Sensitivity and response of Bhutanese glaciers to atmospheric warming

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[1] Glacierized change in the Himalayas affects river-discharge, hydro-energy and agricultural production, and Glacial Lake Outburst Flood potential, but its quantification and extent of impacts remains highly uncertain. Here we present conservative, comprehensive and quantitative predictions for glacier area and meltwater flux changes in Bhutan, monsoonal Himalayas. In particular, we quantify the uncertainties associated with the glacier area and meltwater flux changes due to uncertainty in climate data, a critical problem for much of High Asia. Based on a suite of gridded climate data and a robust glacier melt model, our results show that glacier area and meltwater change projections can vary by an order of magnitude for different climate datasets. However, the most conservative results indicate that, even if climate were to remain at the present-day mean values, almost 10% of Bhutan's glacierized area would vanish and the meltwater flux would drop by as much as 30%. Under the conservative scenario of an additional 1°C regional warming, glacier retreat is going to continue until about 25% of Bhutan's glacierized area will have disappeared and the annual meltwater flux, after an initial spike, would drop by as much as 65%. **Citation:** Rupper, S., J. M. Schaefer, L. K. Burgener, L. S. Koenig, K. Tsering, and E. R. Cook (2012), Sensitivity and response of Bhutanese glaciers to atmospheric warming, *Geophys. Res. Lett.*, *39*, L19503, doi:10.1029/2012GL053010.

1. Introduction

[2] Glaciers are particularly sensitive to climate change, making them vulnerable elements of the environment. Of potential concern for societies is the rapid glacier retreat of Himalayan glaciers. Besides the vast potential for hydroelectric power, these glaciers contribute to the major rivers in Asia [*Immerzeel et al.*, 2010; *Kaser et al.*, 2006], and glacier meltwater is critical for agriculture in many, especially drier, regions in summer. Beyond, glacial lake outburst floods are one of the major natural hazards in this region, and the hazard potential is rapidly growing as a result of glacier thinning and retreat [*Richardson and Raynolds*, 2000]. Nevertheless, estimates of ongoing and near-future glacier change in the Himalayas relative to the climate forcing remains poorly quantified and thus highly controversial [e.g., *Cogley et al.*, 2010; *Immerzeel et al.*, 2010; *Jacob et al.*, 2012; *Bolch et al.*, 2012].

[3] Recent studies have estimated large-scale Himalayan glacier change through remote sensing techniques. However, the results range from dramatic ice mass loss [e.g., *Dyurgerov et al.*, 2009; *Bolch et al.*, 2011] with some estimates for high Asia as large as ∼50 Gigatons per year [*Matsuo and Heki*, 2010], to almost constant glacier mass [*Jacob et al.*, 2012]. These discrepancies could be partially explained by aspects inherent to differing remote sensing approaches, such as short observation periods, uncertainty in the remote sensing algorithms applied, and spatial resolution of the data. Detailed, regional glaciological mass-balance studies integrating multi-decadal glacier change are therefore desirable for comparison to both remote sensing studies as well as local, field-based, mass balance studies. One of the greatest challenges is the severe lack of field data for model and remote sensing validation. This stems, in part, from the immense number of glaciers spread over a vast region, the complex politics of the region, and the rugged terrain. Modeling of glacier mass balance and sensitivity can complement, extend, and motivate field and remote sensing studies of mass balance. Therefore, quantifying the uncertainties that attend model estimates of glacier mass balance and sensitivity in the absence of accurate validation data is critical. From the perspective of a glacier modeling approach to estimating glacier changes, these uncertainties stem from uncertainties in the glacier models, glacierized area, and climate data. Indeed, most studies use a single climate data set to quantify glacier changes and projections [e.g., *Rupper and Roe*, 2008; *Immerzeel et al.*, 2010], without quantifying the uncertainties associated with these data. In this study, we assess the uncertainties in projected glacier changes associated with the climate data and derive a conservative scenario for recent and ongoing glacier change in the Kingdom of Bhutan, in the monsoonal Himalayas.

