

# Climate change, cryosphere and impacts in the Indian Himalayan Region

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**Climate change and related impacts over the Indian Himalayan Region (IHR) remains poorly quantified. The present study reviews observed and modelled changes in the climate, cryosphere and impacts related to hazards, agriculture and ecosystems. An increasing temperature trend over the IHR is reported, which over a few locations is found to be higher than the global average. For precipitation, a complex and inconsistent response with considerable variation in the sign and magnitude of change is observed. Future projections show significant warming. Climate-driven changes and impacts are clearly observed. Snow cover has declined since the 1960s, with an enhanced decreasing trend during the 1990s and variable trends since 2000. Glaciers are losing mass and retreating at varying rates since the early 20th century, with an exception over the Karakoram region. An observed heterogeneous response of glaciers to atmospheric warming is controlled by regional variations in topography, debris cover, circulation and precipitation. Initial assessments of permafrost extent of 1 million km<sup>2</sup> across the IHR roughly translate into 14 times the glacier area. Extreme floods represent the most frequent natural disaster in the IHR. Studies have highlighted the significant threat from glacial lakes. Landslides occur in combination with heavy rainfall and flooding, with poor land-use practices such as road-cutting and deforestation being additional drivers. Climate change has also stressed traditional subsistence agriculture and food systems. Improving systematic and coordinated monitoring of climate and related impacts is crucial to contribute to effective climate change adaptation and response strategies.**

**Keywords:** Climate change, cryosphere, glacier, permafrost, run-off.

## Introduction

MOUNTAINS roughly cover 25% of the Earth's surface<sup>1</sup>, with about 915 million people or 12% of the global population living in mountain regions, and 90% thereof in developing countries. Much larger number of people, however, benefit from sustenance provided by mountains to downstream regions. Associated rivers fed by snow and icemelt critically contribute to life-support systems<sup>2-4</sup> as well as the social and economic welfare<sup>5</sup>. Mountain systems are, highly sensitive to climatic variability and change<sup>6-9</sup>. This is especially true for the mountain cryosphere with respect to glaciers, snow and permafrost – all interacting and responding to climate in a distinct way. Recent global assessments from the Intergovernmental Panel on Climate Change (IPCC)<sup>10-12</sup> have documented observed and projected impacts of climate change on the cryosphere<sup>13,14</sup>. The recent Hindu Kush Himalayan Monitoring and Assessment Programme (HIMAP)<sup>15</sup> report provides comprehensive information over the region. Yet mountain regions, and in particular the high mountains, suffer from the scarcity of observational data, and climate models are challenged by the complexities of mountain climate, which is strongly controlled by topography.

The Himalaya and its sub-regions prominently feature in this debate because of their importance for the vast number of people inhabiting these and the downstream regions (Figure 1). This is in contrast to the paucity of data and information available over the region. While the status and changes in the glaciers in Himalaya have been the focus of several studies in recent years<sup>15-17</sup>, some

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other groups have examined the hydrology and associated changes in the region<sup>18–20</sup>. Yet, the broader impacts of changes in climate and cryosphere on ecosystems, people and economy are either scarcely documented or quantified. The Government of India (GoI) recognized this challenge, with one of the National Missions of the National Action Plan on Climate Change (NAPCC) focusing on sustaining the Himalayan ecosystem. For the 12 States falling within the Indian Himalayan Region (IHR), State Action Plans on Climate Change have been developed for implementation. Scientific evidence on observed and projected climate, cryosphere changes and associated impacts is crucial in this context. Here we provide a review on the current state of knowledge on the IHR, focusing on climate (i.e. temperature and precipitation), and all components of the cryosphere (i.e. glaciers, snow and permafrost). In terms of impact, we concentrate on glacier lake outburst and other floods, landslides, hydrological changes and briefly on related agriculture, ecosystem and livelihood impacts. Our primary focus is the IHR, but for some cases such as for the climate, we need to extend beyond the IHR due to the importance of the context of the greater Himalayan region.

## Changes in climate and cryosphere over the Indian Himalaya

### *Present and future warming*

Warming over the Himalaya has exceeded the global average rise in temperature<sup>11</sup> having different annual/seasonal warming rates over its different sub-regions. Increasing temperature trends of 0.12°C/yr (ref. 21) and 0.4°C/yr (ref. 22) are reported over the middle Mountains and Himalaya respectively. An increase of 0.03°C/yr from 1985 to 2002 in Bhutan in the Eastern Himalayas is also reported<sup>23</sup>. Pre-monsoon warming of 2.7°C/yr due to aerosol interaction has been found along the Himalayan slopes<sup>4</sup>. Higher winter warming is reported over Nepal Himalaya<sup>21</sup>, western/northwestern Himalaya<sup>24,25</sup>, upper Indus basin (UIB)<sup>26</sup> and the Tibetan Plateau<sup>27</sup>. The increasing trend in maximum temperature is higher than that of minimum temperature over the western Himalaya<sup>25,28</sup>, but increasing warm nights over western Himalaya<sup>28</sup> are also an indication of the rising trend in minimum temperature. A greater warming rate at higher elevation zones over Nepal Himalaya<sup>21</sup> and greater warming with increasing altitude over India and Pakistan Himalaya<sup>24</sup> has been documented. While more warming over higher mountains than low elevations at the same latitude has been reported<sup>29</sup>, more recent research has found that such elevation dependent warming (EDW) is not consistent across different mountainous regions, with the Tibetan Plateau being a region where EDW has been found<sup>30</sup>. Regional heterogeneity of EDW is considered to be a function of various physical temperature-relevant

processes such as snow albedo and surface-based feedbacks, water vapour changes and latent heat release, aerosols and others<sup>31</sup>. Generally, decreasing number of meteorological stations with increasing elevation limits better understanding in the IHR.

