wet periods [*Hock et al.*, 2005].

4.2. Past and Present Glacier Contribution

[39] The contribution of glacier storage change to runoff $C_{\Delta S,m}$ is evaluated for four periods in the past (1908–2008, 1961–1990, 1988–2008, 2004–2008), and two extreme years

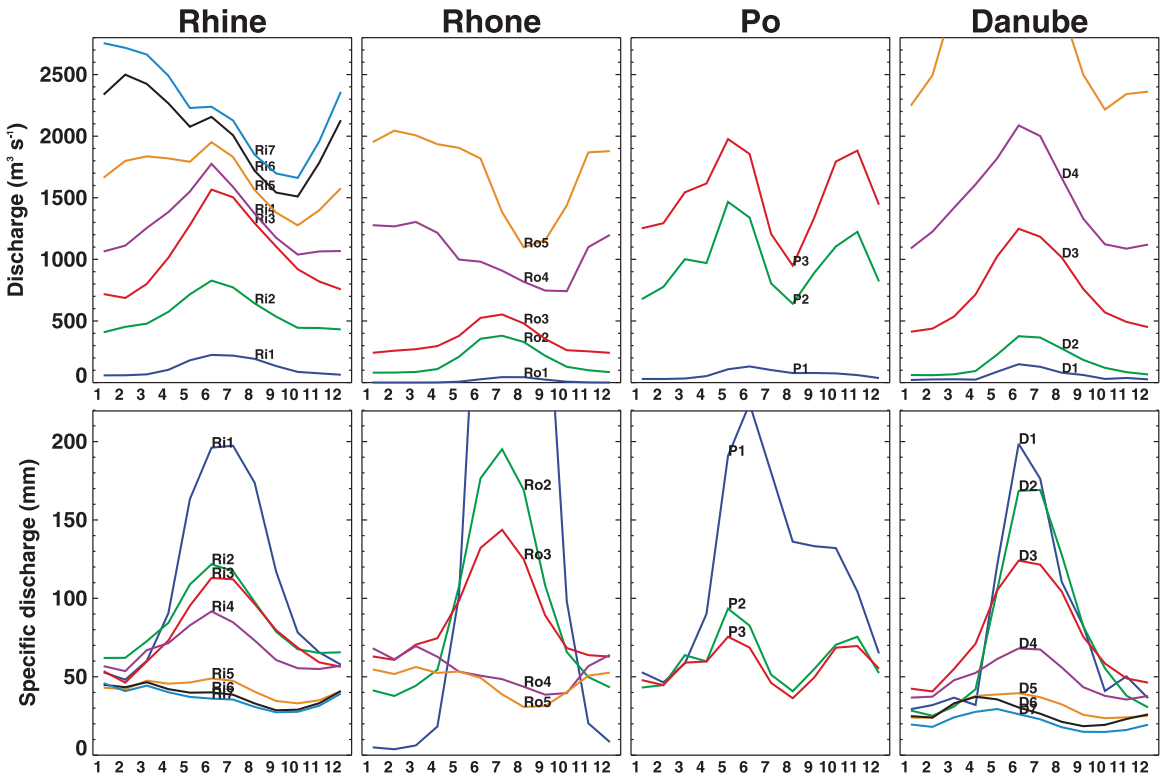

Figure 5. (top) Monthly mean runoff and (bottom) specific discharge (runoff volume divided by catchment area) along the investigated streams (see Table 2 for the IDs of the gauges). Note that for the gauges on the lower Danube only specific discharge is shown.

Table 3. Contribution $C_{\Delta S,m}$ of Glacier Storage Change in Four Periods to Runoff Near the Mouths of the Four Streams for the Months June to October[a]

River	Period	$C_{\Delta S,m}$ (%)				
		June	July	Aug.	Sept.	Oct.
Rhine	1908–2008	0.8	4.3	6.6	4.5	0.2
Rhine	1988–2008	1.2	4.3	6.8	4.5	0.2
Rhine	2004–2008	1.3	5.0	4.8	2.8	0.8
Rhine	2003	4.8	11.3	14.3	11.0	0.6
Rhone	1908–2008	4.0	17.5	24.8	13.1	−0.7
Rhone	1988–2008	5.5	19.5	29.4	13.4	−0.2
Rhone	2004–2008	6.4	21.3	21.4	9.7	1.5
Rhone	2003	16.3	37.3	40.3	23.1	0.2
Po	1908–2008	2.9	14.9	20.1	7.6	−0.7
Po	1988–2008	3.2	13.9	20.6	6.7	−0.3
Po	2004–2008	3.8	14.6	15.0	4.9	0.5
Po	2003	9.1	25.4	27.3	11.4	0.0
Danube	1908–2008	−0.5	0.6	2.8	3.9	2.1
Danube	1988–2008	−0.3	0.9	2.8	3.8	1.7
Danube	2004–2008	−0.2	0.8	2.4	2.5	1.3
Danube	2003	0.2	4.4	7.4	9.0	3.6

[a]The four periods are 1908–2008, 1988–2008, 2004–2008, and 2003. Locations near the mouths of the four streams are Lobith, Beaucaire, Pontelagoscuro, and Ceatal Izmail (see Figure 1).

