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## LETTER

# An assessment of climate change impacts on glacier mass balance and geometry in the Chandra Basin, Western Himalaya for the 21st century

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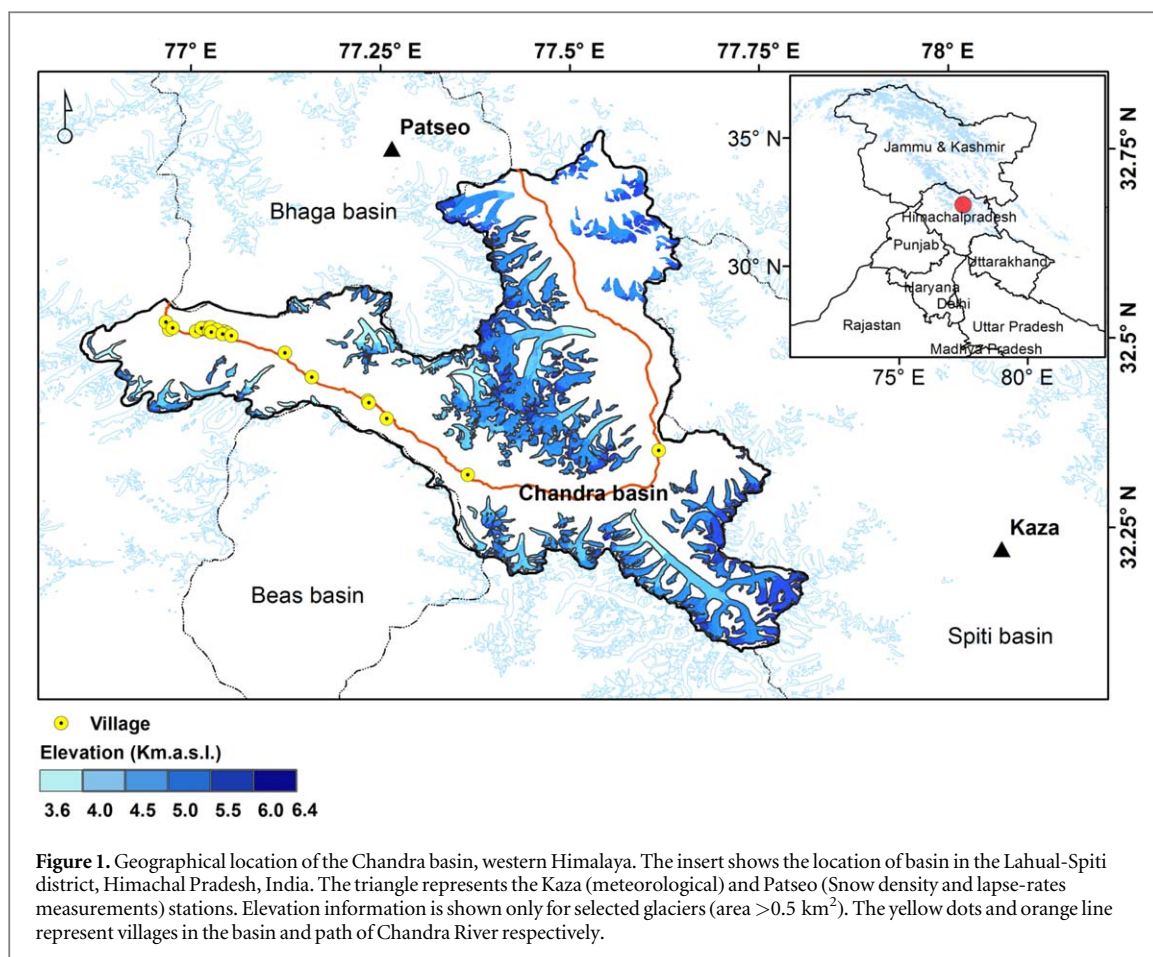
## Abstract

The Himalayan glaciers are a major source of Perennial River systems in South Asia and the retreat of these glaciers under climate change could directly affect millions of people who depend on them. In this study, we assess the glacier mass balance, area and volume changes at basin scale for the Chandra Basin in the western Himalaya due to projected climate change in the 21st century. The Chandra basin occupies  $\sim 2440$  km<sup>2</sup> of area and hosts  $\sim 200$  glaciers and 23 small villages. The multi-model projections used in this study indicate a temperature increase of 2.2 °C–2.9 °C and 4.3 °C–6 °C for the RCP 4.5 and RCP 8.5 scenarios by the end of the century with a steady or decreasing trend in snowfall in the basin. In response to the projected climate, the basin is likely to retain only 50%–52% (RCP 4.5) and 40%–45% (RCP 8.5) of the areal extent of glaciers by the end of the century. Corresponding volumes of glacier water retained are much lower at 40%–43% and 29%–34%, but the volume loss could be as high as 97% for low altitude glaciers. Overall, our study highlights the likely severe impacts to water resources in the Himalaya if CO<sub>2</sub> emissions follow the high-emission scenario of RCP8.5.

