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Glacier Environment and Climate Change in Bhutan—An Overview

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Abstract: Bhutan, a part of the Eastern Himalayas, is a tiny land-locked country hosting rich biodiversity apart from glaciers and snow capped mountains. With ~70% of Bhutan under forest cover, this water-rich country promises to maintain at least 60% of the landmass under forest in perpetuity at any given point of time. Yet, climate change hasn't pardoned this carbon-neutral nation. This article conveys a brief idea about the dent that climate change is leaving on the glacier environment in Bhutan. Bhutan is undergoing warming at an unprecedented rate with evidences suggesting higher warming trends during winter months and also at higher altitudes (>4000 m.a.s.l.) (Sharma et al., 2009). With large diversity of glaciers in the region, comprehensive field-based studies have been difficult due to rugged terrain, political issues and limited manpower and financial aid. Yet several remote sensing based have suggested glaciers in Bhutan are melting. Evidences suggest oldest stage of glaciers in Bhutan extended down to 2600 m.a.s.l. (Mool et al., 2001); whereas in the present day, they are found only above 4000 m.a.s.l. Glacial retreat in Bhutan has been extensive (Karma et al., 2003; Rupper et al., 2012; Naito et al., 2012; Bajracharya and Shrestha, 2011; Bajracharya et al., 2014; Veettil et al., 2015) leading to formation of supra-glacial, pro-glacial and moraine dammed lakes. Particularly in Bhutan and Eastern Himalayas, threat from glacial lake outburst floods is high. With 22 potentially dangerous glacial lakes, there is high risk and hazard potential to the regions lying downstream from outburst. In spite of being an environmentally sustainable country with a conservative approach, Bhutan is at the frontline of climate change-related threats. Future water security is not warranted under this scenario. This can have serious implications on water-dependent-economy of Bhutan that thrives on hydropower, agriculture and tourism. Extensive research is called for in Bhutan, apart from efforts to adapt and mitigate climate change.

Keywords: Bhutan; Eastern Himalayas; Climate change; Glacier retreat; GLOF; Water security.

Introduction

Climate change is real. It can be stated with confidence that recent climate change is being caused due to release of excess greenhouse gases in the atmosphere from anthropogenic activities (IPCC, 2007). In comparison to the global average temperature rise for past 10 decades, regional warming has been high in the Himalayan region (Sharma et al., 2009). Many natural systems have significant impact due to these

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changes, particularly the rise in temperature (IPCC, 2007; Rosenzwig et al., 2008). The Himalayan system that is a water source to 20% of the world's population (Hoy et al., 2016; Immerzeel et al., 2010), is at threat. It is observed that 1.6% and 11.7% of the snow extent has decreased per decade for March and April, and June months respectively in the northern hemisphere since 1960s (IPCC, 2013), leaving a significant impact on the availability of water resources of the downstream ecosystems and causing sea level rise.

Spanning several countries, the Hindu Kush Himalaya (HKH) extends over 2,000 kms from the west to the east. After the poles, the Himalayas hosts the largest mass of snow and ice on the planet and hence is referred to as the Third Pole (Qiu, 2008; Yao et al., 2012a; NRC, 2012). These glaciers are the headwaters to major rivers of Asia that provide water to over a billion people across the continent. The observations of declining glacier mass, enhanced glacier shrinkage and the recent controversies regarding Himalayan glaciers (Yao et al., 2012a) has encouraged several intensive studies in the region. Although multiple studies have been taken up focusing different aspects, there is a need for comprehensive transboundary monitoring and extensive analyses of glacier health in the region. The objective of this article is to briefly highlight the impacts of climate change on glacial landscapes of Bhutan. This, now agreed to be unnatural, phenomenon has left a dent on the glacial ecosystem of Bhutan leading to disturbance in water availability and security. It will be vital to understand how the changing climate scenario will evolve and how it would pronounce its effects of the dependent elements such as glacier melt, water flow and ecosystem survival.