[4] Bhutan is chosen for several reasons. First, Bhutan exemplifies an area where little data on glacier changes are available and where it is logistically difficult to obtain field-based studies, a common problem for many regions of the Himalayas. Few glaciological studies have addressed glacier changes in Bhutan, with the exceptions of a glacier area inventory [*Mool et al.*, 2001], quantitative estimates of glacier retreat and area decrease from 1963 to 1993 for a sampling of ∼15% of Bhutan's glaciers [*Karma et al.*, 2003] and an atlas of glaciers of Bhutan [*Iwata*, 2010]. Not all of these

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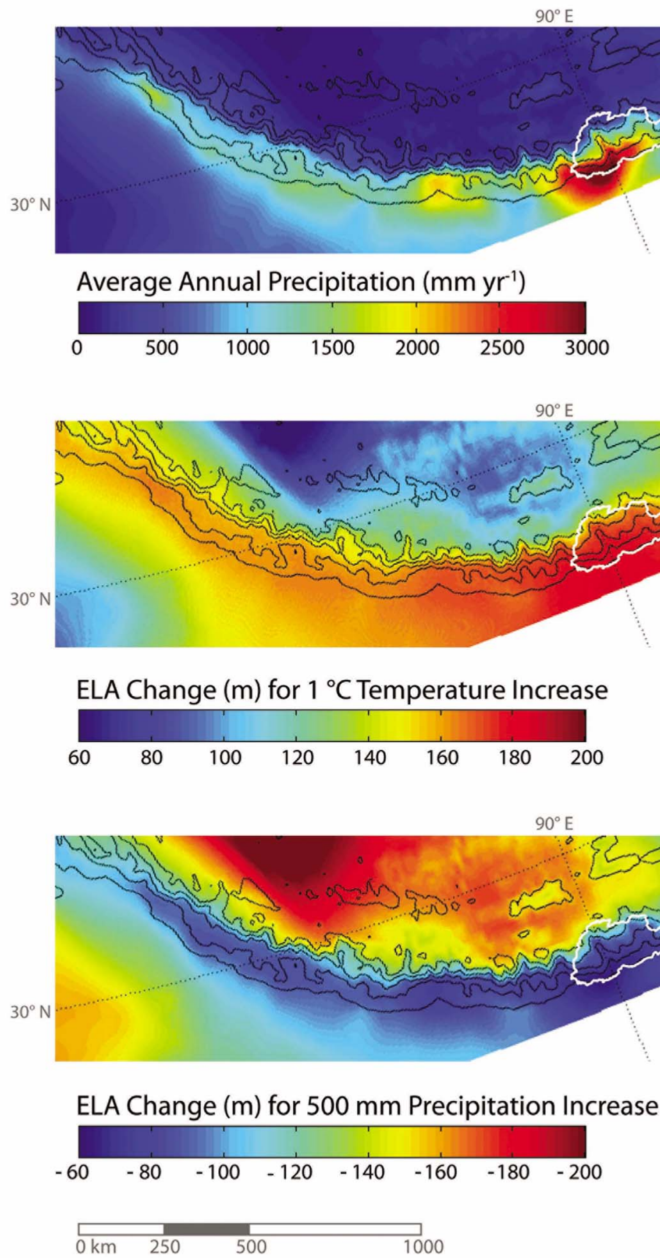

Figure 1. Equilibrium Line Altitude Sensitivity to Climate Change. All Panels: Black contours are elevations in 1000 m intervals. White outline is the Kingdom of Bhutan. (top) Average annual precipitation from the Climate Research Unit Climatology 2.0 (CRU CL 2.0) gridded data. Note the extremely high precipitation rates centered over Bhutan and adjacent regions. (middle) Change in glacier equilibrium line altitude (ELA) for a 1°C increase in temperature. Note the high glacier sensitivity to temperature change throughout the non-arid Himalayas (>~500 mm/yr), peaking over Bhutan and the neighboring Himalayas of Nepal, India, and Myanmar. (bottom) Change in glacier ELAs for an increase in precipitation equal to 500 mm. Note that ELA sensitivity to even this large increase in precipitation is quite low over the non-arid regions.

studies are peer-reviewed, and the uncertainties associated with the reports are not well known. All of these studies and reports do provide important insights into the rapid changes occurring in the large glacierized areas in Bhutan over the past half century. However, to date there are no published field- or modeling-based mass balance estimates for these glaciers, no estimates of glacier sensitivity to climate in the region, and no estimates of related change in meltwater flux over time. Thus, while there is significant evidence that the glaciers in Bhutan have been retreating over the past half century, we know little about the causes of those glacier changes and what the future glacier change will be.

