Collaboration for Environmental Evidence
Library

CEE review 10-008

WHAT IS THE EVIDENCE FOR GLACIAL SHRINKAGE ACROSS THE HIMALAYAS?

Systematic review

MILLER, J. [1], REES, G. [1], WARNAARS, T. [1], YOUNG, G.[2], COLLINS D.[3] & SHRESTHA, A[4].

[1] Centre for Ecology and Hydrology Wallingford, Maclean Building, Crowmarsh Gifford, Oxfordshire, OX10 8BB

[2] Wilfrid Laurier University, Canada

[3] University of Salford

[4] International Centre for Integrated Mountain Development

Correspondence: J. Miller *millj@ceh.ac.uk*

Draft protocol published on website: 21 July 2010 - Final protocol published on website: 8 December 2010 - Draft review published on website: 4 March 2011 – Final review posted on website: 19 February 2013

Cite as: Miller, J., Rees, G., Warnaars, T., Young, G., Collins D. & Shrestha, A. 2013. What is the evidence for glacial shrinkage across the Himalayas? CEE review10-008. Collaboration for Environmental Evidence: www.environmentalevidence.org/ SR10008.html.

Summary

1. Background

There has been concern in the scientific community surrounding the claim that Himalayan glaciers are shrinking at an alarming rate as a result of climate change, leading to significant impacts on the water resources of populations in the downstream basins. Despite much research, there remains no clear understanding of how glacier shrinkage varies across the region, or how it might impact downstream stakeholders. Clearly this hinders well-informed, evidence-based decision and policy making. A rigorous systematic review, to discern what is the evidence about glacier shrinkage across the Himalayas, is a major step to support policy-making in the region.

This systematic review assesses the primary evidence regarding physical changes in glaciers in order to ascertain what evidence is available, whether glaciers are shrinking in mass, reducing future melt-water availability, and whether the rate of shrinkage is changing. Four main measurement types have been employed to assess such changes: terminus position, area, volume, and mass balance. Some measurements are more appropriate and indicative than others in assessing changes in glacier mass. As well as assessing the available evidence, the review provides an appraisal of current understanding and corresponding knowledge.

2. Objectives

The primary objective of this systematic review is to compile the evidence relating to the question;

- What is the evidence for glacial shrinkage across the Himalayas?

A series of secondary questions have been identified that focus the research and reporting of the review;

- *Are glaciers shrinking or growing in mass, and are there regional differences?*
- *Is the rate of glacial shrinkage changing across the region?*
- *In what areas of research is evidence lacking and how best could future work ensure a more complete evidence base is developed?*

3. Methods

Systematic searches of electronic databases, internet search engines, websites of specialist organisations and expert consultation were employed to identify published and unpublished literature relevant to the review question.

The following predefined inclusion criteria were applied to each article identified, in order to refine the search results and select articles relevant to the review:

Relevant subject: Glaciers within the Himalaya, Karakoram, and Hindu-Kush mountain regions that feed the Ganges, Indus and Brahmaputra river basins.

Types of exposure: Climatic changes

Types of outcome: Changes in the physical state of glaciers post Little Ice-Age (c. 1860AD).

Types of study: Primary measurements of glaciers, presenting comparisons in the physical state of glaciers over time in mass balance, volume, area, and terminus.

All available data from selected studies were assessed using objective quality criteria that allowed relative confidence of data representativeness and accuracy to be assigned. Method of measurement and clarity/quality of reporting were similarly assessed. Standard meta-analysis was deemed inappropriate, so, a narrative approach was applied, presenting quantitative data in order to inform thematic analysis of evidence.

4. Main results

Application of the above criteria identified 52 studies for review. The majority of these studies focused on Himalayan glaciers feeding the Ganges and Indus basins. Few studies exist for glaciers of the Karakoram and Hindu-Kush mountain ranges, or for those that feed the Brahmaputra river basin. There is a scarcity of good-quality data prior to 1960, and all data prior to 1900 were deemed to be of uncertain accuracy. Most studies report changes in terminus positions, and, indeed provide the only means of describing long term (>50 years) change.

Collating the findings from all available measurement types, through application of a confidence matrix, it was possible to provide an objective assessment of change. Shrinkage of glaciers was the predominate pattern observed across the studies considered. However, there was a weaker indication of regional differences between the eastern/central Himalaya and western Himalaya/Karakoram, whereby the latter showed some evidence of growth and fluctuation.

Analysis of quantitative measurements corroborated narrative findings but went further in allowing additional aspects of change (e.g. relative change/rate of change) to be assessed. Mass balance and area data were found to provide the most rigorous indicators of changes in glacier mass, also indicating that, within a wider pattern of shrinkage, high inter-annual variability can exist, even growth, which might not be demonstrated without more continuous measurements. Taking area-loss data as indicative of shrinkage, average annual loss in the greater-Himalaya is estimated to be 0.4-0.5% per annum since the 1950s. There was no consistent evidence to conclude the rate of shrinkage was increasing.

5. Conclusions

Systematically reviewing the available evidence has enabled greater transparency and objectivity in the interpretation of evidence on glacier shrinkage. Too often, the rhetoric surrounding Himalayan glaciers has focused on isolated data or individual perceptions that neither provide an objective or systematic assessment of the evidence base, nor provide a true representation of physical changes.

Results from the review indicate a general trend of glacial shrinkage across the Himalayan region. However, there is a lack of data from which to assess regional variation and rates of change, or provide quantitative assessments of relative changes in glacier mass. Further research should focus upon mass balance and area measurements from glaciers that have already been studied and in data sparse regions (Karakoram and Hindu-Kush), also where the threat to downstream fresh-water availability is greatest (Indus basin). Greater use of remote-sensing observations is recommended as they allow cross-border assessments and reduce the costs/difficulties in accessing such terrain. Systematic research on benchmark glaciers and standardised reporting will enable more robust analysis and provide better information for users, especially when trying to predict future impacts of climate change within the region on water resources.

It is hoped this review will go some way to realizing the immediate needs for systematic measurement and reporting to inform future research, along with providing an objective source for discussion of the available evidence. This review has not sought to provide an assessment of how glacier shrinkage compares to other glacierized regions of the world or to provide future predictions of change.

1. Background

1.1 Introduction

Mountain glaciers are amongst the most sensitive and readily visible indicators of climate change (Kaab et al, 2007). Worldwide, glaciers have been reported to be generally retreating since the end of the little ice age (Mayewski et al, 1980; Grove, 2004), dated between AD1700-1850. There is concern in some quarters at the rate of retreat of Himalayan glaciers (Barnett et al, 2005) as they are claimed to be vital sources of freshwater in one of the world's most populous, economically important and politically sensitive regions.

It has been claimed that Himalayan glaciers will disappear by 2035, leading to widespread and catastrophic water shortages (WWF, 2005). Repeated by the Intergovernmental Panel on Climate Change (IPCC) in their 2007 assessment report (IPCC, 2007), these claims were recently exposed (Cogley et al, 2010) as having limited scientific basis, and have forced the vice-chairman of the UN's climate science panel to admit mistakes were made in producing the report. The claims appear to originate from a press interview of an Indian glaciologist in 1999, who, it is thought, misread findings of an earlier study (Kotlyakov, 1996), which suggested that, world-wide, mountain glaciers would be drastically reduced in volume by 2350. This study never suggested glaciers of the Himalaya and Karakoram would completely disappear. Such lack of scientific rigour and disregard of proper review procedures, coupled with a degree of journalistic licence, has resulted in many sceptics doubting scientific evidence used within such reports. The resulting furore demonstrates the importance of conducting reviews systematically. Only with transparent collation of evidence, based upon objective protocols, will truly critically appraised syntheses be available.

Despite much research, there remains no clear understanding of how glacier shrinkage varies across the region or how it might impact downstream stakeholders. Clearly this hinders well-informed, evidence-based decision and policy making. A rigorous systematic review, to discern *what is the evidence about glacier shrinkage across the Himalayas,* is a major step to support policy-making in the region, supporting the Department for International Development's (DFID) increasing reliance on systematically derived evidence upon which to base policy decisions (*pers. comms,* 2010).

Studies that collate evidence across the region generally indicate that glaciers in the Himalayas have retreated since the early 20th Century (Raina, 2009; Mayewski & Jeschke, 1979; Rees, 2008). However there are a few exceptions showing glaciers advancing in certain areas (Hewitt, 2005), or exhibiting conflicting behaviours within the same region (Fushimi et al, 1979). Such studies highlight the potential difficulties in characterising glacier retreat or advance across regions, and both also point to the importance of localised factors. Unfortunately, few studies draw on primary sources for their conclusion in a systematic manner, and instead reference findings from other sources without due consideration of the methods and accuracy applied.

Systematic reviews apply rigour and objectivity through all stages to provide such transparency in method and provide an independent approach to the available evidence (CEBC, 2010). Applying such objectivity allows the spatial and temporal patterns to be identified according to the relative accuracy and weight applied to evidence so that as complete a picture as possible is gained of glacier changes across the region. Such an approach also serves to highlight quality data and point to deficiencies in monitoring programmes across sparse areas that will not allow any regional syntheses to be possible.

It is considered that this review will be particularly useful to those responsible for regional water resource planning and natural hazard management. However, evidence pertaining to water resources and impacts upon human populations downstream of glacierized areas will not be systematically assessed within this particular review, merely considered to frame the review findings implications for policy and research.

1.2 Geographical and temporal extent of the review

For the purposes of this study, we define the Himalayan region as those mountainous areas of the Hindu Kush, the Karakoram and the Himalaya within the watersheds of the Indus, Ganges and Brahmaputra rivers (Figure 1). The temporal focus is solely upon measured data from the region post-1860 AD, marking the end of the Little Ice Age maximum extent and the beginning of glacier measurements within the region.

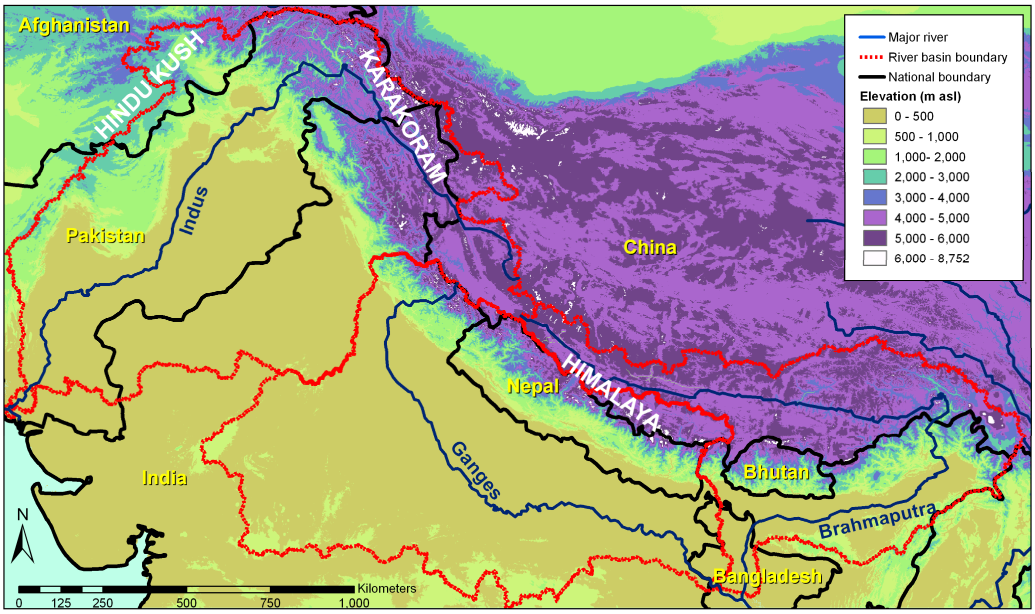

Figure 1 Geographical extent of the review

1.3 Regional climate

The Himalayan region is characterized by a diversity of climate. The eastern part of the region is dominated by the monsoon. Light winter precipitation contrasts with the torrential rains (snowstorms at higher altitudes) of summer. Glaciers, thus, gain mass from snowfall while also providing melt-water when temperatures are relatively high at lower altitudes. These glaciers are at the same time accumulating mass in their upper reaches, while losing mass in the lower parts, termed ‘summer-accumulation type glaciers’ (Ageta & Higuchi, 1984). In the east, the seasonal (summer) meltwater component of river flow is much less significant than that from monsoon rainfall (Kattelmann, 1993).

Moving westward along the Himalayas, monsoon intensity diminishes to such an extent that in the Karakoram it is only in an exceptional year that there is intensive summer rainfall. The lower mountains of south west Kashmir tend to receive heavy monsoonal summer storms, which can be the source of floods, but the Karakoram proper is usually much less affected by the monsoon than the Himalaya. Rainfall in the Hindu Kush is more influenced by Mediterranean disturbances in winter and spring, producing less annual rainfall on average than the Karakoram region (Winiger et al, 2005). The Karakoram receives much of its precipitation from winter storms coming from the west. Glaciers here typically experience winter accumulation and summer ablation. Mountain communities and more arid downstream areas are thus more likely to rely on glacier meltwater for river flows during dry periods. However, the exact contributions of runoff from glaciers can vary widely between Indus tributary river systems (Thayyen & Gergan, 2010), while total annual runoff in downstream reaches is more affected by precipitation than glacier mass balance (Winiger et al, 2005).

Besides the seasonal contrasts in the spatial distribution of precipitation, total volume of precipitation varies enormously; from some of the heaviest annual precipitations in the world on the southern flanks of the eastern Himalaya, to the much more arid mountains of Xizang in China (Thayyen & Gergan, 2010).

Mountain ranges the world-over are characterized by sudden changes in climate over very short distances. Slopes facing rain-bearing winds are typically much wetter than lee slopes; radiation climates change suddenly from sunny slopes to slopes in shadow; temperatures change with elevation. Local variations are particularly marked in the Himalayan region where local relief can be extreme.

Glacier extent and mass balance are greatly affected by differences in climatic inputs and, thus, it is not surprising that there is considerable variation in rates of mass loss, or gain, on glaciers within the region.

1.4 Cryo-hydrology

High mountain hydrology is very dependent on temperature fluctuations around the freezing point of water, with changes in the glacial environment (cryosphere) having impacts upon downstream hydrology as a result of glacier melt. There are two basic components of precipitation – rain and snow. Rainfall usually predominates at lower elevations with higher elevations characterized by snowfall and the very highest elevations generally below freezing point. In the highest elevations, where snow accumulation exceeds snowmelt, glaciers form and the resulting ice slowly moves down-slope to the valleys below. When a glacier is in equilibrium with climate, accumulation in its upper portion is balanced by melt of snow and ice in its lower parts.

There are three basic components of stream-flow in a mountain glacier environment:

1. Rainfall;
2. Snowmelt;
3. Icemelt;

These components vary in relative importance from season to season, from year-to-year, and from one part of the Himalayan region to another.

With rising global temperatures, the hydrology of the Himalayan region is changing. Changes in the glacial environment (cryosphere) that provides a store of potential melt-water will have impacts for downstream rivers. Both permafrost and glacier covered areas are reducing in extent in many parts of the region (Rees, 2008). Increasing temperatures cause a greater proportion of total precipitation to fall as rain instead of snow and thus snowmelt starts earlier in the season and winter is essentially shorter. These changes are potentially important in affecting the flow regimes of rivers and on subsequent water use. With temperatures trending upwards, it is to be expected that glaciers will, in general, lose mass – termed 'glacier shrinkage'. Note that this is not necessarily the case where increased snowfall more than compensates for increased melt in the lower reaches of the glaciers. However, while in a majority of years glacier shrinkage may be expected as a result of negative mass balances, there may well be years of positive mass balance and increase in glacier volume embedded within the general trend of shrinkage.

In those areas, and at those times when there is glacier shrinkage, then a further component to the cryosphere hydrology is introduced – the additional water to the annual downstream runoff as a result of water being released from permanent storage in glacier ice. Melting of glaciers is a normal process and is an important component of basin hydrology. What is of concern is enhanced melting that negatively impacts the "health" of a glacier and results in shrinkage of the glacier. The resulting shrinkage, while in the short-term providing additional melt water, will in the long-term inevitably lead to diminished stores of melt water being available. *Thus it is the main purpose of this study to identify changes in glacier shrinkage, which, in turn, will have consequences for the long-term discharge of downstream rivers.*

Glacial lakes can form from enhanced melting of glaciers and localised geological processes. The review will not separately consider evidence relating to the formation of glacier lakes and the potential flooding that can occur when the structures containing such lakes fails. Only where primary data on both glacier and downstream glacier lakes are presented will such relationships be assessed.

1.5 Measurements of change in Himalayan glaciers

In order to assess change in a glacier, so we might understand if the glacier has exhibited shrinkage or growth, a range of measurements can be applied. Each measure has its pros and cons, and the main types covered by studies in the Himalayan region are discussed below. Each measurement fundamentally provides an indication of change in mass of the glacier, with some more robust in providing a representative measure. The measurements have been ranked relative to each other by how representative each is in providing an indication of either glacier growth or shrinkage.

Mass balance
Mass balance provides the most representative measure of change when considering the shrinkage and growth of glaciers (Kaser et al, 2003). The mass balance of a glacier describes the difference between accumulation and ablation, normally, and

preferentially, over a year long period. This is determined by measuring the amounts of snow/ice accumulation compared to the amount removed via ablation. The difference between the two measures provides an indication of whether the glacier has a positive mass balance (accumulation > ablation), or negative mass balance (ablation > accumulation). Mass balance is conventionally expressed as metres of water equivalent (m.w.e.), expressing the average thickness change across the glacier surface. The measurements do not however provide a measure of the actual total mass of a glacier, and thus the volume of melt-water it contains.

In order to identify trends in mass balance, measurements should be conducted over a number of years, preferably decades. Unfortunately in the Himalayan region most records are very short compared to well studied regions such as the Alps, as well as being very sparse; evident in the lack of comparative data from the region within the international Glacier Mass Balance Bulletin (Haerberli et al, 2009). Another difficulty arises from the very difficult terrain of the Himalayan region which makes it impractical to travel to, or on, the vast majority of glaciers. Such difficulties cannot be overcome by the use of helicopters, as in other lower mountain ranges such as the Alps, due to cost and both the thinness of the air and the unpredictable nature of the weather. Many glaciers are also avalanche-fed, increasing the complexity and danger of making measurements. Remote sensing of mass balance is being applied within the region (Berthier et al, 2005) but requires further development and validation before it can replace more established and accurate field-based methods.

Volume

Volume is the second most representative measure that can be taken to assess whether a glacier is shrinking or growing in mass. Comparing glacier volume over a period of time provides a measure of both how much the glacier has changed in mass (applying an average density to the ice) and how that change relates to the total size of the glacier. Theoretically, this would allow determination of how long it would take for such a glacier to disappear. There are however numerous difficulties in accurately measuring the volume of such large and variable expanses of glacier, particularly in determining ice thickness profiles, and especially in such variable and difficult terrain. Most values are based on simplified topography and glacier outlines derived from maps. It must also be considered that extrapolating a single average rate of change would not represent the changing melt dynamics that would occur over time as the glacier surface area and mean altitude shifted. As such, volume provides a representative indicator of shrinkage, albeit one that is highly prone to inaccuracy and error in measurement.

Area

Area is the third most representative measure of a glaciers change in mass. Changes in area only provide a snapshot of shrinkage in the aereal extent of glacier coverage. There is no indication of changes in the thickness of the glacier. The area can be measured in the field, but is more usually determined from aerial images, previously aerial photography and more recently remote sensing. Images must be clear of cloud cover and of sufficient clarity for detailed observation of glacier outlines to be determined. A major source of error arises from the difficulty of defining the edges and terminus of glaciers in their lower reaches where moraine/debris cover predominates. Data for glacier areas is thus highly constrained by the availability of clear images being available from which to calculate area, and also by the availability of trained researchers following standardised techniques for delineation.

Caution must be exercised in equating change in area with change in mass, but in assessing change across all exposed parts of glacier a robust indication of shrinkage can be obtained. Measurements do, however, provide perhaps the most reliable and indicative data from which to assess the relative scale of change against an informative baseline condition.

Terminus position

Terminus data provides the least representative measure of change in glacier mass. Comparing the position of a glacier terminus over time only provides a measure of whether that part of the glacier is receding or advancing. This is no indication of how the rest of the glacier is changing, either in area or thickness. Such measurements merely reflect changes in the lower part of a glacier, which are most responsive to short-term climatic changes. Terminus changes thus only provide a limited indication of shrinkage of the whole glacier.

Terminus position can easily be measured in the field (as the majority of historical measures have been), but recently aerial images or remote sensing are increasingly being used. For most glaciers, it is relatively easy to plot year-to-year changes in position of glacier termini; this has been done for many glaciers in the region (Bhambri & Bolch, 2009; WWF, 2005). However for many debris-covered glaciers this is far from simple, and thus many such glaciers are omitted from studies in the region. The situation is further complicated in the case of surging glaciers, of which there are many in the Karakoram region, where there have been sudden forward advancements, sometimes of several kilometres, resulting in a significant increase in glacier area with possibly no immediate loss in total glacier mass (Hewitt, 2005) In the years after a surge, mass loss can accelerate as a result of greatly increased surface area due to crevassing and increase in surface area, but such mass loss may be independent of any change in climate.

Surge glaciers excepted, it can be argued that, in general, glacier terminus retreat is *indicative* of glacier shrinkage. However it is not a robust measure of the state of the whole glacier, and the use of values referring to retreat of a glacier terminus should not reliably be used to infer quantitative analysis of glacier shrinkage.

2. Objectives

2.1 Primary objective

The primary objective of this systematic review is to compile the evidence relating to the question;

- What is the evidence for glacial shrinkage across the Himalayas?

2.2 Secondary objective

In order to answer the above primary question a series of secondary questions have been identified that will focus the research and reporting of the review;

- Are glaciers shrinking or growing in mass, and are there regional differences?
- Is the rate of glacial shrinkage increasing across the region?
- In what areas of research is evidence lacking and how best could future work ensure a more complete evidence base is developed?

3. Methods

This section details the systematic methods applied by the review team to identify and refine the search for available studies that would be used within the review. An *a-priori*, review protocol was developed and finalised following consultation and peer review (available at www.environmentalevidence.org/SR10008.html). This is followed by the quality appraisal approach developed to assess data extracted from the selected studies, and an outline of the approach whereby findings from these studies were synthesized in order to answer the review question.

3.1 Question formulation

This review was commissioned by the Department For International Development (DFID) to provide a systematic assessment of the evidence about glacier shrinkage across the Himalayas. The original question set by DFID (What is the evidence of changes in glacier melt across the Himalayas?) was further developed by the review team via consultation with the Centre for Evidence Based Conservation (CEBC). This consultation and development of the question through a period of scoping led to a review focusing on the measured physical changes in glaciers within the Indus, Ganges and Brahmaputra river basin catchments.

3.2 Search strategy

The search strategy was developed through consultation with CEBC and partners to ensure an unbiased and comprehensive literature sample. The search was limited to literature in the English language due to resource constraints. It was conducted over the period between the 20th July and 6th August 2010. However the review does acknowledge there is considerable literature in other languages that would be useful and could be implemented as an upgrade to this review.

3.2.1 Database search

Databases containing access to most of the journal papers provided the most substantial source of evidence for the review. Two of the most widely used computerised journal databases were searched - ISI Web of Science and Science Direct - along with searches of the following databases;

- BioOne
- Centre for Ecology and Hydrology Library Catalogue
- Directory of Open Access Journals
- Google Scholar (Searches of web based databases)
- Ingenta Connect
- J STOR
- NERC Open Research Archive
- Science
- Springer Link
- Wiley Interscience
- Zetoc

The method used a key-word search from a list of selected key words prepared by the review researchers (with input from partners) based on the title question as well as from the list of possible studies to be included in the review that are listed in the project proposal.

Test searches were conducted to develop an effective search strategy that would capture as much relevant literature as possible, validated through the testing of various search terms against existing reference lists from previous reviews on this subject area. Fundamentally these terms reflect both an optimum return of 'hits', refined and developed through consultation with review partners, and subsequent testing to ensure they reflect as complete a search for the subject considering resource constraints. The final search terms that were used, and the Boolean operators applied, are outlined in the following tables.

Words reflecting impacts and methodology

Glaci*	AND	(Himalaya*	AND	impact*
		OR Karakoram		monitor*
		OR Hindu Kush)		predict*
				evidence
				melt AND evidence
				measur*
				model*
				asses*

Words reflecting change in Himalayan glacier melt

Glaci*	AND	(Himalaya*	AND	melt*
		OR Karakoram		retreat*
		OR Hindu Kush)		shrink*
				chang*
				differenc*
				fluctuat*
				varia*
				"mass balance"
				"mass balance" AND melt*
				“Glacial lake*”
				Remote-sensing
				surge
				advanc*
				ablation

Words reflecting change in Himalayan glacier hydrological impacts

Glaci*	AND	(Himalaya*	AND	“water resources”
		OR Karakoram		climate
		OR Hindu Kush)		"climate change"
				hydrol*
	AND	(Indus	AND	temperature*
		OR Ganges		flood*
		OR Brahmaputra)		flow*
				streamflow*
				extreme*
				precipitation
				Jökulhlaup*

Words reflecting measurements and change in Himalayan glacier ice melt

(Himalaya*	AND	Ice AND	melt*
OR Karakoram			retreat*
OR Hindu Kush)			shrink*
			advance*
			change*
			differenc*
			fluctuat*
			Variation*
			“mass balance”
			"mass balance" AND melt*
			“Glacial lake*”
			GLOF
			distribut*

Words reflecting change in Himalayan glacier snow melt

(Himalaya* AND OR Karakoram OR Hindu Kush)	Snow AND	melt* retreat* shrink* advanc* change differenc* fluctuat* variation* "mass balance" "mass balance" AND melt* "Glacial lake*" distribut* ELA TSL AAR snowline

3.2.2 Selected organisation search

A number of selected international organisations linked with research into this subject area were searched for relevant material, namely;

- ICIMOD (International Centre for Integrated Mountain Development)
- FRIEND (Flow Regimes from International Experimental and Network Data)
- WWF (World Wildlife Fund)
- UNESCO (UN Educational, Scientific and Cultural Organisation)
- UNEP (United Nations Environment Programme)
- WGMS (world glacier monitoring service)
- IAHS (International Association of Hydrological Sciences)
- GLIMS (Global Land Ice Measurements from Space)
- DFID (Department For International Development)
- World Bank
- INSTAAR (Institute of Arctic and Alpine Research)
- NSIDC (National Snow and Ice Data Centre)
- IGBP (International Geosphere and Biosphere Programme)
- GWSP (Global Water Systems Project)
- IACS (International Association of Cryospheric Sciences)
- GCOS (Global Climate Observing System)
- GTN-G (Global Terrestrial Network-Glaciers)

All potentially relevant sources of evidence were recorded. The search terms were broad compared to the database search, and included these key search terms and Boolean operators where possible;

Glaci* AND (Himalay* OR Karakoram OR "Hindu Kush") AND melt*
Glaci* AND (Himalay* OR Karakoram OR "Hindu Kush") AND "climate chang*"
Glaci* AND (Himalay* OR Karakoram OR "Hindu Kush") AND evidence

Most of the organisations searched had fairly simple search engines available, and some had no functioning search engine, thus for each site the search had to be adapted. It was necessary to read through the titles of all the hits returned, as many were irrelevant. Thus the exclusion criteria developed were applied directly at reading of the returned titles.

3.2.3General web search

Both the Google and Bing search engines were utilised in a search of the internet using the same search terms as the organisation search. Only the top 25-50 hits were recorded as the quality of the material was perceived to be much less useful for the review than the peer reviewed sources after trial searches. Many were simply blog pages discussing the recent 'glacier-gate' incident. All the search results were then assessed using the inclusion criteria outlined in section 3.3.

3.2.4 Further sources and validation

Review partners were approached to provide specialist studies known to them that might otherwise be missed by standard searches, particularly where only hard copies might exist. A physical library of potential studies held by CEH was also searched.

A list of key studies was also identified by review partners that could provide further studies through scoping of reference lists from papers including: Bajracharya, et al. (2008); Bhambri & Bolch (2009); Dyurgerov & Meier (2005); Haeberli (2009); Mayewski & Jeschke (1979); Vohra (1981); Young & Neupane (1996); WWF (2005).

Additional studies identified from these publications were requested where available via inter-library loan. Not all literature identified by the searches was available within the time frame and resources of the review. A record of these was kept and is detailed in the appendices accompanying this review.

3.3 Study exclusion and inclusion criteria

3.3.1 Exclusion criteria

Due to the large number of results from the different searches a simple set of exclusion criteria were developed that could be easily applied at the title level to remove those papers that had nothing to do with the subject in question. If there was any uncertainty the paper was not excluded. The exclusion criteria considered 5 main points;

1. Subject – not Himalayan glaciers
2. Timeframe – not a study focusing on glacial changes in the last two hundred years
3. Comparator – no comparator for analysis of change (the study must conduct an assessment of change in glacier shrinkage, not be simply a point measurement)
4. Subject –biological or chemical studies
5. Outcome / measure –modelling based studies, as this review is assessing only measured changes

Two researchers independently applied the exclusion criteria to sections of the search results, recording their results so that a clear record of the process remains. Each researcher also checked 20% of the other researchers' results to ensure consistency in application of the exclusion criteria. A Kappa test was conducted on the results giving a Kappa value >0.95, indicating very good agreement.

3.3.2 Inclusion criteria

In order that only those sources of evidence that are relevant to the review subject are selected a set of inclusion criteria were developed prior to the review. These were developed from definitions of components identified as part of the review question (Table 1) and are as follows:

Table 1: Definition of components of the primary systematic review question

Subject	Exposure	Outcomes	Comparators
Himalayan Glaciers (Glaciers within the mountainous areas of the Himalaya, Karakoram and Hindu-Kush – that feed the Ganges, Brahmaputra and Indus rivers)	Climate and potential climatic changes, such as, changes in precipitation or temperature	Glacier fluctuation (variable rates of change, change in mass balance), leading to changes in downstream hydrology	Baseline data for glaciers, regional characteristics, localised factors

Relevant subject(s): Studies that focus upon the physical aspects of glacier fluctuation within the geographical scope of the Himalayan region, encompassing the mountain regions of the Himalaya, Karakoram and Hindu-Kush (Fig 1). This has been refined so that we only consider evidence on glaciers from these regions that feed the Ganges, Indus and Brahmaputra rivers, as shown in Figure 1**.**

Types of exposure: Studies that explore potential links between local, regional and global climate and glacier melt in the Himalayan region would be included. These studies must, however, use primary research data on glacier changes.

