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To cite this version:

Mohd Farooq Azam, Patrick Wagnon, Etienne Berthier, Christian Vincent, Koji Fujita, et al.. Review of the status and mass changes of Himalayan-Karakoram glaciers. Journal of Glaciology, 2018, 64 (243), pp.61-74. 10.1017/jog.2017.86 . hal-01952828

HAL Id: hal-01952828
https://hal.science/hal-01952828

Submitted on 22 Nov 2021

Journal of Glaciology (2018), **64**(243) 61–74 doi: 10.1017/jog.2017.86

Review of the status and mass changes of Himalayan-Karakoram glaciers

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ABSTRACT. We present a comprehensive review of the status and changes in glacier length (since the 1850s), area and mass (since the 1960s) along the Himalayan-Karakoram (HK) region and their climate-change context. A quantitative reliability classification of the field-based mass-balance series is developed. Glaciological mass balances agree better with remotely sensed balances when we make an objective, systematic exclusion of likely flawed mass-balance series. The Himalayan mean glaciological mass budget was similar to the global average until 2000, and likely less negative after 2000. Mass wastage in the Himalaya resulted in increasing debris cover, the growth of glacial lakes and possibly decreasing ice velocities. Geodetic measurements indicate nearly balanced mass budgets for Karakoram glaciers since the 1970s, consistent with the unchanged extent of supraglacial debris-cover. Himalayan glaciers seem to be sensitive to precipitation partly through the albedo feedback on the short-wave radiation balance. Melt contributions from HK glaciers should increase until 2050 and then decrease, though a wide range of present-day area and volume estimates propagates large uncertainties in the future runoff. This review reflects an increasing understanding of HK glaciers and highlights the remaining challenges.

KEYWORDS: climate change, glacier fluctuations, glacier hydrology, glacier monitoring, mountain glaciers

1. INTRODUCTION

The 2500 km long Himalaya-Karakoram (HK) region – extending westward from Yunnan Province (China) in the east, across Bhutan, Nepal, southern Tibet, northern India, and into Pakistan – is one of the most glacierized regions on Earth. A large fraction of the subcontinent's fresh water is locked in this dynamic storage (Frey and others, 2014). HK glaciers influence the runoff regime of major regional river systems (Immerzeel and others, 2010; Kaser and others, 2010), for example the Indus, Ganges and Brahmaputra, by releasing water mainly in warm summer months in the Karakoram and western Himalaya, and in the dry-season spring and autumn months in most of the central and eastern Himalaya. This meltwater helps to sustain more than 750 million people and the economy of the surrounding countries by providing water for irrigation, hydropower, drinking, sanitation and manufacturing (Immerzeel and others, 2010; Pritchard, 2017).

Recent estimates of the glacierized area in the HK region varies from 36 845 to 50 750 km^2 (Supplementary Table S1), with roughly half of the area in the Karakoram Range. The ice volume estimates depend on the inventory and method; consequently, available volume estimates, varying from 2 955 to 4 737 km^3, also indicate large uncertainties (Frey and others, 2014). The estimated impacts of these glacierized areas on river hydrology are influenced by each study's region of analysis and the area and volume of ice estimated from different sources. This review inherits such heterogeneities, gaps and uncertainties of the published record, but gradually the problems are being remedied. The relative percentage of glacier meltwater to the total runoff is an indicator of the vulnerability of river systems to climate. Therefore, future climate changes are expected to alter the melt characteristics of the HK rivers, for instance, seasonal shifts in stream flow (Mölg and others, 2014). Further, the potentially important contributions of sub-surface ice contained in the active layer and of massive segregation ice of permafrost in HK river hydrology remains unknown.

The HK glaciers gained attention after the typographic error in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report that suggested a catastrophic loss of HK glaciers by 2035 (Cogley and others, 2010). Moreover, while glaciers worldwide are in a recession (Zemp and others, 2015), stable or advancing glaciers dominate in the Karakoram (the 'Karakoram Anomaly') (Hewitt, 2005; Gardelle and others, 2012; Kääb and others, 2012), an anomaly which seems to be centered in the western Kunlun Shan (Kääb and others, 2015). The way-off IPCC typographic mistake (which was later retracted and then corrected (Vaughan and others, 2013)) and various conflicting and confusing publications led to a review (Bolch and others, 2012) 5 years ago that summarized the existing knowledge about HK glaciers and highlighted the gaps in the HK glaciology. Since then, as a result of growing interest in the international scientific community, great progress has been achieved. Some key advancements are recent glacier trends (Brun and others, 2017), their climatology (Azam and others, 2014a, b; Maussion and others, 2014; Sakai and others, 2015), contributions to local (Nepal and others, 2014) or regional (Racoviteanu and others, 2013; Lutz and others, 2014; Mukhopadhyay and Khan, 2014a) water supply and sea-level rise (Jacob and others, 2012; Gardner and others, 2013; Huss and Hock, 2015) and natural hazards (Khanal and others, 2015). This rapid recent expansion of knowledge about HK glaciers has motivated this up-to-date review. We present: (i) the most complete compilation of in situ-, model- and remote-sensing-based glaciological studies from the HK region, (ii) analysis to check the reliability of available data (length/area changes and mass changes from different methods) with a focus on glaciological mass balances, (iii) discussion of glacier behaviors under regional climatic settings and (iv) future research strategies to strengthen the cryospheric knowledge in the HK region.

2. CLIMATE DYNAMICS AND GLACIER CHARACTERISTICS

The hydrological cycle of the HK region is complex because of the impact of two circulation systems, the Asian Monsoon (AM) and Western Disturbances (WD) (Bookhagen and Burbank, 2010). Most glaciers in the eastern and central Himalaya experience maximum accumulation in the summer due to high monsoonal precipitation and high elevations, where periods of summertime ablation punctuate overall summer-long snow accumulation (Ageta and Higuchi, 1984). The summer accumulation in the western Himalaya is weak while the AM barely reaches to the Karakoram Range (Bookhagen and Burbank, 2010). In the Karakoram, WD is the important source of moisture providing maximum precipitation during winter due to strong storms (Lang and Barros, 2004) with generally short life spans of 2–4 days (Dimri and Mohanty, 2009). The western Himalaya is a transition region receiving precipitation from both the AM and WD (Azam and others, 2016). Further, there are strong orographic differences in precipitation from south to north across the HK (Shrestha and others, 1999). The HK is a barrier to monsoon winds, causing maximum precipitation on southern slopes with a regional east to west decrease in the monsoon intensity (Shrestha and others, 1999) and large local orographic controls on climate. For instance, AM provided low precipitation (21% of the annual sum) on the leeward side of the orographic barrier at Chhota Shigri Glacier (western Himalaya) and high precipitation (51% of annual total) on the windward side at Bhuntar city (~50 km south from Chhota Shigri) (Azam and others, 2014b). Therefore, depending on their geographical position and regional orography, the glaciers in the HK region are subjected to different climates. This variability of precipitation regimes along the HK region begets varying types and behaviors of glaciers over short distances (Maussion and others, 2014). Five classes of glaciers were defined (Maussion and others, 2014): two dominant classes with winter (DJF) and summer (JJA) accumulation type, a class with maximum precipitation in pre-monsoon (MAM) months and two intermediate classes which tend to receive either winter (DJF/MAM) or summer (MAM/JJA) precipitation but with less pronounced centers (precipitation amounts) in winter or summer seasons, respectively.