(1977, 2003). $C_{\Delta S,m}$ is also significant in the other summer months, but is maximal in August for most basins (Table 3), because snowmelt runoff from nonglacierized regions of the catchment is then small, and specific runoff from European macroscale basins is relatively limited [e.g., *Weingartner et al.*, 2007]. Thus, mainly contributions to runoff in August $C_{\Delta S,Aug}$ are discussed here (Figure 6).

[40] The contribution of glacier storage change to summer runoff from large-scale drainage basins is considerable. Over the last century, glacier runoff contributed by 6.6% on average to runoff in August near the mouth of the Rhine although the catchment glacierization seems to be negligible (currently 0.20%). A still more important relative glacier contribution is found for the Rhone that has a larger ice-covered area. At Beaucaire with a basin area of 96,000 km^2, glacier mass change accounted for 25% of August runoff (Figure 6). The Danube catchment has by far the largest area of all streams draining the Alps, and the glacierization near its mouth is as low as 0.06%. Compared to the limited ice coverage, the 100 year average glacier contribution to August runoff (2.8%) is noteworthy. Due to the long transit time of glacial meltwater to the Black Sea the maximum contribution (3.9%) occurs in September.

[41] Contributions of the ice melt component only (C_{IM}, equation (4)) in comparison to $C_{\Delta S}$ is lower by 45% for August, and only by 11% for September (1908–2008). For extreme years (such as 2003) the difference between C_{IM} and $C_{\Delta S}$ is smaller (17% for August, 5% for September). This indicates that, at least for the late summer months, contributions from glacier storage change (consisting of snow and ice melt, and solid precipitation over ice covered surfaces) are similar to bare ice melt contributions.

[42] As expected, the relative contribution of glacier storage change to runoff decreases from the source to the mouth as total discharge increases (Figure 6). The Po River is an exception due to the choice of a tributary river (Ticino) in the headwaters that has a relatively small catchment glacierization. Also after the gauging station at Piacenza the major tributary of the Adda contributes an important fraction of glacial meltwater leading to a stable $C_{\Delta S,Aug}$ for the lower reaches of the Po (Figure 6).

[43] For all streams it is evident that $C_{\Delta S,Aug}$ decreases at a much lower rate than the drainage basin size increases. The smallest (Blatten) and the largest (Beaucaire) catchment analyzed in the Rhone basin, for example, show a difference in area of almost 500 times, however, the glacier contribution only diminishes by a factor of less than three. The same pattern is observable for all streams. This is explained by the important difference in specific runoff from glacierized catchments, especially in the summer months, and macro-scale basins that are dominated by vast flat areas characterized by little precipitation and high evapotranspiration (see Figure 5).

[44] Runoff contribution during the climatic normal period 1961–1990 was similar as over the last century (Figure 6). Whereas for the stations in the upper Rhone basin $C_{\Delta S,Aug}$ was slightly higher, the August contribution was 12% lower on average in the other catchments. This is attributed to the higher number of large glaciers drained by the Rhone (Figure 2) that did not reach a balanced mass