Types of comparator: Baseline studies for glacier condition, carried out since 1860 AD, will form the core baseline comparator from which to assess the relative change in glacier area and mass, in order to assess the potential changes in melt that may have occurred over that period. Baseline data must be available to the researcher for comparisons to be made (whether it is the physical map or actual photographs), with studies simply comparing recent data to referenced sources not being admissible.

Types of outcome: Evidence on glacial growth or shrinkage (wastage), where physical change in the glacier over time is assessed, forms the core part of the review. The study focuses on contemporary changes since the Little Ice Age (c. 1860AD), while geomorphic evidence relating to longer scale changes was not included. This encompasses the period in which measurements of glacial extent have been conducted within the region.

Types of study: All types of study that enable assessment of the physical change in glacier mass, volume, area and terminus position over time through primary measurements are included. Geomorphological evidence has not been included due to resource constraints; however the review team recognise the importance of such evidence, especially in developing an understanding of long-term changes in glaciers. Only English language references have been considered, again due to resource constraints, and the review recognises the existence of further evidence in other languages. Studies focusing on micro-scale changes or on biological or chemical changes are not included.

The inclusion criteria were first applied at the abstract level to remove citations that were clearly not related to the review subject. Where there was uncertainty, or the abstract was unavailable, the article was included for assessment at the full-text level. The remaining sources were then assessed at the full text level using these criteria but with a particular focus on whether the research was primary data, whether the method was clear enough for assessment, and finally that there is a clear comparator to assess change. The same process was applied to the web, organisation and grey literature sources.

Consistency in reviewer application of the inclusion criteria was tested by comparing the level of agreement of two sets of 100 independently identified articles at the abstract stage. Application of the Kappa statistic resulted in a score above 0.80, indicating very good agreement between the two independent reviewers.

3.4 Study quality assessment

To transparently assess the quality and appropriateness across the variety of data available, in providing evidence of changes in glacier mass within the selected studies, a relative confidence framework was defined comprising objective criteria.

Trial data extraction and synthesis identified four main measures of glacier change that are undertaken by glacier studies in the Himalayan region. These were ranked after consultation with review team members according to how well the measure represents the fundamental question of glacial shrinkage. Further details on the rationale for this ranking are included in Section 1.1 and Appendix C. The resulting ranking is shown below, where 1 is the highest (most robust) and 4 is the least ranked;

1. Mass balance
2. Volume change
3. Area change
4. Terminus movement

Considering each in turn, it was apparent that a diverse variety of methodological techniques are employed to determine each measurement. It was also not sufficient to assess studies solely on the basis of the measurement type rating alone because considerable variation exists in the quality and clarity of reporting of the method and results between studies. Simply applying a robust methodology is not sufficient cause for high confidence in data if such data are not backed-up by a detailed and transparent description of the process. Thus, an approach was sought that considers both the relative confidence ascribed to certain methodological approaches while also considering the clarity of the reported method and findings.

The assessment thus comprises two main aspects: first, how representative and accurate the methodological approach is in obtaining the measurement of change; and, second, the confidence assigned to the measurement when considering clarity of method and reporting. Five levels of confidence were expressed for each assessment, similar to the qualifiers to be used by the IPCC in the fifth assessment report (IPCC, 2010), from “very-low” confidence, to “very-high”. These can then be combined through the application of a confidence matrix table (Table 2). This section details the process by which criteria were developed to address the two main aspects, and how they were applied to the evidence.

Accuracy of measurement was trialled as a separate detail that would allow objective weighting of results according to the relative accuracy assigned to the results. However only 12 of the 52 studies presented a clear assessment of accuracy ascribed to the results presented, and analysis of the 12 studies indicated no consistent method for comparing reported accuracies, as each had been calculated using variable factors within the methods employed. Some studies merely state a figure of accuracy without any firm basis for its derivation, while others simply apply an assumption based on the method or previous reporting. Most of the sources reporting any form of accuracy measure are remote sensing studies measuring glacier area, generally reporting accuracies of between ±15-30m, well within reported changes (<5% of the measured change). Some of the data presented by Salerno et al (2008) did contain some high potential errors (>20% of the measured change), but it is difficult to assess whether such inaccuracies could exist within other studies that do not provide such a detailed and honest assessment of measurement accuracy. It was deemed that the rating of method employed generally reflected the relative accuracy of results from all studies, and that further confidence in the accuracy could be considered by objective assessment of the method reporting.

Ideally all reported data should be assessed with some objective criteria that could allow a quantitative assessment of accuracy, similar to the approach employed by Diolaiuti et al (2003) in assessing the accuracy of a range of historical data sources. Further assessment of the inaccuracies that can be obtained in many of the measurements detailed, and how more standard assessments of accuracy are obtained, can be found in a paper assessing glacier mapping in the Himalaya by Bhambri & Bolch (2009). However, as shown by both cases, it is necessary to have the raw data (maps, remote sensing images, etc); as only so much can be determined from the studies’ reported findings.

Mapping of the glacier terminus provides the only form of evidence pre 20th Century for use in baseline comparisons of terminus changes, but there are serious doubts over the accuracy of all these earliest measurements and accounts. Bhambri & Bolch (2009) question the accuracy of maps produced pre 1900 of the Indian Himalaya. They highlight both the inaccurate delineation of earlier maps reported by more recent expeditions (primarily due to a lack of training for surveyors in glacier morphology), and the inherent shortcomings of the techniques available at the time. Diolaiuti et al. (2003) also raise similar concerns after assessing maps of Liligo glacier pre 1900, finding potential errors in excess of 50%. With the advent of the Geological Survey of India (GSI) initiating a programme of measurement of glaciers during 1906-1908, as part of the programme of the Commission International des Glaciers, more standardised and systematic measurements were taken that provided more accurate baseline measurements for future studies. Establishing accurate baseline estimates of glacier position is vital as they fundamentally provide all further assessments of change a benchmark. The review has not been able to undertake appropriate assessments of the pre 1900 data reported in some studies due to many of these original sources being inaccessible, however, even if they were, the review's data confidence assessments probably would have rejected them. The review, therefore, excludes quantitative evidence from measurements pre 1900 due to the surrounding uncertainty in the methods applied and the associated topographic mapping imprecision.

Measurement

Differing methodological techniques were identified and ranked. Table 2 outlines the different methodological approaches employed for each measurement and the relative confidence assigned in providing a rigorous measurement. The technical basis for the relative confidence ascribed to methods is included in Appendix C.

Table 2: Confidence assessment rating of various methodological approaches to obtaining measurement of glacier change

	Relative confidence rating of method – with increasing confidence signalling greater accuracy and scientific rigour Very low → Very high				
Mass balance	Vertical balance profile / Climate records	Flux divergence method	Hydrological method	Geodetic method / Remote sensing	Glaciological method
Volume	Thickness profiling & Field Mapping	Remote sensing with baseline field mapping	Remote sensing and digital elevation model		
Area	Description	Terrestrial photography	Field mapping / Mapping from aerial photographs	Remote sensing with baseline geo-referenced field mapping	Remote sensing
Terminus	Description	Terrestrial photography	Field mapping / Mapping from aerial photographs	Remote sensing with baseline geo-referenced field mapping	Remote sensing

Method and Reporting

For each selected item of evidence, it was also necessary to assess the study's clarity in reporting the method and results of the measurements taken. Clear differences were evident even between studies employing the same methods to obtain the same measurement. Thus, criteria were developed that would allow an objective comparison of how clear the studies method and reporting were, in order to identify those which gave greater confidence. A range of assessment "areas" were defined and various criteria specific to each area were assigned. Table 3 outlines these assessment areas and the criteria for ascribing confidence within each study. The confidence rating across all areas was then combined to provide an overall rating of confidence for the method of reporting, from very low to very high. Further details on the assessments and the associated ranking are included in Appendix C.

Table 3: Confidence assessment of method and reporting of evidence

	Confidence assessment scoring				
Assessment area	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Method description	Not given	Unclear	Mentioned	Clear	Very clear
Uncertainty	No mention	Unclear	Mentioned	Accuracy only	Fully Given
Standardised approach	No standard	Unclear	Consistent approach	Elements of standardised approach	Standard[1] method employed
Research team	No mention	Other	Previous team[2]	Team	Author
Reported resolution	Vague	Decade	Year	Season	Date
Reported location of measurements	Vague	Country	Region	Glacier	Precise location
Frequency of measurements	1 in 50 years >	1 in 25 > 1 in 50 years	1 in 10 > 1 in 25 years	1 in 5 > 1 in 10 years	>1 in 5 years
Clarity of reporting	Unable to extract evidence	Unclear	Requires effort	Clear	Very clear
Validation of evidence	No validation	Unclear	Mentioned	Partial validation	Full validation

Confidence matrix

In order to consider jointly both the type of method and quality of reporting, a matrix table that combines the two confidence assessments has been developed, illustrated in Figure 2.

---

[1] Use of referenced method for measurement

[2] Where data has been collected by a previous team, but the methodology has been detailed in the cited source used within this study.

The matrix is applied as follows: first, the methodological approach is assigned an x-coordinate on the matrix (A-E) according to the relative scoring of the approach from Table 2 for that measure (very low=A, very high=E). For example, when considering the satellite imagery approach for terminus measurements a confidence rating of 'very high' is qualified from Table 2, thus a value E is assigned within the matrix, designating it as the approach that gives the greatest confidence. Secondly, the quality of reporting is assigned along the y-axis (1-5) according to the assessment reached from Table 3 (very low=1, very high=5). Thus a study having a high confidence in reporting is assigned the value 4.

The two assessments can then be combined to define a co-ordinate within the matrix, from A1 through to E5, and provide an overall assessment of the confidence of the item of evidence. This follows a similar approach as outlined by the IPCC (IPCC, 2010), whereby a level of confidence is used to synthesize judgement on the validity of findings through evaluation of evidence. As shown below in Figure 2, the cells within the matrix have been coloured, and each colour has been assigned an overall confidence assessment from 'very low' to 'very high'. For use within the review, only evidence awarded an overall assessment of medium or above will be used in any quantitative analysis. The overall outcome of this matrix approach is that as the confidence in the methodological approach reduces, so the quality and clarity of the method and reporting must be increased to provide a more confident assessment of the measurements accuracy and robustness. In this way the reviewers were able to interpret the findings from studies to ascertain those that employed clear and robust methods in an objective manner, while also considering the general opinion of how accurate the methodological approach is, rather than a subjective 'feel' for assessment.

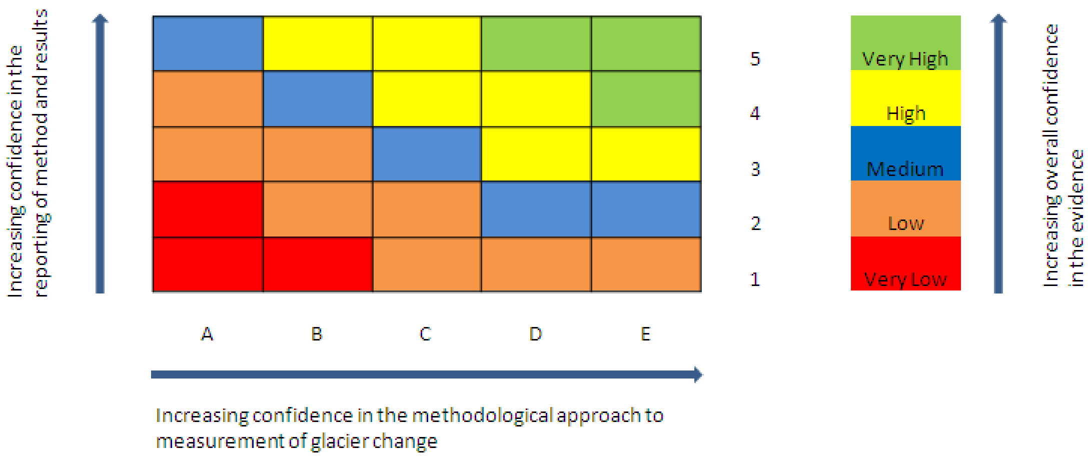

Figure 2: Confidence matrix, illustrating how data is given an objective score that indicates the relative confidence ascribed to the data; combining method and reporting assessments.

To clarify the process of overall confidence assessment, let us consider a hypothetical study that comprises four quantitative positions for the fluctuation of a specific glacier terminus, from a composite of three different methodological approaches. The first measurement is a simple description of a glacier terminus given in the late 19th Century, with little detail or clear reference to a geographic point. The next available value for the glaciers position comes from a Geological Survey of India (GSI) map from around the early 1960s, complete with scale and geomorphic detail and completed by a trained team using standardised practices. The final two positions are from the 1990s and are derived using satellite imagery, analysed using advanced software by a trained team who are able to geo-reference the earlier map. Consider first the earliest description and any assessment of change compared to the subsequent mapping of the glacier. With no clear geographic position to compare to and no reporting of any standardised approach this measurement would likely only score A1-A2 on the matrix, and would not be suitable quantitative data, but could inform some narrative. Next the author compares the first satellite image to that of the GSI map, clearly stating the method employed and how it was geo-referenced using ground control points, but with no clear mention of error or accuracy. Using the assessment ranking we define the methodological approach as having a medium value, with the reporting criteria eliciting an overall assessment of high-confidence. The overall assessment, for this measure of change, results in a matrix value of D3, and a resulting high-confidence. The final measurement of change is taken from a comparison of two satellite images within a 10 year period with full reporting of accuracy and error, and clear reporting of the method, resulting in a very-high overall assessment matrix value of E5. So finally we have two measurements of change in terminus position, one of higher confidence than the other, plus a rejected description that was not deemed of sufficient quality for use in a quantitative analysis. For evidence deemed of lower confidence in the accuracy in the methodological approach, the clarity of the reporting and quality of the method applied must be of the very highest quality. This reduces the uncertainty surrounding the methods accuracy and provides a more robust piece of evidence.

3.5 Data extraction

Data were extracted using a standardised template (Appendix B), developed through an iterative process of narrative and data extraction, facilitating extraction of data from the diverse study types. A study sheet records the overall details about a study, with particular emphasis on methods employed and the components of the evidence conveyed that would affect the assigned confidence. Data from each study were then recorded on one of two sheets, one set up for recording data from single glacier studies, the other for studies that cover wider areas of glacier coverage as a grouping. Quantitative data were assessed using the study quality assessment tools outlined in section 3.4. The extraction summary details for each study assessed are provided in Annex A.

Systematic extraction of data was made difficult by the diverse study types and lack of standardised reporting of research findings. Much effort was expended in actually abstracting the relevant data from the study due to a lack of clear reporting, particularly of calculations used to derive reported numerical conclusions. Defining baseline conditions was also problematic, especially with data referring to terminus fluctuations. Changes were reported, but with no direct reference to the relative scale of this change compared to the glacier as a whole, plus indications of how accurate the measure was rare or typically un-systematic in derivation. Where multiple studies approached an assessment of the same glacier there was a particular effort made to ensure data would be comparable.

3.6 Data synthesis

Trial synthesis of data was conducted after discussions with CEBC and statisticians at CEH. The problem with conducting any kind of traditional statistical analysis of the data, or a meta-analysis, arises because data are derived from different types of measurements, from many different glaciers, and over differing timescales. To address the question “are glaciers shrinking or growing”, and “is the rate of change increasing”, we must first establish what period of time we are comparing. Data from glaciers in the region are not neatly ordered giving measurements every year, or even every decade. What is available is a set of independent measurements from different glaciers or regions, at different times, making comparisons difficult. Studies that investigate multiple glaciers, over a similar time period using a consistent method, do however provide a source of comparable data, but lack the detail available from studies on a single glacier. Some narrative of such findings is reported where this provides evidence to answer the questions considered.

Accordingly, most of the available data were deemed unsuitable for standard quantitative meta-analysis. However, a significant amount of data were available to allow a narrative synthesis of the available evidence, with a thematic analysis of the data features. This approach allows for a wide range of different research designs to be integrated in order that we might approach the review question with as much evidence as possible. Mays et al (2005) describe that the narrative approach will ‘summarise, compare, explain and interpret evidence of all types relevant to a particular question’. The thematic analysis will help identify the main themes arising from the evidence-base. Then, through application of the quality assessment, applied to each measurement taken, it is possible to weight the findings so that a systematic appraisal of elements within the narrative synthesis could be conducted.

In the context of this review, the approach undertaken considers the question at hand via two levels of synthesis that relate to the primary question, and help focus analysis of the review results in answering the secondary questions;

1 What is the *available* evidence concerning changes in glacier shrinkage in the Himalayas? – This focuses upon analysis of results from the review statistics.

2 What is the evidence *showing,* concerning changes in glacier shrinkage in the Himalayas? – Here the available evidence is approached, considering each measurement type, to ascertain if there are particular ‘themes’ in the various study findings, while considering the relative weight ascribed to the various approaches.

The first question/analysis provides a picture of what kind of evidence is available on the subject of Himalayan glaciers, in the context of studies assessing shrinkage/growth in glacier dimensions. Numeric data are not required, rather an overall assessment of glacier change for the particular glacier/region in focus were extracted to form part of an overall narrative synthesis. The second question/analysis uses the extractable quantitative data from the sources to explore the relationships exhibited within the synthesised data, to identify themes or patterns that exist within the data, via a thematic analysis of data presented in relative formats. This output will go towards examining whether conclusions drawn by existing research, from the various studies, are justified when considering the whole available evidence base.

4. Results

4.1 Review statistics

At each stage of the refinement of search results, those sources that were either rejected or included were recorded. The results of this process can be seen in

Figure 3. Full records of all studies that passed application of the inclusion criteria at abstract level and were read at full text are contained in Appendix A. Full records of all search results are included in Annex B.

Database searches resulted in 1465 articles after all duplicates retrieved by different database engines had been removed. No articles from the searches on either ice or snow have been included as the hits were both too numerous (11,444) and spurious. A test on the first 10% retrieved showed that, of this selection, only three articles passed the exclusion criteria, and all three had already been uncovered by the other various searches. Once the exclusion criteria were applied at the title level 357 (380 minus duplicates) separate articles either passed the exclusion criteria or, where there was ambiguity, were passed on for reading the abstract. The articles read at the abstract level are listed in Annex B.

World-wide-web searches from 400 potential sites returned only 8 sources where the results passed the exclusion criteria. Of these, six had already been uncovered from database searches. Most of the hits returned from searches were blogs, many with practically no scientific element. News articles were the second most numerous, however most of these reported general findings without traceable evidence.

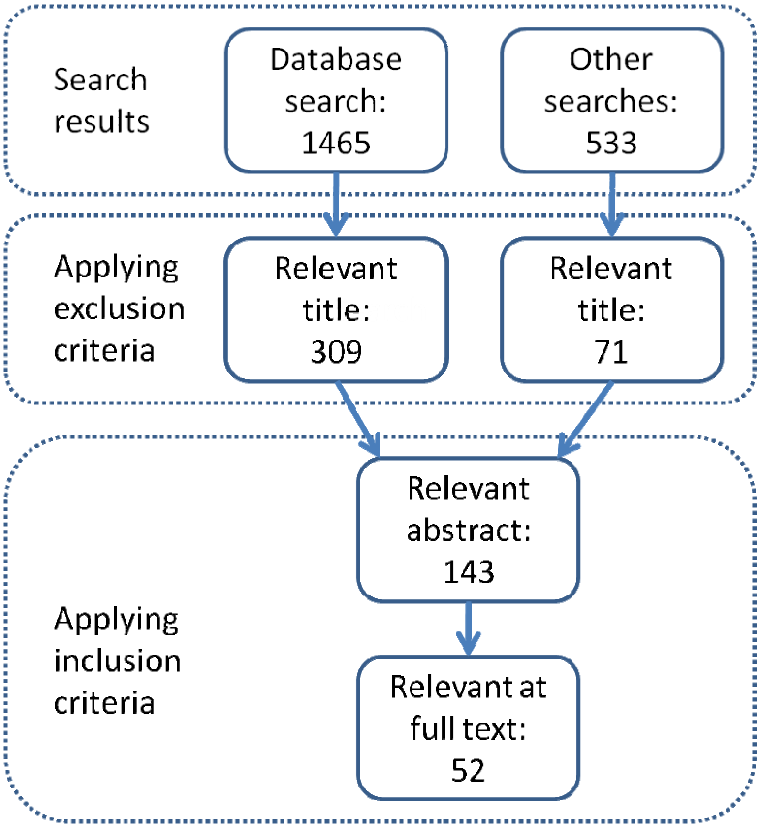

Figure 3: Number of studies retrieved in the review search as passing each stage of relevance assessment

An additional source of articles, not covered by existing database searches, was the Japanese publication *Bulletin of Glaciological Research (Seppyo)*, which is directly accessible from the internet. The same protocol was applied at the title level, resulting in an additional 22 articles being available for the review. After removing duplicates obtained from other sources and applying the exclusion criteria at title level 6 extra articles were included.

Searches of the selected organisations websites generated 71 articles that were relevant to the topic of Himalayan glaciers. From this, only 13 passed the exclusion criteria, mostly due to the fact that many were review papers or reports without primary data.

Members of the review team put forward an extra 14 articles considered relevant to the review, mainly grey-literature or specialist papers. Searches of the reference list of key articles revealed a further 26 extra articles, many referring to Geological Survey of India (GSI) special publications. Such sources would not have been uncovered by standard searches as they are not referenced in a specific database. Obtaining such articles was however difficult and many had to be requested from various specialist libraries, and some, were simply not available. These are listed in Appendix A.

At the abstract reading phase, a total of 309 database abstracts were read, along with an additional 71 articles from other searches. If any ambiguity was perceived when reading the abstract, the article was selected for assessment at full text.

After reading the full text of 143 articles, 58 were selected that met all the inclusion criteria. Further reading found that 6 of these articles were either duplicate reports, published in different publications, or in fact did not meet inclusion criteria. A total of 52 articles thus remained for use in the review[3].

4.2 Description of studies

This section of the review outlines the articles available 'post-filtering' and seeks to provide the material to answer the first part of the narrative synthesis as set out in section 3.6 - What is the *available* evidence about Glacier shrinkage in the Himalayas? By breaking down the evidence into themes of region, river basin, date and study type, it is possible to obtain an overview of the available evidence and to subsequently highlight areas lacking data to inform the review question. This provides the subsequent material for discussion of the secondary question – *In what areas of research is evidence lacking and how best could future work ensure a more complete evidence base is developed?*

A full list of articles that met the inclusion criteria is detailed in Appendix A and these were selected for detailed assessment and data extraction. For each individual source, the main findings of the study were recorded in a common table (Annex A) that enabled key conclusions to be clearly accessible as well as the necessary data for assessment. To gain an overall picture of the available evidence, articles were assessed by: publication year, publication source, and location focus. This enables identification of when and where the evidence comes from, revealing both potential bias in the studies and also highlighting areas where the evidence base is lacking.

Publication Year

Analysis of the publication date of articles used in the review reveal the majority of sources considered for analysis were published post 1997 (Figure 4). The earliest publications (1962) reflect the reporting of measurements from the region by the Geological Survey of India in connection with the International Geophysical Year (1957-1958). The prevalence of publications in the latter part of the 1990s and onwards perhaps reflects the growing awareness of climate change and accompanying interest in conducting research into the effects of increased temperatures on glaciers.

---

[3] An additional paper by Scherler et al (2011) was identified during the latter stages of the review that would have provided a suitable source of evidence and met inclusion criteria, and as such, is considered within the discussion. The paper presents results from a Himalaya-wide analysis of spatially variable responses of glacier termini to climate change by comparing frontal positions identified from remote sensing images. The study considered 286 glaciers, varying in length from 2-70km, with only glaciers in the west Kunlun Shan being outside the geographical scope of this review. Comparing glacier frontal positions over the period 2000-2008 they found that over 50% of observed glaciers in the westerly influenced Karakoram are advancing or stable, contrasting with over 65% of glaciers in other regions exhibiting retreat. The remote approach has also allowed analysis of glaciers in the Hindu-Kush, finding 73% of glaciers in this mountain region are advancing. The findings will be discussed in relation to the findings of this review in section 6.

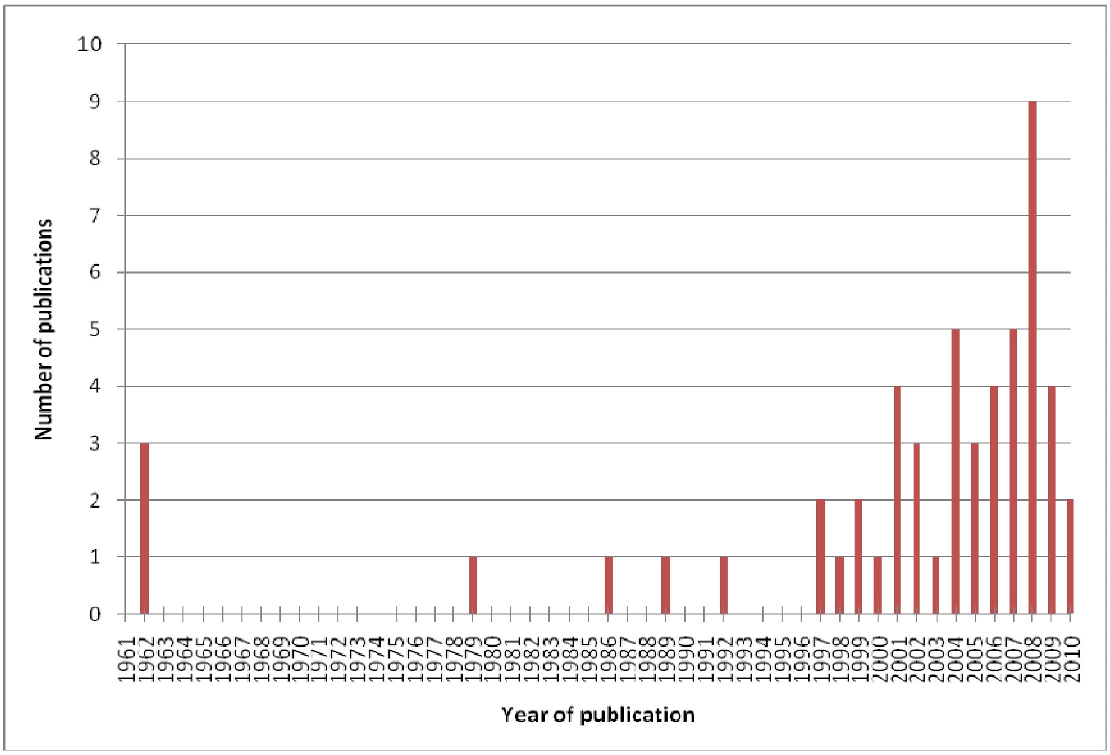

Figure 4 Year of publication of articles included in the synthesis (n=52)

Source

The type and source of publication reporting a study reflects both the potential audience. Figure 5 illustrates in descending order the number of studies used within the review from each publication source. Impact factor has not been used as an element of quality assessment for studies because it is not necessarily representative of a paper's quality, but instead indicates how often the journals papers are referenced. However, the fact remains certain glaciological publications are considered *de-facto* to be of the highest quality in their peer review process due to the fact their readership consists largely of experts in this field. Such considerations are discussed within the concluding sections of the review.

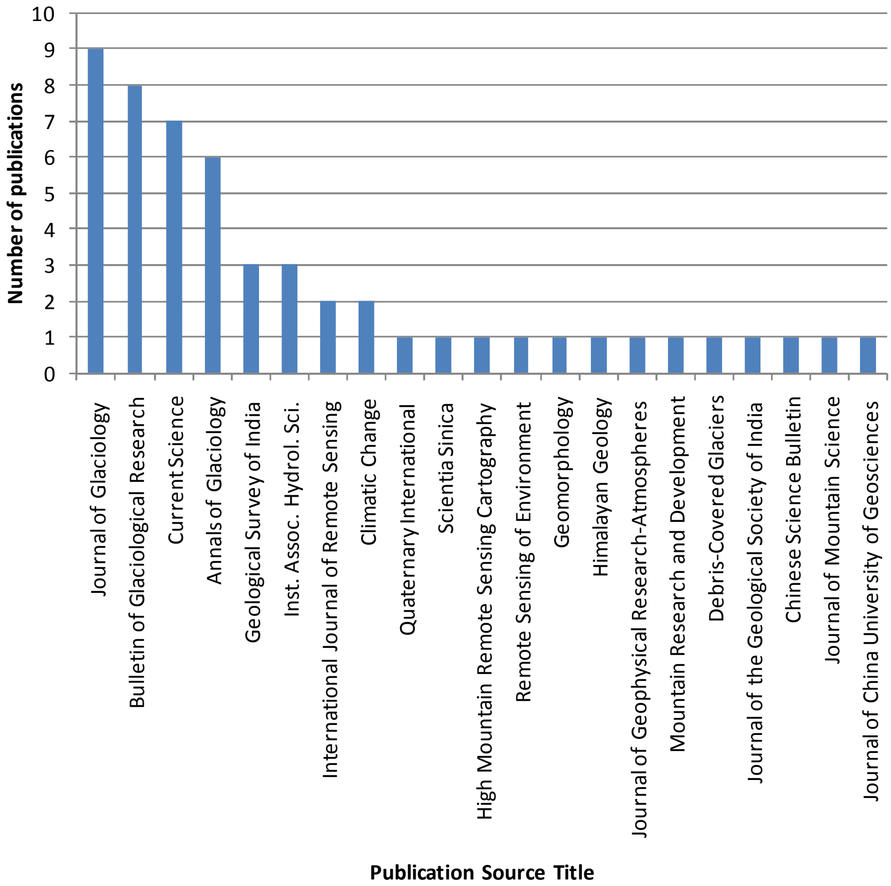

Figure 5 Number of articles included in the review by publication title

Study Location

The regional focus of the evidence is of interest as it clarifies the geographical areas that have been most frequently studied. A number of divisions have been applied to enable an analysis: mountain region, river basin area, country and glaciated area. All four of these provide information of where most studies have taken place, while also highlighting sparsely studied areas. Many further sub-divisions of such areas could be interpreted, such as sub-basin or district, but there is a lack of consistent and systematic reporting at such scales within the studies identified. The overall distribution of study areas considered by this review is illustrated in Figure 6; also delineating glacier outlines available from GLIMS and WGS (WGS mapping includes more extensive mapping of western areas compared to WGMS mapping; unavailable for mapping in GIS). Note that some points represent an area covered by multiple studies and do not represent individual glaciers.