3. GLACIER FLUCTUATIONS AND AREA CHANGE RECORDS

We present the maximum possible compilation of glaciological studies including many Geological Survey of India reports, which are not available easily, but scanned for this study. Compared with snout fluctuation records for almost 100 glaciers/basins in a previous review (Bolch and others, 2012), our compilation includes historical records of 154 glaciers/basins, some available since the 1840s (Fig. 1a). We carefully assess the quality of satellite imageries or topographic maps used to estimate the length changes and assign the caution flags to each length change record (Supplementary Table S2). The longest historical records are for Milam, Gangotri, Pindari, Siachen and Biafo glaciers. Between the mid-19th and mid-20th century, glacier fluctuation records (Fig. 2a) are at multi-decadal scale, extracted from field photographs or maps. After that, the records are usually available at decadal scale, and for some glaciers like Chorabari, Pindari and Raikot records are available annually for recent years. There are 25 records available per year between the mid-19th and the mid-20th century (Fig. 2b). An abrupt increase of records occurred in the early 1960s, with a peak exceeding 125 records per year in the 1975–2000 period (Fig. 2b). This is because Survey of India maps, available since the 1960s, were combined with recent satellite images or field surveys to estimate the fluctuations (Supplementary material).

Since the mid-19th century, a majority of Himalayan glaciers retreated with rates varying regionally and from glacier to glacier, while in the Karakoram, the glaciers snouts have been retreating, stable or advancing (Fig. 2a; Supplementary Table S2). The interpretation of the length record in the Karakoram is complicated by the occurrence of surges. For example, in upper Shyok Valley in the Karakoram, 18 glaciers (1 004 km^2) out of 2 123 glaciers (2 978 km^2) showed surge-type behavior (Bhambri and others, 2013).

Glacier area change studies were performed generally at basin-wide scale with few individual glacier estimates (Fig. 1b; Supplementary Table S3). We assign the caution flags to each area change record based on the quality of satellite imageries and topographic maps used in the studies (Supplementary Table S3). Along the Himalayan Range shrinkage is common over the last 5–6 decades (Fig. 1b) with high variability in rates ranging from –0.07% a^{-1} for Kimoshung Glacier over 1974–2015 to –1.38% a^{-1} for Ganju La Glacier over 2004–14 (Fig. 2c). Conversely, glaciers in the Karakoram Range showed a slight shrinkage or stable area since the mid-19th century (Supplementary Table S3).

The example of the Khumbu Region (Everest) is striking to illustrate how difficult it can be to compare different area change estimates. A small fraction of the glaciers in this region (~92 km^2) showed an area reduction of –0.12% a^{-1} over 1965–2005 (Bolch and others, 2008). Another study (Salerno and others, 2008), using historical maps (1 : 50 000 scale), reported similar reduction rate of –0.14% a^{-1} over a 404 km^2 glacierized area in the same region for 1956–90. A study covering 4000 km^2 over the Koshi Basin (including Khumbu Region) estimated the much more negative rate of area changes of $-0.59 \pm 0.17\%$ a^{-1} over 1976–2009 (Shangguan and others, 2014). The large discrepancies in those estimates can be attributed to the differing extents of

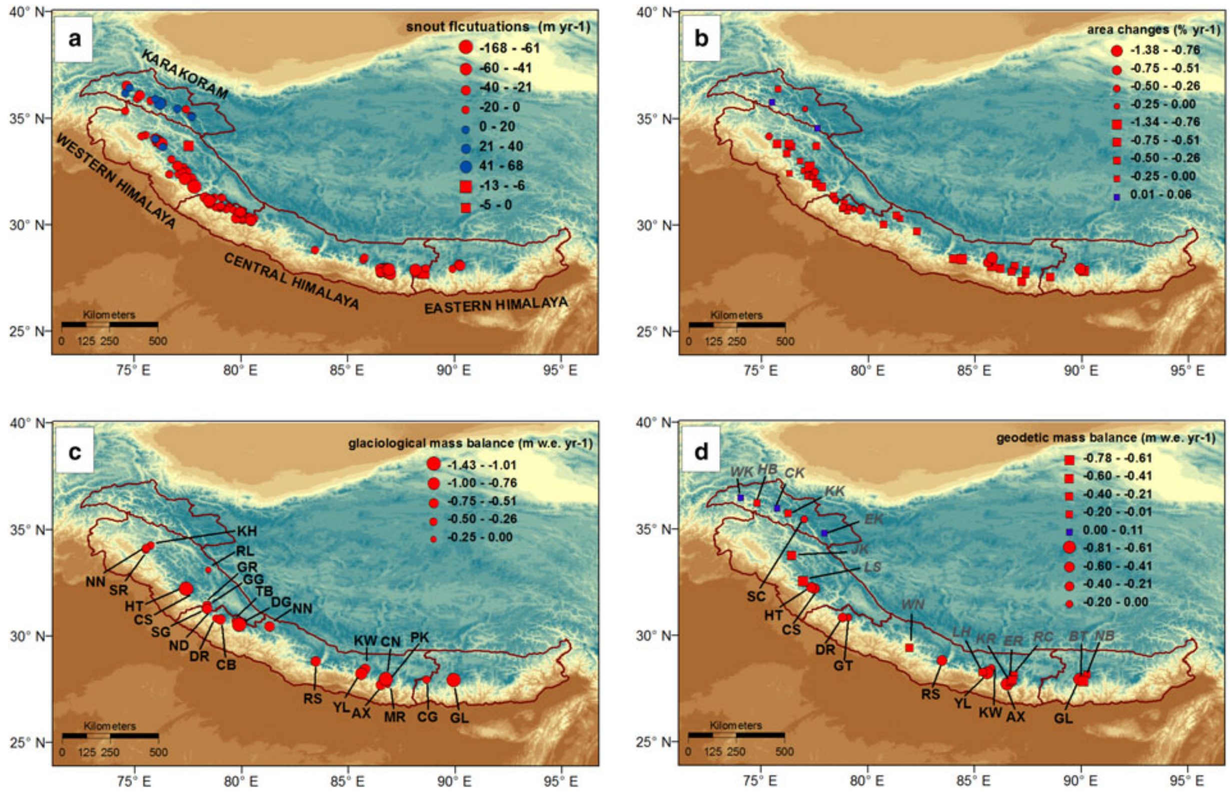

Fig. 1. Spatial glacier/basin behaviors over the HK region (Note: the observation time is different and given in corresponding supplementary tables). The regions are defined following (Bolch and others, 2012). Symbology: Circles represent the glacier scale observations while squares represent basin/regional scale observations. Red (or blue) color represents negative (or positive) changes in length, area or mass balance. The abbreviations are given in corresponding supplementary tables. (a) Glacier snout fluctuations for 152 glaciers and 2 basins (Supplementary Table S2). (b) Area changes for 24 glaciers and 47 basins (Supplementary Table S3). (c) Glaciological mass balances for 24 glaciers (Supplementary Table S4 and S6) and (d) geodetic mass balances for 10 glaciers and 24 basins/regions (Supplementary Table S8).

the glacierized area, difficulties in mapping debris-covered glaciers, different observation periods, methodologies, data used and related uncertainties.

The glacier area shrinkage causes fragmentation of large glaciers; consequently, the number of glaciers increased in the Himalaya over the past 5–6 decades (Kulkarni and others, 2007; Ojha and others, 2016). The area shrinkage of clean-ice areas, and perhaps reducing glacier flow speeds and possibly accelerating mass wasting from deglaciated surfaces also resulted in increasing supraglacial debris-covered area in the Himalaya (Scherler and others, 2011; Nuimura and others, 2012; Thakuri and others, 2014). Small and low elevation glaciers were found to be shrinking faster than larger ones (Thakuri and others, 2014; Ojha and others, 2016). Studies with multiple observation periods revealed specific trends of area shrinkage rates from different regions of the HK. Steady trends in the eastern Himalaya (Racoviteanu and others, 2015), accelerated shrinkage in the central Himalaya (Bolch and others, 2008; Thakuri and others, 2014) and decreasing shrinkage in Zanskar and Ravi basins of the western Himalaya (Schmidt and Nüsser, 2012; Chand and Sharma, 2015) were found over the last 5–6 decades.