Bhutan, a country atop the eastern Himalayas, is one of the richest countries in terms of water resources and biodiversity. Hosting a huge mass of endemic and key species, this region also houses glaciers and ice caps (Figure 1) that are the source to water in the rivers and ecosystems located downstream. Glaciers and meltwater play an important role in the hydrological cycle in the region ensuring perennial flow of water throughout the region. Bhutan glaciers are among the Himalayan glaciers which are projected to have the highest negative impact on water resources due to climate change. Very minimal field-based studies have been carried out in Bhutan to understand the glacial changes in the changing climate scenario; the reasons can be attributed to the harsh mountainous terrain, lack of trained manpower and financial constraints to carry

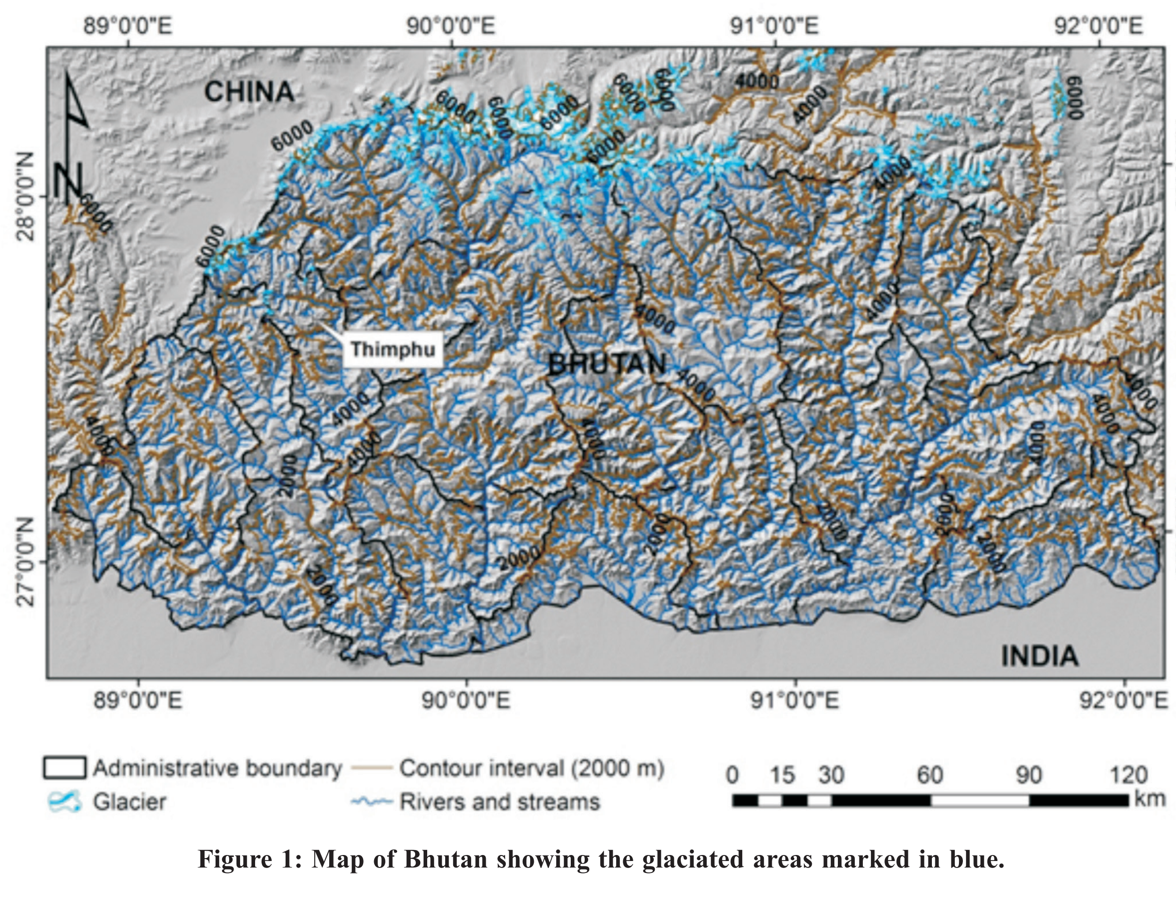

Figure 1: Map of Bhutan showing the glaciated areas marked in blue.

out extensive glaciological research. Among the least developed countries in Asia, the economy of Bhutan relies majorly on tourism, hydropower, and agriculture; all of these sectors directly or indirectly depend on the water resource in the region. Hence, it is important to better understand the glacier behaviour in the region and the impacts climate change would have over it.