[5] Second, glaciers in Bhutan, just as neighboring glaciers in India, Nepal, and Southwest China, sit in the bulls-eye of high snow accumulation glaciers (Figure 1, top) (see Text S1 for methods detail).[1] Sensitivity tests using a temperature-melt model (Text S1) support prior work

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053010.

that show that high accumulation regions are extremely temperature-sensitive [e.g., *Rupper and Roe*, 2008; *Fujita and Nuimura*, 2011]. Therefore, Bhutan's glaciers form a highly suitable natural laboratory to investigate glacier sensitivity and response to temperature change in the monsoonal Himalaya (Figure 1).

[6] Finally, there are socio-economic reasons to focus work on the glacierized regions of Bhutan. The Kingdom of Bhutan is a country at the forefront of climate change mitigation strategies (Bhutan was the first developing country to receive climate mitigation monies from the UN's Least Developed Countries fund), and faces many of the economic and hazard challenges associated with glacier changes in the larger Himalayan region [*Nayar*, 2009]. For example, Bhutan's main economic export is hydroelectric power and the powerplant safety and viability depends critically on prediction of glacial lake outburst floods and related mitigation measures [*Belding and Vokso*, 2011]. Therefore, the well-being of Bhutan's society requires accurate estimates of glacier change and meltwater production.

[7] This work provides a comprehensive study of glacier systems in Bhutan, and the first associated quantification of present and near-future glacierized area loss and related changes in melt water flux with particular emphasis on the sensitivity of these quantifications to the choice of different climate input data sets. We base our investigations on new glacier mapping from satellite imagery, a suite of gridded climate data, and a robust glacier melt model. This approach provides a range in mass balance estimates over the entire glacierized region.

2. Results and Conclusions

2.1. Glaciated Area

[8] In the Himalayas, widely used glacier data sources are the World Glacier Inventory (WGI) [*World Glacier Monitoring Service and National Snow and Ice Data Center*, 2011], the Global Land Ice Measurements from Space (GLIMS) [*Armstrong et al.*, 2012], and the Natural Earth data (NE) [*Patterson and Kelso*, 2011]. We merged these datasets into a single glacierized area, and then refined this merged area by using 1999–2010, June through September, Landsat Enhanced Thematic Mapper Plus (ETM+) images and 1999 i-cubed eSAT imagery (see Text S1 for additional details). The total, refined glacierized area for Bhutan and the Bhutan watershed is presented in Figure 2a, resulting in 1930 km^2 and 3120 km^2, $\pm$3%, respectively. Our area estimates are larger than earlier estimates for Bhutan's glacierized area [*Mool et al.*, 2001], with the greatest discrepancy occurring in the perennial snowpack and glacier accumulation areas.

2.2. Mass Balance and Glacierized Area Changes

[9] In order to calculate the net mass balance for Bhutan's glacierized area, we determine both, the melt and accumulation rates across the glacierized area. Here we use a commonly applied degree-day melt model [*Hock*, 2003] to estimate melt rates across the glacierized region of Bhutan, modified to capture spatial variations in surface conditions. The model assumes melt is proportional to the sum of all temperatures greater than zero (the degree-days), and that the proportionality constant relating melt to the degree days varies depending on the glacier surface (e.g., dirty ice, clean ice, fresh snow). While the melt factors are uncertain without validation, the melt factors used here are likely conservative estimates. (See Text S1 for a more detailed description of the melt model.) Total annual accumulation is calculated as the sum of all precipitation. The precipitation magnitudes and patterns in this region of complex topography are highly uncertain. Here we err on the side of maximizing accumulation by assuming all precipitation falls as snow. This minimizes the net imbalance across the region for the given precipitation data.

[10] If the integrated mass balance is negative (positive), the glacierized area will decrease (increase); if glaciers are in steady state with climate the integrated mass balance equals zero. Mass balance for each 250 m $\times$ 250 m grid cell is calculated as the total incoming accumulation minus the total outgoing melt, averaged over the period 1980 to 2000 (Figure 2c) (see Text S1 and Table S1). This temporal range provides the average climate over which most Bhutanese glaciers have already adjusted to or are currently responding to, given estimates of glacier response times (see Text S1). In addition, defining the mean climatology using twenty years of data helps insure that a few anomalously warm years do not significantly inflate the results.

