Advances in Asian Human-Environmental Research

Kenneth Hewitt

# Glaciers of the Karakoram Himalaya

## Glacial Environments, Processes, Hazards and Resources

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Bualtar Glacier descends northwards from Minapin Peak (7,266 m) in the Rakaposhi Range, a fall of some 4,965 m in 22 km to its snout. The extreme steepness and elevation ranges of larger Karakoram glacier basins are indicated, and a sense of the great vertical changes in conditions from the debris covered ice of lower tongue to precipitous, avalanched walls at the head

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*To Farida*

# Preface

This book mainly concerns the present-day glaciers of the Karakoram Himalaya: the conditions that sustain them, the landscapes they have helped to shape and broader environmental, water resources and hazards issues associated with them. The core region involves about 16,500 km$^2$ of perennial snow and ice in the headwaters of the Indus and about 4,000 km$^2$ in the Yarkand drainage. In an otherwise extreme continental, arid region, the glaciers comprise large stores of freshwater. Meltwaters from glacier basins make up between 30 % and 40 % of the average annual flows of these rivers where they leave the Karakoram and dominate their discharges for 2–3 months of summer. Seasonal snowmelt makes up most of the balance. Yields from snowmelt seem, on an average, to be somewhat greater than those from glaciers but may be less in some years. By contrast, glaciers are relatively minor contributors and snowmelt much more important for tributaries of the indus draining the southern flank of the Greater Himalaya. Rainfall is the largest contributor, as it is in most years for the Indus basin as a whole. The upper Indus and Yarkand are among the few large river basins in South Asia where rainfall is not the dominant source of stream flows. It would be difficult to overemphasise the unique ecological and human significance of the glaciers and snowfields in the two basins. They will become more critical with anticipated climate change and economic developments.

Water demands and shortages in surrounding, populous lowlands are placing ever-greater pressures on mountain resources or the desire to exploit them. A sense of urgency arises from national and trans-boundary development plans for water and power. There are existing conflicts in the high mountain areas that could be aggravated, and new ones may arise. More hopefully, rational approaches based on mutual benefits could bring improved relations and greater security in the high mountains.

At the time of writing, a commonly expressed concern is how climate change may greatly reduce the glaciers and water supplies from them. The concern is justified, although some misleading or exaggerated accounts and the talk of ‘disappearing glaciers’ have confused the issue. In many parts of High Asia, glaciers have undergone large retreats and loss of mass in recent decades. However, changes turn out to have been less rapid than widely suggested, quite variable in different regions and, to date, substantially different in the Karakoram (Hewitt 2005; Raina 2009; Scherler et al. 2011). There were appreciable losses of glacier mass through much of the twentieth century. Since the 1960s, they have been relatively small and inconsistent. In some cases, glacier advances are causing problems. The most likely explanation is that increased warming is being compensated in these high mountains by increased snowfall and summer cloudiness. As global warming intensifies, that may, or may not, continue. For the moment, the more worrying responses concern the timing or greater unpredictability of river flows, and environmental extremes.

From a scientific perspective, a balanced assessment of snow, ice and glacial environments in the region, and just how changes have occurred, is constrained by patchy and limited research (Kaul 1999; Hagg et al. 2009; Raina 2009; Armstrong 2010; Shroder and Bishop 2010). Although it is widely stated that the Karakoram glaciers are vital for water supply and at great risk from climate change, there is almost no continuous or widespread monitoring of them. Indeed, no adequate account is available of what is already known about them. It is over 75 years since the last book-length treatment was published. Moreover, this last major study has never been translated into English (Visser and Visser-Hooft 1935–38). The most extensive overview from a decade earlier is still only available in Italian (Dainelli 1924–35); the exceptional study of High Asian snow and ice by von Wissmann (1959) is available only in German. There have certainly been some valuable, more narrowly focused papers and overview chapters in more recent publications (Mercer 1975; Goudie et al. 1984; Haserodt 1984; Kuhle 2004; Hewitt 2006, 2011; Smiraglia et al. 2008; Shroder and Bishop 2010; Shroder 2011). Constraints of space, interests and language limit their coverage.

