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Glacier volume and area change by 2050 in high mountain Asia

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ABSTRACT

We estimate individual area and volume change by 2050 of all 67,028 glaciers, with a total area of 122,969 km^2, delineated in the Randolph Glacier Inventory 2.0 of high mountain Asia (HMA). We used the 25 km resolution regional climate model RegCM 3.0 temperature and precipitation change projections forced by the IPCC A1B scenario. Glacier simulations were based on a novel surface mass balance–altitude parameterization fitted to observational data, and various volume–area scaling approaches using Shuttle Radar Topography Mission surface topography of each individual glacier. We generate mass balance–altitude relations for all the glaciers by region using nearest available glacier measurements. Equilibrium line altitude (ELA) sensitivities to temperature and precipitation change vary by region based on the relative importance of sublimation and melting processes. We also made simulations with mass balance tuned to match satellite observations of glacier thickness changes in HMA from 2003 to 2009. Net mass loss is half as much using the tuned model than using just glaciological calibration data, suggesting the representativity of benchmark glaciers is a larger source of uncertainty in future HMA contributions to sea level rise than errors in glacier inventories or volume–area scaling. Both models predict that about 35% of the glaciers in Karakoram and the northwestern Himalaya are advancing, which is consistent with the observed slight mass gain of glaciers in these regions in recent years. However, we find that 76% of all the glaciers will retreat, most of which are of the maritime type. We project total glacier area loss in high mountain Asia in 2050 to be 22% (in the tuned model) or 35% (un-tuned) of their extent in 2000, and they will contribute 5 mm (tuned model) to global sea level rise.

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1. Introduction

High mountain Asia (HMA) possess tens of thousands of mountain glaciers which provide water for many large and important rivers (e.g. Brahmaputra River, Ganges River, Yellow River, Yangtze River, Indus River, Mekong River). Hence their future evolution will have important impacts on the lives of millions of people. There are many studies in the literature monitoring glacier change over time across HMA. The longest records of glacier length and area change since the middle 19th century from across the whole Himalaya and Karakoram were reviewed by Bolch et al. (2012), who found general retreat but a more complex picture in Karakoram, consistent with remote sensing studies reported by Gardelle et al. (2013) for the Karakoram. Sorg et al. (2012) reviewed recent change on glaciers in Tien Shan, finding extensive retreat over the 20th century. Ding et al. (2006) looked at glaciers in China using remote sensing data and maps since the 1950s and report stable conditions in the central and northwestern regions, but extensive retreat in the periphery of the Tibetan Plateau. Yao et al. (2012) gave a comprehensive overview of mass balance studies on glaciers in the Chinese part of HMA, and additionally a few glaciers have received particularly detailed remote sensing studies (Ye et al., 2006a, b). These authors suggest that most HMA glaciers have retreated over the past few decades with an accelerating shrinkage trend. However, there are significant regional differences in the on-going response of HMA glaciers to climate change. A recent overview based on remote sensing from 2003 to 2009 (Gardner et al., 2013) finds that glaciers are thinning most rapidly in the Himalaya and Tien Shan mountains, moderately thinning in eastern and southern Tibet, and near balance in the western and central portions (Pamir, Karakoram, and western Kunlun). This regional variability in behavior across HMA is also reflected in results from the GRACE satellite gravity observations (Jacob et al., 2012), with no clear net trend and large interannual variability between 2003 and 2010. This is related to ice being converted to water, and Zhang et al. (2013) note a 61% increase in mass derived from GRACE which they explain by increasing lake mass.

Studies focusing on the future response of glacier systems such as HMA to climate change must rely on approaches based on readily available datasets. Previous work has used a mixture of observational and climate forcing of differing sophistication. Radić et al. (2014) used

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statistical downscaling of global climate model output (typically at 200 km resolution) to drive individual mass balance of all individual glaciers globally, including HMA, validating and tuning their model regionally with 137 glaciers (10 in HMA) where mass balance measurements exist. This model is essentially a refinement of Radić and Hock (2011), including most relevantly for HMA, improving the annual precipitation bias from climate models to include the seasonal cycle. For HMA, Radić and Hock (2011) suggested a sea level rise contribution from −1 mm to 9 mm, whereas Radić et al. (2014) suggest about 18 ± 5 mm under A1B by 2100. Marzeion et al. (2012) also used a global climate model driven mass balance parameterization, again validated by glaciological observations, finding similar results as Radić et al. (2014), estimating about 15 ± 10 mm of global sea level rise from HMA under RCP6 (which is similar to the A1B scenario) by 2100. Giesen and Oerlemans (2013) estimated glacier sensitivity to changes in temperature and precipitation using an hourly energy-balance approach to parameterize mass balance validated with an 80 glacier global dataset. Under the A1B scenario they estimated the change of glaciers in HMA as 4.8 mm and 20.9 mm of global sea level for the periods 1980–2011 and 2012–2099 respectively. Problems with lack of validation from automatic weather stations in HMA and difficulties with the summer accumulation type of glacier lead to large uncertainties in this approach for HMA.

Even earlier attempts at modeling glacier evolution are notable, but are limited in their spatial coverage. Shi and Liu (2000) estimated the decrease in glacial area for Chinese glaciers over the 21st century by using simple empirical relations between glacier retreat and temperature rise since the Little Ice Age, and predicted shrinkage by 45%–75% by 2100 under a temperature rise of 2 K–4.5 K. Xie et al. (2006) predicted glacier response to climate warming using a complex regional model of glacier mass balance validated by observed areal retreat rates, and concluded that glacier area in China will be reduced by 14%, 40% and 60% by the end of this century under different climate scenarios with temperature increase rates of 0.01, 0.03 and 0.05 °C a^{-1}, respectively.