## 1. Introduction

Glaciers in the Himalaya and around the globe have undergone an accelerated retreat and mass loss since the mid-1990s (Kulkarni *et al* 2007, Zemp *et al* 2009, Bolch *et al* 2012, Gardelle *et al* 2013, Vincent *et al* 2013). Therefore, considerable efforts have been made in recent years to assess the future distribution of glaciers based on climate projections simulated by General Circulation Models (GCM) (Marzeion *et al* 2012, Giesen and Oerlemans 2013, Bliss *et al* 2014, Huss and Hock 2015, Kraaijenbrink *et al* 2017). For the Himalaya, the likely future changes in volume, mass budget and runoff at glacier scale (Adhikari and Huybrechts 2009, Shea *et al* 2015, Douglas *et al* 2016, Engelhardt *et al* 2017) and basin/regional scales (Immerzeel *et al* 2012, Chaturvedi *et al* 2014, Ahmad 2016, Lutz *et al* 2016, Shea and Immerzeel 2016, Zhao *et al* 2016, Kraaijenbrink *et al* 2017) have been investigated.

These previous investigations project that the glacier mass balance would be more negative in the Himalaya by the end of the century (Chaturvedi *et al* 2014, Huss and Hock 2015, Ahmad 2016, Douglas *et al* 2016) when compared to the current mass balance. In association with the accelerating negative mass balance, glacier area and volume are projected to decline. By 2100, it has been projected that  $\sim 30\%$ – $88\%$  of the present glacier ice volume could vanish in the Himalaya, indicating a major threat to water resources (Immerzeel *et al* 2012, Huss and Hock 2015, Zhao *et al* 2016, Engelhardt *et al* 2017, Kraaijenbrink *et al* 2017). The changes in glacier areas are also likely to influence the runoff trends in the 21st century i.e. runoff could increase in the initial decades and then



decrease or cease due to substantial decrease in glacier area (Bliss *et al* 2014, Lutz *et al* 2014, Shea and Immerzeel 2016, Huss and Hock 2018).

The Himalayan glaciers are a key component providing water to upstream reservoirs that support agricultural practices and avoid water-stress conditions downstream in summer. In winters, these glacier-fed reservoirs and base flows supply freshwater to downstream communities for livelihood (Wester *et al* 2019). The Indus river basin system support almost 300 million people in India and Pakistan (Cheema and Qamar 2019). Hence, for proper management of water resources downstream, it is crucial to quantify current and future variability in glaciers stored water at basin/sub-basin scales (Khan and Adams 2019). Studies on future changes in glacier cover in major river basins of the Himalaya could provide the context for adaptation in water stressed conditions and geophysical hazards in a warmer climate. Therefore, in this paper, we provide the long-term glacier mass balance and area change analysis for one of the river basins in western Himalaya.

In an earlier study (Tawde *et al* 2016), we improved one of the existing mass balance methods for the Chandra basin, western Himalaya, and estimated annual mass balance of the basin for recent decades (Tawde *et al* 2017). Here, we assess the potential future changes in glacier mass budget and geometry for 145 glaciers (~637 km<sup>2</sup>) in the same basin (figure 1) by the end of the century for two different emission scenarios. The study basin is a fifth order basin of the Indus and is situated in Lahaul-Spiti valley, Himachal Pradesh. The elevation of the basin is from 2800 to 6600 m.a.s.l. The Chandra River which is fed by snow and glacier melt traverses ~131 km of distance in the valley (Jain *et al* 2007) and there are ~23 small villages on the riverbank. Melt water from upstream glaciers and seasonal snow serve as a major source of water for irrigation and hydropower generation in the region (Field investigations during 2016–17; Khan and Adams 2019). The Chandra river flow contributes to one of the major tributaries of Indus i.e. Chenab, where 2015 MW of hydropower is generated from river runoff (Cheema and Qamar 2019). The snow and glacier cover contributes ~50% to the total river flow of Chenab (Singh *et al* 1997) and Chandra basin occupies ~23% of the total glaciated area of Chenab basin.

The mass balance analysis suggest an acceleration in basin wide mass loss since mid-1990s and a mean mass balance of  $-0.61 \pm 0.46$  m w.e./a during 1984–2012 (Tawde *et al* 2017). The novelty of this study is the estimation of future changes to individual glaciers at river basin scale using the improved Accumulation Area Ratio (AAR)- mass balance method (Tawde *et al* 2016, Tawde *et al* 2017) which is calibrated and validated for the basin, along with a glacier geometry model (Huss *et al* 2010) driven by finer resolution climate data.