The Karakoram has a fairly long history of modern investigations, more so perhaps than newcomers to the topic might imagine. Scientific studies go back almost 200 years (LIGC 1984; Allen 1995). A number of large expeditions and scientists from several countries brought great advances in knowledge (see Chap. 1). Their work is an essential resource, although its limitations must be noted. As a whole, coverage is patchy – discontinuous in time and space. Much of the work pre-dates the development of some basic glaciological concepts and, as noted, may not be available in English or any other but the original language. Rugged terrain and harsh climates have limited scientific work in much of the region, and security issues often prevent it. Few investigations have gone beyond the lower parts of the glaciers and rarely above 4,000 m.[1] Yet, 80 % of glacier basin areas and all the sources of glacier ice occur above this elevation. It makes the few studies at higher elevations that much more important, although these too are biased towards a few valleys and their larger glaciers. Most of the region has received little or no attention, including some of the largest glaciers, but especially the lesser ranges where smaller glaciers prevail. 'Small' in this context is taken to mean less than 15 km in length. Collectively,

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[1] Measurements of elevations above sea level will be written with a comma separating 100s from 1000s (e.g. 3,000 rather than 3000). This will distinguish elevations, from elevation spans, length or relative height measurements which, unless over 10,000 units, will not include commas.

however, these glaciers alone comprise a greater area than, say, the 2,896 km$^2$ of glaciers in the European Alps (Haeberli 1998).

Until recently, information about the glaciers was almost entirely a product of expeditions coming from outside the region and, usually, a secondary concern compared to mountaineering or military and commercial intelligence. Most were more or less short term, logistically and spatially limited, usually for a few weeks or months of summer. Those making observations in winter can be counted on the fingers of one hand and for most of the region are non-existent. Members have tended to be new to the region and visited only once, rarely more than two or three times, with some important exceptions (Dainelli 1959; Hewitt 1989, 2007). A few major expeditions by Italian, German, Austrian and Japanese teams were extensive in space and time and made detailed investigations of the glaciers. Many of their results, however, are only available in brief summaries and short papers in English. The more numerous and oft-quoted English sources are mainly from before 1947, when the region was part of the British Empire.

Nevertheless, there are some great advantages of writing this study today: the richness of the literature on glacial environments and processes worldwide and ever-improving coverage of the Karakoram region by satellite imagery. Invaluable background is provided by a number of substantial texts and works of reference on glaciers (Drewry 1986; Hambrey 1994; Paterson 1994; Menzies 1995; Benn and Evans 1998; Singh et al. 2011). The present work benefits hugely from these sources. It should be added, however, that Karakoram glaciers have only rare and minor appearances in any of them, usually in terms of certain exceptional or hazardous phenomena such as glacial lake outburst floods and surge-type glaciers.

In the past decade or so, more frequent and higher-definition satellite imagery has transformed spatial and temporal coverage of the region (Williams and Ferrigno 2010; Bishop and Colby 2011). New monitoring and analytical possibilities are opening up all the time. They offer opportunities for more representative, region-wide and all-season characterisations. An attempt is made here to take advantage of this, especially in relation to the higher, more rugged parts of glacier basins and the least-visited areas. Nevertheless, the dangers of limited or no ground control, or lack of experience in areas of interest, are constant problems. Not only has most information about Karakoram glaciers themselves come from ground-based observation and phenomena, so too has the development of the basic concepts of mountain environments and glaciology. Fully effective translation between them and remotely sensed information and analyses is a work in progress.

Problems can also arise because the most intensively studied mountain glaciers occur in other, very different environments – typically, midlatitude and subpolar regions. They tend to be relatively small ice masses, generally at lower elevations and of much less elevation range than Karakoram glaciers. This applies to most reference or ‘benchmark’ glaciers so fundamental for tracking and comparing mountain ice globally (Oerlemanns 2001; Haeberli et al. 1998; Bolch 2011). The Karakoram is in an extreme continental, subtropical location. More than half of all its glacier ice occurs in 15 basins, in glaciers more than 40 km long and with the highest areas well over 7,000 m. Many glaciers have elevation ranges of more than 4,000 m, some over

5,000 m. As a result, sets of distinctive conditions must be addressed that are of minor significance elsewhere and absent from most of the glaciers literature and research. It is important to have some of these in mind from the beginning.