[11] Errors in the mapped areas, modeling approach, and climate input data can all lead to considerable uncertainties in glacier meltwater flux and mass balance estimates. Here we present conservative values for glacier mass balance and, in turn, minimum values for glacier change in Bhutan by using the following estimates: First, our high elevation perennial snowpacks and glacier accumulation areas are larger than those of earlier glacierized area estimates [*Mool et al.*, 2001]. The use of Landsat imagery to map these regions likely increases the mapping accuracy as compared to the coarse resolution data used previously by *Mool et al.* [2001] (30 m grid resolution versus 1:50,000 scale topographic maps), but the differences in mapped regions may also reflect uncertainties in glacierized area. Importantly, these high and cold regions contribute very little to the total melt, but increase the net accumulation across the region significantly. Therefore, using upper bounds for the glacierized area estimate in higher accumulation regions minimizes the resulting glacier change. We assume the total glacierized area is reasonable for this study. Future work should focus on quantifying the uncertainties associated for these areas further. Second, we assume all precipitation falls as snow. This errs on the side of maximizing snow accumulation and mass balance. Third, we use conservative melt factors in relating temperature to melt in order to err on the side of minimizing melt and glacier change. Indeed, our modeled results for much of the region fall within the range of mass balance and melt rate estimates for similar glaciers in similar settings in the Himalayas [e.g., *Bolch et al.*, 2011; *Fujita and Nuimura*, 2011; *W. Yang et al.*, 2011]. Here we focus on the regional-averaged changes and, therefore, rely less on providing the accuracy necessary to confidently assess the mass balance of any single glacier. This approach to the mapping and modeling provides conservative mass balance estimates for the region of Bhutan. One exception is over glacierized regions with thick debris cover. Thin debris-cover lowers the albedo and increases melt rates, while the insolating effects of thick debris-cover cm) can reduce melt rates below that of clean ice [*Scherler et al.*, 2011]. The model used here only accounts for the influence of debris on albedo, and, therefore melt may