**Table 1.** Description of the climate data used in this study.

Climate projections	Models	Downscaling method	Spatial resolution	Historical period	Future period
NEX-GDDP	21 CMIP5 models	Statistical	25 km	1986–2005 (1995s)	2041–2060 (2050 s) 2081–2100 (2090 s)
ICAR	Regional model Remo driven by NorESM	Quasi-dynamic	5 km	2004–2013 (2008s)	2026–2035 (2030 s)  2036–2045 (2040 s) 2046–2055 (2050 s) 2056–2065 (2060 s) 2066–2075 (2070 s) 2076–2085 (2080 s) 2086–2095 (2090 s) 2089–2099 (2099 s)

## 2. Method

An estimation of future changes in glacier mass balance requires the projected climate variables for the 21st century as inputs. Therefore, high resolution GCM data for temperature and precipitation is used in this analysis for the 21st century for two climate change scenarios: Representative Concentration Pathways (RCP) 4.5 and 8.5 (table 1). We use data from two sources (1) NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) from 21 GCMs and (2) Intermediate Complexity Atmospheric Research (ICAR) climate projections from one GCM (supplementary text S1 is available online at [stacks.iop.org/ERC/1/041003/mmedia](https://stacks.iop.org/ERC/1/041003/mmedia)). Monthly climate projections data at the location of Kaza meteorological station (3600 m.a.s.l.) are used after pre-processing i.e. bias-corrections and rain-snow discrimination (supplementary text S2–S4). As can be seen from the last column of table 1, projections are made 2050 s and 2090 s when NEX-GDDP data is used and projections are made for every decade when ICAR data is used.

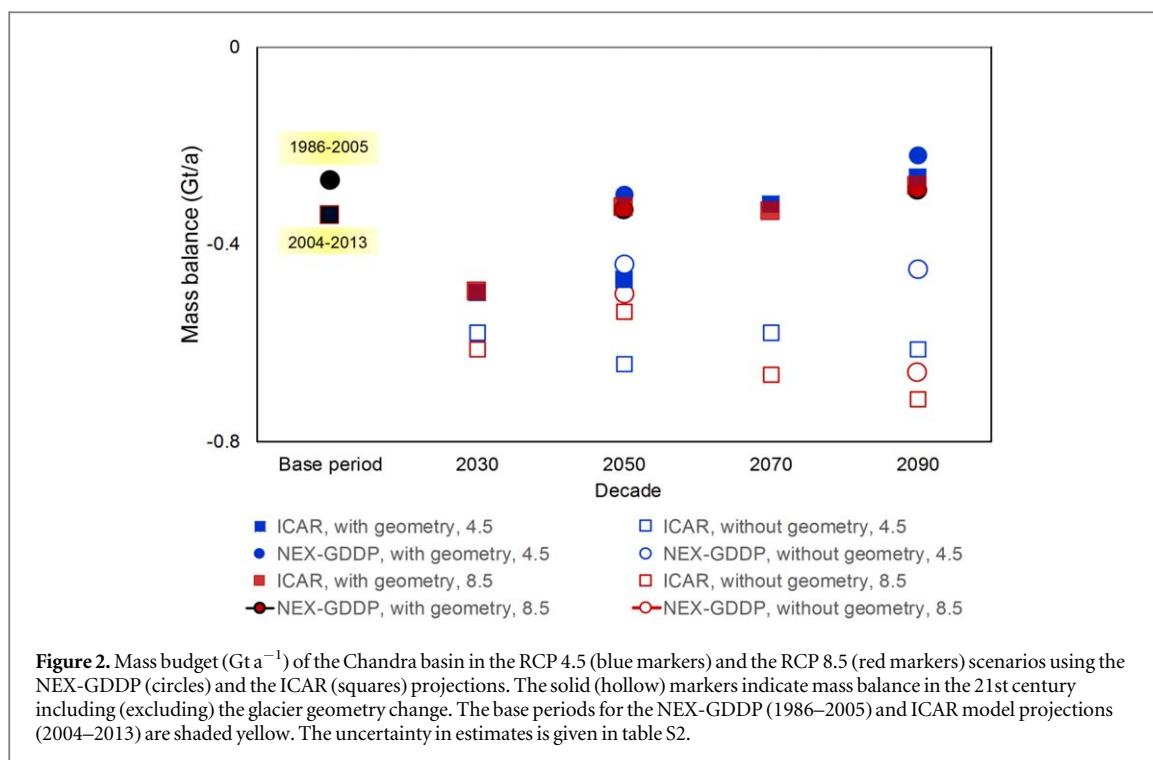
The glacier mass balance and geometry models are forced with climate anomalies to estimate the potential future changes in glaciers. For mass balance estimates, the improved AAR method is used which was developed and validated for the study basin (Tawde *et al* 2016, Tawde *et al* 2017). In this method, the position of equilibrium line altitude (ELA, altitude of the snowline at the end of melting season) and hence accumulation area of glacier is modelled using climate data. Further, the linear relation between mass balance and accumulation area is used to calculate glacier mass budgets (supplementary text S5). Changes in glacier area and volume are assessed using mass balance estimates and the  $\Delta h$  parameterization (Huss *et al* 2010). In  $\Delta h$  parameterization, simulated mass changes are redistributed across all elevation bands of a glacier to calculate thickness change at the glacier surface. According to the changes in ice thickness, the hypsometry of the glaciers is adjusted for future periods. The detailed description of  $\Delta h$  parameterization is given in the supplementary text S6. The parameters in the mass balance model and the  $\Delta h$  parameterization are assumed constant for the present and future periods. Finally, the uncertainties in projections of glacier extent are estimated by perturbing input variables to the models. The uncertainties in glacier metrics are estimated based on (1) uncertainty in climate change projections, and other inputs parameters or assumptions in (2) the glacier mass balance model and (3)  $\Delta h$  parameterization (figure S3).

