

Glaciers in the Earth's Hydrological Cycle: Assessments of Glacier Mass and Runoff Changes on Global and Regional Scales

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Abstract Changes in mass contained by mountain glaciers and ice caps can modify the Earth's hydrological cycle on multiple scales. On a global scale, the mass loss from glaciers contributes to sea-level rise. On regional and local scales, glacier meltwater is an important contributor to and modulator of river flow. In light of strongly accelerated worldwide glacier retreat, the associated glacier mass losses raise concerns over the sustainability of water supplies in many parts of the world. Here, we review recent attempts to quantify glacier mass changes and their effect on river runoff on regional and global scales. We find that glacier runoff is defined ambiguously in the literature, hampering direct comparison of findings on the importance of glacier contribution to runoff. Despite consensus on the hydrological implications to be expected from projected future warming, there is a pressing need for quantifying the associated regional-scale changes in glacier runoff and responses in different climate regimes.

Keywords Glaciers · Mass balance · Glacier runoff · Sea-level rise · Mass-balance observations · Glacier projections · Modeling

1 Introduction

Mountain glaciers and ice caps, covering 734,400 km² on Earth (Gardner et al. 2013), are an integral part of the Earth's hydrological cycle affecting water balances on all spatial

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scales. Meier (1984) was the first to recognize that these glaciers outside the two vast ice sheets in Antarctic and Greenland—though only comprising < 1 % of the Earth's total ice volume—are major contributors to global sea-level rise due to worldwide glacier wastage in response to global warming. Various studies have attempted to quantify the mass losses of these ice bodies and their effect on rising sea level indicating that glaciers outside the ice sheets have contributed between one-third and one-half of global sea-level rise during the last decades (Dyrgerov and Meier 2005; Kaser et al. 2006; Cogley 2009a, b; Gardner et al. 2013). The glacier contribution to future sea-level rise is expected to remain significant as the global temperature is expected to further increase (Lemke et al. 2007).

On regional and local scales, glaciers are significant contributors to seasonal riverflow, serving as frozen reservoirs of water that supplement runoff during warm and dry periods of low riverflow. The ongoing glacier retreat has important implications for downstream river flows, regional water supplies, sustainability of aquatic ecosystems, and hydropower generation (e.g., Kaser et al. 2010; Huss 2011; Immerzeel et al. 2010). Glacier runoff is intrinsically linked to the glacier's mass balance, the latter defined as the sum of its total accumulation (mostly due to snowfall, windblown snow, avalanches, and condensation) and ablation (mostly due to melt, calving of icebergs, wind erosion, evaporation, sublimation) over a stated period of time (Cogley et al. 2011). Note that mass loss is defined negatively. Despite the importance of glaciers as modifiers of global and regional water cycles, there are relatively few attempts to assess recent and project future glacier mass changes and quantify their impacts on riverflow on global and regional scales.

Previous review-type publications have focused either on glacier mass changes and their measurement (Braithwaite 2002; Cogley 2011) or on glacier runoff and its characteristics (Jansson et al. 2003; Hock et al. 2005; Hock and Jansson 2005) generally focusing on local catchment or glacier scales. In contrast, here we combine both themes to highlight the links between glaciers and river runoff focusing exclusively on regional and global scales. Our goal is to provide a critical overview of studies that have attempted to quantify recent and future glacier mass changes and to assess the importance of these mass changes in streamflow on larger scales. We only consider glaciers distinct from the two ice sheets in Greenland and Antarctica. First, we will provide an overview on global glacier mass balances including assessment techniques (Sect. 2) and modeling of recent and future changes (Sect. 3). Then, we will discuss the characteristics and definition of glacier runoff (Sect. 4) followed by a discussion of studies exploring the role of glaciers in regional and global hydrology (Sect. 5).

2 Assessing glacier mass balance on regional and global scales

Simulating glacier runoff requires accurate modeling of the components of the glacier mass balance which in turn requires mass-balance measurements for calibration and validation of mass-balance models (Konz and Seibert 2010). Below, we will briefly introduce the techniques for assessing glacier mass balance on global scales before reviewing the results of assessments and projections.

2.1 Assessments by in situ mass-balance measurements

Until recently, all global assessments of the mass balance of glaciers relied on some form of extrapolation of available glacier-wide mass-balance measurements. The most traditional of these techniques, the so-called glaciological method, is based on snow probings

and ablation stake measurements (Østrem and Brugman 1991; Kaser et al. 2002; Zemp et al. 2013), and provides a measure of the surface mass balance. The glacier-wide surface mass balance is estimated from extrapolation of the point measurements over the glacier surface. The earliest mass-balance measurements were taken on the Rhône Glacier, Swiss Alps, providing intermittent observations during 1874–1908 (Mercanton 1916). Annual mass-balance measurements have been taken at two stakes on Claridenfirn in Switzerland since 1914 (Müller-Lemans et al. 1994). The longest continuous glacier-wide mass-balance time series exists for Storglaciären, Sweden, reaching back to 1945 (Zemp et al. 2010). In situ measurements of mass balance have been obtained for ~ 340 glaciers worldwide, of which ~ 70 glaciers have continuous annual observations longer than 20 years (Dyurgerov 2010). The records of glacier mass balance are compiled and distributed by the World Glacier Monitoring Service (WGMS, Zemp et al. 2009).

Dyurgerov and Meier (1997a, b) provided the first detailed assessment of annual glacier mass balances on global and regional scales followed by updates in Dyurgerov (2002, 2003), Dyurgerov and Meier (2005), and Dyurgerov (2010). Global averages were obtained from area-weighted specific mass balances of smaller subregions whose balances were estimated from the single-glacier observations. A similar approach was taken by Ohmura (2004), while Cogley (2005) used a different approach by applying a spatial interpolation algorithm, fitting a second-degree polynomial to the single-glacier observations to extrapolate the mass-balance observations to all glacierized cells in a $1 \times 1^\circ$ global grid. In contrast to Cogley (2005) who used only glaciological mass-balance measurements, Cogley (2009a, b) also included geodetic observations (Sect. 3.2) from more than 250 glaciers in the interpolation. His estimate was about 30 % more negative than the one derived solely from direct measurements possibly due to a better representation of marine-terminating glaciers (which, in addition to surface melting, lose mass by iceberg calving and submarine melting); however, it was questionable whether the difference represented adequately the global-average ablation by calving and submarine melt (Cogley 2009a, b).

Three global estimates (Ohmura 2004; Dyurgerov and Meier 2005; Cogley 2005) were synthesized into a “consensus estimate” (Kaser et al. 2006) that was used in the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC; Lemke et al. 2007). Not surprisingly, since they were based on the same observations, the three assessments agree well with each other. A glacier mass loss rate of 0.50 ± 0.18 mm sea-level equivalent (SLE) year^{-1} was found for the period 1961–2004 and an increased rate of 0.77 ± 0.22 mm SLE year^{-1} for 1991–2004, thus a considerably higher mass loss rate than found for both ice sheets together in both periods (Lemke et al. 2007). Gardner et al. (2013) applied the methods of Cogley (2009a, b) to all glaciers other than the ice sheets and found a mass loss rate of 1.37 ± 0.22 mm SLE year^{-1} (0.92 ± 0.34 mm SLE year^{-1} excluding the glaciers in the Antarctica and Greenlandic periphery) for the period 2003–2009, comparable to the estimate for 2006 by Meier et al. (2007) derived from the interpolation of local glaciological records (1.11 ± 0.26 mm SLE year^{-1} , Table 1).

