

The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods

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Abstract: *The Greater Himalayas hold the largest mass of ice outside polar regions and are the source of the 10 largest rivers in Asia. Rapid reduction in the volume of Himalayan glaciers due to climate change is occurring. The cascading effects of rising temperatures and loss of ice and snow in the region are affecting, for example, water availability (amounts, seasonality), biodiversity (endemic species, predator-prey relations), ecosystem boundary shifts (tree-line movements, high-elevation ecosystem changes), and global feedbacks (monsoonal shifts, loss of soil carbon). Climate change will also have environmental and social impacts that will likely increase uncertainty in water supplies and agricultural production for human populations across Asia. A common understanding of climate change needs to be developed through regional and local-scale research so that mitigation and adaptation strategies can be identified and implemented. The challenges brought about by climate change in the Greater Himalayas can only be addressed through increased regional collaboration in scientific research and policy making.*

Keywords: alpine ecosystem, cascading effects, climate change, glaciers, Himalayas, water resources

Las Himalaya Se Derriten: Efectos en Cascada del Cambio Climático sobre el Agua, la Biodiversidad y los Medios de Vida

Resumen: *Las Himalaya contienen la mayor masa de hielo fuera de las regiones polares y son la fuente de los 10 ríos principales de Asia. La rápida reducción en el volumen de los glaciares del Himalaya se debe al cambio climático. Los efectos en cascada de la elevación de la temperatura y la pérdida de hielo y nieve en la región afectan, por ejemplo, la disponibilidad de agua (cantidad, estacionalidad), la biodiversidad (especies endémicas, relaciones depredador-presa), cambios en los límites de ecosistemas (movimiento de línea de árboles, cambios en los ecosistemas de elevación alta) y cambios globales (cambios en los monzones, pérdida de carbono del suelo). El cambio climático también tendrá impactos ambientales y sociales que probablemente incrementarán la incertidumbre en las reservas de agua y producción agrícola para poblaciones humanas de Asia. Se requiere desarrollar un entendimiento común del cambio climático por medio de investigación regional y a escala local para que se puedan identificar e implementar estrategias de mitigación y adaptación. Los retos derivados del cambio climático en el Himalaya solo pueden ser abordados mediante mayor colaboración regional en investigación científica y definición de políticas.*

Palabras Clave: cambio climático, ecosistema alpino, efectos en cascada, glaciares, Himalaya, recursos hídricos

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Introduction

The Greater Himalayan region, also known as the Water Tower of Asia, covers approximately 7 million km², the general area of high mountains and plateaus in Central, South, and Inner Asia (Fig. 1) (Qiu 2008; Xu 2008). With a highly heterogeneous geography, the region has great climatic variability and forms a barrier to atmospheric circulation for the summer monsoon and winter westerlies. Average annual precipitation, for example, ranges from <50

mm in the Taklimakan Desert in the northwest to about 11,117 mm in Cherapunji, India, in the eastern Himalayas (Hofer & Messerli 2006). The region's climatic zones contain a rich diversity of species and ecosystems that exist along a pronounced humidity gradient. Vegetation changes from subtropical semidesert and thorn steppe formation in the northwest to tropical evergreen rainforests in the southeastern Himalayas (Schickhoff 2005). Among the 34 biodiversity hotspots, four are located in the Himalayas, including the mountains of Central Asia,