## 3. Results

### 3.1. Projected climate in the 21st century

The NEX-GDDP projections show that the annual mean temperature at the Kaza station location would increase by 2.2 °C (2050 s) and 2.9 °C (2090 s) in the RCP 4.5 scenario compared to the period 1986–2005 (figure S4). The surface temperature change projected by the ICAR model is +1.5 °C (2050 s) and +2.2 °C (2090 s) relative to the period of 2004–2013. The annual mean temperature observed at this station for the historical period is between 3 °C (1986–2005) and 3.9 °C (2004–13), and the annual mean precipitation is between 1.42 mm day<sup>-1</sup> (1986–2005) and 1.03 mm day<sup>-1</sup> (2004–13). The NEX-GDDP projections indicate an increase in the annual mean precipitation by 4% (2050 s) and 11% (2090 s) for the RCP 4.5 scenario, while the projected changes by the ICAR model are –18% (2050 s) and +6% (2090 s). However, the winter snowfall (Oct.–Apr.) received by the basin changes by +1% (2050 s) and +3% (2090 s) in the NEX-GDDP projections and by –20% (2050 s) and +2% (2090 s) in ICAR projections for the RCP 4.5 scenario.

As for the RCP4.5 scenario, the NEX-GDDP projections of air temperature are slightly higher than the ICAR projections for the RCP 8.5 scenario. The ensemble output of NEX-GDDP shows an increase of 2.8 °C (2050 s)



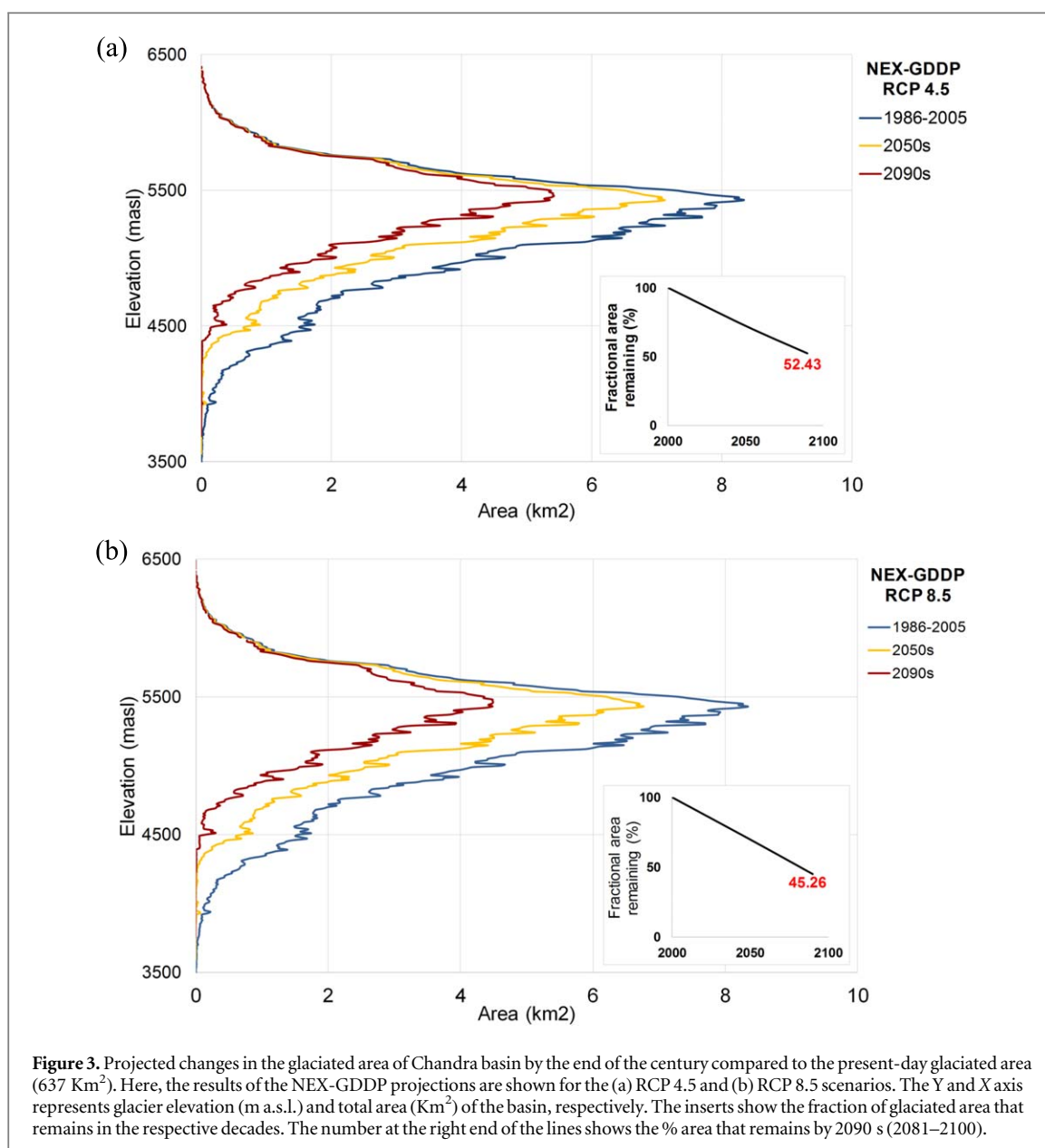
**Table 2.** Projected changes in glacier mass balance, area and volume of the Chandra basin in the RCP4.5 and RCP8.5 scenarios for the mid- and the end of the 21st century relative to the historical periods (table 1).  $\Delta T$  are the changes in annual temperature projected by GCMs.