All these assessments suffer from serious under sampling. Direct observations of glacier mass changes exist on fewer than 1 % of the glaciers worldwide (~ 300 out of $\sim 200,000$). These are geographically biased with more than 60 % of the records originating from the European Alps, Scandinavia, Western Canada and USA, and parts of the former Soviet Union (Dyurgerov 2010). They are also biased toward smaller, land-terminating glaciers in maritime climates. The assumption that very few benchmark glaciers with observed mass balances over short-term time period (< 10 years) are representative for the region-wide mass balance over ~ 40 years is a major but inevitable

Table 1 Overview of recent studies assessing the global glacier mass budget

Period	Mass budget Gt a ⁻¹ (mm SLE year ⁻¹)		Method	Area km ²	Reference
	All glaciers	Excl. A + G			
1961–2004	-182 ± 78 (0.50 ± 0.22)	-155 ± 67 (0.43 ± 0.19)	Glaciological	785,000 <i>546,000</i>	Kaser et al. (2006)
2006	-402 ± 95 (1.11 ± 0.26)		Glaciological	763,000	Meier et al. (2007)
1961–2004	(0.79 ± 0.34)	(0.51 ± 0.29)	Modeling	704,000 <i>518,000</i>	Hock et al. (2009)
2001–2005		-740 ± 62 (1.12 ± 0.14)	Glaciological and geodetic		Cogley (2009a, b)
1961–2004		-153 (0.42)	Modeling	535,000	Hirabayashi et al. (2010)
1902–2009	(1.07 ± 0.05) ^a		Modeling	590,900 ^d	Marzeion et al. (2012)
1948–2005		(0.45 ± 0.02) ^b	Modeling	517,000	Hirabayashi et al. (2013)
1971–2010	-247 ± 190 ^c (0.68 ± 0.53)		Modeling based on AAR observations	734,430 ^c	Mermild et al. (2013)
10/2003–10/2009		-170 ± 32 (0.47 ± 0.09)	GRACE (method by Jacob et al. 2012)	734,430 <i>511,800</i>	Gardner et al. (2013)
10/2003–10/2009		-166 ± 37 (0.46 ± 0.10)	GRACE (method by Wouters et al. 2008)	734,430 <i>511,800</i>	Gardner et al. (2013)
10/2003–10/2009	-495 ± 78 (1.37 ± 0.22)	-335 ± 124 (0.92 ± 0.34)	Glaciological (method by Cogley 2009a, b)	734,430 <i>511,800</i>	Gardner et al. (2013)
10/2003–10/2009	-259 ± 28 (0.71 + -0.08)	-215 ± 26 (0.59 ± 0.07)	Combination of GRACE, ICESat, glaciological	734,430 <i>511,800</i>	Gardner et al. (2013)

Numbers in italic refer to those excluding the glaciers in the Antarctic (A) and Greenland (G) periphery

^a Here calculated as the average rate over the period with total glacier mass loss of 114±5 mm SLE (Marzeion et al. 2012). Total area of 590,900 km² (excluding glaciers peripheral to Antarctic ice sheet) is the modeled area at 2009

^b Here calculated as the average rate over the period with total mass loss of 25.9±1.4 mm SLE (Hirabayashi et al. 2013)

^c Here calculated from the average global mass balance of -336±260 kg m⁻² year⁻¹ (Mermild et al. 2013), using glacierized area of 734,430 km² (Gardner et al. 2013) and ocean surface area of 362×10⁶ km²

limitation in these assessments. Another source of uncertainty is poor knowledge of glacier inventory data at that time, i.e., data on glacier location and surface area. Nevertheless, these assessments provide continuous annual or pentadal time series of mass balance reaching back into the mid-twentieth century.

2.2 Assessments by geodetic method

With the geodetic method, the glacier mass balance is estimated by repeated mapping, either by ground-based surveys or remote sensing (laser, radar altimetry, stereoscopic imagery). The change in glacier volume (obtained from the difference in glacier surface elevations over the glacier area) multiplied by the average density of the removed or added material gives the change in glacier mass. In contrast to in situ measurements, geodetic observations generally have good regional but poor temporal coverage, since surveys are often separated by multi-annual to multi-decadal gaps. On the other hand, the geodetic method can observe the mass changes of tidewater glaciers, which are not included in traditional glaciological measurements.

Initially, geodetic surveys have been mostly used to assess the mass changes of individual glaciers (Cogley 2009a, b); however, increasing availability of remote sensing data (in particular satellite laser altimetry after the launch of ICESat in 2002) triggered a number of studies covering entire glacier regions. Geodetic estimates of mass changes on regional scale exist for Alaska (Arendt et al. 2002; airborne laser altimetry, Berthier et al. 2010; satellite remote sensing), Arctic Canada (Abdalati et al. 2004; airborne laser altimetry; Gardner et al. 2011; satellite remote sensing), British Columbia (Schiefer et al. 2007; satellite radar altimetry), Svalbard (Nuth et al. 2010; Moholdt et al. 2010; satellite laser altimetry), Iceland (Bjornsson et al. 2013; airborne and satellite remote sensing), Russian High Arctic (Moholdt et al. 2012; satellite laser altimetry), Austrian Alps (Lambrecht and Kuhn 2007; DEM from aerial photographs), Swiss Alps (Paul and Haeberli 2008; satellite radar altimetry), parts of central Asia (Gardner et al. 2013; satellite laser altimetry), Patagonia (Rignot et al. 2003; Willis et al. 2012; satellite remote sensing), the peripheral glaciers in Greenland (Bolch et al. 2013; Gardner et al. 2013; satellite laser altimetry), and the glaciers on the islands surrounding the Antarctic mainland (Gardner et al. 2013; satellite laser altimetry). Most of these estimates are derived for relatively short recent (after 2000) time periods.

2.3 Assessments using satellite gravimetry

Gravimetric measurements have become a popular tool to estimate glacier mass changes since the launch of the satellites of the Gravity Recovery and Climate Experiment (GRACE) in March 2002. GRACE consists of a pair of satellites orbiting together and measuring variations in the terrestrial gravity field, therefore detecting mass movements. The twin satellites orbit the Earth 15 times a day, recording minute variations in the Earth's gravitational pull. When passing over a region of larger gravity, the first satellite is pulled ahead of the trailing satellite, thus increasing the distance between the satellites. Mass changes are derived from the constantly changing distance between the twin satellites combined with precise positioning measurements (Tapley et al. 2004).

GRACE observes mass changes with high temporal resolution (e.g., sub-monthly), but the spatial resolution is relatively poor (roughly 100×100 km). In contrast to the methods above, no density assumptions are needed because mass change is measured directly. However, since the satellites detect the total mass changes over a large area, and are unable

to resolve individual components of the mass changes, the signal needs to be decomposed in order to identify the signal due to glacier mass changes. The decomposition is relatively complex and, because it relies on the accuracy of models used to simulate Earth system processes (isostatic rebound, tectonics, hydrology, atmosphere), it may introduce large uncertainties into the derived mass balances (e.g., Jacob et al. 2012).