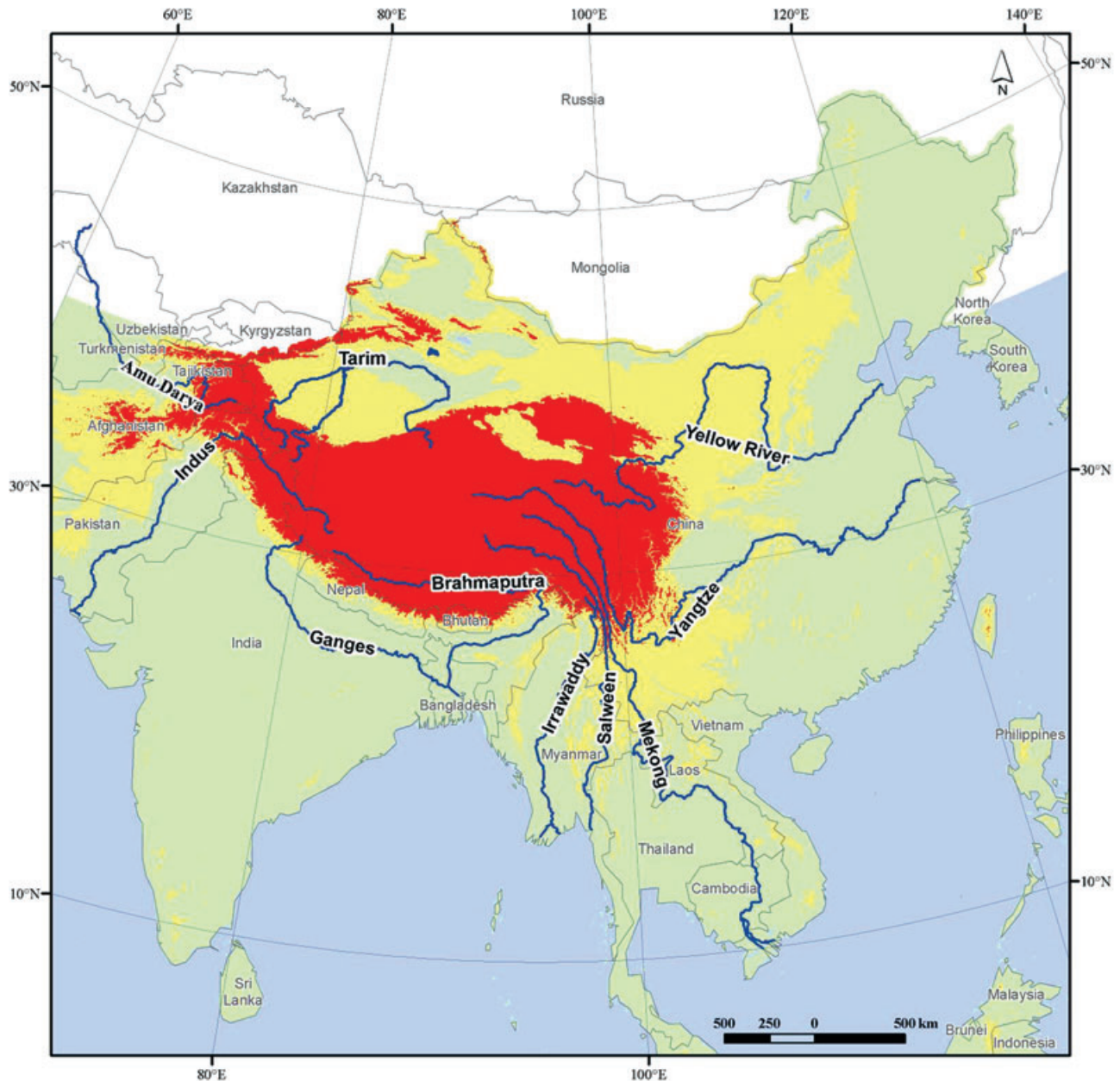


Figure 1. The Greater Himalayan region (alpine, all areas above 3000 m asl; montane, elevations falling between 1000 and 3000 m asl; lowland, elevation below 1000 m asl). The Greater Himalayan region includes all areas with alpine (red) and montane (yellow) zones and has impacts on lowland areas (light green) through 10 rivers.

Himalaya, southwestern China, and Indo-Burma. Beyond biodiversity, the Greater Himalayas are the source of 10 of the largest rivers in Asia: Amu Darya, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, and Tarim. Collectively, these basins provide water for about 1.3 billion people (J. Xu et al. 2007; Bates et al. 2008).

Climate-change impacts are already occurring in the Greater Himalayas (Beniston 2003; Cruz et al. 2007). The most widely reported effect is the rapid reduction of glaciers, which has implications for future downstream water supplies (Yao et al. 2004; Barnett et al. 2005; IPCC 2007*b*; Nogues-Bravo et al. 2007). Ongoing climate change over succeeding decades will likely have additional negative impacts across these mountains, including significant cascading effects on river flows, groundwater recharge, natural hazards, and biodiversity; ecosystem composition, structure, and function; and human livelihoods (Nijssen et al. 2001; Parmesan 2006; Bates et al. 2008; Ma et al. 2009).

Despite these projections, integrated ecological and hydrological studies have not addressed the significance of the Greater Himalayas. We qualitatively examined projected cascading effects of climate change on water resources, biodiversity, and local livelihoods across alpine, montane, and lowland zones to establish a framework to guide future quantitative assessments and appropriate policy responses.

Current Conditions

In the Greater Himalayas, the regional monsoon is a function of distance from the main sources of moisture (the Bay of Bengal, Arabian, and Mediterranean seas), montane orographic influences, and global atmospheric circulation systems (Hahn & Manabe 1975). Currently, however, rainfall measurements are taken primarily in valley bottoms, resulting in significant underestimates of precipitation amounts. Much subbasin variation is masked by current dependence on regional rainfall and temperature data that do not capture local variation.

The high Himalayan and Inner Asian ranges have 116,180 km² of glacial ice, the largest area outside polar regions (Owen et al. 2002; Li et al. 2008). Throughout the Greater Himalayas, water melts from permanent snow and ice and from seasonal snow packs and is stored in high-elevation wetlands and lakes. Melting occurs mainly in high summer, but when this coincides with the monsoon, it may not be as critical for water supply as melting in the spring and autumn shoulder seasons. When the monsoon is weak, delayed, or fails to materialize, melted water from snow and ice limits or averts catastrophic drought (Meehl 1997).