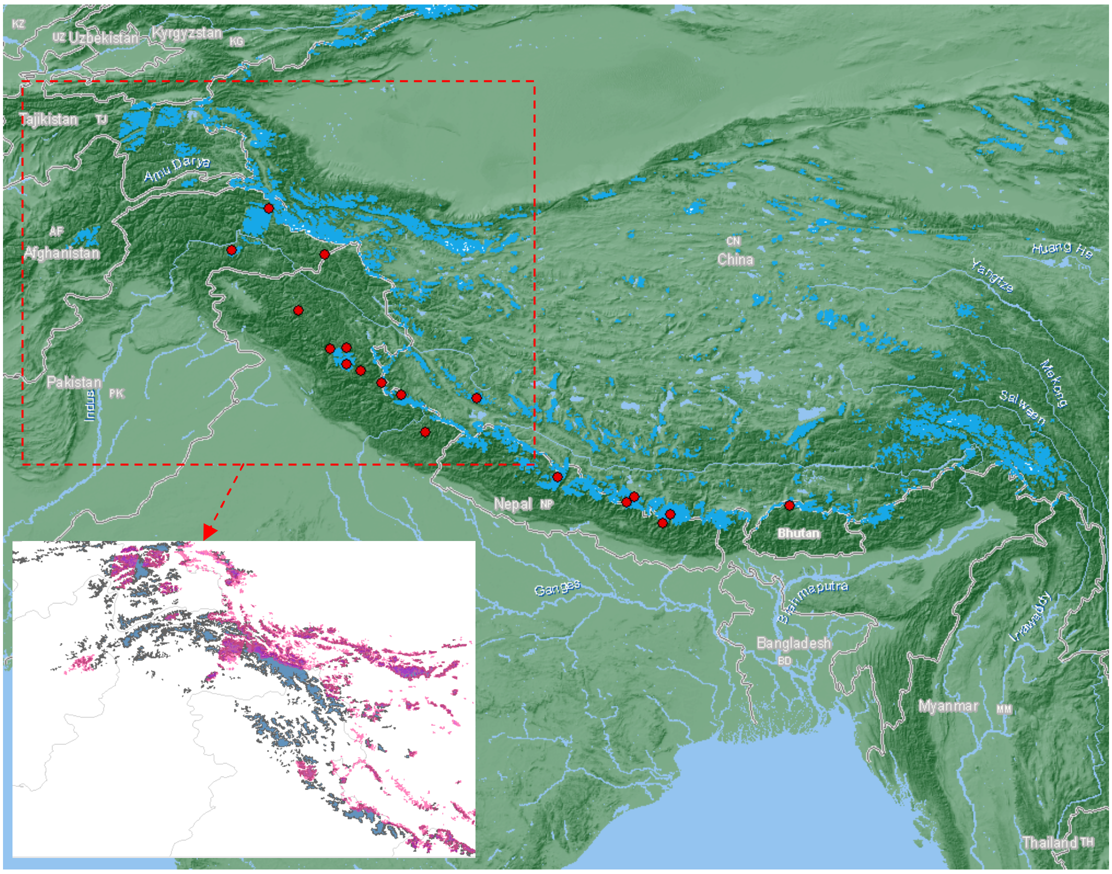

Figure 6: Areas of glacial study identified by this review; blue areas show glacier areas mapped by GLIMS, red points represent areas of glacial measurementidentfied by the review, inlay shows more detailed WGMS mapping of glaciers in western areas.

Mountain regions

The Himalayas comprise the most studied region within the Himalayan arc, with 45 of the 52 studies focusing upon glacier(s) from this mountain range. Only 7 studies included in this review cover glaciers within the Karakoram mountain range. The review did not identify any relevant studies conducted in the Hindu Kush region.

River Basin Area

The region considered in this review encompasses three major rivers that are fed by glacier meltwater (Figure 1). Analysis of studies reveals that significantly fewer studies of glaciers feeding into the Brahmaputra basin (4) compared to the Ganges (31) or Indus (21) (Figure 7). Not all studies clearly reported the locations accurately for river basin identification, and in three cases (Ye et al, 2006; Ye et al, 2008; Yang et al, 2008) it was necessary to determine the relevant river basin from other sources. Glaciers identified in two of these studies are located in the region that is the source of all three river basins and thus have been counted as more than one study location in Figure 7. Systematic reporting at sub-basin level was not possible.

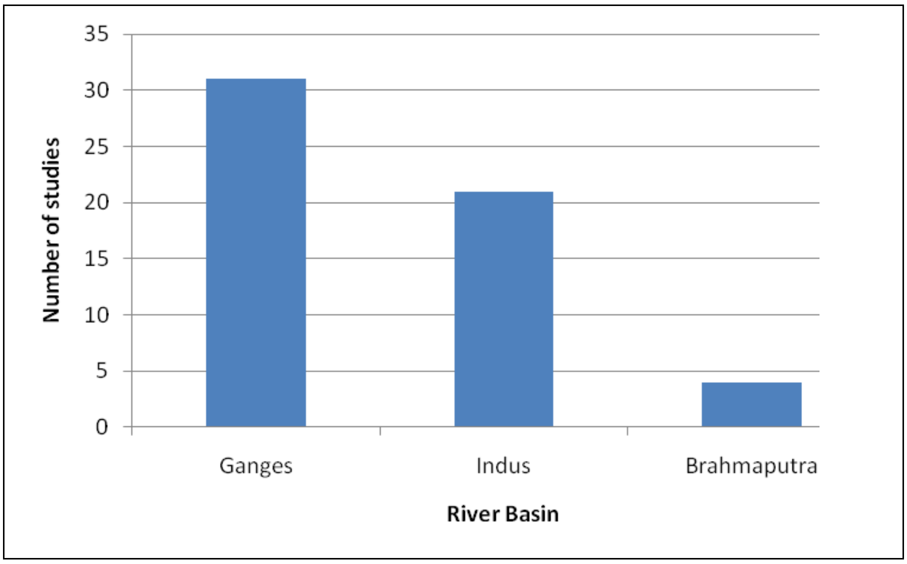

Figure 7 Location of studies by river basin

Country

The countries where the glaciers studied were located are plotted in Figure 8. India and Nepal account for over half of all glacier studies selected by this review.

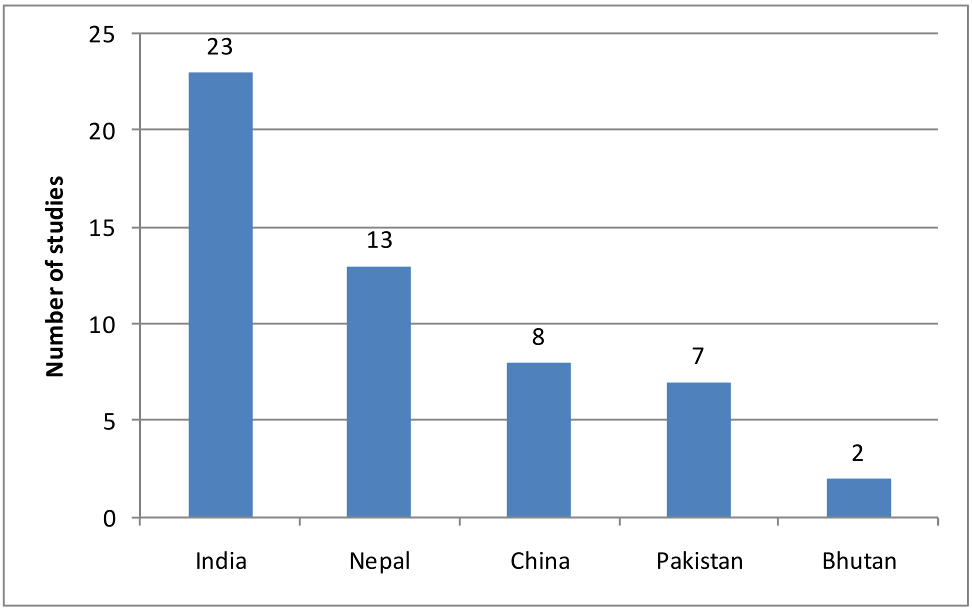

Figure 8 Count of study location by country

Glacierized area and glacier size

Figure 9 provides an overview of the spread of glacier size from those articles that actually reported individual glacier size. It should be noted that several studies reported on a region of glaciers as a whole. Many merely did not state the glacier area. Where data are available, analysis suggests the primary research focus has been on glaciers between 1-10 km^2, and there have been far fewer studies of glaciers over 30 km^2. The average and median glacier size from the sources considered is between 5 km^2 and 10 km^2.

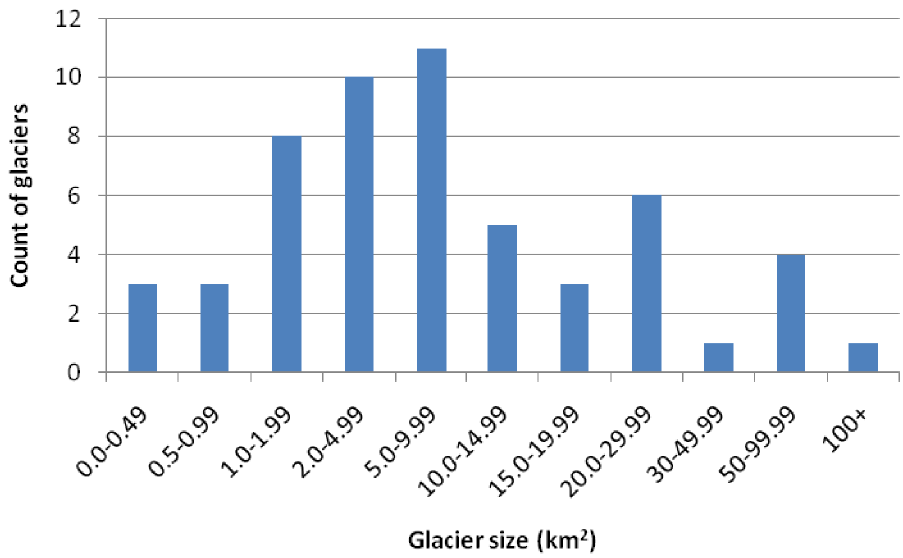

Figure 9 Count of individual glacier areas included within the synthesis[4]

Measurement type
It was essential for this review to establish that the method(s) used were identified and clearly explained, so that an objective assessment of the evidence could be made. As previously discussed, four main measurements were considered: terminus, volume, area, and mass balance. The relative proportion of each within the studies used in the review is shown in Figure 10. Terminus was clearly the most commonly reported measure of the studies assessed.

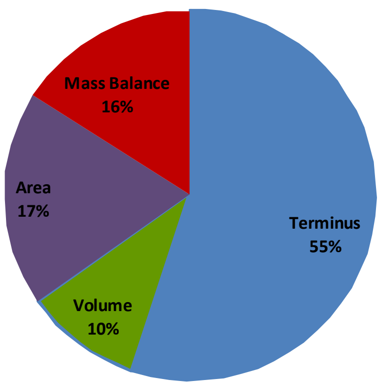

Figure 10 Proportion of measurement type employed by articles included in review

To further assess the available evidence base selected by this review, a plot (Figure 11) has been used to illustrate the relative contribution of measurement type and how this changes over time. The plot only contains data points that met the quality criteria for quantitative data as set out in section 3.4. It must also be considered that while some studies report a single measurement of change across a wide region, others

[4] Not all studies included data on the area of individual glaciers; this figure represents only a count of the glaciers used within the synthesis where individual glacier area was reported.

report specific findings for individual glaciers, thus producing more numerous measurements, but not necessarily covering as wide a study area. This explains the numerous glacier area measurements for 1955 and 1990, from reporting of thirty measurements of glacier area in a single study (Salerno et al, 2008). The peaks of 1955 and 1990 need to be taken in context as the localised study area and large volume of resulting data means this single study could distort overall conclusions, especially as it is chiefly a comparison between two distant time periods. The significant number of measurements obtained in 1962/3 primarily reflects the activity of the Geological Survey of India (GSI) in measuring glaciers around this period.

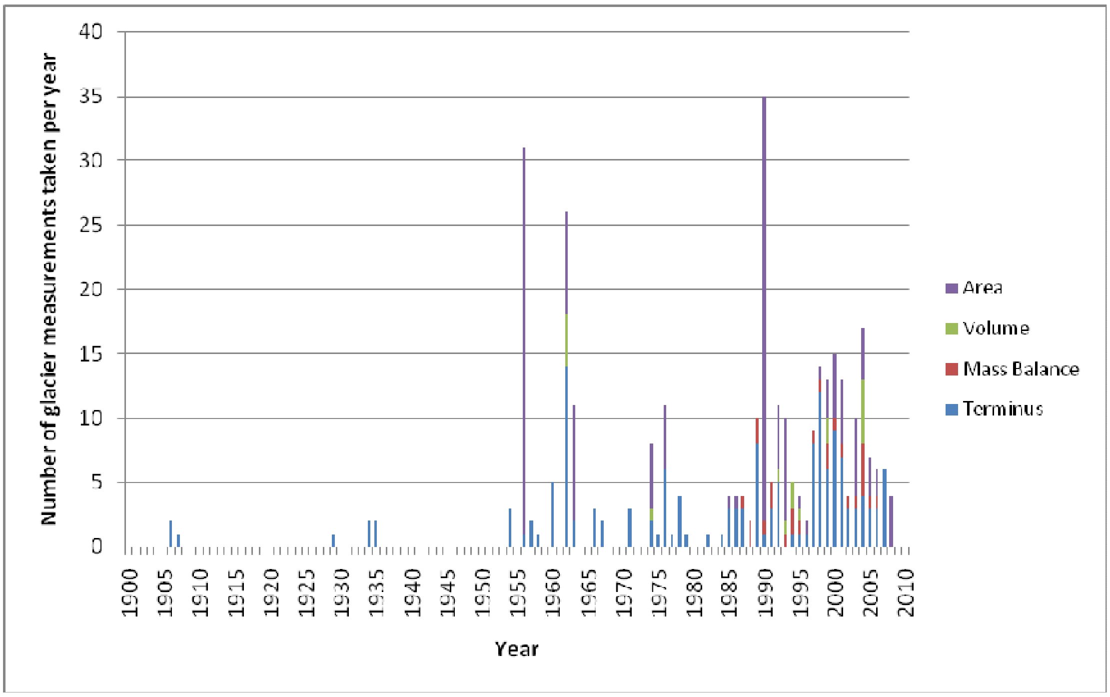

Figure 11 Breakdown of glacial measurements from each year by each measurement type

There were some earlier reported points in certain studies (Mukherjee & Sangewar, 2001; Raina & Sangewar, 2007) and the review found reference to other existing early sources. However, as previously noted, there exist high potential errors and much subjectivity in measurements prior to 1900. Many of these baseline values for comparison are simply historical references of glacier position, not measurements taken by the research team. The review team is aware of many early surveys and subsequent reports on Himalayan glaciers, by persons such as Godwin-Austen (1864) and Conway (1893), among others. The potential inaccuracies that could exist in such early surveys is highlighted by Bhambri & Bolch (2009) and discussed further in Section 3.4, reporting the incorrect nature of many early measurements when subsequent researchers re-visited the same glacier locations. This again emphasizes the need for any study to critically assess any early data that could be used as a baseline for glacier change. A clear approach on how early mapping has been geographically referenced onto more modern mapping is also essential.

4.3 Study quality assessment

Results from the study quality assessment (Figure 12) show that the relative proportion of quality-assessed data differs significantly between measurement types. Over 50% of data available for "mass balance" has been scored with a high to very-high rating, reflecting that most of the evidence has been obtained from field glaciological measurements reported with clear methodologies. Over 50% of "volume" data are of a low quality or below, demonstrating the difficulties in making such measures, leading to very basic estimates. Over 90% of "area" data were scored above medium, reflecting the clear methodologies employed from predominantly remotely sensed image analysis. Around 70% of "terminus" data were scored at medium quality, due mostly to the fact that most of the data are field based measurements of medium methodological assessment. Results generally indicate the relative accuracy ascribed to the various measurements, with measurements of area from remote sensing and aerial images, along with field glaciological mass balance values, providing the highest quality data.

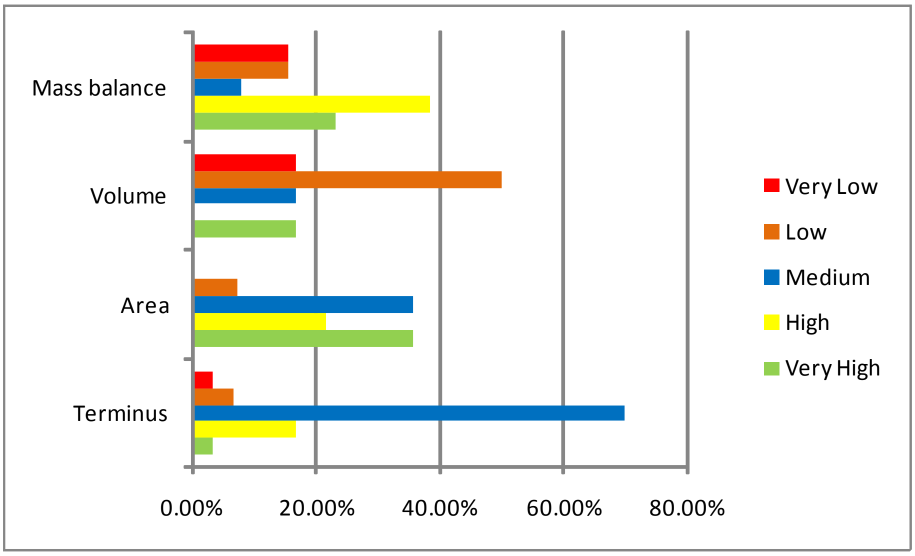

Figure 12: Relative proportion of quality assessed data available from studies for each measurement type

4.4 Narrative synthesis / Thematic analysis

This section of the review aims to synthesize the findings of studies included within the review, to investigate the available evidence on Himalayan glacial shrinakge. This is the second level of synthesis discussed in Section 3.6, whereby the review seeks to answer the question – "What is the evidence *showing* about Glacier shrinkage in the Himalayas?" This will provide the subsequent material for discussion of the secondary questions;

- *Are glaciers shrinking or growing in mass, and are there regional differences?*
- *Is the rate of glacial shrinkage increasing across the region?*

These two questions are addressed first with a narrative synthesis of all the evidence, and then undertaking a thematic analysis of the data from each of the four measurement types that have met quality criteria outlined in section 4.3.

The narrative synthesis conveys the overall picture emerging from the qualifying studies, employing a critical appraisal to ensure that the more robust evidence are assigned greater weight. All evidence has been considered, from "very low" to "very high" confidence data.

The thematic analysis was used to summarise the quantitative findings from the studies to identify trends and themes. Only quantitative evidence meeting medium confidence assessment criteria were used in this section, removing any data with significant uncertainty. Where studies report errors in excess of 20% of the measured change, these values were highlighted and discussed, but not excluded if the minimum confidence assessment criteria had been met. Omitting evidence on such a basis would have undermined the whole systematic review approach because the majority of evidence featured some degree of uncertainty surrounding unreported potential. Where possible, graphical exploration of the data has been used to explore the relationships within, and between, studies of different measurement type.

An initial assessment involved visualizing the reported conclusion of studies, with respect to glacier shrinkage or growth, to discern if there were clear differences in the reported assessments of glacier change (Figure 13). To enable collation of results from all various measurement types, considering both the quality of the method and reporting, along with how appropriate the measure actually is in indicating either shrinkage or growth in the glacier(s), the ranking method outlined in Section 3.4 was applied.

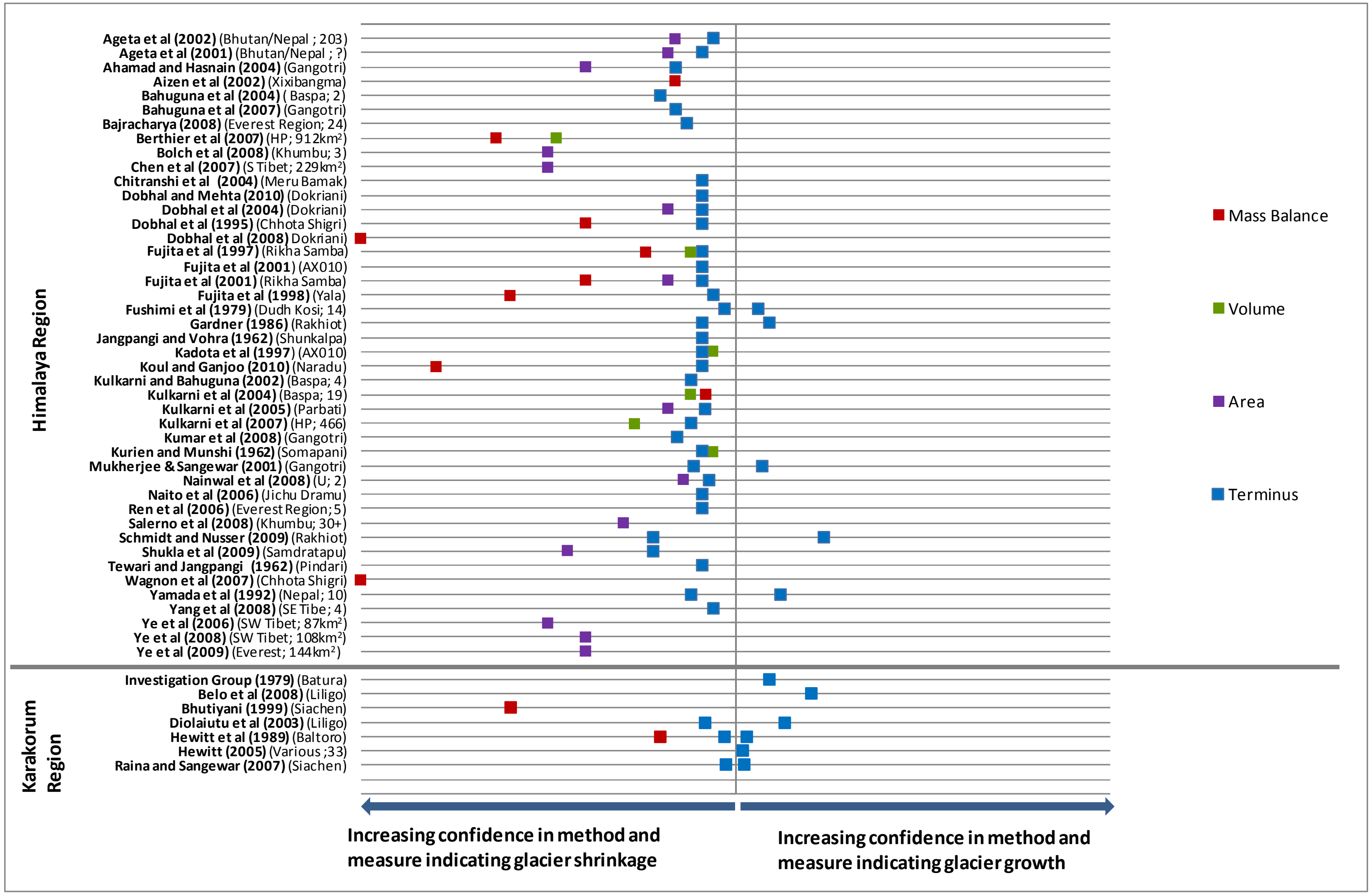

Figure 13: Relative assessment of reviewer confidence in reported study outcomes according to method employed, clarity of reporting and measurement type (Brackets include glacier or region name with associated number/area of glaciers studies if more than one single glacier; U=Uttarakhand, HP=Himachel Pradesh)

Reported changes in glacier mass

Figure 13 has been broken down by mountain region to enable a clear comparison of results from glaciers in each region. Different symbols illustrate the different measurements employed. For each study, the glacier, or region assessed, is detailed, along with information on the number of glaciers, or, glacier area

Each point in Figure 13 represents the review teams' confidence in the overall conclusion of articles regarding the change by each study, for each measurement type. The Figure does not indicate the magnitude of shrinkage/growth, but shows the review teams confidence in a study's findings. The following notes should also be considered when interpreting Figure 13;

- For studies that contain a series of a particular measurement, but obtained using various methodologies (typically using less accurate baseline methods compared to more accurate methods employed by the research team) rated with different confidence, then an average of the quality assessments made is applied.
- If a study covered multiple glaciers within a region, then the overall conclusion for the change in glaciers across the region was used. To clarify; where a number of glaciers were studied within a region then the dominant change identified and reported across the glaciers considered was reported.
- Where a study concluded that there is no dominant pattern and that the glaciers sampled show both growth and shrinkage in equal or near equal measures (fluctuating), then a point is placed on both the shrinkage and growth sections of the plot.
- Where the overall finding was of the glacier(s) remaining stationary during the study period, then a point is placed directly on the centre axis.
- If the study utilized various measurement approaches within the same study, then there exist various different markers for the conclusion derived from each measurement type.

Figure 13 indicates that most of the available evidence (44 of 52) found shrinkage to be the dominant behaviour across the studies considered. Every measurement type corroborates this observation, with higher quality evidence from mass balance and area backing-up lower confidence findings from studies that used volume and terminus measurements. Studies employing different measurements on the same glacier/region provide an even clearer indication of this overall behaviour, highlighting that even though terminus is not a 'robust' indicator of glacial shrinkage, it is, a valid and corroborated indicator.

Of the 52 studies assessed, only 2 studies found growth as the dominant characteristic, and both were from the Karakoram region. These use only terminus changes as an indicator. However, one of these studies (Belo et al, 2008) presents data for Liligo glacier covering the period post 1970, omitting the early 20th Century retreat reported by Diolaiuti et al. (2003). This is a clear example of how the period of measurement selected can have significant impact on how glacier changes are perceived.

In certain cases, both advance and retreat were reported; as represented in Figure 13 by a symbol occurring on both sides (Gardner 1986; Hewitt et al 1989; Diolaiuti et al, 2003; Schmidt & Nusser, 2009; Fushimi et al, 1979). In the first four of these studies, what is being observed are surging glaciers, all within either the western most fringes of the Himalaya or in the Karakoram. Data from Fushimi et al. (1979) is from the Dudh Kosi region of Nepal. Again, all evidence scored low for how indicative was of variable growth and shrinkage behaviour, mainly because evidence was from terminus measurements. As before, that four of these studies are from the Karakoram or on its eastern fringes corroborates the observation that distinct regional differences exist.

Studies conducted on Himalayan glaciers show that shrinkage is the predominant finding indicated by measurements taken, with only 5 of 43 illustrating periods of any growth, and no study indicating growth to be the dominant measure of change.

Considering the evidence from the Karakoram, terminus evidence indicates both growth and shrinkage, while more robust evidence from mass balance studies indicates only shrinkage. Only one single study showed shrinkage to be the dominant measure of change (Bhutiyani, 1999), but, it must be considered that all available evidence from this region scored relatively low compared to Himalayan glaciers regarding confidence in the results indicating glacial growth or shrinkage. Thus it is not only the lack of data from the Karakoram that limits comparative assessment, it is the low confidence ascribed to the data available. However, despite a low confidence scoring, the fact only one study finds retreat to be the dominant change observed within the region, does provide further validation that there exist distinct differences in the behaviour of glaciers between the two mountainous regions.

Note, Figure 13 does not provide an indication of temporal changes in the glaciers studied, and only provides an overall indication of changes in glacier mass reported by the articles considered. Further consideration of temporal changes in measurements will be provided in Section 4.5.

A narrative assessment of how glacier debris-cover might affect measured changes has not been undertaken because there was no systematic reporting of debris-cover across the studies, and many studies deliberately excluded debris covered glaciers due to the difficulties in accurately defining the outline and terminus

Few studies that present primary data on glacial changes combine associated primary data from downstream glacier lakes. Those that did were not able to quantitatively explain the variation in lake area by changes in upstream glaciers. Ageta et al. (2001) report glacier lakes in Bhutan have expanded in recent decades as a result of glacier retreat, but give no clear method or reporting of evidence. An overall reduction in glacier lake area of 2.9% was found within the Mapam Yumco basin of the Tibetan Plateau, but no quantitative assessment of the link to changes in glacier area was undertaken (Ye et al, 2008). The authors clearly state such analyses are impossible without adequate hydrological data for glacier melt and lake levels, critical for understanding the water balance. Chen et al. (2007) report a 47% increase in lake area between 1986 and 2001 in the Poiqu River basin of Tibet, and found no distinctive relationship between the reduction in upstream glacier area and increased lake area. Bajracharya (2008) notes both retreat of glaciers and increases in the number of glacier lakes within the Dudh Kosi basin of Nepal, but no direct relationships were explored. All the evidence considered points towards significant difficulties in accurately assessing direct relationships between glacier shrinkage and the formation of glacier lakes.

An overall narrative assessment of how the rate of glacial shrinkage has changed was not possible due to the lack of appropriate evidence. For instance, several simply compared the average rate of retreat between two terminus measurements to an earlier reported rate of retreat, also based upon two comparative measurements of terminus position. Inferring acceleration from only two separate measurements of change lacks scientific rigour and can be misleading. Quantitative analysis of changes in the rate of change is considered further in section 4.5.

4.5 Analysis based on measurements and methodologies

The range of studies carried out in the Himalayan region is large and an appraisal of methods and measurements employed was conducted to provide a clear analysis of findings from each measurement type, in order to better understand the evidence from the. The different approaches employed in the selected studies to measure glacial shrinkage/growth were subject to a critical appraisal. Data from each measurement can thus be considered according to the confidence ascribed, point by point, rejecting data that does not meet objective quality criteria outlined previously. This approach has the advantage of allowing investigation of the varying confidence ascribed to data presented within the studies, not simply interpreting data at ‘face value’. Combining the analysis of data from each measurement type in such a manner enables objective interpretation of the evidence, further developing the findings of the narrative synthesis.

Information on reported accuracy of measurement and error in reported changes has been patchy and inconsistent across the studies considered. Where available it is presented, but should not be taken as representative of any errors that might exist in other studies employing the same measurement approach that do not provide such detail. The lack of consistent error reporting means that clear comparisons between data from different studies cannot be systematically assessed. Thus, data are presented graphically without information regarding potential errors. The potential existence of such errors within all data should however be considered and is discussed where available.

4.5.1 Mass Balance

In total, thirteen studies, representing twelve glaciers, reported mass balance. All these studies were conducted in the Himalayan region, with the exception of studies by Bhutiyani (1999) and Hewitt (1989) whose test sites were located in the Karakoram. However data from 5 studies (Kulkarni et al, 2004; Fujita et al, 1997, 2001b; Aizen et al, 2002; and Hewitt et al, 1989) were not included in a quantitative analysis of the measurements, either because their methods were found to have insufficient robustness after application of the quality assessment criteria, or the data were in formats that prevented comparison. All 5 reported a negative mass balance in their overall findings, but further clarity on the applied methods should be sought before considering the values given in a quantitative analysis.