While the recent decade or so has provided a rich supply of remote sensing products, field measurements of glacier thickness and mass balance are very limited because of the practical and sometimes political difficulties in accessing the glaciers. This pattern of data availability suggests a statistical approach with considerable extrapolation from observations, but with useful constraints from the extensive (but temporally limited) remote sensing data. Furthermore Gardner et al. (2013) observed that estimates of mass loss based on extrapolation from glaciological measurements on the few glaciers studied in HMA tend to produce much larger rates of mass loss than is inferred from the 2009–2003 glacier elevation changes, motivating altimetry data assimilation with statistical modeling as a way forward in projecting future glacier change.

In this article, we propose and apply a simplified method to estimate area and volume change for glaciers in high mountain Asia by 2050 using climate scenarios from a relatively high resolution regional climate model. We make use all the available data including glacier outlines from Randolph Glacier Inventory (RGI) (Arendt et al., 2012), surface elevation from Shuttle Radar Topography Mission (SRTM), glacier equilibrium line altitude (ELA) contour map from the first Chinese glacier inventory, surface mass balance (SMB)–altitude profiles of “benchmark” glaciers, and temperature and precipitation change trend from the 25 km resolution regional climate model coupled to a global climate model running the commonly used A1B forcing scenario. We also differentiate the ELA sensitivity to changes in temperature and precipitation between maritime, sub-continental and continental locations. We calculate volume change for every individual glacier, and convert it to area change by volume–area scaling. This methodology thus makes improvements on previous estimates by using high resolution climate forcing, by making calculations for all glaciers in the region using varying ELA sensitivities, and by using all available SMB data to parameterize the glacier response.

2. Data

The Randolph Glacier Inventory database contains outlines of almost all glaciers and ice caps outside the two ice sheets. We use the data covering South-Asia East, South-Asia West and Central Asia regions from RGI version 2.0 (Arendt et al., 2012). We define these three regions as our HMA study area, containing 122,969 km^2 of glaciated area and a total of 67,028 glaciers (Fig. 1). We calculated the glacier area after correcting for mistaken doubly reported polygons. The RGI data for China, the northern slopes of the Himalayas and the northeastern part of Karakoram are based on topographic maps from the first Chinese glacier inventory (Shi et al., 2009), most of which were made in the 1970s, with some from the 1960s and 1980s. Data in these regions suffer from areal inaccuracies and location uncertainties, and are of heterogeneous but slightly lower quality than the other glacier data in HMA. Most glacier data in HMA from outside China are from the late 1990s or 2000s. For simplicity, we take 1980 and 2000 as the beginning years of our model for glaciers inside, and outside China, respectively.

The Central Asia region contains outlines of glacier complexes rather than individual glaciers, and we do not explicitly correct for this (unlike, for example, Radić et al., 2014). The division of glacier complexes into individual glaciers has an impact on the volume estimate because of the non-linearity of volume scaling relationship (Grinsted, 2013); grouping a glacier complex into a single glacier increases the estimated volume, and we can, to some extent quantify this, by examining a range of volume-area scaling laws. We used the SRTM version 4.1 (void filled version) digital elevation model (DEM) with a horizontal resolution of 90 m to estimate the elevation range spanned by each glacier (Jarvis et al., 2008).

The Chinese Glacier Inventory (Shi, 2005; Chap. 3) provides an ELA contour map (see also Fig. 1 in Yao et al., 2012) over HMA. The ELA on most glaciers was estimated from aerial photogrammetry of glacier shape with the assumption of a convex accumulation region and a concave ablation area (the Hess method) — this is reported to be difficult on small glaciers and fairly subjective. Leonard and Fountain (2003) tested this method on alpine glaciers and found that it worked quite well for detecting the long term ELA (though it was at a slightly lower altitude than the measured ELA). Assuming the glaciers were in steady state through the 1960s and 70s, we take the year 1980 as our ELA reference datum.

Long period variation in ELA can be reconstructed using temperature and precipitation change trends rather than annual variability (e.g. Wang et al., 2010a, b). Here we use the results from the Regional Climate Model Version 3.0 (RegCM3, Fig. 2); the horizontal grid spacing of RegCM3 is 25 km, and the model domain covers all of China and surrounding East Asia areas (Gao et al., 2012). The model makes simulations from 1948 to 2100, a total of 153 years. The RegCM3 model was one-way nested in the 125 km resolution global climate model, MIROC3.2_hires, which was forced using the IPCC A1B greenhouse gas scenario (Meehl et al., 2007). The first three years are used for model spin-up, so the effective range of simulation years spans 1950 to 2100. We make use of results from 1980 to 2050 here. RegCM3 reproduces the present-day (taken to be 1981–2000) observed spatial distribution of surface air temperature and precipitation well (Gao et al., 2012).

3. Methods

We start from known glacier outlines and ELA of all glaciers at the relevant datum years. We take the sensitivity of ELA to temperature and precipitation from energy balance modeling of glaciers in HMA by Rupper and Roe (2008). The mass balance–altitude profile relative to the ELA for each glacier is parameterized from all available measurements on glaciers where SMB is given as a function of altitude. The general approach to evolve the glaciers is a repeated series of annual time steps driven by the regional climate model changes in temperature and precipitation. We use our SMB–altitude profiles to calculate the

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