The mean shrinkage rates were computed for the Himalayan glaciers using 60 data series (excluding highly uncertain data; Supplementary Table S3). The shrinkage rates were available since the 1950s to present, but a time window from 1960 to 2010 was selected to avoid the sparse data outside this window. Despite the regional variation in shrinkage rates, Himalayan glaciers showed a continuous mean area shrinkage over the last 5 decades which is slightly higher (more negative) between 1980 and 2000 (Fig. 2c). The calculated unweighted mean area shrinkage for Himalayan glaciers is –0.36% a^{-1} for 1960–2010. This rate is less than the unweighted mean shrinkage rate (–0.57% a^{-1}) and very close to the weighted mean shrinkage rates (–0.40% a^{-1}) calculated for the whole of High Mountain Asia (HMA) (Cogley, 2016) for the same period. Only four area change studies are available from the Karakoram Range covering different regions (Supplementary Table S3). A time window of 1980–2010 was selected to get at least three estimates for the mean rate of area change. The unweighted mean rate of area change for the Karakoram glaciers varies from ~–0.06% a^{-1} during the 1980s to almost 0% a^{-1} in 2000s (Fig. 2c), but the temporal trend is hard to interpret and probably not significant given the scarcity of the measurements. Overall, these close to 0% a^{-1} area changes rates are in line with the Karakoram Anomaly (Hewitt, 2005; Gardelle and others, 2012; Kääb and others, 2012). Importantly, due to the unweighted nature of these mean rates, and the fact that small glaciers tend to lose area faster than big ones when expressed in % change, these means are different than the mean rate of change of total glacierized area.

4. GLACIER MASS CHANGES

Although the databases of the glacier changes in the HK have greatly improved recently, field observations about mass balance are still scarce. In this review, we include results of

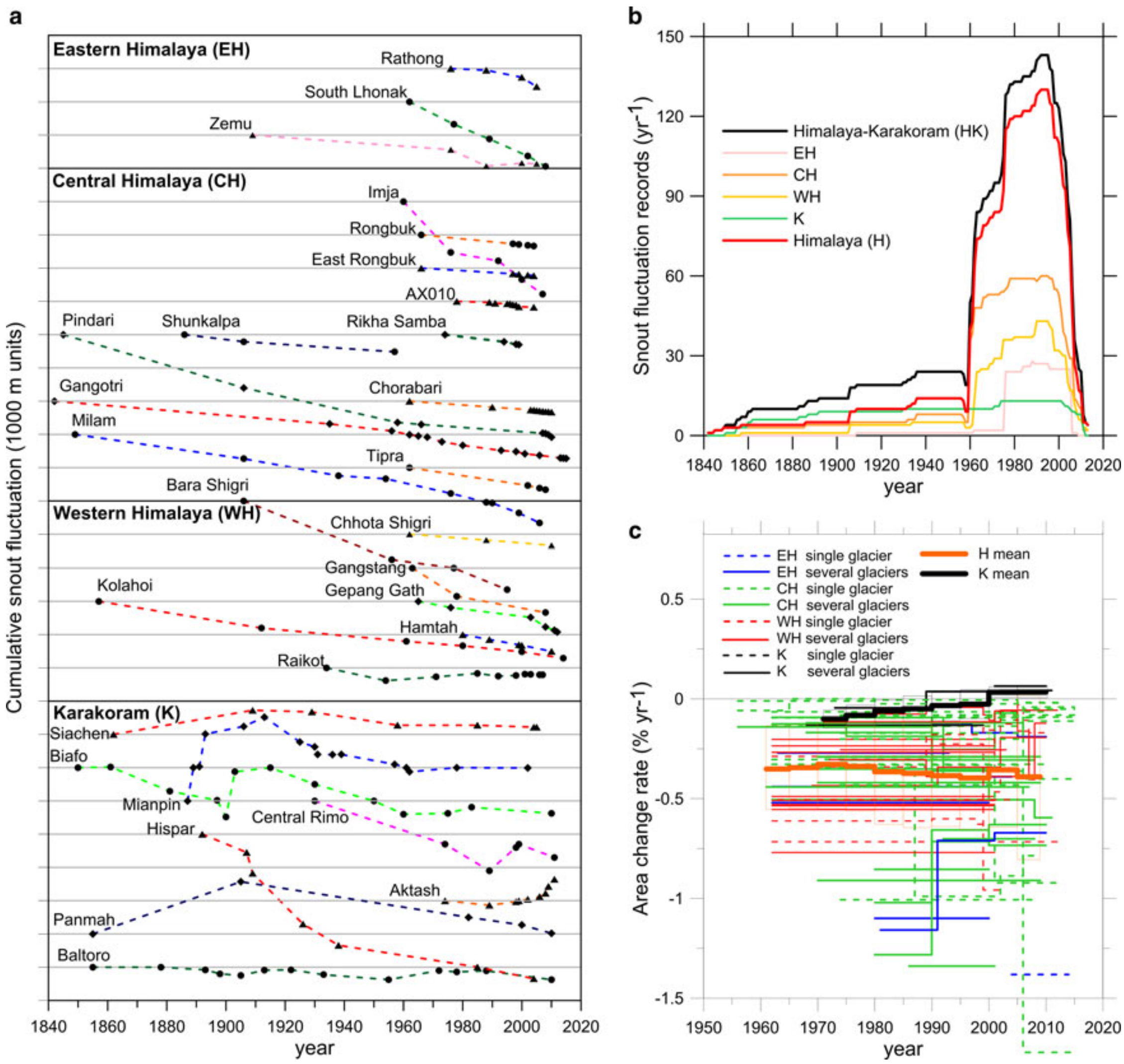

Fig. 2. (a) Length change of selected glaciers in the HK region over the last 170 years (b) Number of data records (c) Area change rates for HK region. The rates were calculated in percent change per year with respect to the initial observed area. Note that the unweighted mean area rates are calculated for 5-year period from a varying number of values depending on the period. The black and orange boxes represent the ±1 Std dev. envelope for each 5-year mean area change rate and calculated from the area change rates available for the corresponding period. Data and references used in the figure are listed in Supplementary Table S2 and S3.

mass-balance changes at both glacier scale (from the glaciological method, geodetic method and model results) and regional scale (geodetic method).

The glaciological mass balance is an undelayed, direct response to meteorological changes (Oerlemans, 2001) and thus mass-balance observations are needed to study the climate change especially in remote areas such as the HK, where our knowledge of climate–glacier relationship is still partial. Regrettably only 24 glaciers, covering an area of ~112 km^2 (~0.5% of the total Himalayan glacierized area (Bolch and others, 2012)), have been surveyed in the Himalayan Range using the glaciological method (Supplementary Tables S4–S5), which is sparse in comparison with most other large glacierized regions of the world (Zemp and others, 2015). Glaciological mass-balance measurements in the Himalayan Range are often challenging because of the vast glacierized area, high altitude, rugged terrain, extreme climate, and political and cultural boundaries. In the Karakoram, where the challenges are the toughest, the glaciological measurements were performed only on the ablation area of Baltoro Glacier (Mayer and others, 2006). Since the first mass-balance observation on Gara Glacier in 1974/75, the annual mass balances in the Himalaya have mostly been negative, with only 16 positive annual mass-balance observations out of a total of 142 observations (see the unweighted mean mass-balance series in Fig. 3a and Supplementary Table S6). The longest continuous series is just 12 years for Chhota Shigri Glacier (–0.56 ± 0.40 m w.e. a^{-1} over 2002–14) (Azam and others, 2016).