Characteristics of Bhutan

Bhutan is a naturally bio-diverse country with an array of ecosystems within a small geographical area of land. Spanning from the low altitudes of Brahmaputra floodplains to the northernmost mountains, Bhutan reaches an elevation of 24,000 ft in some places, thus sub-dividing the country into three physiographical units – *the northern great Himalayan zone*, *the central inner Himalayan mountain and valley zone* and *the Sub-Himalayan foothills zone* or *the lower Himalaya* (Fraser et al., 2001).Due to fluvial activities, valleys in Bhutan are fertile and host agricultural plantations which are majorly for self-sustenance. High valleys up to an altitude of 12,000-14,000 ft are being used for grazing during the summer months. It is a completely landlocked country with highly rugged terrain. Geologically, Bhutan represents the old Tethys sea that got transformed into the complex mountain system during the Tertiary period. Mountains largely consist of gneiss, pre-Cambrian and early-Paleozoic quartzites (Fraser et al., 2001).

Bhutan is one of the least populated countries with a very low population density. Out of 672,425 people in Bhutan as estimated in Bhutan Census 2005, 70% resides in the rural areas (NSB, 2014). Out of the total land area of Bhutan, 70.46% is covered by forests, 10.43% by shrub land, 7.44% by snow and ice cover, 2.93% by cultivated agricultural land and 4.10% are meadows (Figure 2). Built up area accounts for only 0.16% of land cover in Bhutan. Water bodies accounting for a small fraction of 0.72% land cover still play a crucial role in sustenance of Bhutan and its economy. Rest of the land share is taken over by bare land and degraded areas (3.20% and 0.54% respectively). The marshy areas and non-built-up areas occupy 0.1% of land each.

Water is abundant in Bhutan. The water bodies which occupy a minute fraction of total area, undoubtedly, play a crucial role in maintenance of economy of Bhutan. Agriculture was largest contributor to economy of Bhutan in the 1950s. Economy of Bhutan started undergoing a phase of transformation since the 1960s after the establishment of basic infrastructure like roads, transportation, communication and power industries (Whalley, 2004; Uddin et al., 2007). This development has contributed to robust growth of Bhutan's economy, which has transformed to modern wage-based economy from traditional agriculture-based economy (Frame, 2005). The contribution of agriculture to Bhutan's economy has gradually decreased since the transformation (Figure 3), 16.5% in 2015 (NAS, 2016) down from 37% in 1991 (NAS, 2004). Hydropower is the major source of electricity in Bhutan and this sector has gained importance for its growing share in country's GDP (Figure 3 – represented under Electricity and Water); 15% in 2015 (NAS, 2016) up from 9.1% in 1991. The tourism sector has also seen increase in the share over the period of time helping it contribute significantly to the GDP of Bhutan. These three sectors, the agriculture, hydropower and tourism, are major drivers of Bhutan's economy. Construction has also

