“Melting Glaciers: Current Status and Future Concerns”

USAID Asia Glacier Melt Project: expert summary of science regarding glacier melt/retreat in the Himalaya, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges

Dr. Richard L. Armstrong
Senior Research Scientist
Cooperative Institute for Research in Environmental Sciences
University of Colorado, Boulder
21 May 2010

1. Background

News of glaciers retreating in the high mountains of Asia have intensified concerns about impacts of climate change on the hydrologic systems of central, south, and east Asia. The overall purpose of this report is to provide a summary of the scientific knowledge about glacier melt/retreat in the high mountains of Asia. This summary will provide the scientific basis for related studies that will evaluate the impacts of glacier melt/retreat. This will support an integrated analysis that will determine appropriate interventions to mitigate or adapt to such impacts and will serve as the evidence base for future USAID glacier melt-related activities. Major points of the report include the following:

- Glaciers are one of the most obvious, and seemingly simple, indicators of climate change. However, glaciers themselves are complex mechanisms.
- The dramatic statements that glaciers are smaller than they have been for over two hundred years since the Little Ice Age (LIA) are not particularly surprising or enlightening. However, the increasing rate of change raises concerns.
- Glacier data in the Himalaya are very sparse, limited mostly to terminus location data that do not comprehensively describe overall conditions of the glaciers.
- Many of the glaciers in the Himalaya are retreating, but there is no spatially comprehensive or region-wide evidence that the glaciers of the Himalaya are retreating faster than glaciers in any other location in the world.
- Efforts to quantify the contribution of melting glacier ice to regional hydrology are in the early stages of development, but it is already clear that conditions vary significantly along the south-east to north-west transect of the Himalaya-Karakoram-Hindu Kush mountain ranges, extending from eastern Nepal and Bhutan to northern Afghanistan.

The report begins by describing ways to measure changes in glaciers and basic factors that affect both change and the rate of change. The scope of the report and differences in climate and glaciers between the east and the west are discussed, then specific questions related to current and projected rates of retreat and/or disappearance are addressed, along with the role of black carbon. The report then takes up questions about impacts on surface water supply, the environment, and health. The conclusions section draws out implications for downstream users, future research, and societal responses.

1.1 Glaciers as indicators of climate change

Glacier retreat provides a clear indication of a global climate that has been warming since the Little Ice Age (LIA), which occurred from approximately 1650 to 1850 (Oerlemans 2005).

Throughout the world, including the Himalaya, evidence left by glacier moraines shows the maximum extent of these glaciers during the LIA and quantifies the fact that glaciers have been retreating since this period in response to a warmer climate.

There is now clear evidence that the retreat of glaciers in many locations of the world has accelerated in recent decades (Zemp et al. 2008). However, glacier systems at the highest elevations, 4000-7000 m, have not responded to recent climate warming in the same way as glaciers that extend to lower elevations, simply because glaciers at higher elevations remain below freezing during much of the year, even in the presence of a warmer climate. Therefore, although glaciers are retreating both in the European Alps and in the Himalaya, one cannot always make direct comparisons and extrapolations from the well-studied lower elevation glaciers to the more poorly observed higher elevations of the Himalaya.

1.2 Glacier terminus fluctuation measurements

Perhaps the simplest method to monitor mountain glacier change is by recording the annual location of the glacier terminus, the location at which the glacier extends furthest down valley. Abundant terminus histories are available from several regions of the world, Europe in particular. Field-based measurements in remote glacierized areas such as the Himalaya are often, by necessity, limited to a few measurements and typically limited to easily accessible glaciers at the lower elevations. Therefore, the sample is biased by elevation.

In addition, it is necessary to understand that the location of a glacier’s terminus is not a comprehensive assessment of total glacier condition or health. Such measurements represent nothing more than the location of the terminus at a given point in time as it responds to both the dynamics of the ice body and the current climate. For example, if a glacier is noted to be retreating, this simply means that the ice at the terminus is melting faster than the rate at which ice is being supplied to that location by movement (dynamics) of ice from further upslope in the system. It is possible that a glacier may be gaining in total mass from one year to the next, due to increasing amounts of snow arriving at the higher elevations by precipitation, wind deposition and avalanching, while the terminus, at the lowest elevation, is retreating. Therefore, it should be understood that measurements showing short-term retreat only indicate that the recent climate does not support the extension, or even stability, of the lowermost elevation of a given glacier, and does not define the current conditions controlling the changes in volume over the entire glacier at all elevations. Certainly, however, when glaciers are observed to have been in retreat consistently over many decades, they are not in balance with the recent climate.

1.3 Glacier mass balance measurements

More direct and comprehensive methods have been developed to determine the year-to-year condition of a total glacier system through measurements of “mass balance.” During the accumulation season (often, but not in all locations, the winter season), a glacier gains mass from accumulating snow. During the following summer melt season, some or all of that winter accumulation is lost to ablation, predominantly by melt, but may include sublimation/evaporation as well as calving where a glacier enters a water body. The upper elevation zone where the glacier experiences an annual net gain in mass is called the accumulation area; the lower elevation zone where the glacier experiences a net mass loss is called the ablation area. The elevation contour at which these two zones meet is called the equilibrium line altitude (ELA) representing the point on the glacier where the annual net mass balance is zero (see Figure 1.) The difference between the accumulation and ablation for a given year describes the annual net mass balance, which corresponds to the change in total glacier volume and mass. Methods to monitor mass balance vary but are always complex and time consuming, so only a few dozen such records in the world exist that cover significant periods of time (decades). There are currently no such long-term records for the Himalaya (Kaser et al. 2006).

1.4 Glacier dynamics

An understanding of the response of glaciers to climate change must include basic concepts of ice dynamics. Glaciers continually move, carrying mass downhill somewhat like a conveyor belt. If the combination of climate (principally precipitation and temperature) and ice dynamics (internal deformation of the ice and sliding at the base in response to the force of gravity) determines that the glacier is extending further down slope with time, this advance of the terminus will increase the glacier length and total area. Because glaciers move slowly, however, a significant time lag occurs between the changing climatic conditions and the resulting glacier advance or retreat. This response time may last several decades or longer for mountain glaciers, determined by complicated processes that control how fast the glacier moves; that is, how quickly a glacier transfers mass from the higher elevations of the accumulation zone to the lower elevations of the ablation zone. Therefore, year-to-year glacier terminus fluctuations may be a response to climatic events that occurred several decades or more in the past.