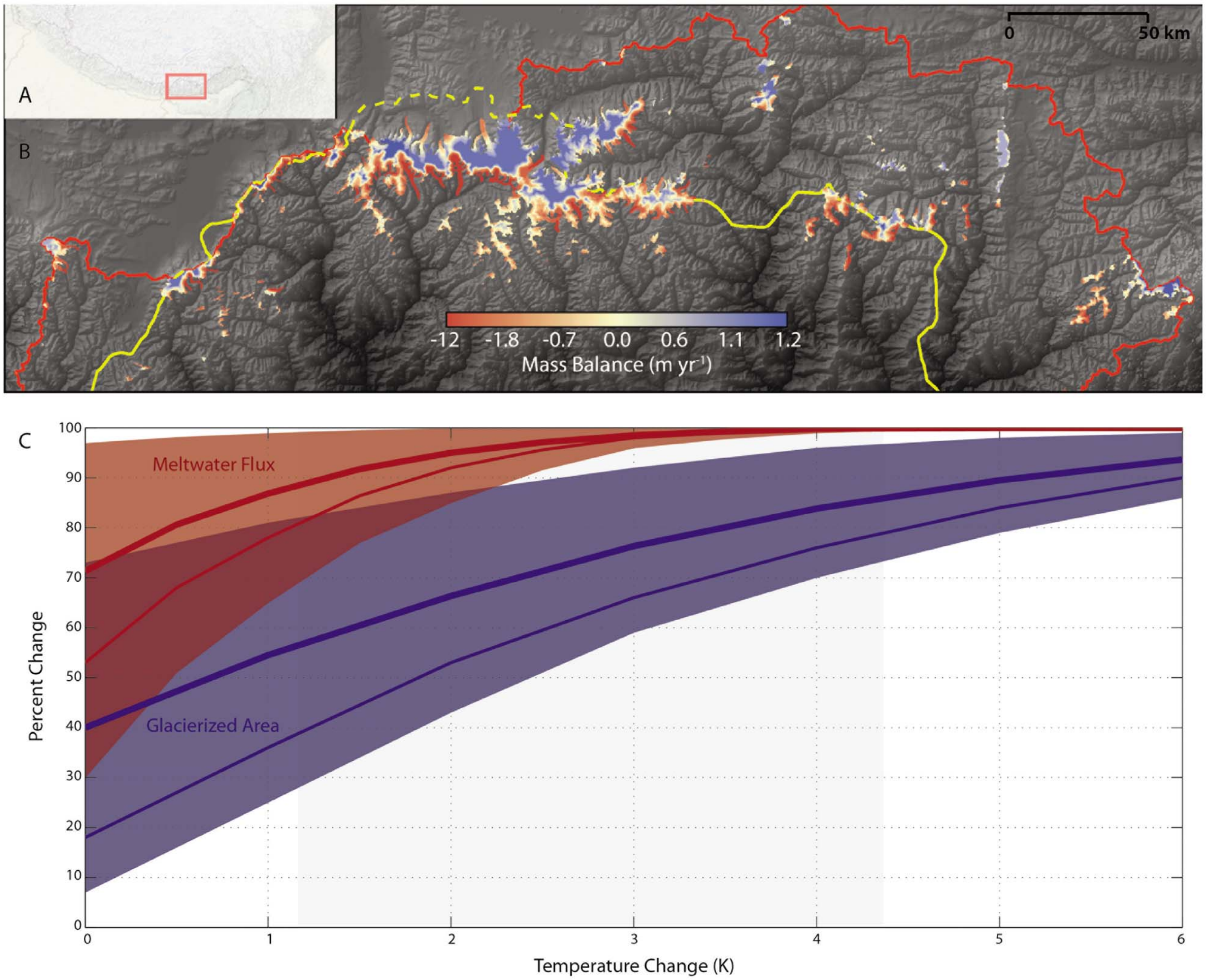

Figure 2. Mass balance of glacierized areas in the Bhutanese watershed. (a) Index map showing location of Bhutan relative to greater Himalaya. (b) Modeled average 1980–2000 annual mass balance (total annual snowfall minus total annual melt) using the CRU TS 3.1 gridded climate data as input. Note nonlinear mass balance color scale. Base map for Figures 2b and 2c are a 7.5 arc-second digital elevation model (GMTED2010) (darker to lighter grays = lower to higher elevations). Bhutan is outlined by the yellow line (recently disputed borders dashed) and all watersheds that feed Bhutan are outlined by the red line. (c) Calculated changes in meltwater flux (red) and glacierized area (blue) as a result of step-wise temperature changes from 0 to 6°C. Bold lines are the ensemble model means (Tables S1 and S2). The thin lines are the results using the CRU TS 3.1 data, illustrated spatially in Figure 2c. The gray shading represents the spread in projected June, July, August warming between 1980 to 1999 and 2080 to 2099 (based on the MMD-A1B models) for South Asia [*Christensen et al.*, 2007].

be overestimated in regions of thick debris cover (Text S1). We quantify the potential impact of this effect below.

[12] Important additional uncertainty arises from errors in the climate input data, which is the focus of this study. In the absence of a dense network of weather stations, we use gridded climate data from Climate Research Unit Time Series 3.1 (CRU TS 3.1) [*Jones and Harris*, 2011], WorldClim [*Hijmans et al.*, 2005], and Aphrodite [*Yatagai et al.*, 2009] to provide a suite of possible estimates of regional climate across the glacierized region (see Table S2 and Text S1). These are commonly used datasets in high Asia. The combination of possible climate estimates used here provides some test of the uncertainties associated with choice of climate data used.

[13] For the given mass balance model and assumptions outlined above, the area-averaged, net mass balance is -1.4 ± 0.6 m/yr (Table S1). The lower range of the mass balance estimates is within the range of estimates from other mass balance studies in the Himalayas [e.g., *Bolch et al.*, 2012]. Importantly, this implies that the Bhutanese glacierized area is considerably out of balance with the recent climatology, or in other words, even if no additional warming were to occur, the glacierized area of Bhutan will decrease in order to reach steady state (mass balance equal to zero) with mean climate. We calculate the change in area required to reach steady state with recent mean climate and the current mean mass imbalance by stepwise removing the 250 m × 250 m glacierized grids that have the most negative mass balance until the regionally integrated mass balance is equal

to zero (see Text S1 for more details). Consistent with the approach above, this provides again the minimum change of Bhutan's glacierized area required to reach steady state with modern mean climate, yielding a decrease of 40 ± 19% over the next decades, in the absence of any additional climate change (Figure 2c and Table S1). In steady state, this minimum area loss results in an annual glacial meltwater flux decrease by 71 ± 20%. The 95% confidence intervals provided for the mean changes in mass balance, glacierized area, and melt volume flux (on the order of 25–50%) are due only to the differences in climate datasets, illustrating the sensitivity of these results to the uncertainties in climate data. However, even the most conservative values (Figure 2 and Table S1) show that glaciers in Bhutan are out of equilibrium and that changes in glacierized area and meltwater flux are going to be significant.