GRACE-derived regional-scale mass balances have been reported for the Canadian Arctic (Gardner et al. 2011), Alaska (Tamisiea et al. 2005; Chen et al. 2006; Luthcke et al. 2008; 2013; Wu et al. 2010), Patagonia (Chen et al. 2007; Ivins et al. 2011), and High Mountain Asia (Matsuo and Heki 2010). Jacob et al. (2012) were the first to compute GRACE-derived mass-balance estimates for all glacierized regions outside Greenland and Antarctica, followed by Gardner et al. (2013) who updated their estimate and generated a new one based on the methods of Wouters et al. (2008). These two analyses report a total mass budget for these regions of -170 ± 32 Gt year⁻¹ and -166 ± 37 Gt year⁻¹, respectively, for the period 2003–2009. Jacob et al. (2012) note that their results are roughly 30 % smaller than the most recent available estimate at that time, obtained from the interpolation of glaciologically derived in situ observations by Dyurgerov (2010).

2.4 Assessments by other approaches

2.4.1 AAR method

Bahr et al. (2009) derived global glacier mass changes using an approach based on the observations of the accumulation area ratio (AAR), i.e., the ratio of the accumulation area to the total glacier area. AAR is closely related to the mass balance of a glacier in the case when calving and submarine melt are negligible (Dyurgerov and Meier 2005). AARs can be relatively easily approximated from aerial and satellite observations of the end-of-summer snowline. For a glacier in balance with the climate, the AAR is equal to its equilibrium value, AAR_0 , whose average value from a sample of ~ 100 glaciers has been found to be 58 % (Dyurgerov et al. 2009).

Glaciers with $AAR < AAR_0$ will retreat to higher elevations, typically over several decades or longer, and the AAR may return to the equilibrium value. Using AAR observations of ~ 80 glaciers collected during 1997–2006, Bahr et al. (2009) computed a mean AAR of 44 ± 2 %, with $AAR < AAR_0$ for most glaciers in the dataset. Mernild et al. (2013) revised the methodology, expanded and updated their data, and found an average AAR of 34 ± 3 %, for the period 2001–2010. Using the empirical relationship between the ratio AAR/AAR_0 and annual glacier mass balance, Mernild et al. (2013) reconstructed pentadal global glacier mass balances for 1971–2010, showing a good agreement with estimates from Cogley (2009b). However, they also found much larger uncertainties in the global estimate than in the original study by Bahr et al. (2009).

This AAR-based approach has also been used to provide estimates of future glacier area and volume changes assuming that the future climate resembles the one of the recent few decades. Bahr et al. (2009) estimated that, even without additional atmospheric warming, the volume of glaciers must shrink by 27 ± 5 % to return to a balanced mass budget. Assuming that the total volume of the Earth's glaciers and ice caps is 650 mm SLE (Dyurgerov and Meier 2005), the fractional losses would raise global mean sea level by 184 ± 33 mm. With the updated AAR dataset and updated estimate of total glacier volume (430 mm SLE by Huss and Farinotti 2012) and accounting for the larger errors due to regional and global undersampling, Mernild et al. (2013) revised this estimate to 163 ± 69 mm. We note that, because of its simplicity, the AAR-based approach may only

give an indication of future mass changes, and projections should preferably be addressed by models describing the physical processes involved and using transient climate scenarios.

2.4.2 Multi-method approach

Gardner et al. (2013) synthesized a consensus global mass-balance estimate for the period October 2003–October 2009 by standardizing existing and generating new, regional estimates for 19 individual glacierized regions (Fig. 1) while investigating the large discrepancies between the estimates obtained from GRACE and those from interpolating local glaciological records (Table 1). The analysis is based on a new globally complete glacier inventory (Randolph Glacier Inventory, RGI, Arendt et al. 2012). ICESat and GRACE estimates agreed well in large glacierized regions, where results from spatial interpolation of local records tended to give considerably more negative mass budgets. Their analyses suggest that available local glaciological records are negatively biased in larger regions, indicating that previous assessments based on spatial interpolation (Sect. 2.1) may have overestimated mass losses. GRACE results tend to have large uncertainties in regions with little ice cover. Therefore, averages of available ICESat and GRACE estimates were generally used for the larger glacierized areas while results from spatial interpolation of local measurements updated from Cogley (2009a) were adopted for the smaller ($< 5,000 \text{ km}^2$) regions where the density of in situ measurements tends to be high.

Results show that all glaciers other than the ice sheets lost $259 \pm 28 \text{ Gt year}^{-1}$ accounting for $29 \pm 13 \%$ of the observed sea-level rise of $2.50 \pm 0.54 \text{ mm SLE year}^{-1}$ during 2003–2009, thus matching approximately the combined contribution of the two large ice sheets (Shepard et al. 2012). Glacier mass was lost in all 19 regions during this period with the largest losses from Arctic Canada, Alaska, and peripheral Greenland.

3 Modeling glacier mass balance on regional and global scales

State-of-the-art simulations and projections of global mass changes of glaciers and ice caps have relied on low-complexity models of surface mass balance and glacier dynamics. These modeling studies have commonly assumed that the main drivers of glacier mass balance are air temperature and precipitation, while glacier dynamics, involved in changes of glacier area and thickness, are assumed to be successfully simulated by scaling methods (Bahr et al. 1997). In the following sections, we will briefly discuss a selection of the modeling studies (listed in Tables 1 and 2), narrowing our review to the most recent studies (last few years) and to those that used some type of meteorological/climate data. Methodological approaches fall broadly into two categories: (1) models based on mass-balance sensitivities to temperature and precipitation changes (e.g., Hock et al. 2009; Slangen et al. 2012), and (2) direct modeling of transient surface mass balance (e.g., Raper and Braithwaite 2006; Radić and Hock 2011; Marzeion et al. 2012). Most of the latter studies have used an ensemble of global climate model (GCMs) to provide climate forcing for their models. The use of a multimodel ensemble is a common way to provide a range of projections and uncertainties in any climate change impact studies. Also, studies that evaluated GCM simulations of mean climate on global and regional scales have shown that the multimodel ensemble average is superior to any individual model (e.g., Gleckler et al. 2008; Pierce et al. 2009).