In the Karakoram, it will be shown that the greater fraction of all glacier ice is input to the glaciers by avalanches rather than direct snowfall. Yet, while there has been a great deal of research into avalanches, it has largely ignored avalanche-fed glaciers, let alone valley glaciers that can be more than 50 km in length. Rock walls too steep to support seasonal or perennial snow build-up account for over 60 % of most glacier basins, more than 80 % in many. These are the main source areas of Karakoram glaciers. In addition, wind action and redistribution of snow have major influences. They probably affected the larger part of all the snow mass that is eventually incorporated into glaciers. The greater part of the vertical descent of most of the glacier ice itself is in icefalls. Much or all of the ice in the most widely observed and studied main and lower ice streams has passed through one or more icefalls. This will be shown to open up a range of situations that can affect or modify the properties and behaviour of the ice. Such uniquely ‘Himalayan’ conditions are frequently remarked upon but only rarely investigated, even in research on Himalayan glaciers (Yafeng and Wenying 1980; Benn et al. 2003; Cogley 2011; Hewitt 2011). They have to be addressed here, despite the lack of well-developed empirical and conceptual work.

This book can hardly escape the constraints of past work, whether in the studies on which discussion must be based or the author’s experience and limitations. The strategy adopted is, however, partly chosen so as to deal with this: a regional approach paying particular attention to the terrain and environmental conditions in and around glacier basins and, to the extent possible, types, forms and features of the ice masses. Although essentially descriptive, terrain classification and distributions offer a more representative sense of the region’s glacierised areas and environments and a balanced way to explore where further research is most needed.

The approach is described in more detail at the end of Chap. 1. Chapters 2, 3, 4, 5, 6 and 7 focus on present-day glacier basins, ice masses and their maintenance. Glacial landforms and earth surface processes related to them are considered in Chap. 8. In Chaps. 9 and 10, some more extreme, short-lived glacial phenomena and hazards to human inhabitants are looked at, in particular surge-type glaciers, glacial impoundments and outburst floods. Chapter 11 draws attention to the huge numbers and great diversity of rock glaciers in the region, a part of the Karakoram cryosphere largely neglected in the past. Questions of recent glacier change are elaborated in Chap. 12. A concluding chapter looks at issues relating to people, glaciers and, especially, regional water supply.

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# Contents

# Chapter 1
# The Regional Context

**Abstract** The Karakoram Himalaya comprises the highest, most heavily glacierised watersheds of the upper Indus and Yarkand River basins. It is set within other vast mountain systems of High Asia that support more than 100,000 km$^2$ of perennial snow and ice cover. The chapter situates the Karakoram in this Central Asian context and outlines key aspects of the regional environment. A variety of other cold region or cryosphere features are of interest including seasonal snow covers and perennially frozen ground or permafrost. These affect much greater areas than the glaciers, as do periglacial conditions and snow avalanches. Rock glaciers are concentrated in some parts, periglacial systems closely related to glaciation in distribution, climate responses and genesis. Two main aspects of the Karakoram environment are reviewed: the region's geology and geotectonic evolution, and its climate. The glaciers would not exist at all, or be so extensive, without the great elevations created by mountain-building forces. Significant aspects of their morphology and behaviour relate to rugged, steep landscapes developed through deep dissection by rivers and past glaciations. The Karakoram climate is influenced by three seasonally varying weather systems: the predominantly winter Westerlies, the summer monsoon and Inner Asian high-pressure systems. The glaciers are affected by each system, their relations to one another, by their strong year-to-year variations and how, in turn, they are influenced by the high mountain terrain. In the lower Karakoram valleys and surrounding high plateaux, dry conditions are found, including where most weather stations are located. However, the glacierised area is, in fact, largely humid. Measured snowfall and water yields from glacier basins challenge a long-held view of the Karakoram as part of what has been termed 'the semiarid Himalaya'. Snowfalls in glacier source areas are in the range 1,000–2,000 mm water equivalent. Also, summer snowfall at high elevations will be shown to be a major factor in sustaining the glaciers, whereas winter precipitation dominates in weather station records. Estimates of the much-studied snowlines are shown to be problematic since they occur where freeze–thaw cycles, wind and avalanche redistribution of snow, are concentrated. The importance of Karakoram glaciers for the flows of the Yarkand River and main stem of the Indus is outlined.