Mass balance data for the measurements analysed are plotted in Figure 14, encompassing data from 7 separate glaciers, and one regional analysis. The overall trend observed is of negative mass balance, further corroborating the outcome of Figure 13 in the narrative synthesis. The time period for which mass balance values are reported is relatively short, with data used within the synthesis only spanning a 20 year period, and a maximum continuous series length of 5 five years. Some earlier data exists, such as early mass balance estimates from AX010, however the primary source for the reporting of these estimates (Ageta et al, 1983) was not available in English.

The only assessment of accuracy in mass balance measurements come from two studies: Bhutiyani et al. (1999) indicate that mass balance measurements derived using the hydrological method have a standard error of ±10-15%, but this was an assumed value, not based upon an analysis of the data collected. Wagnon et al. (2007) measure mass balance using the glaciological method and indicate measurement accuracy of ±0.3m. As no consistent analysis or reporting of accuracies has been provided by the studies considered, Figures 14 and 15 both omit any information on accuracy.

Data from Chhota Shigri, Bara Shigri, Naradu, Spiti/Lahul, and Siachen provide information on glaciers within the upper Indus Basin. All other data are from glaciers feeding into the upper Ganges basin. The only data for glaciers situated within the Karakoram is from the Siachen glacier. There are no apparent differences in the mass balance measurements between river basin or mountain region when data are brought together. An average annual negative mass balance value of 0.57 m.w.e. was derived when considering all the data illustrated in Figure 14.

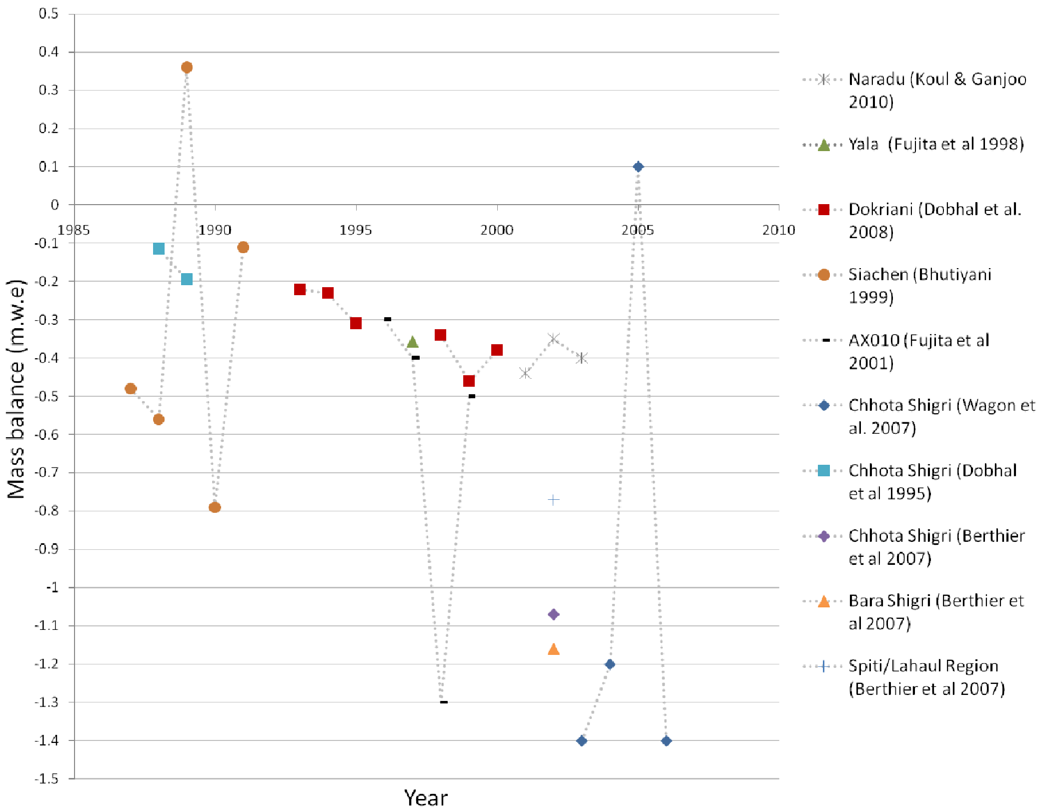

Figure 14 Annual mass balance plot for glaciers (Spiti/Lahul region includes the Bara Shigri and Chhota Shigri glaciers)

Mass balance data can also be plotted on a cumulative mass balance plot, typically used by glaciologists to illustrate long-term changes in the mass balance of a glacier. This review identified only 5 glaciers having continuous measurements of more than 2 years (Figure 15). Figure 15 further demonstrates the negative trend in annual mass balance measured on all glaciers from the region, while also highlighting the need for annual measurements. Where certain years are omitted, as for Dokriani, the cumulative mass balance must be calculated from the last measurement taken. If there was in fact sustained negative mass balance over the two year period omitted, then the year 2000 value could be even lower. However, the potential for significant inter-annual change is evident and thus inferring a continued trend is not a suitable assumption. If for example the 2005 point was not available for Chhota Shigri, but a sustained negative trend was assumed, the 2006 value would be over one metre less than the continuous series value.

For all studies presenting more than two periods of mass balance measurement it is apparent (Figure 14) that mass balance fluctuates on a yearly basis. Glaciers AX010 and Siachen both exhibit significant variations in year-to-year mass balance values, both experiencing large swings between negative and positive values. Despite such fluctuations the overall trend for all glaciers, when change is assessed cumulatively (Figure 15), is a rapid loss of mass during all the periods considered.

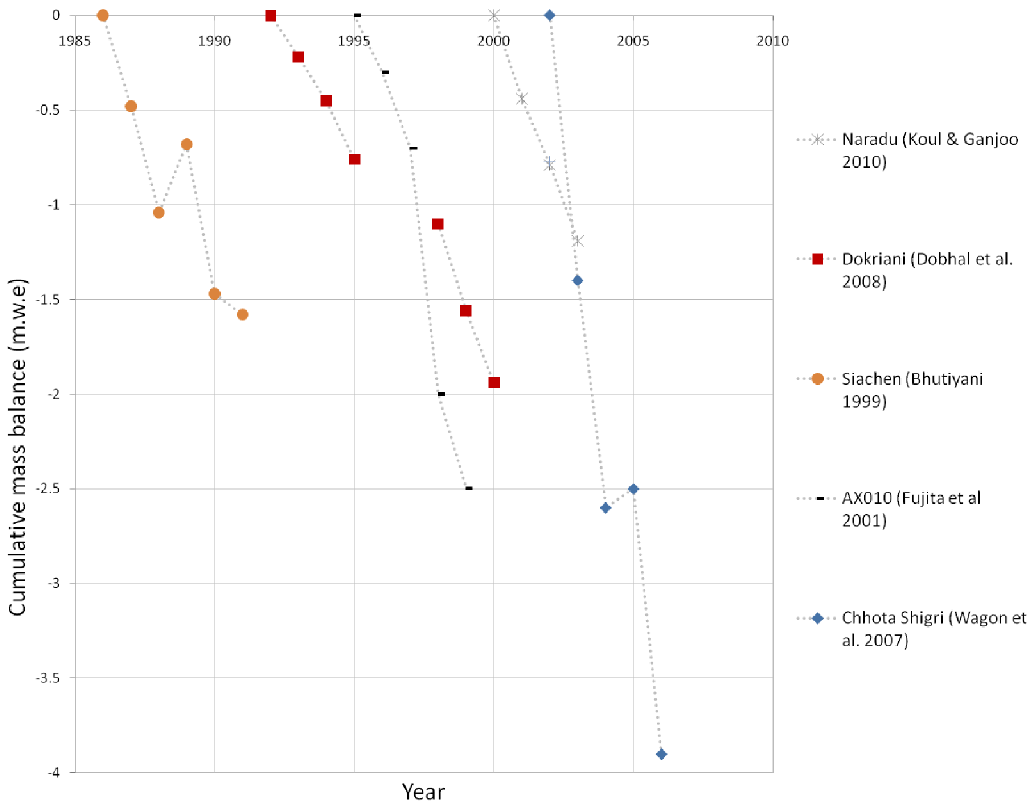

Figure 15: Cumulative mass balance plot for glaciers

Too few measurements exist from which to make an analysis of whether the annual rate of mass loss is increasing for glaciers within the region. Much longer continuous periods of measurement are required, as highlighted by the significant inter-annual variation exhibited on certain glaciers. The only series of measurements that could be used to infer a general trend of increasing rates of negative mass balance is that of Dokriani glacier (Figure 14). On the basis of 6 annual mass balance estimates for the period 1993-2000 (with no data available for the years 1996-1997) mass balance loss does exhibit a general rate increase, equating to around 0.02 m.w.e. per annum. However, considering that this acceleration is less than 10% of the potential error in measurement accuracy indicated by Wagnon et al. (2007), there is significant uncertainty surrounding this observation.

Chhota Shigri has been measured by three separate studies at different times, providing the longest running series of measurements, all ascribed high quality data or above. The overall picture for the Chhota Shigri glacier is negative mass balance over the period 1988 to 2006 with the only one positive value of 0.1 m.w.e reported by Wagnon et al. (2007) for the year 2004-2005. Early field measurements by Dobhal et al. (1995) indicate a slight increase in the rate of mass loss, with mass balance measures significantly less than later estimated by other later studies. The data point for measurements reported by Berthier et al. (2007) in Figure 14 indicates the mean annual mass balance over the period 1999-2004, and as such has been placed on the year of 2002 to represent an average change for the period. The value was calculated using remote sensing, and the fact field measurements from Wagnon et al. (2007) validate the estimated value provides a good indication that such ‘remote’ methods might become both accurate and applied more within the region. The most recent measurements, all from field methods, by Wagnon et al. (2007) cover the period 2002-2006 and indicate generally high values of mass loss, with one year of positive mass gain. Considering all the values together, it could be inferred that the rate of mass loss has increased significantly since the late 1980s, but the lack of any intervening data throughout the 1990s does make such assertions difficult to substantiate, with no indication of how the glacier mass changed during that period is available.

4.*5.2 Volume*

In total, only 5 sources reported volume to any level that could be assessed (Dobhal et al, 2004; Fujita et al, 1997; Kulkarni et al, 2007; Kurien & Munshi, 1962; Berthier et al, 2007) and all of which are located in the Himalaya region. All studies reported an annual rate of decrease for a given period rather than mention of the actual volume change of the glacier relative to a baseline volume, thus making relative comparisons or plotting of results between studies problematic.

Care should be taken when interpreting results as volume is a challenging measure. One of the larger studies by Kulkarni et al. (2007) investigated 466 glaciers and the authors report a volume loss of 30.8% between 1962 and 2001-2004. However as the authors report an error of 10-20% in their volume measurements, it shows how inaccurate volume measurements can be. As such, with generally no baseline value available from which to normalize findings from large areas compared to single glaciers, combined with high potential errors in any estimate of volume, no numerical analysis of the volume data was undertaken.

4.5.3 Area

The review identified fourteen studies evaluating area change. All reported decreases in area over various durations as the predominant outcome. The review did not identify any studies addressing area change for glaciers in the Karakoram or Hindu-Kush.

This section explores the reported glacier area changes by first assessing those studies that provide evidence of change of single glaciers and, subsequently, those studies considering measurements of multiple glaciers across a particular region. Changes in the rate of area loss are then assessed by exploring data from studies that allow temporal comparisons of area loss.

Single glaciers

Reported changes in area for single glaciers within the selected studies are summarised in Table 4. Of the 39 glaciers having area change measurements; 7 report an increase in area, while the rest indicate a decrease in glacier coverage. Decreases in area appear substantially greater than reported increases. As previously noted, in Section 3.4, there is a significant bias in the available area data due to the fact that the majority of measurements (28 of 39 glaciers) are derived from one study by Salerno et al (2008) that covers one single region within Nepal (Khumbu Himal, Sagarmartha National Park). Therefore, the data set must be approached with the knowledge that it is not necessarily representative of the whole Himalayan. However, it does provide a unique data set that illustrates the significant variation in area change that can occur within a single region over a common period. The reported variation, from an increase of 25% to a decrease of 54%, across the 28 glaciers highlights the significance of local scale factors. However, the paper notes its estimates of area change are subject to significant errors arising from cartographic interpretation, (i.e. comparing two topographic maps). Values where the potential error exceeds 20% have been highlighted in red in Table 4. This demonstrates that caution should be applied when analysing the figures presented, and is particularly important when considering that all data indicating an increase in glacier area have errors exceeding 20%. Such data have not been rejected according to the justification outlined in Section 4.3, whereby, without consistent reporting of errors by all studies, it would be un-systematic to remove data that clearly had reported errors. Without associated error estimates from all data, confidence assessments provide an objective and consistent approach to assess relative accuracy and robustness of data.

The review identified only two studies on single glaciers within the Indus basin having area change data, and both were from Himachel Pradesh in north-west India. Measurements from Parbati glacier (Kulkarni et al, 2005) show a large decrease of 24% during the period 1962-2001, however, it must be noted that data met only a medium confidence assessment and no assessment of accuracy is provided. More weight is however assigned to the findings from Samudra Tapu glacier (Shukla et al 2009); which indicates less overall retreat of 12% over a similar measurement period (1963-2004), but also with no estimation of accuracy.

The remaining evidence all comes from the Ganges basin, and apart from the study by Salerno et al (2008), which found some increases in area within a wider pattern of loss, all the evidence indicates reduction in the area of glaciers. Aside from this study, there is, significant variation in the retreat of these glaciers, from practically no retreat for Satonopath (Nainwal et al, 2008) over a 44 year period, compared to a significant retreat of 26% for glacier AX010 (Fujita et al, 2001a) over a considerably shorter 21 year period. There are insufficient data on the accuracy of measurements taken across these studies to assess the associated potential errors. Fundamentally the data points to overall reduction in glacier area albeit there is significant variation in the magnitude of the changes. Furthermore it is problematic to compare changes between glaciers when the periods of comparison are not identical and no estimation of relative accuracy is available for the whole data set.

Summarising the data from Table 4, an average decrease in area of 16% over an average 34 year period is found for the glaciers considered. Taken as an average yearly loss of area, this equates to a decrease in area of 0.5% per annum for the average 34 year period of comparison. In assessing only the data ascribed with the highest confidence, an average area loss of 11% over an average 36 year period equates to an average annual loss of 0.3% per annum, slightly lower than the previous assessment of all data, but perhaps understandable as derived from a relatively small data set with data from only two glacier systems. As 21 of the glaciers with area data are below $10km^2$ it is worth considering the change in area relative to the baseline glacier area. For those glaciers below $10km^2$ the average change in area is 0.73% per annum, while for glaciers above $10km^2$ it is 0.17% per annum. This shows that average area loss for larger glaciers is less than the overall average, which is heavily weighted towards representing smaller glaciers.

Table 4: Percentage changes in glacier area for studies providing quality measurements of single glaciers (Green cells indicate Very High confidence data, Red cells indicate High confidence data, Blue cells indicate Medium confidence data; Changes with reported errors exceeding 20% of measured change are highlighted in red)

Glacier	Glacier baseline Area (km^2)	Basin	Baseline year	Comparator year	Period of comparison (years)	Percentage change (%)	Associated error
Kdu_gr 38	2.6	Ganges	≈1956	≈1990	≈34	-53.5	±7.4%
Chhule	5.8	Ganges	≈1956	≈1990	≈34	-52.4	±5.5%
Machhermo	2.2	Ganges	≈1956	≈1990	≈34	-44.5	±5.9%
Duwo	2.2	Ganges	≈1956	≈1990	≈34	-39.3	±6.3%
Nare	10	Ganges	≈1956	≈1990	≈34	-37.3	±3.7%
Thyangbo	16.5	Ganges	≈1956	≈1990	≈34	-36.8	±5.1%
Langmuche	5.5	Ganges	≈1956	≈1990	≈34	-36.1	±4.5%
Cholotse	2.4	Ganges	≈1956	≈1990	≈34	-35.8	±7.5%
Cholo	2.1	Ganges	≈1956	≈1990	≈34	-31.2	±10.1%
Kdu_gr 125	1.9	Ganges	≈1956	≈1990	≈34	-30.5	±7.1%
W.Lhotse	5.9	Ganges	≈1956	≈1990	≈34	-27.9	±5.2%
Melung	5.8	Ganges	≈1956	≈1990	≈34	-27.4	±4.4%
Langdak	2.7	Ganges	≈1956	≈1990	≈34	-27.2	±7.3%
AX010	0.57	Ganges	1978	1999	21	-26	n/a
Parbati	48.44	Indus	1962	2001	39	-23.8	n/a
Kdu_gr 181	1.3	Ganges	≈1956	≈1990	≈34	-23.7	±10.5%
Kyajo	1.4	Ganges	≈1956	≈1990	≈34	-23.7	±5.5%
Nareyargaip	6.8	Ganges	≈1956	≈1990	≈34	-14.3	±4%
Gangotri	87	Ganges	1985	2001	16	-13	n/a
Phunki	2.3	Ganges	≈1956	≈1990	≈34	-12.9	±7.9%
Samdura Tapu	110.5	Indus	1963	2004	41	-12.4	n/a
Rongbuk East	30.02	Ganges	1974	2008	34	-12.2	±0.76%
Rongbuk West	42.56	Ganges	1974	2008	34	-10.9	±0.76%
Khumbu	41.2	Ganges	≈1956	≈1990	≈34	-9.8	±4.4%
Dokriani	7.74	Ganges	1962	1995	33	-9	n/a
Rongbuk Middle	20.43	Ganges	1974	2008	34	-8.96	±0.76%
Lobuje	1.9	Ganges	≈1956	≈1990	≈34	-8.4	±7.8%
Khangri	19.5	Ganges	≈1956	≈1990	≈34	-4.6	±4.3%
Imja	31.7	Ganges	≈1956	≈1990	≈34	-2.4	±3.7%
Satanopath	21.17	Ganges	1962	2006	44	-1.4	n/a
Bhagirath Kharak	31.17	Ganges	1962	2006	44	-0.42	n/a
Ama Dablam	10.9	Ganges	≈1956	≈1990	≈34	0.5	±3.5%
Ngojumba	98.7	Ganges	≈1956	≈1990	≈34	6.1	±3.4%
Lumsamba	21.3	Ganges	≈1956	≈1990	≈34	7.6	±4.4%
Lhotse	14.8	Ganges	≈1956	≈1990	≈34	8.3	±4.6%
Chhuitingpo	7.3	Ganges	≈1956	≈1990	≈34	10.3	±7%
Bothe Kosi	43.8	Ganges	≈1956	≈1990	≈34	12.6	±3.4%
Nuptse	7	Ganges	≈1956	≈1990	≈34	25.4	±7.3%
Average	20		1960	1994	34	-16	

A logarithmic plot (Figure 16) of data from Table 4, comparing baseline glacier area against the associated average annual area loss reveals a general trend of average annual area loss is higher for smaller glaciers, but that there is a low certainty in this relationship. This relationship could be explored further through linear regression analysis of other co-existing variables such as mean glacier elevation, slope, aspect and debris cover. However, as discussed previously, there is no consistent reporting of such localised variables across the studies considered, which limits further consideration analysis.

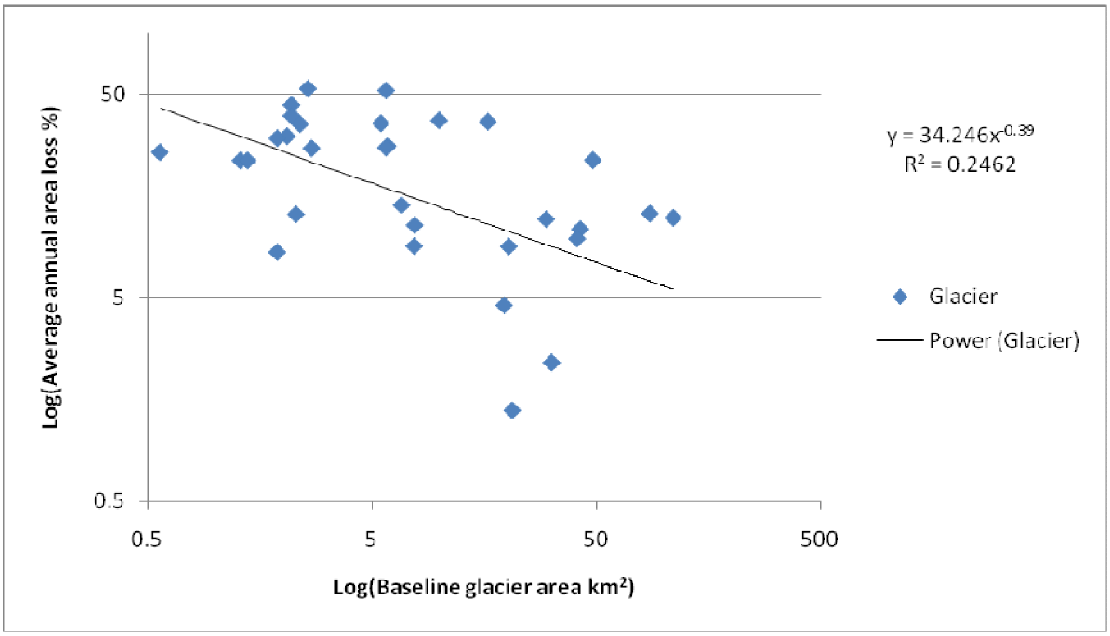

Figure 16: Relationship between glacier baseline area and associated measured average annual area loss

Glacierized area

Several studies provide area change data across a wide region, reporting findings as a percentage change in glacierized coverage across the study area. Such studies, while lacking the detail of single glaciers, provide a broad-scale indicator of change. Data from these studies has been detailed in Table 5, indicating that a decrease in glacier area was measured in all regions and river basins, while also highlighting the significant variation in changes measured between regions studied. Despite more data on the Indus basin being available from such studies, no clear pattern in change in glacierized area between river basins are evident from Table 5.

Data from two studies within the Khumbu region (Salerno et al, 2008; Bolch et al, 2008) indicates the high potential errors that can exist in area estimates collected for a large glacierized area, despite scoring well in the confidence assessments. Through detailed assessment of errors that could manifest when comparing topographic or remote sensing data, they indicate potential measurement errors between ±2-5%. Thus, when assessing changes within this range, a relatively wide margin of error can exist. Although the high potential errors reported could result in excluding such data from further assessments, it must be acknowledged that both studies have clearly reported their methods and recognise errors inherently exist in any analysis encompassing cartographic mapping or remote sensing imagery, particularly over large areas. That these values are higher than other reported area mapping errors may simply indicate more rigorous analysis of error has been undertaken or that source data are less accurate. Such considerations are, however, not possible when comparing different error estimation techniques applied to different data measured using different methods.

Table 5 reports an average loss of 13% in glacierized area from over an average period of 34 years, indicating an average loss of area of around 0.4% per annum. Assessing only the very highest confidence data, the average percentage change is a loss of 11% over an average 30 year period, also equating to an average loss of 0.4% per annum, thus validating the lower confidence data.

Table 5: Percentage change in glacierized area for studies providing measurements of multiple glaciers (Green cells indicate Very High confidence data, Red cells indicate High confidence data, Blue cells indicate Medium confidence data; Changes with reported errors exceeding 20% of measured change are highlighted in red)

Region	Glacierized baseline area (km^2)	Basin	Baseline year	Comparator year	Period of comparison (years)	Percentage change (%)	Associated error
Parbati Basin	488	Indus	1962	2004	42	-22	n/a
Chenab Basin	1414	Indus	1962	2004	42	-21	n/a
Poiqu River Basin	229	Ganges	1986	2001	15	-20	n/a
Baspa Basin	173	Indus	1962	2004	42	-19	n/a
Everest Region	144.14	Ganges	1974	2008	34	-10	±0.76%
Naimona'nyi region	87	Indus/ Ganges/ Brahmaputra	1976	2003	27	-8.8	n/a
Mapam Basin	108	Indus/ Ganges/ Brahmaputra	1974	2003	29	-6.9	±0.01km^2
Khumbu Region[5]	92.96	Ganges	1962	2005	43	-5.3	±2%
Khumbu region[6]	403.9	Ganges	≈1956	≈1990	≈34	-4.9	±4.9%
Average	**370**		**1969**	**2003**	**34**	**-13**	

Rate of change

Only 7 of the 14 studies featuring area as a measure of change present primary data on glacier area measurements for more than two periods that would allow an assessment of the rate of change. One of these studies (Nainwal et al, 2008) only provides a third measurement point for two glaciers, separated by one year from the second, and almost no change is detected during this subsequent short period of measurement. The remaining 6 studies assess change over periods ranging from 28 to 43 years over

[5] Bolch et al's (2008) study includes data from 3 main glaciers in the region; Khumbu, Nupste and Lhotse glaciers

[6] Salerno et al's (2008) study includes 30+ glaciers from the region, including Khumbu, Nupste and Lhotse glaciers

1962-2008. Measurements are plotted in Figure 17, displaying the area change as a percentage difference from the baseline measurement. This baseline is depicted at zero on the Y axis and all subsequent measures are plotted against the year measured. Once a measure of change was established from the baseline, all subsequent measures can be expressed as either an increase in the rate of area reduction, or a decrease in the rate of area reduction. The rate refers to the average annual loss of area over time. The variable confidence ascribed to data by the review team has also been illustrated through variable plotting colours. The river basin that glacial meltwater feeds into has also been indicated; in the case of the studies from the Naimona'nyi region and Mapam Yumco basin, meltwater can feed into all three major river systems (it was not possible to determine which system exactly).

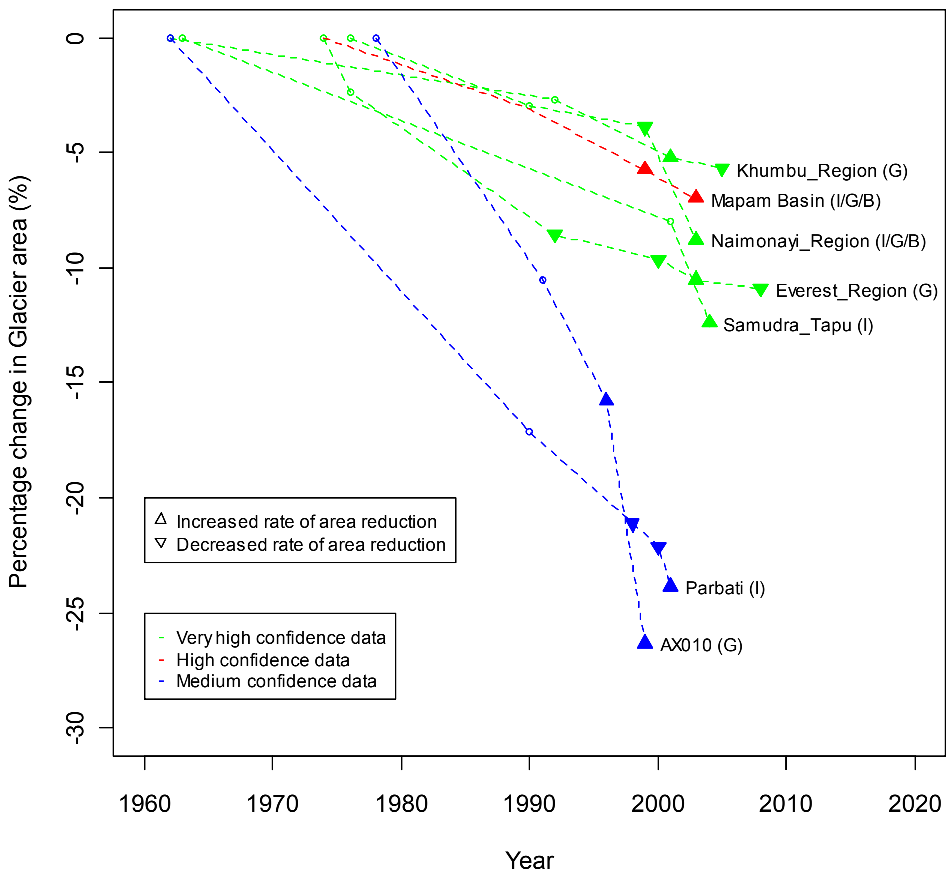

Figure 17: Percentage change in glacier area over time (triangles represent an increase or decrease in average rate of area decrease compared to baseline measure of change; G indicates Ganges basin, I indicates Indus basin, B indicates Brahmaputra basin)

Figure 17 indicates that, from the data available to the review, it is not possible to discern any significant changes in the average rate of area loss for any glaciers/regions prior to the 1990s. Findings from Parbati glacier (Kulkarni et al, 2005) and AX010 (Fujita et al, 2001a) reveal the most significant negative changes during the period measured yet these data are given the lowest confidence rating (medium). All other data, given a high confidence or above, show a wide range of different changes in the rate of glacier retreat over time. Findings from the Naimona'nyi region of the western Tibetan Plateau (Ye et al, 2006), Parbati glacier (Kulkarni et al, 2005) and Samudra Tapu glacier in the Indian Chenab basin (Shukla et al, 2009) show a similar distinct rapid increase in the rate of glacier area retreat around the year 2000, which is interesting because they all are in the Indus basin and may be considered representative of the western Himalaya.

Evidence from glaciers feeding into the Indus Basin suggests a mixed pattern of changing rates of glacier area loss since the 1990s. Measurements from the Naimona'nyi region indicate a decrease in rate while measurements from the neighbouring Mapam Yumco basin show an increase. Evidence from Parbati glacier indicates a gradual decrease in area loss rates during the 1990s but, again, the data were of lower confidence. Data post 2000 is available from four glacier/regions and points to an increase in the rate of area loss during this period.

Analysis of area loss in glaciers from the Ganges basin also indicates a mixed pattern of change during the 1990s. A reduction in the rate of loss during the 1990s in 2 of the 4 studies (all ascribed very high confidence) contrasts to an increase in the rate of loss from 2 other studies (one of medium and one high confidence data). Measurements from the 4 studies that provide measurements post 2000 indicate that the rate of area loss briefly accelerated around 2001, but, in the two studies that provide longer term measures, the rate of loss subsequently decreases thereafter.

In summary:

- There is limited data prior to 1990 from which to assess changes in the rate of area loss;
- There is only one comparative measure of change post 2005 available for assessment, limiting any consideration of recent changes in the rate of area loss for glaciers within the region;
- There is no corroborated increase in the rate of area loss during the 1990s;
- Evidence from glaciers feeding into the Indus basin indicate a general and corroborated increase in the rate of area loss during the period post 2000;
- No clear pattern of an increase in rate loss of area was evident from glaciers feeding into the Ganges basin, but all studies indicated an increase in the rate loss around the year 2001, though the available evidence from two studies indicate this subsequently decreased;
- Measures of change for glaciers feeding into the Brahmaputra basin come from the two studies located in the Mapam Yumco basin and Naimona'nyi region, which also feed into both other catchments. Rates during the 1990s increased slightly within the Mapam Yumco basin, though higher confidence evidence from the Naimona'nyi region exhibited a slight drop. Both studies showed rates around the year 2000 to have increased;
- The rates of area loss reported were highest in those measurements that were given the lowest confidence assessment;
- Caution must be applied to the lack of error estimation applied to the all data assessed, with estimates from those studies reporting potential errors varying

significantly from less than 0.01% (Mapam Yumco) up to 2% (Khumbu Region).

