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Divergent Climate Vulnerabilities in South Asia: A Comparative Analysis of India and Bhutan

[*1]**Dr. Sushma Mishra**

[*1]Associate Professor, Department of Sociology, University of Lucknow, Lucknow, Uttar Pradesh, India.

Abstract

This study provides a comparative assessment of climate risks and vulnerabilities in India and Bhutan using document analysis of authoritative scientific assessments, including IPCC reports, national climate profiles, and peer-reviewed literature. Although geographically proximate, the two countries exhibit sharply contrasting climate risk profiles shaped by differences in topography, socioeconomic structures, and development trajectories. India faces a wide spectrum of hazards: extreme heat, monsoon volatility, floods, droughts, cyclones, and coastal impacts driven by projected temperature increases exceeding 3°C under high-emission scenarios and substantial exposure of coastal and agrarian populations. In contrast, Bhutan's vulnerabilities are more geographically concentrated, with warming projected to approach 3–4°C by late century, intensifying cryosphere degradation, glacial lake outburst flood (GLOF) risks, and hydropower sensitivity. While both countries show increasing precipitation variability, the consequences differ: India faces recurrent large-scale inundation affecting millions, whereas Bhutan experiences highly localized but severe flood and landslide risks that threaten critical infrastructure and national revenue. The comparison reveals how biophysical context and economic structure shape differentiated climate vulnerabilities within South Asia, underscoring the need for country-specific adaptation pathways alongside strengthened regional cooperation for shared hydrological and cryosphere-related risks.

Keywords: India, Bhutan, Climate Profile, Comparative Analysis, Climate Vulnerability.

1. Introduction

South Asia is universally recognized as one of the world's most climate-vulnerable regions, experiencing rapid and intensifying climate hazards across temperature, hydrology, and cryosphere systems (IPCC, 2022; World Bank, 2020a). Rising mean temperatures, increasing frequency of extreme heat events, monsoon instability, accelerated glacier retreat, and a growing incidence of compound hazards are reshaping risk profiles in India and Bhutan at unprecedented speed. The Intergovernmental Panel on Climate Change (IPCC) notes that South Asia is already experiencing warming at a pace exceeding the global average, with high confidence that heat extremes, short-duration intense rainfall, and cryospheric changes will intensify through the 21st century (IPCC, 2021).

India's climate risks emerge from its continental scale, geographic diversity, population density, and high dependence on climate-sensitive sectors such as agriculture, fisheries, water resources, and labour-intensive outdoor work (Krishnan *et al*., 2020; World Bank, 2020a) [12]. Extreme heat and humidity threaten human health and labour productivity (Im *et al*., 2017) [9], while monsoon variability produces alternating drought and flood cycles with cascading impacts on water security, food production, and rural livelihoods. Coastal regions are home to more than 170 million people that are additionally exposed to sea-level rise, cyclones, storm surges, and saltwater intrusion (Oppenheimer *et al*., 2019) [16]. India thus faces a multi-hazard landscape, requiring integrated adaptation across scales and sectors.

Bhutan's climate risk profile is more concentrated but uniquely severe. As a high-mountain country in the eastern Himalaya, Bhutan depends heavily on cryospheric stability and hydropower generation is its primary economic pillar (Schneider *et al*., 2021) [24]. Accelerated glacier thinning, proglacial lake expansion, and unstable moraine-dammed lakes significantly increase the probability of Glacial Lake Outburst Floods (GLOFs), which threaten downstream settlements, critical infrastructure, and national energy security (Bajracharya *et al*., 2020; Bolch *et al*., 2019) [1, 2]. Steep terrain further magnifies landslide and flash-flood risks during intense monsoon rainfall. While Bhutan has relatively strong governance readiness and environmental protections, its narrow economic base and limited fiscal space heighten systemic vulnerability to climate shocks.

Despite their contrasting geographies and socio-economic contexts, India and Bhutan share interconnected hydrological and climate risks. Changes in Himalayan cryosphere and upstream hydrological patterns influence downstream river basins, flood regimes, and water availability across borders (Pritchard, 2019) [18]. Increased frequency of extreme events such as GLOFs, cloudbursts, and landslides has amplified the need for coordinated monitoring, transboundary early warning systems, and integrated basin-scale planning.

This paper provides a detailed comparative assessment of climate hazards, exposure, vulnerability, and adaptation needs in India and Bhutan. Using credible scientific assessments and global climate datasets, it synthesizes evidence on emerging climate patterns and identifies actionable adaptation pathways. Section 1 introduces the regional context, while Section 2 examines the dominant climatic drivers shaping risk in South Asia. Together, these sections establish the scientific and policy basis for deeper country-specific analysis in later sections.

2. Regional Climate Context (South Asia)

2.1. Climatic Drivers and Regional Trends

South Asia's climate is shaped by the interaction of the South Asian monsoon system, the warming Indian Ocean, Himalayan cryosphere dynamics, and land–atmosphere feedback regimes (Roxy *et al.*, 2017; IPCC, 2021) [22]. The region has warmed by approximately 0.7°C since the early 20th century, while extreme heat events have increased in frequency, intensity, and duration (World Meteorological Organization [WMO], 2023) [34]. Projections under intermediate (SSP2-4.5) and high (SSP5-8.5) scenarios indicate accelerated warming across the subcontinent, with dangerous wet-bulb temperatures threatening human survivability in low-lying, humid regions (Im *et al.*, 2017; Matthews *et al.*, 2017) [9, 13].