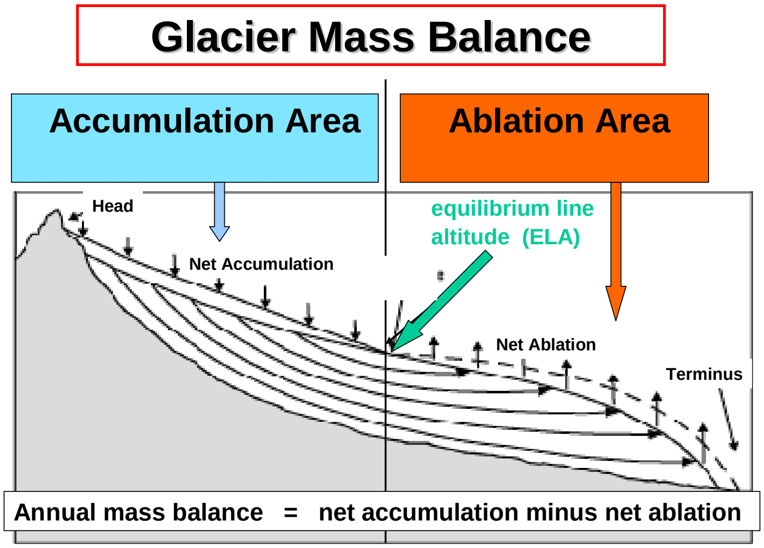
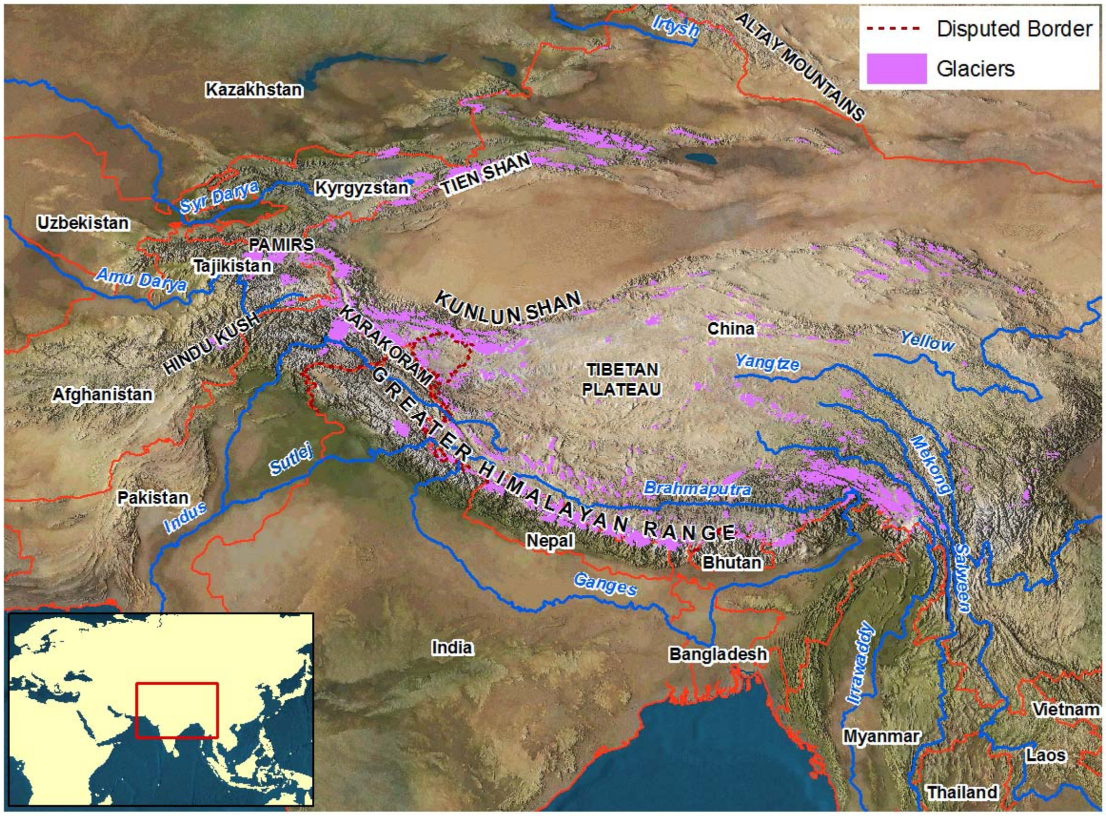


Figure 1. Glacier accumulation and ablation areas, and equilibrium line altitude (ELA).

Response times for the majority of Himalayan glaciers are most likely decades to centuries, appropriate for glaciers whose movement results mainly from internal ice deformation (i.e. in contrast to surging or dramatic basal sliding examples). Rough estimates of glacier response time can be based on size and slope. Large low-slope glaciers may have response times on the order of centuries. Length changes of such glaciers, especially if debris-covered, can therefore not be used as indicators of recent (decadal) climate change. Such decadal changes are much better reflected by smaller/steeper glaciers. Response time scales have been described by Raper and Braithwaite (2009); Adhikari et al. (2009); McClung and Armstrong (1994) and Johannesson et al. (1989).

2. Geographic extent of the review

The focus here is on those regions of “High Asia,” (see Figure 2.) sometimes referred to as the Greater Himalayan region, including the Himalaya, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges, where current glacier coverage exists.



Map credit: Brian Melchior

Figure 2. Mountain ranges, river systems, and glaciers of High Asia.

3. The east-west glacier/climate pattern of the Greater Himalayan Region

It is not appropriate to treat the greater Himalaya as one single region: the eastern Himalaya are separated from the Karakoram-Hindu Kush mountains by approximately 2,000 kilometers. These two areas, east and west, differ in climate, especially in sources and types of precipitation, and in glacier behavior/dynamics. Moreover, no sharp dividing line exists between east and west; rather, conditions change from the east moving to the west.

3.1. Climate

Precipitation and basin runoff generally decrease from the east to west as a direct result of the weakening of the summer monsoon as it moves westward along the Himalayan range. In the east summer monsoon precipitation dominates, while in the west, westerly circulation and cyclonic storms contribute two-thirds of high altitude snowfall during winter, with one-third resulting from summer precipitation mainly due to monsoon circulation (Wake 1989). Hewitt and Young (1993) note that a very significant source of nourishment for many Himalayan glaciers is avalanche snow.

The orographic runoff gradients (variation in runoff with elevation) are also very different between east and west. While data from Nepal show the maximum runoff being generated at approximately 3,000 m with decreasing amounts at both lower and higher elevations (Alford 1992), data from regions further to the west indicate more linear gradients of steadily increasing values up to a maximum at 5,000 m to 6,000 m (Hewitt and Young 1993). This results in a gradual shift upwards in the altitude of the zone of maximum runoff from east to west. This high-altitude runoff would indicate that glaciers in the western Himalaya, Karakoram, and Hindu Kush mountain ranges are an increasingly important source of streamflow volume. However, the total runoff in the western mountains is considerably less than that in the east at all altitudes – an expected condition given the relative aridity of the western mountains. Moreover, throughout the greater Himalaya, most available precipitation data come from lower elevation stations, generally below 2,000 m, and a very significant increase in precipitation can occur between those lower elevations and the accumulation zones of glaciers (Alford 1992).

3.2. Glaciers

The glacier accumulation and ablation patterns are distinctly different, seasonally and spatially, across the region. In the east, the summer season combines both accumulation and melt (accumulation at the highest elevations with melt below) while in the west there is a clear pattern of summer melt and winter accumulation, similar to North America and Europe. Glacier termini extend to lower elevations, approximately 2,500 m in the west, compared to approximately 3,500m to 4,500m in the east, due primarily to the lower temperatures at the higher latitudes of the more western mountain ranges.

Although there are reports of widespread glacier retreat in the east (e.g. Bajracharya et al. 2007; Kayastha and Harrison 2008), in the west, Hewitt (2005) and Immerzeel et al. (2009), for example, report that there has been expansion and thickening of the larger glaciers in the central Karakoram since the 1990s, accompanied by an exceptional number of glacier surges (i.e., rapid advances). This may result from the high elevation combined with a possible increase in orographic precipitation leading to accelerated accumulation. Other studies also showed positive mass balance anomalies in the Karakoram for the same period, based on multi-sensor remote sensing analysis and gravity data from the Gravity Recovery and Climate Experiment (GRACE) (Bishop et al. 2008). Some Karakoram weather-station records, and gauging station data that show reduced runoff from the heavily glacierized Hunza basin, indicate that a general shift to a positive mass balance regime may be taking place (Fowler and Archer 2006).