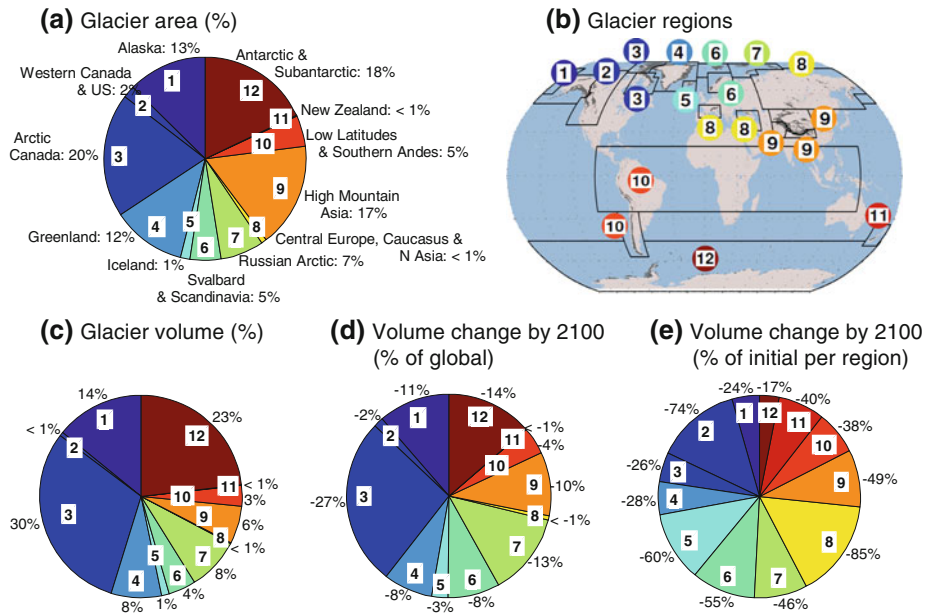


Fig. 1 **a** Regional glacier area in % relative to the global glacier area of 744,430 km² (Gardner et al. 2013). **b** 12 glacierized regions containing all the Earth’s mountain glaciers and ice caps (Randolph Glacier Inventory; Arendt et al. 2012). Some of the 19 primary regions from Randolph Glacier Inventory (*black polygons*) are combined here. **c** Regional glacier volume in % relative to the global glacier volume of 522 mm SLE (Radić et al. 2013). **d** Regional contribution of glacier volume loss (%) to global volume loss of 155 mm SLE projected for 2006–2100 as a mean of 14 GCMs with RCP4.5 (Radić et al. 2013). **e** Total regional volume change of glaciers over 2006–2100, expressed in % of initial regional glacier volume, as a mean projection from 14 GCMs with RCP4.5 (Radić et al. 2013). Here, each region’s pie size is proportional to its regional volume change (therefore the sum over the pie sizes is not 100 %). Numbers in the pies correspond to the regions in (b)

To account for glacier area changes, most models apply volume–area (or volume–length) scaling, which states that the volume of a mountain glacier is proportional to its area (or length) raised to a power (Bahr et al. 1997). Considering the lack of data required for higher-order glacier dynamics models, these methods are shown to be a good first-order approximation of glacier dynamics for the assessments of global-wide and region-wide glacier mass changes (Radić et al. 2007, 2008; Adhikari and Marshall 2012). Though simple, the approach allows modeling of the tendency of mountain glaciers to reach a new equilibrium in a warming climate since the specific mass balance (i.e., mass change per unit area) tends to become less negative as the glacier retreats from low-lying, high-ablation altitudes.

3.1 Models based on mass-balance sensitivity

Mass-balance sensitivities refer to the changes in mass balance that result from instantaneous changes in temperature and precipitation, and are generally estimated from mass-balance modeling of glaciers with mass-balance observations (e.g., Braithwaite and Zhang 2000; de Woul and Hock 2005). In combination with the data on temperature (ΔT) and precipitation change (ΔP), glacier mass change (ΔM) over a time window (Δt) can be obtained from

Table 2 Overview of studies projecting global glacier mass changes for the twenty-first century

Period	Projected SLE (mm)		Climate Scenario	Reference
	All glaciers	Excl. A + G		
2001–2100		46, 51	SRES A1B, 2 GCMs	Raper and Braithwaite (2006)
2001–2100	124 ± 37	99 ± 33	SRES A1B, 10 GCMs	Radić and Hock (2011)
2006–2100	148 ± 35		RCP2.6, 13 GCMs	Marzeion et al. (2012)
2006–2100	166 ± 42		RCP4.5, 15 GCMs	Marzeion et al. (2012)
2006–2100	175 ± 40		RCP6.0, 11 GCMs	Marzeion et al. (2012)
2006–2100	217 ± 47		RCP8.5, 15 GCMs	Marzeion et al. (2012)
2000–2099	159 ± 52	116	SRES A1B, 12 GCMs	Slangen et al. (2012)
2001–2100	150 ± 37	114 ± 30	SRES A1B, 10 GCMs	Radić et al. (2013)
2006–2100	155 ± 41	122 ± 36	RCP4.5, 14 GCMs	Radić et al. (2013)
2006–2100	216 ± 44	167 ± 38	RCP8.5, 14 GCMs	Radić et al. (2013)
2006–2099		73 ± 14 ^a	RCP8.5, 10 GCMs	Hirabayashi et al. (2013)
2012–2099	102 ± 28	64	SRES A1B, 8 GCMs	Giesen and Oerlemans (2013)

^a Here calculated by subtracting the reported projections for the period 1948–2005 (25.9±1.4 mm SLE) from the period 1948–2099 (99.0±14.9 mm SLE) in Hirabayashi et al. (2013).

$$\frac{\Delta M}{\Delta t} = S \left(\frac{db}{dT} \Delta T + \frac{db}{dP} \Delta P \right)$$

where $\frac{db}{dT}$ and $\frac{db}{dP}$ are mass-balance sensitivities to temperature and precipitation change, respectively, and S is glacier surface area (e.g., Hock et al. 2009). The specific mass-balance rate, \dot{b} , is typically in m water equivalent (w.e.) year⁻¹.

Several studies have found that glaciers in wetter or maritime climates tend to be more sensitive to temperature and precipitation changes than subpolar glaciers or glaciers in continental climates (e.g., Oerlemans and Fortuin 1992; Braithwaite and Zhang 1999; de Woul and Hock 2005). Quantifying the relations between mass-balance sensitivities and climate variables enables extrapolation of the sensitivities to glaciers without mass-balance observations. For the purpose of projecting global glacier mass changes, this approach was first applied in Gregory and Oerlemans (1998), further developed in Van de Wal and Wild (2001), and recently used for regional projections of twenty-first century sea-level change based on IPCC AR4 SRES scenarios (Slangen et al. 2012). In Slangen et al. (2012), the mass balance sensitivity ($\frac{db}{dT}$) is differentiated between summer and non-summer months, accounting for seasonality in glacier mass balance. Future scenarios of temperature and precipitation changes are taken from an ensemble of 12 global climate models (GCMs), and the results for the A1B emission scenario show a glacier contribution to the twenty-first century sea-level rise of 130–250 mm.

Hock et al. (2009) used a mass-balance sensitivity approach to reconstruct the average global glacier mass balance spatially resolved on a 0.5° global glacier grid (Cogley 2003) for the period 1961–2004 using gridded reanalysis temperature and precipitation trends. At the time of publication, this study was the only alternative approach to spatial interpolation of local mass-balance observations (Sect. 2.1). Their global estimate of 0.79 ± 0.34 mm SLE year⁻¹ was larger than the consensus estimate of 0.50 ± 0.22 mm SLE year⁻¹ by Kaser et al. (2006) for the same period, mainly due to large modeled mass loss of glaciers

peripheral to the Antarctic ice sheet (28 % of the global estimate), where large temperature sensitivities, temperature trends, and glacier area combined to yield large mass losses. In contrast, the Gardner et al. (2013) ICESat analyses found very little mass loss for the Antarctic periphery during 2003–2009.

3.2 Models of surface mass balance

This approach directly models the evolution of surface mass balance in time by simulating surface melting and accumulation using climate data. Melt is most commonly modeled by so-called degree-day models, mainly because of their simplicity and the fact that the positive degree days are shown to be good indicators for glacier melt (Ohmura 2001; Hock 2003). Raper and Braithwaite (2006) were the first to perform global-scale projections of glacier mass balance based on a degree-day model. Resulting mass-balance gradients were regressed against annual precipitation and summer temperature from gridded climatology, and the relation applied to all $1^\circ \times 1^\circ$ grid cells with glaciers (Cogley 2003). Based on the initial, calibrated equilibrium line altitudes (ELAs), upscaled glacier size distributions for each glacier grid cell, and derived vertical extent for each glacier, the model was run by perturbing the ELAs according to summer temperature anomalies. The resulting changes in total area and area–altitude distribution were computed annually with a simple glacier geometry model assuming a generic area–altitude distribution triangular in shape between its minimum and maximum altitude. Driven by climate data from two GCMs with A1B emission scenario, the projected sea-level rise for all glaciers, but excluding the glaciers peripheral to the Antarctic and Greenland ice sheet, was 46 and 51 mm for 2001–2100 (Table 2).