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**Keywords** High Asia • Cryosphere • Greater Karakoram Range • Indus River • Yarkand River • Regional tectonics and geology • Regional climate • Snowlines

## 1.1 High Asia

The Karakoram is distinguished, primarily, by the extent and development of high mountain topography and by its location in the southwest central part of High Asia. These two geographical elements combine to affect the occurrence, maintenance and forms of glaciers in the region. The broad geographical setting is variously referred to as the 'Greater Himalayan Region', 'the Tibetan Plateau and Adjoining Regions' or, for some, 'The Third Pole' (Tandong 2007; Qui 2008; Hilton 2012). It includes the Hindu Kush, Greater and Lesser Himalaya and Tibetan Plateau (Fig. 1.1). Here are the headwaters of rivers that drain to the vast surrounding lowlands: the Amudar'ya, Indus, Ganges, Tsangpo-Brahmaputra, Irrawaddy and Sichuan basins. The mountains also form rugged fringes to the basins of interior drainage north and west of the Tibetan Plateau, including the Yarkand system.

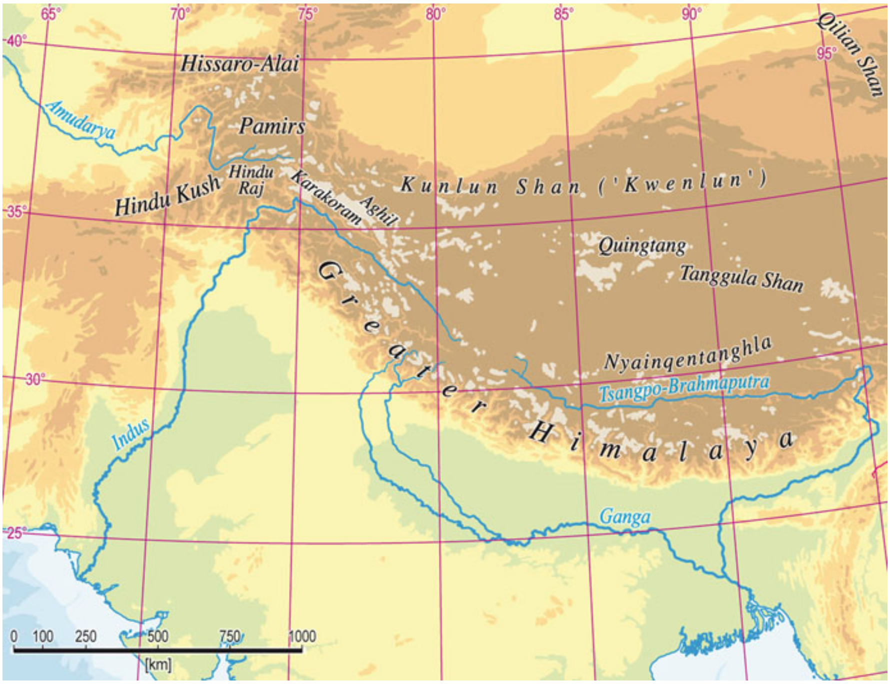

**Fig 1.1** The Greater Himalayan Region showing major river systems, the Karakoram and other main mountain ranges with concentrations of glaciers