A critical driver of regional variability is the rapid warming of the Indian Ocean, which has warmed at a rate faster than the global ocean average (Roxy *et al.*, 2015) [21]. This warming weakens monsoon circulation, alters rainfall distribution, intensifies marine heatwaves, and contributes to stronger tropical cyclones in the Bay of Bengal and Arabian Sea (Murakami *et al.*, 2017) [15]. The resultant monsoon instability is characterized by longer dry spells punctuated by short, intense rainfall bursts that has amplified the frequency of both droughts and floods (Gadgil *et al.*, 2021) [7].

i). Himalayan Cryosphere Transformation

The Hindu Kush Himalaya (HKH) region, spanning Afghanistan to Myanmar, is warming at nearly twice the global average (Bolch *et al.*, 2019; Wester *et al.*, 2019) [2, 35]. South Asia relies on meltwater from HKH glaciers that feed major rivers such as the Ganga, Brahmaputra, and Indus. Current trends include:

- Rapid glacier mass loss since the late 20th century
- Formation of new proglacial lakes behind unstable moraines
- Rising probability of GLOFs (Bajracharya *et al.*, 2020) [1]
- Shifts in streamflow seasonality, threatening hydropower, irrigation, and urban supply

These changes underpin severe risks for Bhutan and northern India, where hydrological regimes depend on glacier melt, snowpack, and monsoon interaction.

2.2. Increasing Frequency of Extreme Events

South Asia is projected to experience some of the deadliest heat stress conditions globally (Im *et al.*, 2017) [9]. Urban heat islands compound baseline warming, creating acute health and productivity impacts. Observational studies reveal a threefold increase in widespread extreme rainfall events over central India (Roxy *et al.*, 2017) [22]. The thermodynamic effect of warmer air holding more moisture, combined with monsoon perturbations, has intensified both riverine and flash floods (Mukherjee *et al.*, 2018) [14].

Monsoon rainfall deficits, groundwater over-extraction, and warming-driven evapotranspiration contribute to recurrent drought cycles. South Asia is already home to several of the world's most water-stressed countries (UNESCAP, 2021) [27]. The Bay of Bengal produces some of the world's most powerful cyclones; warming sea-surface temperatures and moisture-rich atmospheres have increased cyclone intensity (Murakami *et al.*, 2017) [15]. Combined with sea-level rise of 3.7 mm/year (WMO, 2023) [34], coastal megacities such as Kolkata, Mumbai, and Chennai face escalating flood risk.

2.3. Compound, Cascading, and Systemic Hazards

The interaction of heatwaves, droughts, floods, and cryospheric change increasingly produces **compound events**, where simultaneous or sequential stressors amplify societal impacts (Zscheischler *et al.*, 2018) [37]. Examples include:

- Heat → crop failure → food price shocks → rural distress migration
- Drought → weakened dams → extreme rainfall → catastrophic floods
- Glacial melt → landslide lakes → GLOF → downstream multi-sector disruption

IPCC AR6 identifies South Asia as a region with high systemic vulnerability due to the coupling of climate hazards with socio-economic precarity, dense population clusters, and infrastructure deficits (IPCC, 2022).

2.4. Regional Implications

The combined effects of heat stress, hydrological variability, cryosphere loss, and exposure concentration will:

- Increase mortality and disease burdens (WHO, 2021)
- Reduce labour productivity, especially for outdoor workers (Sarkar *et al.*, 2020) [23]
- Undermine agricultural output and food security (World Bank, 2020b)
- Damage critical infrastructure (roads, hydropower, urban drainage)
- Intensify migration, water conflicts, and livelihood volatility

These region-wide transformations create the foundation for the differentiated, country-specific vulnerabilities explored in subsequent sections.

Table 1: Major Climatic Drivers and Trends in South Asia

Climatic Driver	Key Regional Trend	Evidence/Notes
Temperature Rise	~0.7°C regional warming since early 20th century	IPCC (2021), WMO (2023) [34]
Heat–Humidity Stress	Rising wet-bulb temperatures approaching survivability thresholds	Im *et al.* (2017); Matthews *et al.* (2017) [9, 13]
Monsoon Variability	Longer dry spells + short intense rainfall bursts	Roxy *et al.* (2017) [22]; Krishnan *et al.* (2020) [12]
Indian Ocean Warming	Faster warming than global average	Roxy *et al.* (2015) [21]
Cyclonic Activity	Increasing intensity of severe cyclonic storms	Murakami *et al.* (2017) [15]
Cryosphere Decline	Rapid glacier mass loss and lake expansion	Bolch *et al.* (2019) [2]; Wester *et al.* (2019) [35]
Compound Events	Heat–drought, drought–flood, GLOF–monsoon sequences	Zscheischler *et al.* (2018) [37]

Data and Methodology

This study employs a mixed-methods, multi-source research design drawing upon authoritative scientific assessments, global climate projections, empirical studies, and major institutional reports. The methodological foundation follows the IPCC's hazard–exposure–vulnerability–adaptive capacity (HEVAC) framework, which provides an integrative structure for examining how climatic hazards interact with socioeconomic conditions to produce differentiated risks across regions (IPCC, 2022). To capture past and future climate dynamics, the analysis synthesizes evidence from multi-model ensembles derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which projects temperature, precipitation, cryosphere changes, and hydrological shifts under various emissions pathways (Eyring *et al.*, 2016) [5]. These projections are complemented by observational climate datasets, including ERA5 reanalysis, CRU-TS temperature and rainfall series, and long-term records from the Indian Meteorological Department, all of which support trend detection and validation of model outputs (Krishnan *et al.*, 2020) [12].