Previous compilations of field-based mass balances (Cogley, 2011; Bolch and others, 2012) yielded regional mean mass balances for the Himalaya using all available glaciological mass-balance data without quality checks. As already highlighted (Gardner and others, 2013), this problem, combined with bias and lack of representativeness due to benchmark glacier selection, results in regional glaciological mass balances that are more negative compared with the values derived from remote-sensing data, and might lead to an overestimation of the sea-level rise contribution of Himalayan glaciers. The surveyed glaciers are generally chosen for their easy access, low altitudes, small sizes (mean area of surveyed glaciers is 4.6 km^2; Supplementary Table S4) and low coverage by debris. Selection criteria introduce a strong bias toward rapid

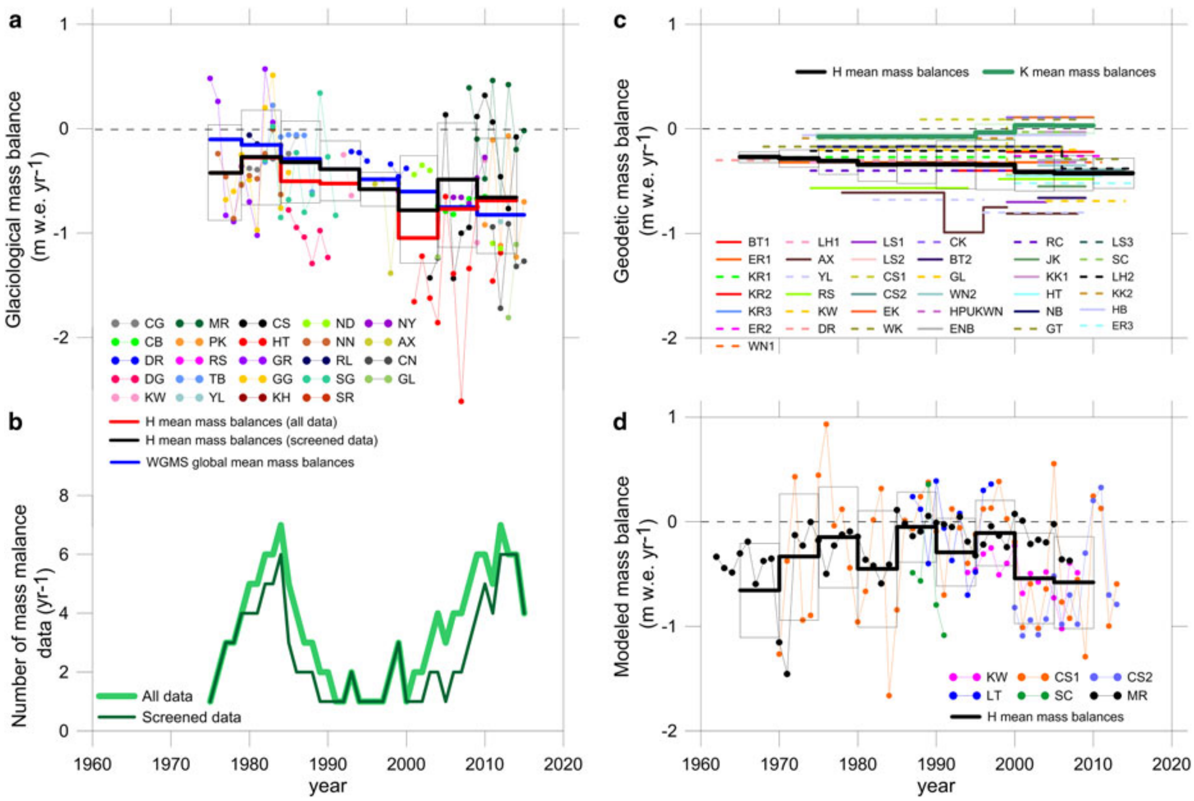

Fig. 3. Mass balances in the HK region. (a) Annual glaciological mass balances for all 24 glaciers. Red thick line is the mean mass balances for the Himalayan Range calculated using 24 glaciers' data, black thick line is the mean mass balances for the Himalayan Range calculated using 18 screened glaciers, and the blue thick line represents the global mean mass balances between 1975 and 2014 calculated from 37 reference glaciers of the World Glacier Monitoring Service (Zemp and others, 2012, WGMS 2013). (b) Number of data points available each year. (c) Geodetic mass balances. Black thick line is the mean geodetic mass balances for the Himalayan Range while green thick line is the mean geodetic mass balances for the Karakoram Range and (d) Annual modeled/hydrological mass balances. Black thick line is the mean modeled mass balances. Abbreviations in different panels are glacier/region names, available in Supplementary Tables S4, S8, and S9. Note that the mean mass balances are unweighted and calculated for the 5-year period from a varying number of mass balance values available for each period. The black boxes represent the ±1 Std dev. envelope for each 5-year mean mass balance and calculated from the mass-balance values available for the corresponding period.

response type glaciers, or at least does not represent the population as a whole; representation is especially lacking for the large, complex glaciers, which dominate the total ice mass in the HK region. Further, almost half of the glaciological studies were conducted by the Geological Survey of India and are published in internal reports (Supplementary Table S4) and often lack the details of mass-balance observations (Supplementary Table S5). These problems make difficult the identification of the reliable mass-balance data series and extension of the data to represent the Himalayan region as a whole. The mass balances of the avalanched-fed Hamtah Glacier (–1.43 m w.e. a^{-1} between 2000 and 2012) were already found to be negatively biased (Vincent and others, 2013). Therefore, we performed a detailed systematic check of the reliability of each mass-balance time series using several criteria, such as density of point measurement network, stake material, availability of snow density field measurements, error analysis in mass-balance estimates, map quality, debris-cover extent, avalanche contribution, verification of glaciological mass balance with geodetic mass balance and relationships of mass balances with equilibrium line altitude, temperature and precipitation, etc. and classify the mass-balance time series in four categories (excellent, good, fair and dubious; Supplementary Table S7) (details are in the Supplementary material).

Mass balances of six glaciers are dubious (Supplementary Table S7) and might have biases. Except for Kangwure Glacier, these glaciers either receive their accumulation through avalanches (Changmekhangpu, Dunagiri, Hamtah and Kolahoi glaciers) or are highly debris covered (50–80% debris-covered area on Changmekhangpu, Chorabari, Dunagiri, Hamtah glaciers) (Supplementary material). Due to steep topography, many HK glaciers receive a large part of their accumulation from avalanches (Racoviteanu and others, 2014), a mass input that has not been quantified yet (Laha and others, 2017). Avalanches sometimes destroy the ablation/accumulation stakes. Most accumulation is close to the glacier headwalls and cannot be safely monitored with the glaciological method. Full representation of all glacier types should include avalanche-fed glaciers, but for the preceding reasons, these glaciers themselves cannot be fully and correctly surveyed. The debris distribution on highly debris-covered glaciers is, generally, heterogeneous across the surface (often the stakes are installed over a few decimeter thick debris cover); hence the ablation measurement with stakes is location specific. Further, the stakes are generally installed at locations easy to access, and so the effects of supraglacial ponds or ice cliffs, known to be melt 'hot spot' (Sakai and others, 2002), is not included in the mass-balance estimates. In support of previous studies (Buri and others, 2016; Miles and others, 2016; Vincent and others, 2016), we find that conventional glaciological mass-balance methods applied to highly debris-covered and avalanche-fed glaciers are error prone, but the selection of simple, safe, clean-ice glaciers might introduce a bias toward more negative regional assessments. Therefore, glacier-wide mass balance on highly avalanche-fed and debris-covered glaciers should be estimated by remote-sensing methods. Despite errors and biases, in situ glaciological data on avalanche-fed and debris-covered glacier are needed for ground truthing of remotely sensed data, modeling and process understanding (Banerjee and Shankar, 2013; Vincent and others, 2016). It is thus necessary to recognize and explain the biases pertaining to the benchmark glacier sample of the whole glacier population, versus biases which may render an individual glacier's data misleading and thus favoring exclusion.