The contribution of snow and glacial melt to the major rivers in the region ranges from <5 to >45% of average flows (J. Xu et al. 2007). Melting snow and ice contribute about 70% of summer flow in the main Ganges, Indus, Tarim, and Kabul Rivers during the shoulder seasons (i.e., before and after precipitation from the summer monsoon) (Singh & Bengtsson 2004; Barnett et al. 2005). The contribution of glacial melt to flows in the Inner Asian rivers is even greater (Yao et al. 2004; Xu et al. 2004; Chen et al. 2006). Indus River irrigation systems in Pakistan depend on snowmelt and glacial melt from the eastern Hindu Kush, Karakoram, and western Himalayas for about 50% of total runoff (Winiger et al. 2005). In western China, about 12% of total discharge is glacial melt runoff, providing water for 25% of the total Chinese population in the dry season (Li et al. 2008; Xu 2008).

Climate also determines biodiversity, and the Greater Himalayas have much higher biodiversity values than the global average (Körner 2004); the eastern Himalayas have the highest plant diversity and richness (Xu & Wilkes 2004; Mutke & Barthlott 2005; Salick et al. 2006). Changes in hydrology can influence biodiversity in a variety of ways; moisture availability governs physiology, metabolic and reproductive processes, phenology, tree-line positions, and the geographic distribution of freshwater and wetland habitats (Burkett et al. 2005; Holtmeier & Broll 2005; Parmesan 2006; Bates et al. 2008; He et al. 2008). In turn, these influences affect the ability of biological systems to support human needs.

Observed and Projected Changes

Temperature and Precipitation

The Greater Himalayas as a whole is very sensitive to global climate change. Progressive increases in warming at high elevations are already occurring at approximately 3 times the global average (Liu & Hou 1998; Shrestha et al. 1999; Liu & Chen 2000; IPCC 2007*a*; Nogues-Bravo et al. 2007). The Intergovernmental Panel on Climate Change (IPCC) has projected that average annual mean warming will be about 3 °C by the 2050s and about 5 °C in the 2080s over the Asian land mass, with temperatures on the Tibetan Plateau rising substantially more (Rupa et al. 2006; IPCC 2007*a*). Given that current discussions about dangerous climate change are centered around increases of 2–3 °C, these temperatures are potentially catastrophic for Greater Himalayan peoples and ecosystems (Anderson & Bowie 2008; Hansen et al. 2008; Solomon et al. 2009).

During the last few decades, the Greater Himalayas have experienced increasing and decreasing precipitation trends (Shrestha et al. 2000; Z. Xu et al. 2007; Ma et al. 2009). Monsoon patterns have shifted, but the picture remains ambiguous (Shrestha et al. 2000). The IPCC

predicts that average annual precipitation will increase by 10–30% on the Tibetan Plateau as a whole by 2080, although rising evapotranspiration rates may dampen this effect (IPCC 2007a).

Glacial Response

Glaciers, ice, and snow cover 17% of the Greater Himalayan region and are receding more rapidly than the world average (Dyurgerov & Meier 2005; IPCC 2007a). The rate of retreat has increased in recent years (Ren et al. 2004; Liu et al. 2006; Zemp et al. 2008). If current warming continues, glaciers located on the Tibetan Plateau are likely to shrink from 500,000 km² (the 1995 baseline) to 100,000 km² or less by the year 2035 (Cruz et al. 2007; Ye & Yao 2008).

Runoff and River Responses

In the Greater Himalayas processes determining the conversion of glaciers, ice, and snow into runoff and downstream flow are complex, but the impact of climate change on river regimes will very likely be profound. Initially, increased melting will result in increased discharge. With time, however, as glaciers completely disappear or approach new equilibria, long-term effects will be increasing water shortages and limited supplies for downstream communities, particularly during the dry season (Fig. 2). Based on current knowledge, the rivers most likely to experience the greatest loss in water availability due to melting glaciers are the Indus, Tarim, Yangtze, Brahmaputra, and Amu Darya (Table 1). Changes have already been observed, but there is still uncertainty regarding when tipping points will be reached.

Water-Related Hazards

Water is not only a source of life, livelihoods, and prosperity but also a cause of death, devastation, and poverty (Grey & Sadoff 2007). Water-related hazards and risks are omnipresent in the Greater Himalayas, and landslides, debris flows, and flash floods are projected to increase in frequency in the uplands (300–3000 m), with riverine and coastal floods likely increasing in the lowlands (<300 m) (Xu & Rana 2005). Significant fluctuations in snow and ice melt will likely result in periodic excessive (short to medium term) or insufficient (long term) water supplies.