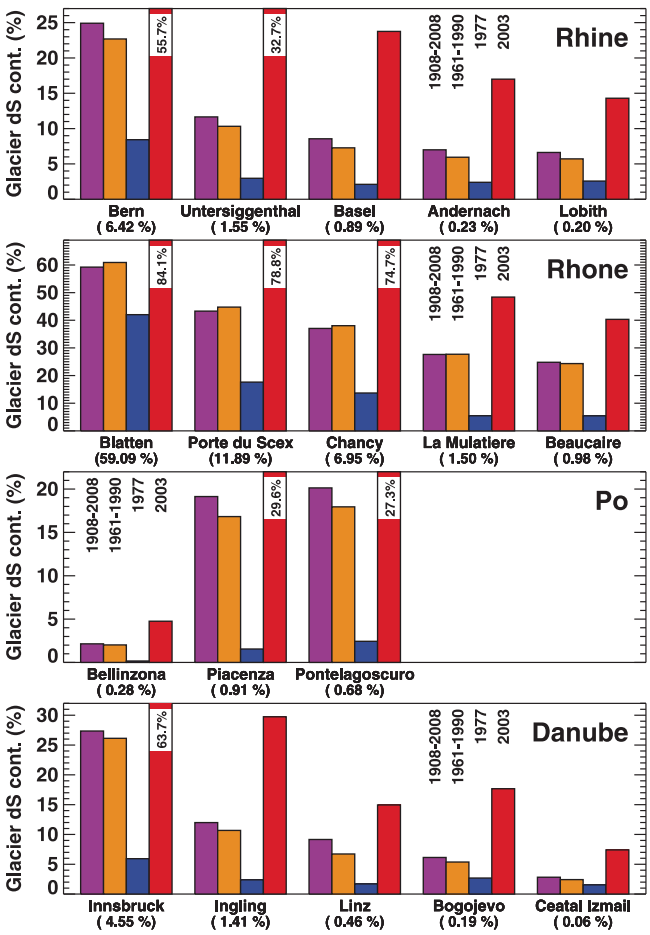

Figure 6. Relative contribution of glacier storage change to August runoff $C_{\Delta S,Aug}$ (see equation (3)) from drainage basins along the four streams. The name of the gauging station and current catchment glacierization is given. Data are evaluated for the period 1908–2008, 1961–1990, and the extreme years of 1977 and 2003. Note that the bar for 2003 is cut off in some cases, and the contribution is stated with numbers.

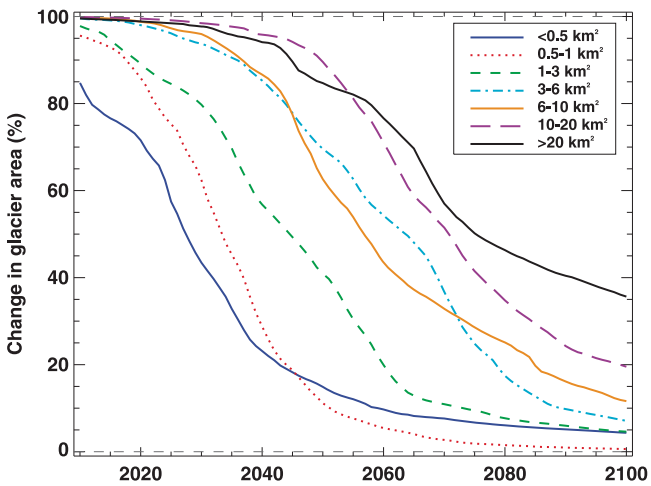

Figure 7. Calculated future change in glacier area for seven size classes relative to 2008 (Table 1). The results are based on transient simulations of ice volume and glacier extent for each of the 50 glaciers.

budget due to their longer response times. Smaller glaciers, showed slight mass gains (positive annual storage change) in the period 1961–1990 [*Huss et al.*, 2010a], leading to a reduced glacier contribution to runoff. Furthermore, the total surface covered by small glaciers (showing fast relative area changes [*Paul et al.*, 2004]; see also Table 1) was already significantly below the centennial mean during this period.

[45] The present contribution of glacier storage change (mean over the last two decades) is significantly higher compared to the secular average (Table 3). Glaciers now contribute 13% more water to the hydrological cycle in the month of August. This effect currently masks the possible future water shortage during the summer months that might occur if the glaciers are completely gone [e.g., *Braun et al.*, 2000; *Hock et al.*, 2005; *Nolin et al.*, 2010]. There are, however, already some catchments with minor glacier cover that show only slightly larger glacier runoff contributions in August. This might be due to the significantly reduced area of the small glacier size classes [see also *Collins*, 2008].

[46] For Rhine, Rhone and Po it is the July and August runoff that is most importantly affected by glacier storage change (Table 3). Due to the transit times t_w of some weeks there is also a significant impact on September runoff.

[47] In addition, $C_{\Delta S,m}$ was evaluated for 2004–2008 (Table 3). Interestingly, glacier contributions for the months August and September are below the average of the two last decades, but slightly higher for June and July. This cannot be explained with the effect of the extreme year of 2003 alone. The changes occurring in the last years indicate a shift in the hydrological regime toward more melt in early summer and less runoff contribution in late summer due to the ongoing shrinkage of ice-covered surfaces in the Alps.

[48] Glacier contribution to runoff strongly varies from year to year, in particular due to the differences in bare ice melt driven by different meteorological conditions in the summer (see Figure 4). Consequently, the contribution from glacier storage change was 70% smaller in August 1977 compared to the secular average with cool and wet conditions in the Alps and glacier mass gains (Figure 6).

[49] The summer of 2003 was characterized by extreme heat waves affecting the entire European continent, and is often interpreted as a precursor of the coming decades [*Beniston and Stephenson*, 2004; *Schär et al.*, 2004]. Glaciers in the Alps showed record mass losses since the beginning of the measurements in the 1960s [*Zemp et al.*, 2009]. In the hydrological year 2002/2003 the 50 glaciers in the data set showed a mean ice thickness loss of −2.3 m, equivalent to 4% of the current ice volume in the Swiss Alps [*Farinotti et al.*, 2009]. Melting was strongest in June, leading to an early disappearance of the snow cover on the glaciers, and in August (Figure 4). The equilibrium line was at 3500 m a.s.l. according to the glacier mass balance data set. Thus, large parts of the European Alps were completely snow-free favoring high rates of bare ice melt [*Koboltschnig et al.*, 2008].