Excluding these six dubious mass-balance series (total 37 annual mass-balance data points), the mean mass balances for the Himalayan range were less negative (Fig. 3a). The revised mean mass balance during 1975–2015 for 18 screened glaciers is –0.49 m w.e. a^{-1} versus –0.59 m w.e. a^{-1} for all 24 glaciers. These revised mean mass balances show a moderate wastage since 1975 that generally follows the global trend before 2000 (Fig. 3a). After 2000, a positive deviation of Himalayan mean mass balances from the increasingly negative global mean seems to be consistent with the regional satellite-based mass changes estimated over recent years that suggest two or three times less negative mass balances for the Pamir-Karakoram-Himalaya than for the global mean (Kääb and others, 2012; Gardelle and others, 2013). We note that our inference of reduced Himalayan glacier mass loss after 2000 is based on a changing sample of field-monitored glaciers and thus need to be confirmed in the future. In particular, rare remote-sensing mass-balance estimates for several periods do not show such a trend (Ragettli and others, 2016). However, remote-sensing estimates themselves carry their own uncertainty, as illustrated by the fact that the glacier-wide mass balance in the Langtang area (Nepal) had to be revisited by Ragettli and others (2016) compared with a similar earlier assessment by Pellicciotti and others (2015). Two major sources of uncertainty in DEM-based geodetic mass-balance estimates are the poor quality of DEM in the texture-less accumulation areas (Ragettli and others, 2016) and the unknown penetration of the SRTM C-band and X-band radar signal into dry snow and firn (Barandun and others, 2015; Kääb and others, 2015; Dehecq and others, 2016; Round and others, 2017).

With recent progress in satellite data acquisitions and processing, and the availability of declassified stereo images from spy satellites, several estimates provided the geodetic mass changes at glacier- or region-wide scale (Fig. 3c; Supplementary Table S8). Several comprehensive assessments of glacier mass changes in the HK have been obtained from 2003 to 2009 using ICESat laser altimetry (Kääb and others, 2012, 2015; Gardner and others, 2013; Neckel and others, 2014) and, despite differences, revealed a contrasted pattern of mass change in the HK with strong thinning in the south-east Tibetan Plateau and in the western Himalaya and no significant elevation change in the Karakoram and over the Western part of the Tibetan plateau. These ICESat-based mass-balance estimates tended to be more negative than the ones derived by comparing SPOT5 and SRTM DEMs for nine sub-regions of KH (Gardelle and others, 2013). The differences in these estimates are difficult to investigate as the study periods and sample regions are mismatched (Supplementary Table S8). However, the difficulty of accounting for the penetration of the SRTM radar signal into snow and ice may explain some of these differences (Kääb and others, 2015) and the varying treatment of errors (not all studies account for systematic errors), but we also note that at the error limits, the estimates overlap. Hence, we find an encouraging approach toward consistency. The contrasted pattern of change has recently been confirmed for a longer time period (2000–16) and at the scale of individual glaciers using multi-temporal analysis of 50 000 ASTER DEMs (Brun and others, 2017).

Measurement of the time-varying gravity fields by the GRACE (Gravity Recovery and Climate Experiment) satellites have led to varying estimates of glacier mass changes in our study region (Jacob and others, 2012; Gardner and others, 2013). However, they remain difficult to interpret glaciologically due to their coarse resolution, leakage of the strong signal of groundwater depletion from north India (Rodell and others, 2009), the fact that glacier meltwater may be stored in nearby glacier lakes (Song and others, 2014) and the apparent large positive mass change anomaly over the Tibetan Plateau (Yi and Sun, 2014), probably due to increased precipitation (Zhang and others, 2017). As an example, in their sea-level budget assessment during 2002–14, Reager and others (2016) were cautious not to use GRACE data to update glacier mass loss in High Mountain Asia, relying instead on the 2003–09 ICESat mass change estimates.

The individual geodetic mass balances are available at multiannual scale (Supplementary Table S8). The mean geodetic mass balance for the Himalayan Range was –0.37 m w.e. a^{-1} between 1962 and 2015. Conversely, the Karakoram Range exhibited balanced mass budget with –0.01 m w.e. a^{-1} between 1975 and 2010 against the mean mass balance of –0.37 m w.e. a^{-1} for the Himalayan region over the same period. Therefore, the 'Karakoram Anomaly' can be extended back at least to the mid-1970s (Bolch and others, 2017; Zhou and others, 2017). The mean balanced mass over the Karakoram Range is consistent with recent glacier snout stability (Fig. 2a), whereas the continuing negative balances over the Himalaya are consistent with glacial lake growth since the early 1960s (Bajracharya and Mool, 2009).

Some discrepancies in glaciological and geodetic mean mass-balance estimates are obvious because of (i) selection bias and lack of representativeness of glaciers used for glaciological measurements (ii) different satellite data types and methodologies for geodetic mass balance and (iii) the larger area covered by geodetic estimates. Compared with mean mass balance of –0.59 m w.e. a^{-1} for all 24 observed glaciers between 1975 and 2015, the screened mean mass balance of –0.49 m w.e. a^{-1} over the same period is closer to the agreement with the geodetic mean mass balance of –0.37 m w.e. a^{-1} for the Himalayan Range over 1975–2015. However, these screened glaciological mass balances remain too sparse in time and space to obtain a robust regional average and an unambiguous temporal trend. Our analysis highlights the sensitivity of the regional average to the addition/subtraction of just a few glaciological measurements. Glaciological measurements should be retained for the understanding of physical processes, validation of remotely sensed measurements, calibration/validation of glacio-hydrological models and development of process-based models for future glacier changes. Our recommendation is that glaciological mass balances should not be used for the computation of regional mass balance (Sherpa and others, 2017) and for sea-level rise contribution from the Himalayan range. This recommendation is paired with suggested improvements in the benchmark glacier network.

Mass-balance modeling is becoming widely used in the HK region with growing satellite and recent in situ meteorological data availability. A few studies estimated mass balances using different models such as the hydrological model for Siachen Glacier; temperature index model for Chhota Shigri, Langtang and Mera glaciers; albedo model for Chhota Shigri and regression (mass balance-meteorological parameters) model for Kangwure Glacier (Fig. 3d; Supplementary Table S9). Modeling of mass balance over the historic period of observations using both in situ and satellite measurements may finally give high spatial and temporal resolution, long-term continuity and geographic completeness, thus filling data gaps and addressing current inhomogeneities (Supplementary Tables S4 and S8).

Based on in situ field measurements, Vincent and others (2013) showed that Chhota Shigri Glacier was near balanced conditions during the1990s. The reconstructed mass change of Chhota Shigri Glacier corresponded to a moderate mass loss of -0.30 ± 0.36 m w.e. a^{-1} between 1969 and 2012, with, interestingly, no significant mass change between 1986 and 2000 (-0.01 ± 0.36 m w.e. a^{-1}) (Azam and others, 2014a). Further, Mera Glacier mass-balance reconstruction over 1961–2007 showed strong similarities with the Chhota Shigri reconstruction with balanced conditions from the late 1980s to the early 1990s (Shea and others, 2015) (Fig. 3d, Table S10). Our glaciological mean mass balances for the Himalayan glaciers, do not show balanced conditions over the mid-1980s to the late 1990s (Fig. 3a). Few measurements are available for this period (Fig. 3b) when the glaciers may have been in balance. Supporting the modeling studies, only Tipra bank glaciological mass-balance series was close to steady state with mean mass balance of -0.14 m w.e. a^{-1} between 1981 and 1988. The appearance of nearly balanced conditions on Chhota Shigri, Mera and Tipra Bank glaciers could be because of regional orography and glacier-specific dynamics. For instance, Mera Glacier showed almost no mass change (-0.02 m w.e. a^{-1}) between 2010 and 2015, while Pokalde and Changri Nup glaciers, in the nearby interior of the range, showed a rapid wastage of -0.63 and -1.24 m w.e. a^{-1}, respectively, over the same period (Supplementary Table S6, Sherpa and others, 2017). Given the limited number of modeled mass-balance series for mean mass-balances computation, we believe these means should not be considered as regional representative and must be handled cautiously.