Hirabayashi et al. (2010) used a degree-day model specifically designed to feed into a global hydrological model. Consistent with the resolution of the latter model, the mass-balance model was run with daily time steps and on a $0.5 \times 0.5^\circ$ grid, treating each grid cell's glacier area as one large glacier, but allowing for sub-grid elevation bands. The model was initially used for the reconstruction of mass balance for the period 1948–2004, where gridded datasets of daily precipitation and near-surface temperature (Hirabayashi et al. 2005, 2008) were used as forcing. The modeled parameters were tuned to maximize the match between modeled and observed mass balance from 110 glaciers (Dyurgerov and Meier 2005); thus, the modeled global mass balance of 0.42 ± 0.15 mm SLE almost replicated the consensus estimate from Kaser et al. (2006). Recently, the model has been refined and run with the new Randolph glacier inventory (Arendt et al. 2012) to project glacier mass changes in response to the more extreme climate scenario (RCP8.5) from 10 GCMs prepared for the IPCC AR5 (Hirabayashi et al. 2013). They projected global glacier mass loss, excluding glaciers peripheral to the ice sheets, to be 73 ± 14 mm SLE for the period 2006–2099 (Table 2).

Radić and Hock (2011) developed a global-scale mass-balance model for the elevation-dependent mass balance of each individual glacier in the world glacier inventory by Cogley (2009a). The inventory comprised $\sim 120,000$ glaciers, covering 40 % of the total global glacier area. A degree-day model was calibrated using in situ mass-balance observation from 36 glaciers. The parameter values for all other glaciers were derived from established relationships with climate variables. Projections were made in response to downscaled monthly temperature and precipitation scenarios of ten GCMs from IPCC AR4 based on the A1B emission scenario. For the regions with incomplete glacier inventories, the projected volume changes were upscaled with a scaling relationship between regional ice volume change and regional glacierized area. The multi-model mean suggested sea-level rise of 112 ± 37 mm for the period 2001–2100. In a follow-up study, Radić et al. (2013)

updated the projections by using the new Randolph Glacier Inventory (Arendt et al. 2012). They modeled volume change for each glacier in response to transient spatially differentiated temperature and precipitation projections from 14 GCMs with two emission scenarios (RCP4.5 and RCP8.5) prepared for the IPCC AR5. Radić et al. (2013) arrived at much higher values than Hirabayashi et al. (2013) for the period 2006–2100: 155 ± 41 mm SLE (RCP4.5) and 216 ± 44 mm SLE (RCP8.5), and projected the largest regional mass losses from the Canadian and Russian Arctic, Alaska, and glaciers peripheral to the Antarctic and Greenland ice sheets. Although small contributors to global volume loss, glaciers in Central Europe, low-latitude South America, Caucasus, North Asia, and Western Canada and USA were projected to lose more than 80 % of their volume by 2100 (Fig. 1. Note that the region names are adopted from the Randolph Glacier Inventory).

Marzeion et al. (2012) applied a similar approach to model global mass balances to reconstruct the mass changes in the past and project future glacier mass evolution. Following Radić and Hock (2011), they modeled the surface mass balance of each individual glacier in the Randolph Glacier Inventory and coupled it with volume–area and volume–length scaling to account for glacier dynamics. The model was validated by a cross validation scheme using observed in situ and geodetic mass balances. When forced with observed monthly precipitation and temperature data, the world’s glaciers are reconstructed to have lost mass corresponding to 114 ± 5 mm SLE between 1902 and 2009. Using projected temperature and precipitation anomalies for 2006–2100 from 15 GCMs prepared for IPCC AR5, the glaciers are projected to lose 148 ± 35 mm SLE (scenario RCP2.6), 166 ± 42 mm SLE (scenario RCP4.5), 175 ± 40 mm SLE (scenario RCP6.0), and 217 ± 47 mm SLE (scenario RCP8.5). Based on the extended RCP scenarios, glaciers are projected to approach a new equilibrium toward the end of the twenty-third century, after having lost 248 ± 66 mm SLE (scenario RCP2.6), 313 ± 50 mm SLE (scenario RCP4.5), or 424 ± 46 mm SLE (scenario RCP8.5).

Giesen and Oerlemans (2013) provided an alternative to the degree-day modeling approaches and projected global glacier mass changes using a simplified surface energy balance model. The model separates the melt energy into contributions from net solar radiation (computed by multiplying the incoming solar radiation at the top of the atmosphere by atmospheric transmissivity and subtracting the part of the incoming radiation that is reflected by the surface) and all other fluxes expressed as a function of air temperature. The model was calibrated on 89 glaciers with mass-balance observations, whose mass changes were then projected in response to A1B emission scenario from 8 GCMs from IPCC AR4. Volume–area scaling was applied to account for changes in glacier hypsometry. The simulated volume changes from 89 glaciers were then statistically upscaled to all glaciers in Randolph Glacier Inventory larger than 0.1 km^2 , resulting in 102 ± 28 mm SLE for the period 2012–2099.

3.3 Model limitations

The models above are subject to large simplifications necessary for operation on global scales. Transferability of model parameters in time and space is questionable (e.g., Carenzo et al. 2009; MacDougall and Flowers, 2011). In addition, some studies have pointed out that variations in solar radiation have a significant effect on glacier mass changes (e.g., Ohmura et al. 2007; Huss et al. 2009). To address these concerns, a better approach than the generally applied degree-day approach would be to apply a physically based mass-balance model, accounting for all energy and mass fluxes at the glacier scale (Hock 2005). These high-complexity models have been applied successfully on many individual glaciers worldwide (e.g., Klok and Oerlemans 2002; Reijmer and Hock 2008; Mölg et al. 2009;

Anderson et al. 2010). However, the models require detailed meteorological input data, obtained at a glacier surface, which often are not available. Alternatively, these data can be obtained by dynamical downscaling of climate reanalysis products, i.e., by running mesoscale atmospheric models at high spatial resolution (less than 1 km in horizontal) over a region of interest. This approach has only recently been attempted in studies of glacier melt over a few summer seasons in Kilimanjaro and Karakoram (Mölg and Kaser 2011; Collier et al. 2013). Despite promising results, the applicability of this approach in order to simulate long-term surface mass balance on regional scale still needs to be investigated. In addition, the validation of surface mass-balance models should ideally be performed on sub-annual temporal scales, e.g., comparing modeled versus observed winter and summer mass balances, rather than only annual net mass balances. However, very few glaciers with annual mass-balance observations have the seasonally resolved components.

The representation of glacier dynamics using volume–area scaling remains a first-order approximation that is necessitated by the lack of input and validation data needed for physically based ice dynamics models. However, as shown by Lüthi (2009), volume–area scaling has some serious shortcomings in modeling glacier volume evolution. Glacier flow models of high complexity have been successfully applied on individual mountain glaciers (e.g., Picasso et al. 2004; Deponti et al. 2006; Juvet et al. 2009). However, it is challenging to simulate the flow of a full suite of glaciers within a region of complex topography (Jarosch et al. 2012). Such ice-flow models require detailed information of the underlying bedrock topography, which has been observed for fewer than 1 % of glaciers in the world (Huss and Farinotti 2012). In the absence of abundant measured data on glacier thickness and volume, various alternative approaches to derive ice thicknesses have recently been developed (e.g., Clarke et al. 2012; Huss and Farinotti 2012; Linsbauer et al. 2012; McNabb et al. 2012). In particular, promising is the first globally complete dataset of glacier bed topographies derived from inverse modeling by Huss and Farinotti (2012), which will open new avenues for modeling glacier dynamics on the global scale.