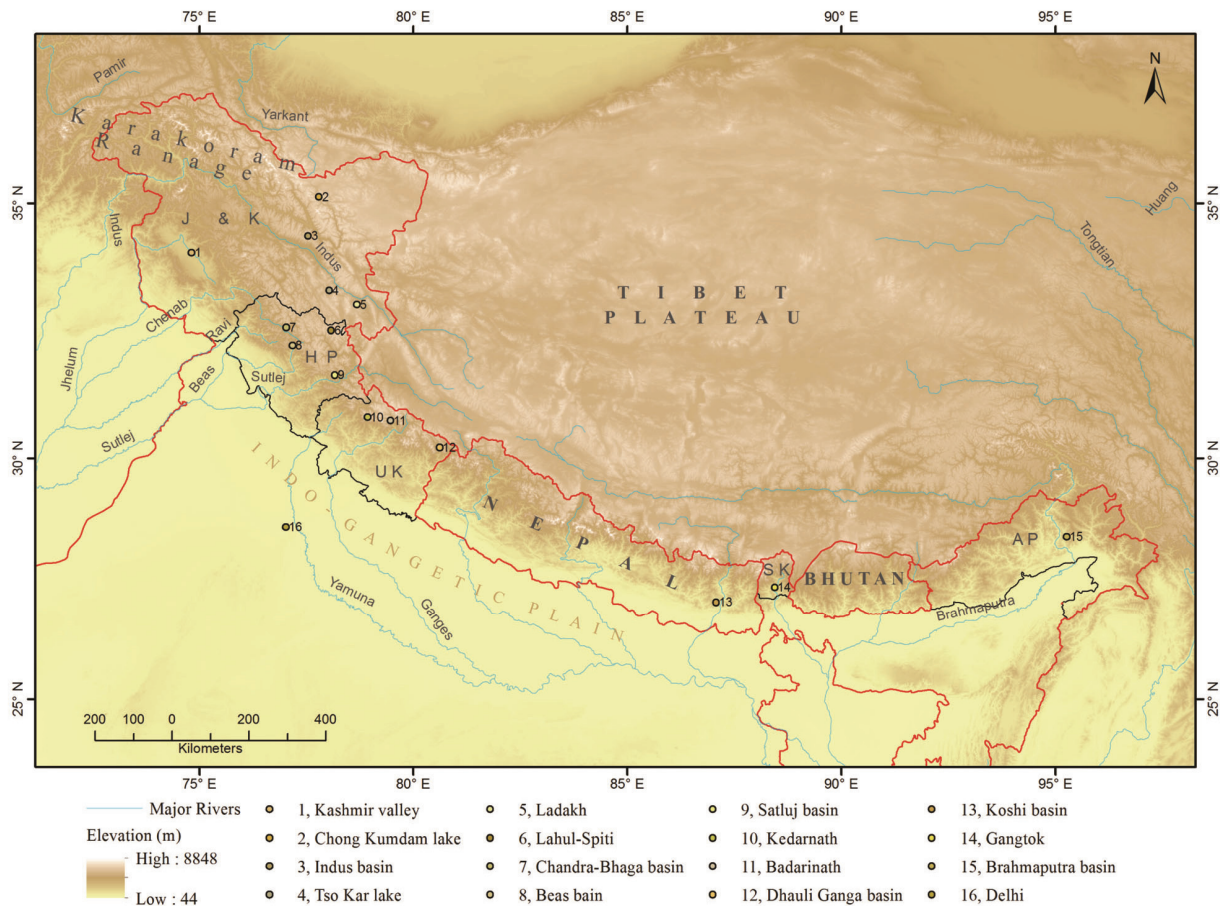
Future climate projections from the Coordinated Regional climate Downscaling Experiment-South Asia (CORDEX-SA) show an underestimation of mean monthly or annual temperature. However, winter warming trend over the IHR has been observed<sup>32</sup>. Increasing maximum temperature during winter reported from various models<sup>33</sup> agrees with earlier findings<sup>34</sup>. In addition, minimum and maximum temperatures show a decreasing trend with elevation. CMIP3 and CMIP5 models studies for the period 1960–2000 suggest an increase in annual average temperature over eastern (2.5°–4°C) and western Himalaya (2.8–4.5°C) by the end of 21st century<sup>35</sup>. Over the Tibetan Plateau a projected rise of 4°C is estimated by 2100 compared to 1950 (ref. 25).

The projected increase in winter temperature from the present to the end of 21st century is reported to be 5.4°C under RCP8.5°C over Karakoram and Northwest Himalaya<sup>36</sup>. The increase of projected minimum temperature and warm nights over the southern Koshi basin in the Nepal Himalaya<sup>37</sup> and UIB in the Western Himalaya, will be higher compared to the lower Indus basin (LIB)<sup>34</sup>. Various modelling studies have shown amplified warming with altitude during winter over the Tibetan Plateau<sup>25,30</sup> and the IHR<sup>38–40</sup> under increasing CO<sub>2</sub> concentrations. Supplementary Figures 1–3 show average mean, minimum and maximum temperature respectively, over the IHR based on model results. These results indicate that projected climatological mean and trends of temperature are increasing, thus the climate is moving towards a warmer regime.

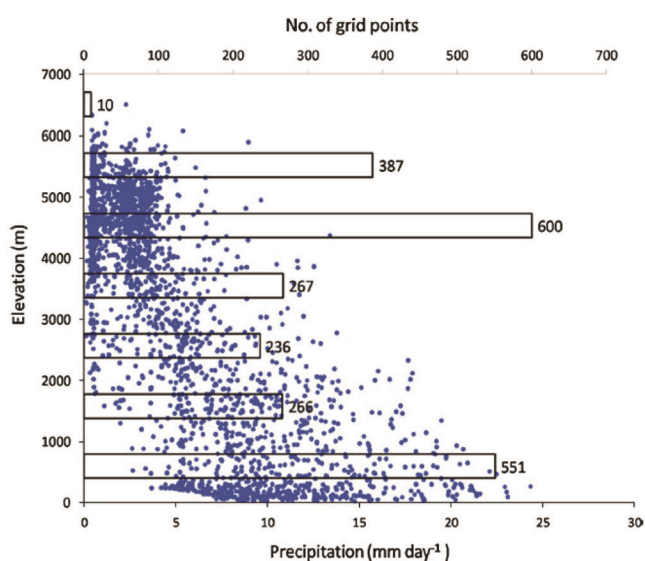
Based on these studies, it can be summarized that both observational and modelling studies show that there are warming trends, although with different rates, along and across the IHR.

### *Present and future precipitation*

The Himalayan folded mountain structure leads to mountain lee wave and Bergeron's seeder-feeder mechanisms<sup>41,42</sup>. Moist orographic interactions modulate precipitation distribution over the IHR<sup>43–45</sup>. Orographic interactions block and force moisture upwards resulting in strong vertical, horizontal and slope-wise precipitation gradients<sup>42,46–48</sup>. Windward sides receive higher precipitation than leeward sides<sup>49</sup>. The uneven distribution of rainfall in the mountains results in differential rainfall trends within small distances, and leads to floods and droughts<sup>45</sup>. Eastern and Central Himalaya receive 80% of the annual precipitation due to the Indian summer monsoon (ISM), whereas the western Himalaya receives ~30% due to western disturbances (WDs)<sup>16,50</sup> which, however, are embedded in the



**Figure 1.** Location of study area with important places referred to the paper. The red line indicates the international boundary of India, while the grey lines indicate the boundaries of Himalayan states in India. J&K, Jammu and Kashmir; HP, Himachal Pradesh; UK, Uttarakhand; AP, Arunachal Pradesh. State of J&K and HP belongs to western Himalaya; UK and Nepal to central Himalaya and SK, Bhutan and AP to eastern Himalaya. Various locations are as well marked for better understanding of the region. The background elevation (ASTER GDEM V2) is obtained from earthexplorer.usgs.gov.