Understanding sectoral and social impacts requires drawing from multiple disciplinary sources. Agricultural vulnerability is assessed using climate–crop modelling studies and national-level food system analyses by the World Bank (2020) and Food and Agriculture Organization (FAO, 2021) [6]. Cryosphere change, glacial retreat, and GLOF risk assessments are based on high-resolution satellite observations, glacier mass-balance studies, and regional inventories compiled by ICIMOD and recent Himalayan glaciology research (Bolch *et al.*, 2019; Bajracharya *et al.*, 2020) [2, 1]. Heat stress impacts rely on wet-bulb temperature projections and empirical studies that document reductions in labour productivity and increased heat-related mortality in South Asia (Im *et al.*, 2017; Sarkar *et al.*, 2020) [9, 23]. Infrastructure and hydropower vulnerability assessments draw on hydrological modelling and sedimentation research relevant to high-mountain river systems (Zheng *et al.*, 2021) [36].

The analytical process integrates three layers of evidence. First, physical hazard characterization identifies key climatic stresses including extreme heat, heat–humidity coupling, monsoon instability, extreme rainfall events, tropical cyclones, droughts, and cryosphere-driven hazards that are supported by consensus findings from IPCC AR6 and region-specific scientific literature. Second, exposure and vulnerability mapping considers demographic patterns, settlement geography, livelihood dependence, and governance indicators, referencing socioeconomic databases, ND-GAIN readiness metrics, and country-level vulnerability studies (Chen *et al.*, 2015) [4]. Finally, policy and governance assessment draws upon reviews of national adaptation frameworks, disaster management strategies, hydropower governance, and institutional capacity analyses from UN agencies and sectoral reports (UNDP, 2021) [26].

This methodological approach is not without limitations. Climate projections for the Himalaya exhibit higher uncertainty due to sparse observational data, complex topography, and model sensitivity in simulating precipitation extremes (Wester *et al.*, 2019) [35]. Subnational vulnerability data in India and Bhutan also vary in consistency and granularity, limiting fine-scale quantification of exposure. To mitigate these constraints, the analysis prioritizes multi-model ensembles, cross-validates trends across independent studies, and emphasizes high-confidence evidence. The resulting synthesis aims to provide a balanced, scientifically grounded, and policy-relevant understanding of climate risks across India and Bhutan.

3. Climate Hazards in India

India faces one of the world's most complex and diverse climate hazard environments due to its vast geography, dense population, and strong dependence on climate-sensitive sectors. Recent decades have seen a marked intensification of extreme heat, with heatwaves becoming longer, more frequent, and more severe. Combined heat and humidity produce dangerously high wet-bulb temperatures, particularly in the Indo-Gangetic Plain and coastal regions, where several districts are projected to breach human survivability thresholds under high-emission scenarios (Im *et al.*, 2017; Matthews *et al.*, 2017) [9, 13]. These conditions pose severe risks to public health and significantly diminish labour productivity, especially among outdoor workers in agriculture, construction, and transport (Sarkar *et al.*, 2020) [23]. Urban areas experience amplified risks because of heat island effects and limited green infrastructure, making heat adaptation one of India's most urgent priorities.

Monsoon variability further complicates India's climate risk profile. Shifts in the timing, distribution, and intensity of rainfall have increased the occurrence of both droughts and floods. Central and eastern India have experienced a notable rise in short-duration extreme rainfall events, driven by atmospheric warming, moisture flux changes, and Indian Ocean warming (Roxy *et al.*, 2017) [22]. These events lead to severe flooding, particularly in major river basins, and overwhelm urban drainage systems in rapidly growing cities such as Mumbai, Chennai, and Hyderabad. Conversely, extended dry spells and rising evapotranspiration intensify drought conditions in peninsular India, while depletion of groundwater a key buffer during drought periods raises concerns about long-term water security (Rodell *et al.*, 2018) [19]. Together, these patterns highlight the growing instability of India's hydrological systems.

India's 7,500 km coastline faces additional challenges from sea-level rise, intensifying cyclones, storm surges, and salinization. Warmer sea-surface temperatures in the Indian

Ocean have contributed to an increase in the frequency of extremely severe cyclonic storms, particularly in the Arabian Sea, where historically weaker storms are becoming stronger and more unpredictable (Murakami *et al*., 2017) [15]. Low-lying deltas such as the Sundarbans and densely populated coastal cities like Mumbai and Kolkata are highly exposed to compound coastal hazards, raising the stakes for coastal zone management and resilience planning.

In the northern states, Himalayan cryosphere change introduces an entirely different hazard dimension. Accelerated glacier retreat, the formation of unstable glacial lakes, and changing snowmelt patterns create heightened risks of landslides, debris flows, and glacial lake outburst floods (Bolch *et al*., 2019) [2]. These cryosphere-driven hazards pose threats to hydropower facilities, mountain communities, and downstream river basins. Infrastructure development in fragile slopes has increased exposure, making climate-informed land-use planning and hydropower stress-testing essential.

These climate hazards collectively undermine key sectors of India's economy. Agriculture, which provides livelihoods to millions, is affected by heat stress, rainfall variability, pest outbreaks, and water scarcity (Chakraborty & Newton, 2011; World Bank, 2020) [3]. Water resources are strained by groundwater overdraft and declining surface-water reliability. Energy systems face rising cooling demand, hydropower variability, and grid stress. Urban systems struggle with drainage failures, heat stress, and infrastructure bottlenecks (Pathak *et al*., 2022) [17]. India's climate challenges, therefore, are not isolated phenomena but interconnected stresses that require integrated, multisectoral adaptation strategies.