Projections	Climate scenarios	Mass balance ( $\text{Gt a}^{-1}$ )									
		$\Delta T$ ( $^{\circ}\text{C}$ )		With geometry		Without geometry		Area change (%)		Volume change (%)	
		2050 s	2090 s	2050 s	2090 s	2050 s	2090 s	2050 s	2090 s	2050 s	2090 s
NEX-GDDP	RCP 4.5	+2.2	+2.9	-0.30	-0.22	-0.44	-0.45	-28	-48	-37	-57
	RCP 8.5	+2.8	+6.0	-0.33	-0.29	-0.50	-0.66	-30	-55	-40	-66
ICAR	RCP 4.5	+1.5	+2.2	-0.47	-0.26	-0.64	-0.61	-24	-50	-33	-60
	RCP 8.5	+2.0	+4.3	-0.33	-0.28	-0.54	-0.71	-32	-60	-42	-71

and  $6.0^{\circ}\text{C}$  (2090 s) in the annual mean air temperature compared to 1986–2005 in the RCP 8.5 scenarios; whereas, the increase is about  $2.0^{\circ}\text{C}$  (2050 s) and  $4.3^{\circ}\text{C}$  (2090 s) in the ICAR projections compared to 2004–2013. The annual mean precipitation increases by 16% (NEX-GDDP) and 4% (ICAR) in the RCP8.5 scenario by 2090 s (figure S4). However, the snowfall in winter months is projected to change by +6% (NEX-GDDP) and -36% (ICAR) by the end of the century, likely due to higher air temperatures influencing the fraction of liquid precipitation. Standard deviation of precipitation in the ensemble is  $\sim 30\text{--}32\%$  in both scenarios by the end of the century, which is used to estimate the uncertainty in future glacier changes.

### 3.2. Future glacier mass budgets

The present-day mass budget of the basin is  $-0.27 \text{ Gt a}^{-1}$  during 1986–2005 and  $-0.34 \text{ Gt a}^{-1}$  during 2004–2013 (Tawde *et al* 2017). The mass balance of the basin becomes more negative throughout the 21st century (table 2) and the ELA moves upwards (figure S5), when climate change projections are included in mass balance calculations (*with constant glacier geometry*). A mass loss of  $-0.44 \text{ Gt a}^{-1}$  ( $-0.70 \text{ m w.e. a}^{-1}$ ) by 2050 s and  $-0.45 \text{ Gt a}^{-1}$  ( $-0.75 \text{ m w.e. a}^{-1}$ ) by 2090 s is estimated for the basin using climate projections of the NEX-GDDP RCP 4.5 scenario. The magnitude of this change is less than the mass balance changes projected when ICAR data are used i.e.  $-0.64 \text{ Gt a}^{-1}$  ( $-1.01 \text{ m w.e. a}^{-1}$ ) by 2050 s and  $-0.61 \text{ Gt a}^{-1}$  ( $-0.96 \text{ m w.e. a}^{-1}$ ) by 2090 s (figure 2). The mass balance projections for the RCP 8.5 scenario show an accelerated mass loss during the same period (table 2). The mass budget of the basin is estimated as  $-0.54 \text{ Gt a}^{-1}$  ( $-0.84 \text{ m w.e. a}^{-1}$ ) by 2050 s and as  $-0.71 \text{ Gt a}^{-1}$  ( $-1.12 \text{ m w.e. a}^{-1}$ ) by 2090 s when ICAR data for the RCP 8.5 is used. However, when the NEX-GDDP projections are used, the projected climatic mass balance is  $-0.66 \text{ Gt a}^{-1}$  ( $-1.03 \text{ m w.e. a}^{-1}$ ) by 2090 s.