4.5.4 Terminus

Data on glacier terminus changes for 37 glaciers (from 33 studies) met the review's confidence requirements. Of these terminus data for 2 glaciers were identified in the Karakoram, while no terminus measurements were found for glaciers in the Hindu Kush. Within the Himalayan mountain region, terminus data were identified for 13 glaciers in the Indus basin and 24 glaciers in the Ganges basin. No data were identified that met confidence requirements in the Brahmaputra basin. The available data were assessed first for themes relating to size and method that exist within the retreat data, followed by a consideration of changing rates of terminus retreat and advance.

Changes in terminus position

The only net advancement in glacier terminus reported was from the three studies undertaking measurements on glaciers in the Karakoram (Belo et al, 2008; Diolaiuti et al, 2003; Batura Investigation Group, 1979). All glaciers within the Himalaya were found to exhibit net retreat, with the only periods of advance measured within series being recorded on Rakhiot glacier (Gardner, 1986; Schmidt & Nusser, 2009), located on the western most fringes of the Himalaya range. No clear difference in the magnitude or timing of glacier retreat between glaciers in the Indus or Ganges basin was found upon inspection of the data. There is however a difference in the availability of terminus change data from these basins, with data for Himalayan glaciers feeding into the Indus basin lacking any information on glaciers longer than 20km, and containing only one measure of change for glaciers less than 5km in length.

Accuracy of reported terminus position and changes relative to baseline positions was not consistently analysed by the studies considered. Only four studies considered and reported positional errors, all indicating highly variable approaches and estimates. None were found to provide a systematic assessment of the errors arising from comparison of topographic mapping sources. The general reported findings on accuracy include;

- Bahuguna et al (2004) report terminus positional errors from remote sensing images of between ±15-25m, compared to observed retreats in excess of 600m;
- Belo et al (2008) find positional error using satellite data of around ±28m, compared to observed advances of around 2km;
- Diolaiuti et al (2003) provide a rare assessment of the accuracy of historical measurements, showing early measurements on Liligo glacier to have an accuracy of ±200m, increasing to ±5m with modern satellite remote sensing images;
- Kumar et al (2008) report positional accuracy from kinematic GPS survey of ±1cm.

There was no consistent method or reporting of accuracy in any of the studies considered. Indications from the studies outlined above show the errors to be minor compared to the changes measured. Thus, the accuracy of study measurements cannot be systematically considered and the confidence matrix scoring again will be used as an objective proxy to explore issues pertaining to measurement accuracy of terminus change.

In order to explore this large data set further, a series of plots of glacier length have been provided to identify any themes that might exist in the terminus data. The plots, categorised by initial (baseline) glacier length, allow clear presentation of the changes relative to glacier size. This type of plot was chosen in preference to plots that merely present the change in terminus position because such plots give no indication of glacier size and therefore the change in length relative to the glacier length. The size categories are arbitrarily chosen sizes that encompass the varying lengths and allow comparative visual inspection. No lines have been provided to 'join' measured changes because of the risk of incorrect inferences. It must also be noted that while the measurements of change in the position of glacier terminus have all been assessed using the quality assessment criteria it was not possible to assesses all figures for the baseline length given. Many of these seem to be estimates given to the nearest 100m. Estimates of baseline length do however provide a useful perspective on the changes measured.

a) Small glaciers (0-5km length)

Figure 18 reveals the retreat was the dominant trend over the various study periods for all of the smallest glaciers investigated. Glaciers of this size were all within the Himalayan range and within the Ganges basin. Within this size range only one series of terminus retreat measurements are available, for glacier AX010 in the Khumbu region of Eastern Nepal (Fujita et al, 2001a) The majority of terminus data detail a single change in glacier length from the late 1970's to the late 1980s. All glaciers were found to be retreating apart from AX030 (Yamada et al,1992), which was found to be a stationary glacier.

Maximum measured retreat was 305m at Shunkalpa (Jangpani & Vohra, 1962), and the average measured retreat was 83m. Maximum retreat, as a proportion of baseline length estimates, was found to be 14% with glacier EB010 in Nepal (Yamada et al, 1992), while the average retreat for glaciers of this length was 5.3% over an average 18-year period, equating to an average annual retreat of 0.3%.

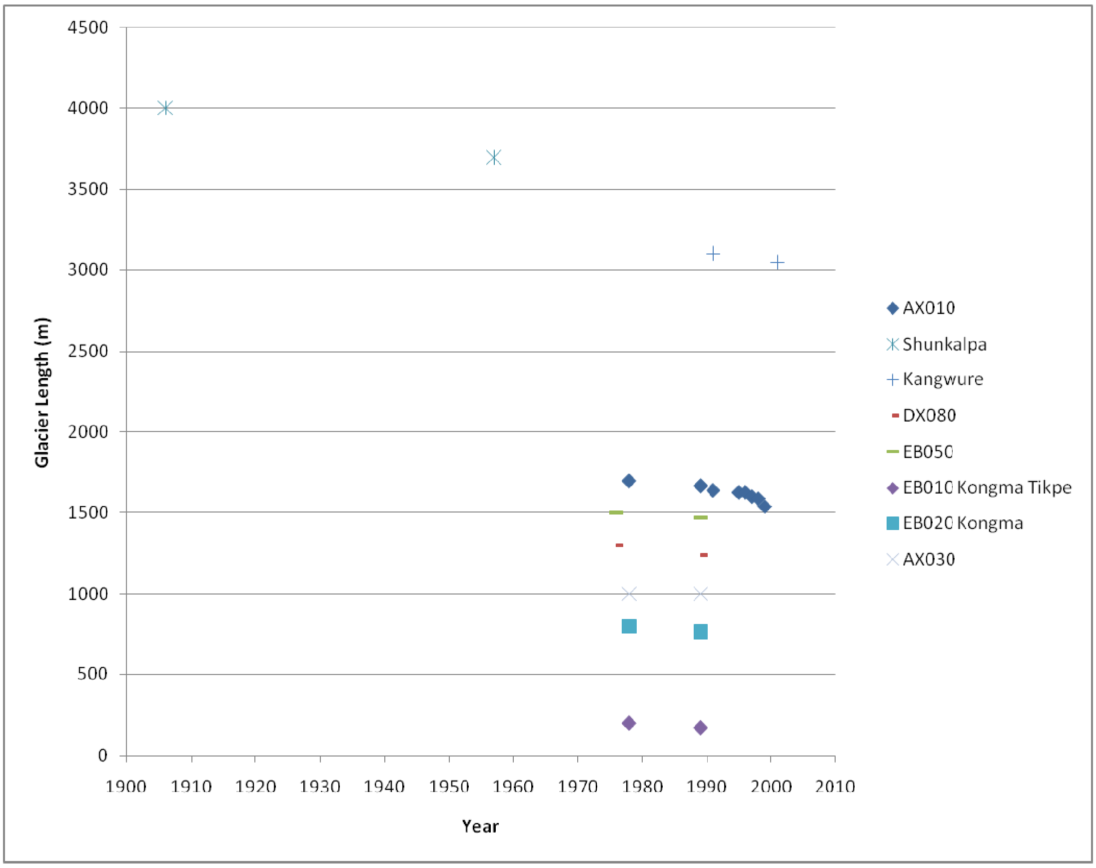

Figure 18: Glacier length for small size glaciers between 0-5,000m in length

b) Medium glaciers(5-10km length)

Figure 19 reveals all 13 glaciers of this size exhibit retreat over the periods reported. All glaciers are located in the Himalayan region, with an equal spread of data from glaciers in the Indus and Ganges basins. From inspection of the data and trend analysis there is no clear difference in the retreat of glaciers between these two basins Seven glaciers provide a series of measurements, typically over the period from the early 1960's to the first decade for the 21st century.

Maximum measured retreat of 1256m was measured at Imja glacier (Bajracharya, 2008); minimum retreat of 11m was Naradu glacier; average retreat from this set of glaciers was 560m. Maximum retreat as a percentage of baseline estimations was 16% at Pindari glacier (Tewari & Jangpani, 1962), minimum of 0.2% at Naradu glacier (Koul & Ganjoo, 2010), with an average of 8% over an average 32-year period for glaciers in this category. This equates to an average annual retreat of 0.26%.

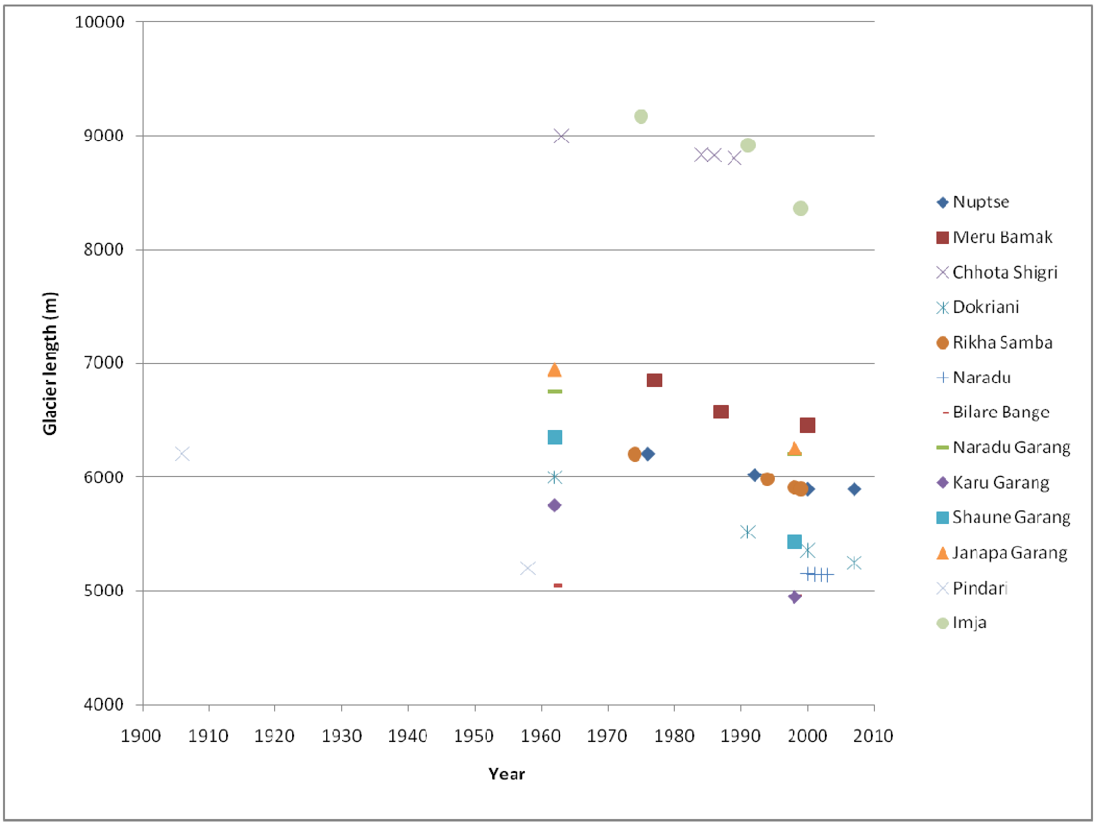

Figure 19: Glacier length for medium size glaciers between 5,000-10,000m in length

c) Large glaciers(10-20km length)

Figure 20 covers large glaciers and reveals some clearly different patterns in terminus movements compared to smaller glaciers, with both advance and retreat evident along with much greater variation in terminus movement. Data from Rakhiot (Gardner, 1986; Schmidt & Nusser, 2009) reveals glaciers exhibiting fluctuating behaviour, with periods of both retreat and advance. Liligo glacier (Diolaiuti et al, 2003: Belo, 2008) was measured to advance significantly. Both these glaciers are far to the west of other glacier areas considered, with Liligo being well within the Karakoram Range and Rakhiot situated on the western most fringes of the Himalaya. Data for glaciers of this size provide a much larger temporal spread than other sizes, along with having many series of measurements to assess changes over time. The majority of data are within the period from the early 1960's to the mid 2000's.

The most significant total retreat measured, and retreat as a percentage of baseline length, was for Parbati glacier (Kulkarni et al, 2005), with over 6500m of retreat in only 30 years, a loss of over 39% in length. The data were given a medium confidence, but further consideration of this data could be warranted considering the extreme nature of reported change. Measurements from Baspa Bamak over a similar period and a similarly sized glacier however, reveal significantly less retreat (Kulkarni & Bahuguna, 2002) The next highest retreat, as a percentage of length, was around 8% (Satopanth – Nainwal et al, 2008).

Measurements of Liligo glacier in the Karakoram showed significant advance of the glacier terminus: Belo et al (2008) found over 2000m of advance, an overall 14% increase in the length of the glacier. Long-term data from Rakhiot (Schmidt & Nusser,

2009) indicate glacier length has barely changed over time (1% retreat over 43 years) despite decadal periods of advance and subsequent retreat.

Overall, glaciers of this size have retreated 564m on average, a figure heavily influenced by the 6000m plus retreat of Parbati. This equates to an average retreat of 4% in length over an average 42-year period, or 0.09%, as an average annual rate.

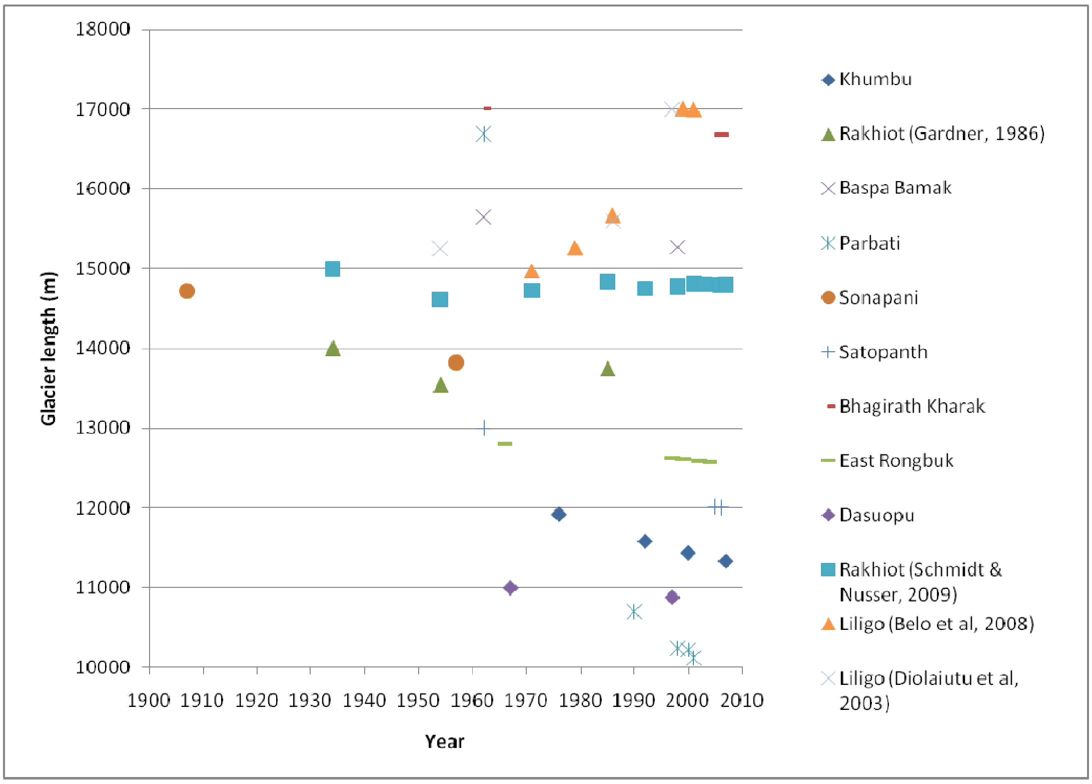

Figure 20: Glacier length for large size glaciers between 10,000-20,000m in length

d) Very large glaciers(>20km length)

Figure 21 covers the largest glaciers where terminus measurements were taken. Data for Batura glacier are omitted from the graph because it totally distorts the scale and little change can be viewed for any other glacier (it is nearly twice the length of Gangotri glacier). Batura glacier, located in the Karakoram, does exhibit the only advance, some 100m, but this equates to only 0.2% as a total of the glacier length. over a relatively short period, from1966 to 1975 (Batura Investigation Group, 1979). Evidence of earlier periods showing retreat were detailed, however sufficient confidence in the figures presented limited use in any quantitative analysis.

The displayed data are from 3 separate glaciers located in the Ganges basin (Gangotri, Rongbuk and Ngojumpa). All show consistent long-term retreat. Most of these data come from four studies of Gangotri glacier, which generally agree on a consistent retreat of the glacier terminus, albeit with some disagreement in the extent and rate of retreat. This is to be expected when one considers the various methods used and differing periods of measurement. The longest series of data for Gangotri (Kumar et al, 2008), also has the highest data confidence. Other studies include some earlier measurements but these do not meet the minimum applicable confidence assessment. However, Bahuguna et al (2007) found practically the same 1500m retreat as Kumar et al (2008), even though the period of comparison was some 22 years shorter. This highlights the high variability in measurement when using different methods by different research groups on the same glacier.

The most significant retreat measured was 1530m at Gangotri (Kumar et al, 2008), some 4.8% of glacier baseline length. Average retreat was 740m over a 30 year period, some 3% of total baseline glacier length, equating to an average annual retreat rate of 0.08%.

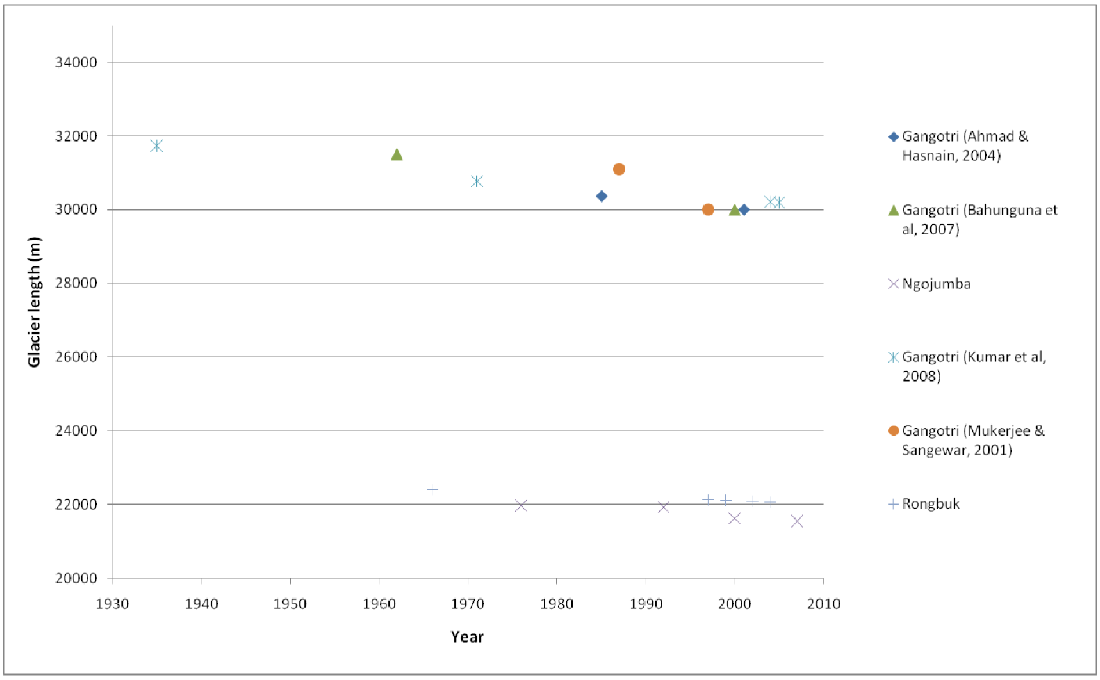

Figure 21: Glacier length for very large size glaciers over 20,000m in length

Rate of terminus changes

To determine whether there is any change in rate of terminus movement, it was necessary to identify first those studies with 3 or more separate measurements. The selection was refined further by only considering those data sets where evidence had been collected at a frequency greater than 1 in every 10 years, so that only the more continuous series of data are considered. This resulted in the selection of data for 15 separate glaciers, as shown in Figure 22. Lines are used to join points on this plot, but these only serve to illustrate the relative variation between glaciers in the rate of terminus loss (indicated by slope). They are not intended to infer a constant rate of loss.

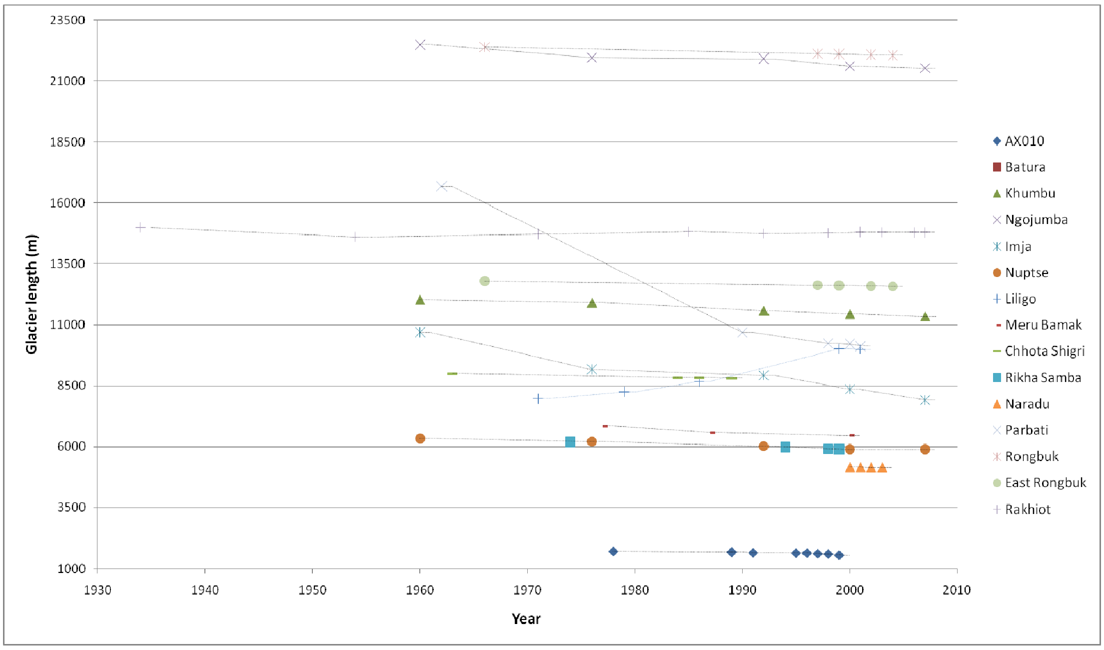

Figure 22: Glacier length over time as reported by studies that measure more than one period of change with measurements taken above an average frequency of 1 in 10 years

One of the main questions regarding retreat of glacier termini in the Himalaya is whether rates of retreat have accelerated in recent decades. Results from analysis of the data for the 15 glaciers are summarised as follows:

- 7 glaciers provide annual average retreat rates for the periods 1960-1979 and 1980-1989; 2 show termini rates of retreat have increased since the earlier period; 4 reveal rates of retreat have decreased; 1 study provides evidence of increasing rates of advance.
- 11 glaciers provide annual average retreat rates for the periods 1980-1989 and 1990-2000; 7 show increased annual average rates of retreat in the latter period; 2 have decreased rates of retreat, and 2 exhibit increased annual average rates of advance.
- 9 glaciers provide sufficient evidence to consider changes in the average annual retreat rate between the periods 1990-1999 and 2000 onwards; 5 indicate an increase in the rate of average annual retreat; 3 a decrease, and 1 indicates an increase in the rate of average annual advance.

Retreat of the Ngojumba and Imja glaciers in Nepal (Bajracharya, 2008) in the early 1990s show the most significant increases in the rate of retreat from the 15 glaciers assessed and provide the only readily visible indicators of such increases. The issue of scale, and how reported increases in the rate of retreat should be considered in relation to glacier length, was not considered by any of the studies. Studies simply reported the average rate of change for a certain comparison period, and did not consider change relative to glacier dimensions or temporal resolution of measurements. Data from 2 glacier positions on Everest, as reported by Ren et al., (2006), provides relatively continuous long-term evidence of a gradual increase in the rate of retreat, increasing from 8.7 ma^{-1} and 5.5 ma^{-1} in 1966 up to 9.5 ma^{-1} and 8.3 ma^{-1} in 2004 on the Rongbuk and East Rongbuk glaciers respectively. However, when we consider these glaciers have lengths of around 22.4 km and 12.8 km respectively, the increases in rate are relatively small in magnitude, and the more recent continuous measurements provide averages of change derived from much more continuous time-series compared to earlier single measures of change averaged over 20 years.

Localised factors such as valley shape and slope are not consistently reported upon and could be highly influential in determining observed changes. Without such consistent data, or the availability of additional variables that could be important drivers of the change measured, it is problematic to draw systematic conclusions.

The problem of temporal resolution and lack of continuous long term measurements of terminus movement is particularly evident when we consider many of average rates of retreat established represent long periods. Much of the retreat measured may have occurred during a short period. Subsequent measurements of change on the same glacier over a shorter period might in fact encounter a rapid period of change, ultimately then causing the comparison of rates to be based on an un-systematic approach of untypical and skewed measurements. To systematically assess long-term changes in the rate of retreat, average rate of retreat (obtained from more than one measurement) from each decade for each glacier would, at minimum, be required.

In summary, there appears to be an average increase in the rate of terminus retreat during the 1990s, but due to the lack of continuous records and systematic reporting a definitive quantitative analysis is not possible. Average rates of retreat are also generally calculated from long periods of change and thus do not provide any proof of change at an inter-annual or decadal scale.

4.5.5 Outcome of analysis of measurements

In combining the analysis of each measure, and considering the variable confidence ascribed to each measurement type, the various findings can be synthesized into a coherent and objective assessment, identifying common features that exist within and between measurement types.

Mass balance

Negative mass balance has been identified as the most robust indicator of glacier shrinkage, and over 90% of all the selected data give a clear indication that is the predominant behaviour across the Himalayan region. Some particular features were identified within the data assessed:

- Where positive mass balance has been measured, it forms part of a highly variable inter-annual series of measurements. However, when plotted as cumulative mass balance plots, there was a clear and corroborated picture of rapid mass loss on all glaciers considered by the review;
- None of the available mass balance measurements considered comprise long-term data series for analysis, but such data are usually of good resolution and continuity, providing arguably the best set of year-to-year changes of glacier shrinkage;
- No discernable pattern of differences in shrinkage exists between mountain ranges or major river basins;
- For the period 1987-2006 glaciers experienced an average annual mass balance loss of -0.57 m.w.e;

- The lack of long term data prevents an assessment of whether rates of shrinkage are increasing;

Volume

Although volume was indicated as the second most reliable measure of glacial shrinkage, analysis of the data has highlighted the typically low temporal resolution and potentially high inaccuracies associated with such measurements. Much of the data are also over large regions, providing little information about changes on particular glaciers. No assessment of how rates of volume loss are changing was possible due to the lack of comparable periods, and thus it was not possible to determine whether shrinkage rates are increasing. However a trend in volume loss over time is reported in all studies.

Area

Area provides a relatively good data set compared to volume, in terms of quality, coverage and resolution. Data from the various studies highlights the highly variable level of areal retreat and advance measured between glaciers/regions, but some observations can be made when considering features within the data:

- Combined measurements from studies on single glaciers provide an average retreat of 16% over an average 34 year period, a loss of around 0.5% per annum. For highest confidence data, an average area loss of 11% over an average 36 year period was obtained, an average annual loss of some 0.3% per annum;
- Average annual area loss as a proportion of glacier baseline area is greater for smaller glaciers below $10km^2$ (-0.73%) compared to larger glaciers above $10km^2$ (-0.17%). However, further analysis of area loss in relation to the baseline glacier area reveals that although relative average annual area loss is highest for smaller glaciers, there is a low statistical certainty in this relationship;
- The only evidence of increases in glacier area are accompanied by potential errors exceeding 20% of the measured change;
- Measurements from studies of large glacierized areas found average area loss of 13% over an average period of 34 years, an average loss of around 0.4% per annum. For highest confidence data, average loss is 11% over an average 30 year period, also equating to an average loss of 0.4% per annum, which corroborates the lower confidence data;
- Errors in comparative measurements of glacier area vary considerably between those studies that present such analysis and no consistent error estimation methodology was identified;
- There is limited data prior to 1990 and from 2005 with which to assess changes in the rate of area loss;
- There is no corroboration from the selected data that the rate of area loss increased during the 1990s. The only evidence of any rapid increase in the rate of area loss comes from glacier AX010, but the measurements were ascribed the lowest confidence and come from a relatively small glacier;

- Evidence from glaciers in the Indus basin indicate a general increase in the rate of area loss since 2000 with rapid increases in the rate of mass loss in the Naimona'nyi region, and the Parbati and Samudra Tapu glaciers;
- No discernable pattern of an increase in rate loss of area is evident from glaciers in the Ganges basin. However, there appeared to be some corroboration of an increase around the years 2001-2002, followed by a subsequent decrease;
- Data for the Brahmaputra were limited to two studies and showed similar patterns to the Ganges basin.