[14] In order for the climate to compensate for even the most conservative scenario, precipitation would need to almost double, which is outside of most reconstructions from paleoclimate proxies or from future and past climate model estimates [e.g., *Jiang et al.*, 2011; *Hu et al.*, 2008; *Hewitt and Mitchell*, 1996; *Johns et al.*, 2003; *Christensen et al.*, 2007]. Alternatively, regional cooling would need to occur, which would contradict recent and current climate trends and atmospheric CO_2 increases [*Christensen et al.*, 2007; *X. Yang et al.*, 2011]. Therefore, the current glacier-climate imbalance will near-certainly result in a large reduction in glacierized area and melt water resources in Bhutan.

[15] Given the fact that melt may be over-estimated for heavily debris covered areas (see Text S1), we repeat the mass balance, percent area change, and meltwater flux changes for only the clean glaciers for comparison. Clean glacierized areas are identified using the Landsat imagery and the model applied to only those areas. The most conservative area-averaged net mass balance for only clean glaciers is −0.3 m/yr. In order to reach steady state with this mass imbalance, area must decrease by nearly 6% and annual melt water flux would decrease by at least 25%. The clean glacier scenario is likely a best case scenario, and still represents significant imbalance between the glacierized area and climate. Thus the results for the entire glacierized area and clean glaciers both indicate that, even if no additional warming were to occur, the glacierized area of Bhutan must decrease significantly to reach steady state with recent mean climate.

2.3. Future Climate and Glacier Scenarios

[16] To test the sensitivity of the glacierized area to ongoing warming, we calculate the area and meltwater volume change for each step-wise 0.5°C increase in temperature up to 6°C (Figure 2 and Table S1) (see Text S1) for the full glacierized area. Even for a conservative warming of 1°C, at minimum 25% of the glacierized area will be lost and present meltwater flux will decrease, after an initial melt spike, to 35% of today's value. A warming of 2.5°C, the average projected temperature change for the next century over South Asia [*Christensen et al.*, 2007], results in the loss of more than half of the glacierized area. Importantly, annual meltwater flux becomes negligible.

[17] As for the time-scale of change, most future climate scenarios project 1°C warming within the next 50 years [*Christensen et al.*, 2007]. By this scenario, the estimates of glacier area and meltwater changes in Bhutan are likely going to occur within decades, putting considerable time pressure on acquiring accurate climate data and developing robust glacier models to improve the accuracy of the results presented here. It also highlights the need to clearly identify regions where high efficiency projects to mitigate and adapt to glacier change in the monsoonal Himalayas are needed.

3. Discussion

[18] The lion's share of the glacial melt in the monsoonal Himalayas occurs during the peak summer months, after the spring snowpack melt and before the peak torrential rains of the summer monsoon, so during a period where the regional water supply may depend predominantly on glacier melt. In some regions, the glacial melt creates excess flow in summer, contributing to annual river flooding hazards. In drier regions of the monsoonal Himalayas, decreases in meltwater may lead to significant drying of rivers during summer months [*Immerzeel et al.*, 2010; *Bolch et al.*, 2012]. In consequence, any venture relying on water during peak summer months, including hydroelectric power generation or agriculture, will have to take the potentially large decrease in annual melt water flux into account.

[19] The approaches and results presented here likely carry relevance for the wider monsoonal Himalayas where glacier sensitivity to climate change is similar (Figures 1, middle, and 1, bottom).

[20] Despite the geographically and topographically complex distribution of glaciers throughout South Asia, the conservative scenarios of glacierized area and meltwater flux changes presented here are unlikely to be limited to the glaciers of Bhutan, because numerous glacierized regions of the monsoonal Himalaya are situated in similar geologic, glaciologic and climatic settings. In turn, our results strongly suggest that the conclusions of a recently published remote sensing study by *Jacob et al.* [2012], implying quasi-constant volume of large ice-masses (>100 km^2) in the Himalayas over the last decade, are highly unlikely to be representative of glacier changes in the monsoonal Himalayas in the near future.

[21] Importantly, the large uncertainty that attends any given climate dataset represents a significant difficulty in quantifying glacier mass balance and associated glacier changes in the Himalayas. Even if the uncertainties in glacierized area and the mass balance model were minimized, uncertainty in the climate inputs would represent a significant uncertainty. This is true not only for gridded climate data, but also for weather station data that are extrapolated to glacierized areas. Continued focus on quantifying regional glacier mass balance and climate through the wider Himalaya region is called for to further reduce the uncertainties in glacier sensitivity to climate change.

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