[50] In August 2003, water provided by glacier storage change accounts for percentages of runoff from macroscale drainage basins higher by a factor of more than two compared to the long-term average (Figure 6). The highly glacierized catchment at Blatten only showed a slightly higher relative glacier contribution (+42%), because its runoff is determined to a high degree by melt water and the other components of the water balance are of minor importance. August 2003 contribution from glacier storage change in the Danube at Ceatal Izmail (Figure 1), however, was almost three times greater compared to the 100 year average. This is due to severe droughts in large part of the European continent [*Schär et al.*, 2004; *Fink et al.*, 2004] that increased the importance of glacier meltwater in streamflow runoff. The overall runoff of the Danube was 51% below the long-term average in the summer of 2003 (July through September). The glacier melt signal in the lower Danube is strongest in September (Table 3): With a catchment glacierization of only 0.06% a glacier contribution to September runoff of 9.0% is found.

4.3. Future Glacier Contribution

[51] The modeling of future ice volume and glacier extent shows that glaciers in the Alps will strongly retreat over the 21st century (Figure 7). Glaciers with a current size of less than 3 km^2 are expected to have lost 50% of their area by 2050. Very small glaciers might have already disappeared completely by then. Large glaciers show an acceleration of their retreat after 2040, and a slight slow-down toward the end of the century as they are approaching a new equilibrium. Nevertheless, an area loss of about 65% is anticipated for glaciers larger than 20 km^2, and of 80%–99% for glaciers below this limit by 2100 (Figure 7). Overall, the modeling results extrapolated to all glaciers in the European Alps indicate that ice-covered area will be reduced to 12% of the current value until 2100 according to the median of the 16 RCMs.

[52] The anticipated glacier mass loss over the 21st century will have strong impacts on the components of glacier storage change. In the next decades, a transition of the runoff regime of many glacierized drainage basins from a glacial to a nival type is expected [e.g., *Braun et al.*, 2000; *Middelkoop et al.*, 2001; *Horton et al.*, 2006]. This transition will be characterized by an initial increase in glacier runoff due to release of water from long-term storage, and terminate in a shift of the peak discharge from August to early summer [*Jansson et al.*, 2003; *Huss et al.*, 2008]. According to the model results, the transition already has

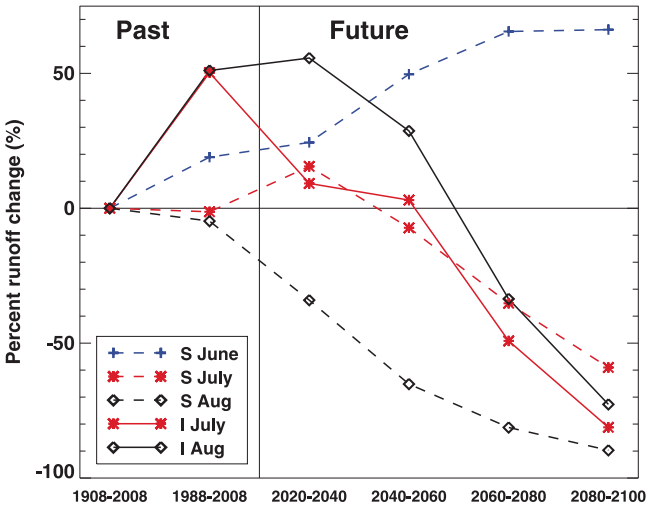

Figure 8. Time series of the relative change in the components of glacier melt (solid lines, ice melt i; dashed lines, snowmelt s) in the last two decades and four periods in the future (Scenario 2) compared to the 1908–2008 average.

started in the last decades. Compared to the mean over the 20th century, ice melt in July and August has increased by 50%, and snowmelt is higher in June, and slightly lower in August (Figure 8).

[53] Until 2060, bare ice melt is expected to remain above the long-term average, but below the value of the last two decades (Figure 8). Toward the end of the 21st century, ice melt will strongly decrease and tend toward zero as most of the glacier ice volume is lost (Figure 7). The temporal changes in snowmelt from currently glacierized basins shows different features. Snowmelt in June is expected to continuously increase due to higher air temperatures, but insignificantly reduced winter snow amounts at high elevations. Conversely, the snow cover in August will only exist at very high elevation leading to a 89% decrease in snowmelt contribution to runoff from glacierized basins until 2100 (Figure 8).

[54] The components of glacier storage change show significant differences for the three climate scenarios considered. The cold-wet Scenario 1 leads to an increase in snowmelt in June and July, and a moderate decrease in ice melt (Table 4). Snowmelt in August is expected to decrease in all scenarios. According to Scenario 3 (warm-dry) snowmelt will only intermittently increase in June, but tends toward zero in all other summer months. A significant increase in ice melt is evident for the next decades, but glaciers are expected to disappear almost completely in the Alps in this scenario, soon leading to a strong reduction in ice melt (Table 4). Thus, glacier storage change might become negligible by the end of the century given this climate evolution.