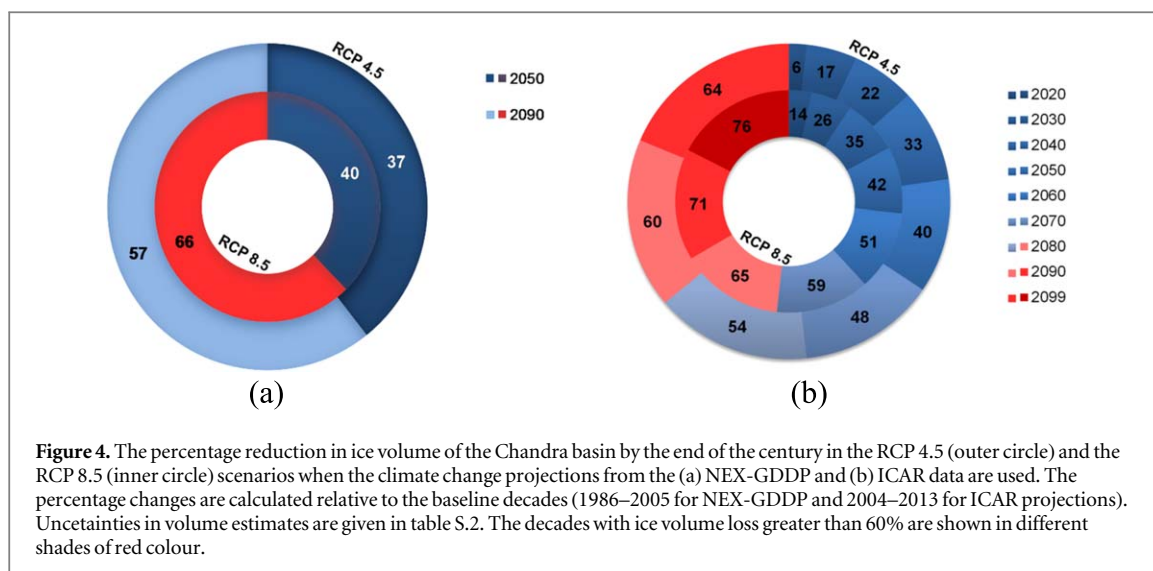


When geometric factors (area, volume) along with the climatic factors are allowed to change in the mass balance calculations, for the RCP 4.5 scenario, the mass loss of the basin is reduced to  $-0.30$  (2050 s) and  $-0.22$  (2090 s)  $\text{Gt a}^{-1}$  for the NEX-GDDP projections (figure 2). The mass budget changes to  $-0.47$  (2050 s) and  $-0.26$  (2090 s)  $\text{Gt a}^{-1}$  for the ICAR RCP 4.5 projections. Similarly, the mass budget of the basin reduces from  $-0.33$  (2050 s) to  $-0.29$  (2090 s)  $\text{Gt a}^{-1}$  when NEX-GDDP projections for the RCP 8.5 scenario are used and it decreases from  $-0.33$  (2050 s) to  $-0.28$  (2090 s)  $\text{Gt a}^{-1}$  in ICAR (table 2).

The rate of mass loss ( $\text{Gt a}^{-1}$ ) is similar by the end of the century in RCP 4.5 and RCP 8.5 scenarios when the glacier geometry is taken into account (figure 2) as larger negative mass balance ( $\text{m w.e.a}^{-1}$ ) in RCP 8.5 scenario is compensated by smaller residual glacier areas (figure 3). However, the cumulative loss of glacier volume is more in the RCP8.5 scenario by the end of the century (figure 4) as discussed below. Glaciers start retreating as a response to a warmer climate (Solomon *et al* 2007, Cuffey and Paterson 2010) and are smaller in size in the future. Therefore, the rate of mass loss in the future is less than today when glacier geometry is included but larger than today's values when geometry is not included. Our results hence indicate a larger sensitivity to the inclusion of glacier geometry in future mass balance estimates.

### 3.3. Projected changes in glacier area and hypsometry

In response to the mass loss in the 21st century, glacier area is projected to decline in both RCP 4.5 and RCP 8.5 scenarios (figure 3). The present-day areal extent of the Chandra basin (637 Km<sup>2</sup>) decreases by 28% (2050 s) and 48% (2090 s) relative to the current period when NEX-GDDP climate projections are used for the RCP 4.5



scenario (figure 3(a)). However, the basin area is projected to decline by 24% (2050 s) and 50% (2090 s) relative to the current period when data from ICAR model is used for the same emission scenario (figure S6). In the case of very large glaciers in the basin such as Samudra Tapu Glacier ( $\sim 80 \text{ Km}^2$ ) and Bara Shigri Glacier ( $\sim 112 \text{ Km}^2$ ), the area loss is 28%–34% and 13%–17% respectively by the end of the century in the RCP 4.5 scenario (figure S7). Out of the 145 selected glaciers (of area  $> 0.5 \text{ Km}^2$ ),  $\sim 45$  to 55 glaciers are projected to shrink to an area  $< 0.1 \text{ km}^2$  by the end of the century for the RCP 4.5 scenario.