Phenology, Pollination, and Predator–Prey Interactions

Changes in plant phenology will be one of the earliest responses to global warming and will likely have serious consequences for both plants and animals that depend on periodically available resources (Corlett & Lafrankie 1998). Phenological patterns are poorly understood in the Himalayas because of the region's richness

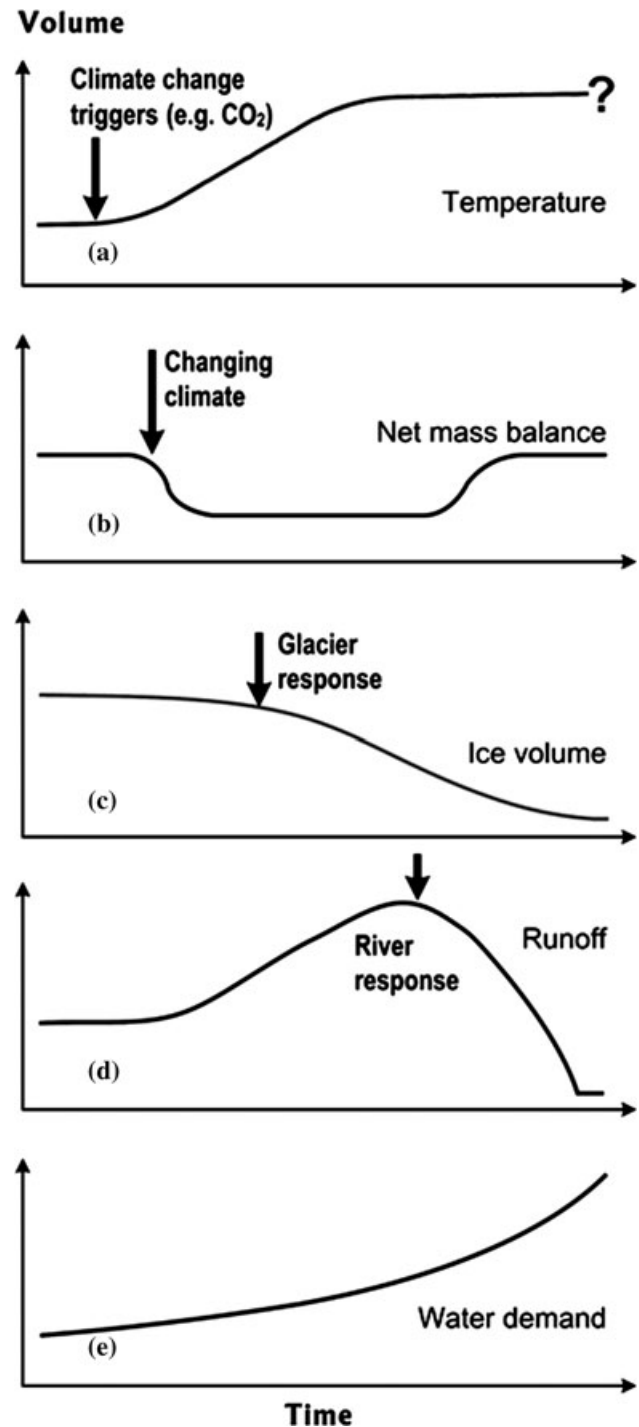


Figure 2. A climate-glacier-water cascade in a mountain region: (a) climate-change affects (b) glacier net mass balance (temporarily negative) which affects (c) ice volume, (d) river runoff, and simultaneously (e) demand for water.

in species and lack of historical data. A total of 517 species of rhododendrons, for example, are found in the Himalayas, roughly two-thirds of all known species in the world (Cox & Cox 1997). Pollinated by wild bees, honey bees, bumble bees, and butterflies, several

Table 1. Predicted hydrological responses of 10 rivers in the Greater Himalayan region to climate change.