[55] The runoff contribution of ice-covered surfaces in the future is based on detailed glacier modeling, but does not take into account changes in the runoff regime in the large-scale catchments. The simulated water yield from glaciers is compared to the mean runoff in the period 1908–2008. The values thus indicate hypothetical contributions. The assumption that the runoff regime in the major streams does not change significantly might not be justified due to changes in precipitation and evapotranspiration rates [e.g., *Horton et al.*, 2006; *Weber et al.*, 2010].

[56] Contribution of glacier storage change to August runoff along large European streams is expected to decrease significantly throughout the 21st century (Figure 9). $C_{\Delta S,Aug}$ in the period 2020–2040 is slightly higher than in the past

Table 4. Calculated Future Changes in the Components of Glacier Storage Change for 20 Year Periods[a]

Period	Sc	Snowmelt			Ice Melt	
		s_{Jun}	s_{Jul}	s_{Aug}	i_{Jul}	i_{Aug}
2021–2040	sc1	3	22	0	−36	9
2041–2060	sc1	20	24	−13	−31	11
2061–2080	sc1	34	24	−23	−51	−16
2081–2100	sc1	45	22	−31	−72	−39
2021–2040	sc2	24	15	−34	9	55
2041–2060	sc2	49	−7	−65	3	28
2061–2080	sc2	65	−35	−81	−49	−33
2081–2100	sc2	66	−59	−89	−81	−72
2021–2040	sc3	48	−17	−71	81	87
2041–2060	sc3	47	−67	−92	9	−6
2061–2080	sc3	−1	−91	−98	−73	−76
2081–2100	sc3	−58	−98	−99	−89	−92

[a]All numbers are relative to 1908–2008. Results refer to three different climate scenarios (sc1–sc3). Percent changes in snowmelt s are given for the months June to August, and changes in ice melt i are given for July and August.

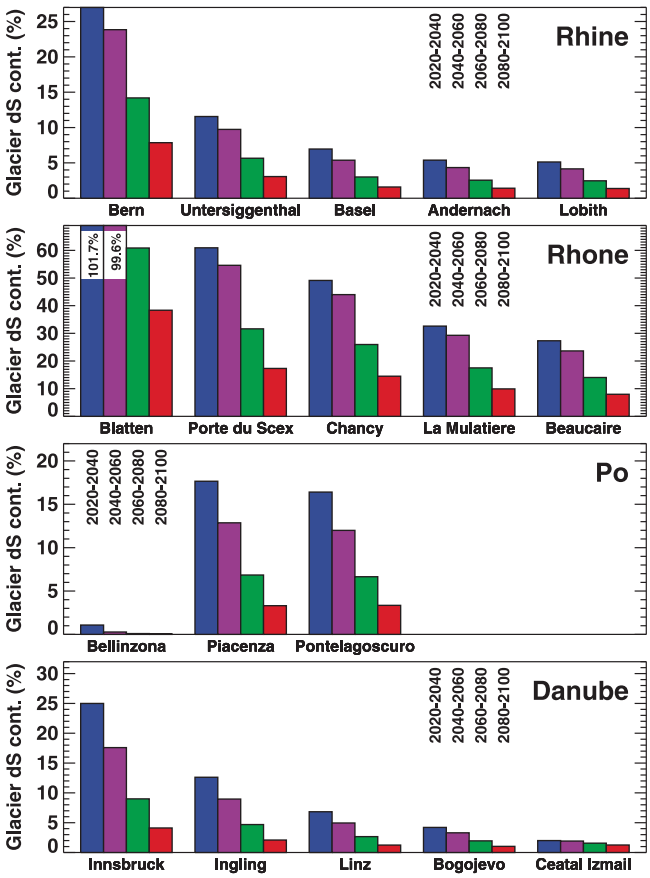

Figure 9. Hypothetical relative contribution of glacier storage change to future August runoff in 20 year periods (Scenario 2). Simulated future water yields from glacierized catchments shifted by the transit time t_w were compared to the observed runoff in the past (1908–2008).

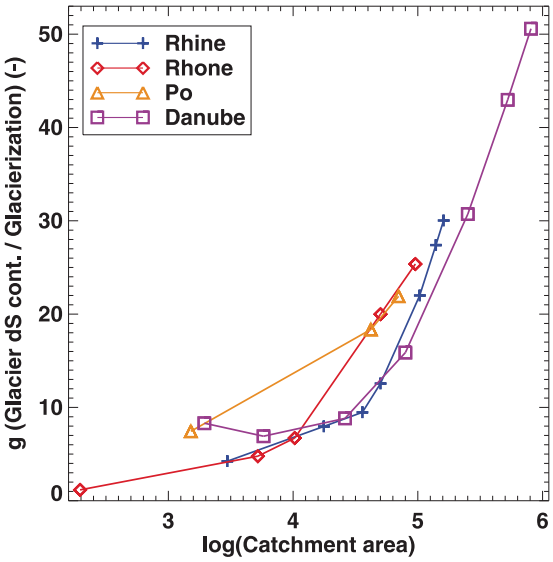

Figure 10. The contribution-glacierization coefficient g (see equation (5)) for August glacier storage change in function of logarithmic drainage basin size. Symbols refer to gauging stations along each of the four streams.