**Table 1.1** Summary of four inventories of major glaciated areas in the Greater Himalayan Region

| | Mountain range (countries) | Glacier area ($km^2$) | | | |
|---|---|---|---|---|---|
| # E-W | Source | von Wissmann (1959) | UNESCO 1998 | Dyurgerov and Meier (2005) | USGS 2010 |
| 1 | Hissaro-Alai | 1,830 | 2,328 | 1,750 | 2,336 |
| 2 | Pamirs | – | 7,116 | – | 10,200 |
| | CIS | 11,738 | 4,493 | 12,260 | 7,493 |
| | China | – | 2,623 | – | 2,696 |
| 3 | Tien Shan | 16,500 | – | 15,417 | – |
| | CIS[a] | 9,000 | 7,311 | – | 7,251 |
| | China | 7,500 | 9,257 | – | 9,225 |
| 4 | Hindu Kush | 3,900 | – | 3,200 | – |
| | Afghan | – | – | – | 2,700 |
| 5 | Hindu Raj | 2,300 | – | 2,700 | – |
| 6 | Karakoram | | | | |
| | Pakistan/India | 15,145 | – | 16,600 | 15,000 |
| | China | – | 4,769 | – | 6,262 |
| 7 | Aghil | 1,700 | – | – | – |
| 8 | Kunlun Shan ('Kwenlun') | 11,500 | 12,263 | 12,260 | 12,267 |
| 9 | Greater Him. | 31,530 | 27,960 | – | 35,100 |
| | India | – | 21,590 | – | 8,500 |
| | China | – | 11,000 | 33,050 | 8,418 |
| | Nepal | – | 2,620 | – | 5,324 |
| | Bhutan | 3,300 | 2,730 | – | 1,317 |
| 10 | C. and E. Tibet[b] | | | | |
| | Quingtang | | 3,355 | 1,802 | – |
| | Tanggula Shan | 1,195 | 2,206 | 2,206 | 2,213 |
| | Nyainqentanglha | | 11,000 | 7,536 | 10,700 |
| 11 | Quilian Shan | – | 1,930 | 1,970 | 2,206 |
| | Totals | | | | |
| | High Asia | 120,091 | – | – | – |
| | CIS | – | 18,501 | 116,180 | 22,044 |
| | China | – | 58,000 | – | 59,425 |

[a] *CIS* Commonwealth of Independent States (Former Inner Asian members of USSR)

[b] Central and Eastern Tibet

In the Greater Himalayan Region, there are about a dozen major concentrations of glaciers at high elevations (Table 1.1; Plate 1.1). The total perennial snow and ice cover is thought to exceed 100,000 $km^2$ of which the Karakoram share is about 20 %.[1] This refers to the areas covered by snow that remains through the summer

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[1] There are considerable differences in the glacial areas quoted in the literature, evidently due to differing nomenclatures, sources of information and classifications. Over the years, various students, including myself, have come up with different numbers as measurement opportunities and concepts have changed (see Annex 1).

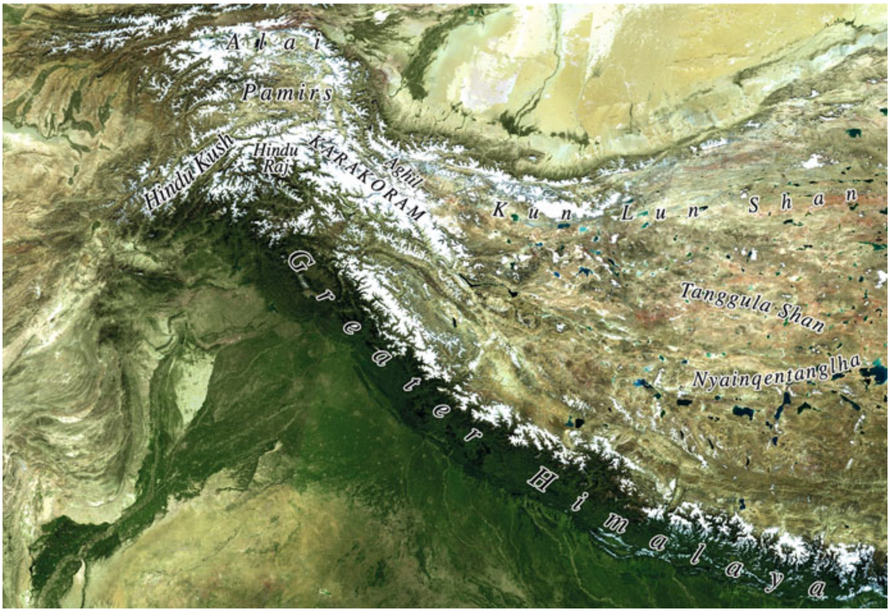

**Plate 1.1** Satellite image showing main concentrations of perennial snow and ice in the Greater Himalayan Region

and ice above glacier termini. In much of High Asia the true glacierised area, meaning that which is actually covered by glacier ice, is rarely more than half the perennial snow and ice cover (Mayer et al. 2006, p. 126; Hewitt 2011).[2] Higher-resolution and more frequent satellite coverage has made clearer the extent of the areas that are perennially frozen but too steep to support glacier ice or parts of active ice streams. There may be a permanent snow cover or thin veneers of ice or avalanche flutings. They are certainly part of glacier basins and will be shown as critical for glacier nourishment in the Karakoram, but they are not underlain by glacier ice (Plate 1.2). Most work on the region has, however, treated glacier area as synonymous with, or close to, the perennial snow and ice cover. Most estimates including my own have tended, therefore, to exaggerate the true *glacierised* area in the more rugged parts of High Asia while underestimating the scale and roles of off-ice areas within glacier basins (Chaps. 3 and 4).