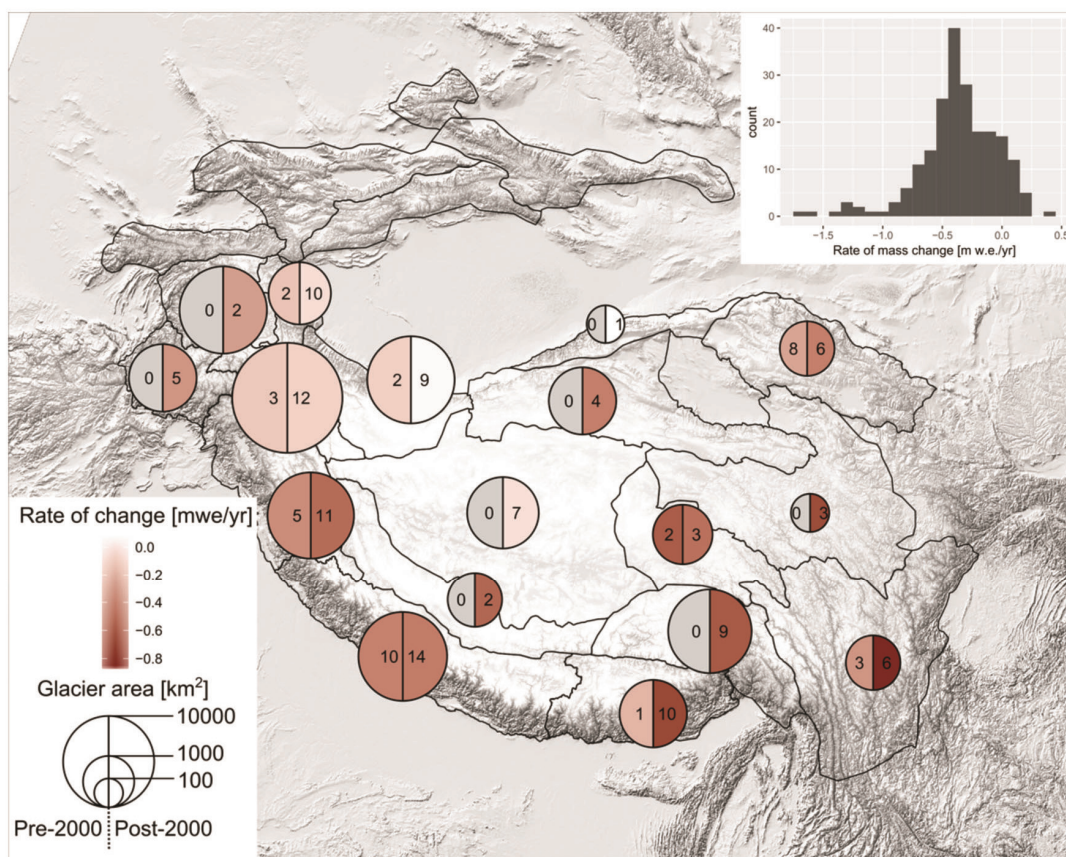
**Figure 2.** Variation in observed monsoonal precipitation with elevation. The bars show the number of grid points at each 1000 m elevation bins<sup>67</sup>.

Indian winter monsoon (IWM)<sup>34,44,51</sup>. The precipitation relevant east–west divide is around the Sutlej valley in the western Himalayas. Catchments towards the east (west) get 70% (50%) annual precipitation due to ISM<sup>49</sup>. Figure 2 shows a modelled elevation-dependent precipitation distributions. It clearly shows that higher elevations receive precipitation within a smaller range and vice versa.

The increase of extreme rainfall events leading to floods seems to be heterogeneous across India, showing a slight decrease in the central and northern parts of the country, and an increase of extreme events in the east and North East of India<sup>52</sup>. An increase of cloudburst events has been furthermore recorded in the Central Himalaya<sup>53</sup>, although limitations associated with the length of observations have to be considered. Increases in extreme rainfall events during the last decades have been associated with an increase in sea surface temperature over the tropical Indian Ocean<sup>54</sup>.

Observational studies show no clear seasonal and annual precipitation trends over the IHR, but regionally some changes are observed. For instance, increased





**Figure 3.** Summary of 164 glaciological, geodetic, and modelling estimates of rates of glacier mass change (m w.e./yr) by glacier region. The arithmetic average of data from all studies pre and post-2000 is shown by the shading of half circles (pre-2000 left, post-2000 right), together with the number of studies available for each period; periods without data are coloured in grey. A histogram of all reported regional mass change rates is given in the upper right (Source: Bolch *et al.*<sup>219</sup>).

average precipitation and significantly decreased light precipitation events are reported for the Hindu-Kush Himalaya (HKH) and the central Indian region<sup>55</sup>, while increased winter precipitation is noted for the Karakoram<sup>35</sup>. Increased precipitating WDs<sup>56</sup>, increasing (decreasing) seasonal winter (summer) precipitation and mild increase in annual precipitation have been found over the Beas basin in Himachal Pradesh<sup>57</sup>, and the Koshi basin in the Nepal Himalaya<sup>46,47</sup>, whereas decreasing monsoonal precipitation has been observed over the Uttarakhand region, Central Himalaya<sup>45,58</sup>. For the Eastern Himalaya annual precipitation is declining, but precipitation has increased during the later phase of the monsoon period<sup>58,59</sup>.

Changes in precipitation extremes are challenging to detect in sparsely equipped mountain areas, but have been found for a number of regions: over the western Himalaya increasing extreme precipitation up to 3000 m and decreasing at higher elevations can be observed<sup>60</sup>. Also, decreased monsoon precipitation over the Hindu-Kush and the western Himalaya, and increasing extreme precipitation over the Karakoram, the western Himalaya and UIB have been reported<sup>55,61–63</sup>, with a periodicity of 2.7 years in extremes<sup>59</sup>.

Regional climate models (RCMs) are not capable of accurately resolving the precipitation distribution over the IHR<sup>41,64</sup>, being sensitive to horizontal resolution, variable topography and heterogeneous land use<sup>43,44</sup>, local atmospheric circulation<sup>44</sup> and extremes<sup>65</sup>. Improved parameterization is able to reproduce extreme wet and dry years<sup>44,64</sup>, and precipitation (snow cover) over the foothills (central Himalayas), but underestimates snow cover over the eastern Himalaya<sup>66</sup>. A wet bias over the western Himalaya<sup>64</sup> and elevation dependency of summer precipitation can be observed<sup>67</sup>. Projected increased monsoonal precipitation<sup>68,70–72</sup>, with increased extreme events<sup>35,63,69</sup> and decreased number of rainy days<sup>69</sup>, is predicted for the end of the 21st century. Increased converging moisture from the Arabian Sea leading to increased ISM precipitation over western Himalaya is projected<sup>68,69</sup> whereas a few researchers reported no specific precipitation trends<sup>63</sup>. Global climate model (GCM) based projections show increased summer (23–35%) and winter (17–28%) precipitation along with precipitation extremes over eastern Himalaya. RCMs depict decreased (increased) projected summer rainfall over the Central (eastern and western) Himalaya<sup>35,68,73</sup>. A model-based distribution of

monsoonal precipitation averaged over the IHR is shown in Supplementary Figure 4.

Based on the above discussion of precipitation distribution and variability, higher elevation regions have a higher drying rate than the lower elevation regions. This is primarily due to orographic forcing in association with increased surface warming. However, in the IHR, the coupling between moisture and temperature is complex and the primary precipitation mechanisms (and thus associated precipitation) are not simple to characterize.