<i>River (basin area, km²)</i>	<i>Glacial melt in river flow (%)</i>	<i>Signal of trends</i>	<i>Probable future</i>	<i>References</i>
Tarim (1,152,448)	40.2	wetter in past half century; increasing river flow in some tributaries; 9 tributaries dried up	sharp drop in runoff in glacier retreated catchment, floods occur owing to extreme rainfall	Chen et al. 2006
Amu Darya (534,739)	10–20	increase in precipitation but drop in annual runoff	by 2100, probability of river runoff increase of 83–87% owing to mainly an increase in precipitation	Aizen et al. 1997, 2007
Indus (1,081,718)	44.8	significant increase in rainfall (19%); increase in river flow between 14 and 90%	flow from glacial sub-basin peaks at about 150% of initial flow around 2060; 4% less annual mean flow	Rees & Collins 2006; Singh et al. 2008
Ganges (1,016,124)	9.1	slight increase in rainfall and heavy rain; decrease in rainy days per 100 years	flow from glacial sub-basin peaks at about 170% of initial flow around 2070; 18% less annual mean flow	Rees & Collins 2006; Singh et al. 2008
Brahmaputra (651,335)	12.3	increase in runoff (low flow and high flow); nonsignificant change in precipitation but change in runoff at lower basin	annual flow in Lhasa River increases by 11.3% and monthly maximum flow increases by 45% in 2050s	Gong 2006; Milliman et al. 2008
Irrawaddy (413,710)	small	unknown	unknown	not available
Salween (217,914)	8.8	increase in river flow during monsoon	river-flow decrease over short term (2010–2039) and increase over long term (2070–2099)	Ma et al. 2009
Mekong (805,604)	6.6	increase in precipitation during early monsoon; increase in runoff	rainfall and extreme floods increase	Costa-Cabral et al. 2008; Nijssen et al. 2001
Yangtze (1,722,193)	18.5	increase in precipitation, extreme rainfall and frequent floods; no significant change in runoff	glacier areas in upper Yantze decrease by 11.6% and glacial discharge runoff increases 28.5% by 2050	Su et al. 2005; Wang et al. 2005; Zhang et al. 2006
Yellow (944,970)	1.3	no significant change in precipitation, but significant decrease in runoff	rainfall and evapotranspiration increase; river flow decreases	Xu 2005; Milliman et al. 2008; Nijssen et al. 2001
17.4 (average)				

species of rhododendrons are now flowering a month earlier than normal. Rising temperatures will strongly influence plant reproduction, timing of leaf flush and flowering, and activities of flower-visiting animals in monsoonal Asia (Corlett & Lafrankie 1998). The flowering of most alpine species is also significantly influenced by the pace of snow melt (Kudo 1991). Alpine plants and flower-dependent animals may be particularly vulnerable to climate change due to disruptions in pollinator relationships.

The large decrease in the length of dry season predicted for much of the Greater Himalayas is likely to have a direct impact on plant phenology. In the low-elevation tropical Himalayas, inadequate dry period or intensity may fail to trigger flowering. A shortened dry season may also disrupt herbivore populations during the main period of leaf expansion. Brown locust (*Locustana pardalina*) outbreaks, for example, are believed to be associated with climate variability (Todd et al. 2002). Historical plagues of the high-elevation Tibetan migratory locust (*Locusta migratoria tibetensis*) are closely related to droughts (Chen & Zhang 2008). Grasshopper survival is associated with soil type and adequate topsoil mois-

ture (Ni et al. 2007). Spiders also play important roles in limiting prey populations, but rising temperature significantly decreases the effect of spider predation, even as it increases the number of grasshopper adults by lengthening the period of reproduction of mature adults in late summer (Logan et al. 2006). This can lead to increases in grasshopper populations the following year if overwintering conditions are ideal for egg survival. This is but one illustration of a previous synchronous predator-prey relationship that may unravel (see Parmesan 2006).

Endemism and Extinction

Because of the combination of climatic-zone compression along elevational gradients, exposure effects, and great habitat diversity, species richness in the Greater Himalayas commonly exceeds that of the lowlands. Within mountain regions, species richness decreases with increasing elevation, but endemism often increases, due partly to topographic isolation (Körner 2004; Salick et al. 2004). The Greater Himalayas exhibit both paleoendemism—the survival of evolutionary relict flora—and neoendemism—more-recent speciation

originating in the late Tertiary due to the rise of the mountains (Wu et al. 2007). Several studies predict that warming will cause significant declines in biodiversity across a wide variety of alpine habitats in the Greater Himalayas, including tundra and rangelands (Klein et al. 2004; Walker et al. 2006). With their limited geographic range, endemic species are particularly susceptible to climate change (Salick et al. 2009). In general, alpine plant communities will likely increase in height and cover and decrease in species diversity and evenness in a nonlinear response to global warming (Luo et al. 2004).

The ability of species to respond to climate change depends on their being able to “track” shifting climatic zones and colonize new territory or to adapt their physiology and seasonal behavior to changing conditions (Menzel et al. 2006). Existing species appear, however, to shift their geographical distributions as though tracking the changing climate, rather than remaining stationary and evolving new forms (Grace et al. 2002; Holtmeier & Broll 2005; Parmesan 2006). Along elevational gradients, the niches for shifting species may decrease in size (Körner 2007). The climatic, orographic, and geological barriers of the Greater Himalayas may also prevent migration of species along latitudinal gradients.

