Glacier area and the variability of glacier change

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ABSTRACT. Large-scale remote-sensing data on ice loss in the Himalaya and other glacierised regions indicate that the differences in glacier area do not significantly influence the glacier-to-glacier variability of the thinning rate. An analysis of the available data from several regions across the globe reveals another general feature of the recent shrinkage glaciers: the rate of area loss grows sub-linearly as a function of glacier area. These two general characteristics of recent glacier change data are shown to be consistent with each other when the well-known area-volume scaling relation for mountain glaciers is considered. These empirical trends may be helpful in benchmarking simulations of recent and future glacier shrinkage.

INTRODUCTION

The recent large-scale ice-loss pattern in the High Mountain Asia is characterised by a strong spatial inhomogeneity (Bolch et al., 2011; Scherler et al., 2011; Nuimura et al., 2012; Gardelle et al., 2013; Kääb et al., 2012, 2015; Vijay and Braun, 2016; Brun et al., 2017). Investigations of the factors driving the inhomogeneity have revealed the role of a spatially variable climate forcing (Rupper and Roe, 2008; Fujita and Nuimura, 2011; Yao et al., 2012; Mölg et al., 2014; Kumar et al., 2015), the variability of the sensitivity of mass balance to temperature change (Sakai and Fujita, 2017), and effects related to the insulating supraglacial debris layer that often covers portions of ablation zone of Himalayan glaciers (Scherler et al., 2011; Banerjee and Shankar, 2013; Banerjee, 2017). The abundance of supraglacial ponds/cliffs on the debris-covered glaciers that enhances melt rates locally (Sakai et al., 2000; Miles et al., 2016; Brun et al., 2018), and that of moraine-dammed terminal lakes (King et al., 2018) are also possible factors contributing to the variable mass loss.

Apart from the above factors, which exert influence by altering the surface mass-balance forcing, various geometrical variables like slope, area, aspect and hypsometry of glaciers have also been investigated for their possible influences on the glacier-to-glacier variability of thinning rates. These studies have revealed, for example, a significant control of glacier slope on regional-scale glacier thinning rate distribution in the high mountain Asia (Salerno et al., 2017; Brun et al., 2018) or in the Alps (Huss, 2012; Fischer et al., 2015; Rabatel et al., 2016), with gently sloping glacier showing higher loss rates. These trends may be understood in terms of a larger climate sensitivity and response time of the gently sloping glaciers (Oerlemans, 2001). Interestingly, the above studies have also concluded that glacier thinning rates are largely independent of glacier area, despite area of the studied glaciers varying over several orders of magnitudes. In this letter, we compile evidence from existing remote-sensing data on glacier shrinkage to find another empirical relation between the rate of change of glacier area and the total area of the glacier. The area-independent thinning, and the specific form of dependence of the rate of area loss on the glacier area, are shown to be consistent with each other in the light of a well-known scaling relation between glacier area and volume (Bahr et al., 2015).

GLACIER AREA AND THE THINNING RATE

Area-independent net specific mass balance of glaciers have been observed in the Swiss and french Alps (Fischer et al., 2015; Rabatel et al., 2016), although an earlier study from Swiss Alps (Paul and Haeberli, 2008) had reported a higher net specific mass loss on larger glaciers. The area-independent thinning rate of glaciers have also been observed in the Khumbu region of the Himalaya (Salerno et al., 2017). Strong evidence in favour of this trend in several glacierised regions of High Mountain Asia has recently been provided by an analysis of thinning data from more than 6000 glaciers larger than 2 km^2 (Brun et al., 2018).

To illustrate the above trend, here we use recent large-scale 30 m resolution glacier elevation change data from more than 8300 glaciers in the Himalaya (Brun et al., 2017) that are larger than 0.25 km^2 and has more than 50% data coverage. For these glaciers, glacier-wide mean thinning rate is plotted as a function of glacier area (Fig. 1a). Both the area-weighted mean thinning rate within different area classes, and the thinning rates of individual glaciers when plotted as a function of area, demonstrate that the thinning rate of glaciers in the Himalaya are relatively insensitive to the variability of glacier area. There is very