Table 2: Key Climate Hazards and Sectors Affected in India

Hazard	Sector(s) Affected	Representative Impacts
Extreme Heat & Humidity	Labour, health, agriculture, energy	Productivity loss, heat-related mortality, higher cooling demand
Monsoon Floods	Urban systems, transport, agriculture	City flooding, crop losses, drainage failure
Drought	Agriculture, water supply, rural livelihoods	Groundwater depletion, yield loss, migration
Cyclones & Coastal Hazards	Coastal settlements, infrastructure	Storm surges, erosion, infrastructure damage
Cryosphere Change	Hydropower, mountain communities	Landslides, debris flows, GLOF risk
Compound Events	Multi-sectoral	Food price shocks, cascading infrastructure failures

4. Climate Hazards in Bhutan

Bhutan's climate risk landscape is shaped primarily by its high-altitude Himalayan geography and its economic dependence on hydropower. The most critical threat arises from cryosphere change, as Bhutan's glaciers are retreating rapidly due to warming that exceeds the global average (Bolch *et al*., 2019) [2]. This retreat is causing the expansion of glacial lakes, many of which are dammed by unstable moraine walls. As these lakes grow, they increase the risk of glacial lake outburst floods (GLOFs), which can release massive surges of water and debris into downstream valleys. Bhutan has already experienced destructive GLOFs in the past and recent assessments identify several lakes particularly in the Lunana region and the Pho Chhu basin as high-risk sites (Bajracharya *et al*., 2020) [1]. Given the narrow, steep valleys that characterize much of the country, even moderate glacial floods can cause extensive damage to settlements, agricultural land, and critical infrastructure.

Beyond cryosphere hazards, Bhutan experiences frequent flash floods and landslides during the monsoon. Intensifying rainfall, consistent with broader South Asian monsoon instability, triggers slope failures and debris flow that disrupt transport routes, damage hydropower infrastructure, and isolate remote communities (Wester *et al*., 2019) [35]. Landslides are particularly disruptive because Bhutan's road network forms the backbone of its internal connectivity, and transportation blockages affect essential services, emergency response, and trade.

The country's heavy dependence on run-of-river hydropower heightens its economic vulnerability. Hydropower accounts for a major share of national revenue and export earnings, primarily through electricity sales to India. Climate-induced changes in river flow—such as reduced dry-season discharge due to declining glacier melt and increased sediment loads from landslides pose operational challenges for hydropower plants (Zheng *et al*., 2021) [36]. Extreme events such as GLOFs and debris flows can trigger sudden shutdowns, damage turbines, and disrupt power transmission. The long-term sustainability of Bhutan's energy sector thus hinges on addressing both cryosphere and hydrological changes.

Rural livelihoods add another layer of sensitivity to climate hazards. Approximately half of Bhutan's population relies on subsistence agriculture, livestock rearing, and forest resources for income and nutrition (FAO, 2021). Climate variability threatens crop yields through erratic rainfall, increased pest pressure, and soil erosion. Remote high-altitude communities, dependent on seasonal access routes, face heightened food security risks when climate events disrupt connectivity. Warmer temperatures and shifting precipitation regimes also affect Bhutan's biodiversity-rich forests and alpine ecosystems, contributing to species migration, increased forest fire risk, and stress on ecosystem services (Schneider *et al*., 2021) [24].

Overall, Bhutan's climate risks emerge from the convergence of rapid environmental change and structural exposure linked to its geography and economic structure. Although governance systems are comparatively strong, the capital-intensive nature of cryosphere adaptation, the fragility of high-mountain infrastructure, and the reliance on hydropower make Bhutan uniquely vulnerable to climate extremes.

Table 3: Bhutan's Major Climate Hazards and Exposure Pathways

Hazard	Primary Exposure Pathways	Key Vulnerable Assets
Glacial Lake Outburst Floods (GLOFs)	Unstable moraine-dammed lakes; glacier retreat	Hydropower stations, river-valley settlements, bridges
Flash Floods & Landslides	Steep terrain + intense monsoon rainfall	Mountain roads, rural communities, agricultural terraces
Seasonal Flow Changes	Declining dry-season meltwater	Hydropower revenue, electricity exports
Sedimentation Surges	Glacier retreat → increased debris	Turbines, water intakes, run-of-river plants
Temperature Rise	Upslope species migration; forest stress	Ecosystems, biodiversity, alpine pastures

5. Comparative Vulnerability and Exposure: India and Bhutan

India and Bhutan exhibit fundamentally different climate risk archetypes shaped by geography, demographic patterns, and structural economic characteristics. India's vulnerability emerges from its continental scale, dense population clusters, extensive coastlines, and high dependence on climate-sensitive sectors such as agriculture, fisheries, and informal outdoor labour (World Bank, 2020). Exposure is magnified by the spatial concentration of people and economic assets in hazard-prone regions. For instance, more than 170 million people reside in low-elevation coastal zones, while the Indo-Gangetic Plain is home to nearly 500 million people is acutely sensitive to extreme heat, air stagnation, and hydrological variability (Oppenheimer *et al*., 2019; Im *et al*., 2017) [16, 9]. Rural vulnerability remains severe due to reliance on monsoon-dependent agriculture, limited irrigation coverage, and persistent groundwater depletion (Rodell *et al*., 2018) [19]. Urban vulnerability is intensified by informal settlements, inadequate drainage networks, heat island effects, and infrastructure congestion (Pathak *et al*., 2022) [17]. These overlapping exposures make India one of the world's most climate-sensitive nations and create systemic risks that cascade across food systems, health, energy supply, and labour productivity.