Terminus

As previously noted, terminus data provides solely a picture of glacial retreat at one point on the glacier but, as discussed, such measurements appear to be valid indicators of shrinkage. Although such data are deemed of low confidence in demonstrating glacial shrinkage, clear patterns of differences in terminus movements are worthy of consideration. From an assessment of the changes in terminus position relative to the glacier length some particular features were identified:

- Small and medium sized glaciers (0-10 km long) were found to have the average annual rates of retreat relative to glacier size of around 0.3%, while larger glaciers (>10 km long) revealed average annual rates of retreat less than 0.1%;
- Average total measured retreat for each glacier size class was lowest in small glaciers (0-5 km long, 83 m) and highest in very large glaciers (>20 km long, 740 m);
- Maximum glacier retreat was measured at Parbati glacier, exceeding 6500m over a 30 year period, some 39% loss of total length. However the extreme nature of the measured retreat was not corroborated by any other evidence and warrants further attention;
- Advance and fluctuation of glaciers was only identified in 3 separate glaciers, all either in the western most fringes of the Himalaya or in the Karakoram;
- An interesting observation omitted from the data synthesis due to low confidence scoring of the baseline measurements comes from the two studies that consider changes in glacier termini relative to baseline positions before 1900. In both cases (Gangotri - Mukerjee &Sangewar, 2001; Siachen - Raina & Sangewar, 2007), a significant advance was indicated during the late 19th Century, but the evidence was ascribed low confidence due to the uncertainty surrounding methodological approach and accuracy. However, the fact that the only measurements of change pre-1900 considered by this study both indicate glacial growth during the late 19th Century does provide some validation to the observations;
- Analysis of changing retreat rates in glacier termini revealed a lack of consistent and continuous measurements from which to draw quantitative assessments of decadal changes in retreat rates. However there is indication (from those few studies in which such comparison are possible) that there were marked increases in the rates of retreat for over 70% of glaciers with available data from the 1980s to the 1990s. There were too few reported

changes during the 2000s to make any comparative assessment for this later period.

5. Discussion

5.1 Outcome of analysis/review

This review is arguably the first to formally use systematic review methods to assess evidence of glacier shrinkage in the Himalayan region in order to discuss potential impacts for future meltwater availability and identify research needs. A synthesis of the reviewed studies helps answer the first level of synthesis in the primary review question; "What is the evidence for glacial shrinkage across the Himalayas?
"

- Studies for glaciers in the Himalayan mountain range are much more prevalent (45) than in the Karakoram (7), while no studies were identified from the Hindu Kush;
- 50% more studies referred to glaciers feeding the Ganges (30) than the Indus (20). Only two studies referred to glaciers feeding the Brahmaputra; neither of these studies met the quantitative assessment criteria;
- Most studies focused on glaciers in India (23) and Nepal (13); far fewer studies were undertaken in China (8) Pakistan (7) and Bhutan (2);
- Glaciers having a surface area below 10 km^2 provide the majority (>60%) of selected measured data, with an average size around 5 km^2;
- Articles providing comparative measurements of glacier shrinkage/growth have been more abundant since 1990 (41 of the 52 articles considered were published post-1990);
- Of post-1990 papers, the majority were published in four main publication sources, namely Journal of Glaciology, Bulletin of Glaciological Research, Current Science, and Annals of Glaciology.
- Increased publication since the late 1990s suggests increased attention to, and corresponding increased funding of, climate change research;
- Terminus measurements are the most prevalent form of glacier measurement in the region, providing the only long-term data series;
- Since the early 1990s, there has been a notable increase in both area and mass balance measurements.

Evidence from the wide range of studies considered in this review reveals a high degree of variation and complexity in glacier behaviour across the region, making it difficult to draw too many general conclusions. Such difficulty is compounded due to the lack of long-term continuous glacier monitoring in the region; much of the evidence presents singular measurements of change over long time periods, yet fails to describe the behaviour of the glacier during that period. Even where two or more change measurements are provided, different glaciers are difficult to compare because of inconsistencies in the timing and periodicity of data.

Despite the complexity of the evidence, some general traits can be identified through the second level of synthesis that may help answer the review question; "What is the evidence *showing* concerning changes in glacier shrinakge in the Himalayas?"

- Himalayan glaciers have been exhibiting shrinkage as the predominant change, according to all measurement types, since 1900;
- Some evidence of growth and fluctuation (growth and shrinkage over time) exists for some glaciers in the western parts of the Himalaya and the Karakoram;
- Studies classified as higher confidence and reporting shrinkage corroborate the behaviour reported by the more numerous lower confidence studies;
- The seven studies identified for the Karakoram region indicate patterns of both shrinkage and growth. Higher confidence mass balance data show shrinkage, while terminus data describe instances of growth and fluctuation. This suggests that glaciers in the region may undergo periods of terminus advancement even when the overall glacier may be thinning and losing mass;
- The only corroborated trend in the timing or magnitude of shrinkage on decadal scales is that glaciers from the western Himalaya, that feed the Indus, show an increase in the rate of area loss since around 2000;
- Significant local variation is observed between glaciers and regions for every measurement type;
- Average annual rates of glacial shrinkage in mass or volume relative to glacier size were not possible due to the limited data available to the review. However, indicative values can be found in the average annual change in glacier area and terminus position. Average area change of between 0.4-0.5% per annum when considering all the available area data, with average area loss for smaller glaciers (<10km2) of 0.73% per annum greater than an average area loss of 0.17% per annum for larger glaciers (>10km2). Average annual change in glacier terminus position was an overall retreat of between 0.3% per annum for the smallest glaciers (<5 km long) and 0.08% per annum for the largest (>20 km long);
- From the data assessed, it would seem relative retreat in both area and terminus increases as glacier size decreases. However there are exceptions and low statistical certainty in this relationship, possibly due to a multitude of localised factors that could not have been possibly considered by this review and a relative lack of data from larger glaciers;
- Discerning whether the rate of glacial shrinkage is increasing is problematic due to the lack of long-term continuous data from all measurement types. The few long-term terminus measurements reveal a mixture of increasing and decreasing rates of shrinkage but with some corroborated indication of an increase in retreat and advance rates during the 1990s. For glaciers feeding the Indus basin, there are corroborated increases in the rate of area loss since 2000. A more variable pattern is evident from those glaciers feeding into the Ganges basin. Overall there are no corroborated increases across the measurement types considered for any particular region or period.

5.2 Limitations of the review

An assessment of the evidence highlights a number of limitations with the review which would aid interpretation of the findings and inform the conclusions:

- Additional evidence may be available in non-English (language) publications that were not considered by the review. The reviewed studies indicate also a significant body of unpublished data from across the region, mainly from the Indian Himalaya. Recent reviews by Raina (2009) and the USGS compilation (Williams & Ferrigno, 2010) show there is a considerable volume of evidence that either have been published in little-known isolated sources (grey literature) or remain unpublished. However the lack of transparency in the derivation of such evidence would probably limit its inclusion in this particular review;
- Due to time and resource constraints, geomorphological evidence was omitted from this particular review. Such evidence can provide valuable information on the movement of glaciers within the region and would warrant further analysis of the available evidence and its relative accuracy;
- The data available to the review generally were limited both in duration and frequency (of measurement) and were devoid of long-term continuous series that would allow systematic characterisation of temporal variations in behaviour;
- The lack of consistent and standardised reporting of errors in the measurements of change presented in studies hinders systematic comparison of data accuracy. Studies in the region rarely describe measurement uncertainty; amongst those that do there is no consistency. Confidence and data quality assessments were thus based upon criteria that were deemed to reflect accuracy of measurement and the clarity of method. Such an approach, however, does not provide a categorical description of uncertainty. Measurement error exists in all data assessed, but inferring error from those few studies that do report measurement accuracy would not seem a robust approach considering the significant variation in accuracy assessment and reported errors that exist between those studies that do report accuracy within the region;
- The review has identified that much of the available evidence is concentrated in a few, relatively limited, areas of the region (i.e. north-west India and central and eastern Nepal) and, as such, cannot be considered representative of glaciers across the region as a whole. Many glaciers have been monitored due to the relative ease of access, or availability of clear remote sensing images. The difficult conditions and high costs involved in field research have also limited the availability of good quality field measurements from the region. On-the-ground field measurements are severely limited by difficulty of access. Those glaciers that can be accessed and travelled upon are atypical and therefore not representative of the totality of glaciers. Inferences for the entire region from such subsets should therefore be made with caution;

- Political sensitivities around border regions further limit the availability of good quality data. Sometimes data are deemed "classified" on national security grounds;
- Translating mass balance changes to volumetric changes in glaciers, and corresponding change to meltwater, or water resources, availability, is hindered by a lack of information on the variation of glacier cross-sectional area with elevation;
- The lack of good quality data (i.e. meeting minimum confidence criteria) prior to the early 1960s, makes it difficult to assess recent changes in glacier mass against earlier patterns and hinders the ability to assess long-term changes in the rate of glacier shrinkage;
- Both length and area changes are indicative of mass changes, but the relationship is not straightforward; changes in glacier dimensions are strongly dependant of the local topography, and mass balance changes can produce delayed responses in terminus movement and glacier area;
- There were relative few good quality studies that provided assessments of change from primary measurements. Many studies failed the inclusion criteria by comparing their own measurements with other studies but without having assessed the accuracy of, or even described, the methods employed in those studies.

6. Reviewers' Conclusions

6.1 Conclusions

This section summarises the outcomes of the review in relation to the Primary question, "What is the evidence for glacial shrinkage across the Himalayas?", and the 3 secondary questions, "are glaciers shrinking or growing, and are there regional differences"; "is the rate of glacial shrinkage increasing across the region", and "in what areas of research is evidence lacking and how best could future work ensure a more complete evidence base is developed?". Reviewers' views on the possible implications of the study's findings on policy development and research are proffered in the two subsequent sections, Sections 6.2 and 6.3.

6.1.1 Primary question: 'What is the evidence about glacier shrinkage across the Himalayas?'

The review focused on physical changes measured by previous studies in the region, interpreting evidence by measurement type and assessing how such evidence is indicative of glacier shrinkage and changes to meltwater. The systematic approach maximised the likelihood that the assessment was based on unbiased, good quality evidence and, thus, provides more objective conclusions than other reviews on glacier shrinkage that all too often highlight only evidence that concur with pre-conceived views on what is happening (e.g. WWF, 2005).

The evidence gathered, supported by all measurement approaches, provides an overall picture of glacial shrinkage across the Himalaya, with some regional and local variation. This suggests future long-term availability of meltwater from glaciers is likely to diminish. However, assessment of how much the resource has decreased (or will decrease) is highly problematic. Terminus data should be interpreted with caution; changes in terminus position provide only limited information of change in the glacier at its lowest point and can be significantly affected by local physical factors. Volume data has been shown to contain a high degree of inaccuracy. Mass balance data, though providing the most robust indicator of glacial shrinkage, does not provide an indication of how much mass is left. Area data provides a clear 'before/after' surface indicator of glacial shrinkage, but does not provide measurements of volumetric or total mass changes of a glacier. There also exist high potential errors in assessing any changes through the comparison of existing topographic map sources; both in the source mapping accuracy and the subsequent cartographic comparison. Whether the rate of loss has increased according to globally observed increases in temperature was not possible to assess due to the lack of associated long-term meteorological data available within studies.

Deriving accurate figures for glacier shrinkage to inform quantitative analysis of the changes to Himalayan glaciers has been shown to be highly problematic due to the limitations of the available data. The lack of consistent approaches, particularly in describing error and uncertainty of measurements, limits confidence in the data. However, collations of area and terminus measurements do provide data-sets of relative measurements of change in glacier dimensions. That area data, which was shown to be more rigorous and representative data of glacier shrinkage, is broadly in agreement with terminus data, provides further validation that terminus measurements are valid indicators of shrinkage. The terminus data also indicates that retreat relative to glacier size is clearly greater for smaller glaciers, an observation shown to have a similar relationship in area data, albeit with a low level of certainty.

Collating data from various measurement types provides a systematic approach to assessing questions on glacier shrinkage. Caution should be applied to inferring too much from terminus measurements alone, as they merely provide an indication of change at the lowest part of the glacier and are subject to considerable uncertainty in accurate delineation of earlier baseline position. In particular, one of the most extreme measurements of shrinkage on Parbati glacier (Kulkarni et al, 2005) warrants further investigation. Analysis of these measurements by Bhambri & Bolch (2009) suggested the area measured in 1990 was unlikely following comparison with maps from 1987. This highlights the significant challenges in assessing evidence from different sources and the need to collate findings in an objective and systematic manner.

The review identified a lack of studies that directly compare primary data on glacier shrinkage with changes in downstream glacier lakes. The findings from those few did not provide any clear relationship and revealed the difficulties in assessing such relationships without significant field data.

In order to give context to the review findings, it is necessary to consider the relative scale of the evidence being discussed in comparison to the subject of the discussion. Successive reports, such as those for Chhota Shigri, AX010 and Dokriani, go some way to increasing understanding of the functioning of single glaciers. However, data from such glaciers merely represents a minute fraction of the glaciers within the Himalaya and cannot be representative of the majority. Various estimates of ice and glacier cover across the Himalayan mountain region have been made: estimates range from around 33,000 km^2 (Dyurgerov & Meier, 2000; von Wissman, 1959) up to 35,000 km^2 (Qin, 1999) and 38,000 km^2 (Kaul, 1999), a total of over 5,000 glaciers. Data available to this review from the selected studies represents a fraction of this total area, and thus bias towards the studied glaciers/areas is inevitable.

The average glacier size assessed by studies considered was found to be around 5 km^2, which accords well with estimated average glacier sizes within the Himalaya region of between 7.2 km^2 (Kaul, 1999) and 1.9 km^2 (Qin, 1999). However it is important to consider that it is the largest glaciers that contain by far the largest stores of ice and meltwater; with glaciers in the Karakoram being much larger than the Himalaya, yet are significantly less represented in the research communicated through the articles identified.

Recent evidence from a paper by Scherler et al. (2011) provides a cross-border systematic study of glacier change over a constant time period. Such an approach typifies the type of standardised and holistic research that has been recommended by this review to better understand changes in Himalayan glaciers and provides a good example for future methodological approaches. Though no quantitative assessment of shrinkage can be determined from such a study (as only advance or retreat is detailed), findings provide validation to this review's conclusions on regional differences and the fact there is no uniform response of Himalayan glaciers to climate change.

This review did not seek to provide an assessment of how glacier shrinkage compares to other glacierized regions of the world or to provide future predictions of change. Neither did it attempt to assess evidence related to the downstream contribution of glacier melt to available water resources. The review does, however, provide a systematic analysis of the evidence relating to the changes in glacier mass, which provides an important step towards answering such important questions.

The Himalayan region is a unique and challenging environment for glacier research. There is a long way to go before the changes, and the drivers of change are fully understood; allowing more robust predictions of future change and potential impacts. This review will hopefully contribute to realizing the immediate needs for systematic measurement and reporting to inform future research, along with providing an objective source for discussion of the available evidence.

6.1.2 Secondary questions

Are glaciers shrinking or growing, and are there regional differences?

Evidence from the studies considered by this review reveals a corroborated general pattern of shrinkage across studies considered, reflected by all types of measurement. However, it is also observed that there is localised variation and corroborated regional differences between the central/eastern Himalaya and the Karakoram and western-most fringes of the Himalaya, where growth and fluctuation are the dominant changes observed across the studies considered. A lack of good quality and continuous data inhibits clear regional comparisons to be made, but both narrative and thematic assessments of data corroborate the patterns observed. Caution must, however, be applied in concluding that an advancing glacier terminus indicates overall growth without accompanying high quality evidence on changing mass balance, as the advancing terminus could be accompanied by an overall thinning of the glacier and associated shrinkage. Hewitt (2005) similarly discusses the need to understand the processes that drive surges in glaciers.

No corroborated differences were found to exist between glaciers feeding the Indus and Ganges rivers. It would perhaps be more appropriate to divide the glaciers into divisions based on smaller sub-basins or climatic zones, but this was not possible given the information provided by the studies assessed. Defining a clear cross-border system of hydrological sub-basins and reporting findings on such a scale would provide a valuable tool for water resource planning. This would be particularly useful if representative glaciers from each sub-basin could be identified and studied systematically. A lack of studies on glaciers in the Brahmaputra basin limits any comparative analysis.

Findings by Scherler et al (2011) validate the regional differences observed across the studies considered by this review. They attributed this to the presence of debris on the glacier, with debris-covered glaciers of the Karakoram show signs of advance while those to the east that predominantly lack debris-cover show mainly retreat.

Is the rate of glacial change increasing across the region?

There were insufficient data to assess whether glacial shrinkage has been accelerating or slowing. Mass balance and volume data did not provide long-term measurements of change. Area data were limited to assessments of change from 1990. Longer periods of comparison were available for terminus measurements but it was found that many average annual rates lacked temporal resolution and did not provide systematic measurements for analysis. The only findings that indicated any corroborated increase in the rate of shrinkage across the region were that area loss in the Indus has accelerated since 2000 and that terminus retreat rates were generally highest in the 1990s. Terminus advance of Liligo glacier in the Karakoram was, however, also shown to have exhibited increased rates of advance during the 1990s.

The limited evidence available shows significant variability both between regions and over time. Bold statements, to the effect of accelerated glacial shrinkage, made by various studies are typically based upon the comparison of two measurements of change, predominantly of terminus position, in a non-systematic manner, do not consider inter-annual variation or the change relative to glacier size/local factors. Comparisons with retreat rates of other glaciers published in other articles do not consider such factors and thus do not provide proper systematic comparisons. More careful consideration of the sources and periods assessed to make such assumptions from evidence across the Himalayan region is warranted.

In what areas of research is evidence lacking and how best could future work ensure a more complete evidence base is developed?

The review has identified a lack of continuous long-term measurements from which to assess glacier shrinkage across the region. There is insufficient information collected over time by consistent methods to allow conclusions to be drawn with respect to whether the rate of glacier melt has increased in recent years relative to earlier conditions. Most long-term evidence is from the movement of glacier termini.

Reliable information about long-term changes in mass, that would provide more appropriate assessments of changes, was not available.

There is a comparative lack of evidence from glaciers within the Karakoram and Hindu Kush compared to the Himalayan range, with much of this evidence found to be of low confidence in determining changes in glacier mass. This leads to a poor understanding of the behaviour of large glaciers that feed the Indus River. There also appears to be a significant level of selection bias in both the glaciers chosen for study and the method of measurement applied, which means observed behaviour may not be representative of the area/region.

Collating annual mass balance information is beneficial to develop a link between climate and glacier dynamics and mountain hydrology. Successive yearly reports of negative mass balance provide clear indications of inter-annual variations of glacier shrinkage/growth. The importance of reporting mass balance findings in the public domain through directly comparable values of metres water equivalent (m.w.e) cannot be understated, especially when comparisons are sought to be made with global patterns of glacier change. However, only by generating successive values over time can a clear picture be made of the status of a glacier. The lack of data from the region in the most recent Glacier Mass Balance Bulletin (Haerberli et al., 2009) hinders comparison to global trends. The future work proposed by Wagnon et al., (2007), to investigate glacier mass balance response to regional climate will go some way to expanding understanding and aiding predictions of change in response to climatic changes. However, there is a scarcity of such information, and their work highlights the importance of building a catalogue of information.

Few studies attempt cross-border, trans-boundary assessment of glacier fluctuations; those that do lack consistency in method, measurement type and importantly, a prolonged period-of-measurement. This hinders direct comparison within the study and limits the usefulness and potential confidence such data might have when considering the evidence in other studies. Studies by Berthier et al. (2007) and Scherler et al. (2011) demonstrate the power and usefulness of remote sensing. Through such techniques, large numbers of glaciers of different sizes from all parts of the region can be monitored simultaneously according to a standardised methodology. These types of studies, combined with on-the-ground surveys at a small number of selected glaciers, present opportunities for future research. Cross-border measurements of multiple glaciers from a single study source provides an even greater benefit by presenting standardised data across a wide area, allowing regional patterns to be compared systematically.

Future work in research of glacier change across the Himalaya could ensure a more complete evidence base by addressing the comments noted above and thus providing a more systematic coordinated programme of research is conducted. Further conclusions regarding how this could be achieved are provided in section 6.3.

6.2 Implications for policy

Policy development in the Himalayan region and other regions with high mountain areas will benefit from the improved, unbiased, understanding of glacier behaviour this systematic review provides. Local/regional policy, focused primarily on management of water resources, can draw upon the regional variations within the available evidence. However, as discussed in Section 6.1, until similar rigorous assessment of data relating to hydrology and water resources in the region is conducted, implications can often only be considered against observations generally generated from models or sporadic field-measurements. Suggested implications of the review's findings, from a policy/water management perspective, are as follows:

i. Sustained glacier shrinkage will impact upon future water availability in the region, albeit non-uniformly (due to regional variation in glacial meltwater contributions to downstream river flows). For example, higher proportions of downstream flow in the Indus are derived from glacier melt compared to the Ganges (Kattelmann, 1993; Immerzeel et al, 2010) and there are significant variations within river basins (Thayyen & Gergan, 2010). Future development of water resource policy should thus focus on areas of potentially greatest impact (e.g. Upper Indus) and lacking information (e.g. Karakoram and Hindu-Kush), seeking to strengthen monitoring and research in such key areas;

ii. Both the appropriateness and quality of studies should be considered in making evidence-based decisions. Selective use of evidence, without proper consideration for what it actually represents for water resources that originate from glacial melt across the region, could lead to misinformed decisions. The review has revealed that many of the more alarmist claims made regarding the loss of Himalayan glaciers are not fully corroborated by the data that are readily available from the region. Policy development should seek to be based upon objective and systematic interpretation of all evidence available, as detailed by this review;

iii. Understanding the state of glaciers across the region, and what drives glacial shrinkage, is crucial for predicting the impacts of future climate change. Glaciers should not be considered in isolation from other aspects of the hydrological cycle. Governments of the region need to invest further in improving hydro-meteorological monitoring and data management generally across the region and in particular in upland areas (e.g. denser monitoring networks; networks that are more representative of conditions at higher elevations; sustained long-term monitoring; adoption of international standards for monitoring and data management; implementation of improved sensor and communications technologies and specialist computer hardware and software; appropriate training and remuneration of observers and technical staff). International investment should be sought to improve the available evidence, initially focusing on areas of greatest neglect and concern;

iv. Himalayan glaciers are the source of many international rivers. The trans-boundary nature of all three major river systems concerned (Ganges, Indus, Brahmaputra) means the sharing of water resources between countries is challenging. Glacier shrinkage and downstream impacts are regional problems that no single country can be expected to deal with alone. Effective management of such trans-boundary water resources ideally should be undertaken collaboratively between governments through policies that are mutually compatible and based on a common, consistent, understanding of conditions. Such compatibility would partly be achieved by increased openness over, and sharing of, glaciological and hydro-meteorological knowledge and data between countries. Future policy development in all countries should address this need and foster co-ordinated research and collaboration. International and regional institutions such as ICIMOD have a vital role to play in this regard.

6.3 Implications for research

This review has identified a lack of both consistent research approaches and sustained, long-term, monitoring to be a major obstacle in assessing glacier shrinkage and downstream impacts across the Himalayan region. Such assessment is vital when considering that these glaciers are both key indicators of global climate change and that any changes observed have important implications for regional/local water management and associated policy/actions.

The geographical spread of glaciers considered by this review indicates uneven distribution across the whole region and a lack of data from large areas of the Karakoram and Hindu-Kush in particular (Figure 6). The Karakoram in particular contains much larger glaciers than other regions (Williams & Ferrigno, 2010), underlying the importance of obtaining measurements from such glaciers in order to understand the particular impacts of climate change and associated implications for water resources. Obtaining high-confidence mass balance and area measurements from this region are critical for understanding the changes that are ongoing, both in terms of climate change and associated water management. Such data is also invaluable for development and validation of regional hydrological models such as SAGRMARTHA (Rees & Collins, 2004).

Major obstacles in obtaining field-based measurements, such as inaccessibility, cost, conditions and political sensitivities are unlikely to be overcome. The extreme nature of the Himalayan environment, with the highest altitudes and most demanding mountainous terrain on Earth, mean that techniques and methods developed elsewhere are not necessarily transferable. The remoteness and lack of accessibility provides significant barriers to research groups, with danger implicit for visiting teams. Many areas are located within border regions subject to either national dispute and hostility or even terrorism.

Considering the importance placed upon glaciers as global indicators of climate change there is a relative lack of research and understanding surrounding Himalayan glaciers compared to other mountainous regions. This stems primarily from the various difficulties mentioned in obtaining measurements from the region, but also, as highlighted by this review, a scarcity of good quality evidence and standardised reporting of findings. These pristine environments are direct indicators of the impacts of a warming climate and the Himalayas represent a significant part of global glacier coverage (Figure 23). Developing research to enhance understanding of global patterns of glacier change should thus be considered a priority when considering the valuable information they could provide in the future.

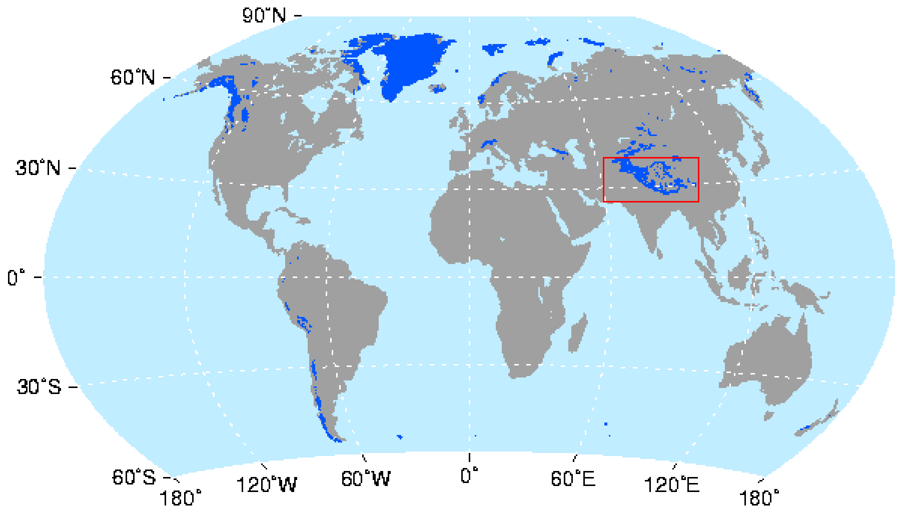

Figure 23: Global extent of glacier coverage; with the Himalayan region highlighted in red (http://nsidc.org/glims)

From a research perspective, therefore, the review leads further to the following recommendations:

i. Recent advancements in remote sensing technology potentially offers solutions to many of the physical and logistical problems that hitherto have hampered glacier monitoring and research in the region. For example, the possibility of using remote sensing to measure glacier mass balance (Berthier et al, 2007) or in providing region-wide patterns of change (Scherler et al, 2011) would help considerably towards reducing the costs and environmental impacts of field-based campaigns. This review also attests to the higher level of confidence that can be placed in measurements derived from earth observation technologies when standardised methodologies are applied by trained teams. Considerable scope remains for realising the potential benefits of remote sensing to glaciological and hydrological research within the Himalayan region. Future funding should focus upon improving the methodology and standardisation of techniques to derive measurements of glacial change from remote-sensing data, particularly for mass balance;

ii. Existing programmes of measurement on key "benchmark" glaciers, particularly those having continuous series of mass balance measurements, such as AX010, Chhota Shigri, and Dokriani, should continue and be sustained in the long-term. Data from these glaciers are invaluable as they provide the only continuous and long-term evidence of change within the region. Some glaciers, such as AX010, already have their highest altitude below the ELA and therefore are unlikely to have positive mass balance in the future. Nevertheless, continued monitoring on these glaciers is important in developing a picture of change across all types of glacier;

iii. Several "benchmark" glaciers should be selected from across the entire Himalayan arc, from the Karakoram and Hindu Kush to the eastern Himalaya, to form a network of representative glaciers. Theoretically, these would represent various glacier types, sizes, aspects, altitude, latitude and longitude.

However, as discussed, the reality is there are major obstacles to realizing such a situation and thus realistic compromises should be sought. Experts should convene to agree how best a balance can be achieved and which glaciers would feature in the network, including those which already possess valuable continuous long series of mass balance measurements. Regional governments and donor agencies need to commit to sustain such a network for the long-term (10-20 years). For each glacier in the network, standardised glacier measurements of mass balance, area and glacier terminus should be conducted at a high temporal resolution;

iv. Further to point (iii) above, to understand the effects of glacier shrinkage on downstream river flows, gauging stations should be installed immediately downstream of all glaciers in the proposed "benchmark" network. More generally, a far higher number of gauging stations should be installed on glacier-fed rivers across the region;

v. Hydro-meteorological measurements, including temperature and precipitation, should be collected within the catchments of the selected benchmark glaciers. This would greatly aid development of models to predict glacier mass changes in response to climate change;

vi. Across the region, and certainly within the benchmark network, data should be collected using identical methods, conforming to the same international standards. Recent guidance notes from the IPCC, concerning the treatment of uncertainties on data, requires authors for the Fifth Assessment Report (AR5) to assign a level of confidence in findings used to provide expert judgements (IPCC, 2010). Evidence that allows objective description of confidence clearly reduces uncertainty in findings and is critical in maintaining transparency within assessments. Thus, in light of the findings from this review, it is recommended that standardised data collection and reporting guidelines be developed, facilitating the collation of data from various methodologies and measurements and improving the confidence ascribed when comparing studies on diverse glaciers. Some key criteria include;

    - Undertaking measurement methodologies in accordance with existing standardised best practice (e.g. Kaser et al, 2002; GLIMSView - http://www.glims.org/GLIMSView/);
    - Developing international standards for glacier measurement and reporting to allow systematic collation of international data that meets approved guidelines;
    - Comprehensive reporting of location and glacier characteristics;
    - Full reporting of method and transparent annotation of calculations;
    - Providing a rigorous assessment of accuracy in measurements taken;
    - Such data should be submitted to an international organisation such as WGMS or NSIDC to populate a growing database of global information on glaciers.

vii. There should be no political barrier to data exchange; knowledge, expertise and experiences should be shared openly between researchers in all countries. Regional research projects, such as the UNESCO-IHP Hindu Kush – Himalayan FRIEND (Flow Regimes from International Experimental and Network Data) project, could be used as platforms for data exchange, scientific collaboration and capacity building;

viii. Structured programmes of training and capacity building, targeted at regional technicians and scientists, are considered essential to ensure the future delivery of more robust data and to support sustained glacial monitoring and research for the long-term;

To enact the above recommendations, improved dialogue between research institutions, government departments and funding agencies (both international and from within the region) is needed to agree a more efficient and targeted systematic programme of Himalayan glaciological and hydrological research and capacity building. Such a dialogue could be facilitated by United Nations research programmes (e.g. UNESCO-IHP; WMO–WCRP) in conjunction with the scientific associations of ICSU/IUGG, particularly the International Association of Hydrological Sciences (IAHS) and the International Association of Cryospheric Sciences (IACS).

7. Acknowledgements

We would like to thank Dr D.P. Dobhal and Dr G. Cogley for support in identifying potential studies.

We would also like to thank all the team at the Centre for Evidence Based Conservation for their support in realizing this review.

8. Potential Conflicts of Interest and Sources of Support

No potential conflicts of interest were identified.

This review was funded by the Department For International Development (DFID).

This research was supported by the European Union (FP6) funded Integrated Project called WATCH (contract number 036946).

9. References

Ageta, Y. (1983) Characteristics of mass balance of the summer accumulation type glacier in the Nepal Himalaya. Seppoyo, 45(2) 81-90.