The area loss is larger in the RCP 8.5 scenario (table 2). The glaciated area of the basin is projected to shrink by 30%–32% in the RCP 8.5 scenario by 2050 s (figure 3(b)). By the end of the century, the basin area is predicted to reduce by 55% (NEX-GDDP)- 60% (ICAR). Samudra Tapu glacier is projected to retain only 32%–38% of its present area and for Bara Shigri glacier it is only 20%–22% by 2090 s (figure S6). We find that  $\sim 52$  to 77 out of the 145 glaciers would end up with an area  $< 0.1 \text{ km}^2$  by the end of the century in the RCP 8.5 scenario.

Our projected future values of area (along with uncertainties) are within the range of results from previous studies at different spatial scales and GCM resolutions. At glacier scale, Engelhardt *et al* (2017) estimate a 70% loss in the Chhota Shigri glacier area by 2099 (RCP 8.5) using the ICAR simulations. According to our estimates, a loss of 50%–68% in area is projected for the same glacier by the end of the century. At sub-basin scale, Immerzeel *et al* (2012) project 80% loss in area across the Langtang river catchment in Nepal by 2100 (A2B scenario: temperature rise  $\sim 5 \text{ }^\circ\text{C}$ ). Our analysis for the Chandra basin projects a 55%–60% decline in area by 2090 s for the same scenario. Also, a regional scale analysis of the Western Himalaya projects an area loss of 87% by the end of the century in the RCP 8.5 scenario (Kraaijenbrink *et al* 2017).

### 3.4. Ice volume projected by the end of the century

Large reduction in the ice volume is also projected for all glaciers by the end of the century in both emission scenarios (figure 4). For the RCP 4.5 scenario, the ice volume of basin is projected to decline by 37% (2050 s) and 57% (2090 s) compared to its present value (59 Gt) when climate change projections from NEX-GDDP data are used (figure 4(a)). Similarly, the ice volume is projected to decline by 33% (2050 s) and 60% (2090 s) when ICAR projections are used (figure 4(b)).

In the high emission RCP 8.5 scenario, the reductions are 40% (2050 s) and 66% (2090 s) relative to the current value when climate projections of the NEX-GDDP are used (figure 4(a)). Similarly, the ice volume is estimated to decline by 42% (2050 s) and 71% (2090 s) when ICAR projections are used (figure 4(b)). However, for the twenty-nine identified small (mostly with area  $< 2 \text{ km}^2$ ) and low altitude (3600–5000 m.a.s.l.) glaciers in the basin (Tawde *et al* 2017), the volume loss by the end of the century is much larger i.e.  $\sim 92\%$  (NEX-GDDP) to 97% (ICAR) in both the emission scenarios.

The previous studies that investigated the global scale changes in glacier volume, also assess the South Asia West (SAW) region which includes the western Himalaya and hence the Chandra basin (Marzeion *et al* 2012, Radić *et al* 2013, Huss and Hock 2015). These projections suggest that a volume loss for the SAW region would be 62%–87% by 2100 in the RCP 8.5 scenario. Some studies at sub-basin scales, such as Immerzeel *et al* (2012) projects 88% loss in volume for the Langtang river catchment (Nepal) by 2100. Another study (Shea *et al* 2015) for the Nepal region projects a volume loss of 94.7% in the Dhudh Koshi basin by the end of the century in the RCP 8.5 scenario. The NEX-GDDP (ICAR) projections in the present analysis show a decrease in the volume of Chandra basin by 66% (76%) in 2090 s (2099) for the RCP 8.5 scenario (table 2). Engelhardt *et al* (2017) estimate

an 88% loss in the Chhota Shigri glacier volume by 2099 (RCP 8.5) using the ICAR simulations. According to our estimates, a loss of 83%–92% in volume is projected for the same glacier and for the same scenario by the end of the century.

### 3.5. Uncertainty in projections

An understanding of uncertainties in future projections is crucial for assessing risks due to climate change on glacier-stored water. Therefore, here we discuss the most crucial sources of uncertainty estimated for the RCP 8.5 scenario by 2090 s. We quantify the errors due to the inputs and assumptions in models which propagate through the future periods (table S2). First, the standard deviation in projections of temperature (0.53 °C–0.7 °C) and precipitation (30%–32%) for a given emission scenario lead to an uncertainty. Uncertainty in glacier area and volume projections by 2090 s in the RCP 8.5 scenario is estimated as 2.9%–7.1% and 7.0%–12% respectively, due to standard deviation in climate projections. Second, the uncertainties in inputs (temperature, snowfall, snow melt factor, temperature lapse rate and precipitation gradient) to the mass balance model (Tawde *et al* 2017) amplify the uncertainty in future area-volume estimates to 30%–40% (table S2). The third major source of uncertainty is associated with calculations of the present and future glacier ice thickness distributions. The uncertainty in ice-thickness distribution model (12%; Huss and Farinotti 2012) used to calculate the present ice volume leads to an uncertainty of 8.6% and 26% in future area and volume estimates respectively. Further, the  $\Delta h-h$  curves used here for the projection of future ice thickness can lead to an uncertainty of 12% and 13% in area and volume estimates respectively by 2090 s in the RCP 8.5 scenario.