Bhutan faces a narrower but more intense risk profile. As a predominantly high-mountain country, Bhutan's population, infrastructure, and economic system are disproportionately exposed to cryosphere-driven hazards, particularly glacier retreat and glacial lake outburst floods (Bolch *et al*., 2019) [2]. The country's steep valley geography funnels landslides, flash floods, and debris flow directly into settlements and agricultural pockets located along narrow river corridors. Hydropower is Bhutan's economic backbone and depends on stable river flows yet is acutely sensitive to changing seasonal discharge patterns, increased sediment loads, and episodic extreme events (Zheng *et al*., 2021) [36]. Hydropower revenues fund much of Bhutan's social services and development spending, climate shocks can translate rapidly into fiscal pressures, macroeconomic instability, and welfare losses. Rural vulnerability is compounded by isolation, limited livelihood diversification, and the reliance of high-altitude communities on road access that is frequently disrupted by monsoon-induced slope failures (Schneider *et al*., 2021) [24]. Although Bhutan's governance system is generally strong and socially cohesive, the capital-intensive nature of cryosphere adaptation such as lake lowering, engineering works, and early warning systems pose significant financial and operational challenges.

Despite their differences, India and Bhutan share important transboundary climate linkages, particularly through the Himalayan river systems that connect upstream cryosphere processes with downstream hydrological exposure. Glacial lake outburst floods originating in the eastern Himalaya can affect downstream populations and infrastructure in India, while shifts in seasonal meltwater contribute to basin-wide changes in water availability, irrigation potential, and flood regimes (Pritchard, 2019) [18]. These shared risks underscore the need for coordinated monitoring networks, interoperable early warning systems, and joint hydrological planning between the two countries.

Climate impacts in both nations are also regressive, disproportionately affecting low-income households and marginalized groups. In India, migrant labourers, smallholder farmers, women, and informal workers bear the brunt of heat stress, flood losses, and livelihood disruptions (Sarkar *et al*., 2020) [23]. In Bhutan, remote mountain communities and subsistence farmers face greater exposure to landslides, food insecurity, and climate-induced isolation (FAO, 2021). These distributional inequalities highlight the importance of embedding equity and social protection mechanisms within climate adaptation strategies.

Overall, India's vulnerability is broad and systemic, spanning multiple sectors and climatic hazards, while Bhutan's vulnerability is concentrated yet severe, shaped by high-mountain geography and economic dependence on cryosphere-regulated hydropower. Understanding these distinctions is essential for designing tailored adaptation strategies that address each country's unique exposure pathways and resilience constraints.

6. Adaptation Strategies and Policy Recommendations

Climate adaptation in India and Bhutan requires multidimensional, evidence-based strategies that reflect each country's unique hazard profile and socioeconomic realities. For India, the scale and diversity of climate risks demand integrated, cross-sectoral interventions capable of reducing exposure while enhancing institutional capacity. For Bhutan, adaptation must prioritize the stabilization of cryosphere-related risks, protection of hydropower assets, and strengthening of mountain community resilience.

In India, a central priority is strengthening heat resilience through the nationwide expansion of Heat Action Plans, accompanied by improved early warning systems, worker safety standards, and urban cooling strategies such as reflective roofing, expanded green cover, and climate-sensitive zoning (Sarkar *et al*., 2020 [23]; Singh *et al*., 2022). Building resilience to monsoon variability requires a combination of nature-based and engineered solutions, including watershed restoration, improved reservoir operations, rainwater harvesting, and urban flood management systems that integrate climate projections into drainage planning (Pathak *et al*., 2022) [17]. Agricultural resilience must focus on climate-smart practices, drought-tolerant crop varieties, improved irrigation efficiency, and scaling of crop insurance schemes with rapid payouts supported by remote-sensing technologies (World Bank, 2020). Strengthening groundwater governance, promoting solar irrigation, and expanding micro-irrigation are critical to mitigating worsening drought risks.

Coastal adaptation strategies in India should combine mangrove restoration, saltmarsh conservation, cyclone-resilient infrastructure, and where necessary, planned retreat from highly exposed zones (Oppenheimer *et al*., 2019) [16]. Disaster management institutions need greater integration with local governments through decentralised planning, real-time risk information, and standardized climate-risk assessments for all major infrastructure investments. Achieving long-term resilience will also require mobilizing climate finance, leveraging blended finance instruments, and fostering private-sector participation in resilient infrastructure and renewable energy expansion (UNDP, 2021) [26].

Bhutan's adaptation priorities are more targeted but technically demanding. Reducing GLOF risk requires robust glacial lake monitoring, engineering interventions such as lake lowering, and expansion of automated early warning systems connected to downstream communities (Bajracharya *et al*., 2020) [1]. Strengthening hydropower resilience demands climate-stress testing of existing and planned facilities, improved sediment management systems, diversified energy portfolios incorporating solar power, and strategic siting of future projects away from high-risk zones (Zheng *et al*., 2021) [36]. Enhancing slope stability through bioengineering, forest restoration, and integrated watershed management can reduce landslide and flash-flood risk during monsoon extremes.

For rural livelihoods, Bhutan must invest in climate-resilient agriculture, improved storage and market access for remote areas, and social safety nets that protect communities during climate-induced disruptions. Ecosystem-based adaptation such as alpine pasture restoration, afforestation, and biodiversity conservation offers co-benefits for tourism, ecosystem services, and long-term resilience (Schneider *et al*., 2021) [24].