### Glacier change

Estimates of glacier coverage in the IHR vary from ~30,000 km<sup>2</sup> (ref. 74), ~25,000 km<sup>2</sup> (ref. 75) to ~14,000 km<sup>2</sup> based on the most recent version of the Randolph Glacier Inventory<sup>76</sup>. These differences could be attributed to the fact that different datasets and varying methodologies were employed, and monitoring was done over sub-regions with disputed boundaries. Many glaciers in the Himalaya are heavily debris-covered at their tongues. Debris coverage varies between ~5% and ~15% of the glacier area in different regions of the Himalaya<sup>77</sup>. Thick debris cover significantly reduces ice melt and many debris-covered glacier tongues are relatively stable<sup>78,79</sup>. However, these glaciers are also significantly losing mass<sup>80,81</sup>. Compilations pertaining to temporal variations suggest that glaciers in the Himalaya have on the average been degenerating at varying rates since the 19th century, with an exception of the Karakoram glaciers which have shown long-term irregular behaviour<sup>16,17,75,82–84</sup>.

Regional estimates of glacier length changes suggest that the western Himalayan glaciers (Jammu and Kashmir, Himachal Pradesh) experienced enhanced retreat compared to those in the Central (Uttarakhand) and eastern Himalaya (Sikkim)<sup>46,79,85</sup>. However, results of snout monitoring might be biased towards larger glaciers as area change estimates show similar or even higher loss rates in Sikkim compared to Himachal Pradesh<sup>86–88</sup>. Glaciers in the Central (Garhwal) Himalaya show average shrinkage rates<sup>87–89</sup>, while small glaciers in the eastern parts of Jammu and Kashmir (Ladakh) experience relatively little recession<sup>90</sup>. Kraaijenbrink *et al.*<sup>91</sup> have shown that a global temperature rise of 1.5°C will lead to a warming of  $2.1 \pm 0.1^\circ\text{C}$  in High Mountain Asia (HMA), and that about  $64 \pm 7\%$  of the present-day ice mass stored in the HMA glaciers will remain by the end of the century.

Glaciers in the Karakoram have shown individually contrasting behaviour, but on average stable areas<sup>92,93</sup>, and balanced mass budgets since the 1970s<sup>94–96</sup>. Many glaciers in the northwestern IHR are of surge type; hence they periodically speed up and advance rapidly<sup>83,92,97,98</sup>. Surface velocity measurements also reveal that glaciers in

the Karakoram region are almost active at their snouts. The concentration of stagnant glaciers is highest in the Central and eastern Himalaya and can be related to local topography and the presence of debris cover<sup>79,99,100</sup>. In contrast to the Karakoram, clear mass loss was found for almost all other Himalayan ranges. *In situ* measurements indicate moderate mass loss until the ~mid 1990s and an increased mass loss thereafter<sup>16</sup>. However, glaciers in northern Himachal Pradesh (Lahaul-Spiti) might have experienced a period of only slight mass loss during the 1990s (ref. 101). The highest loss rates after ~2000 are seen in the western Himalaya ( $>-0.6 \text{ m w.e. a}^{-1}$ ) followed by the eastern Himalaya including the ranges of Arunachal Pradesh (0.5 to  $-0.6 \text{ m w.e. a}^{-1}$ ), and the least mass loss was found in the central Himalaya (Garhwal in Uttarakhand) ( $\sim 0.4 \text{ m w.e. a}^{-1}$ )<sup>17,102</sup>. However, large variability also exists in glacier mass balances. The observed heterogeneity in the response of glaciers to climate change may be attributed to differences in topography, debris cover and meteorological mechanisms which are regionally unique<sup>47,79,103–105</sup>.

Widespread deglaciation in several regions has led to glacier fragmentation, vanishing of smaller glaciers, formation and enlargement of glacial lakes and increase in supraglacial debris cover<sup>16</sup>. Figure 3 shows the distribution of modelling estimates of rates of glacier mass change.

### Snowcover change

Snow, being one of the most sensitive natural resources, warrants comprehensive temporal assessment of various metrics at different scales. At global scale due to its highly reflective nature, snow greatly impacts climate variations, surface hydrology and energy exchange<sup>5,106</sup>. At the basin scale, seasonal snow cover acts as an important short-term freshwater storage and key input to glacier mass balance, volumetric meltwater run-off modelling and snow hazard prediction studies<sup>10,19,107–114</sup>. Despite its distinct water storage characteristics and immense societal as well as climatic significance, research on snow cover dynamics in the IHR has lagged behind, with limited regional<sup>115–117</sup>, and even fewer basin-scale studies<sup>118–120</sup>.

Data on snow-cover changes over the IHR are scarce. Studies that have examined various mechanisms and processes using satellite-derived snow-cover estimates over the IHR have emphasized the temporal variability of snow cover<sup>121–124</sup>. Studies reporting pre-2000 snow-cover changes in the IHR, though rare, in general point towards a decline after the 1960s which accentuated towards the decade of the 1990s and was also synchronous with an increase in snow melt<sup>115,124,125</sup> (Figure 4). Post-2000, several studies have reported varying rates of snow cover depletion for different regions of the IHR (Figure 4). Using the MODIS eight-day-snow cover product, Gurung *et al.*<sup>116</sup> reported an increasing snow-cover trend of 10–12%

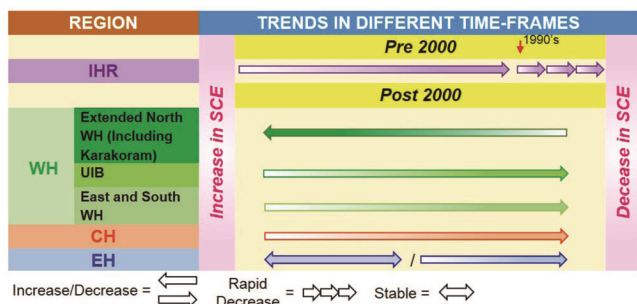
in the eastern and western Himalaya, and a declining trend of 12–14% for the Central region of HKH between 2000 and 2010. For almost the same time period (2000–2011) but at a basin-scale, an increasing snow-cover trend has been found for the Indus basin while decreasing trends have been reported for the Ganga and Brahmaputra basins<sup>117</sup>. Contrasting results have also been reported by Rathore *et al.*<sup>120</sup> for the three sub-basins of Ganga river, where they found a statistically insignificant increase of approximately 1–2% in snow cover in the Central Himalaya (Uttarakhand region). Contrary to Singh *et al.*<sup>117</sup>, but in agreement with Gurung *et al.*<sup>116</sup>, the study by Mukhopadhyay<sup>119</sup> shows that snow cover in the Brahmaputra basin increased by ~32% from 1980 to 2010 and remained stable from 2000 to 2010 (Figure 4). This is attributed to the recent increase in the amount of moisture supplied by moist air mass that incurs into the Brahmaputra valley.