In summary, the west appears to show slower rates of retreat, less formation of pro-glacier lakes associated with flood hazard described below, and frequent observations of advancing glaciers, in contrast to the eastern region.

4. Specific questions addressed in this report

Questions fall into two categories: those that address the phenomenon of glacier melt/retreat itself, and those concerned with the potential impacts of changes in glaciers on the hydrology, environment, and societies within the study region. Questions 4.1-4.4 target the first category, questions 4.5-4.7 the second category.

4.1 What is the areal extent of glacier coverage within the study area? What main mountain ranges are involved?

Although complete glacier inventories do not currently exist, there is general agreement on the area of the glaciers in High Asia. The total glacier coverage is estimated to exceed 110,000 km^2, with the number of identifiable glaciers exceeding about 50,000 (Dyurgerov and Meier 2005). The major concentrations of glaciers are spread across about 12 mountain ranges forming the headwaters of most all the major rivers in the central, south and south-east Asia mainland.

The World Glacier Monitoring Service (WGMS) in "Global Glacier Changes: facts and figures" (Zemp et al. 2008) states that the total glacier coverage for the "greater Himalayan region," is 114,800 km^2, with 33,050 km^2 in the central Himalayan range.

The International Center for Integrated Mountain Development (ICIMOD), Kathmandu, reports that there are 35,110 km^2 within the central Himalayan region, including only the Himalayan, Karakoram and Hindu Kush mountain ranges, sometimes referred to as the HKH region, also defined as those mountain catchments feeding the Ganges, Brahmaputra and Indus river basins.

In the upper Indus and Yarkand basins, glacier coverage equals approximately 21,000 km^2, with the largest fraction in the Karakoram, with about 16,500 km^2. There are more than 5,000 glaciers in this region, but 12 make up almost 50% of the total area. Other mountain glacier coverage amounts to 15,417 km^2 for the Tien Shan, 12,260 km^2 for the Kunlun Shan, and approximately 12,200 km^2 for the Pamir (Dyurgerov and Meier 2005).

4.2 Is glacier melt occurring in the Asia Region?

Glacier melt (but not necessarily negative mass balance) is occurring in the Asia Region. This is a normal warm season phenomenon, more or less a continuous process since the LIA, at the lower elevations of virtually all glaciers. The amount of melt generally depends on elevation, aspect and local climate of the glacier.

- What is the rate of disappearance?

Estimated rates of terminus retreat, typically measured from the point of furthest down-valley extent of a glacier, vary from approximately 2 to 20% over the past 40 years (Kulkarni et al. 2007). ICIMOD reports that glaciers are retreating at rates of 10 m to 60 m per year and many small glaciers (<0.2 km^2) have already disappeared (Bajracharya et al. 2007). Vertical shifts as great as 100 m in terminus elevation have been recorded during the past 50 years and retreat rates of 30 m per year are common. These rates of retreat do not differ to any significant extent from retreat rates measured at other locations throughout the world.

While there is evidence in the eastern Himalaya of increasing rates of retreat during recent decades, a contrasting picture often emerges from the western Himalaya, as noted above, where examples of decreasing rates of retreat are reported, such as that from observations on the Gangotri Glacier (Kumar et al. 2008) and other locations further to the west in the Karakoram (Hewitt 2005).

Temperature data from the Hindu Kush and Karakoram Mountains of the Upper Indus Basin show a variable pattern, but one that would support the stability, if not growth, of glaciers in the region. Since 1961, summer mean and minimum temperatures show a consistent decline while winter mean and maximum temperatures show significant increases, although still remaining well below the freezing level at the elevation of the glaciers (Fowler and Archer 2006). Decreases of approximately 20% in summer runoff of the Hunza and Shyok rivers are estimated to have resulted from the observed 1^{o} C decrease in mean summer temperatures, a pattern consistent with the observed thickening and expansion of some Karakoram glaciers (Fowler and Archer 2006; Hewitt 2005).

Kayastha and Harrison (2008) note that precipitation records for Kathmandu and the Langtang Valley, north of Kathmandu, show no significant trend for the period of record, up to about the year 2000. They therefore concluded that the rates of retreat in recent decades are mainly due to increased air temperature.

Two relatively recent studies have evaluated glacier retreat in the Akshirak and Ala Archa mountain ranges of the Tien Shan. Khromova et al. (2003) used air photo mapping surveys from 1943 and 1977 with ASTER satellite imagery from 2001. They determined a small shrinkage of only a few percent between 1943 and 1977 in contrast to a major shrinkage of more than 20% between 1977 and 2001. The reasons presented for this large reduction in glacier area include increases in annual and summer temperatures, decreases in precipitation, and a decrease in the summer/winter precipitation ratio – less snowfall at the higher elevations on the glaciers during summer results in a lower albedo (reflectivity) and higher melt rates. Another study in the same region by Aizen et al. (2006), using similar input, data found lesser amounts of glacier shrinkage over the later period of 1977 to 2003, 8.7% and 10.6% respectively for the Akshirak and Ala Archa mountains. A third study (Bolch 2007) determined that for the Northern Tien Shan (Kazakhstan/Kyrgyzstan) the average decrease in glacier extent was more than 32% between 1955 and 1999 in the valleys of Zailiyskiy and Kungey Alatau. In Central Asia in general, Kotlyakov and Severskiy (2009) report that during the period 1956 to 1990 glaciers receded by more than one-third and that the current rate of recession is thought to be approximately 0.6 - 0.8% per year.

Glaciers in the Muztag Ata and Konggur mountains of the eastern Pamir plateau, northwestern China, have been monitored by applying aerial photo stereo models (1962/1966) and Landsat TM (1990) and ETM+ (1999) images, which have been compared in order to detect areal and frontal changes through the past four decades (Shangguan et al. 2006). Glaciers in the Muztag Ata and Konggur mountains retreated 6.0 m per year between 1962/66 and 1990, increasing to 11.2 m per year between 1990 and 1999, with an overall glacier length reduction of 9.9% for the whole study period. The glacier area has decreased by 7.9%, mainly due to changes observed in the most recent period (1990-99), when the annual area loss almost tripled.

Yao et al. (2009) describe how the percentage of retreating glaciers within China has increased from about 50% of all glaciers during the period 1950-1970 to more than 90% since 1990. The least amount of retreat has occurred at the higher elevations of the Tibetan Plateau with increasing amounts of retreat toward the lower elevations of the south-east edge of the Plateau and the lower elevations of the Karakoram mountains. This general situation is reflected in Figure 3 where the mass of the glaciers at the higher elevations of the “Tibet” region is shown to be decreasing at a slower rate than glacier mass in the more extensive “Himalaya” region, which includes glaciers found at much lower elevations.

In summary, the rate of retreat and/or down-wasting depends on several factors, independent of dynamics. These include elevation, debris cover, ice thickness, and topographic slope and aspect, and not all investigators consider these variables when they report retreat rates. Clearly, the greatest retreat and or down-wasting is associated with those glaciers located at the lowest altitudes on gentle slopes, with thin ice near the terminus, and a debris-cover thickness that enhances rather than retards melt. Smaller glaciers at the lowest elevations with a southerly aspect, and those "hanging glaciers" cut off from a substantial accumulation area, will be the first to disappear.