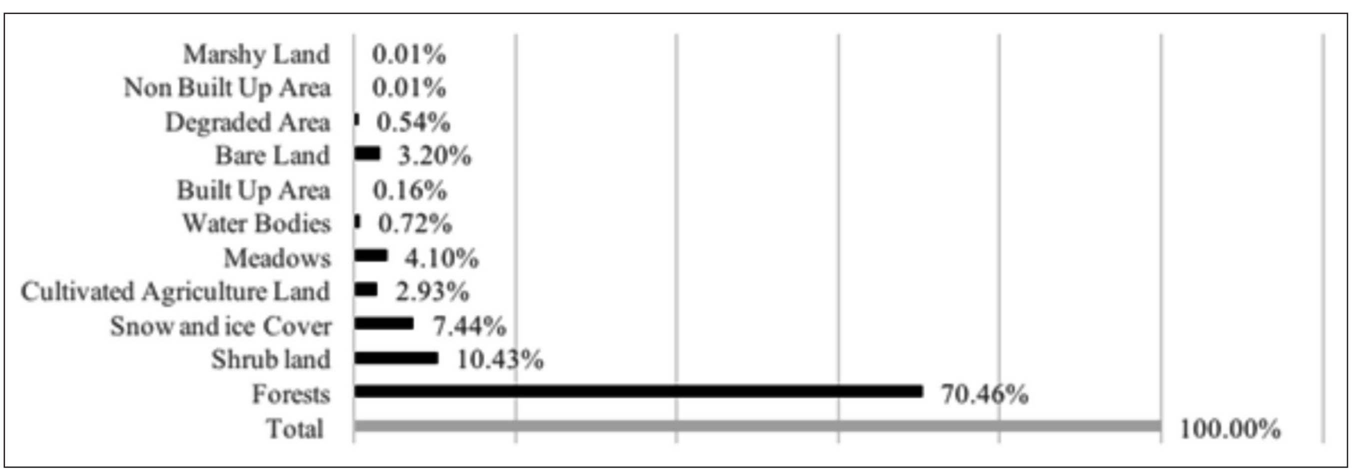

Figure 2: Land cover of Bhutan (Percentage of total land area) (Data Source: LCA, 2010).

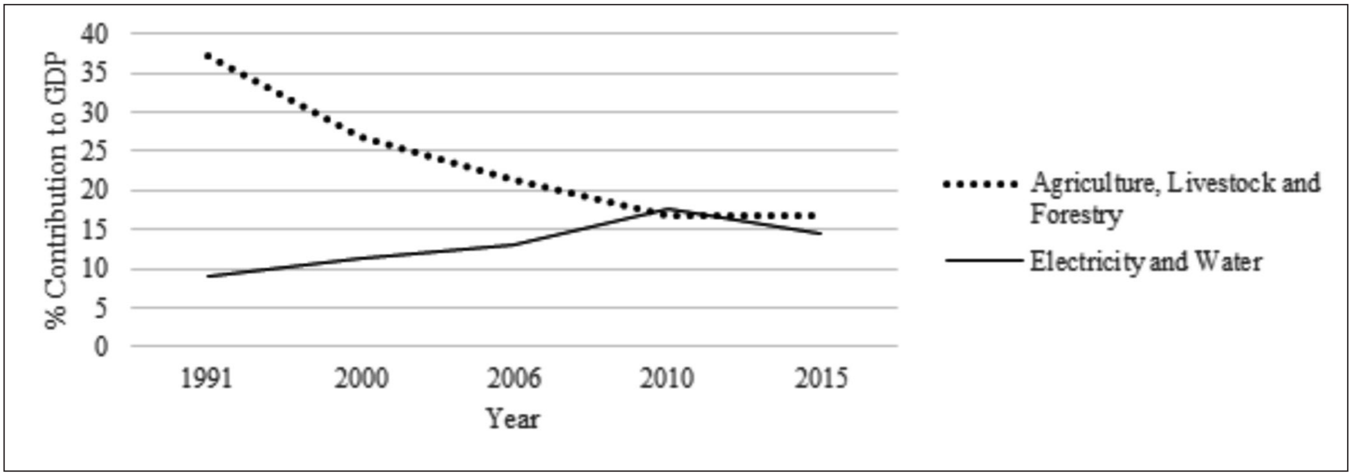

Figure 3: Percentage sectoral contribution to GDP of Bhutan. Data Source: NAS, 2004; NAS, 2012; NAS, 2016.

made significant growth in the past few decades to be recognized as a major contributor. All these sectors are greatly dependent on water resources of Bhutan, which if adversely affected will have a negative impact on the economy of the country.

Weather and climate of Bhutan are controlled by its topography. The mountains rise sharply from the plains, and the entire kingdom of Bhutanis on the windward side of the Indian Summer Monsoon, thus receiving enormous rainfall from the south westerly monsoonal winds. In the south, summers are hot and humid and winters are pleasant; in the central region summers are pleasant with monsoon and winters are moderately cold and in the north climate is generally cold with monsoonal activity (Bhargava, 1995). Precipitation generally declines with rise in altitude in Bhutan (Eguchi, 1997).