Shifting Tree Lines

In montane ecosystems it has been projected that a 1°C increase in mean annual temperature will result in a shift in isotherms about 160 m in elevation or 150 km in latitude. The alpine tree line ecotone is useful for monitoring climate change, although studies are complicated by biogeography, species ecology, site history, and anthropogenic influence (Hartman 1994; Hughes 2000; Camarero & Gutierrez 2002; Grace et al. 2002; Holtmeier &

Broll 2005; Schickhoff 2005; Lenoir et al. 2008). In the Tibetan Plateau, tree lines are expected to shift upward and northward (Song et al. 2004). In northwest Yunnan a comparison of repeat photographs taken in 1923 and 2003 indicate tree lines rose by 67 m and tree limits rose by 45 m (Baker & Moseley 2007). In the eastern Himalayas researchers estimate tree-line movement was 110 m over the past century and predict that by 2100 the elevational range of *Abies georgei* forest will decrease between 4.6 and 25.9% and forest size will decrease between 5% and 38.6% under different emission scenarios (M. H. Wong & Y. C. Long, personal communication). Studies in the western Himalayas have recorded an upward shift of tree-line species of 19 and 14 m over 10 years on south and north slopes, respectively (Dubey et al. 2003). Studies of linkage between tree-line ecotone shifting and climate change in the region are inadequate, however.

Using a simplified Holdridge life zone system, we assessed the potential response of Greater Himalayan life zones to an increase in temperature of 5 °C along elevational gradients (without considering precipitation). Results indicated that elevational distribution of life zones would shift significantly: alpine vegetation shrank, evergreen forest decreased significantly, and tropical lowland forest increased (Fig. 3). The boundaries of farming and pastoral regions in western China also shifted, which increased grassland areas. Farming and agropastoral regions, however, also have a potential for increasing desertification (Li & Zhou 2001; Qiu et al. 2001; Wilkes 2008).

Ecosystem Composition and Dynamics

It is highly likely that climate change will affect the composition and distribution of vegetation types throughout

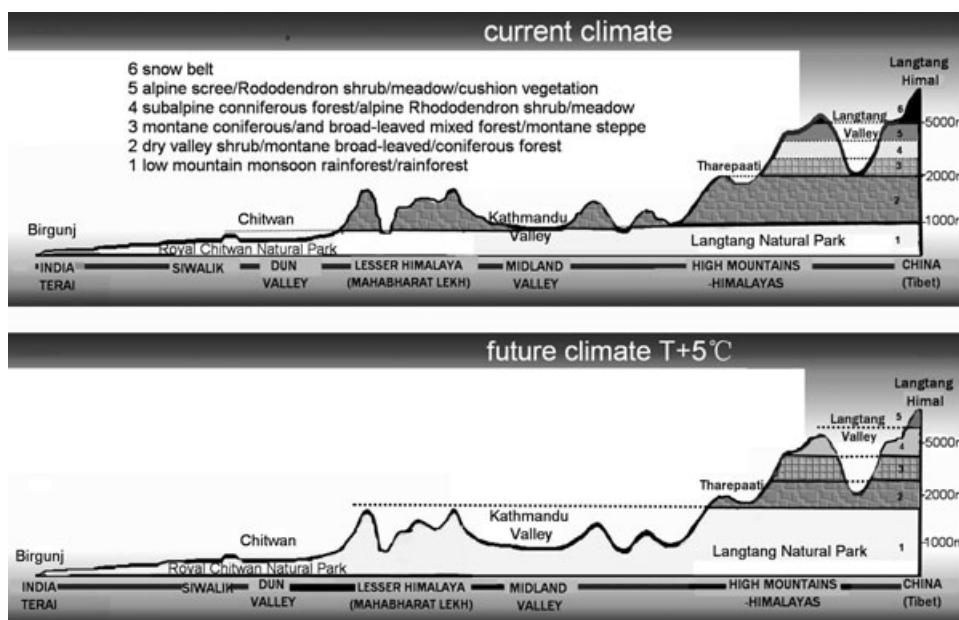


Figure 3. The current elevational distribution of life zones in the Himalayas and their distribution with a 5 °C temperature rise. Projections show a significant decrease in alpine zones, oak forest, and evergreen forest; these ecosystems have the greatest biological diversity in the region.

the Greater Himalayas, including alpine meadows and steppes, wetlands and peatlands, and forests. Alpine meadows are, for example, currently associated with >400-mm annual precipitation, whereas alpine steppe and desert vegetation types are found in areas with <400-mm annual precipitation. These vegetation types are fed by glacier and snowmelt and water discharge into wetlands. Although water availability is key, rangeland degradation on the Tibetan Plateau is also caused by overgrazing (rodents accelerate degradation by consuming both aerial biomass and the roots of plants) and climate warming is but one underlying cause (Zhou et al. 2005). Himalayan grasslands affect regional atmosphere circulation and hydrology through the effects of reflection rates on overall albedo, surface energy, wind drag, evaporation, soil moisture, and precipitation patterns. Grasslands also play a role in regulating the streamflows of major rivers (Wilkes 2008).