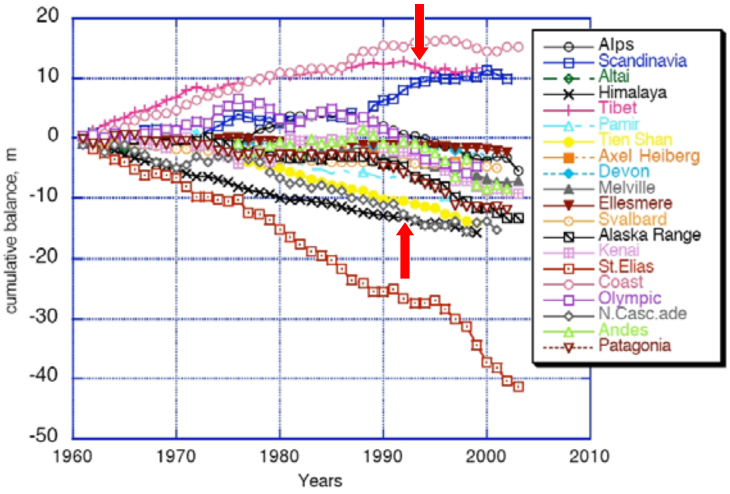


Figure 3. Cumulative mass balances (m) for selected glacier systems compiled from individual glacier time series. Dyurgerov and Meier (2005). Upper red arrow, "Tibet" region, lower red arrow, "Himalaya" region.

- Mass balance measurements

WGMS (Zemp et al. 2008) reports an average global annual ice loss of almost 0.75 m of water equivalent since 1997, twice as much as in the decade before, 1988-1997, and three to four times as much as the time period 1978-1987. However, a key fact to note here is that virtually all of the glaciers in this global sample exist within an elevation range that is well below the average elevation of the Himalayan glaciers. For a review of mass balance monitoring of the past six decades, see the recent publications by Zemp et al. (2009) and Lemke and Ren (2007).

Mass balance records from Himalayan glaciers are extremely rare and of short duration (Zemp et al. 2009). Only records of ten or more years are relevant for climate and hydrological variability and trend studies, and only two glaciers barely meet this threshold. Most glaciers are also very small in size and altitude range and as such are not representative of all Himalaya glaciers.

Data from the higher elevation Langtang and Chhota Shigri glaciers indicate consistently negative mass balance values, but the extent to which they can be considered regionally representative is not known. The glacier AX010 in Nepal has been predicted to disappear by the year 2060 if conditions represented by the period 1992-1996 remain unchanged (Kadota 1997). This could be considered a reasonable prediction, given that the size of this glacier is only 0.57 km^2. The uppermost altitude of AX010 is 5360 m, while approximately 50% of the surface area of all Nepal glaciers exists at altitudes above 5400 m, so AX010 can only be considered representative of the lower elevation glaciers (Alford et al. 2010).

On the Yala Glacier, in Nepal, at a higher elevation than the Langtang, Fujita et al. (2006) have constructed a 30-year mass balance history from ice cores and the inspection of crevasse layers.

They determined that the mass balance on the Yala Glacier at 5,380 m shows a positive balance, about 0.2 to 0.8 m, during the period 1960 to 2000, tending towards zero in the mid-1990s. A limited amount of melt was observed at 5,380 m on the Yala, while no melt was observed in the same region at 7,200 m on the Dasuopu Glacier, located on Mt. Xixabangma in China. No melt at this elevation would agree with calculations by Alford et al. (2010) described in section 4.3 below.

Individual glaciers can respond with great variability to a changing climate. Therefore, it is important to involve more regional-scale estimates in the analysis of Himalayan glacier mass balance. Berthier et al. (2007) compared elevation data from 2000 Shuttle Radar Topography Mission (SRTM) data with a 2004 digital elevation model (DEM) derived from SPOT5 (Satellite Pour l'Observation de la Terre) imagery in the Himachal Pradesh region of northwest India. Results indicated an average mass balance of - 0.7 to - 0.85 m per year of water equivalent over a total glacier area of 915 km^2.

Naz et al. (2008) calculated recent thickness changes on glaciers in the Upper Indus Basin of the Western Karakoram by subtracting SRTM elevation data from Ice, Cloud, and land Elevation Satellite (ICESat) data for the period 2004 to 2008. Preliminary results indicated the average thickness change over glaciers in the Hunza Valley to be approximately + 0.10 m/year in the ablation zone and approximately + 0.64 m/year in the accumulation zone, implying a recent mass balance regime that is positive.

Only one time-series set of mass balance measurements has ever been made in the Karakoram. Bhutiyani (1999) used the hydrological (water-balance) method to compute the mass balance of the Siachen Glacier in the Nubra Valley, eastern Karakoram range of the Himalaya, India, the largest glacier in the Himalaya (1142 km^2) for the period 1986-1991. The average mass-balance was negative, the lowest being in 1990-91 (-1.08 m). A positive mass balance was calculated for 1988-89 (+ 0.35 m) and was attributed to comparatively heavy winter snowfall amounts and low temperatures during the ablation season. Significantly lower runoff was measured during this season. The most negative values of 1989-1990 and 1990-1991 are thought to be the result of comparatively dry winters and warm ablation periods, with monthly mean air temperatures 1.4 to 5.1°C higher at the beginning of the ablation season, June and July, than the mean of the five years.

4.3 What is the projected extent (range and magnitude) of glacier melt in the next 15 to 20 years?

One assessment of future glacier melt in the Himalaya recently receiving widespread attention in the media was published in the 2007 Intergovernmental Panel on Climate Change (IPCC) Working Group (WG) II report (Cruz et al. 2007), "Glaciers in the Himalaya are receding faster than in any other part of the world and, if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate." This statement is not correct. No evidence was presented that Himalayan glaciers are receding faster than those in other parts of the world, as only rates of retreat for the Himalaya were presented. Also, a rough calculation would indicate that melt rates on the order of 20 times the current observed melt rate in the Himalaya would be required to remove all glaciers by 2035. The 2007 IPCC WG I authors of “Changes in Glaciers and Ice Caps” noted that “the glaciers of High-Mountain Asia have generally shrunk at varying rates and that several Karakoram glaciers are reported to have advanced and/or thickened” (Lemke and Ren 2007). The cumulative glacier mass balance data from the high mountains of Asia show values that are in fact approximately mid-way between the global extremes (see Figure 4a.)