5. GLACIER WASTAGE AND DEBRIS COVER

Debris-covered glaciers are widespread in the HK region (Scherler and others, 2011). Thermally insulating debris due to rugged topography and strong avalanche activity might slow the glacier mass wastage, thus resulting in longer timescales of mass loss (Rowan and others, 2015; Banerjee, 2017). This insulating effect has been recently quantified on Changri Nup Glacier (between 5240 and 5525 m a.s.l.) (Vincent and others, 2016) where the area-averaged ablation of the entire debris-covered area is reduced by 1.8 m w.e. a^{-1}. Fine-grained thick and intact debris cover (0.5 m or more) nearly stop the surface ablation (Potter and others, 1998; Konrad and others, 1999). Further, a large number of glaciers in the HK region are avalanche-fed and accumulating debris continuously. Indeed such phenomena exert strong effects on glacier dynamics; the effects that are very poorly understood in the HK region (see Section 6). The role of supra-glacial debris cover and thus melt beneath debris cover has been investigated (Lejeune and others, 2013; Collier and others, 2015). A few recent studies also addressed the role of backwasting of supraglacial ice cliffs (Buri and others, 2016) and supraglacial ponds on melting of debris-covered glaciers (Miles and others, 2016; Watson and others, 2016). Furthermore, internal ablation (enlargement of englacial conduits) has both a direct and indirect effect on mass loss, through melting and collapse of ice surfaces (Thompson and others, 2016; Benn and others, 2017). Recent satellite observations of glacier dynamics (Scherler and others, 2011), supported by simplified models (Banerjee and Shankar, 2013), have shown that debris-covered glacier losses occur mostly by thinning without significant retreat in response to climatic warming (Rowan and others, 2015; Banerjee, 2017). Further, regional-scale studies have shown that the thinning rates of debris-free and debris-covered ice are not different (Kääb and others, 2012; Nuimura and others, 2012); this is ascribed to dynamics (Banerjee and Shankar, 2013; Banerjee, 2017) and strongly enhanced wastage at thermokarst features like supraglacial ponds, ice cliffs and pro-glacial lakes (Sakai and others, 2002; Buri and others, 2016; Miles and others, 2016; Watson and others, 2016), which counteract the effect of insulation by debris. Future investigations are needed to quantify the role of debris cover on HK glaciers.

As a result of mass wastage (Figs 3a, b), increasing supra-glacial debris-covered area was reported in the Himalaya (Scherler and others, 2011; Nuimura and others, 2012; Thakuri and others, 2014) over the last 5–6 decades. Conversely, in the Karakoram Range, the nearly balanced mass budget since the 1970s (Fig. 3b) are accompanied with nearly unchanged supraglacial debris-covered area between 1977 and 2014 (Herreid and others, 2015). Based on glaciers' response times, a study (Rankl and others, 2014) inferred a shift of the Karakoram glaciers from negative to balanced/positive mass budgets in the 1980s or 1990s, but recent findings (Bolch and others, 2017; Zhou and others, 2017) of steady-state mass balances since the 1970s suggest this shift to be during or preceding the 1970s.

6. ADJUSTING GLACIER DYNAMICS

Changes in mass balance (Figs 3c, d) influence the glacier dynamics (Cuffey and Paterson, 2010); hence, an adjustment in HK glacier flow is expected. There has been recent progress in regional satellite-based glacier velocity mapping (Dehecq and others, 2015; Bhattacharya and others, 2016). However, ice thickness data – also scarce in the HK – are needed with velocity measurements to study the glacier dynamics. On Chhota Shigri Glacier, field-based surface velocities and ice thickness were found to be reducing since 2003 (Supplementary material), which suggest that the glacier is adjusting its dynamics in response to its negative mass balances (Azam and others, 2012). Since the Little Ice Age, the mean ice thickness and surface velocities at Khumbu Glacier were also found to be decreasing, suggesting that Khumbu Glacier is out of balance with climate (Rowan and others, 2015), consistent with a lengthy response time (Jóhannesson and others, 1989). The mean velocity on Gangotri Glacier decreased by ~6.7% between 2006–14 and 1993–2006, a likely response to negative mass budget (Bhattacharya and others, 2016). To understand the impact of climate change on the HK glacier dynamics and to confirm these glacier-scale findings, more region-scale dynamics studies are urgently needed. Hitherto these handful studies on Chhota Shigri, Khumbu and Gangotri glaciers support the reduced glacier velocities found in response to the negative glacier mass balances in several regions of the world (Heid and Kääb, 2012). Recent accelerations of Baltoro Glacier (Karakoram, Pakistan) (Quincey and others, 2009) and other Karakoram glaciers may be linked with positive mass balances, but the surging phenomenon and a wide range of flow instabilities (Scherler and Strecker, 2012; Bhambri and others, 2017) complicate this relationship (Heid and Kääb, 2012).

7. GLACIER/CLIMATE RELATIONSHIP

Many glacial processes such as glacier surface mass balance and glacier runoff respond simultaneously with changes in climate; other responses such as length, area, ice velocity, ice thickness profiles are delayed. For example, a step change in climate may take a century or longer to manifest in an approach toward a new equilibrium glacier length, area and thickness profile (Jóhannesson and others, 1989). The glaciers in the region of low annual temperature range ($10 < \Delta T < 20$°C) such as in the Himalaya were found to have higher mass-balance sensitivity to climate (temperature and precipitation) change, while glaciers having a higher annual temperature range ($20 < \Delta T < 30$°C) such as in the Karakoram have lower climate sensitivity (Sakai and others, 2015). Accordingly, eastern and central Himalaya have a higher sensitivity than western Himalaya and Karakoram (Fujita, 2008; Sakai and others, 2015), a feature that alone explains a larger part of the contrasted pattern of mass loss measured using laser altimetry (Sakai and Fujita, 2017). Some studies attempted to understand the mass balances with local meteorological data (Azam and others, 2014a; Sherpa and others, 2017). The glacier wastage in the Himalayan Range is consistent with increasing temperature (Shrestha and others, 1999; Dash and others, 2007; Dimri and Dash, 2012; Banerjee and Azam, 2016) and decreasing precipitation (Bhutiyani and others, 2010; Dimri and Dash, 2012). For instance, on the East Rongbuk Glacier (Everest area) the decrease in snow accumulation from 1970 to 2000 (Kaspari and others, 2008) might be related to the weakening of the AM (Bingyi, 2005). An extremely ambitious global temperature rise of 1.5°C would lead to a warming of 2.1 ± 0.1°C in HMA (including HK region) and that 64 ± 7% of the present-day ice mass stored in the HMA glaciers will remain by the end of the century (Kraaijenbrink and others, 2017). Avalanche-fed glaciers in the HK region are sensitive to rising temperature not only through increased melting, but also through a rise in rain/snow transition elevation during the monsoon; this especially impacts avalanche-fed glaciers because their accumulation zones are relatively low due to the downward transfer of snow into avalanche cones (Benn and others, 2012). The conditions which make Karakoram and Himalayan glaciers different could be attributed to increasing winter precipitation in the former (Fowler and Archer, 2005) or the weaker sensitivity of their winter accumulation to warming (Kapnick and others, 2014; Sakai and Fujita, 2017). Moreover, cooler summers, greater summer cloudiness and snow cover, and decreasing maximum and minimum temperatures (Fowler and Archer, 2005; Shekhar and others, 2010; Bashir and others, 2017; Forsythe and others, 2017) reduce the average ablation rates or the duration of the ablation season (Hewitt, 2005) thereby resulting in quasi-stable mass balance.