In addition to above discussed uncertainties, the resolution of GCM has a pronounced effect on the simulation of the seasonal cycle of precipitation in mountainous Himalaya (figure S1). The annual mean of temperature projected by the NEX-GDDP and the ICAR models are comparable for the RCP 4.5 scenario. However, a difference of  $\sim 0.7$  °C (after adjusting temperature for base periods) is projected by 2090 s in the RCP 8.5 scenario. This difference results in  $\sim 24\%$  more ablation for the NEX-GDDP RCP 8.5 projections compared to projections that use ICAR data. However, the positive anomalies in the monsoon dominated precipitation regime projected by the NEX-GDDP (figure S1) partially offset the effects of a rise in temperature, leading to results comparable to the ICAR projections. However, this offsetting effect may not always be true for other datasets or basins.

## 4. Discussion and conclusions

We have investigated the potential changes in individual glaciers at river basin scale for the Chandra Basin, Western Himalaya by the end of the 21st century. Several studies have investigated the future response of cryosphere to climate at global, regional and glacier scales; however, such analysis is limited in the Himalaya especially at sub-basin scales. Here, the potential changes in glacier cover are assessed for the basin in western Himalaya. According to our assessment, the temperature of the basin is projected to increase by 2.2 °C–2.9 °C and 4.3 °C–6.0 °C in the RCP 4.5 and 8.5 scenarios respectively by the end of the century. Precipitation is projected to increase in both the scenarios, but snowfall is projected mostly to decrease. In response to these changes, the negative mass balance of the basin is found to be continued during the century and hence the glacier area and volume are projected to decrease. According to our estimates, the basin will retain 50%–52% of its current glaciated area in the moderate emission scenario (RCP 4.5) by 2090 s and 40%–45% in the high emission scenario (RCP 8.5). When volume changes are considered, it is projected that only 40%–43% (RCP 4.5) and 29%–34% (RCP 8.5) of the initial water volume stored in these glaciers will remain by the end of the century. However, the volume loss is  $\sim 97\%$  for small and low altitude glaciers in both the emission scenarios, which is consistent with the results of Ahmad (2016) i.e. glaciers at lower altitudes are more vulnerable to climate warming in the future.

Overall, the response of glacier area and volume to the climate is assessed to be rapid for the first few decades and slower by the end of the century. The possible reasons could be: (1) glaciers retreat to the higher elevations is a negative feedback to glacier mass balance (Marzeion *et al* 2014), (2) ice thickness of the glacier at lower elevations are small and confined to the narrow area, and hence ice disappears rapidly during early decades compared to the thicker ice at higher elevations and (3) at lower elevations, the slopes are steeper compared to the high elevations, leading to faster retreats at lower elevations.

The aim of the present analysis is to project the future changes in mass budget and glacier geometry at the river basin scale using computationally simple methods. Our results for the Chandra basin are consistent with earlier studies on future projections across the Himalaya, though the data for climate projections and the mass balance model used here are different from previous studies. However, our study does have some important limitations. The present mass balance model does not take all energy fluxes into accounts for future periods. For an example, the shortwave and longwave fluxes may change in future due to changes in snow albedo in response



of aerosols/dust depositions on glaciers, changes in atmospheric lapse rates, increase in debris or exposed rocks etc. The other limitation is that the AAR-mass balance regression coefficients (equation (S2)) may change with time across the century which is not addressed here due to lack of long-term field observations. However, accounting the changes in glacier geometry would compensate this time-factor, as glacier hypsometry and the regression coefficients are inherently coupled. Also, the  $\Delta h$  parameterization curves (equation (S3)) used to estimate the glacier geometry, are assumed to be constant throughout the future simulations. In the real world,  $\Delta h$ - $h$  curves may change substantially as the retreating glaciers will move to higher elevation with gentle slopes or due to changes in debris cover.

Understanding the potential changes in glacier mass balance and the fate of glaciers in the Chandra-Bhaga river system is crucial because the population downstream depends on water from glacier melt for agriculture and hydro-power generation. The large area and volume loss predicted for low altitude glaciers could increase the stream flow causing floods or glacier lake outbursts which are major concerns in the Indus basin. Most of the flood events in the Indus basin peak in the summer season when stream flow due to heavy monsoon rainfall is enhanced by glacier melt (Tariq and Van de Giesen 2012, Shrestha *et al* 2019). Although runoff from upstream glaciers would replenish the flow reduction due to the loss of low altitude glaciers, the seasonal cycle of water availability could change affecting the agricultural practices in mountain communities. Therefore, assessments of this type for other basins in the Himalaya are needed to understand the changes in water budget at local scales by the end of the century.

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