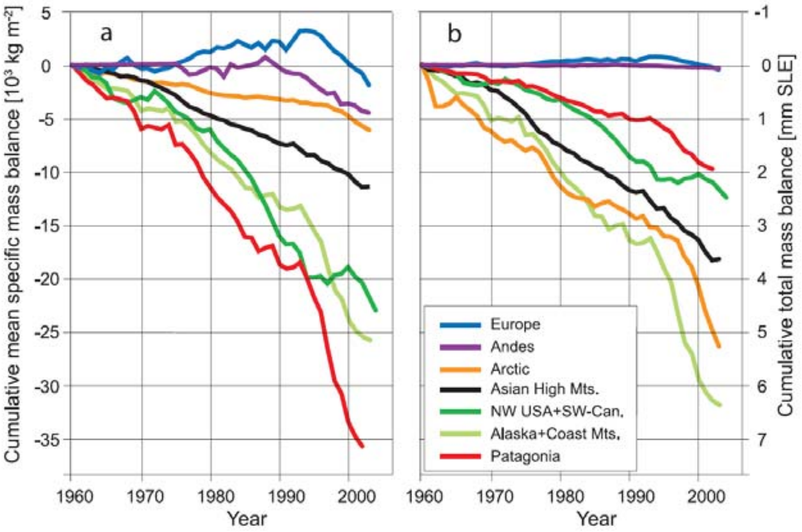


Figure 4. Cumulative glacier mass balance (10^3 kg m^{-2}) for selected glacier systems, (left panel) and cumulative contribution (mm) to sea level (right panel), Lemke and Ren (2007).

In one recent study involving prediction, Ren et al. (2007) applied three GCMs (global circulation models), with warming effects based on a high emissions scenario, over the 30-year period of 2001–30, over the greater Himalayan region. Despite certain regional differences, all three GCMs indicated spatially averaged glacier thickness reduction of approximately 2 m for the 2001–30 period, but only for those areas located below 4000 m.

Rees and Collins (2006) have applied a temperature-index-based hydro-glaciological model in which glacier dimensions are allowed to decline with time to determine by how much and when climate warming will reduce Himalayan glacier dimensions and affect downstream river flows. Two hypothetical glaciers, of equal dimensions and initial geometries, were located within two hypothetical catchments representing the contrasting east and west climates of the Himalaya. The model was applied from a start date of 1990 for 150 years with a uniform warming scenario of 0.06^{o}C year $^{-1}$. Flows for these glacierized catchments attain peaks of 150% and 170% of initial flow at around 2050 and 2070 in the west and east respectively, before declining until the respective hypothetical glaciers disappear in 2086 and 2109. The general modeling approach is appropriate here but model inputs and glacier geometries are hypothetical, and it is assumed that melt is uniform over the total glacier surface with no distinction between specific ablation and accumulation zones. Therefore, the accuracy of results is uncertain.

In summary, where consistent results exist across various modeling efforts, they indicate little potential loss in total melt water available from glaciers over the next few decades. This is because increased temperatures could be compensated by increased precipitation falling as snow at the higher elevations, above approximately 5,000m, as a possible result of a strengthened Indian monsoon (Sreelata 2006).

4.4 What role does black carbon play in causing glacier melt?

Black carbon emissions originate from a variety of sources, including biomass burning, residential burning, transportation, and industry/power production with relative amounts dependent on region (USAID-Asia 2010). Black carbon is a strong absorber of solar radiation and is thought to be the second-largest contributor to global excess radiative forcing after CO_2 (Ramanathan and Carmichael 2008) and, with other aerosols in atmospheric brown clouds (ABCs), a substantial contributor to lower atmospheric warming trends in Asia (Ramanathan et al. 2007). Where black carbon accumulates over a snow or glacier surface, the impact on melt rate can be significant and can be quantified where amount and type of soot/black carbon are known. Kandlikar et al. (2009) point out that black carbon particles that fall on bright snow or ice surfaces may cause several extra months of warming each year. At this time, however, very few in situ measurements are available, although appropriate measurements can be expected to increase in the future.[1]

A recent paper by Xu et al. (2009) describes measurements of black soot in ice cores from Tibetan glaciers and speculates on the melt rate impact. They show that the black soot content is sufficient to affect the surface reflectivity of the glaciers and that the black soot amount has increased rapidly since the 1990s, coincidentally with the accelerating glacier retreat and increasing industrial activity in South and East Asia. They suggest that a successful strategy to retain the fresh water benefits of Himalayan glaciers will need to reduce black soot emissions so as to restore more pristine high-reflectivity snow and ice surfaces. They noted that black carbon concentrations of 10 ng g^{-1} significantly alter the albedo (reflectivity) of a snow layer. The visible albedo of fresh snow, about 0.90–0.97, is decreased by 0.01–0.04 by a black carbon amount of 10 ng g^{-1}, thus increasing absorption (1 minus albedo) of visible radiation by 10–100%, depending on the size and shape of snow crystals and on whether the soot is incorporated within snow crystals or externally mixed (Hansen and Nazarenko 2004). The impact of the albedo change is magnified in the spring at the start of the melt season, because it allows melt to begin earlier.

In November 2009, a French research team (IRD)[2] began work on Kongma La Glacier, a very small and debris-free glacier, located close to Pokalde summit, near the Khumbu Glacier, in collaboration with the Ev-K2-CNR project. This glacier, close to the EVk2 CNR Pyramid laboratory, will be used for studying the impact of aerosols and black carbon on glacier melting. This is part of a project (PAPRIKA) recently funded by the French National Research Foundation that will start officially in 2010 for three years.

4.5 Is glacier melt projected to impact surface water supply in the region? What might be the seasonal effects, and what is the magnitude? What are the other known water resource impacts?

While the mass balance measurements described in 4.2 above do represent the measure of the health of a glacier and its ability to maintain its mass from one year to the next, the values, per se, do not reveal anything about the hydrology. If the mass balance is +/- zero we know the health of the glacier is in balance, but we have no direct quantitative information about how much glacier melt water is being contributed to the river system leaving the basin containing the glaciers.

---

[1] See 2009 AGU Annual Fall Meeting, Lau, W. et al. “Will Black Carbon Siphon Asia’s Drinking Water Away?” - http://www.nasa.gov/topics/earth/features/carbon-pole-briefing.html and proceedings of the UNEP sponsored International Expert Workshop, “Emerging Issues in Climate Change: State of Tropospheric Temperature, Pollution, Snow, Melting Glaciers and Potential Impact on Monsoon in the Himalayas-Tibetan Plateau,” December 28-29, 2009, New Delhi.

[2] Y. Arnaud, personal communication.

Previous assessments of the glacier melt impact on surface water supply have been primarily either highly qualitative or local in scale, or in some cases, simply incorrect. For example, values reported in Singh and Bengston (2004) and Barnett et al. (2005) appear to be far too large. Barnett et al. (2005) stated that "There is little doubt that melting glaciers provide a key source of water for the Himalayan region in the summer months: as much as 70% of the summer flow in the Ganges and 50–60% of the flow in other major rivers." Little evidence supports such high values for the contribution of glacier ice melt to total river flow volume.

Rees and Collins (2006) believe that if all glaciers were to disappear, there would be a much greater impact on the water resources of the west than the east, with reduction in annual mean flow of about 33% in the west, but only about 4–18% in the east, compared to 1990 levels, because of the climatic differences between the drier western and monsoonal eastern ends of the region. They note that high discharge from glacier ice melt often dominates flow for considerable distances downstream, particularly where other sources of runoff are limited. They also speculate that, should Himalayan glaciers continue to retreat rapidly, water shortages might be widespread within a few decades.

A study by Alford et al. (2010) indicates that in Nepal the glacier contribution to sub-basin stream flow varies from approximately 20% in the Budhi Gandaki Basin to approximately 2% in the Likhu Khola Basin, averaging approximately 10% across nine basins. This discharge volume represents approximately 4% of the total mean annual estimated volume of 200,000 million cubic meters for the rivers flowing out of Nepal. Under current climate conditions, results indicated that the glaciers of Nepal experience no significant melt over approximately 50% of their surface area at any time of the year. This is in sharp contrast to lower elevation glaciers of the world that melt over their entire surface during the summer months, often resulting in significant mass loss.