A number of snow-cover monitoring studies have been carried out in the western Himalayan region at the basin scale for varying time-periods ranging between 1988 and 2012 (refs 118, 126–129). Studies spanning the extended western Himalayan regions (including Karakoram) report overall increasing or stable snow cover trends since 2000 (refs 128, 129) except for a decreasing winter snow-cover trend for the UIB<sup>118</sup>. However, studies specifically from the IHR reveal a secular decline in snow-covered areas<sup>126,127</sup> (Figure 4).

*Permafrost*

Permafrost is sediment or bedrock that remains frozen for at least two consecutive years. It mainly occurs in the Arctic<sup>130</sup> and high mountain areas<sup>131–133</sup>. It encompasses around 25% of the land mass of the Northern Hemisphere<sup>134</sup>. A number of studies have shown that permafrost has thawed in the Northern Hemisphere during the past couple of decades<sup>135–138</sup>. However, permafrost studies are sparse in the HKH region in general and the IHR in particular<sup>139</sup>. In the IHR, cryospheric studies are largely

focused on snow and glaciers due to their visible impacts on the environment and resources. More recently, with increasing human stressors and a changing climate, research has begun to focus on the finer details of water resource dynamics in the IHR, to include first studies on subsurface permafrost. Of late, research on permafrost is being initiated by national and international agencies in the IHR. Conclusive evidence of permafrost in the IHR was first gathered from Tso Kar lake area (cold-arid regions of Jammu and Kashmir) in 1975–76 from a study conducted by the Geological Survey of India (GSI)<sup>140</sup>. Boreholes drilled up to 29 m depth had many ice layers interspersed with sandy gravel layers, and annual average temperature of –2°C indicated permafrost area across ~20 km<sup>2</sup>. An initial modelling assessment on a regional scale suggests that the permafrost area in the HKH region could extend up to 1 million km<sup>2</sup>, which roughly translates into 14 times the area covered by glaciers<sup>139</sup>. Studies on rock glacier distribution (a surface landform indicative of permafrost) have also been carried out in the recent past, suggesting that the lower limit of permafrost in the region lies within 3500–5500 m asl (refs 141). Allen *et al.*<sup>142</sup> suggested a permafrost spread of 420 km<sup>2</sup> in Kullu district, located in north-central parts of Himachal Pradesh. The cold-arid region of the eastern parts of Jammu and Kashmir has reported sporadic occurrence of permafrost and associated landforms<sup>139</sup> with sorted patterned ground and other periglacial landforms such as ice-cored moraines. Catchment-scale studies suggest that the ground ice melt component may be a critical water source during dry years in the cold-arid regions of Jammu and Kashmir<sup>143</sup>. This region has large areas of high-altitude wetlands and lakes, and the studies indicated phases of permafrost growth during low lake levels, especially since 5 kyr BP. Continuous development of permafrost mounds and thermokarst features is also inferred during the last 60 years<sup>144</sup>. These studies have firmly established significant permafrost coverage in high mountain areas of the IHR. As glaciers and snow cover are shrinking across most parts of the IHR, in response to changing climate, permafrost areas are also expected to respond in a comparable manner as evident from other similar cryospheric areas globally. Using modelling strategies, Schaphoff *et al.*<sup>145</sup> have shown that vegetation responds more rapidly to warming of the permafrost zone than soil carbon pools due to long time lags in permafrost thawing. Possible permafrost thaw-related impacts have been inferred from other areas which include changing frequency and spatial distribution of landslides, changes to vegetation and runoff patterns, changes in water quality and sediment load in rivers, with important implications for populations dependent on these high-altitude ecosystems<sup>139</sup>. However, long-term monitoring and evidence of such impacts in the IHR are generally lacking. For example, landslides are widespread across the IHR, but interestingly, large high mountain slope failures are rarely documented, and as yet



**Figure 4.** Snow cover trends over the Indian Himalayan region (IHR) in different time frames. Pre-2000 snow cover studies are rare, however, report a generalized decline in snow cover. Post-2000 studies reveal variable snow cover dynamics in different Himalayan regions. WH, western Himalaya; UIB, Upper Indus Basin; CH, central Himalaya; EH, eastern Himalaya; SCE, Snow Cover Extent.



there is no evidence to suggest that thawing of permafrost has any notable influence on mass movement activity in the IHR.

Given that permafrost covers an area 14 times larger than that covered by glaciers, the potential effects of permafrost melting in the IHR need further studies to better understand both immediate and long-term consequences.

## Upstream and downstream impacts

### *Glacier lake outburst floods*

Glacial lakes are a common feature in high mountain regions and are closely associated with regional patterns of glacial response to climate change<sup>111,146</sup>. A first comprehensive inventory of glacial lakes led by ICIMOD (with support of various institutions) revealed around 8790 glacial lakes (1999–2003) across the broader HKH region, from which 1900 were located in the IHR (ref. 147 and references cited therein). In their studies in the IHR, Worni *et al.*<sup>148</sup> and Fujita *et al.*<sup>149</sup> identified 251 and 500 glacial lakes respectively (>0.01 km<sup>2</sup> area). This discrepancy in the results can be attributed to the different thresholds (minimum lake size) and methods (manual or semi-automated lake detection) adopted for the mapping of glacial lakes<sup>150</sup>; Table 1 and Supplementary Table 1. Furthermore, these discrepancies highlight the difficulties in directly comparing different inventories in the region, leading to uncertainties in the baseline data that feed into related adaptation planning and risk reduction strategies.

Across the IHR, the number and area of glacial lakes have rapidly increased as a result of a warmer climate during the last century<sup>146,147,151,152</sup>. According to Nie *et al.*<sup>150</sup>, the number and area of glacial lakes in the IHR on an average has increased by about 8.8% and 14% respectively, during 1990–2015. Glacial lakes connected or located close (less than 2 km) to the glaciers particularly showed enhanced expansion (about 50%)<sup>151,153</sup>, and contributed most (about 83%) to total growth of glacial lakes during 1990–2015 in the region<sup>150,151</sup>. Furthermore, higher growth of glacial lakes is observed on southern slopes of the Himalaya compared to the northern slopes. Longitudinally, highest growth has been observed in central Himalaya, followed by eastern Himalaya, while expansion has been slowest in the western Himalaya<sup>146,150</sup>. The emergence and expansion of new glacial lakes have been mostly concentrated at higher elevations (4800–5700 m), and observed even at 5900 m, indicating enhanced warming at higher elevations<sup>150</sup>. Local assessment studies in the IHR, e.g. Himachal Pradesh<sup>154</sup>, Chandra basin, Himachal Pradesh<sup>155,156</sup>, Chandra-Bhaga basin, Himachal Pradesh<sup>157,158</sup>, Uttarakhand<sup>159</sup>; Alaknanda basin, Uttarakhand<sup>160</sup>; Dhauli Ganga basin, Uttarakhand<sup>161</sup>; Sikkim Himalaya<sup>162–164</sup> confirm the emergence and rapid expansion of glacial lakes across the entire region. While lakes