Climate Change in Bhutan

Temperatures in the Himalayas and Tibetan plateau have increased considerably in the past few decades (Yao et al., 2006; Xie et al., 2010; Dimri and Dash, 2012; Hartmann et al., 2013). Bhutan is a part of Eastern Himalayas, which has been identified as one of the regions that will have a loud impact of climate change, making it a climate change hotspot. Observations in Bhutan Himalaya have suggested that weather has been increasingly variable in the past few years in Bhutan. While rainfall in the lower altitudes has decreased, in the higher reaches, rainfall has increased with a decrease in snowfall precipitation (Macchi et al., 2011). Another study by International Centre for Integrated Mountain Development (ICIMOD) (Devkota, 2010) on the eastern Himalayas shows that major parts in the region are undergoing warming at a rate of 0.01 °C/yr or more. The study also reports that warming trends are greater (>0.02 °C/yr) on the eastern side of Nepal. Warming during winter months is 0.015 °C/yr greater than the annual average warming trends. The rates of warming increase with elevation rise; regions above 4000 m experience the highest warming. *Hadley Centre Regional Model 2* (HadRM2) simulation for eastern Himalayan region projected an increase in average temperature in 2050s by 2.9 °C; while the *Providing Regional Climate for Impact Studies* (PRECIS) model projected an increase of 2.9 °C and 4.3 °C by 2080s for B2 and A2 scenario respectively. The HadRM2 model projected an increase of 18% annual precipitation by 2050s and the PRECIS model projected an increase of 13% and 34% of annual precipitation for B2 and A2 scenario respectively by 2080s (Devkota, 2010). Generally, the A2 scenario is focused on economic issues and B2 scenario on environmental issues.

Glaciers and Glacial Lakes in Bhutan

Understanding of glacier and glacial lake dynamics of Bhutan region is difficult due to its rough topography and inaccessibility. Using topographic maps from the 1970s, Mool et al. (2001) prepared a glacier inventory for Bhutan Himalaya identifying 677 glaciers that covered an estimated area of 1317 km^2. ICIMOD in 2011 (Bajracharya and Shrestha, 2011) estimated glacial area using satellite images from 2005 ± 3 years and observed that glaciers covered an area of 642 km^2. Similar estimate of glacier area, 642 ± 16.1 km^2, covered by a total of 935 glaciers, was observed by Bajracharya et al. (2014), where satellite images of 2010 were used for analyses. Number of glaciers have increased with time due to fragmentation, while a decrease in glacier area is also observed due to mass loss. The glaciers in Bhutan Himalayas are usually found above 4000 m.a.s.l. However, the oldest stage of glaciers extended down to 2600 m.a.s.l. (Mool et al., 2001). Bhutan Himalayas can be divided into Northern basin and Southern basin. Northern basin constitutes mildly sloping and large accumulation areas of debris-free glaciers characterised by the presence of ice field. They flow with high velocities, with high rates of basal sliding (Kääb, 2005). The southern flank is characterized by river basins and steeper slopes, majority of glaciers are located here and have narrow and steep upper basin (Iwata, 2010). Large valley glaciers are associated with debris-mantled snouts at lower elevations (Mool et al., 2001; Karma et al., 2003; Iwata, 2010). Glaciers of Bhutan belong to the summer accumulation type as much of the accumulation and ablation of glacier mass happens during summer-monsoon months (Ageta and Higuchi, 1984). A recent study by Williams et al. (2016) reveals ~76% at 4500 m to ~31% at 3100 m of glacier meltwater contribution to Chamkhar Chhu river during post monsoon season. While these are estimates only for the Chamkhar Chhu basin, for other basins glacier melt contribution is yet to be analyzed.

Number of lakes in the Himalayan region have gradually increased due to accelerated glacier retreat and increased precipitation. This has also caused rise in lake area (Zhang et al., 2014) and water levels (Zhang et al., 2011; Phan et al., 2012). Mool et al. (2001) identified 2,674 glacial lakes in Bhutan. A large number of glacial lakes have formed (Reynolds, 2000; Quincey et al., 2006; Komori, 2007). There are several moraine dammed lakes (e.g. Luggye Tsho, Thorthomi Tsho, Raphsthreng Tsho, Tarina Tsho, ChubdaTsho, Methatshota Tsho) which initially formed as small supraglacial lakes on the surface of debris-covered glaciers before the 1950s (Ageta et al., 2000; Komori, 2007). So far 22 major GLOF events have taken place in Bhutan Himalayas. The comprehensive study by Komori et al. (2012) has reported 21 major GLOF events based on topographical and sedimentological evidences such as V-shaped trenches, debris fan, and devastated river beds located downstream. 17 events have occurred before 1970 and four events between 1970 and 2015. The most recent outburst took place from Lemthangtsho triggered by outburst of supraglacial ponds located above the headwater of the Lemthangtsho (Gurung et al., 2017). Lemthangtsho was one of the 25 potentially dangerous glacial lakes identified in Bhutan Himalayas (Mool et al., 2001). The frequency of GLOFs seems to have decreased in recent decades which could be due to the disappearance of hanging glaciers and reduced glacier velocity thereby decreasing the probability of outburst triggered by calving into lakes at the snout of the glaciers. Hanging glaciers, glacier advance and subsequent calving were major triggers of the reported GLOFs in the past. In contrast to the decrease in the events of GLOFs, the danger cannot be ignored due to the presence of 22 Potentially Dangerous Glacial Lakes (PDGL) (Gurung et al., 2017). They require frequent assessment and monitoring through satellite data and field work.