For the upper Indus basin, Immerzeel et al. (2009) found that the contribution of glacier melt contributed substantially to streamflow – 32% in a reference situation, peaking in July (with snow melt providing 40% of the total with a peak in June, and rain comprising 28% with a peak in July) The removal of all glaciers, with an accompanying increase in the winter and summer temperatures of 4.8° C and 4.5° C respectively and precipitation increases of 19.7% and 15.7% (climate model scenario for 2071-2100) indicated a reduction in summer maximum flow of approximately 30% and the percent of total precipitation falling as snow was reduced from 60% to 48%. In these types of projections there is typically an increase in total precipitation, summer and winter, with melt from snow cover remaining about the same and peak discharge appearing approximately one month earlier than present conditions. Patterns of increased total precipitation and earlier snow melt can be actually beneficial for agriculture, as this pattern would provide more water for local irrigation and increased input to reservoirs when they are most empty at the beginning of the growing season.

Immerzeel et al. (2010, in review) have recently applied their modeling approach across the greater Himalayan region and conclude that glacier melt water is extremely important in the Indus Basin, reasonably important for the Brahmaputra, but only plays a modest role for the Ganges, Yangtze and Yellow rivers. Preliminary results indicate that the snow and glacier melt contribution**,** compared to total runoff generated below 2,000 m**,** is the following: Indus, 151%; Brahmaputra, 27%; Ganges 10%; Yangtze 8% and Yellow 8%. This recent work of Immerzeel et al. represents an important step forward in understanding the regional hydrology of the greater Himalaya.

In Central Asia, Severskiy (2009) reports that glaciers lost volume at about 1% per year during the last 35-40 years of the 20th century. Such losses will result in significant changes in the hydrologic cycle as glacier runoff is responsible for 40-50% of discharge in the Tarim and Balkhash basins (from Dolgushin and Osipova 1989, referenced in Kotlyakov and Severskiy 2009). For the whole Tien Shan, the annual and summer fractions of glacier runoff are approximately 20 and 35% respectively (Aizen et al. 2006).

In summary, a highly accurate assessment of the significance of snow and glacier melt in the overall Asian river hydrology remains largely unaccomplished. There is reasonable confidence in stating that the contribution of glacier ice melt to the downstream hydrology is small in the east, and not expected to change in the next few decades. Contribution is considerably larger in the west, but <u>total volume</u> from glacier melt is still relatively small and there is no apparent reason to think that it would change significantly in the next few decades. It should be noted that while the contribution from melting glacier ice to the hydrology of the lower reaches of mountain rivers is relatively small, melt water increases in significance when moving upward in the basin towards the source of that melt water. However, societies that have adjusted to this current minimal volume of melt water from glaciers are not likely to be in for any great surprises over the next few decades.

4.6 - What are the known and/or projected environmental impacts of glacier melt?

A misconception sometimes found in the popular literature expresses the concern that the rapid melting of glaciers will lead to catastrophic flooding downstream. This is physically impossible. Glacier ice melt rate under any reasonable warming scenario is relatively slow, and thus can not, per se, cause floods. Environmental impacts come in the form of hazards associated with two distinct types of glacier lake outburst floods (GLOFs). Interestingly, these types of floods can result from both retreating and advancing glaciers. One, a moraine-dammed outburst flood, occurs when large volumes of water build up behind the terminal moraine of a rapidly melting, retreating glacier and the moraine dam fails. For example, in 1985 a glacier lake, Dig Tsho in the Khumbu region of Nepal, burst and the flood waters completely destroyed a nearly completed hydro-electric power station at Thame, some 12 km below Dig Tsho that was being built with the assistance of the Austrian government. Thirty houses, many hectares of scarce agricultural land and 14 bridges were also destroyed (Ives 2006). However, only a small number of moraine-dammed lakes are actually dangerous at the present time.

Results from a 20-year study of the moraine-dammed glacier lake at the Imja Glacier in the Khumbu Himal, located a few kilometers south of Mt Everest and often characterized as one of the most dangerous in the Himalaya, show that it is relatively stable (Watanabe et al. 2009, Fujita et al. 2009). Efforts to identify which lakes are actually the most dangerous are currently underway (Bajracharya et al. 2007). Bajracharya and Mool (2009) report that during the past decade the overall area of moraine-dammed lakes has increased, although the number of lakes above the elevation of 3,500 m has decreased.

The other type of outburst flood, which is associated with advancing glaciers, occurs when a glacier tongue reaches the location where a tributary river or stream converges with the advancing glacier and is dammed by the advancing tongue. In this case an outburst flood may occur when the glacier subsequently retreats or breaks up. These glacier outburst floods are often referred to by the Icelandic name of “jökulhlaups” (Ives 1986).

Hewitt (2010) notes that in the Karakoram, there is a greater prevalence of ice-dammed lakes or “jökulhlaups,” formed by advancing glaciers (typically short-lived and unstable), in contrast to moraine-dammed lakes, which are more typical in the east and associated with greater rates of melt. The only types of damaging outburst floods reported from the upper Indus Basin in recent decades have included debris flows (conversion from water flood to debris flow). According to Hewitt (2010), regions where advancing glaciers may possibly soon impound rivers are the Shaksgam, upper Shyok, and Shimshal valleys. In 2009, satellite imagery revealed a sudden advance of the Chong Khumdan Glacier into the Shyok River. Previously, between 1926 and 1932, this glacier formed a series of large ice dams and at least four outburst floods were reported that resulted in a measurable rise in the river 1,100 km away at the Attock gauging station.

4.7 - What are the known and/or projected health impacts of glacier melt?

Health impacts associated with glacier melt found in the literature are limited to the impacts of GLOFs. A GLOF can kill most or all inhabitants in a village, destroy structures and change the land such that it becomes uninhabitable. In non-lethal cases, GLOFs may lead to distress migration, increased poverty, and interrupted education (especially for girls, who are more likely to be taken out of school). GLOFs became more frequent in the second half of the 20th century (WHO 2005).

Researchers have recently begun to pay attention to mental health impacts of disasters, such as the behavioral problems among children after flooding in Bangladesh (Durkin et al. 1993). Distress migration may cause mental health problems as well as raising physical health risks. These impacts would also apply to the aftermath of GLOFs.

Secondary impacts of changes in water supply, although not specifically discussed with regard to glacier melt/retreat, include potentially widespread nutritional deficiencies (including stunting in childhood) and increased disease susceptibilities, with lifelong negative productivity and dependency outcomes. The IPCC (Confalonieri et al. 2007) summarizes:

> Climate change could have a range of adverse effects on some rural populations and regions, including increased food insecurity due to geographical shifts in optimum crop-growing conditions and yield changes in crops, reduced water resources for agriculture and human consumption, flood and storm damage, loss of cropping land through floods, droughts, a rise in sea level, and increased rates of climate-sensitive health outcomes. Water scarcity itself is associated with multiple adverse health outcomes, including diseases associated with water contaminated with faecal and other hazardous substances (including parasites), vector-borne diseases associated with water-storage systems, and malnutrition.

Existing health status is negatively affected by climate via water scarcity and drought, flooding, and rising temperatures; associated diseases and negative conditions include heat stress and vector-borne diseases. Also affecting health are the quality and quantity of public health institutions; air, water, and land pollution; and inadequate sanitation. It is difficult to separate these multiple causes and multiple effects.