Table 4: Priority Adaptation Strategies for India and Bhutan

Country	Priority Area	Recommended Adaptation Action
India	Heat Resilience	Expand Heat Action Plans; worker protection; cooling access
	Water & Flood Management	Aquifer recharge; reservoir optimization; urban flood planning
	Agriculture	Climate-smart crops; irrigation efficiency; index insurance
	Coasts	Mangrove restoration; cyclone-resilient infrastructure; retreat planning
	Urban Systems	Green/blue infrastructure; climate-informed zoning
Bhutan	GLOF Risk Reduction	Lake lowering, barrier stabilization, early warning systems
	Hydropower Resilience	Sediment management; climate stress-testing; diversification
	Slope Stability	Bioengineering, forest restoration, watershed management
	Rural Livelihoods	Climate-resilient agriculture; storage & market connectivity
	Ecosystem-based Adaptation	Alpine pasture restoration; biodiversity conservation

Cross-border cooperation between India and Bhutan is essential for effective climate risk governance. Shared investment in high-altitude monitoring stations, standardized glacial lake hazard assessments, and real-time hydrological data exchange can significantly reduce transboundary disaster risk (Pritchard, 2019) [18]. Joint research programmes, community-based disaster training, and harmonized emergency protocols within shared river basins would further strengthen regional resilience.

Ultimately, climate adaptation in both countries must integrate social equity, institutional strengthening, and long-term planning. India requires broad-based transformation across water, agriculture, urban systems, and coastal governance, while Bhutan needs focused, high-impact investments in cryosphere risk management and hydropower resilience. Both pathways demand sustained financing, science-based policymaking, and inclusive governance to protect vulnerable populations in a rapidly changing climate.

7. Governance, Institutions and Finance

Effective climate adaptation in India and Bhutan depends heavily on the strength, coherence, and responsiveness of governance systems. Although both countries recognize climate change as a national priority, they differ significantly in institutional scale, administrative capacity, and financial resources. India's governance challenge is predominantly one of coordination across multiple administrative layers: central, state, and district. Each holding different responsibilities in disaster management, urban planning, agriculture, and water governance (Government of India, 2019). Fragmented institutional mandates often lead to slow implementation, overlapping jurisdictions, and uneven capacity at the subnational level. While India's national policy framework anchored in the National Action Plan on Climate Change and State Action Plans provides strategic direction, operationalizing these plans requires stronger interdepartmental coordination, predictable financing, and mainstreaming climate risk into infrastructure and development planning (World Bank, 2020). Disaster management institutions have improved since the 2005 Disaster Management Act, but gaps remain in early warning dissemination, local preparedness, and risk-sensitive land-use regulation (UNDRR, 2022).

Bhutan, despite its smaller administrative system, also faces governance constraints but benefits from strong environmental stewardship, centralized planning structures, and consistent commitment to conservation and sustainable development. The country's Gross National Happiness (GNH) framework embeds sustainability and resilience into national planning, enabling a cohesive climate governance system (Royal Government of Bhutan, 2020). However, Bhutan's challenges lie in technical capacity limitations, high reliance on external expertise for cryosphere monitoring and engineering works, and dependence on hydropower revenues that are themselves climate sensitive. The country's limited fiscal base restricts its ability to independently finance major adaptation projects such as glacial lake lowering, hydropower climate-proofing, or nationwide early warning expansion (Schneider *et al*., 2021) [24].

Climate finance represents a critical gap for both nations but manifests differently across them. India requires large-scale, sustained investment to climate-proof infrastructure, diversify energy systems, strengthen agriculture and water resilience, and protect urban populations. Estimates suggest that India needs tens of billions of dollars annually for adaptation alone, far exceeding current domestic and international flows (UNEP, 2022). Mobilizing private finance through blended financing instruments, resilient infrastructure bonds, and regulatory incentives is increasingly essential. Conversely, Bhutan depends largely on external grants and concessional loans from multilateral institutions and development partners. Its adaptation needs are technically intensive but occur at a smaller scale; however, because hydropower revenues are vulnerable to climate-driven fluctuations, Bhutan faces long-term fiscal risks that threaten its capacity to sustain adaptation investments over time (World Bank, 2021).

Institutional readiness is further influenced by the availability of climate data, research capacity, and monitoring systems. India has expanding observational networks and growing climate research ecosystem yet still faces challenges in integrating climate projections into local planning, standardizing risk assessments, and ensuring data accessibility across institutions (Krishnan *et al*., 2020) [12]. Bhutan, while making progress, remains constrained by limited high-altitude monitoring stations, sparse long-term datasets, and dependence on regional or international scientific programs for cryosphere data. Enhancing data-sharing agreements—both internally and between India and Bhutan would strengthen early warning systems, hydrological forecasting, and GLOF preparedness (Pritchard, 2019) [18].

Overall, governance and finance shape the feasibility and effectiveness of climate adaptation in both countries. India must strengthen decentralized implementation capacity, climate-sensitive development planning, and private-sector engagement, while Bhutan must secure sustainable financing, invest in technological capacity for cryosphere monitoring, and diversify its economy to reduce hydropower dependency. In both cases, robust institutions are essential to convert climate assessments into tangible resilience outcomes.

8. Research Needs, Monitoring, and Limitations

Despite growing research on climate impacts in the Himalayan and South Asian region, significant knowledge gaps remain that hinder effective adaptation in India and Bhutan. One of the most pressing needs is improved high-resolution climate modelling, particularly for precipitation extremes in complex mountain terrain. Global climate models continue to struggle with simulating monsoon dynamics, cloudbursts, and high-altitude rainfall patterns, resulting in substantial uncertainty in hydrological projections for both countries (Wester *et al*., 2019 [35]; IPCC, 2021). Downscaled regional climate models are improving but require more robust validation against long-term observational data, which remain sparse in the Himalaya (Bolch *et al*., 2019)[2]. Expanding automatic weather stations, glacier mass-balance sites, and cryosphere monitoring networks is essential for producing accurate projections and early warning systems.