High-elevation wetlands exist in a transition zone between glaciers, permafrost, grasslands, rivers, and lakes, and can be affected by minute changes in hydrology. Shifts in Tibetan Plateau ecosystems due to climate change, however, are not projected to be subtle. Today, alpine steppe and alpine desert cover 53.5% of the plateau; their combined area is projected to contract to 37.9%, a loss of 15.6% (Ni 2003; Wilkes 2008). These shifts have important implications for ecosystem cascading effects due to reduction in permafrost and increased desertification.

Himalayan forests have multiple functions: they harbor biodiversity, anchor soil and water, provide carbon sinks, regulate climate, and temper stream flow. They also supply forest products for local livelihoods and economies. Forest areas are projected to increase in some regions and decrease in others across the Greater Himalaya through the 21st century. On the Tibetan Plateau, for example, forest ecosystems now cover <10% of land area and are projected to increase to 22.4% (Ni 2003). It remains unclear what these ecosystem shifts will mean. There is a disturbing deforestation trend in some areas due to overcutting, inaccurate government reporting of forest cover, and poor land-use decisions. Results of this deforestation have implications for declines in endemic species, but they have not yet been linked to climate-change projections (Pandit et al. 2007).

Cascading Effects

In the Greater Himalayas climate change at projected levels will likely cause substantial cascading effects across ecosystems, leading to fundamental alterations. Projected impacts and their associated responses in this region are especially significant and complex. We focused on four categories of cascading effects—ecological, local liveli-

hoods, downstream watersheds, and global feedbacks. We recognize that all of these are interrelated and full of uncertainty.

Effects on Ecosystems and Livelihoods

Basic research on ecological responses of high-elevation species to climatic variables is notably lacking in the Greater Himalayas, but it is generally expected that rapid responses by individual species to climate change may disrupt interactions. Potential ecological cascading effects include secondary extinctions triggered by losses of key species in the alpine ecosystems. The endemic-rich Himalayas include many plant species that may not respond successfully to projected rates and scale of climate change (Mutke & Barthlott 2005; Salick et al. 2009). One of the obvious risks is species extinctions from mountains not high enough to offer escape routes in the case of upward shifts of taxa (Becker et al. 2007). In general, the response of natural vegetation to projected climate change will be complex; some species will decrease, some increase, and new ones may also appear (Chen et al. 2003; Williams et al. 2007). Invasions of weedy and exotic species from lower elevations are likely (McCarty 2001).

Effective human adaptation to climate change includes the establishment of adaptive capacity—knowledge and governance—and the adaptation itself (i.e., changes in behaviors and livelihood practices to meet new conditions) (Smit & Pilifosova 2001; Mirza 2007). Climate change is not new for Himalayan people. Tectonic uplift and Quaternary climate changes, including recovery from the last major glacial period and Little Ice Age, have led to human adaptations to environmental change through mobility of populations and flexibility in livelihood strategies and institutional arrangements.

Climate-change-induced risks at the rate and scale projected in the Greater Himalayas, however, cannot be eliminated by a natural process of gradual adaptation. People must act now to reduce future negative consequences. Floods, for example, are triggered by precipitation, but riverbank retaining walls, biostabilization of slopes, and terracing fields can mitigate flood impacts. Such measures can also reduce damage from landslides, rockfalls, and mudflows. Mountain people using traditional ecological knowledge and customs have evolved fine-tuned social systems to cope with natural hazards (Xu & Rana 2005; Byg & Salick 2009). Studies on the Tibetan Plateau show inextricable links between rural livelihoods, land use, human health, and climate change (Wilkes 2008; Xu et al. 2008). Although information on the potential impacts of climate change is becoming increasingly available, there have been very few studies of the existing adaptive capacities of communities in the region and their vulnerabilities to predicted changes. The diversity of likely cascading effects of climate change on local peoples need to be

identified, predicted, and filtered through many cultural contexts, but, so far, this has not occurred.

Downstream and Global Effects

It is very likely that changes in flow regimes will have significant impacts on water availability for downstream ecosystems and populations. Yet, quantitative projections of downstream effects of changing water flow regimes in Greater Himalayan rivers are rare (Hofer & Messerli 2006). Although research on glaciers, snowpack, and permafrost has been completed in some areas, there are few baseline studies, particularly for areas above 4000 m asl. The full-scale downstream impact of reduced glacier, snow, and ice cover cannot yet be estimated precisely (Liu & Chen 2000; Messerli et al. 2004; Rees & Collins 2006). Given that some 22% of all people on Earth are sustained by Asia's Water Tower, the cascading effect of most concern is the impact of increased temperatures and reduced water supplies on downstream food production. There are already 523 million people in Asia that are undernourished, and by 2040–2060 average summer temperatures across much of the Greater Himalaya are projected to regularly exceed the warmest readings on record since 1900 (Battisti & Naylor 2009).