Ageta, Y., Higuchi, K. (1984) Estimation of mass balance components of a summer-accumulation type glacier in the Nepal Himalaya. Geografiska Annaler Series a-Physical Geography, 66, 249-255.

Armstrong, R., B. Raup, S.J.S. Khalsa, R. Barry, J. Kargel, C. Helm, and H. Kieffer. (2011) GLIMS glacier database. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Bajracharya, S. R., Mool, P. K., Shrestha, B.R. (2008) Global climate change and melting of Himalayan glaciers. Melting Glaciers and Rising sea levels: Impacts and implications edited by Prabha Shastri Ranade. The Icfai's University Press, India. 28 – 46pp.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066): 303-309.

Bhambri, R. and T. Bolch (2009). Glacier mapping: a review with special reference to the Indian Himalayas. Progress in Physical Geography 33(5): 672-704.

Centre for Evidence-Based Conservation. (2010) Guidelines for Systematic Review in Environmental Management. Version 4.0. Collaboration for Environmental Evidence: http://www.environmentalevidence.org/Authors.htm

Cogley, J. G., Kargel, J. S., Kaser, G., and Van der Veen, C. J. (2010) Tracking the Source of Glacier Misinformation. Science, 327, 522.

Conway, W. M. (1893) The crossing of the Hispar Pass. Geographical Journal 1, 359-375.

Dobhal, D.P., J.T. Gergan and R.J. Thayyen, (2008) Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India, Bulletin of Glaciological Research, 25, 9-17.

Dyurgerov, M.B. and Meier, M.F. (2000). Twentieth century climate change: Evidence from small glaciers. PNAS, 97(4): 1406-1411.

Dyurgerov, M.B. and Meier, M.F., (2005). Glaciers and the changing earth system: a 2004 snapshot. Occasional Paper No. 58. INSTAAR/OP-58. Institute of Arctic and Alpine Research, University of Colorado, Boulder, pp. 117.

Fujita, K., L. G. Thompson, et al. (2006) Thirty-year history of glacier melting in the Nepal Himalayas. Journal of Geophysical Research-Atmospheres 111.

Godwin-Austen, H. H. (1864) On the Glaciers of the Mustagh Range. Journal of Royal Geophysical Society 34, 19-56.

Grove, J. M. (2004) Little Ice Ages: Ancient and modern. Vol I + II, 2nd Edition. Routledge, London and New York.

Haeberli, W., (1996). Fluctuations of mountain glaciers. In: V.M. Kotlyakov (Editor) Variations of snow and ice in the past and at present on a global and regional scale. International Hydrological Programme IHP-IV Project H-4.1. UNESCO, Paris, pp. 35-43.

Haeberli, W. et al (eds) (2009) Glacier Mass Balance Bulletin: Bulletin no 10 (2006-2007). WGMS.

Hewitt, K., (2005) The Karakoram Anomaly? Glacier Expansion and the 'Elevation Effect,' Karakoram Himalaya. Mountain Research and Development, 25(4): 332-340.

Immerzeel, W. W., Van Beek, L. P. H., Bierkens, M. F. P. (2010) Climate change will affect the Asian Water Towers. Science 328, 1382-1385.

IPCC., (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2010)
HTTP://WWW.IPCC.CH/MEETINGS/SESSION32/INF09_P32_DRAFT_GUIDANCE_NOTES_LA_CONSISTENT_TREATMENT_OF_UNCERTAINTIES.PDF

Kääb, A., Chiarle, M., Raup, B. and Schneider, C., (2007) Climate change impacts on mountain glaciers and permafrost. Global and Planetary Change, 56(1-2): vii-ix.

Kaser, G., Fountain, A., Jansson, P. (2003) A manual for monitoring the mass balance of mountain glaciers. IHP-VI Technical Documents in Hydrology 59, UNESCO, Paris.

Kattelmann, R. (1993) Role of snowmelt in generating streamflow during spring in East Nepal. In: Snow and Glacier Hydrology, Proc. Kathmandu Symposium, November 1992. IAHS Press IAHS Publication No. 218, pp. 103-111.

Kaul, M.K. (Editor), 1999. Inventory of Himalayan Glaciers. Geological Survey of India Special Publication, 34. Geological Survey of India, 165 pp.

Kotlyakov, V. M., Ed. (1996). Variations of snow and ice in the past and at present on a global and regional scale. International Hydrological Programme IHP-IV Project H-4.1. Paris, UNESCO.

Longstaff, T. G. (1908) A mountaineering expedition to Himalayas of Garwhal. The Geographical Journal 31, 361-88.

Mayewski, P. A., and Jeschke, P. A. (1979). Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. Arctic and Alpine Research 11(3): 267-287.

Mayewski, P. A., Pregent, G. P., Jeschke, P. A., Ahmad, N. (1980) Himalayan and Trans-Himalayan Glacier Fluctuations and the South Asian Monsoon. Arctic and Alpine Research 12(2), 171-182.

Mays, N., Pope, C., Popay, J. (2005) Systematically reviewing qualitative and quantitative evidence to inform policy-making in the health field. Journal of Health Services Research and Policy 10, 6-20.

Mi, D., et al (2002) The Ganga and Indus drainage basin, Xi'an. In, Glacier inventory of China, XI, Xi'an Cartographic Press.

Qin, D. (ed) (1999) Map of Glacier resources in the Himalayas; 1st ed: Beijing Science Press, scale 1:500,000.

Racoviteanu, A. E., M. W. Williams, et al. (2008). Optical remote sensing of glacier characteristics: A review with focus on the Himalaya. Sensors 8(5), 3355-3383.

Raina, V. K., (2009) Himalayan Glaciers; A State-of-Art Review of Glacial Studies, Glacial Retreat and Climate Change. MoEF Discussion Paper. Government of India, New Delhi.

Rees, G., Collins, D. C. (2004) SAGARMARTHA: An assessment of the impacts of deglaciation on the water resources of the Himalayas. Final Technical Report: Volume 2.

Rees, G., (2008) A review of current knowledge on Himalayan and Andean melting. DFID Report:W/S 011.

Scherler, D., Bookhagen, B., Strecker, M. R. (2011) Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience 4, 156-159.

Thayyen, R. J., Gergan, J. T. (2010) Role of glaciers in watershed hydrology: a reliminary study of a 'Himalayan catchment'. The Cryosphere 4, 115-128.

Vohra, C.P., (1981) Himalayan glaciers, in Lall, J.S., and Moddie, A.D., eds., The Himalaya, aspects of change: Delhi, Oxford University Press, p. 138–151.

Von Wissman, H. (1959) Die heutige Vergletserung und Schneegrenze in Hochasain [Modern glaciers and the snowline in High Asia]: Weisbaden, Akademie der Wissenschaften und der Literatur in Mainz Kommision bei Franz Steiner Verlag. GMBH, 307.

Williams, R. S., Ferrigno, J. G. (eds) (2010) Satellite Image Atlas of Glaciers of the World. U.S. Geological Survey Professional Paper 1386-F-5.

Winiger, M., Gumpert, M., Yamout, H. (2005) Karakoram-Hindukush-western Himalaya: assessing high-altitude water resources. Hydrological Processes 19, 2329-2338.

WWF (2005) An overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India, and China. http://assets.panda.org/downloads/himalayaglaciersreport2005.pdf

Young, G.J. and Neupane, B., (1996). Bibliography on the Hydrology of the Himalaya-Karakoram Region. Glaciological Data Report GD-29. World Data Centre-A for Glaciology (Snow and Ice), Boulder, Colorado.

10. Appendices

10.1 Appendix A

10.1.1 Studies included in the review

Ageta, Y., Naito, N., Nakawo, M., Fujita, K., Shankar, K., Pokhrel, A.P. and Wangda, D., (2001). Study project on the recent rapid shrinkage of summer-accumulation type glaciers in the Himalayas, 1997-1999. Bulletin of Glaciological Research 18: pp 45-49.

Ageta, K.Y. et al (2002) Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalaya. Bulletin of Glaciological Research 20

Ahamad, S. and Hasnain, S. I. (2004) Analysis of satellite imageries for characterization of glacio-mrorphological features of Gangotri Glacier, Ganga headwater. In Srivastava, D., Gupta, K. R. and Mukerji, S. editors, Geological Survey of India Special Publication 80, 61-67

Aizen, V. B., E. M. Aizen, et al. (2002). "Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers)." Quaternary International 97-8: 27-39.

Bahuguna, I. M., A. V. Kulkarni, et al. (2004). "DEM from IRS-1C PAN stereo coverage's over Himalayan glaciated region - accuracy and its utility." International Journal of Remote Sensing 25(19): 4029-4041.

Bahuguna, I. M., A. V. Kulkarni, et al. (2007). "Himalayan glacier retreat using IRS ICPAN stereo data." International Journal of Remote Sensing 28(1-2): 437-442.

Bajracharya, S. R. (2008) Change in Glacial Environment of Everest Region, Nepal. High Mountain Remote Sensing Cartography 8, ICIMOD

Batura Investigation Group (1979). "Batura Glacier in the Karakoram Mountains and its." Scientia Sinica 22(8): 958-&.

Belo, M., C. Mayer, et al. (2008). "The recent evolution of Liligo glacier, Karakoram, Pakistan, and its present quiescent." Annals of Glaciology, Vol 48: 171-176.

Berthier, E., Y. Arnaud, et al. (2007). "Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India)." Remote Sensing of Environment 108(3): 327-338.

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

Bolch, T., Buchroithner, M.F., Pieczonka, T. and Kunert, A. (2008). Planimetric and volumetric Glacier changes in Khumbu Himalayas since 1962 using Corona, Landsat and ASTER data. Journal of Glaciology, 54, 592-600.

Chen, X. Q., P. Cui, et al. (2007). "Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet)." Geomorphology 88(3-4): 298-311.

Chitranshi, A., Sangewar, C. V., Srivastava, D., Puri, V.M.K and Dutta, S. S, (2004) Recession pattern of Meru Bamak Glacier, Bhagirathi Basin, Uttaranchal. In Srivastava, D., Gupta, K. R. and Mukerji, S. editors, Geological Survey of India Special Publication 80, 61-67

Diolaiutu, G., M. Pecci, et al. (2003). "Liligo Glacier, Karakoram, Pakistan: a reconstruction of the recent history of a surge-type glacier." Annals of Glaciology, Vol 36: 168-172.

Dobhal, D. P., Kumar, S., et al. (1995) Morphology and glacier dynamics studies in monsoon-arid transition zone – an example from Chhota-Shigri Glacier, Himachel-Himalaya, India. Current Science, 68(9), 936-944.

Dobhal, D.P., J.T. Gergan and R.J. Thayyen, 2008, Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India, Bulletin of Glaciological Research, 25, 9-17. DX282

Dobhal, D. P. and M. Mehta (2010). "Surface morphology, elevation changes and Terminus retreat of Dokriani Glacier, Garhwal Himalaya: implication for climate change." Himalayan Geology 31(1): 71-78.

Dobhal, D. P., J. T. Gergan, et al. (2004). "Recession and morpho geometrical changes of Dokriani glacier (1962-1995) Garhwal Himalaya, India." Current Science 86(5): 692-696.

Fujita, K., M. Nakawo, et al. (1997). "Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994." Journal of Glaciology 43(145): 583-588.

Fujita, K., Takeuchi, N., and Seko, K. (1998). Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalaya's 1994 and1996. Bulletin of Glacier Research 16, 75-81.

Fujita, K., T. Kadota, B. Rana, R.B. Kayastha and Y. Ageta, (2001a), Shrinkage of AX010 Glacier in Shorong region, Nepal Himalayas in the 1990s, Bulletin of Glaciological Research, 18, 51-54. DX265

Fujita, K., Nakazawa, F., and Rana, B. (2001b). Glaciological observation on Rikha Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999. Bulletin of Glaciological Research 18, 31-35.

Fujita, K., L. G. Thompson, et al. (2006). "Thirty-year history of glacier melting in the Nepal Himalayas." Journal of Geophysical Research-Atmospheres 111(D13).

Fushimi, H., Ohata, T. & Higuchi, K. (1979) Recent fluctuations of glaciers in the eastern part of Nepal Himalayas. Sea Level, Ice, and Climatic Change (proceedings of the Canberra Symposium). IAHS Publ .n. 131.

Gardner, J. S. (1986). "Recent fluctuations of Rakhiot Glacier, Nanga Parbat, Punjab Himalaya, Pakistan". Journal of Glaciology 32(112): 527-529.

Hewitt, K.; Wake, C.P.; Young, G.J.; David, C. (1989) Hydrological investigations at Biafo glacier, Karakoram range, Himalaya: an important source of water for the Indus river. Annals of Glaciology, Vol. 13: pp. 103-108.

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

Jangpang, B.S. and Vohra, C.P. (1962). The Retreat of the Skunkulpa (Ralam) Glacier in the Central Himalaya, Pithoragarh District, U.P., India, Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp234-238.

Kadota, T., K. Fujita, et al. (1997). "Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya." Annals of Glaciology, Vol 24, 1997 24: 90-94.

Koul, M. N. and R. K. Ganjoo (2010). "Impact of inter- and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India." Climatic Change 99(1-2): 119-139.

Kulkarni, A. V. and I. M. Bahuguna (2002). "Glacial retreat in the Baspa basin, Himalaya, monitored with satellite stereo data." Journal of Glaciology 48(160): 171-172.

Kulkarni, A. V., B. P. Rathore, et al. (2004). "Monitoring of glacial mass balance in the Baspa basin using accumulation area ratio method." Current Science 86(1): 185-190.

Kulkarni, A. V., B. P. Rathore, et al. (2005). "Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh." Current Science 88(11): 1844-1850.

Kulkarni, A. V., I. M. Bahuguna, et al. (2007). "Glacial retreat in Himalaya using Indian Remote Sensing satellite data." Current Science 92(1): 69-74.

Kumar, K., R. K. Dumka, et al. (2008). "Estimation of retreat rate of Gangotri glacier using rapid static and kinematic GPS survey." Current Science 94(2): 258-262.

Kurien, T.K. & Munshi, M.M. (1962) Sonapani Glacier of Lahaul Punjab. India, Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp0239-244.

Mukherjee, B. P. and Sangewar, C. V. (2001) Recession of Gangotri glacier through 20th century. Geological Survey of India Special Publication 65, 1-3.

Nainwal, H. C., Negi, B. D. S., Chaudhary, M., Sajwan, K. S. and Guarav, A. (2008) Temporal changes in rate of recession: evidence from Satopanth and Bhagirath glaciers, Uttarakhand, using Total Station Survey. Current Science 94, 653-60.

Naito, N. et al (2006) Glacier shrinkages and climate conditions around Jichu Dramo Glacier in the Bhutan Himalayas from 1998 to 2003. Bulletin of Glaciological Research 23

Raina, V. K. and C. Sangewar (2007). "Siachen glacier of Karakoram Mountains, Ladakh its secular retreat." Journal of the Geological Society of India 70: 11-16.

Ren, J. W., Z. F. Jing, et al. (2006). "Glacier variations and climate change in the central Himalaya over the past few decades." Annals of Glaciology, Vol 43, 2006 43: 218-222.

Salerno, F., E. Buraschi, et al. (2008). "Glacier surface-area changes in Sagarmartha national park, Nepal, in the second half of the 20th century, by comparison of historical maps." Journal of Glaciology 54(187): 738-752.

Schmidt, S. and M. Nusser (2009). "Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan." Journal of Glaciology 55(194): 949-959.

Shukla, A., R. P. Gupta, et al. (2009). "Estimation of debris cover and its temporal variation using optical satellite sensor data: a case study in Chenab basin, Himalaya." Journal of Glaciology 55(191): 444-452.

Tewari, A.P. & Jangpangi, B.S. (1962) The retreat of the Snout of the Pindari Glacier. Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp245-248.

Wagnon, P., A. Linda, et al. (2007). "Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya." Journal of Glaciology 53(183): 603-611.

Yamada T., T. Shiraiwa, T. Kadota, T. Watanabe, B. Rana, Y. Ageta and H. Fushimi, 1992. Fluctuation of the glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang regions, Nepal Himalayas, Bulletin of Glacier Research, 10, 11-19.

Yang, W., T. D. Yao, et al. (2008). "Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo Mountains, southeast Tibetan Plateau." Chinese Science Bulletin 53(16): 2547-2551.

Ye, Q. H., T. D. Yao, et al. (2006). "Glacier variations in the Naimona'nyi region, western Himalaya, in the last three decades." Annals of Glaciology, Vol 43, 2006 43: 385-389.

Ye, Q. H., T. D. Yao, et al. (2008). "Response of glacier and lake covariations to climate change in Mapam Yumco basin on Tibetan plateau during 1974-2003." Journal of China University of Geosciences 19(2): 135-145.

Ye, Q. H., Z. W. Zhong, et al. (2009). "Monitoring Glacier and Supra-glacier Lakes from Space in Mt. Qomolangma Region of the Himalayas on the Tibetan Plateau in China." Journal of Mountain Science 6(3): 211-220.

10.1.2 Studies assessed at full text

From database searches

(1979). "BATURA GLACIER IN THE KARAKORAM MOUNTAINS AND ITS VARIATIONS." Scientia Sinica 22(8): 958-&.

(2010). "Tracking the Karakoram Glaciers." American Scientist 98(2): 156-157.

Achenbach, H. (2010). "Climate change and its impact on the Himalayan glaciers." Current Science 98(5): 599-599.

Ageta, Y., S. Iwata, et al. (2000). "Expansion of glacier lakes in recent decades in the Bhutan Himalayas." Debris-Covered Glaciers(264): 165-175.

Ageta, Y. and T. Kadota (1992). "PREDICTIONS OF CHANGES OF GLACIER MASS BALANCE IN THE NEPAL HIMALAYA AND TIBETAN PLATEAU - A CASE-STUDY OF AIR-TEMPERATURE INCREASE FOR 3 GLACIERS." Annals of Glaciology, Vol 16, 1992 16: 89-94.

Ahmad, S. and S. I. Hasnain (2002). "Hydrograph separation by measurement of electrical conductivity and discharge for meltwaters in the Ganga Headwater basin, Garhwal Himalaya." Journal of the Geological Society of India 59(4): 323-329.

Aizen, V. B., E. M. Aizen, et al. (2002). "Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers)." Quaternary International 97-8: 27-39.

Bahuguna, I. M., A. V. Kulkarni, et al. (2004). "DEM from IRS-1C PAN stereo coverages over Himalayan glaciated region - accuracy and its utility." International Journal of Remote Sensing 25(19): 4029-4041.

Bahuguna, I. M., A. V. Kulkarni, et al. (2007). "Himalayan glacier retreat using IRS ICPAN stereo data." International Journal of Remote Sensing 28(1-2): 437-442.

Barrand, N. E. and T. Murray (2006). "Multivariate controls on the incidence of glacier surging in the Karakoram Himalaya." Arctic Antarctic and Alpine Research 38(4): 489-498.

Belo, M., C. Mayer, et al. (2008). "The recent evolution of Liligo glacier, Karakoram, Pakistan, and its present quiescent." Annals of Glaciology, Vol 48 48: 171-176.

Berthier, E., Y. Arnaud, et al. (2007). "Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India)." Remote Sensing of Environment 108(3): 327-338.

Bhambri, R. and T. Bolch (2009). "Glacier mapping: a review with special reference to the Indian Himalayas." Progress in Physical Geography 33(5): 672-704.

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

Bolch, T., M. F. Buchroithner, et al. (2008). "Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery." Natural Hazards and Earth System Sciences 8(6): 1329-1340.

Burbank, D. W. and M. B. Fort (1985). "BEDROCK CONTROL ON GLACIAL LIMITS - EXAMPLES FROM THE LADAKH AND ZANSKAR RANGES, NORTHWESTERN HIMALAYA, INDIA." Journal of Glaciology 31(108): 143-149.

Chattopadhyay, G. P. (2008). "Recent retreats of glaciers on the southeast-facing slopes of the Kanchenjunga Summit Complex in the Sikkim Himalaya." Himalayan Geology 29(2): 171-176.

Chaujar, R. K. (2009). "Climate change and its impact on the Himalayan glaciers - a case study on the Chorabari glacier, Garhwal Himalaya, India." Current Science 96(5): 703-708.

Chen, X. Q., P. Cui, et al. (2007). "Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet)." Geomorphology 88(3-4): 298-311.

Collins, D. N. (1996). "Sediment transport from glacierized basins in the Karakoram mountains." Erosion and Sediment Yield: Global and Regional Perspectives(236): 85-96.

Cunde, X., L. Shiyin, et al. (2007). "Observed changes of cryosphere in China over the second half of the 20th century: an overview." Annals of Glaciology, Vol 46, 2007 46: 382-390.

Diolaiutu, G., M. Pecci, et al. (2003). "Liligo Glacier, Karakoram, Pakistan: a reconstruction of the recent history of a surge-type glacier." Annals of Glaciology, Vol 36 36: 168-172.

Dobhal, D. P., J. T. Gergan, et al. (2004). "Recession and morphogeometrical changes of Dokriani glacier (1962-1995) Garhwal Himalaya, India." Current Science 86(5): 692-696.

Dobhal, D. P. and S. Kumar (1996). "Inventory of glacier basins in Himachal Himalaya." Journal of the Geological Society of India 48(6): 671-681.

Dobhal, D. P., S. Kumar, et al. (1995). "MORPHOLOGY AND GLACIER DYNAMICS STUDIES IN MONSOON-ARID TRANSITION ZONE - AN EXAMPLE FROM CHHOTA-SHIGRI GLACIER, HIMACHAL-HIMALAYA, INDIA." Current Science 68(9): 936-944.

Dobhal, D. P. and M. Mehta (2010). "Surface morphology, elevation changes and Terminus retreat of Dokriani Glacier, Garhwal Himalaya: implication for climate change." Himalayan Geology 31(1): 71-78.

Duncan, C. C., A. J. Klein, et al. (1998). "Comparison of Late Pleistocene and modern glacier extents in central Nepal based on digital elevation data and satellite imagery." Quaternary Research 49(3): 241-254.

Fujita, K., M. Nakawo, et al. (1997). "Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994." Journal of Glaciology 43(145): 583-588.

Fujita, K., L. G. Thompson, et al. (2006). "Thirty-year history of glacier melting in the Nepal Himalayas." Journal of Geophysical Research-Atmospheres 111(D13).

Gardner, J. S. (1986). "RECENT FLUCTUATIONS OF RAKHIOT GLACIER, NANGA PARBAT, PUNJAB HIMALAYA, PAKISTAN." Journal of Glaciology 32(112): 527-529.

Gardner, J. S. and K. Hewitt (1990). "A SURGE OF BUALTAR GLACIER, KARAKORAM RANGE, PAKISTAN - A POSSIBLE LANDSLIDE TRIGGER." Journal of Glaciology 36(123): 159-162.

Gergan, J. T., D. P. Dobhal, et al. (1999). "Ground penetrating radar ice thickness measurements of Dokriani bamak (glacier), Garhwal Himalaya." Current Science 77(1): 169-173.

Hasnain, S. I. (2002). "Himalayan glaciers meltdown: impact on south Asian rivers." Friend 2002-Regional Hydrology: Bridging the Gap between Research and Practice(274): 417-423.

He, Y. Q., Z. G. Zhang, et al. (2003). "Recent variability of the climate and glaciers in China's monsoon region." Water Resources Systems - Water Availability and Global Change(280): 104-114.

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

Hewitt, K. (2007). "Tributary glacier surges: an exceptional concentration at Panmah Glacier, Karakoram Himalaya." Journal of Glaciology 53(181): 181-188.

Hou, S. G., D. H. Qin, et al. (1999). "Abrupt decrease in recent snow accumulation at Mount Qomolangma (Everest), Himalaya." Journal of Glaciology 45(151): 585-586.

Hou, S. G., D. H. Qin, et al. (2002). "Recent change of the ice core accumulation rates on the Qinghai-Tibetan Plateau." Chinese Science Bulletin 47(20): 1746-1749.

Iturrizaga, L. (2005). "The historical Saklei Shuyinj and Chateboi Glacier Dams as triggers for lake outburst cascades in the Karambar valley, Hindukush." Island Arc 14(4): 389-399.

Jain, S. K. (2008). "Impact of retreat of Gangotri glacier on the flow of Ganga River." Current Science 95(8): 1012-1014.

Kadota, T., K. Fujita, et al. (1997). "Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya." Annals of Glaciology, Vol 24, 1997 24: 90-94.

Kadota, T., K. Seko, et al. (2000). "Shrinkage of the Khumbu Glacier, east Nepal from 1978 to 1995." Debris-Covered Glaciers(264): 235-243.

Kaila, K. L. and V. G. Krishna (1992). "DEEP SEISMIC-SOUNDING STUDIES IN INDIA AND MAJOR DISCOVERIES." Current Science 62(1-2): 117-154.

Kehrwald, N. M., L. G. Thompson, et al. (2008). "Mass loss on Himalayan glacier endangers water resources." Geophysical Research Letters 35(22).

Koul, M. N. and R. K. Ganjoo (2010). "Impact of inter- and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India." Climatic Change 99(1-2): 119-139.

Krishna, A. P. (2005). "Snow and glacier cover assessment in the high mountains of Sikkim Himalaya." Hydrological Processes 19(12): 2375-2383.

Kulkarni, A. V. (1992). "MASS BALANCE OF HIMALAYAN GLACIERS USING AAR AND ELA METHODS." Journal of Glaciology 38(128): 101-104.

Kulkarni, A. V. and I. M. Bahuguna (2002). "Glacial retreat in the Baspa basin, Himalaya, monitored with satellite stereo data." Journal of Glaciology **48**(160): 171-172.

Kulkarni, A. V., I. M. Bahuguna, et al. (2007). "Glacial retreat in Himalaya using Indian Remote Sensing satellite data." Current Science 92(1): 69-74.

Kulkarni, A. V., P. Mathur, et al. (2002). "Effect of global warming on snow ablation pattern in the Himalaya." Current Science 83(2): 120-123.

Kulkarni, A. V., B. P. Rathore, et al. (2004). "Monitoring of glacial mass balance in the Baspa basin using accumulation area ratio method." Current Science 86(1): 185-190.

Kulkarni, A. V., B. P. Rathore, et al. (2005). "Alarming retreat of Parbati glacier, beas basin, Himachal pradesh." Current Science 88(11): 1844-1850.

Kumar, K., R. K. Dumka, et al. (2008). "Estimation of retreat rate of Gangotri glacier using rapid static and kinematic GPS survey." Current Science 94(2): 258-262.

Kumar, S. (1999). "Chhota Shigri Glacier: Its kinematic effects over the valley environment, in the northwest Himalaya." Current Science 77(4): 594-598.

Liu, S. Y., N. L. Wang, et al. (1999). "Regional characteristics of glacier mass balance variations in High Asia." Interactions between the Cryosphere, Climate and Greenhouse Gases(256): 141-153.

Liu, W. G., J. W. Ren, et al. (2010). "Hydrological Characteristics of the Rongbuk Glacier Catchment in Mt. Qomolangma Region in the Central Himalayas, China." Journal of Mountain Science 7(2): 146-156.

Luckman, A., D. Quincey, et al. (2007). "The potential of satellite radar interferometry and feature tracking for monitoring flow rates of Himalayan glaciers." Remote Sensing of Environment 111: 172-181.

Matsuo, K. and K. Heki (2010). "Time-variable ice loss in Asian high mountains from satellite gravimetry." Earth and Planetary Science Letters 290(1-2): 30-36.

Mayewski, P. A. and P. A. Jeschke (1979). "HIMALAYAN AND TRANS-HIMALAYAN GLACIER FLUCTUATIONS SINCE AD 1812." Arctic and Alpine Research 11(3): 267-287.

Mayewski, P. A., G. P. Pregent, et al. (1980). "HIMALAYAN AND TRANS-HIMALAYAN GLACIER FLUCTUATIONS AND THE SOUTH ASIAN MONSOON RECORD." Arctic and Alpine Research 12(2): 171-182.

Mihalcea, C., C. Mayer, et al. (2006). "Ice ablation and meteorolopical conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan." Annals of Glaciology, Vol 43, 2006 43: 292-300.

Nakawo, M. and B. Rana (1999). "Estimate of ablation rate of glacier ice under a supraglacial debris layer." Geografiska Annaler Series a-Physical Geography 81A(4): 695-701.

Nakawo, M., H. Yabuki, et al. (1999). "Characteristics of Khumbu Glacier, Nepal Himalaya: recent change in the debris-covered area." Annals of Glaciology 28: 118-122.

Owen, L. A. and J. England (1998). "Observations on rock glaciers in the Himalayas and Karakoram Mountains of northern Pakistan and India." Geomorphology 26(1-3): 199-213.

Prasad, A. K., K. H. S. Yang, et al. (2009). "Melting of major Glaciers in the western Himalayas: evidence of climatic changes from long term MSU derived tropospheric temperature trend (1979-2008)." Annales Geophysicae 27(12): 4505-4519.

Prasad, C. and A. Naithani (2003). "Glacier morphometry: A case study of Gangotri group of glaciers, Garhwal Himalaya, India." Journal of the Geological Society of India 61(3): 325-334.

Racoviteanu, A. E., M. W. Williams, et al. (2008). "Optical remote sensing of glacier characteristics: A review with focus on the Himalaya." Sensors 8(5): 3355-3383.

Raina, V. K. and C. Sangewar (2007). "Siachen glacier of Karakoram Mountains, Ladakh its secular retreat." Journal of the Geological Society of India 70: 11-16.

Ren, J. W., Z. F. Jing, et al. (2006). "Glacier variations and climate change in the central Himalaya over the past few decades." Annals of Glaciology, Vol 43, 2006 43: 218-222.

Salerno, F., E. Buraschi, et al. (2008). "Glacier surface-area changes in Sagarmatha national park, Nepal, in the second half of the 20th century, by comparison of historical maps." Journal of Glaciology 54(187): 738-752.

Schmidt, S. and M. Nusser (2009). "Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan." Journal of Glaciology 55(194): 949-959.

Shukla, A., R. P. Gupta, et al. (2009). "Estimation of debris cover and its temporal variation using optical satellite sensor data: a case study in Chenab basin, Himalaya." Journal of Glaciology 55(191): 444-452.

Singh, P., U. K. Haritashya, et al. (2006). "Hydrological characteristics of the Gangotri Glacier, central Himalayas, India." Journal of Hydrology 327(1-2): 55-67.

Singh, P. and S. K. Jain (2002). "Snow and glacier melt in the Satluj River at Bhakra Dam in the western Himalayan region." Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 47(1): 93-106.