Data limitations are especially acute in Bhutan, where high-altitude topography makes instrument deployment challenging and where long-term datasets are extremely limited. Research on glacial lake evolution, sediment dynamics, moraine-dam stability, and cascading GLOF impacts needs significant strengthening. Advanced technologies such as UAV-based mapping, high-resolution satellite imagery, geophysical surveys, and coupled hydrodynamic–geomorphic modelling offer crucial opportunities to address these gaps (Zheng *et al*., 2021) [36].

For India, research is needed on how urbanization, land-use change, and groundwater extraction interact with climate variability to shape local flood and drought risks. Studies on compound hazards such as heatwaves following drought, extreme rainfall after prolonged dry periods, or GLOFs coinciding with monsoon storms are increasingly relevant yet understudied (Zscheischler *et al*., 2018) [37].

Social vulnerability and livelihood sensitivity also require deeper investigation. Climate impacts are regressive and disproportionately affect poor households, women, informal workers, and remote communities. However, data on socioeconomic vulnerability remain inconsistent across districts, particularly in India's rural regions and Bhutan's high-altitude settlements (FAO, 2021). Integrated climate–livelihood models that combine climatic, hydrological, economic, and demographic datasets are essential for designing targeted adaptation interventions. Research on behavioural responses, migration patterns, and social protection efficacy during climate extremes is also crucial for anticipating long-term adaptation needs.

Monitoring systems must be substantially expanded to reduce data asymmetry and support climate-risk management. Both countries would benefit from interoperable hydrological monitoring, transboundary information-sharing, and basin-scale risk assessments that integrate cryosphere data, river discharge, sediment loads, and flood forecasting (Pritchard, 2019) [18]. Improved governance frameworks for data-sharing—especially between India and Bhutan—would significantly enhance early warning systems for GLOFs and downstream flooding.

Finally, this study itself has limitations related to the availability and reliability of existing evidence. Uncertainty inherent in climate projections, gaps in cryosphere data, and uneven vulnerability metrics limit the precision of risk quantification. A focus on consensus scientific findings may underrepresent emerging risks that remain poorly understood. Nonetheless, the synthesis draws on the best available evidence from climate science, hydrology, and socioeconomic research to provide a rigorous, policy-relevant foundation for adaptation planning in India and Bhutan.

9. Conclusion

The climate futures of India and Bhutan, although shaped by contrasting geographies and socioeconomic structures, converge around the urgency of accelerating adaptation before climate risks exceed institutional and economic coping thresholds. India's challenge lies in managing a vast and multi-hazard landscape in which extreme heat, monsoon instability, droughts, floods, cyclones, and coastal change interact with high population density, rapid urbanization, and widespread livelihood vulnerability (World Bank, 2020). Bhutan, by contrast, faces a concentrated but severe set of risks anchored in the rapid transformation of the eastern Himalayan cryosphere, the expansion of potentially unstable glacial lakes, and the sensitivity of its hydropower-dependent economy to shifts in river flow and extreme events (Bolch *et al*., 2019; Schneider *et al*., 2021) [2, 24]. Despite these differences, the two countries share transboundary hydrological systems, cross-sectoral exposure to climate-linked shocks, and vulnerability among rural communities reliant on climate-sensitive livelihoods (Pritchard, 2019[18]; FAO, 2021).

Accelerating climate change—manifested through rising temperatures, intensifying precipitation extremes, shrinking glaciers, and increasingly frequent compound events demand adaptation strategies that are proactive, risk-informed, and equity-focused. For India, this entails transformational reforms across water governance, agricultural systems, urban planning, disaster management, and coastal protection. Strengthening heat resilience, modernizing irrigation and groundwater management, adopting climate-smart agriculture, and integrating climate science into spatial planning represent foundational steps for reducing systemic vulnerability (Krishnan *et al*., 2020; Sarkar *et al*., 2020) [12, 23]. Coastal megacities and low-lying deltas require urgent investments in hybrid protection systems combining nature-based solutions with targeted infrastructure, accompanied by long-term pathways for managed retreat in the highest-risk areas (Oppenheimer *et al*., 2019) [16].

For Bhutan, the path to resilience centres on enhancing cryosphere monitoring, securing glacial lake safety through engineering interventions and advanced early warning systems, and climate-proofing hydropower investments. Diversifying the national energy mix by integrating solar power and strengthening regional energy cooperation with India would reduce fiscal exposure to hydrological variability (Zheng *et al*., 2021) [36]. Building resilience in remote mountain communities requires investments in climate-resilient agriculture, improved connectivity, and social protection systems that can buffer the impacts of prolonged disruptions due to landslides or extreme weather.

Both countries also need strong governance systems capable of integrating climate risk into national development planning. This includes enhanced coordination across institutions, greater investment in climate data and research, and stable climate finance to implement long-term adaptation strategies. International cooperation particularly between India and Bhutan remain crucial for shared glacial monitoring, hydrological forecasting, and transboundary disaster preparedness (Pritchard, 2019) [18]. Globally, climate adaptation finance remains far below what is needed, underscoring the urgency of mobilizing domestic resources, private capital, and international climate funds (UNEP, 2022). Ultimately, India and Bhutan stand at a pivotal moment. With evidence showing that climate impacts will intensify significantly even under moderate emissions pathways (IPCC, 2021), the window for effective, low-cost adaptation is narrowing rapidly. By prioritizing risk-informed decision-making, investing in resilient infrastructure and ecosystems, and centering adaptation on vulnerable communities, both nations can reduce avoidable losses and lay the foundations for long-term climate-resilient development. Acting decisively before 2030 is essential not only for safeguarding people and ecosystems but also for protecting economic stability, social progress, and regional security in a warming world.