To our knowledge, none of the current global-scale modeling studies of glacier volume changes incorporates frontal ablation, i.e., mass loss by iceberg calving or submarine melt of marine-terminating glaciers. Studies on marine-terminating ice caps have shown that calving may account for roughly 30 % to the total ablation (e.g., Dowdeswell et al. 2002, 2008), a significant contribution if widely applicable. Burgess et al. (2013) found that regional-scale losses by frontal ablation in Alaska are equivalent to 36 % of the total annual net mass loss of the region. Gardner et al. (2013) estimated that the present-day percentage of glacierized area (excluding the ice sheets) draining into the ocean is ~ 35 %. Hence, the projections of volume loss, in which only the loss due to the surface mass balance is modeled, represent a lower bound. However, estimates of frontal ablation are scarce and lacking on a global scale. Nevertheless, it may be expected that the fraction of total mass change due to frontal ablation will decrease as warming and terminus retreat proceed (McNabb et al. 2012; Colgan et al. 2012).

4 Glacier runoff

4.1 Effects of glaciers on streamflow

Glaciers significantly modify streamflow both in quantity and timing, even with low percentages of catchment ice cover (e.g., Meier and Tangborn 1961; Fountain and Tangborn 1985; Chen and Ohmura 1990; Hopkinson and Young 1998; see Hock et al.

2005 for review). Characteristics of glacier discharge include pronounced melt-induced diurnal fluctuations with daily peaks reaching several fold the daily minimum flows during precipitation-free days. Glacier runoff shows distinct seasonal variations with very low winter flows and a larger and seasonally delayed summer peak compared to non-glacierized basins. Hence, glaciers can sustain streamflow during dry summer months and compensate for otherwise reduced flows. Year-to-year variability is dampened by the presence of glaciers in a catchment with a minimum reached at 10–40 % of glacierization (Lang, 1986). This so-called glacier compensation effect occurs when glacier runoff offsets precipitation variations. Glaciers may also cause sudden floods, often referred to as *Jökulhlaups*, posing a potential hazard for downstream populations. Common causes include subglacial volcanic eruptions or sudden drainage of moraine- or ice-dammed glacial lakes (e.g., Lliboutry et al. 1977; Björnsson 2002).

Annual runoff from a glacierized basin is a function of glacier mass balance, with years of negative balance producing more runoff than years of positive balance. As climate changes and causes specific glacier mass balances to become progressively more negative, total glacier runoff will initially increase followed by a reduction in runoff totals as the glaciers retreat (Janson et al. 2003). With high percentage of ice cover, the initial increase in runoff can be substantial, considerably exceeding the runoff changes to be expected from any other component of the water budget. Adalgeirsdottir et al. (2006) modeled an increase in annual runoff from ice caps in Iceland of up to 60 % until about 2100 followed by a rapid decrease thereafter. However, in the long term, the loss of ice will lead to lower watershed yields of water. Observations from gauge records in glacierized basins show both increases in runoff, for example, along the coast in southern Alaska (Neal et al. 2002) or northwestern British Columbia (Fleming and Clarke 2003) and negative trends in summer streamflow, for example in the southern Canadian Cordillera (Stahl and Moore 2006). The replacement of ice by temperate forest and alpine vegetation will further decrease water yields.

In addition to contributing directly to runoff through ice wastage, glacier coverage within a watershed decreases direct evaporation and plant transpiration, the combination of which can result in substantially higher water yields for watersheds with glaciers compared to unglacierized watersheds (Hood and Scott 2008). In addition, the proportion of streamflow derived from glacial runoff has profound effects on physical (Kyle and Brabets 2001), biogeochemical (Hodson et al. 2008; Hood and Berner 2009; Bhatia et al. 2013), and biological (Milner et al. 2000; Robinson et al. 2001) properties of streams. As a result, changes in watershed glacial coverage also have the potential to alter riverine material fluxes. For example, area-weighted watershed fluxes of soluble reactive phosphorus decrease sharply with decreasing watershed glacial coverage (Hood and Scott 2008). Recent evidence also suggests dissolved organic material contained in glacial runoff has a microbial source and is highly labile to marine heterotrophs (Hodson et al. 2008; Hood et al. 2009).

4.2 What is glacier runoff?

There is substantial ambiguity in the literature with respect to the way the importance of glacier contribution to total runoff is quantified. Different concepts have been used (Table 3), and the importance will depend on how glacier runoff is defined. First, in its most general sense, glacier runoff is defined as the runoff from the glacierized area, and hence it includes all runoff exiting a glacier usually in one or several streams at the glacier terminus (Concept 1 in Table 3; Fig. 2). According to this definition, it is the residual in

Table 3 Different concepts found in the literature to assess the importance of glaciers in total river runoff. Q_g is glacier runoff, P_1 is liquid precipitation, E is evaporation, M is melt, R is refreezing melt or rainwater, and C is snow accumulation

Concept	Equation	Description
1 ^a	$Q_g = M_{ice,firm,snow} - R + P_1 - E$	All runoff from glacierized area
2	$Q_g = M_{ice,firm,snow} - R$	Glacier meltwater runoff
3	$Q_g = M_{ice/firm}$	Ice/firm melt (melt from snow-free surface of the glacier)
4	$Q_g = C - M_{ice,firm,snow} - R$ (for $Q_g > 0$)	Runoff from glacier net mass loss
5	$Q_g = C - M_{ice,firm,snow} - R + P_1 - E$	As 4, but including other water balance components (water balance approach)
6	$Q_g = C$	Runoff assuming balanced glacier mass budget if the budget is negative

All quantities are integrated over the glacierized area

^a Lateral or subglacial inflows/outflows are neglected here.

the water balance equation over the area of the glacier and corresponds to the quantity that is directly measured by gauging the proglacial stream(s) at the glacier terminus. Thus, glacier runoff includes the portion of all water inputs to the glacier through melt, rain, or other inflow at the surface, laterally or subglacially that exit the glacier at the terminus.

Second, the term has also been used to describe only the component of runoff that comes from the melting of the glacier itself, i.e., from glacier ice, snow, and firn (i.e., snow that has survived at least one melt season but has not been transformed to glacier ice yet), hence excluding any rainwater or other inflow to the glacier system (Concept 2). This component is more accurately referred to as glacier meltwater runoff (Cogley et al. 2011).