The southern arc of high mountains, sometimes referred to as the Hindu Kush–Karakoram–Greater Himalaya (HKH), is of singular interest. Rarely more than 200 km wide, it nevertheless supports substantial and diverse glacier systems. The belt spans almost 30° of longitude and 13° of latitude, that is, more than

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[2] For citations, page numbers are only given to refer to a specific statement, measure or finding within a longer work. They are not given where the whole work is involved, or studies deal in several places or more broadly with topics of interest, or are important, useful or representative background reading.

**Plate 1.2** High elevation source zones of Baltoro Glacier in the Karakoram illustrate how large areas comprise off-glacier rock walls. View from Concordia (4,691 m) of the Broad Peak (8,051 m) watershed (Hewitt July 2005)

2,500 km from west to east and 800 km from the most southerly to the most northerly glaciers. The strongest gradients tend to be north–south across the grain of the mountains. A predominantly southeast to northwest trend also introduces considerable climatic and ecological diversity. Rugged terrain and extreme elevations occur throughout and reflect a more than 50 million-year geological history of intense mountain building as described below.

The numbers of individual glaciers in the region have been estimated at around 50,000, over 7,000 of them in the Karakoram (Williams and Ferrigno 2010). The real numbers may be an order of magnitude greater if all minor ice masses are included. The glacier cover is, however, dominated by valley glaciers of exceptional size. Much of the greatest concentrations of glacier ice occur in a few dozen valley glaciers, tens of kilometres in length. Most of them are in the Karakoram (Plate 1.3).

North of the HKH are some small ice caps on peaks rising from the Tibetan Plateau. On the lesser ranges are many small valley glaciers, cirque glaciers and countless minor, avalanche-fed or ‘fall’ glaciers. Individual masses are tiny compared to the major valley glaciers but as a whole comprise substantial parts of the regional and global mountain ice. Those of the Karakoram exceed in total area the ice cover of the European Alps. Moreover, the smaller masses are commonly more critical for local water supply and ecosystems in the HKH than the larger glaciers. Equally numerous at high elevations are small and minor, disconnected glacier masses within the basins of larger valley glaciers. Mostly they form along the lee flank of interfluves, at breaks of slope and other irregularities. Repeated ice avalanches from their termini or icefall sections link them to the main glaciers.

**Plate 1.3** Biafo Glacier mid-ablation zone (ice surface approx. 4,000 m), an example of the large valley glaciers that dominate the Karakoram ice cover and comprise a large fraction of all HKH ice (Hewitt October 2010)

Differences among the various HKH glacierised mountains are related partly to elevation, the mass, ruggedness and alignment of the ranges, partly to latitude and the degree of continentality. Of special significance is location with respect to atmospheric circulation as it controls prevailing or seasonal air masses and how these, in turn, are affected by the high mountains. The more extensive ice covers occur on high ranges facing west, south or east, because they are the first encountered by moisture-bearing winds, respectively, from the western to eastern HKH.

These glaciers are all in more or less extreme continental locations, yet some even have ‘maritime’ qualities due to heavy snowfalls. Chinese inventories and classifications, for example, call glaciers ‘maritime’ if they receive at least 1,000 mm water equivalent of snowfall annually (Tandong 2007). Glaciers in much of the high Karakoram are ‘maritime’ in this sense. Although hemmed in by massifs of the Hindu Kush, Pamir and Northwestern Greater Himalaya, the Karakoram has sufficiently high elevation terrain to generate heavy winter and summer snowfalls (Chap. 4).