A special case is presented by black carbon emissions, which are thought to accelerate glacier melt and which pose an indoor health hazard, particularly for women and children, contributing to excess deaths (especially from pneumonia) and a wide range of respiratory diseases.

In addition to the impact on glacier melt, health hazards could result if melt water quality from snow and ice is negatively affected by accumulation of black carbon and other aerosol deposition.

5. Conclusions

Glaciers can be thought of as "time machines," storing water in one place over many decades – unlike rain, or even seasonal snow melt, that typically reach the stream flow within days to months. This glacier storage acts like a large-volume water tank on the mountain side with new water coming in the top throughout much of the year, and some of the older water running out the bottom during the melt season. The annual balance question involves whether more runs out the bottom during melt than arrives during that year at the top – and of course it is the long term that is more important than the annual or short term – that is, the climate versus the weather.

While the glaciers of the Himalaya do provide a certain amount of the runoff to the 1.5 billion people living downstream, perhaps the smallest amounts correspond to the regions of the highest population: China, India and the Southeast Asia mainland. In the eastern Himalaya the contribution of melting glacier ice to the downstream river flow is most likely about 5% or less. In the western Himalaya, and specifically the Indus Basin, the contribution of melting glacier ice to the rivers is considerably larger. However, it is also thought that the glaciers in the western Himalaya are more in equilibrium with the current climate and may be retreating at a slower rate than those in the east, and in some cases advancing. Glacier melt water is estimated to comprise approximately one-third of the flow of the Indus River, with snow and ice together providing perhaps over two-thirds. It has perhaps the largest ratio of melt water to population of any river system anywhere in the world.

Realistic, accurate and comprehensive assessments of the future availability of water resources in the Himalaya region in the context of glacier retreat are not possible until the existing hydrologic regime of these mountains is better defined, the current relationship between glaciers and streamflow is evaluated in quantitative terms, and the contribution from other sources of streamflow is examined. However, reasonable approximations of the impact of glacier retreat on water resources have been summarized in this report.

For the population relying on the water resources provided by the Himalayan drainages, primary measures should involve well-planned management, conservation, and efficient use of the water people currently have available to them. Rapidly increasing consumption and mismanagement of these existing resources should perhaps be of much greater concern than the relatively small changes that may occur in either the climate or hydrology in the coming decades.

Finally, although glaciers across the Himalaya may not be disappearing at as rapid a rate as had been previously thought, the need remains for mitigation and adaptation to the response of these glacier systems to climate change, as well as for development of accurate estimates of the potential impacts of melting glaciers.

6. References

Adhikari, S., Marshall, S.J. and Huybrechts, P. 2009. A comparison of different methods of evaluating glacier response characteristics: application to glacier AX010, Nepal, Himalaya. The Cryosphere Discussion, 3:765-804 www.the-cryosphere-discuss.net/3/765/2009/tcd-3-765-

Alford, D., Armstrong, R. and Racoviteanu, A. 2010. Glacier retreat in the Nepal Himalaya: An assessment of the role of glaciers in the hydrologic regime of the Nepal Himalaya. Report to South Asia Sustainable Development (SASDN) Office, Environment and Water Resources Unit, The World Bank, Washington, DC.

Alford, D. 1992. Hydrological aspects of the Himalayan region, ICIMOD Occasional Paper No.

18, Kathmandu, Nepal, 68 p.

Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., and Aizen, E.M. 2006. Glacier changes in central and northern Tien Shan during the last 140 years based on surface and remote sensing data. Annals of Glaciology, 43(1):202-213.

Bajracharya, S.R., Mool, P.K. 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal, Annals of Glaciology 50(53) 2009

Bajracharya, S.R., Mool, P.K., and Shrestha, B.R. 2007. Impacts of Climate Change on Himalayan Glaciers and Glacial Lakes, International Center for Integrated Mountain Development (ICIMOD) and UNEP, Kathmandu, 119 p.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., 2005. Potential impacts of warming climate on water availability in snow-dominated regions. Nature, 438: 303-309.

Berthier E., Arnaud Y., Rajesh K., Sarfaraz A., Wagnon P., and Chevallier P. 2007. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). Remote Sensing of Environment, 108(3), 327-338, doi: 10.1016/j.rse.2006.11.017, 2007.

Bhutiyani, M.R. 1999. Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram Himalaya, India, Journal of Glaciology, 45(149):112-118.

Bishop, M. P., Bush, A. B., Collier, E., Copland, L., Haritashya, U. K., John, S. F., Swenson, S. C. and Wahr, J. 2008. Advancing Glaciers and Positive Mass Anomaly in the Karakoram Himalaya, Pakistan, American Geophysical Union, Fall Meeting 2008, abstract #C32B-04

Bolch, T. 2007. Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Global and Planetary Change, 56(1-2):1-12.

Confalonieri, U., B. Menne, R. Akhtar, K.L. Ebi, M. Hauengue, R. Sari Kovats, B. Revich and A. Woodward. 2007. Human health. In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), (eds) Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. Cambridge U.P., UK, pp. 469-506.

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C. and Huu Ninh, N. 2007: “Asia. Climate Change 2007: Impacts, Adaptation and Vulnerability.” Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), (eds) Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. Cambridge U.P., UK, pp. 469-506.

Durkin, M.S., N. Khan, L.L. Davidson, S.S. Zaman and Z.A. Stein. 1993. The effects of a natural disaster on child behavior: evidence for posttraumatic stress. American Journal of Public Health 83, 1549-1553.

Dyurgerov, M. and Meier, M.F., 2005. Glaciers and Changing Earth System: A 2004 Snapshot, INSTAAR Occasional Paper # 58, University of Colorado, Boulder.

Fowler, H.J. and D.R. Archer, 2006. Conflicting signals of climate change in the Upper Indus Basin, Journal of Climate, 19:4276-4293.

Fujita, K., Thompson, L.G., Ageta, Y., Yasunari, T., Kajikawa, Y., Takeuchi, T. 2006. Thirty-year history of glacier melting in the Nepal Himalayas, J. of Geophy. Res. Vol. 111,DO3109.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., Sharma, R. 2009 Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by *in situ* surveys and multi-temporal ASTER imagery, Environ. Res. Lett. 4:045205.

Hansen J, and Nazarenko L. 2004. Soot climate forcing via snow and ice albedos. *Proc Natl Acad Sci USA* 101:423–428.

Hewitt, K. and Young G. 1993. Glaciohydrological Features of the Karakoram Himalaya: Measurement Possibilities and Constraints, *Snow and Glacier Hydrology* (Proceedings of the Kathmandu Symposium, November 1992). IAHS Publ. no. 218.

Hewitt, K. 2005. The Karakoram anomaly?, glacier expansion and the “elevation effect”, Karakoram, Himalaya, Mountain Research and Development, 25(4):332-340.

Hewitt, K. 2010. Understanding glacier changes. China Dialogue, February 1, 2010, www.chinadialogue.net

Immerzeel, W.W., Droogers, P., de Jong, S.M., and Bierkens, M.F.P. 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. Remote Sensing of Environment, 113:40-49.

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P. 2010. Will climate change affect the Asian water towers? (in review).