References

1. Bajracharya SR, Maharjan SB, Shrestha F, Bajracharya OR, Baidya S. *Glacial lake outburst floods in the Hindu Kush Himalaya: Current status and future potential*. International Centre for Integrated Mountain Development; 2020.
2. Bolch T, Shea J, Liu S, Azam MF, Gao Y, Gruber S, *et al*. The state and fate of Himalayan glaciers. *Science*. 2019;365(6456):495–498.
3. Chakraborty S, Newton AC. Climate change, plant diseases and food security: An overview. *Plant Pathology*. 2011;60(1):2–14.
4. Chen C, Noble I, Hellmann J, Coffee J, Murillo M, Chawla N. *University of Notre Dame Global Adaptation Index: Country index technical report*. ND-GAIN; 2015.
5. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, *et al*. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6). *Geoscientific Model Development*. 2016;9(5):1937–1958.
6. FAO. *FAOSTAT statistical database*. Food and Agriculture Organization of the United Nations; 2021.
7. Gadgil S, Nanjundiah RS, Francis PA. The monsoon system: Changing patterns and future projections. *Current Science*. 2021;120(2):215–226.
8. Government of India. *National disaster management plan*. Ministry of Home Affairs; 2019.
9. Im E-S, Pal JS, Eltahir EAB. Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*. 2017;3(8):e1603322.
10. Intergovernmental Panel on Climate Change. *Climate change 2021: The physical science basis*. Masson-Delmotte V, *et al*., editors. Cambridge University Press; 2021.
11. Intergovernmental Panel on Climate Change. *Climate change 2022: Impacts, adaptation and vulnerability*. Pörtner H-O, *et al*., editors. Cambridge University Press; 2022.
12. Krishnan R, Sanjay J, Gnanaseelan C, Mujumdar M, Kulkarni A, Chakraborty S. *Assessment of climate change over the Indian region*. Springer; 2020.
13. Matthews TKR, Wilby RL, Murphy C. Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences*. 2017;114(15):3861–3866.
14. Mukherjee S, Aadhar S, Stone D, Mishra V. Increase in extreme precipitation events under global warming. *Weather and Climate Extremes*. 2018;20:45–53.
15. Murakami H, Vecchi GA, Underwood S. Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nature Climate Change*. 2017;7:885–889.
16. Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, de Conto RM, Kopp RE, *et al*. Sea level rise and implications for low-lying islands, coasts, and communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University Press; 2019. p. 321–445.
17. Pathak M, Sahai AK, Goswami BN. Urban flooding in India: Emerging challenges and adaptation strategies. *Environmental Research Letters*. 2022;17(9):094012.
18. Pritchard HD. Asia's shrinking glaciers protect large populations from drought stress. *Nature*. 2019;569(7758):649–654.
19. Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoing HK, Landerer FW, *et al*. Emerging trends in global freshwater availability. *Nature*. 2018;557(7707):651–659.
20. Royal Government of Bhutan. *National environment strategy and climate action plan*. Royal Government of Bhutan; 2020.
21. Roxy MK, Gnanaseelan C, Parekh A, Chowdary JS, Sindhu B, Rathore L, *et al*. The curious case of Indian Ocean warming. *Journal of Climate*. 2015;28(2):597–617.
22. Roxy MK, Kapoor R, Murtugudde R, Banerjee P. A threefold rise in widespread extreme rain events over central India. *Nature Communications*. 2017;8:708.
23. Sarkar S, Das P, McDonald R, Tiwari A. Heat stress and human labour productivity in South Asia. *Environmental Research Letters*. 2020;15(11):114060.
24. Schneider F, Huggel C, Mehta M. Cryosphere hazards in Bhutan: Emerging risks and adaptation strategies. *Frontiers in Earth Science*. 2021;9:650283.
25. Singh S, Muzumdar P, Niyogi D. Urban heat risk in Indian cities: Intensification, vulnerability, and adaptation strategies. *Sustainable Cities and Society*. 2022;82:103880.
26. United Nations Development Programme. *Global assessment report on disaster risk reduction*. UNDP; 2021.
27. United Nations Economic and Social Commission for Asia and the Pacific. *Responding to the growing risk of drought in South Asia*. UNESCAP; 2021.
28. United Nations Environment Programme. *Adaptation gap report 2022*. UNEP; 2022.
29. United Nations Office for Disaster Risk Reduction. *Global assessment report on disaster risk reduction 2022*. UNDRR; 2022.
30. World Bank. *Climate risk country profile: India*. World Bank & Asian Development Bank; 2020.
31. World Bank. *South Asia agriculture and climate change: Impact assessment and adaptation options*. World Bank; 2020.
32. World Bank. *Bhutan: Climate change and development report*. World Bank; 2021.
33. World Health Organization. *Climate change and health: Country profiles—South Asia*. WHO; 2021.
34. World Meteorological Organization. *State of the global climate 2022*. WMO; 2023.
35. Wester P, Mishra A, Mukherji A, Shrestha A, editors. *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer; 2019.
36. Zheng G, Bolch T, Shea J. Sediment dynamics and hydropower vulnerability in Himalayan glacier-fed rivers. *Journal of Hydrology*. 2021;598:126468.
37. Zscheischler J, Westra S, van den Hurk BJM, Seneviratne SI, Ward PJ, Pitman A, *et al*. Future climate risk from compound events. *Nature Climate Change*. 2018;8:469–477.