## 1.2 The Greater Karakoram Region

The Karakoram is the most heavily glacierised core of a mountain complex in the northwestern part of the HKH. It has a total area of about 60,000 km$^2$ and, as noted, about one-third is covered by perennial snow and ice. Other nearby mountains with lesser but substantial glacier covers are the Pamirs, Hindu Kush, Aghil, Kunlun and Kailas Ranges and the Zanskar and Nanga Parbat Himalayas. Together they comprise the 'South West Central Asian Mountain System' of the Vissers (Visser-Hooft and Visser-Hooft 1935–1938).[3] It serves to define the Greater Karakoram Region within the High Asian context.

The Karakoram glaciers extend over almost 5° of longitude and 3° of latitude.[4] The westernmost parts are 2° or, roughly, 220 km north of the eastern parts. Its glaciers are in the subtropics and some 10° south of the best-known ones of the European Alps. They are 6–7° north of the high Himalayan glaciers of Nepal, Bhutan and Sikkim, which are 660–770 km further into the tropics and much further east. Those of the Indian Himalaya, nearer to the Karakoram, are some 3–4° to the south. The geographical coordinates are associated with various ways in which the Karakoram glaciers differ from the others. However, more crucial are location relative to the circulation of the atmosphere and how the mountain masses affect that. The Everest Massif, for example, has a smaller perennial snow and ice cover and much smaller glaciers than, say, the Batura Mustagh or Haramosh Massif (7,409 m) in the Karakoram, which culminate almost 2,000 m lower.

Elevation is a recurrent theme in identifying and assessing features of high mountain ice. In the Greater Karakoram Region, the mountains that rise above 6,500 m are generally picked out by more extensive glacier covers. The large glaciers of the Karakoram are all associated with watersheds that rise above 7,000 m elevation, and the glacier cover increases in proportion to the height and extent of high elevations up to the highest, the K2 Massif (Chap. 2).

## 1.3 The High Asian Cryosphere

Glaciers are the main focus here but other cold climate or cryosphere phenomena interact with them and help to put glacial environments in context. Some occupy a much larger part of the Karakoram and High Asia generally.

Snowfall is a key concern in relation to glacier nourishment, water supply, ecosystems and climate change. Temporary or seasonal snowfall blankets most of the HKH and all of the Karakoram, varying in duration from days to over 11 months, and in depth with elevation and exposure to moisture-bearing winds. Snowfall is a larger source of streamflows than glacier meltwaters in the upper Indus and Yarkand Basins, on the Tibetan Plateau and High Asia river basins as a whole. The snowfall and glacier contributions exceed that of rainfall in HKH Basins except south of the Greater Himalayan crest where monsoon rainfall dominates.

Permafrost or perennially frozen ground comprises a vast area of Central Asia, the world's largest outside higher latitudes (Brown et al. 1997; Zhang et al. 2003).

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[3] With due respect to the Vissers, this is a mouthful and SWCAMS not much handier. 'The Greater Karakoram Region' is more manageable.

[4] That is from Long. 73° 50′ to 78° 10′ East and Lat. 34° and 36°50′ North.

The Tibetan Plateau contains the greatest area of continuous permafrost. The lower limits decrease from south to north over the plateau and increase in depth with elevation above the lower limit. The picture is more complex in the more rugged mountain terrain where permafrost tends to be discontinuous, interrupted by deeply incised valleys and limited by the dryness of rain-shadowed valleys and, on south-facing slopes, by the greater and more intense sunshine. Permafrost may occur beneath and beside glaciers, especially those with ice temperatures below freezing and frozen to their beds. In the Karakoram, permafrost extent exceeds the glacier cover and occurs throughout intermediate elevations. It can reach down as low as 3,500 m on north-facing slopes and down to 4,000 m or so on south-facing slopes.

It is thought that permafrost is diminishing over most of Central Asia, mainly due to climate warming (Cheng and Wu 2007; Zhao et al. 2010). Mountain permafrost in the HKH is likely to be equally or more sensitive to climate change (Haeberli and Gruber 2009). To date, there are no data that track what changes are happening in the Karakoram.