Glacier Response to Climate Change

Dyurgerov and Meier (2005) reported that glacier retreat rates in the Himalaya are higher than the global averages, but this was later complemented by findings of Bolch et al. (2012) which states that most of the glaciers in Himalayas are losing mass at rates comparable to glacier retreat rates elsewhere in the world except for glaciers of Karakoram. Though rates are comparable, retreat rates are significant in the recent decades (Bolch et al., 2012), causing many large glaciers to shrink in size and undergo fragmentation, and small sized glaciers to disappear. Karma et al. (2003) studied the glacier shrinkage patterns for 30-year period, between 1963 and 1993. They have observed that almost all glaciers in the Himalayan region are retreating, with retreat rates higher in Bhutan when compared to Nepal. Since glaciers in Bhutan belong to summer-accumulation type where temperatures are warmer and precipitation is more, they have undergone extensive retreat and thinning. Glacier terminus average retreat rates in Bhutan for the said period of 30 years has been 7.36 m/yr, while for Nepal the retreat rates have been 6.61 m/yr; corresponding to increased levels of temperatures during the said period. They further suggest that these differential retreat rates may be due to higher influence of summer monsoon in Bhutan, which is projected to increase in the coming decades enhancing the level of threat. Bajracharya et al. (2014) took up a similar study for 30 years, 1980 – 2010, using satellite data and reported similar trends of glacier retreat in Bhutan Himalayas. Glacier area of about 23.3 ± 0.9%was vacated between 1980 and 2010, with highest loss reported in 1980-1990 period and lowest loss between 1990-2010 period. In this 30-year period, the number of glaciers increased by 14.8%. A combined study of atmospheric warming and glacier retreat was performed by Rupper et al., (2012) for Bhutanese glaciers. Considering the most

Table 1: Consolidated information from recently published studies in Bhutan about glacier retreat rates and glaciated area loss over different time periods using different methods

Study period (years)	*Study area*		*Objectives of the study*	*Method adopted*	*Results*	*References*
1974-2006	Bhutan	Clean ice glaciers (10*)	Mean annual geodetic mass balance	Declassified spy satellite imagery and ASTER data	-0.13±0.06 m w.e./yr	Maurer et al., 2016
		Debris covered glaciers (5*)			-0.19±0.11 m w.e./yr	
		Calving glaciers (6*)			-0.28±0.10 m w.e./yr	
		All glaciers combined (21*)			-0.17±0.05 m w.e./yr	
2003-2014	Ganju La Glacier, Bhutan		Decadal mass balance	Field based glaciological mass balance	-1.12 to -2.04 m w.e./yr	Tshering and Fujita, 2016
1990-2010	Bhutan (with National Boundary of Bhutan before 2007)		Change in total glaciated area	Remote sensing, using Landsat images	-22.56%	Veettil et al., 2015
1980-2010	Bhutan		Change in total glaciated area	Multi-temporal Landsat images	-23.3±0.9%	Bajracharya et al., 2014
1999-2011	Bhutan		Geodetic mass balance	Geodetic mass balance by differencing SPOT5 and SRTM DEMs	-0.22±0.12 m w.e./yr	Gardelle et al., 2013
2003-2008	Eastern Nepal and Bhutan		Specific mass balance	Specific mass balance using laser altimetry	-0.26±0.07 to -0.34±0.08m w.e./yr	Kaab et al., 2012

*Denotes the number of glaciers studied.