for some strongly glacierized basins (see Figure 6) because glaciers continue to lose mass at an accelerating rate. However, most basins already show reduced contributions of glacier storage change in 2020–2040. Catchments primarily characterized by small glaciers, such as the Po or the Danube basin (Figure 2), exhibit a fast decay of $C_{\Delta S,\mathrm{Aug}}$ because of a rapid loss of ice storage (Figure 7).

[57] Runoff contribution from currently glacierized areas by the end of the century (2080–2100) is expected to be lower by 75% (mean over the analyzed basins on Rhine, Po and Danube) compared to the 20th century average in August, and by 80% in September. Drainage basins with a large ice volume are expected to yield a slower decrease in $C_{\Delta S,\mathrm{Aug}}$ (Figure 9), as a significant number of glaciers still is present in the second half of the 21st century. A 55% decrease is found for the Rhone catchment. $C_{\mathrm{IM,Aug}}$ (runoff contribution due to the bare ice melt component only) is about 30% lower than $C_{\Delta S,\mathrm{Aug}}$ throughout the entire 21st century (Tables S6 and S7).

5. Discussion

5.1. Importance of Catchment Glacierization

[58] The results presented in Figure 6 indicate that the glacier contribution to runoff does not decrease linearly with the percentage of glacierization. To further investigate this issue the contribution-glacierization coefficient g_m for month m is defined as

$$g_m = \frac{q_{\Delta S,m}/q_{m(t_w)}}{A_{\mathrm{gl}}/A_{\mathrm{c}}}, \qquad (5)$$

where $q_{\Delta S,m}$ is specific glacier storage change in month m, $q_{m(t_w)}$ the specific catchment discharge in the months (weighted average) shifted by the water transit time t_w, and $A_{\mathrm{gl}}/A_{\mathrm{c}}$ is the catchment glacierization. The value g_m measures the importance of its glacierization for a catchment. A large g_m indicates that a given percentage of glaciers importantly affects basin runoff; a small g_m occurs in catchments where glacierization determines runoff to a lesser degree.

[59] Along all streams the same features of g are revealed for the month of August (Figure 10); g_{Aug} is small in the mountainous source regions of the streams and increases with catchment size. The relation is linear and correlation coefficients of between $r^2 = 0.95$ (Danube, n = 7) and $r^2 = 0.99$ (Rhine, n = 7) are found. The value g_{Aug} for a given catchment size is similar for all streams (Figure 10). Differences are due to regional climate conditions. The highest importance of glacierization is found for the Rhone and the Po basins that are influenced by a Mediterranean climate. Their runoff regimes differ from the other streams (Figure 5) due to a distinct precipitation minimum in summer. The linear relation between g and glacier size that holds over the limits of the drainage basins provides a possibility to extrapolate the importance of glacierization to unmeasured large-scale catchments with similar climatic conditions, or to interpolate the relative importance of glacier contribution to additional stations along the same stream.

[60] The results presented in Figure 10 seem to be paradoxical: how can the importance of glacierization for streamflow runoff increase with drainage basin size? As shown in Figure 5, the summer months are characterized by a strong difference in specific runoff between the glacierized head watersheds and the lowlands (the Alps as "the water towers of Europe" [e.g., *Viviroli et al.*, 2007]). Annual precipitation totals of a drainage basin are often maximal near the source of the stream, in the partly ice-covered headwaters. Due to high elevation, little energy is available for evaporation. Furthermore, precipitation during winter, and important parts of the autumn and spring, is temporarily stored as snow and the water is released mainly during July and August (Figure 3). These factors lead to a very high specific discharge during a short period of the year. The low-lying plains of macroscale drainage basins, often occupying much more than half of the entire catchment area, show inversed features. Annual precipitation is relatively small due to the lack of orographic uplift. In most of the considered basins, August precipitation sums are near the annual average. However, potential evaporation exceeds precipitation over large parts of the summer [e.g., *Weingartner et al.*, 2007]. Specific runoff from these regions is thus strongly reduced in the summer months, when the glacier meltwater contribution is maximal. The significance of this asymmetry is increased with the portion of dry lowland areas. Runoff from a given ice-covered area thus becomes more important in relative terms when approaching the mouth of the stream (Figure 10). The evaluation presented in this paper clearly indicates that runoff contribution from glaciers is not negligible in the summer months, also in large-scale drainage basins with a glacierization of much less than 1%.