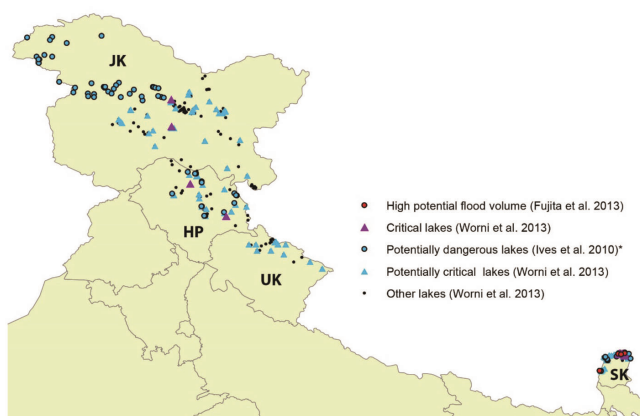
that are no longer fed by glacier melt have remained nearly unchanged in the region<sup>150,151,153</sup>, such lakes can still pose a substantial threat to downstream communities<sup>159</sup>. For example, disconnected lakes at the side of a glacier (ice-marginal lakes) can become unstable where adjacent glaciers are losing mass and thereby removing support from the dam<sup>159,165</sup>. The increasing potential of large ice and rock mass failures into lakes, leading to glacier lake outburst floods (GLOFs), has been demonstrated in the IHR by Allen *et al.*<sup>165</sup>, and hence, an increasing trend in GLOF potential is expected over the 21st century.

In the larger HKH region, the frequency of GLOFs is reported by some authors to have increased around the mid-20th century<sup>152,166,167</sup>. However, in the IHR, GLOFs have been rarely reported<sup>168</sup>, except for the Chong Kumdam GLOFs (1929, 1932, 1933 and 1939) in the UIB<sup>169,170</sup> and the devastating Chorabari GLOF (2013) above Kedarnath in Uttarakhand<sup>165,171–173</sup>. Coxon *et al.*<sup>172</sup> and Sangode *et al.*<sup>173</sup> described evidence of palaeo-GLOFs based on studies of sediment deposits in parts of western Himalaya (Lahaul and Ladakh). Although no GLOF events have been recorded in the eastern Himalaya (Sikkim), field evidence and local knowledge support their past occurrences<sup>164</sup>. The relative lack of GLOF evidence may be explained by the fact that the overall area of glacial lakes and their expansion is comparatively lower in the IHR than other Himalayan regions, e.g. Nepal, Tibet and Bhutan<sup>146,150</sup>. However, there may also be issues of under-recording, with some past GLOF events being recorded as flash-flood events. Several studies provide assessments of current potential GLOF hazards across the IHR, and there is general consensus that the greatest density of critically dangerous lakes occur in Sikkim (Figure 5 and Table 1).

Ives *et al.*<sup>147</sup> reported 70 potentially dangerous lakes in the IHR. By comparison, Worni *et al.*<sup>148</sup> identified 12 critical lakes in the IHR. Local assessment studies reveal even more diverse results as an outcome of differences in the adopted methods (Figure 5 and Table 1). These differences across the studies highlight the need for comprehensive and homogeneous large-scale assessment studies to be undertaken in the IHR. It is important to mention that no earlier assessment studies have identified critical lakes in Uttarakhand (Figure 5 and Table 1). Thus, the processes relating to the Chorabari GLOF above Kedarnath (2013) was clearly not well captured in these previous assessments. Retrospectively, Allen *et al.*<sup>174</sup> analysed the hydrological and topographic characteristics of Chorabari lake, suggesting that such lakes fed entirely from rainfall and snowmelt (without connectivity to glacio-hydrological system), may be most susceptible to breaching during heavy snowmelt and rainfall events<sup>159</sup>. Furthermore, these GLOFs events may become increasingly more important in future, as glacial systems transform into paraglacial systems dominated by fluvial drainage<sup>159</sup>.

**Table 1.** Status of glacial lakes in different states and selected sub-basins in IHR

Area	Number of glacial lakes	Hazard assessment	References
Jammu and Kashmir (Indus Basin)	1400 (>0.01 km <sup>2</sup> )	40 Lakes potentially dangerous	147, 220
	103 (>0.01 km <sup>2</sup> )	2 Lakes critical	148
Uttarakhand	127 (>0.01 km <sup>2</sup> )	0 Lakes potentially dangerous	147, 221
	362	8 Lakes potentially critical	159
	27 (>0.01 km <sup>2</sup> )	0 Lakes critical	148
Dhaulti Ganga basin (Kali Ganga)	7	2 Lakes potentially hazardous	161
Alaknanda basin	45 (>0.01 km <sup>2</sup> )	0 Lake vulnerable and susceptible to outburst	160
Himachal Pradesh	156 (>0.01 km <sup>2</sup> )	16 Lakes potentially dangerous	147, 222
	65 (>0.02 km <sup>2</sup> )	23 Lakes potentially dangerous	154
	45(>0.01 km <sup>2</sup> )	2 Lakes critical	148
Satluj Basin, Himachal Pradesh	40 (>0.01 km <sup>2</sup> )	3 Lakes potentially dangerous	147, 222
Chandra-Bhaga Basin	31	2 Lakes potentially dangerous	157
	26 (>0.005 km <sup>2</sup> )	16 Lakes susceptible to outburst	158
	266(>0.01 km <sup>2</sup> )	14 Lakes potentially dangerous	147, 223
Sikkim	50 (>0.01 km <sup>2</sup> )	8 Lakes potentially dangerous	148
	472 (>0.01 km <sup>2</sup> )	16 Lakes high – medium susceptibility	164
	37 (>0.1 km <sup>2</sup> )	18 Lakes potentially dangerous	163
	–	12 Potentially dangerous	162



**Figure 5.** Comparison of GLOF hazard assessment results conducted across the Indian Himalayan Region (IHR). (\*)<sup>147</sup> is based on underlying inventories compiled for Himachal Pradesh: HP<sup>220</sup>, Uttarakhand: UK<sup>221</sup>, Sikkim: SK<sup>222</sup>, and Indus basin of Jammu and Kashmir – JK<sup>219</sup>. No critical, potentially dangerous or potentially critical lakes have been identified in Arunachal Pradesh.

Given the close proximity of development activities (including roads, dams, hydropower, and tourism infrastructure) to glaciated mountain headwaters across the IHR, a coordinated regional analysis of glacial lake development and associated GLOF risk is urgently required.

### Floods and landslides

Floods and landslides are common across the IHR<sup>175</sup>, and are characterized by extraordinary capacity for fluvial erosion and sediment transport<sup>176</sup>. Triggering processes include intense rainfall associated with the lift of humid monsoon air masses along the Himalayan relief<sup>177</sup>, cloud-burst<sup>39</sup>, and/or snowmelt processes<sup>178,179</sup>. Every year, flood and landslide disasters cause substantial economic

losses and death in populated downstream valleys. Extreme events disrupt infrastructure and can enhance poverty levels within local vulnerable communities<sup>180</sup>. Massive floods can also trigger the outbreak of epidemics<sup>181,182</sup>, and stress crops or ecosystems<sup>183</sup>. Landslides can block river corridors, creating ephemeral lakes with a risk of dam failure causing devastating downstream flooding<sup>184,185</sup>, and provide large amounts of sediment which affects fluvial geomorphology<sup>176</sup>.