The physical basis of glacier/climate relationships can be understood by studying the glacier surface energy balance (SEB). In the HK, only a few SEB studies are available; therefore, we spread our area of interest to the whole HMA region. Generally, the SEB studies are restricted to understand the melt processes at point scale over clean glaciers during the summer-monsoon months (Supplementary Table S11). Some intrinsic discrepancies are evident in the comparison because of different models/methods for SEB calculations, time periods, or climatic conditions. Yet, similar to glaciers worldwide (Favier and others, 2004; Andreassen and others, 2008), net short wave radiation flux is the largest source of energy on glacier surfaces in the HMA region and mainly controls the temporal variability of melting, whereas net longwave radiation flux is the greatest energy sink. The net all-wave radiation flux provides the maximum energy flux with >80% contribution to the glacier surface during the summer for the observed HMA glaciers except for Guxiang No. 3 (65%). Sensible turbulent heat flux, always positive over debris-free areas, complements the net radiation flux. Latent heat flux also brings some energy, at least during the core summer-monsoon period, in the form of re-sublimation/condensation of moisture on the glaciers directly affected by monsoonal activity like Chhota Shigri, AX010, Parlung No. 4 and Guxiang No. 3 (Supplementary Table S11). However, depending on the monsoon intensity, the duration of the re-sublimation period can vary from a few weeks (e.g., on Chhota Shigri (Azam and others, 2014b)) to a few days (on Parlung No. 4, where re-sublimation occurs on rare days (Zhu and others, 2015)). With continuous negative latent heat flux, sublimation prevails in the summer over the ablation zones of the glaciers less affected by the monsoon and more affected by drier conditions (e.g., Zhadang Glacier, central Tibetan Plateau (Zhu and others, 2015) and Baltoro Glacier in the Karakoram (Collier and others, 2013)). Therefore, dry climate conditions over the central Tibetan Plateau, Karakoram and northwest Himalaya (Ladakh, Zanskar regions) point toward mass loss through sublimation. For instance, on Puruogangri ice cap (north-central Tibetan Plateau), sublimation accounted for 66% of its total mass loss from October 2001 to September 2011 (Huintjes and others, 2015). The conductive heat flux or heat flux from precipitation is normally small compared with other terms of the SEB. Therefore, the glaciers under drier conditions seem to lose a significant mass fraction through sublimation, while condensation/re-sublimation dominates over glaciers directly influenced by the monsoon. However, we stress that these conclusions are based on a few sporadic studies and need to be confirmed in near future by developing more glacier-scale as well as region-scale SEB studies.

In the western Himalaya, SEB analysis on Chhota Shigri Glacier suggests a clear control of the summer monsoon on annual mass balance through surface albedo change (reduced absorption of solar radiation when monsoonal snow falls occur) (Azam and others, 2014b). Handling large-scale circulation analysis over HMA, another study (Mölg and others, 2014) suggested that mass balance is mainly determined by the precipitation amounts in May–June and shaped by the intensity of summer-monsoon onset and WD dynamics.

8. HYDROLOGICAL REGIMES OF HK RIVERS

Glaciers in a basin can alter the river discharge characteristics at different temporal scales from daily to multi-century (Jansson and others, 2003). Glacier melt contribution to total river discharge depends on the percentage of glacierized area at any given basin outlet hence, going up in the basin, glacier melt contribution increases (Kaser and others, 2010). Glacier runoff contribution in the HK has strong seasonality and follows the seasonality of precipitation/glacier melt in the basins (Bookhagen and Burbank, 2010; Kaser and others, 2010). Total discharge at any basin outlet is the sum of rain runoff, snow melt, glacier melt and base flow (Lutz and others, 2014). A variety of methods with different complexity such as empirical relationships between precipitation and discharge (Thayyen and Gergan, 2010), ice ablation models (Racoviteanu and others, 2013), the hydrograph separation method (Mukhopadhyay and Khan, 2014a, 2015), chemical tracer methods (Racoviteanu and others, 2013) and distributed glacio-hydrological models (Lutz and others, 2014; Ragettli and others, 2015) are used to understand the discharge composition in the HK. Generally, the meteorological stations are installed at valley bottoms; knowledge of the precipitation distribution at glacier altitudes is nearly lacking, which makes it difficult to develop hydrological models. Few studies (Immerzeel and others, 2015; Sakai and others, 2015) used the glacier mass balances to inversely infer the precipitation at glacier altitudes. They generally suggest that the amount of precipitation required to sustain the observed mass balances is far beyond what is observed at valley stations or estimated by gridded precipitation data (Immerzeel and others, 2015). Another challenge in runoff modeling of the HK glaciers is the presence of debris cover. Detailed glacio-hydrological studies explaining the physical basis of discharge generation from debris-cover glaciers are still regionally sparse (Fujita and Sakai, 2014; Ragettli and others, 2015). Further, most models do not include sublimation and wind erosion in these methods/models, yet sublimation may be a vital share of the glacier mass wastage in the dry conditions of the Tibetan Plateau and parts of the Karakoram (see Section 7) or even on wind-exposed high-elevation slopes in the Himalaya due to strong winds mostly in winter (Wagnon and others, 2013).

The HK glaciers play a significant role with varying contributions of glacier and snow melt to the total discharge of HK rivers (Lutz and others, 2014; Pritchard, 2017). For instance, over 1998–2007, in the upper Indus Basin (whole basin excluding Indo-Gangetic plains) stream flow was dominated by glacier meltwater, contributing almost 41% of the total discharge, while in the upper Ganges and upper Brahmaputra basins (whole basins excluding Indo-Gangetic plains) contribution was much lower, i.e., ~12 and 16%, respectively (Lutz and others, 2014). In general, glacial melt dominates snow melt in all these basins (Lutz and others, 2014) but it varies intrabasinally. In the upper Indus Basin, glacial melt dominates in the Karakoram, while in the western Himalaya, snow melt contributes more than glacial melt to the total discharge (Mukhopadhyay and Khan, 2015). Initially, the positive mass budgets of the central Karakoram (Gardelle and others, 2012) were linked with decreased river flow (Fowler and Archer, 2006). Recently, this relationship was questioned with the finding of increasing river flows in the central Karakoram during the melt season from 1985 to 2010 (Mukhopadhyay and Khan, 2014a) and the nearly balanced mass budgets (Kääb and others, 2015). The increasing river flows are now thought to be associated with increasing mass turnover as a result of increased temperature and precipitation, but under near-neutral mass balance (Mukhopadhyay and Khan, 2014b). Mass wastage over the Himalayan region is expected to modify the runoff regimes. The glacier-wastage contribution (net water withdrawal from glacier storage) is a moderate fraction of the total annual glacial meltwater (Kääb and others, 2012; Gardelle and others, 2013), hence, discharge composition and its seasonal variation will shift in the future due to changing climate, partly but not only because of changing glaciers.