At intermediate elevations, permafrost is associated with what are termed 'periglacial conditions'. Unlike the perennially frozen high elevations, surface processes involve seasonal freezing and thawing, including a near-surface 'active layer' in permafrost (French 2011). In unconsolidated surface materials, patterned ground is observed, generated by needle ice growth and frost heaving. More generally, freeze–thaw processes are of interest in relation to water locked up in, or released by, melting of snow, glaciers, permafrost and other forms of ice (Harris and Murton 2005). Frequent freeze–thaw cycles affect most of the Karakoram below the perennial snow zone and, in summer, can involve south-facing slopes as high as 6,000 m (Hewitt 1968a). In midwinter, freeze–thaw is confined to the lowest valley areas. These cycles are associated with frost weathering, which can dislodge debris from surrounding slopes onto the glaciers. Permafrost is also present in the vast areas of rock wall in the glacier zone. At lower elevations, the countless talus cones, fans and aprons of debris below rock slopes and chutes indicate activity in which freeze–thaw has a major role (Hewitt 1968a). Steep rock walls will be shown to be the dominant landform in the Karakoram, playing a key role in what happens to snowfall in and around glacier basins (Chap. 8). Everywhere, on and below them, the work and deposits of snow avalanches are observed.

At elevations near and somewhat below where glaciers form, the combination of snow avalanches and debris falling from rock walls is a key to the widespread occurrence of rock glaciers. These are debris-covered lobes that resemble glaciers, typically moving very slowly and with steep rims (Chap. 11). They are closely associated with permafrost areas and periglacial processes. In the Karakoram, most occur in valleys below existing glaciers, sometimes issuing from them or seeming to have replaced former glaciers (Owen and England 1998; Shroder and Bishop 2010). They share some common features of location and genesis with the glaciers but are among the most neglected cryogenic features in the region.

In general, these other cryosphere phenomena have received much less attention than the glaciers, especially in the Karakoram, and there are only a few studies to draw upon. An effort will be made to sketch their main characteristics, but the lack of research limits definitive conclusions. It does seem important to identify questions for future research and how they are involved in environmental change (Chap. 12).

The Karakoram glacial environment is also singled out by the widespread occurrence of surge-type glaciers – ice masses that advance suddenly and quickly over exceptional distances in a few months or years. They may amount to as much as a third of Karakoram valley glaciers (Kotlyakov 1997; Hewitt 1998b, 2007). The Pamirs form the only other High Asian mountains with many surge-type glaciers, and there are few or none in the Greater Himalaya. This seems related to distinctive conditions in the Karakoram and raises major questions about the stability and dynamics of its glaciers and in tracking glacier change (Chap. 9).

Glacial lakes of small and large size are associated with glaciers and glacier change. A wide variety of impoundments is found in the HKH region, and there is a history of catastrophic floods (Chap. 10). In recent years, those posing unusual dangers of outburst floods have received particular attention (Richardson and Reynolds 2000; Mool et al. 2001; Kattelmann 2003). Reports suggest that climate warming and glacier retreat have increased the incidence of these lakes and dangers of outburst floods. How far, and in what way, this has affected the Karakoram will be shown to involve special problems, and concerns in relation to a history of very large ice dams (Hewitt and Liu 2010).

Another development concerning high mountain glaciers arises from increased evidence of catastrophic landslides in and near glacier basins (Hewitt 1988). They arise from the prevalence of steep rock walls around the glaciers and interact with the ice in ways that modify its behaviour and the fate of landslide materials. A sense of their importance has only emerged in the past couple of decades (McSaveney 2002; Hewitt et al. 2010). It now seems that many hundreds if not thousands could have occurred in the Greater Karakoram Region in the Holocene. They have had significant impacts on the advance and retreat of some glaciers (Hewitt 2009a).

The glacial legacy is not confined to today's perennial snow and ice areas. Much of High Asia was glaciated in the Quaternary and most if not all of the Karakoram one or more times. Throughout the upper Indus and Yarkand valleys, and far beyond today's glaciers, are ice-sculpted features and glacial deposits. In lesser and surrounding ranges of the Greater Karakoram Region are hundreds of glacial cirques and innumerable small lakes derived from glacial activity. Neoglaciation, glacier fluctuations since the last major glaciation, has also left distinctive marks. Of special interest is the 'Little Ice Age' (Kick 1989). It was the last major event of cooling and ice advance, which extended from roughly the fifteenth to the early twentieth centuries (Chap. 12).

## 1.4 Indus and Yarkand River Basins

The broad ecological, hydrological and human significance of the Karakoram glaciers relate to location in the Indus and Yarkand Basins and contributions to their rivers. Most of the meltwaters drain to the Arabian Sea through the Indus Plains,