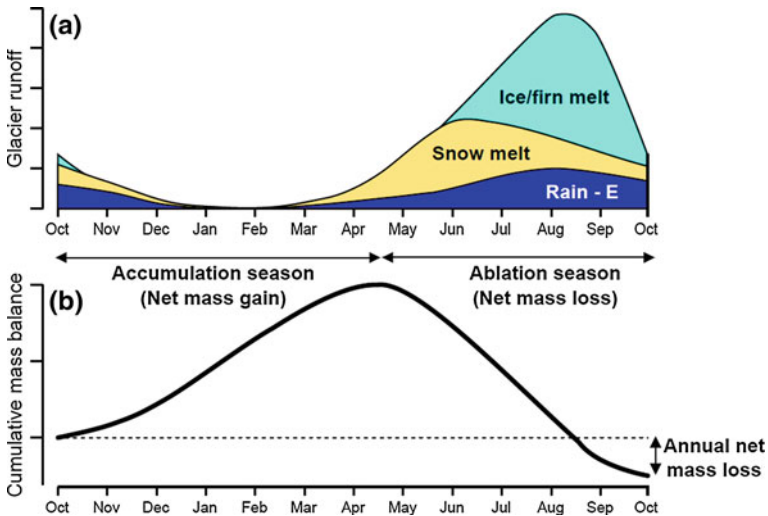


Fig. 2 **a** Schematic seasonal variation of total glacier runoff and its components following Concept 1 (Table 3), E is evaporation. **b** cumulative glacier mass balance in specific units ($m\ w.e.\ year^{-1}$) showing a year with negative annual balance. According to Concept 4 (Table 3), annual glacier runoff corresponds to the annual mass loss

It is important to note that this definition is not equivalent to the glacier's mass balance (budget) since it does not include the accumulation term but only the fraction of meltwater that does not refreeze, and exits the glacier.

Third, sometimes glacier runoff is understood as the meltwater runoff originating solely from ice/firn melt, i.e., melt of snow on the glacier is accounted for separately (Koboltshnik et al. 2007; Weber et al. 2010). This definition is consistent with the view that all other components (snow melt, rain etc.) would exist for the glacierized area even if the glacier did not exist. Hence, only the excess water due to the presence of the glacier is considered (Concept 3). This component is difficult to measure directly since it requires detailed measurements of melt at the surface in concert with the observations of snow line retreat and therefore is better quantified by mass-balance modeling which can separate the components of mass change.

Glacier runoff following Concepts 1–3 will affect river runoff in a glacierized catchment no matter whether or not the glacier over the time span considered had a positive, a negative, or a balanced mass budget. In contrast, glacier runoff is sometimes defined as the runoff component that is due to glacier net mass loss, hence referring only to the water originating from the glacier volume (storage) change (Concept 4, Huss 2011). Lambrecht and Mayer (2009) refer to this component as “excess discharge” since it constitutes additional water due to the reduced storage volume of glaciers that is not available in unglacierized catchments. Accordingly, in contrast to Concepts 1–3, glacier runoff is zero when the glacier's mass budget is balanced or positive, no matter how much meltwater is leaving the glacier. Hence, a glacier only affects runoff if there is a net mass loss during the considered time period. In this case, the glacier runoff is equivalent to the glacier's (negative) mass budget, which can be measured directly using the methods described in Sect. 2. Some studies have extended this definition to include the balance of liquid precipitation and evaporation (P_1-E ; Concept 5; Dyurgerov 2010). Finally, Kaser et al. (2010) consider glacier mass loss assuming a balanced annual mass budget, i.e., water from net mass loss is not considered. In this case, annual glacier runoff effectively corresponds to annual snow accumulation (Concept 6).

In summary, definitions vary with respect to the inclusion of water not generated from melt and whether snow accumulation is included. Snowmelt runoff from the glacier can be substantial (Fig. 2) and is included in some, but excluded in other studies. It is obvious that the absolute amounts of glacier runoff and the degree to which glacier runoff affects total runoff of a glacierized catchment depend on the concept used in defining glacier runoff. It is paramount that any investigations aimed at assessing the importance of glacier runoff in total runoff clearly define the quantity used.

5 Assessing global-scale impacts of glaciers on the hydrological cycle

Analyses based on the observations or modeling in individual glacierized river basins have highlighted the role of glaciers in the hydrological cycle and indicated significant hydrological changes in response to climate change, including changes in total water amounts and seasonality (e.g., Braun et al. 2000; Casassa et al. 2006; Rees and Collins 2006; Hagg et al. 2006; Horton et al. 2006; Yao et al. 2007; Huss et al. 2008; Immerzeel et al. 2013; Koboltshnik et al. 2008; Stahl and Moore 2006; Kobierska et al. 2013). However, few studies have investigated the hydrological effects of glaciers on regional or global scales.

Dyurgerov (2010) updated an earlier study by Dyurgerov and Carter (2004) and investigated the role of glaciers in freshwater inflow to the Arctic Ocean by comparing the

estimates of river discharge from gauging stations to estimates of meltwater fluxes and annual mass changes of all glaciers draining to the Arctic Ocean including the Greenland ice sheet. Annual glacier runoff (Concept 5, Table 3) was found to have increased substantially from 1961 to 1992 to 1993–2006 (from 146 ± 338 to 202 ± 48 Gt a⁻¹) while glacier mass loss more than doubled. The increase in glacier runoff was the same order of magnitude as the observed increase in river runoff (Bring and Destouni 2011), suggesting an important role of glacier melt in Arctic freshwater budgets.

Neal et al. (2010) adopted a water balance approach to estimate the contribution of glacier runoff to freshwater discharge into the Gulf of Alaska, a 420,230 km² watershed covered 18 % by glaciers. Glacier runoff (Concept 1) contributed 47 % of the total runoff (870 km³ a⁻¹), with 10 % originating from glacier net mass loss alone (Concept 4, Table 3).

Dyrgerov (2010) analyzed all available mass-balance profiles, which describe the distribution of mass change with altitude, and found an increase in both accumulation and ablation in the observed period (1961–2006), with major increases since the late 1980s, and a steepening of the mass-balance gradient. The latter was attributed to an increase in meltwater production at low elevations combined with more snow accumulation at higher elevations and interpreted as evidence of an intensified hydrological cycle in times of global warming.

Huss (2011) assessed the contribution of glaciers to runoff from large-scale drainage basins in Europe with areas up to 800,000 km² over the period 1908–2008 based on modeled monthly mass budget estimates for all glaciers in the European Alps. The glacier runoff defined as the water due to glacier mass change (Concept 4, Table 3) was computed for each month and compared to monthly river runoff measured at gauges along the entire river lengths. Although glacierization of the investigated basins did not exceed 1 % of the total area, the maximum monthly glacier contributions during summer ranged from 4 to 25 % between catchments, indicating that seasonal glacier contributions can be significant even in basins with little ice cover. Comeau et al. (2009) analyzed annual runoff in a large catchment in Western Canada and found that reductions in glacier volume due to receding glaciers (Concept 4, Table 3) contributed 3 % to total runoff during 1975–1998.

Kaser et al. (2010) performed the only global-scale study on the effects of glaciers on freshwater resources and provided a first-order estimate of the role of glaciers to water availability and their societal importance. For 18 large glacierized river basins, the fraction of runoff that is seasonally delayed by glaciers was computed based on gridded climatologies and theoretical considerations rather than glacier mass balance and runoff data. Monthly accumulation was computed as a function of elevation using gridded climatological data from the Climatic Research Unit (CRU). Assuming the glaciers to be in equilibrium with climate, an equal amount of annual ablation was distributed to each month based on monthly air temperatures. Any excess ablation beyond accumulation, for a given month, was considered seasonally delayed glacier runoff and weighted with population to assess the societal impact of delayed runoff. Results showed that seasonally delayed glacier runoff is most significant in seasonally arid regions and of moderate importance in midlatitude basin, but negligible in lowland basins affected by monsoon climates. This underlines the importance of climate regimes in determining the importance of glaciers on runoff.

6 Synthesis and discussion

Accelerated glacier wastage in many parts of the world and the resulting impacts on sea-level rise and water resources is a topic of global concern. Mass losses from the Earth's

mountain glaciers and ice caps contribute to the freshwater influx to the ocean and make up one-third of recent sea-level rise (the remaining parts come in equal shares from ice sheet mass losses and thermal expansion of seawater). They also influence the runoff characteristics of glacierized basins with significant effects even at low levels of glacierization. The expected changes in glacier runoff may be larger than those generally projected for other components of the water cycle.