conservative scenario of 1°C rise in temperature, 25% of glacierized area in Bhutan will be lost to melting, thereby greatly increasing the meltwater flux for a short period, followed by a decrease of close to 35% of current levels. Considering 2.5 °C rise in temperature over the next century, the modelled results indicate loss of almost 50% of the glacierized area in Bhutan, leading to negligible annual meltwater flux (Rupper et al., 2012). Such modelling results portray the fate of glaciers due to increase in the temperature. As discussed, the glacier areal shrinkages (Rupper et al., 2012; Bajracharya and Shrestha, 2011; Veettil et al., 2015), terminal retreat (Karma et al., 2003; Naito et al., 2006), mass loss (Rupper et al., 2012), surface lowering (Naito et al., 2006; Naito et al., 2012) and glacier fragmentation (Veettil et al., 2015) could be all linked to the changes in the climate parameters. Table 1 displays consolidated information on glacier retreat rates and loss in glaciated area in Bhutan from some of the recently published studies.

Shrinkage and retreat of glaciers is complimented by formation of glacial lakes, which has been reported from Bhutan (Fujita et al., 2008; Komori, 2008). Constant retreat of glaciers has caused four to eight-fold increase in size of glacial lakes in the last three decades. Five large lakes have shown remarkable growth in the water area (Komori, 2008). Formation of glacial lakes has been more common in Bhutan than in any other region (Richardson and Reynolds, 2000) where GLOFs pose a major threat. Luggye Tsho and ChubdaTsho are two among the many glacial lakes in Bhutan that have been studied for their growth and vulnerability to causing an outburst flood. Bechung Glacier which lies in the Lunana region has a lake developing in front, called the Bechung lake. Figure 4 shows the lake's development during 1990-2015; it can be clearly observed that the lake has grown considerably in size while the glaciers have been retreating.

Mool et al. (2001) identified 24 potentially dangerous lakes over the entire region of Bhutan Himalayas. Most of these lakes have undergone multiple fold rise in glacier area and length as shown in Table 2 for three of the potentially dangerous glacial lakes of Lunana region. Breaching of these potentially dangerous lakes can be catastrophic, as it was in 1994 after the breach of Luggye Tsho, causing flash floods and damages to lives and property downstream. Under the changing climate scenario where the glaciers are undergoing an extensive retreat, it can be expected that the glacial lakes will continue to grow, becoming a significant threat to downstream ecosystems. With the projected rise of meltwater flux, water input to glacial lakes will increase,