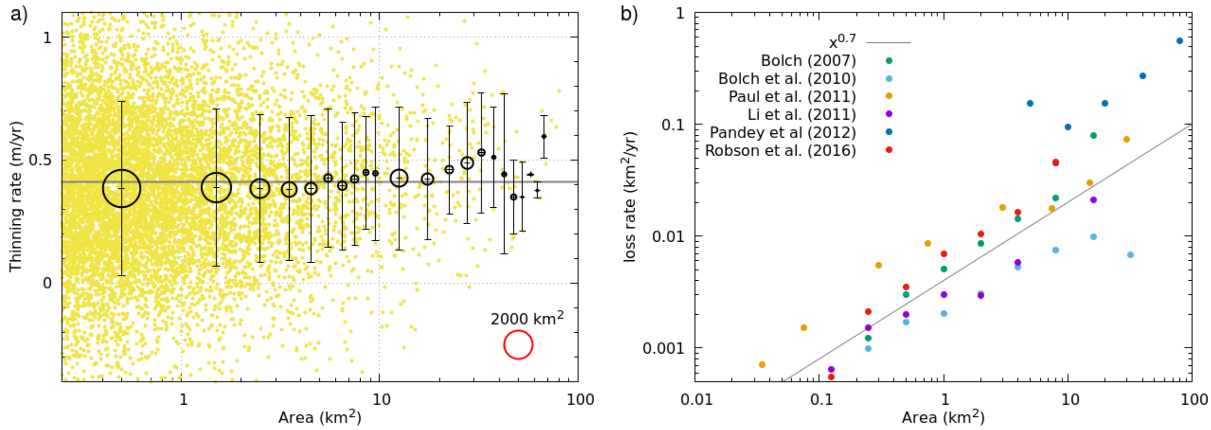

Fig. 1. (a) Glacier-wide mean thinning rates are binned according to the glacier area with bin size of 1 km^2 below 10 km^2 and 5 km^2 above it. The area-weighted mean thinning rate for each of the bins are plotted with open black circles with vertical bars showing the corresponding standard deviation. The circle size denotes the total glacier area in the bin, with red open circle showing an area of 2000 km^2 for scale. Thinning rate data for the individual glaciers studied are plotted with yellow dots. The gray horizontal line denotes the region-wide mean thinning rate as a reference. (b) Available data of the rate of area loss from six different regions in the world, binned according to glacier area, suggest an approximate power-law scaling of the rate of area loss as a function of glacier area, with a scaling exponent of ~0.7.

little systematic variation of thinning rates with glacier area, even as area varied by about two orders of magnitude among the glaciers considered here. Although the mean rate of thinning of glaciers larger than 10 km^2 or so may be marginally higher than that for smaller glaciers (Fig. 1a). Overall, this analysis supports the observed area-independent thinning of glaciers in the Himalaya (Salerno et al., 2017; Brun et al., 2018) and the Alps (Fischer et al., 2015; Rabatel et al., 2016) as discussed above.

GLACIER AREA AND THE RATE OF AREA LOSS

To the best of our knowledge, any functional relationship, either empirical or theoretical, between glacier area and the rate of area change has not been discussed in the literature before. Here, we compiled six data sets from around the world (Bolch, 2007; Bolch et al., 2010; Li et al., 2011; Paul et al., 2011; Pandey et al., 2012; Robson et al., 2016) including that from the Himalaya and the Alps (Fig. 1b) to show that on an average, glaciers are losing area at rates that systematically grow with glacier area. Up to some noise, the functional dependence has an approximate sub-linear power-law form,

$$\dot{A} \approx c_1 A^{0.7}. \tag{1}$$

Here, A denotes glacier area, $\dot{A}$ is the rate of area loss, and c_1 is a dimensionful empirical constant that vary between regions. We are unable to provide any theoretical explanation of this empirical scaling behaviour.

IMPLICATION OF THE AREA-VOLUME SCALING

The intriguing trends of area-independent glacier thinning and a sub-linear power-law scaling of the rate of area loss with area, as discussed above, can be reconciled with the help of the area-volume scaling law for glaciers (Bahr et al., 2015) as follows.

The approximate scaling law relates glacier area and volume (V) as,

$$V = c_2 A^{\gamma}, \tag{2}$$

where, c_2 is a dimensionful fitting parameter and $\gamma = 1.375$ (Bahr et al., 2015). Using the fact that $V = hA$, a relation between mean thinning rate and glacier area can then be obtained,

$$\dot{h} = c_2 A^{\gamma-2} \dot{A}. \tag{3}$$

The dependence of $\dot{h}$ on A can now be derived from the above equation, if the dependence of $\dot{A}$ on A is known, and that is provided by Eqn (1). Thus,

$$\dot{h} \approx c_1 c_2 A^{\gamma-1.3}. \tag{4}$$

With the power-law exponent $\gamma = 1.375$, Eqn (4) would then imply that mean thinning rate of glaciers is nearly independent of, or rather, varying very weakly with glacier area ($\dot{h} \sim A^{0.075}$).

Thus, the area-volume scaling law (Bahr et al., 2015), together with the empirical scaling of $\dot{A}$ with A, provide an understanding of the area-independent thinning rate as observed in the Himalaya (Salerno et al., 2017; Brun et al., 2018) or Alps (Fischer et al., 2015; Rabatel et al., 2016).

DISCUSSIONS

The above trends of area-independent thinning and rate of glacier area loss having a $\sim A^{0.7}$ behaviour could be useful in benchmarking glacier model simulations. A variety of approximate methods have been developed for efficient dynamic simulation a large number of glaciers. The simplest of these approaches (Immerzeel et al., 2010; Cogley, 2011; Radić and Hock, 2011; Kumar et al., 2015) usually relies on parameterising the glacier area change with area-volume scaling relation (Bahr et al., 2015). These models often ignore the changes in the hypsometry (Cogley, 2011; Kotlarski et al., 2010; Kumar et al., 2015).

Approximate parameterisation of ice-flux effects using more complex optimisation schemes that mimic sliding or deformation of ice have been used to track the evolution of hypsometry (Immerzeel et al., 2013; Lutz et al., 2014; Kraaijenbrink et al., 2016). Purely empirical approaches to hypsometric adjustments also exist in the literature (Huss, 2010). Given the large number of such approximate methods, some general large-scale feature of transient retreating states of glaciers could be useful to validate the method chosen. The empirical trends of area-independent thinning and power-law scaling of the rate of area loss with glacier area, that are established above with the help of remote-sensing data and theoretical arguments, are potential candidates for such diagnostic criteria.

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