Recent disasters in the IHR have highlighted the vulnerability of the population living in the region (Figure 6), most notably with the catastrophic June 2013 events in Uttarakhand<sup>174</sup>, and during September 2014 and March 2015 in Jammu and Kashmir<sup>186</sup>. According to Singh and Kumar<sup>180</sup>, more than 88,000 lives have been lost in India since the 1950s due to floods alone, with an average economical cost of almost US\$ 460 million/yr. Main contributing factors increasing the risk from extreme events include the intensified human use of exposed mountain catchments and downstream flood plains, poor land-use practices such as deforestation and road construction, as well as issues of illiteracy, gender and other social characteristics of the population living in rural zones<sup>187–191</sup>.

Positive trends in flood occurrences have been reported over India during the last few decades<sup>180,192</sup>. Kumar and Santosh found positive, but not statistically significant trends in flood peaks during the last five decades in Himachal Pradesh. This observation agrees with the reconstructed regional tree-ring flood records from the north-central parts of Himachal Pradesh<sup>193</sup>, and the increasing trends observed over the northwestern IHR during the last three decades<sup>194</sup>. Long-term palaeoflood and historical records can provide a stronger basis from which to assess extreme events and associated trends over recent decades. Based on such records<sup>195</sup>, it has been concluded



that the frequency of high-magnitude floods has increased significantly during the last decades of the 20th century across India, while Ely *et al.*<sup>196</sup> reached similar conclusions for the central part of India. In the Kashmir valley, the magnitude of recent floods events (including the devastating events of 2014) is comparable to the extreme events that took place during the last centuries<sup>197</sup>. Multi-centennial palaeoflood records in the central Indian Himalaya indicate an increase in flood frequency during the last two centuries<sup>198</sup>, and show the key role of landslide lake outburst floods (LLOFs). Kale *et al.*<sup>195,199</sup> suggested an analogy between the cluster of large flood events in the recent decades and those identified during the medieval warming period. Overall, while there is some consistency in increasing flood occurrences over the past decades across the IHR, underlying trends in extreme rainfall events are heterogeneous, thus suggesting that other factors such as land-use change likely play a role.

### Hydrology, agriculture and ecosystems

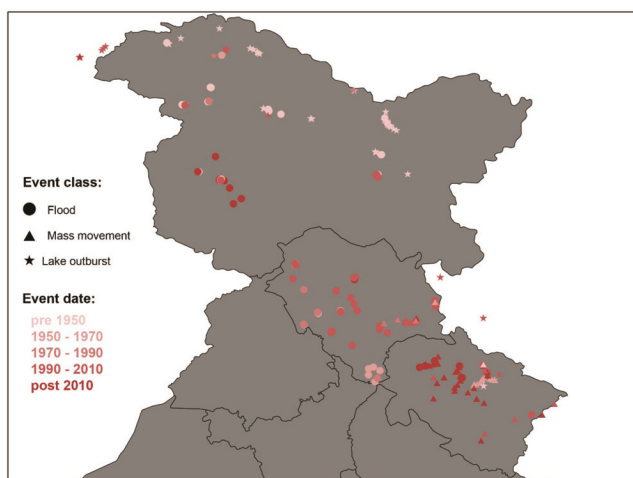
The extent to which changes in climate and the high-mountain cryosphere have and will translate into impacts on run-off and hydrology varies significantly across different basins of the IHR, owing to the contrasting influences of monsoon, snow, and glacier regimes<sup>200</sup>. Whereas earlier assessment reports of the IPCC have generalized the role of the Himalayan cryosphere as sustaining run-off during the summer melt season (as is valid for many other alpine regions of the world); a more complex picture is now evident. The present-day contribution of snow and ice meltwater is considered important to river run-off in the Indus and Brahmaputra basin<sup>19</sup>, with overall relative annual melt contributions of up to 46% and 19% respectively<sup>201</sup>. However, in the monsoon-dominated

Ganges basin, the contribution is more modest at only 9%. Here, meltwater typically only supplements the peak summer flow generated by the monsoon rainfall, although glaciers play an important buffering role during low monsoon years<sup>200</sup>. Under projected future changes in climate, a general increase in runoff is consistently demonstrated across all basins until around the mid-21st century, owing to changes in precipitation and/or accelerated melt<sup>19,20</sup>. However, as glacier area decreases, late spring and summer discharges will eventually reduce considerably, particularly for the Indus and Brahmaputra basins, with potentially severe consequences for food security<sup>19</sup>.

One of the largest sources of uncertainty in understanding past and future changes in run-off relates to the paucity of *in situ* measurements of snow cover<sup>202</sup>. This is crucial, because even where snowmelt contributes only modestly to annual run-off totals, as in the case of the Ganges, the contribution may be significant during the spring months<sup>203</sup>. It is therefore evident that climatic changes – in the form of increasing temperature or decreasing winter precipitation – might have important and as yet poorly quantified impacts on the timing or amount of spring snowmelt, with related implications for sustaining agriculture when other sources of run-off are scarce.

Additional to the impacts of changing cryosphere-related run-off on agriculture, the Himalayan agro-ecosystems have been stressed through higher mean annual temperatures, altered precipitation patterns and frequent extreme weather events<sup>12,21,204</sup>. However, a variety of changes have emerged in traditional resource utilization patterns mainly in response to population growth and rapid urbanization in the region<sup>205,206</sup>. These changes have sharply accentuated pressures on food and livelihood systems through disruption of ecosystem services and collapsing of conventional production systems, where subsistence agriculture in the Himalayan region often constitutes a main source of rural food and livelihood<sup>207,208</sup>.

For example, Xu *et al.*<sup>209</sup> discuss that changes in climate and melting of the Himalayan glaciers are expected to provoke cascading effects in the region, which would affect water availability (amount seasonality), biodiversity (endemic species, predator–prey relations) and ecosystem boundary shifts (tree-line movements, high-elevation ecosystem changes). This will also have environmental and social impacts that likely increase uncertainty in water supply and agricultural production for human populations<sup>209</sup>. Some studies demonstrate that Himalayan production systems are already declining due to various drivers, as reported by Tiwari and Joshi<sup>210</sup> for the Central Himalayas and by Sharma *et al.*<sup>211</sup> for the Sikkim Himalaya. These drivers are often climate change related, but there may be also a nexus to socio-economic developments and/or institutional/governance aspects.



**Figure 6.** Overview of major flood, lake outburst (GLOFs and LLOFs) and mass movements across Jammu and Kashmir, Himachal Pradesh and Uttarakhand. Event locations are based on a review of published literature.