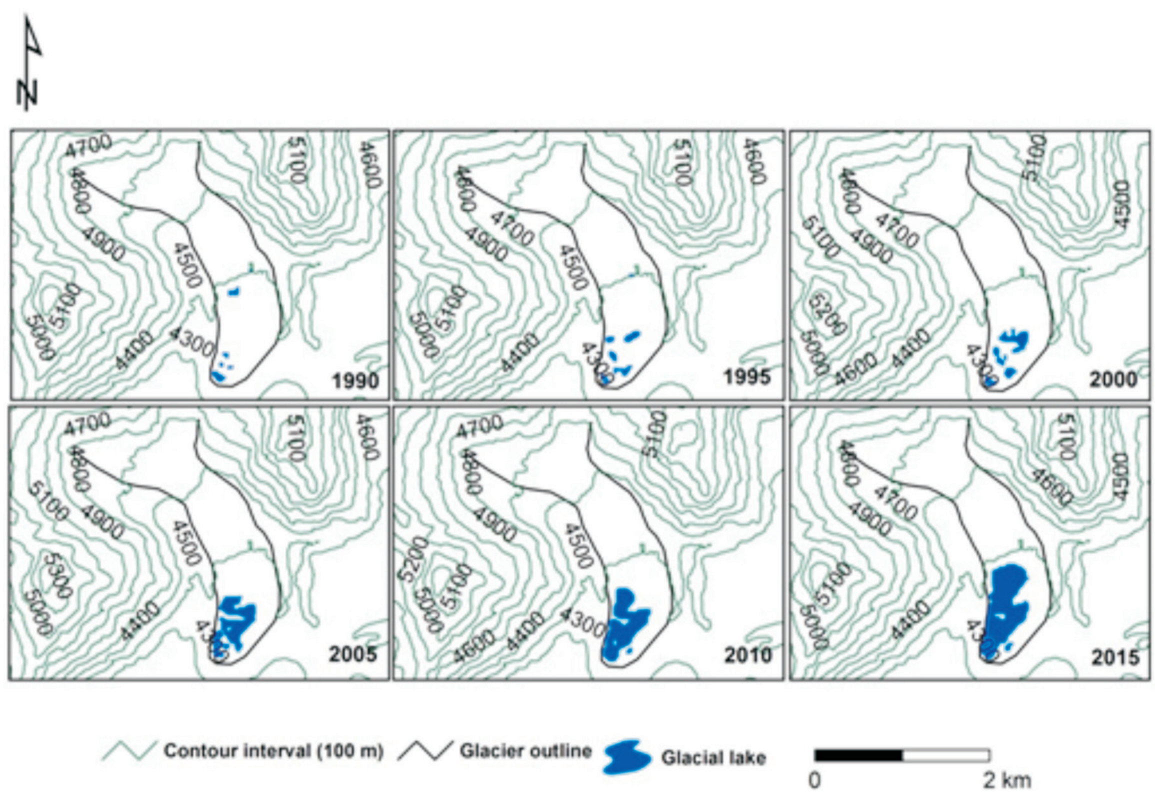

Figure 4: Periodic expansion of Bechung Lake in Lunana region.

Table 2: Lake area changes of three potentially dangerous lakes of Lunana region in Bhutan

Name of the lake	*Lake first appeared in year*	*Lake area (km^2)*				
		1968	*1978*	*1988*	*1998*	*2001*
Raphstreng Tsho	1958	0.16	1.02	1.18	1.23	1.23
Thorthormi Tsho	1967	0.02	0.13	0.38	1.2	1.28
Luggye Tsho	1967	0.02	0.16	0.84	1.06	1.12

Source: Bajracharya et al., 2007

enhancing its vulnerability to GLOF. Hence, extensive monitoring and measures to lower the water levels by different methods is warranted from time to time.

Impacts of Climate Change on Other Sectors in Bhutan

The country has always been conservative in approach towards development. Among the many, there is a law in Bhutan that demands that at any given time, at least 60% of land cover in Bhutan should be occupied by forests; which currently is roughly 70%, much more than what is mandated. Plastic bags are banned all over Bhutan, and a whopping 26% of land in Bhutan is protected by reserves and national parks (Frame, 2005; Planning Commission, 1999). Forest carbon sequestration in Bhutan is about three times larger than national greenhouse gas emissions (NEC, 2011). Inspite of all that, the country is at the frontline of climate change-related threats.

Much of the river systems in Bhutan are glacier fed and receive water from the melt of glaciers; thus these systems will have a profound impact due to climate change and the water levels are projected to decrease in future due to extensive mass loss leaving a threat on various socio-economic sectors of Bhutan. Hydropower, a rapidly growing economic sector, is under threat greatly from climate change. While water levels in the rivers and streams would fall, the GLOFs will also be a threat with possible dam breach that can cause havoc downstream. Glacial hazards such as avalanches and floods will be on rise damaging public and private property downstream all along the way. Providing employment to more than 60% of population (NSB, 2013), agriculture is one of the most important sectors and greatly under threat; as it is vulnerable to even slight rise in temperatures and change in precipitation patterns. The high-value and low-impact tourism industry of Bhutan also thrives directly and indirectly on water resources of the region. Hence the impact on water resources due to climate change will be passed on to the tourism industry of Bhutan as well. Overall, the impact of climate change and vulnerability of different sectors from climate change is very high in the climate change hotspot region – Bhutan.

Conclusion

Climate change is a global phenomenon. Individual efforts will not help mitigate climate change, but a global movement on ensuring better strategies towards mitigation might delay the process of climate change. Studies with robust models have indicated that the glaciers in eastern Himalayan region are temperature sensitive and completely out of balance with the present climatic conditions (Maurer et al., 2016). Hence, even if climate stabilizes in near future, for which possibility is bleak, the glaciers will continue to melt until they attain a balance with surrounding climate. All these factors of climate change have worsened the scenario across the world, calling for immediate attention in the form of better research to understand, better methods to adapt and better strategies to mitigate increasing effects of climate change. Extensive transboundary collaborative research that will involve both remote sensing-based and field-based techniques to understand complex dynamics of glacial behaviour is called for.

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