The main impacts of glacier wastage vary regionally. For sea-level rise, the most important regions are found in high-latitude regions where large ice volumes are typical, such as the Antarctic and Greenland peripheries, Canadian Arctic, Alaska, and the Russian Arctic (Gardner et al. 2013). In contrast, mid- and low-latitude regions (e.g., European Alps, Scandinavia, Tropical Andes, and Western Canada/USA) have relatively little ice cover and therefore (except for the High Asian Mountains) less potential impact on sea-level change. However, many of these regions have relatively large populations and the hydrological consequences of glacier wastage are of concern.

Assessing and projecting the effects of glaciers on sea level and terrestrial hydrology requires accurate assessments of the glacier mass balance and its components. In recent years, much progress has been made in measuring glacier mass changes on regional and global scales, mostly due to the launch of the ICESat and GRACE satellites in the beginning of the twenty-first century. For the first time, regional scale mass-balance observations were possible in regions with sparse local in situ observations. These results will be valuable for calibration and validation of global hydrology models. Although the traditional technique of extrapolating local observations is problematic in regions with sparse data, as it can bias global results (Gardner et al. 2013), in situ measurements are essential for calibration and validation of glacier mass-balance and runoff models. Unfortunately, the number of mass-balance monitoring glaciers has declined in recent years.

Until recently, the lack of basic inventory data was a major impediment in global mass-balance assessments and projections resulting in large uncertainties in the results due to necessary upscaling procedures or other workarounds (e.g., Raper and Braithwaite 2005; Radić and Hock 2010). The recently completed Randolph Glacier Inventory, the first globally complete glacier inventory (Arendt et al. 2012), is a major step forward toward reducing uncertainties in global-scale studies. Also, for the first time, it has become possible to model global mass balances for each glacier in the world individually (Radić and Hock 2011; Marzeion et al. 2012; Radić et al. 2013). However, there is a large range in the twenty-first century projections from the three independent studies (Marzeion et al. 2012; Radić et al. 2013 and Hirabayashi et al. 2013) that use the new inventory despite using the same climate forcings (RCP scenarios) and largely overlapping selection of GCMs. Hirabayashi et al. (2013) projections are at the low end. Results also indicate that previously found large uncertainty due to the choice of the GCMs (e.g., Radić and Hock 2011) has not been reduced. Glacier models also still suffer from the omission of frontal ablation (calving and submarine melt) due to the inherent difficulty in modeling these processes and the lack of data to develop parameterizations suitable for regional scales.

For sea-level change calculations, rates of regional or global glacier net mass loss are generally converted into sea-level equivalent simply by dividing the volume of water lost by the ocean area ($362.5 \times 10^{12} \text{ m}^3$, Cogley et al. 2011), thus neglecting the effects of altering ocean area and terrestrial hydrology. The effect of flow of meltwater into groundwater aquifers or enclosed basins rather than the oceans is virtually unknown and should be addressed by coupling glacier mass-balance models with global hydrology models. For future scenarios, it is important that hydrology models have the capacity to

model glacier retreat. Few studies on local scales have incorporated simple parameterizations (Stahl et al. 2008; Huss et al. 2010) into their glacier runoff models; however, while there are examples of macroscale models using glacier models for local applications (Zhao et al. 2013), we are not aware of any current global-scale watershed models (e.g., Hanasaki et al. 2008; Wisser et al. 2010) incorporating glacier modeling in macroscale applications. The Randolph Glacier Inventory will further facilitate the inclusion of glacier mass changes into global hydrology models.

Many studies on various spatial scales have investigated the effects of glaciers on hydrology under a warming climate. Generally, annual glacier runoff is found to increase initially due to increased meltwater, followed by reduced flows as glaciers recede, and their ability to augment flows diminishes. However, contradictory results are reported with regard to the importance of glacier runoff relative to total runoff in glacierized catchments (e.g., Weber et al. 2010; Huss 2011). While this can at least partially be attributed to differences in physical factors such as climate regimes, catchment size, degree of glacierization, or glacier mass change rates, these differences also depend on the way the glacier runoff is quantified. In fact, studies on the relative importance of glaciers for runoff are difficult to compare, because authors use different concepts to compute the contribution of glaciers to runoff (Table 3). Definitions of glacier runoff fall into two principal categories (Comeau et al. 2009): (1) those that only consider the net mass loss component of a glacier due to glacier wastage, i.e., runoff is zero (Concept 4) or equal to $P_1 - E$ (Concept 5, Table 3) if the glacier is in balance or gains mass, and (2) those that consider all meltwater originating from a glacier no matter the magnitude or sign of the mass budget (Concepts 1–3, Table 3). It is obvious that for the concepts in (2), glacier runoff generally is much larger than for the concepts in (1), and consequently the relative importance of glacier runoff to total runoff will differ between these two categories.

Concepts based on net glacier mass loss are most useful over annual timescales as they provide a measure for how much water is added to (or withdrawn from) the hydrological cycle through glacier volume storage changes. In contrast, concepts considering all meltwater are useful on seasonal timescales in order to assess the effects of glaciers on seasonal hydrographs. Precipitation that has fallen as snow is released later during the melt season and hence modulates the seasonality of flow even if the glacier's annual mass budget is zero. Such concepts are also useful on longer timescales, for example when physical properties of the meltwater, such as temperature or conductivity, are of relevance.

Considering only ice or firn melt (Concept 3, Table 3) aims to isolate the effects of glaciers on seasonal or annual flows compared to non-glacierized catchments. Thus, melt of snow on the glacier surface is excluded from the glacier contribution because this component also occurs in unglacierized catchments. However, this approach is not unproblematic since typically some winter snow remains on the glacier by the end of each melt season, a necessity for a glacier to survive. Hence, in contrast to unglacierized regions, snowmelt from the glacier surface occurs over the entire length of the summer (Fig. 2) and therefore is a characteristic feature of a glacier that is eliminated in Concept 3. The surviving winter snow is also directly linked to the glacier system through subsequent transformation of snow to ice.

Overall, all concepts found in the literature are legitimate, and the choice of concept will depend on the purpose of the investigation. It is paramount that glacier runoff is clearly defined to avoid confusion and allow fair comparison between studies.

7 Conclusions

In light of strongly accelerated glacier wastage, there is an urgent need for further investigations quantifying and projecting the changes in glacier mass and runoff, and their importance for the Earth's hydrological cycle. We identify the following issues that need special attention:

- The current decline of the in situ glacier monitoring programs is a matter of concern. Although the remote sensing techniques have overcome many obstacles encountered by the traditional in situ observations, the latter are essential for calibration and validation of glacier mass-balance and runoff models.
- Despite the recent progress in the development of the global-scale glacier models, they still suffer from the omission of physics-based simulation of glacier dynamics and frontal ablation (calving and submarine melt).
- The effect of flow of meltwater into groundwater aquifers or enclosed basins is virtually unknown and should be addressed by coupling glacier mass-balance models with global hydrological models.
- For future scenarios, it is important that these hydrological models have the capacity to model glacier retreat.
- It is essential that glacier runoff is clearly defined in studies aiming to quantify the contribution of glacier runoff to streamflow to avoid confusion and facilitate fair comparison between studies.

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