### Synthesis of key impacts

Across the IHR, mean temperature has increased over the past century at a rate that far exceeds the global average, while changes in precipitation show heterogeneous patterns and no clear trends at the regional scale are available. Resulting impacts on the cryosphere are seen in the glaciers and snow cover. Warming has driven widespread shrinkage of glaciers, and corresponding formation and enlargement of thousands of glacier lakes. While catastrophic outburst events from these lakes have been rarely documented in the IHR, several critically dangerous lakes have been identified, and in general, the outburst potential is expected to increase as glacial lakes continue to expand over the 21st century. Snow-cover data are relatively scarce, but nevertheless, a general decline in snow cover has been observed since the 1960s, with more variable trends since 2000. Permafrost, as the subsurface component of the cryosphere, has only recently become a focus of systematic studies in the IHR, and as such, there is currently insufficient evidence to link warming and thawing of permafrost to impacts. Floods and landslides have caused particular devastation across several Indian Himalayan states, and are clearly linked to weather and climate extremes. However, the observed increase in flood and landslide events over the past few decades must be viewed in the broader context of anthropogenic effects such as deforestation, road-cutting, increasing exposure of people and assets, and other poor land-use practices that have become evident. Nevertheless, in some catchments there is evidence that both heavy rainfall-triggering events and flood frequencies have increased over the past several decades compared to earlier period documented in long-term palaeo archives.

In general, changes in climate, when coupled with other socio-economic drivers of changes, are expected to have significant impacts on lives and livelihoods across the IHR (Supplementary Figure 5). For some catchments or villages, this has been clearly demonstrated, with crop failure and loss of agricultural productivity linked to changes in hydrological regimes and impacts of extreme weather (both floods and droughts). Likewise, for specific catastrophic events, far-reaching societal impacts have been documented. For example, following the 2013 flooding in Uttarakhand, which has been linked to extreme rainfall, snowmelt and breach of a glacier lake, there was a 85% reduction in tourism, with an estimated loss of US\$ 1850 million to the State's tourism sector<sup>212,213</sup>. In fact, the impacts of lake outbursts, flash floods and landslides on mountain communities and livelihoods, and transport and energy infrastructure are among the most prominent features of climate and cryosphere changes. The energy sector faces particular challenges. Since India's energy consumption increased by 51% between 2000 and 2010 and is likely to continue to experience substantial growth, further development of hydropower in

the IHR is therefore a national priority. However, both the existing and planned hydropower plants are exposed to potential outburst floods from glacial lakes, often with 10 to >100 lakes upstream of single plants<sup>214</sup>. Some recent disasters have highlighted the transboundary nature of climate impacts in the Himalaya, with LLOFs in 2000 and 2005 originating in Tibet, causing loss of life and substantial economic impact over 100 km downstream in the Indian State of Himachal Pradesh<sup>185</sup>. Hence, monitoring and exchange of knowledge needs to take place across political boundaries, guided by international best practices.

Overall, systematic studies linking climate change in the IHR with downstream impacts and risks are lacking, and studies have been seriously hampered by limitations in monitoring, data availability and knowledge exchange. The sparsity and paucity of hydro-meteorological observations over the IHR are crucial limitations, with most stations located in the valley bottoms, hence unrepresentative of the high alpine areas<sup>26,215</sup>. In addition, the coarse representation of high-altitude topography/mountains in climate models limits understanding of present as well as the future climate, and RCMs are still not capable of resolving precipitation distribution over the IHR due to high uncertainties with increased greenhouse concentration<sup>216,217</sup>. Heterogeneity in results relating to precipitation changes may be attributed to the dataset, methodology, parameterization scheme used in data reconstruction and model simulation, and the domain of study chosen for the analysis. In addition, various model results have defined uncertainties embedded within them, and hence these results need to be used with utmost care for hydrological and glaciological studies. Improvement in model parameterization and increased observational data will thus play an important role in better understanding of rainfall distribution over the IHR and related impacts at present as well in future.

In case of glacier and snow cover studies, *in situ* data need to be strengthened as the basis for improved modelling<sup>202</sup> and further ice-core studies are needed to ascertain past snow-ice evolution. Further, regional estimates on variation of the derived snow parameters (such as snow-line altitude, snow depth and snow-water equivalent) need to be made available for the wider research community, and regional variations in glacier response need to be addressed in detail focusing on causative factors, including regional climate feedbacks relating to black carbon. The World Meteorological Organization lists permafrost as an essential climate variable and some encouraging firm steps have been taken by the national, regional and international agencies to promote permafrost research in the IHR<sup>142</sup>.

### Conclusion and recommendations

Future warming over the IHR is projected to exceed 2.5°C by the end of 21st century, based on 129-yr period

(1971–2099) analysis, even under low greenhouse gas emission scenarios, and consistent increases in monsoon precipitation are expected. Furthermore, studies point out an increase in the occurrence of extreme phenomena such as floods, which when combined with increased human pressure on the natural environment and land-use degradation in the region, have in some instances led to catastrophic consequences.

Limitations in spatial and temporal data coverage, and heterogeneous research methodologies have been identified as key factors leading to uncertainty in observed and projected impacts of climate change in the IHR. In this regard, we recommend improved coordination of research activities across institutional divides, facilitated at the national level through programmes that support and enhance cooperation. India is a world leader in remote sensing technology, and India Meteorological Department has invested significantly in improved monitoring of rainfall over mountain regions. Yet, there are often difficulties for researchers to access such data.

Diversity in research approaches and methodologies, and the critical debate over it, are important, but as seen in the example of GLOFs, different methodologies can lead to vastly different implications for assessed levels of hazard and risk which eventually and occasionally can result in confusion at the level of decision-making. Hence, we call for regular and coordinated reassessment of such threats, to use latest best practices, and furthermore, to account for the fact that environmental and societal baseline conditions are rapidly changing. International collaboration is also seen as important factor for strengthening institutional and scientific capacities in the IHR. For example, mountainous countries such as Switzerland have a long history of responding to the challenges of climate change, therefore experiences may be shared with Indian counterparts on both academic and political levels. Indian science has a broader role to play here, as a leading knowledge partner in the wider Himalayan region. This is particularly important, given that many potential downstream impacts are far-reaching and transboundary in nature. Meanwhile, at the local level, there are opportunities to engage communities directly in the knowledge-generation process to better understand observed changes, timing and magnitude of impacts at the ground level. Such ‘citizen science’ activities are growing internationally, for example, with landslide-mapping initiatives based on smartphone apps. Finally, we highlight the importance of interdisciplinary approaches that are required to truly understand and address complex upland–lowland linkages driven by climate change and additional socio-economic stressors. This applies for all sectors, but undoubtedly becomes most pronounced when considering climate change impacts on rural livelihoods. We recommend bottom-up approaches, starting with a comprehensive framing of social dimensions and identifying potential risks through stakeholder discussions, before

progressing to physical modelling and assessment of how such risks will be influenced by climate and related biophysical impacts<sup>218</sup>.

Considering wide-ranging ways in which societies interact with and depend upon mountain environments, improved systematic and coordinated monitoring across the IHR, feeding into comprehensive and interdisciplinary assessment approaches, will be essential to ensure that local adaptation decisions are evidence-based, take diverse sources of knowledge into account and are well supported by latest scientific understanding.

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