[61] Only a few studies have quantified the contribution of glaciers to runoff from large-scale catchments so far. *Comeau et al.* [2009] found that additional meltwater originating from receding glaciers in the Canadian Rockies enhanced annual runoff at Edmonton (28,000 km^2, roughly 1% glacierized) by 3% in the period 1975–1998. Detailed modeling of smaller basins showed that glaciers in catchments with more than 1% ice cover contribute more than 27% to July through September runoff [*Comeau et al.*, 2009].

[62] *Immerzeel et al.* [2010] compared modeled discharge from snow and ice melt in several Asian large-scale basins to simulated downstream runoff. They found that for the Indus basin (1 mio. km^2, 2% glacierized), the relevance of meltwater exceeded water yields from downstream areas, whereas melt was less important in other macroscale basins such as the Yangtze River. This is explained by the seasonality and the spatial distribution of precipitation in the basins [see also *Kaser et al.*, 2010].

[63] Based on a comprehensive distributed model, *Weber et al.* [2010] come to the conclusion that the current contribution of ice melt in the catchment of Achleiten (Danube, 77,000 km^2) is 2% on average over the year. The view of the present study is different in two ways, and does not necessarily contradict this result (for a comparable basin of the Danube a $C_{\Delta S,Aug}$ of 9.2% is found).

[64] 1. The evaluation is performed on a monthly basis, contributions are not stated as a percentage of the annual mean. This allows focusing on the season when glaciers are important to the hydrological cycle, that is, the summer months.

[65] 2. Glacier storage change, and not only bare ice melt ($C_{IM,Aug}$ = 5.1% for the same catchment), is evaluated. Melt water originating from glacierized surfaces in late summer is also importantly due to snowmelt (Figure 4).

5.2. Uncertainties

[66] Data on glacier storage change used in this paper are based on field data combined with highly resolved modeling (spatial/temporal), and are thus assumed to be relatively accurate. Uncertainties involve (1) the extrapolation of storage changes to unmeasured glaciers and (2) variations in the total glacierized area in the Alps throughout the 20th century. Overall, the error in the calculated monthly water yield by glaciers is estimated not to exceed 10%.

[67] The presented methodology relies on streamflow runoff measurements, which are also assumed to be relatively accurate. Because the net water yield of the streams is used, the cumulative effects due to water withdrawal or other processes reducing actual water availability in the streams is indirectly accounted for. For these reasons, the presented results are almost unaffected by uncertainties inherent to a pure modeling study of stream discharge.

[68] One of the most important uncertainties in the evaluation is the time delay of glacial meltwater between the headwaters and the gauges (see Table 2). This transit time is only considered in a rudimentary way. The uncertainty in the estimates of the time delay is significant and could only be addressed with a comprehensive hydraulic model for the propagation of the pressure pulse along the entire length of the streams. This is outside of the scope of the present study, and an empirical approach calibrated with transit time data along the investigated streams was employed (see equation (2)).

[69] The statistical basis for the relation is relatively poor. Therefore, a Monte Carlo simulation was performed, in order to evaluate the effect of uncertainties in the transit time t_w on $C_{\Delta S}$. A set of 1000 values for t_w was randomly drawn in the interval [$0.5 \times t_{w,0}$, $2 \times t_{w,0}$], where $t_{w,0}$ is the best guess for t_w (see Table 2). The standard deviation of $C_{\Delta S}$ due to variations in t_w can thus be evaluated. Results are presented in the auxiliary material (see Table S3). In general, the relative effect of an uncertainty in the time delay of meltwater is small in the headwaters (<2% of $C_{\Delta S,Aug}$). For the mouth of the streams, uncertainties in $C_{\Delta S}$ for late summer are typically in the order of 5%–25%. This uncertainty analysis takes into account both the uncertainty in the transit times induced by large lakes in the course of the Rhine and the Rhone, and the impact of the annually varying effective discharge on t_w.

[70] Hydropower lakes in the European Alps have a total capacity of more than 5 billion m^3. This storage capacity would be sufficient to accommodate all water released from glacierized surfaces within the summer months. However, by far not all hydropower lakes are directly fed by glaciers, and snowmelt from nonglacierized surfaces and precipitation are as well important components of the water balance in mountain catchments contributing to the filling of the lakes. Particularly in the catchment of the Rhone, an important fraction of glacial meltwater is temporarily stored in reservoir lakes [e.g., *Schaefli et al.*, 2007]. Hydropower production is slightly less important in the headwaters of the other streams, but might still be a significant modification of the natural runoff regime. Estimating the integrated effect of hydropower production on the glacier meltwater release is difficult as detailed data on the management of all hydropower lakes in the European Alps are not available.