Singh, P., N. Kumar, et al. (2000). "Influence of a fine debris layer on the melting of snow and ice on a Himalayan glacier." Debris-Covered Glaciers(264): 63-69.

Singh, P., K. S. Ramasastri, et al. (1995). "HYDROLOGICAL CHARACTERISTICS OF THE DOKRIANI GLACIER IN THE GARHWAL HIMALAYAS." Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 40(2): 243-257.

Thayyen, R. J. and J. T. Gergan (2010). "Role of glaciers in watershed hydrology: a preliminary study of a "Himalayan catchment"." Cryosphere 4(1): 115-128.

Thayyen, R. J., J. T. Gergan, et al. (2005). "Monsoonal control on glacier discharge and hydrograph characteristics, a case study of Dokriani Glacier, Garhwal Himalaya, India." Journal of Hydrology 306(1-4): 37-49.

Thayyen, R. J., J. T. Gergan, et al. (2007). "Role of glaciers and snow cover on headwater river hydrology in monsoon regime - Micro-scale study of Din Gad catchment, Garhwal Himalaya, India." Current Science 92(3): 376-382.

Wagnon, P., A. Linda, et al. (2007). "Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya." Journal of Glaciology 53(183): 603-611.

Wake, C. P. and M. P. Searle (1993). "RAPID ADVANCE OF PUMARIKISH GLACIER, HISPAR GLACIER BASIN, KARAKORAM HIMALAYA." Journal of Glaciology 39(131): 204-206.

Watanabe, T., J. D. Ives, et al. (1994). "RAPID GROWTH OF A GLACIAL LAKE IN KHUMBU-HIMAL, HIMALAYA - PROSPECTS FOR A CATASTROPHIC FLOOD." Mountain Research and Development 14(4): 329-340.

Wu, Y. H. and L. P. Zhu (2008). "The response of lake-glacier variations to climate change in Nam Co Catchment, central Tibetan Plateau, during 1970-2000." Journal of Geographical Sciences 18(2): 177-189.

Xiao, X., B. Moore, et al. (2002). "Large-scale observations of alpine snow and ice cover in Asia: Using multi-temporal VEGETATION sensor data." International Journal of Remote Sensing 23(11): 2213-2228.

Yang, W., T. D. Yao, et al. (2008). "Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo Mountains, southeast Tibetan Plateau." Chinese Science Bulletin 53(16): 2547-2551.

Ye, Q. H., T. D. Yao, et al. (2008). "Response of glacier and lake covariations to climate change in Mapam Yumco basin on Tibetan plateau during 1974-2003." Journal of China University of Geosciences 19(2): 135-145.

Ye, Q. H., T. D. Yao, et al. (2006). "Glacier variations in the Naimona'nyi region, western Himalaya, in the last three decades." Annals of Glaciology, Vol 43, 2006 43: 385-389.

Ye, Q. H., Z. W. Zhong, et al. (2009). "Monitoring Glacier and Supra-glacier Lakes from Space in Mt. Qomolangma Region of the Himalayas on the Tibetan Plateau in China." Journal of Mountain Science 6(3): 211-220.

Young, G. J. and K. Hewitt (1993). "GLACIOHYDROLOGICAL FEATURES OF THE KARAKORAM HIMALAYA - MEASUREMENT POSSIBILITIES AND CONSTRAINTS." Snow and Glacier Hydrology(218): 273-283.

Provided by partners

Bolch, T., Buchroithner, M.F., Pieczonka, T. and Kunert, A. (2008). Planimetric and volumetric Glacier changes in Khumbu Himalayas since 1962 using Corona, Landsat and ASTER data. Journal of Glaciology, 54, 592-600.

Dobhal, D.P., J.T. Gergan and R.J. Thayyen, 2008, Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India, Bulletin of Glaciological Research, 25, 9-17. DX282

Fujita, K., T. Kadota, B. Rana, R.B. Kayastha and Y. Ageta, 2001, Shrinkage of AX010 Glacier in Shorong region, Nepal Himalayas in the 1990s, Bulletin of Glaciological Research, 18, 51-54. DX265

Hewitt, K.; Wake, C.P.; Young, G.J.; David, C. (1989) Hydrological investigations at Biafo glacier, Karakoram range, Himalaya: an important source of water for the Indus river. In Annals of Glaciology, Vol. 13: pp. 103-108.

Hewitt, K. 1998. Glaciers receive a surge of attention in the Karakoram Himalaya. EOS Transactions, American Geophysical Union 79 (8):104–105.

Nijampurkar, V.N., N. Bhandari, C.P. Vohra and V. Krishnan, 1982, Radiometric chronology of Neh-Nar Glacier, Kashmir, Journal of Glaciology, 28, 91-105. DX055

Raina, V.K., M.K. Kaul and S. Singh, 1977, Mass balance studies of Gara Glacier, Journal of Glaciology, 18, 415-423. DX061

Su, Zh., and Y. Shi, 2002, Response of monsoonal temperate glaciers to global warming since the Little Ice Age, Quaternary International, 97/98, 123-131. DS0062

Thayyen, R. J. (2008) Lower recession rate of Gangotri glacier, during 1971-2004. Current Science **95**, 9-10.

Vohra, C.P., 1981, Himalayan glaciers, in Lall, J.S., and Moddie, A.D., eds., The Himalaya, aspects of change: Delhi, Oxford University Press, p. 138–151.

Yamada T., T. Shiraiwa, T. Kadota, T. Watanabe, B. Rana, Y. Ageta and H. Fushimi, 1992. Fluctuation of the glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang regions, Nepal Himalayas, Bulletin of Glacier Research, 10, 11-19.

Papers from Journal source reference lists

Ahamad, S. and Hasnain, S. I. (2004) Analysis of satellite imageries for characterization of glacio-mrorphological features of Gangotri Glacier, Ganga headwater. In Srivastava, D., Gupta, K. R. and Mukerji, S. editors, Geological Survey of India Special Publication 80, 61-67

Chitranshi, A., Sangewar, C. V., Srivastava, D., Puri, V.M.K and Dutta, S. S, (2004) Recession pattern of Meru Bamak Glacier, Bhagirathi Basin, Uttaranchal. In Srivastava, D., Gupta, K. R. and Mukerji, S. editors, Geological Survey of India Special Publication 80, 61-67

Dyurgerov, M. B. and Meir, M. (1997) Mass balance of mountain and subpolar glaciers: a new global assessment for 1961-1990. Artic and Alpine Research, 29, 379-91.

Jangpang, B.S. and Vohra, C.P. (1962). The Retreat of the Skunkulpa (Ralam) Glacier in the Central Himalaya, Pithoragarh District, U.P., India, Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp234-238.

Kadota, T., Seko, K. and Ageta, Y. 1993. Shrinkage of glacier AX010 since 1978, Shorong Himal, east Nepal. In: Young, G.J. (ed.) Snow and Glacier Hydrology (Proc. Kathmandu Symp. Nov. 1992) IAHS Publ. No. 218, 145-154.

Kurien, T.K. & Munshi, M.M. (1962) Sonapani Glacier of Lahaul Punjab. India, Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp0239-244.

Mukherjee, B. P. and Sangewar, C. V. (2001) Recession of Gangotri glacier through 20th cebtury. Geological Survey of India Special Publication **65**, 1-3.

Nainwal, H. C., Negi, B. D. S., Chaudhary, M., Sajwan, K. S. and Guarav, A. (2008) Temporal changes in rate of recession: evidence from Sapopanth and Bhagirath glaciers, Uttarakhand, using Total Station Survey. Current Science **94**, 653-60.

Naithani, A. K., Nainwal, H. C., Sati, K. K. and Prassad, C. (2001) Geomorphological evidences of retreat of the Gangotri glacier and its characteristics. Current Science **80**, 87-94.

Oberoi, L. K., Sidduqui, M. A. and Srivastave, D. (2001) Recession pattern of Miyar glacier, Lahaul and Spiti district, Himachel Pradesh. Geological Survey of India Special Publication **65,** 57-60.

Tewari, A.P. & Jangpangi, B.S. (1962) The retreat of the Snout of the Pindari Glacier. Inst. Assoc. Sci. Hydrol., Publ. No. 58, pp245-248.

Bulletin of Glaciological Research Extra sources

Ageta, K.Y. et al (2002) Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalaya. Bulletin of Glaciological Research **20**

Ageta, Y., Naito, N., Nakawo, M., Fujita, K., Shankar, K., Pokhrel, A.P. and Wangda, D., (2001). Study project on the recent rapid shrinkage of summer-accumulation type glaciers in the Himalayas, 1997-1999. Bulletin of Glaciological Research 18: pp 45-49.

Fujita, K., Nakazawa, F., and Rana, B. (2001). Glaciological observation on rika Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999. Bulletin of Glaciological Reaserch 18, 31-35.

Fujita, K., Takeuchi, N., and Seko, K. (1998). Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas 1994 and1996. Bulletin of Glacier Reaerch 16, 75-81.

Naito, N. et al (2006) Glacier shrinkages and climate conditions around Jichu Dramo Glacier in the Bhutan Himalayas from 1998 to 2003. Bulletin of Glaciological Research **23**

Organisation searches

Fushimi, H., Ohata, T. & Higuchi, K. (1979) Recent fluctuations of glaciers in the eastern part of Nepal Himalayas. Sea Level, Ice, and Climatic Change (proceedings of the Canberra Symposium). IAHS Publ .n. 131.

Haritashya, Umesh K.; Michael P. Bishop; John F. Shroder; Andrew B.G. Bush; Henry N.N. Bulley. (2009) Space-based Assessment of Glacier Fluctuations in the Wakhan Pamir, Afghanistan. Climatic Change **94**, 5-18.

Bajracharya, S. R. (2008) Change in Glacial Environment of Everest Region, Nepal. High Mountain Remote Sensing Cartography **8,** ICIMOD

Studies the review was unable to locate

Ageta, Y. (1983) Characteristics of mass balance of the summer accumulation type glacier in the Nepal Himlaya. Seppoyo, 45(2) 81-90.

Clapperton, C. M. (1989). "THE INTERNATIONAL KARAKORAM PROJECT - MILLER, K. J." Scottish Geographical Magazine 105(1): 54-55.

Kaul, M. N., (1986), Mass balance of Liddar glaciers, Transactions of the Institute of Indian Geographers, 8, 95-112. DX044

Kulkarni, A. V., and =Dhar, s. et al. (2006). "Recession of Samudra Tapu glacier, Chandra River basin, Himachal Pradesh." Photonirvachak-Journal of the Indian Society of Remote Sensing 34(1): 39-46.

Kulkarni, A. V and Suja, A. (2003) Estimation of recent glacial variations in Baspa Basin using remote sensing techniques. Journal of Indian Society of Remote Sensing **31**, 81-90.

Qinghua, Y., Y. Tandong, et al. (2008). "Response of Glacier and Lake Covariations to Climate Change in Mapam Yumco Basin on Tibetan Plateau during 1974-2003." Journal of China University of Geosciences 19(2): 135-145.

Surendra, K., Dobhal, D. P. (1994) Snout fluctuation study of Chhota Shigri Glacier Lahaul and Spiti District, HP. Journal Geological Society of India 44, 581-585.

Wake, C.P. (1987) Snow accumulation studies in the central Karakoram, Proceedings of the Eastern Snow Conference (North America), 44th Annual Meeting, Fredericton, pp. 19-33.

Singh, Deepak Srivastava, A. Mishra (2001) Proceedings Symposium on snow, ice and glaciers : a Himalayan perspective / eds R. K. Special publication / Geological Survey of India ; 53. Published: Calcutta : Geological Survey of India, Palaeontology Library - Serials S 1114.

Srivastava, D. (2004) Recession of Gangotri glacier. In Srivastava, D., Gupta, K. R. and Mukerji, S. (eds) Geological Survey of India Special Publication 80. 21-32.

10.2 Appendix B – Data extraction templates

10.2.1 Template for recording overall study characteristics and design for studies included in the review

Reference	Location & Period	Project details	Methodology	Summary of findings
Insert reference source	*Define geograhical location details including: Country, Region, Valley, Glacier, Latitude-Longitude*	*Relay as much information as possible concerning the type of study, measurements taken, comparator type, include any notes on exposure data*	*Detail the methods applied and an assessment of the confidence to be ascribed, using the method assessment criteria sheet*	*Summarise findings, leave numerical details to the data sheet.*
Reviewer	**Date**			
Checker	**Date**			

10.2.2 Template for recording of data from studies reporting measurements of change on single glaciers

Glacier	*Enter glacier name or number - Check spelling!*
Glacier type	*Type of glacier as noted*
Debris covered	*Note if glacier 'debris covered' or 'debris free'*
Country	*Country name*
Region	*Himalayan region - Insert drop down menu*
Sub-region	*Sub-region e.g Garwhal Himalaya*
Catchment	*Catchment name*
Snout elevation	*Elevation of glacier terminus (m)*
Aspect	*Aspect of glacier (N,S,E,W)*
Area	*Enter glacier area (km2)*
Length	*Enter glacier length(km)*
Volume	*Enter volume estimate (km3)*
Baseline date	*First date of data used in study as comparator*
Final date	*Final date of measurements taken*
Frequency of measure	*Divide measurements taken by total record length*
Comparator Measurement	*Define the mesurement type - Insert Drop down menu*
Result - period	*The mesurement of change given for total period (If negative indicate)*
Result - average	*Mesurement of change expressed as average yearly variation*
Baseline method	*Method used to obtain baseline data - Insert Drop down menu*
Comparator method	*The method applied to make measurement - Insert Drop down menu*
Quality assessment	*Where does the study sit in the 'method confidence' table?*
Melt?	*Is the overall findingthat the glaciers are melting? (R (retreat),S (Stationary),A (Advance),F(Fluctuate))*
Rate of melt increase?	*Is the overall findingthat the glacier is retreating as a faster rate? (Y,N,S)*

This sheet is for use with studies that contain data on specific glaciers only. If there is no way of identifying the glacier then the sheet should be left blank. If the study refers to multiple glaciers without identfying results for individual glaciers then the data should be placed in the following 'Region Data Sheet'.

For items requiring input from drop down menu's, use the menus provided below - if additional inputs identified then ensure communication with partner and update of combined list.

Notes:

Where **more then one glacier is studied** - copy column B into C etc.

Where **more than one method** is applied over time **to obtain a single comparator measurement** of change, note both methods in the Baseline and Comparator boxes from the drop down menu and ensure details are noted on the project sheet

Where **multiple measurements** of the same glacier are taken simply create new columns, pasting over glacier data from previous, and infill with new measurement, method, result etc.

Measurement type - Drop down	**Method - Drop down**	**Region**
Terminus change (m)	Satellite data	HKH
Area change (km2)	Field mapping	Karakoram
Volume change (m^3)	Aerial photography	Himalaya
Mass-balance (kg/m2)	Glaciological MB	
Terminus elevation change (m)	Geodetic MB	
Mass balance (m w.e.)	Hydrological MB	
Specific mass balance (m w.e.)	Flux divergence	
Net Mass balance (m^3 w.e.)	VPP - ELA	
Area change (%)	GPS mapping	
	Aerial mapping	
	Terrestrial photography	
	GPR	
	Ice Core	
	Description	
	Thickness profiling	
	Gravimetric profiling	

10.2.3 Template for recording of data from studies reporting measurements of change for multiple glaciers

Country	*Country name*
Region	*Himalayan region - Drop down menu*
Sub-region	*Sub-region e.g Garwhal Himalaya*
Catchment	*Catchment name*
Snout elevation	*Elevation average of glacier terminus(m)*
Debris covered	*Note if glacier 'debris covered' or 'debris free'*
Aspect	*Aspect of glacier (N,S,E,W)*
Area	*Enter total area of glaciers in study (km^2)*
Number	*Number of Glaciers within study*
Baseline date	*First date of data used in study as comparator*
Final date	*Final date of measurements taken*
Frequency of measure	*Divide measurements taken by total record length*
Comparator Measurement	*Define the mesurement type - Drop down menu*
Result - period	*The mesurement of change given for total period*
Result - average	*Mesurement of change expressed as average yearly variation*
Baseline method	*Method used to obtain baseline data - Drop down menu*
Comparator method	*The method applied to make measurement - Drop down menu*
Quality assessment	*Where does the study sit in the 'method confidence' table?*
Glacier melt?	*Is the overall findingthat the glaciers are melting? (R (retreat),S (Stationary),A (Advance),F(Fluctuate))*
Rate of melt increase?	*Is the overall findingthat the glaciers are retreating as a faster rate? (Y,N,S)*

This sheet is for use with studies that contain data on general areas of the Himalaya region. They may contain a number of glaciers, this should be noted in the table if available.

Where disticntions are made within the overall group of glaciers studied, such as by grouping them by Aspect, or by Area, then complete a column for each disticntion as possible. With area define the range covered in the Area box; e.g 10-20km2, or >50km2, etc

For items requiring input from drop down menu's, use the menus provided below - if additional inputs identified then ensure communication with partner and update of combined list.

10.3 Appendix C – Ranking of methods and reporting assessment

Appendix C details the rationale for the ranking of methodological approaches and the reporting of the method and results. The overall confidence ascribed to each studies finding after considering both these assessments, through the use of an overall confidence matrix (as outlined in section 3.4) is detailed in Annex A.

10.3.1 Ranking of methods

The various methods employed within the region, to make measurements of glacier changes, have been ranked according to the reviewers' confidence in accuracy and scientific rigour. This has been based upon objective assessment of the methods employed in the various studies included in the review, ands some outside literature noted. For each measurement the methods employed have been detailed briefly, noting elements that have been used to objectively rank the methods.

A team of glaciologists was consulted in order to develop a robust rational for the ranking of methods, including:

- Prof Gordon Young of Wilfrid Laurier University, Canada, and President of IAHS.
- Prof David Collins of Salford University.
- Dr Arun Shrestha of ICIMOD, Nepal.
- Gwyn Rees of CEH.

The overall ranking of how representative the various methodological approaches are in indicating change in glacier mass, either positive (growth) or negative (shrinkage), has been developed through consultation of the experts outlined above through consideration of the elements discussed below.

Mass balance

The primary source of information regarding the relative accuracy of the various methods employed to measure mass balance comes from the 'manual for monitoring the mass balance of mountain glaciers' by Kaser et al (2003). This is a technical document contribution by the International Commission on Snow and Ice (ICSI) to the UNESCO HKH-Friend program, designed to provide standardised techniques particularly to guide the monitoring of glaciers in the Himalayan region. This document provides a wealth of information surrounding the methods that can be employed, and clearly outlines the relative accuracy and rigour of methods. Further consideration was also employed by the review team. The main points determining the ranking developed are detailed below;

1. Glaciological method – The only method based on *in-situ* methods, and is considered the most accurate method to date. It provides the most detailed information on the spatial variation of mass balance magnitudes.
2. Geodetic method / Remote Imagery – By calculating a volume change from surface elevation and extent at two different times, then applying surface density estimates, a mass change can be calculated. The method is prone to inaccuracy in that it is not reasonably possible for the entire glacier surface to be surveyed in difficult conditions. Remote imagery can be used but there are difficulties in accurately identifying surface definition. Also there is no

indication of how mass balance varies with elevation. This is a complementary method to the glaciological method and over long time steps to assess change.

3. Hydrological method – This method, based upon calculating the changing mass from precipitation, evaporation and runoff data, requires significant gauged data from these variables. Inaccuracy can develop in extrapolating precipitation from a single gauge site to the surrounding mountainous terrain. Care should also be taken as numerical calculation of mass balance can lead to high error from the measured variables.
4. Flux divergence – With recent development of airborne laser scanners in providing high-resolution digital terrain models of glaciers and velocity vectors it becomes possible to combine geodetic methods with ice-flow calculations, in order to obtain spatial distribution of glacier mass balance. However there is an inability to derive sufficiently accurate vertical velocities, and the instruments are subject to bad weather conditions.
5. Indirect methods / Climate records – Indirect methods using the Vertical Balance Profile (VBP) require both long time series of data and contain various assumptions. Also the timing of the imagery is crucial because early snowfall can blanket the ELA. Determining mass balance from climate data fundamentally requires a model to be used, requiring high quality climatic data. However most models rely on simple extrapolation from precipitation data, and models must be calibrated to the glacier, thus needing previous mass balance data to validate the model and results.

Volume

Determining volume in a challenging environment such as the Himalaya is extremely difficult in the field. Covering the whole surface of the glacier is not possible with any field approaches, so there must be a balance between selected measurements and extrapolation. More complete measures can be obtained from remote sensing data, but as noted previously there must be detailed assessment of accumulation zone images using standardised methods so that accuracy can be improved. The raking of methods reflects the difficulties noted and is based upon consideration by the review team of the studies measuring volume;

1. Remote sensing and digital elevation model (DEM) – Digital elevation models are generally accepted as being accurate when developed from high-resolution remote sensing data. The accuracy is reported, as it is available, so it can be possible to assess how accurate the estimate is. This was noted above in the geodetic method approach to mass balance as being necessary due to the potential accuracy issues that can be involved. Only one study (Berthier et al, 2007) used this approach and state that it is difficult to estimate the uncertainty in volume for individual glaciers, but that errors are reduced for larger glacier areas. Furthermore season is important, with most usable images limited to the summer season when surrounding snow cover is minimal and facilitating the delineation of the glacier in question.

2. Remote sensing with field mapping baseline – Modern remote sensing imagery can be used to derive estimates of glacier volume using the geodetic method; this volume can then be compared to baseline values calculated from earlier field mapping. Only one study (Kulkarni et al, 2007) uses this approach, providing a very approximate error estimate of between 10-20%.
3. Field measurements of thickness profiling and mapping – By comparing toposheets of areas at two different periods it is possible to calculate volume change by preparing area average thickness maps, based on elevation measurements and slope, and aided by thickness profiling, usually by means of ground penetrating radar. There are potential inaccuracies involved in all the component measures used to calculate volume, particularly in applying a uniform slope in calculations of volume, something that is unlikely to exist in the valley under the glacier surface. This is the most applied method for calculating volume, yet without rigorous validation of thickness estimates from GPR there is no scope for using the numerical data, due to the high inaccuracies involved.

Area

Area is another challenging measurement to make in the challenging terrain of the Himalaya, which is why airborne imagery is used by most studies. Remote sensing data normally provides the user with some indication of accuracy and, combined with the methods used to delimit the glacier extent studies, should allow assessment of the overall relative accuracy and confidence to be ascribed. The ranking of the methods reflects this distinct difference between field measurements and airborne imagery, and was developed according to review team assessments of the studies available and general perceptions on the methods when applied to the Himalaya;

1. Remote sensing – As discussed this provides a snapshot of the whole glacier area for desk based delimiting of the glacier extent. It is hindered by the availability of clear images, but all reviews acknowledge this, using only cloud-free images where glacier edges can be identified. Comparison of two images at different dates presents the most complete and accurate dataset for defining glacier area, with differences in the approaches used considered in the detailed assessment of method and reporting. The errors in the images are reported to be very low by Bolch et al (2008); findings accuracy of ±2% using manual delineation of high quality images. However this is likely to vary considerably between studies, depending on the image quality, whether the glacier is debris covered, and the training/equipment of the team. Furthermore season is important, with most usable images limited to the summer season when surrounding snow cover is minimal and facilitating the delineation of the glacier in question.
2. Remote sensing with baseline field mapping – The use of previously mapped areas for baseline data are necessary for studies without access to remote sensing images or when comparing changes over periods for which such

information is unavailable. The accuracy of the baseline will reduce the accuracy of the overall estimate of change, but no studies make specific estimates of the error in the baseline maps, or in the processes used to compare these to remote sensing images.

3. Mapping from aerial images / Field measurements – Both these technique are usually applied to develop field mapping of glaciers on toposheets. There is little reporting of the accuracy and errors involved in the production of the maps, simply scale and method used to measure and map. Deducing the errors involved is, as Salerno et al (2008) note 'not a simple matter, as it would require retracing the process by which the cartographers discriminated between what is and what is not mapped as a glacial feature'; fundamentally not possible. It is possible to evaluate the areal error associated with delimiting the glacier from these maps, Salerno et al (2008) reporting an average error of 4.9%, which agrees with findings from Mi et al (2002) of 5%.
4. Terrestrial photography – Changes in glacier area derived by such an approach cannot realistically encompass the whole glacier, and normally focus on changes in the area of the glacier terminus. There are no direct measurements; the change must be calculated upon desk based inspection using scale references. The errors would be high, and as such are only really be used to indicate change.
5. Description – Some studies do report change from descriptions of visiting scientists, but do not make quantitative assessments. This is only an indicator and is not subject to any standardised techniques.

Terminus

Measurements of terminus position provide the longest time series of measurements within the Himalayan region, simply by being the most easily recorded measure of the glacier. However many of the earliest field visits simply reported a description of the glacier position, took a photograph, or produced a simple sketch map. More detailed measurements became available in field maps developed using standardised survey equipment and from aerial photography from the 1950's onwards. Modern advances in remote sensing mean detailed images are now available for certain periods, from which to determine terminus position. The ranking of these methods follows common sense related to mapping of any geographic point, but with a focus upon the relative difficulties experienced within the Himalaya;

1. Remote sensing – Comparing two clear and detailed images from satellites provides a clear comparison of the terminus position over time. Accuracy should be noted by studies, but few provide any details. Errors involved are typically between 15-30m (Belo et al (2008).
2. Remote sensing with baseline geo-referenced field mapping – In order to compare more recent images with historical maps it is necessary to geo-reference the mapping so that a clear and accurate comparison can be made. This is done by most studies; however no real assessment of the historical mapping accuracy is typically made. Diolaiuti et al (2003) do make an assessment of the measurement accuracy and geo-referencing of early

mapping of Liligo glacier, finding that the earliest measures (Pre 1900) have significant inaccuracy, being over 50% of the reference point measured. This highlights the issue of not being able to properly assess the accuracy of early mapping, and points to the fact data pre-1900 should not be admissible to the review as quantitative evidence.

3. Topographic maps – Early maps (Pre 1950) were typically produced by field based mapping of the glacier terminus. Later maps involved field based techniques to determine the terminus position along with aerial images to develop more accurate maps. There is no indication of accuracy, but scale provides a reference to how accurate the map might be. Better reporting of glacier changes, using such sources, utilizes reference points for validation of quantitative measures of change.
4. Terrestrial photography – Comparison of two images taken at different times but from the same vantage point provides a clear indicator of change, but determining a measure of change is more problematic and prone to inaccuracy.
5. Description – Early visits to glaciers provide description of a glacier terminus relative to surrounding features. Unless such descriptions include clear and rigorous use of reference points that later mapping can reference to validate measured change, the only use of such evidence is to indicate advance or retreat.

10.3.2 Confidence assessment of reported method and results

A range of assessments were identified that would allow the review team to assess confidence in the method applied and results reported. The scoring from very low, up to very high, reflect the various confidence the review team ascribes to such elements of the reports. Taken together these permitted an objective overall assessment of how clear and rigorous the measurements reported in the studies were.

Method description – The method was rated from 'not given', up to 'very clear', and reflects the transparency of the study in reporting the method applied to make measurements. The elements considered to assess methodology and reporting are:

- Very High - Providing detail of all methods used in both the collecting and processing of data, best presented as a separate section within the paper, providing detailed illustration of methods and locations where appropriate and , where applying standardised methodologies, clear reference to the source is made.
- High – As above but lacking clarity in the detail provided, such as omitting detail required to repeat the measurements taken or not providing additional illustration.
- Medium – The method is mentioned within the paper but is not presented clearly in a separate section and the reader is uncertain as to all the methods applied.
- Low – The method is unclear to the reader, lacking detail.
- Very Low – The method is not provided

Uncertainty – Few studies included any assessment of error or accuracy, so it was deemed those studies clearly reporting both would be scored higher that a study that simply mentions that some uncertainty exists. The greater the examination by study teams into the accuracy of their results, the greater the confidence in how rigorous a process they followed. The elements considered to warrant confidence assessments are:

- Very High – There is clear reporting of both accuracy and error within the paper, both assessed using standardised approaches
- High – Only the accuracy of the measurements is provided
- Medium – There is some mention of the accuracy and uncertainty but this has not been based upon the measurements taken
- Low – The accuracy or uncertainty is discussed but no quantitative assessment has been provided or undertaken
- Very Low – No assessment of accuracy is provided

Standardised approach – While some studies would employ a standard measurement technique, as outlined in a measurement manual or from some referenced source, others would apply what would seem very unclear approaches. A consistent approach signals a study that applies a clear and consistent approach to measurement. Conversely studies where no indication has been given of following or building from a methodological protocol previously developed by other researchers, were not deemed to be standardised in their approach. The elements considered to warrant confidence assessments are:

- Very High – Application of a standardised referenced method that is recognised and applied in glaciological research measurements
- High – Contains elements of a standardised approach, as above, but with adaptations and perhaps no direct reference to the method
- Medium – The approach taken is a consistent method across the two measurements, but no reference to any standardised approach is provided
- Low – It is unclear how the approach is standardised
- Very Low – No standardised approach considered

Research team – Research conducted by the author was found to be much clearer in the reporting of other elements considered, and when considering two measures over time, more consistent. Consistency was also apparent from measurements conducted by a single team over time. Such consistency reduced dramatically when different team's research was collated. Other studies did not report who actually carried out the research, further reducing confidence in the measurements.

Reported resolution – Consideration of when the research was conducted is necessary for glacier measurements, as it can be important to know whether the measurement was taken in the ablation or accumulation period. Some studies clearly reported the date of the measurement, others simply the season. At a minimum the year should be reported, but some studies merely reported findings to be indicative of the decade.

Reported location of measurements – Most studies investigating a single glacier did provide either an exact location or glacier name. Some studies reported findings for a region, so it was unclear what glaciers exactly were included. Better definition of the location provides greater transparency and clarity in reporting, along with more rigorous and repeatable measurements.

Frequency of measurements – There was considerable variation in the temporal resolution of measurements between studies, from those that take measurements every year, to those that simply compare a recent measure to a more historical baseline from the early to mid 20th C. Increasing frequency of measurements provides a more continuous series from which to assess change, providing higher confidence in the changes reported.

Clarity of evidence reporting – There was considerable variation in this area, with some studies making it almost difficult to extract the quantitative data. Very clear studies provided tables and full calculations; clear studies contained easily extractable data. Less confidence was assessed where effort was required to extract data, normally from the text. Studies that reported a finding without any clear thread of how data was derived were deemed unclear.

Validation of measurements – Studies that gave full validation of evidence, through checking by other measurements or other means, were rated with very high confidence. Where studies provided some indication that validation had been carried out, a high confidence rating was applied. Mentioning that validation was carried out, but not providing a clear indication of how and why, resulted in a medium confidence. Where validation was unclear only low confidence was ascribed.