Future expected temperature increase over the HK region will affect river hydrology in three ways: (i) phase change of precipitation from snow to rain directly contributes to the discharge, (ii) the reduced albedo because of less snow imparts more absorption of solar radiation and thus enhances melting, and (iii) earlier seasonal onset and later end of snow/ice melting. In the Shigar catchment (upper Indus basin), snowmelt is projected to occur earlier in the melting season (Soncini and others, 2015). In the HK region, the glacier melt contribution is projected to increase until 2050 and then decrease (Immerzeel and others, 2013; Soncini and others, 2015; Shea and Immerzeel, 2016). Discharge is projected to increase at catchment (Immerzeel and others, 2013; Soncini and others, 2015) and basin scales (Lutz and others, 2014) up to at least 2050 in HK rivers. The projected increase in discharge is mainly due to the enhanced melt for the Indus Basin and increase in precipitation for the Ganges and Brahmaputra basins (Lutz and others, 2014; Tahir and others, 2016). However, partly due to the large differences in glacier area/volume estimates, the future predictions inherit large uncertainties.

9. CONCLUSIONS AND OUTLOOK

With increasing recent attention of the scientific community, the understanding of the HK glaciers has grown swiftly, yet this understanding remains weak in spatial and temporal coverage compared with many other mountain ranges of the world. Most glaciers are retreating, shrinking and losing mass with variable rates along the Himalayan Range. These trends are generally consistent with climate warming and decreasing precipitation. The supraglacial debris-covered area in the Himalaya has increased due to glacier shrinkage and debris accumulation. Since the 1970s, the mass budget of Karakoram glaciers has been almost balanced, a global exception initially referred as the 'Karakoram Anomaly' and now known to extend to the west of the Tibetan Plateau (western Kunlun and eastern Pamir). This multi-decadal mass stability is in line with nearly unchanged debris-cover. The anomalous behavior of Karakoram glaciers can be linked with increased precipitation and cooler summers as well as their lower sensitivity to temperature change. Often, the climatic response of HK glaciers has been analyzed using temperature and precipitation data generally from meteorological stations at low altitude. Glacier SEB studies, explaining the physical processes of mass change, are still sparse. We suggest that glaciers in dry regions lose a significant amount of mass through sublimation, while condensation/re-sublimation is dominant over glaciers more directly influenced by monsoons. Thus, sublimation should be included in hydrological modeling at least over dry regions, such as the northwest Himalaya and Karakoram, especially on the cold, dry Tibetan side.

Some glaciological measurements are likely errant and together they contribute to regional glaciological mass balances that are more negative than geodetically based measurements. Once the dubious glaciological data are excluded, the mean regional mass balance has better agreement with the geodetic mass balance in the Himalaya. Considering the deficient statistical representation of glaciers in glaciological mass-balance data, this improved agreement with geodetic mass balances could be somewhat fortuitous. Our screening of all 24 glaciological mass-balance series from the Himalaya identified possible biased series and the evidence suggests that the glaciological method is unsuitable if the glacier is highly debris-covered or surrounded by steep valley walls that induce avalanches. Yet, point mass-balance measurements on such glaciers are of great importance for process understanding and modeling. While most Himalayan glaciers have lost mass over the last 5–6 decades, a few showed steady-state mass-balance episodes. Temporal and spatial variability of mass balances relate to heterogeneous climatic conditions, which vary among or within mountain ranges, or even within the same valley. These findings pose vexing questions about the representativeness of benchmark glaciers and highlight the importance of selection of glaciers for field measurement.

Bolch and others (2012) tracked mass wastage from 1963 to 2010 and saw accelerating ice loss, especially after 1995, with the mean Himalayan glacier wastage trend generally following that of the global mean. Our unscreened dataset, covering a similar but updated time span, leads to a similar conclusion as that of Bolch and others (2012), but our screened data indicate either nearly constant magnitudes of wastage rate or at least less acceleration, in agreement with geodetic mass-balance estimates. Due to the scarcity and biases of glaciological measurements, remote-sensing methods should be preferred for the computation of sea-level rise contribution from the HK region.

Studies have shown decreasing glacier thickness and velocities due to mass wastage in the Himalaya, while in the Karakoram velocities are temporally more variable, but not much is known about local responses of glaciers in the HK range. Though melt contributions from the HK glaciers are projected to increase until 2050 and then decrease (Immerzeel and others, 2013; Soncini and others, 2015; Shea and Immerzeel, 2016), the wide range of area and volume estimates (glacier inventories still have ~30% range in estimates) introduces big uncertainties in runoff. Accurate glacier inventory and additional in situ measurements of glacier volumes are needed to validate the area-volume parameterizations and volume distribution models (Frey and others, 2014; Farinotti and others, 2017) used in hydrological modeling. These models are hampered by poor information on the amount, spatial distribution and phase state of high-elevation precipitation, and of permafrost in the HK.

The projected increase in discharge if coupled with extreme rainfall in the future may result in floods that may further induce rapid erosion, landslides, glacial lake outburst floods (GLOFs), etc. Such an event occurred in Kedarnath (Uttarakhand, India) during 15–17 June 2013 when extreme 1-day rainfall of 325 mm was recorded; this extreme event is believed to be a result of the summer monsoon and WD convergence (Bhambri and others, 2015). This rainfall event also caused the collapse of the moraine-dammed Chorabari Glacier Lake. The resulting flood devastated the Kedarnath valley and downstream, and killed hundreds of people (Dobhal and others, 2013). Several glacial lakes were found potentially dangerous in the HK (Bajracharya and Mool, 2009; Fujita and others, 2013), but the prediction of extreme rainfall events, the growth of possible future lakes (Linsbauer and others, 2016), related risks or GLOFs is still difficult because of limited regional forecasting abilities (Bookhagen, 2010). Sometimes glacial surges develop a natural dam and block the river streams that further result in outburst floods (Hewitt and Liu, 2010; Round and others, 2017).

Our mass-balance reliability assessment using scoring method highlights the weaknesses in available mass-balance series. We recommend long-term continuation and expansion of ongoing in situ glaciological observations in the HK so that these glaciers can be used for climate change and applications studies. Further, for ongoing or future observations, we suggest to systematically include uncertainty estimates, use an optimized density of ablation stakes, perform systematic accumulation measurements with appropriate methods (e.g., use of artificial layer to mark the glacier surface), and verify in situ glaciological mass balances with geodetic mass balances.

We also propose the establishment of a network of high altitude meteorological and discharge stations covering more glaciers/watersheds in the HK region, adoption of a holistic approach to understand mass-balance-climate/hydrology relationships, and development of data sharing policies among the HK countries so that the large-scale modeling of the future glacier and runoff evolution can be done with improved accuracy.

The pace of glacier change is fast enough that many applications and interests should consider climate-change induced glacier responses and associated hydrological changes, but is slow enough that well-planned and locally tailored approaches to adaptation are both possible and needed.

SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found at https://doi.org/10.1017/jog.2017.86

AUTHOR CONTRIBUTIONS

MFA compiled and analyzed the data, generated the figures and wrote the review. All authors contributed significantly to writing and improving this review.

ACKNOWLEDGEMENTS

MFA acknowledges the research grant from INSPIRE Faculty award (IFA-14-EAS-22) from Department of Science and Technology (India) and National Institute of Hydrology

(India) for hosting INSPIRE Faculty tenure. Thanks to Antoine Rabatel for his suggestions for mass-balance analysis, Argha Banerjee on his suggestions on debris cover section and Joseph Michael Shea for providing modeled mass balances on Mera Glacier. EB acknowledges support from the French Space Agency (CNES) through the TOSCA and ISIS programs and from the Programme National de Télédétection Spatiale (PNTS, http://www.insu.cnrs.fr/pnts), grant PNTS-2016-01. JSK acknowledges support as part of NASA's High Mountain Asia Team. KF acknowledges support from JSPS-KAKENHI grant number 26257202. We thank the scientific editor Hester Jiskoot and two anonymous reviewers for their constructive suggestions.

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MS received 11 August 2017 and accepted in revised form 4 December 2017; first published online 9 January 2018