[71] Data of the Swiss Mattmark basin used for hydropower production (29% glacierized) show that maximum lake filling levels are normally achieved at the end of August. Thus, glacier meltwater in summer could potentially be stored. The importance of the glacier contribution to the filling of the lake relative to other water balance components (precipitation, snowmelt in nonglacierized regions) could only be separated with detailed hydrological modeling of the entire basin. Simple water balance considerations based on observed monthly changes in reservoir volume and precipitation data indicate that the retention of glacier meltwater in the hydropower lake in the summer months, particularly in August, has a large interannual variability. Whereas in some years almost all water of glacial origin is temporarily stored, other years are even characterized by a net release of glacier water in individual months. In general, there is no clearly recognizable pattern regarding the temporary storage of glacial water.

[72] Many hydropower lakes were built in the mid-20th century. Values for $C_{\Delta S,Aug}$ were compared for the 50 year periods 1908–1958 (runoff regime not strongly affected by hydropower production) and 1958–2008 (runoff regime affected by hydropower lakes). For Rhine, Po and Danube, a decrease in $C_{\Delta S,Aug}$ of 11%–14% is found. The Rhone catchment, however, shows a 15% increase in $C_{\Delta S,Aug}$ in spite of the largest storage capacity of hydropower lakes. In addition to temporal water storage in hydropower reservoirs, a decrease in $C_{\Delta S,Aug}$ could also be explained by the generally smaller glacier surface areas generating less meltwater in August. An impact of hydropower production on calculated values of $C_{\Delta S}$ is likely, but does not significantly affect the conclusions presented in this paper.

[73] Glacier storage change contributions presented for the future need to be interpreted with care. As no simulations of changes in runoff for the entire catchments were performed, future water yields from glaciers were compared to mean observed runoff in the last century. Climate change might considerably affect basin-wide precipitation sums,

and thus contribute to increased evapotranspiration [e.g., *Christensen and Christensen*, 2007]. In addition, current climate models still show a considerable uncertainty in predicting future changes in the precipitation regime over Europe [*Kjellström et al.*, 2011]. Shifts in the seasonality of precipitation will most probably lead to important changes in the runoff regime of large streams irrespective of the decrease in glacier contribution. Thus, $C_{\triangle S}$ values given for the future are uncertain. Considering a likely overall runoff decrease in macroscale drainage basins [*Middelkoop et al.*, 2001], the relative glacier contribution might be less significantly reduced although absolute water yields from glacierized surfaces will strongly recede (Table S8).

6. Conclusion

[74] By comparison of runoff provided by glacier storage change and monthly discharge from several macroscale drainage basins along the major streams leaving the Alps, the relative glacier contribution during the summer months was quantified. Monthly glacier mass balance data for 50 glaciers covering the entire 20th century are available and allow the extrapolation of glacier storage change to all ice-covered surfaces in the European Alps. Meltwater originating from glaciers represents a significant component of streamflow runoff, also in large catchments with seemingly negligible glacierization. This is due to the large difference in specific runoff from high-mountain basins and flat lowland areas. The results indicate that the relative importance of a given glacierized surface for runoff generation increases with drainage basin size.

[75] The Alpine glacier retreat that has been accelerated since two decades has caused a 13% increase in glacier contribution to August runoff due to release of water from long-term glacial storage. With future glacier wastage, the potential of glaciers to show significant storage changes in summer decreases. In future, snowmelt from currently glacierized regions will occur earlier and specific glacier runoff, particularly in the months of August and September, will be drastically reduced. Currently glacierized basins might contribute 55%–85% less water to streamflow runoff by the end of the 21st century.

[76] Especially in catchments that show a high portion of glacier meltwater in August nowadays, the lacking glacier contribution could result in a water shortage and might entail serious economic consequences as European streams are the lifeline of many countries. For example, irrigation for agriculture might be at risk, groundwater levels could be sinking, shipping traffic on the major streams might be affected, and important ecological impacts on habitats along the streams are possible. This study shows that the consequences of future glacier retreat on the hydrology of large streams might be more severe than previously assumed.

[77] The European continent is, compared to similar highland-lowland systems, not particularly dry. Furthermore, countries in Europe will probably be able to afford the financial means to adapt to the consequences of future changes in hydrology. However, the problems outlined and quantified in this paper are even a more significant threat to the water supply in regions with a dry summer climate such as central Asia or the South American Andes [*Kaser et al.*, 2010]. It is thus of crucial importance to account for the impact of the ice cover on the hydrological regime, and its future changes, also in poorly glacierized drainage basins. Detailed glaciological investigations combined with glacier inventory data are one of the key factors for assessing the impacts of climate change on future water supply security in glacierized watersheds.

[78] The method presented here is potentially applicable to many mountain ranges on the earth with scarce observational data. It requires runoff measurements, an inventory of glacierized surfaces and an estimate of the seasonality of glacier mass balance that could, in principal, be provided by a single glacier record. Thus, this simple approach yields a promising alternative to complex modeling for estimating the glacier contribution to runoff from macroscale watersheds, and to investigating future low-flow conditions in streams with a glacial influence all over the world.

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