Ives, J.D. 2006. Himalayan Perceptions: Environmental Change and the Well-being of Mountain Peoples, 2nd addition, Jagadamba Press, Hattiban, Lalitpur, Nepal, 285 pp.

Ives, J.D. 1986. *Glacier Lake Outburst Floods and Risk Engineering in the Himalaya.* ICIMOD Occnl. Paper 5, International Centre for Integrated Mountain Development, Kathmandu, Nepal.

Jóhannesson, T., Raymond, C., and Waddington, E. 1989. Time-scale for adjustment of glaciers to changes in mass balance, Journal of Glaciology, 35(121):355-369.

Kadota, T. 1997. Study on the relation between climate and recent shrinkage of small glaciers in the Nepal Himalaya, PhD thesis, Nagoya University, Japan, 76 pp.

Kandlikar, M., Reynolds, C.C.O., and Grieshop, A. 2009. A perspective paper on black carbon mitigation as a response to climate change. Copenhagen Consensus Center, Denmark.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura. 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. Geophysical Research Letters, 33(19), L19501.

Kayastha, R.B. and S.P. Harrison. 2008. Changes of the equilibrium-line altitude since the Little Ice Age in the Nepalese Himalaya. Annals of Glaciology, 48:93-99.

Khromova, T.E., Dyurgerov, M.B. and Barry, R.G. 2003. Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery. Geophysical Research Letters, 30(16): 1863, doi:10.1029/2003GL017233.

Konz, M., Braun, L., Grabs, W., Shrestra, A., and Uhlenbrook, S., 2006, Runoff from Nepalese Headwater Catchments – Measurements and Modeling, Deutsches Nationalkomiteefur das International Hydrological Programme (IHP) der UNESCO und das Hydrology und Water Resources Programme (HWRP) der WMO, Koblenz, 2005.160 pp.

Kotlyakov, V. M. and Severskiy, I. 2009. Glaciers of Central Asia: current situation, changes, and possible impact on water resources, (in) Assessment of Snow, Glacier and Water Resources in Asia, IHP/HWRP – Berichte, Heft 8, Koblenz 2009, ISSN 1614-1180 (selected papers from the workshop in Almaty, Kazakhstan, 2006).

Kulkarni, A.V., Bahuguna, I., Rathore, B., Singh, S. Randhawa, S., Sood, R., and Dhar, S. 2007. Glacial retreat in Himalaya using Indian Remote Sensing satellite, Current Science, 92(1), 69-74. DS0097

Kumar, K., Dumka, R.K., Miral, M.S., Satyal, G.S., and Pant, M. 2008. Estimation of the retreat of Gangotri glacier using rapid static and kinematic GPS survey, Current Science, 94(2):258-262.

Lemke, P. and Ren, J. (eds.) 2007. Observations: Changes in snow, ice, and frozen ground, Chapter 4, Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge U.P., UK, pp. 338-383.

McClung, D.M. and R.L. Armstrong, 1994: Temperate glacier time response from field data. J. of Glaciology 39(132):323-326.

Naz, B.S., Bowling, L.C., and Crawford, M.M. 2008. Quantification of glacier changes using ICESat elevation data and the SRTM elevation model in the Western Karakoram Himalaya Region. American Geophysical Union, Fall Meeting, abstract # C23A-0592.

Oerlemans J., 2005: Extracting a climate signal from 169 glacier records. *Science*, 308, 675–677.

Ramanathan, V. and Carmichael, G. 2008. Global and regional climate changes due to black carbon, *Nature Geosci* 1(4):221-227.

Ramanathan, V., Ramana, M.V., Roberts, G., Kim, D., Corrigan, C., Chung, C., and Winker, D. 2007. Warming trends in Asia amplified by brown cloud solar absorption. *Nature* 448:2, 575-578. doi:10.1038/nature06019

Raper, S.C.B. and Braithwaite, R.J. 2009. Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry. The Cryosphere, 3:183-194.

Rees, H.G. and D.N. Collins, 2006. Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming *Hydrological processes* 20(10), 2157-2169.

Ren, D., Karoly, D.J, and Leslie, L.M. 2007. Temperate Mountain Glacier-Melting Rates for the Period 2001–30: Estimates from Three Coupled GCM Simulations for the Greater Himalayas, Journal of Applied Meteorology and Climatology, 46(6): 890-899.

Severskiy, I. 2009. Current and projected changes of glaciation in Central Asia and their probable impact on water resources, (in) Assessment of Snow, Glacier and Water Resources in Asia, IHP/HWRP – Berichte, Heft 8, Koblenz 2009, ISSN 1614-1180 (selected papers from the workshop in Almaty, Kazakhstan, 2006).

Shangguan, D., Liu, S., Ding, Y., Ding, L., Xiong, L., Cai, D.,Li, G., Lu, A., Zhang, S., Zhang, Y. 2006. Monitoring the glacier changes in the Muztag Ata and Konggur mountains, east Pamirs, based on Chinese Glacier Inventory and recent satellite imagery, Annals of Glaciology,43(1):79-85.

Singh, P. and L. Bengtsson, 2004. Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. *Journal of Hydrology* **300**, 140-155.

Sreelata, M. 2006. Indian monsoon intensified by climate change, Science and Development Network, http://www.scidev.net/en/news/indian-monsoon-intensified-by-climate-change.html

USAID [United States Agency for International Development] Asia. 2010. *Black Carbon Emissions in Asia: Sources, Impacts, and Abatement Opportunities*. USAID Regional Development Mission for Asia, Bangkok, Thailand.

Wake, C.P. 1989. Glaciochemical investigations as a tool for determining the spatial and seasonal variation of snow accumulation in the Central Karakoram, Northern Pakistan. Annals of Glaciology 13:279-284.

Watanabe, T., Lamsal, D. and Ives, J.D. 2009. Evaluating the growth characteristics of a glacial lake and its degree of danger: Imja Glacier, Khumbu Himal, Nepal." *Norsk Geografisk Tidsskrift,* Vol. 63: 255-267.

WHO [World Health Organization] 2005. *Human Health Impacts from Climate Variability and Climate Change in the Hindu Kush-Himalaya Region: Report of an Inter-Regional Workshop*. WHO Regional Office for South-East Asia, Mukteshwar, India.

Xu, B., Xua, B., Caob, J., Hansen J., Yao, T., Joswiaa, D., Wang, N., Wua, G., Wang, M., Zhaoa, H., Yanga, W., Liue, X., and He, J. 2009. Black soot and the survival of Tibetan glaciers. *Proc Natl Acad Sci USA.*

Yao, T., Wang Y., Liu, S. Pu, J., Shen, Y., Lu, A. 2009. Recent glacial retreat in the Chinese part of High Asia and its impact on water resources in Northwest China, in: Assessment of Snow, Glacier and Water Resources in Asia, IHP-UNESCO/HWRP-WMO – Berichte, Heft 8, Koblenz 2009, ISSN 1614-1180 (selected papers from the workshop in Almaty, Kazakhstan, 2006).

Zemp, M., Roer, I., Kääb, A., Hoelzle, M., Paul, F., and Haeberli, W. 2008. Global Glacier Changes: facts and figures. World Glacier Monitoring Service, UNEP, 88 p.

ISBN:978-92-807-2898-9.

Zemp, M., Hoelzle, M., and Haeberli, W. 2009 Six decades of glacier mass balance observations: a review of the worldwide monitoring network. Annals of Glaciology, 50:101-111.