The Greater Himalayas play a key role in global atmospheric circulation (Zachos et al. 2001). The Himalayan environmental changes have climatic effects, and those changes have consequences on precipitation and temperature patterns on a global scale (Wang et al. 2002). Glaciation and snow cover at low latitudes likely play an important role in Earth's radiation budget. In summer, the vast highlands in Asia heat up more than the Indian Ocean, leading to a pressure gradient and a flow of air and moisture from the ocean intensifying the Indian monsoon (Qiu 2008). This pressure gradient may be changing owing to loss of glacial and snow cover in the Greater Himalayas.

Loss of Greater Himalayan ice and snow will have still-unknown cascading effects on global sea-level rise. The IPCC's most conservative average sea-level rise estimate of 40 cm does not account for loss of terrestrial ice and snow; recent research projects a minimum average rise of 80 cm by 2100 (Cruz et al. 2007; Pfeffer et al. 2008). These levels would lead to further global cascading effects, including submerged coastlines on the megadeltas of Asia, hundreds of millions of environmental migrants, and loss of agricultural lands due to rising coastal and riverine salinity levels (Cruz et al. 2007; Dhar 2009).

The Greater Himalayas are also an important carbon sink. Studies estimate that the organic carbon content of soils subtending grasslands on the Qinghai-Tibetan Plateau composes about 2.5% of the global pool of soil carbon (Wang et al. 2002). In grassland ecosystems net productivity (the amount of carbon sequestered) is very small compared with the size of fluxes, so climate im-

pacts affecting fluxes could possibly change the net flow of carbon, transforming grasslands from CO₂ sinks to CO₂ sources (Jones & Donnelly 2004; Wilkes 2008). In similar alpine ecosystems under the range of climate changes projected for Himalayan wetlands, researchers have reported a doubling of annual emissions (Bohn et al. 2007). Projected shifts in Tibetan Plateau ecosystems, from alpine steppe and desert to alpine meadow and shrublands, may cause the near-complete disappearance of permafrost with the potential cascading effect of releasing most of the region's soil carbon (Ni 2003; Anismov 2007; Wilkes 2008). No model exists yet that captures the interactions of these critical variables: melting Himalayan glaciers, degraded permafrost and wetlands, shifting alpine ecosystems, and changes in monsoon climates.

Conclusions

On current evidence, as this review shows, we recognize uncertainty in this region on a Himalayan scale: physical manifestations of climate change will include broad, heretofore unknown temperature increases (with decreases in some places), shifts in ecosystems, and increased frequency and duration of extreme events. Certainly, there will be significant changes in volumes and timing of river flows and freshwater sources, but precise responses are unknown. To address data gaps, we recommend more widespread and long-term tracking of glacial ice volumes, monitoring of alpine flora and fauna, landscape and transboundary approaches to biodiversity conservation, open data exchange, and cooperation between all countries in the Greater Himalayas (Sarkar 2007).

Given levels of scientific uncertainty, we highlight three critical scales of adaptation: local community, urban and rural, and regional and transboundary. For local adaptations, as in much of the less-developed world, rural people in the Greater Himalayas remain divorced from natural resource decision making (Ribot et al. 2006; Agrawal & Chhatre 2007; Larson & Soto 2008). This complex topic is beyond the scope of this paper, but one thing is clear: if local peoples' successful adaptations to past environmental change are to be learned from, local and regional governments will need to reach out and collaborate more actively with villagers.

At the urban-rural scale, there are inherent differences between city and village dwellers over specific climate-change adaptations. Policies addressing centralized, downstream populations, urban infrastructure, and large-scale agricultural systems must be integrated with those for local peoples living montane livelihoods. Designing integrated land and water resource management at river-basin levels would help bridge this urban-rural divide (Gleick 2003; Grey & Sadoff 2007). In both urban and rural areas, attention should focus on reducing overall

water demand and modernizing irrigated agriculture. Urban demands should not trump the creation of low-cost community-scale adaptations.

At the regional-transboundary scale, current research makes clear that adaptations must be designed for the long term because some climate impacts are already likely irreversible over the next 1000 years even after emissions cease (Solomon et al. 2009). Regional risk assessment and mapping across the Greater Himalayas would help decision makers select appropriate strategies. Nevertheless, we found no regional or transboundary authority addressing the complexities of climate change that we have discussed. This situation must change if climate-change adaptations and mitigations are to be successful. China and India play critical roles here because most of the Greater Himalayas are within the boundaries of these two nations.

As much as we would welcome the formation of a regional Greater Himalayan climate change authority, we recognize that top-down policy making has a decidedly mixed track record in this region (Blakie & Muldavin 2004). This status quo can no longer hold; political leaders must act. Whatever the scale or policy arena, the onus is on scientists to generate knowledge to reduce uncertainty.

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